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Virtual reality systems modelling haptic two-finger contact with deformable physical surfaces

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Abstract—**Real-time cloth simulation involves many computational challenges to be solved, particularly in the context of haptic applications, where high frame rates are necessary for obtaining a satisfying experience. In this paper, we present an interactive cloth simulation system that offers a compromise between a realistic physics-based simulation of fabrics and a haptic application meeting high requirements in terms of computation speed. Our system allows the user to interact with the fabric using two fingers. The required performance of the system is achieved by introducing an intermediate layer responsible for the simulation of the small section of the surface being in contact with the fingers. We compare several contact models to obtain the best compromise in the context of haptic applications.**

Index Terms—**virtual reality, haptics, deformable objects**

I. INTRODUCTION

Virtual Reality has a lot of applications ranging from entertainment to mechanical design and medical training. With the appearance of virtual worlds where users can interact via avatars over the Internet (e.g. Second Live), companies started to promote their products as virtual artifacts — another emerging application of Virtual Reality. Virtual reality systems can be categorised by the modalities they support. In today's systems the modalities of seeing and hearing are the most commonly employed as these are also the modalities in which we as human beings mostly exchange information. They require least effort in terms of energy transfer, the corresponding sensory receptors are concentrated in the retina and the cochlea and can be excited remotely with light and sound waves respectively.

In contrast to seeing and hearing the creation of appropriate haptic stimuli demands very sophisticated hardware. Firstly, the skin with its size of 1.5 to 2 square meters is a very large organ. Therefore most haptic devices focus on a rather small part of the human body — usually the fingertip. Secondly, forces cannot be transmitted contact-free with current technology. Thus haptic devices always need direct contact to the parts of the skin where the forces are applied. Thirdly, the amount of energy is relatively high compared to other modalities, e.g. if one wants to simulate the lifting of an object with a mass of 500 g the haptic device has to create a force of approximately 5 N. All these properties make haptic simulation a complex task still presenting a lot of problems awaiting a good solution. But these efforts will result in a richer, more convincing virtual reality making applications like the promotion of textiles via the Internet possible. The haptic device used for this work is described in Section III-A.

Although many objects may be simulated as static non-deformable objects, many applications demand the simulation of deformable objects, e.g. organs for medical training, deformable parts like flexible tubes for mechanical design or cloth for entertainment. An accurate physical simulation usually employs complex models that have to be numerically solved, whereas the real-time demands of Virtual Reality — especially haptics — require high update rates. A trade-off between these two requirements is offered in this paper for the modeling of fabrics. But the approach used here may be generalised to a larger class of deformable objects.

This work is part of the EU project HAPTEX. Its main goal is to develop a Virtual Reality system for visuo-haptic interaction with virtual textiles. Although the tactile simulation of fabrics' surface properties is also part of the HAPTEX project only the force-feedback rendering is described here. For a description of the tactile rendering see [1], [2]. The integration of force-feedback and tactile rendering into a single system is described in [3].

II. STATE OF THE ART

While graphical rendering has become quite sophisticated giving the user a from reality nearly indistinguishable view of objects, the haptic rendering still faces a lot of problems [4]. Most of these problems arise due to the bidirectional interaction with the user and his requirements in having a realistic impression of the feeling from virtual objects. The two main omnipresent problems in haptics are the stability of the force feedback and the short response time of 1 ms. The latter one is easy to solve for simple algorithms [5], [6], but to satisfy the user by having a more realistic behaviour like deformable objects it becomes quite difficult. In recent years, many solutions have been proposed to solve the problem of response time, i.e. by pre-computing the forces under deformation [7]. But a more widely used approach

