From Physics-based Simulation to the Touching of Textiles: The HAPTEX Project

N. Magnenat-Thalmann, P. Volino, U. Bonanni, I. R. Summers, M. Bergamasco, F. Salsedo and F.-E. Wolter

***Abstract*—While the animation and rendering techniques used in the domain of textile simulation have dramatically evolved during the last two decades, the ability to manipulate and modify virtual textiles intuitively using dedicated ergonomic devices has been definitely neglected. The project HAPTEX combines research in the field of textile simulation and haptic interfaces. HAPTEX aims to provide a virtual reality system allowing for multipoint haptic interaction with a piece of virtual fabric simulated in real-time. The fundamental research undertaken by the project ranges from the physics-based simulation of textiles to the design and development of novel tactile and force-feedback rendering strategies and interfaces.**

***Index Terms*—Cloth simulation, haptics, virtual reality.**

I. INTRODUCTION

Designing and manufacturing clothes requires fashion designers to create garment patterns, build garment models on mannequins to assess the fitting and drape, and possibly correct the design if needed. This loop makes the creation of garment prototypes a complex process with several constraints which significantly limit the designer's creativity. In this context, virtual simulation of garments is a great help for fashion designers not only to speed up their creative work, but also to bring their creations to life through high-quality mechanical simulation on animated characters. Also, simulating ancient cloth materials can bring old heritage garments back to life.

Because of its applications in the textile industry, its benefits for the artistic garment design process and its use within the movie and entertainment industry, cloth simulation is a popular topic in the computer graphics research community, and the cloth animation and rendering techniques have dramatically evolved during the last two decades [1]. However, while there have been spectacular advances in the visual realism of simulated clothes, there has not been a similar progress in the related interaction modalities. The ability to manipulate and modify virtual textiles intuitively using dedicated ergonomic devices has been definitely neglected. Humans are used to handle clothing materials with their hands since prehistoric ages. Nowadays, comparable interaction methods for handling virtual textiles do not exist, and the limits imposed by the use of mouse and keyboard decrease many a potentiality. Using the sense of touch to interact with computer-simulated clothes would significantly increase the realism and believability of the user experience and ease the creation process of virtual textiles. Moreover, being able to render the feeling of touching digital clothes would introduce a completely new way of communicating 3D products, e.g. during the online purchase of garments or when assessing the fabric hand of specific materials.

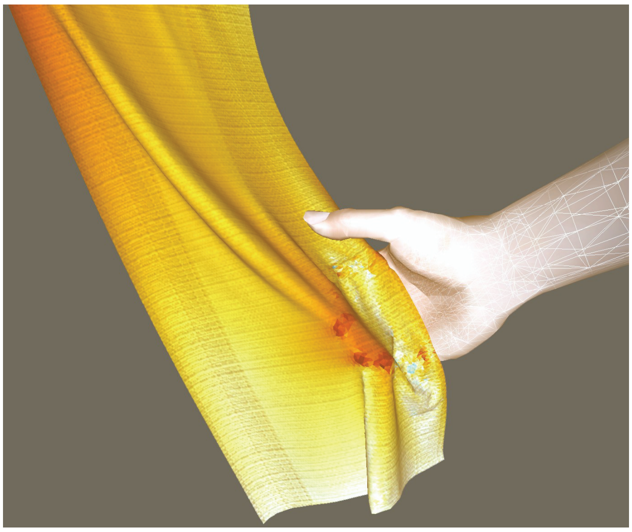

Fig. 1. HAPTEX aims to provide a VR system allowing for haptic interaction with virtual textiles. See Color Plate 12.

The vision of stimulating both the sense of vision and touch when interacting with virtual textiles is the leitmotif of the project HAPTEX. The project acronym stands for "HAPtic sensing of virtual TEXtiles". Haptics refers to technology interfacing the user via the sense of touch. The main goal of HAPTEX is to provide a multimodal system able to simulate virtual textiles in real time, allowing multipoint haptic interaction with a piece of virtual fabric [2], ideally depicted by Fig. 1. In the HAPTEX system, haptic manipulation takes place through a novel haptic interface, which provides both force and tactile feedback and aims to reproduce the feeling of touching a cloth surface with two fingertips. Both the visual simulation and the haptic rendering are based on the physical properties of real textiles. The HAPTEX project tackles the challenge of providing a virtual reality system for manipulating virtual textiles and undertakes fundamental research ranging from the

Manuscript received July 10, 2007. This work was supported in part by the project "HAPTEX - HAPtic sensing of virtual TEXtiles", funded by the Sixth Framework Programme of the European Union (Contract Nr.: FP6-IST-6549).