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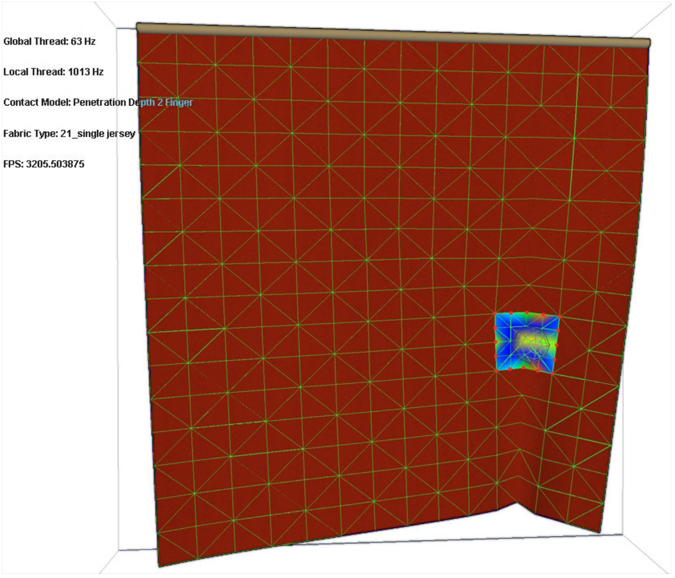
especially for deformable object was first introduced in [8]. The author proposes to use a local buffer model to generate the force outputs for haptic feedback. The local model reproduces the behaviour of the object under local deformation within the contact area. Furthermore, different models have been presented to simulate deformable objects for haptics, i.e. linear FEM [9], different meshes for local and global [10] or precomputed force functions [11]. The most sophisticated approach in haptic rendering has been proposed by [12]. The method is based on the Signorini contact problem commonly used in contact mechanics to model objects in contact. As a result of the comprehensive treatment of the contact it requires much computation time and cannot achieve full haptic realtime. Besides the response time the other aforementioned issue in haptics is the stability of the rendering which heavily depends on the device and on the rendering itself. Analysis of the stability has been contributed to the multirate rendering algorithms guaranteeing the stability between local and global model running at different update rates [13], [14].

III. VR-System Architecture

The goal of the HAPTEX system is to feature virtual fabrics that resemble as much as possible their real counterparts. Therefore a set of real fabrics has been selected and their physical properties have been measured (see [15]).

The simulated fabrics are square shaped with a side length of 20 cm. The user can select a fabric from the property database which is then simulated hanging from a stand (see Figure 1). The user can touch the virtual fabric with his thumb and index finger. The fabric can be squeezed, stretched, rubbed and lifted.



Global Thread: 63 Hz

Local Thread: 1013 Hz

Contact Model: Penetration Depth 2 Finger

Fabric Type: 21_single jersey

FPS: 3205.503875

Fig. 1. The virtual fabric hanging from a stand. (The area in contact with the fingertip is displayed in false colour to reflect the internal forces.)

In Figure 2 the haptic loop is depicted. During the interaction with the fabric the position of the user's fingers and the shape of the fabric change. Both is considered by the contact model that computes the forces affecting the finger and the fabric. Here a problem becomes evident: to create a convincing illusion and to avoid stability problems the system needs to react to the user's motion within one millisecond which is not possible involving the slower simulation of the fabric. However, note that the single loop depicted in Figure 2 can also be seen as two loops: one between the user and the contact model and the other between the simulation and the contact model. This view led to the solution described in Section IV. A dual-layer approach is employed there to allow the two loops to run at different speeds.

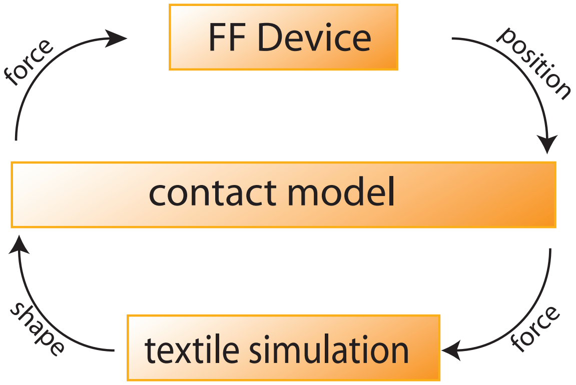


Fig. 2. The haptic interaction loop.

In the following sections we describe the hardware that allows the user to interact with the system (Section III-A) and the simulation of the fabric (Section III-B). Later on, in Section V, several aspects of contact models are treated. There we describe the solution chosen for the HAPTEX project.

A. System Hardware

The GRAB device is a force feedback device consisting of two identical and independent robotic manipulators (see Figure 3), each having the base link fixed to the desktop and the end-effector (contact part) attached to the palmar surface of the user's thumb or index fingertips. Each manipulator measures the absolute position and orientation of the contact part. These are used by the haptic renderer to compute an appropriate force. The manipulator is able to generate this force on the contact part within a workspace of 400 mm in width, 300 mm in height and 200 mm in depth. The workspaces of both manipulators overlap. Force errors are limited in a range of about +/- 10 grams (0.1 N). The device can exert forces up to 20 N. The GRAB device used for the HAPTEX project is described in [16].

B. Textile Simulation Method

The simulation of the fabric has to ensure that the mechanics are modeled appropriately while keeping the computational costs low to reach real-time requirements. For the simulation of large scale deformations it is necessary to use a nonlinear model to reflect the behaviour of textiles correctly. At global

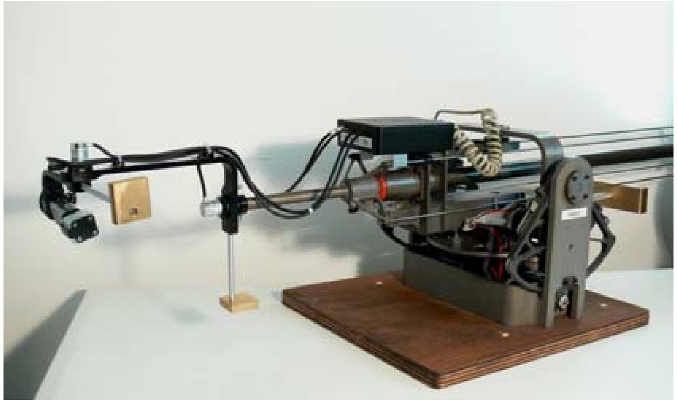


Fig. 3. The modified GRAB device (only one arm shown).

level we therefore use the textile simulation library from [17], which uses spline curves to reproduce this nonlinear strain-stress relationship according to real measurements.

We analysed different approaches [18], [19], [20], [17] to realise a local model fulfilling our different requirements. Thus, for our local geometry a linear mechanical model was best suited as it is fast and accurate enough. It also provides sufficient flexibility in contact formulations due to its low computational demands. Therefore we are able to increase the complexity of our contact model to ensure the precision we need to drive the haptic interfaces.

1) Local Mesh Topology: The textile is discretized using particles that incorporate the physical properties of the surface. The surface topology itself is stored in a triangle surface defining relationships between the particles. Being independent of the implemented dynamic refinement algorithm, the force functions evaluated at each triangle have to consider the orientation in parameter space accordingly. Moreover, the evaluation of bending force requires the surface curvature as an input parameter. The determination of these parameters without efficient data structures for the different kinds of geometric queries can be costly. Thus, we decided to use a half-edge data structure which is well suited for such queries.

2) Force Computation: In our mass/spring system we describe the occurring forces in the deformation of the textile in each triangle by looking at the change of the unit warp and weft-vectors. Afterwards, the forces are integrated over the triangle and distributed among the particles.

a) Stretch / Tensile Force: The stretch forces are measured by the elongation in warp and weft direction. For the simulation of these forces we have to know the elongation of the unit warp and weft vectors at each point which define the rest state. Assuming the stretch is constant over a triangle leads to a single computation for warp and weft directions.

This yields the following equation:

$$(W_u W_v) = (P_2 - P_1 P_3 - P_1)(x_2 - x_1 x_3 - x_1)^{-1}$$

where the term on the right hand side remains constant under deformations. By the given length of the warp and weft vectors, an approximation the corresponding force within a triangle can be obtained.

b) Shear forces: Shear forces are generated by a movement parallel to a fixed axis. The forces measured by the Kawabata System are determined by the inner angle between warp and weft direction. Therefore we compute the angle between those respective directions to evaluate the force at the current angle.

c) Bend forces: Forces generated by bending are important for folding behaviour. In our representation of the textile folds can only be aligned to edges of the triangles. The occurring forces are proportional to the angle Θ between two neighbouring triangles. Thus we need to compute the required angle in order to apply the force generated by bending. In contrast to shear and tensile forces, bending forces are not evenly distributed throughout the triangle. In the computation only the opposite vertices of an edge are affected by this force as the other particles are corresponding to the fold.