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physics-based simulation of textiles to the touching of virtual garments.

This paper describes the use of measured physical parameters of real textiles in the domain of virtual textile simulation and recent advances in the HAPTEX platform, an interactive real-time haptic system for touching virtual textiles. Section II explains the challenges in the domain of textile simulation, giving an overview of the physical parameters of cloth and the real-time method used in the HAPTEX Project. Section III describes the force and tactile rendering strategies, while Section IV and V deal with the tactile and force-feedback hardware components respectively, which have been designed and developed in the context of HAPTEX. Section VI concludes this paper with a brief description of the final HAPTEX demonstrator and future work.

II. TEXTILE SIMULATION

Clothes are composed of sets of textile patterns, and are very difficult to simulate because of their complex viscoelastic materials properties. Moreover, textile simulation faces several challenges:

- The intricate and highly variable shape of garments, which interact through complex contact patterns with the body (which is itself a complex deformable entity) as well as with other garments.
- The highly deformable nature of cloth, which translates very subtle mechanical variations into large draping and motion variations that modify completely the visual appearance of garment models.
- The highly intricate anisotropic and nonlinear mechanical behavior of garments, requiring accurate measurement, modeling, and complex numerical methods for their resolution.

Modeling the behavior of textiles is a complex task because of its dependency on several parameters such as flexibility, compressibility, elasticity, resilience, density, surface contour (roughness, smoothness), surface friction and thermal character [3]. Textiles must have sufficient strength and at the same time they have to be flexible, elastic and easy to pleat and shape.

Research on cloth modeling started in the 1930s, when the textile engineering community started to measure fabric parameters and analyze the handle of cloth as a measurable quantity [4].

2.1 Mechanical and Physical Parameters of Textiles

Today the main mechanical and physical properties of textiles can be obtained from objective fabric characterization methods. The garment industry needs the measurement of major fabric mechanical properties through normalized procedures that guarantee consistent information exchange between garment industry and cloth manufacturers. The Kawabata Evaluation System for Fabric (KES) is a reference methodology for the experimental observation of the elastic properties of the fabric material [5]. Using five experiments, fifteen curves are obtained (Fig. 2), which then allow the determination of twenty-one parameters for the fabric, among them all the linear elastic parameters described above, except for the Poisson coefficient.

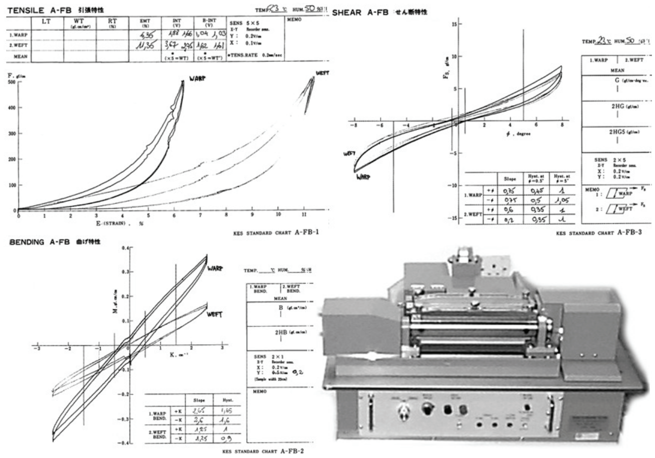

Fig. 2. Measuring cloth properties using KES.

Five standard tests are part of KES for determining the mechanical properties of cloth, using normalized measurement equipment. The tensile test measures the force/deformation curve of extension for a piece of fabric of normalized size along weft and warp directions along with other parameters assessing nonlinearity and hysteresis. The shearing test is the same experiment using shear deformations. The bending test measures the curves for bending deformation in a similar way. Finally, the compression test and the friction test allow the measurement of parameters related to the compressibility and the friction coefficients. While the KES measurements allow determination of parameters assessing the nonlinearity of the behavior curves and some evaluation of the plasticity, other methodologies, such as the FAST method, use simpler procedures to determine the linear parameters only.