Although the determination of the edge angle is fairly easy, the measurements cannot be used right away as the values are given in moments (M) to curvature (K). Thus we have to transform them as in [21]. An approximation of the normal curvature K orthogonal to the edge can be computed by following formula:

$$K = \frac{2}{\sigma} \cos\left(\frac{\Theta}{2}\right)$$

where σ denotes the mean distance between edge and opposing particles. Treating the yarns within the triangle as elastic beams of length l leads to the formulation of the occurring force:

$$F_b = \frac{M}{l}$$

d) Damping forces: All aforementioned internal forces result from the absolute position of the textile. But it is also important to incorporate forces which relate to the movement. These damping forces have to be considered not only for modelling the energy dissipation during the deformation but also for the stability of the simulation which would otherwise cause the simulation to oscillate. The damping forces are counteracting to stretch, shear and bend motion. As each case is independent, the impact of damping is computed separately. For modelling the damping, motion/velocity vectors of the particles are projected along the direction of each force. The obtained values can now be used with a damping factor to generate an opposing force. Additional external damping forces are disregarded as they are too small to have an effect upon the deformation of local part of the textile.

IV. DUAL LAYER APPROACH

Achieving a convincing virtual textile simulation requires a good compromise between the need for accuracy in the material representation and the need for speed for obtaining simulation frame rates compatible with real-time perception. These factors have to be considered both in the visual and the haptic fields. However, the graphics rendering loop has different requirements compared to the haptic rendering loop in terms of refresh frequencies. While in graphics a refresh rate of 30 fps is quite acceptable, in haptics a response frequency of 300–1000 Hz is needed to ensure accurate interaction. A dedicated structure has therefore been defined for adapting the different frame rates required by the mechanical simulation and the haptic rendering computations. Hence, two separate computation threads were implemented: The first is a low-frequency thread for dealing with the complex large-scale simulation of the whole cloth surface, and an accurate particle system representation integrated with state-of-the-art numerical methods for achieving quantitative accuracy of the nonlinear anisotropic behavior of cloth in real-time. The second is a high-frequency thread for computing the local data necessary for haptic rendering and for accurately sending haptic forces back to mechanical simulation.

The force feedback thread is implemented by the driver of the GRAB device, i.e. in the kernel space of the operating system. This guarantees a reliable frame rate of 1 kHz. As the haptic renderer is implemented within the user space of the operating system it has to provide a method to the driver, which receives the position and orientation of the contact parts of both robotic manipulators and sends appropriate forces back to the driver.

Maintaining the update rate in the high-frequency thread requires that we restrict ourselves to a small section of the surface for physically accurate interactions. The motion area is well defined by the position of the cursor and its finite velocity. Hence, we can define a proximity region given by a bounding sphere restricting the volume where the cursor and the surface may possibly have contact. Restricting our local consideration and computation to be performed in the haptic loop to the parts of the surface in the bounding sphere allows us to reduce our computation effort to a minimum. This so-called local geometry is used for our computations in the high-frequency thread.

Due to the small deformations occurring in a time frame of milliseconds, the mechanics can be described sufficiently well by the laws of elasticity neglecting external forces like gravity. As a result we can use the simpler spring-mass-model to model the local geometry under deformation without loosing much accuracy compared to the physically precise mechanical model.

To prevent the local geometry, i.e. the small section of the surface in contact with the haptic cursor, from diverging too far from the main mechanical simulation we assume constant velocity at its border. This implies that no forces affect the particles on the border of the local geometry.

The flow of data within the haptic rendering is depicted in Figure 4. The architecture of the renderer is conceived to functionally separate the stages in the haptic interaction. Apart from performance gains on multi-core systems the design allows to work independently on different parts relevant for the complete integration of all hard- and software components provided by the partners.

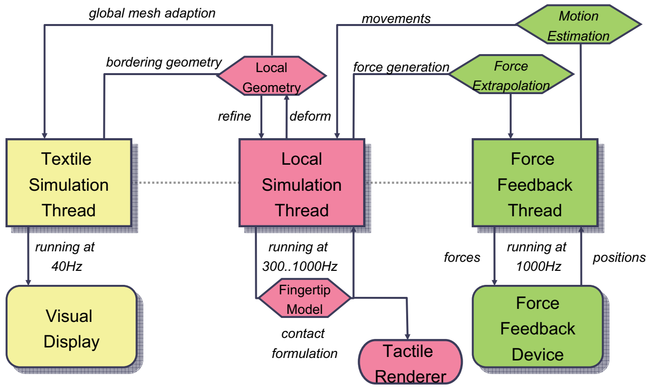


Fig. 4. Threads of the HAPTEX system.

Figure 5 depicts the chronological order of events in the communication between the components. In the initial stage all threads are running at their dedicated update rate. The force-feedback thread is constantly fetching new positions from the force-feedback device. These positions are processed to predict the user's motion and to estimate the next position. At the same time the (global) textile simulation thread is computing the deformations of the global model caused only by gravity, while the local simulation thread waits for new local geometries to simulate.

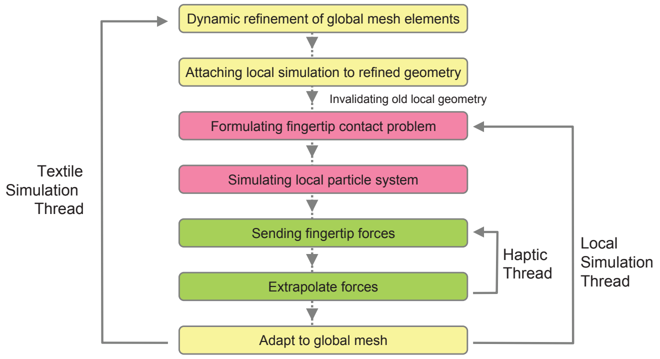


Fig. 5. Sequential order of communication.

At each simulation step of the global thread it receives fingertip dimensions, the current position and the predicted position. The global thread analyses its underlying mesh for potential collisions with the fingertip for the next time step. These parts are sent to the local thread to be refined and inserted into the local simulation. Afterwards both simulation threads continue to run according to their data.

With the newly added local mesh, the local thread checks if a collision has taken place in between the last two local simulation time steps. In case of a contact the occurring deformation of the local part of the textile is computed according to the fingertip model used. The forces at the fingertip generated during the contact are sent to the force feedback thread. When the next global time step is reached the changed geometry of the local mesh and the present forces in the local simulation are transferred to the global model.

V. CONTACT RENDERING

It is certainly desirable to express all possible contact states within a single contact model. However, real-time demands and stability issues dictate the use of several contact models specialised to different contact states.

Table I lists the possible contact states. The fabric is in contact either with zero, one or two fingers. The model of the system also depends on whether the fingers touch each other or not. Note that ”touch” is also used in this context if there is a fabric between the fingers, i.e. the fabric is squeezed by the two fingers. The third property determining the contact state is the kind of friction to be used, i.e. whether friction is static or dynamic.

Fingers touch	no		yes	
Friction	static	dynamic	static	dynamic
no contact	I		II	III
one contact point	IV	V	–	–
two contact points	VI	VII	VIII	IX

TABLE I
POSSIBLE CONTACT STATES.

When there is no contact at all, i.e. the fingers neither touch each other nor touch the fabric, friction certainly does not occur. Therefore the contact state is independent of the kind of friction in this case.

In the HAPTEX system the index finger is always assumed to be in contact with the back side of the fabric only whereas the thumb’s contact is restricted to the front side. Furthermore the mechanical setup restricts the contact between the fingers to the palmar part of the fingertip. As a result it is not possible to have only one contact point while the fingers touch each other.

The different contact states shown in Table I can be expressed with the models which are described in the following sections.

A. *Contact state I: Zero Force*

In this contact state the fingers neither touch each other nor touch the fabric. As a consequence no contact forces occur. The implementation of this contact model is very simple as it always returns a contact force of 0 N.