The Kawabata measurements and similar systems summarize the basic mechanical behaviors of fabric material. However, the visual deformations of cloth, such as buckling and wrinkling, are a complex combination of these parameters with other subtle behaviors that cannot be characterized and measured directly. In order to take these effects into account, other tests focus on more complex deformations. Among them, the draping test considers a cloth disk of given diameter draped onto a smaller horizontal disc surface. The edge of the cloth will fall around the support, and produce wrinkling. The wrinkle pattern can be measured (number and depth of the wrinkles) and used as a validation test for simulation models.

Tests have also been devised for measuring other complex deformations of fabric material, mostly related to bending, creasing and wrinkling.

Fabric parameters provide essential information for achieving an accurate reproduction of the mechanical behavior of textiles in terms of draping and motion. These measured parameters can serve as input for physically based textile simulation models and represent a stringent requirement for a realistic computer simulation. Despite the complexity involved in cloth simulation, computation algorithms have been developed over many years and evolved to such a level so that today we are able to not only simulate simplified, static clothes, but also complex dynamically moving garments [6].

2.2 The HAPTEX real-time Textile Simulation

In the context of interactive haptic applications, textile simulation is constrained to real-time performance. Here, the challenge is mainly to combine state-of-the-art simulation techniques that offer the best trade-off between computational speed, accuracy and robustness. Additional challenges stemming from real-time requirements include:

- The design of a fast simulation system for simulating the tensile and bending elastic properties of cloth materials, which may possibly be anisotropic and nonlinear.
- The implementation of an efficient numerical integrator that offers robust simulation ensuring stability despite possible irregular frame rates and other artifacts related to motion tracking techniques.

The first approach of real-time garment simulation is to optimize usual cloth simulation methods for better performance. This is usually carried out through the use of particle systems, which allow simple computation of approximate mechanical models. Spring-mass systems are typically used in this context. When high accuracy is still needed, some particle systems allow the expression of viscoelastic materials with the accuracy of continuum mechanics [7, 8].

In order to obtain sufficiently high frame rates at reasonable simulation accuracy, the HAPTEX system limits the size of the textile to be simulated. Most of the existing approaches use a general-purpose simulation method using collision detection and physical simulation for the whole garment. Unfortunately, simulations that simply calculate all potentially colliding vertices may generate a highly realistic movement, but do not provide a guaranteed frame time. The HAPTEX Project required a new simulation model avoiding heavy calculation of the collision detection and particle system wherever possible. The goal of this model is to simulate the nonlinear and anisotropic behavior of cloth materials, which are typically described as strain-stress curves measured along the weft, warp and shear deformation modes [9]. The major challenge is to find the best compromise between the high requirement for mechanical accuracy (quantitative accuracy with anisotropic nonlinear strain-stress behavior) and the drastic performance requirements of real-time and interactive applications. One of the most efficient solutions is to take advantage of the particle system described in [8]. The mechanical model is indeed based on continuum mechanics, but is still a particle system. Hence, it follows many of the properties initially found in finite elements [10]. Basically, the system evaluates the strain of each triangle element according to the position and speed of the particles, then uses the mechanical properties of the material for computing the stress of the elements, and converts back the stresses into equivalent particle forces.

This scheme has strong analogies to first-order finite elements. However, we have carried out some developments aimed at significantly improving the computation speed without too many sacrifices in the accuracy. Among these developments, computational simplifications are obtained by avoiding the computations required for the linearization of the strain and stress tensors [11]. Furthermore, an adapted accurate computation of the Jacobian is implemented for ensuring numerical stability even with very severe deformations [12]. Our system offers all the performance and flexibility related to particle systems, particularly trough the possibility of handling directly geometrical constraints such as collisions. Bending stiffness should also be considered. However, bending forces are quite low in actual cloth materials, and through the use of large elements, it becomes quite useless to waste computation time evaluating forces that have almost no effect in the simulation. Still, when stiff bending forces are to be considered, new fast linear bending simulation schemes [13] may offer a very good computation compromise.

The discussed real-time textile simulation method is used in the HAPTEX System to display the virtual textile and calculate its deformation on a large scale. For the above mentioned haptic interaction with the textile, however, another computation layer needs to process the forces arising during the haptic interaction, in order to render the tactile and force feedback to the user.