B. *Contact states II and III*

These states define the rendering of the contact force of the two fingers when no textile is in between. The Coulomb friction model is chosen to determine the (friction) states of the haptic response when the finger are moved against each other. By observing the movement of index finger in the reference frame of the thumb, we can apply the proxy model [5] since we have only one finger moving whereas the other is fixed. Note that it makes no difference which finger is chosen as frame of reference because the force will act on both fingers and changes its sign only. In case of an intersection of the two fingers the proxy is placed on the thumb surface in relation to the touching point of the fingers (given by eq. 1). The penetration depth d is used for computing the normal force. The force function used to compute the normal force F^N is based on the instantaneous elastic response of tissue. It is expressed by the following term:

$$\frac{b}{m} \cdot \left(e^{m \cdot d} - 1\right) \tag{1}$$

where the experimentally determined constants of [22] $m = 2.1mm^{-1}, b = 0.19\frac{N}{mm}$ are the mean of the measured deformation force responses. We also need to address the tangential friction due to the movement of the fingers against each other. A potential next proxy position is given by the device at a new time step and the aforementioned positioning rule. Based on the distance Δx between both proxy positions, the tangential force F^T is estimated by a spring with an artificial stiffness parameter. Together with the obtained normal force the stick-slip condition 2 is then checked to determine the proxy movement.

$$F^T \leq \mu_s F^N \tag{2}$$

If the condition holds, the proxy remains on the actual position and the combined forces F^N, F^T are sent to both fingers. Otherwise the proxy is moved towards the next proxy position to fulfill the condition and the tangential force is recomputed according to the dynamic friction.

C. *Contact states IV, V, VI and VII: V-Proxy*

For dealing with contact situations in haptic interactions an abstract object called *God-object* or *Proxy* was introduced by [5]. It is a point-like object unable to penetrate other objects. It therefore follows in contrast to the position of the force-feedback device the physical laws defined in our virtual environment (see Figure 6). The proxy follows the force-feedback device, as long as the user’s movement does not intersect an object. However, in these contact states the finger touches the fabric whereas the proxy is set on the object’s surface and a virtual spring is placed between the force-feedback device’s position and the proxy. The spring constant is chosen according to the combined elasticity k^K of the touching objects. By moving the proxy to the point with the shortest distance to the device position the spring’s potential energy will be minimized.

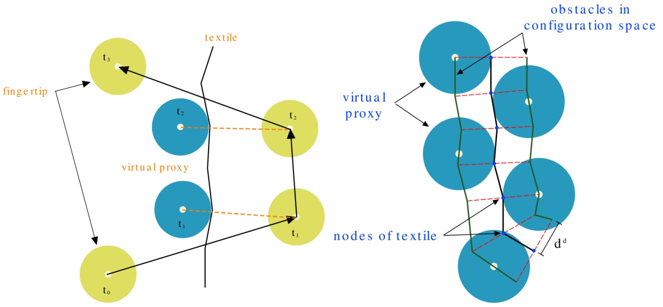


Fig. 6. Trace of proxy in accordance with device position (left), possible proxy positions in configuration space (right).

An extension of the algorithm was made in [6] and [23] to support contact rendering with arbitrarily shaped proxies. Obstacles and collisions are observed within the configuration space. The configuration space is defined as the space of possible positions the proxy may attain, possibly subject to external constraints. Instead of looking for a valid position on the obstacle, a position on the border of the configuration space is chosen.

For friction modelling the movement of the proxy is controlled. The force resultant of the force-feedback device is computed by

$$F^d = k^K \|x^p - x^d\|.$$

To distinguish between static and kinetic friction we separate the force F^d into tangential F^T and normal F^N components. If the forces satisfy the stick condition equation as seen below, we use static friction.

$$F^T \quad < \quad \mu_S F^N$$

If this condition holds the proxy position is constrained. Otherwise a different constraint for the movement can be found. Combining the generic motion and kinetic friction equation yields the following proxy motion equation

$$F^d - \mu_K (F^d \cdot n) \frac{\dot{x}}{\|\dot{x}\|} = m\ddot{x} + b\dot{x}$$

restricting the velocity of the proxy.

D. Contact states VIII and IX: Two Finger Model

These contact states deal with the two finger textile contact. In the previous section we have applied a finger contact model based on the virtual proxy model but for this specific case of having the textile between the fingers the proxy model is unsuitable. This is mainly due to the algorithm finding the local minimum of the distance between proxy and the haptic device position. If we have a situation of the proxies lying on opposite sides of the hanging textile, a slight movement in a direction normal to the textile can cause the proxies to move around each other. This unwanted movement is a result of the deformation caused by the corresponding proxy in the movement direction. The pushing finger will increase the curvature at the contact point and produce a focal point near the surface leading to an unstable solution in the minimal distance search for the other proxy. For that reason we created a more stable approach enforcing the fingertips to remain at the contact in the following way: Firstly, reaching the state of the two finger model requires a set of same collision points being the particles of the textile mesh found by the collision detection. These points are treated solely by this model and are disregarded by the previous models. As the collision detection works in preparation to the models it classifies the contact points according to their contact state. Therefore it is possible to fold the textile over one finger while having it tightly grasped with both fingers. In the latter case we use a shared frame of reference using the intersection line of the two fingers and its perpendicular bisector as axes. We assume the contact surface of both fingers to be planar with respect to the finger deformation. According to the orientation of the fingers the colliding particles are projected onto the plane as illustrated in 7. The desired position of the textile particles results in this projection for every update of the haptic device. In the initial state we assume the particles to be in static contact. Consequently, we keep the initial positions in the local frame of reference to define the new positions upon the haptic update. The distance between ideal and actual positions of each textile particle is related to the force applied using a nonlinear spring. By doing so, we force each vertex of the textile mesh inside the two finger collision area to move towards the contact plane defined by the current finger positions.

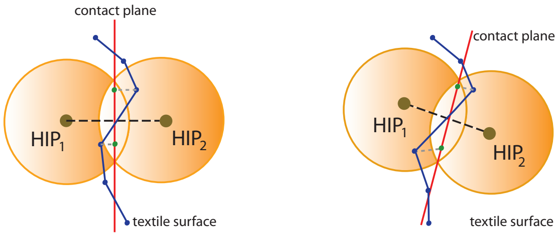


Fig. 7. Handling of textile nodes with two finger contact

VI. SYSTEM EVALUATION

The evaluation of the proposed model is required to ensure the that all relevant features are transmitted by the system allowing the user to assess the mechanical properties of the hanging fabric. While for the visual the most important feature is the dynamics of the textile, whereas it is for the haptic perception the static behavior. We therefore focused in a first evaluation on static tests verify the correct transmission of forces between the model and the user. At the next step we are going to verify the contact forces that are sent to the haptic device. By defining a fixed movement of the fingers reproducing the grasp and stretch we are able to observe the transitions between the friction states. Furthermore, it is foreseen to validate the dynamics of the simulation by video motion analysis of real textiles with a defined contact action in comparison to the virtual counterparts.

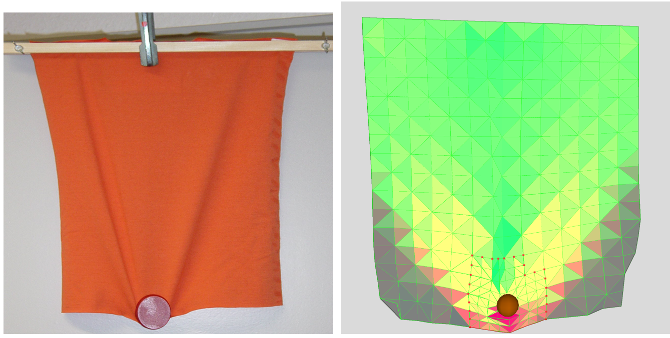


Fig. 8. comparison between real and simulated deformation during contact

A preliminary validation has been conducted to compare the simulation with the real deformation of a hanging fabric. The test setup consisted of a fixed fabric with dimensions of 20cm x 38cm as seen in figure 8 on the left. We applied a static force at the bottom of the fabric and measured the elongation in the force direction. Moreover, we varied the force from 0.4N up to 2.4N to determine the deviation of the model. As the result we got a maximal error of 4mm at 2.4N in the simulation which is smaller than 1% of the total length of the textile.

VII. CONCLUSION

Haptic interaction with deformable physical objects poses a lot of interesting challenges. Due to conflicting requirements in terms of physical accuracy and computation speed a compromise has to be found. In this paper we presented our approach largely satisfying both requirements. The idea is to introduce an intermediate layer simulating the part of the deformable object that is in contact with the user. In this way we can accurately model the mechanics of the contact in real-time while still considering the global behaviour of the deformable object. The solution presented in this paper is tailored to the interaction with virtual fabrics but may be generalised to a larger class of deformable objects.

Unlike many other haptic rendering systems our renderer allows for more than one contact interaction, namely with the user's thumb and index finger. This poses additional challenges to be met. To avoid stability issues we decided to use several contact models specialised to different contact states, making almost optimal use of the computation power available.

The system described abouve was specifically designed for the GRAB force-feedback device. Within the HAPTEX project a Hand Exoskeleton is currently developed (see [24]) which will be investigated as an alternative to the GRAB device. This device was designed for the specific needs of the HAPTEX project. The system described in this paper will be adapted to this new device in the near future.

Part of the HAPTEX project is also the tactile simulation of the fabric's surface. Therefore the force-feedback device will be equipped with a tactile display. The integration of force-feedback and tactile rendering is described in [3].

A. General Perspective

On a general level the system at hand requires a description of the energy transfer between parts of the deformable objects and between the deformable object and the human user. Typically this energy exchange takes place and becomes visible via the boundary surfaces (e.g. via their deformation) of the 3-D objects being involved suggesting the development of appropriate boundary models of the respective objects mimicking the physics of 3-D-volumetric objects. The transmission of energy defining the physical process becomes visible and measurable via physical signals displaying changes of the physical states of the respective objects. Some of the physical signals result in "biological signals" in the human user involved in the interaction with deformable objects. To some extent the aforementioned biological signals create "perceivable signals" e.g. needed by humans to control the interaction with objects. At this point two key problems become important. In order to create a realistic haptic / tactile illusion by our VR-system we have to find simplified models telling what physical or biological signals create equivalently perceived signals or illusions. Examples for the latter are presented by the RGB-, CMY-, CIE-color models describing different physical signals creating equivalently perceived colors. Examples for this are also given by our recent research (see [1]) on tactile colors modeling different vibrations causing equivalent perceptions of roughness. Furthermore it is well known that in acoustic data compression psycho acoustical models are used to describe simplified acoustic signals being perceived as equivalent to more complicated acoustic signals. Vice versa we must deal with the inverse problem of the aforementioned one. Here we must find out when our perception distinguish physically different (multimodal) signals and can attribute these signals to different e.g. haptic, tactile, visual features? Therefore the latter problem may be viewed as task to model some basic cognitive capabilities of our haptic/tactile perception. The work presented in this paper may be seen as a part of this general perspective.

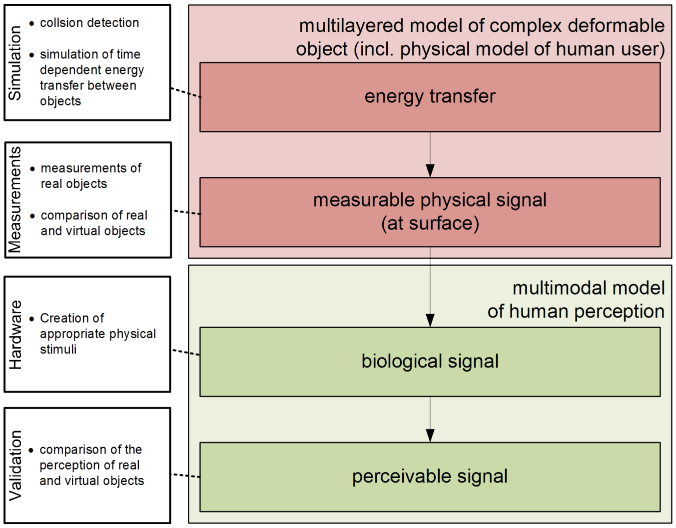


Fig. 9. Overview of the issues and problems involved in a systematic treatment of haptic rendering.

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