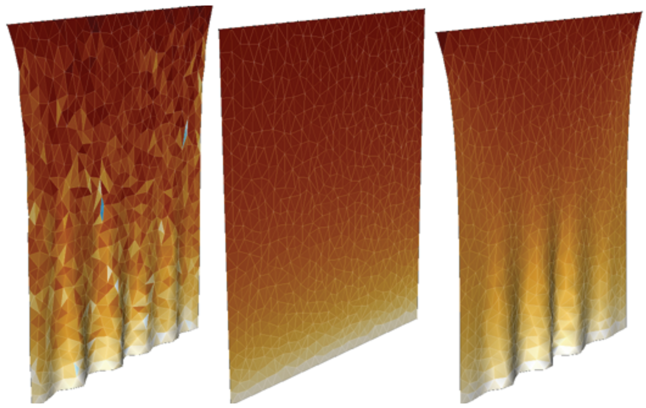

Fig. 3. Drape accuracy between a simple spring-mass system along the edges of the triangle mesh (left) and the proposed accurate particle system model without (center) and with (right) transverse shrinking. Colorscale shows internal strain.. See Color Plate 13.

III. HAPTIC RENDERING

The compromise between accuracy and speed mentioned for the achieving real-time performance in the textile simulation has to be considered also in the haptic rendering layer. 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 running the large-scale textile simulation of the whole cloth described in Section II. An efficient non-linear minimization method computing spline functions approximating the aforementioned non-linear strain-stress curves is presented in [14]. The second thread is a high-frequency thread for computing the local data necessary for haptic rendering and for accurately sending haptic forces back to mechanical simulation.

Although parallelization is possible, we also synchronize the threads as follows: in the initial stage all threads are running on 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 caused only by gravity. The local simulation thread waits for new local geometries to be simulated. At each simulation step of the global thread the local thread receives fingertip dimensions, the current and predicted position. The global thread analyses its underlying mesh with respect to potential collisions with the fingertip for the next time step. These regions including their physical states are sent to the local thread in order to be geometrically 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 any collision has taken place in between a local simulation time step. In case of a contact the occurring deformation of the local part of the textile is computed according to the fingertip model being used. The forces at the fingertip generated during the contact are sent to the force feedback thread.

The contact area estimated by the contact model is transmitted to the tactile renderer whereby for each pin a contact force is computed. According to the defined positions of the pins on the finger the local velocity is also provided.

The schematic in Fig. 4 shows the separation of the computational tasks into the different threads.

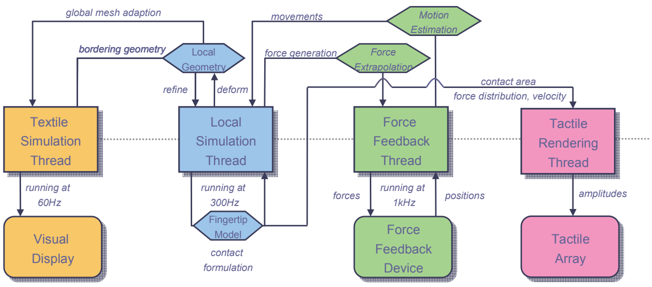

Fig. 4. Different threads within the HAPTEX system. See Color Plate 11.

3.1 Force-Feedback Rendering

The force-feedback renderer is responsible for the modeling of the interaction between the fingertip and the fabric. This implies the computation of forces occurring at the contact considering the physical properties of the objects involved. In the haptics literature there exist several approaches to render contact forces. In [15] an effective point-based rendering algorithm was firstly introduced and constantly improved by others, i.e. [16, 17]. Ruspini et al. [18, 19] extended the algorithm to support contacts of arbitrary shapes. In contrast to the well known proxy method a recent approach (see [20]) suggests to compute the contact forces by solving the Signorini contact problem employing finite elements. The latter method models the deformation of the fingertip at the contact appropriately. However it is consuming precious computation time because it requires iteratively solving non-linear equation systems. A good compromise between accuracy and computational effort is offered by a penetration or penalty-force based method, which computes the force as a result of the contact proportional to the penetration depth or intersecting volume. The depth is given as the length of the vector defining the shortest translation of the colliding bodies to a touch situation. For computational reasons we use the penetration depth for force calculations.

The mechanical equivalent to the aforementioned situation can be described by a spring attached to both bodies enforcing repulsion in case of a collision. The forces being applied on both bodies are computed by the length of the depth vector and differ only in the direction. If no additional external forces are applied, then after several simulation steps the bodies will reach force equilibrium as depicted in Fig. 5. At this stage the bodies are still intersecting. In this strategy the fingertip is modeled as a rigid sphere being the first contact body.

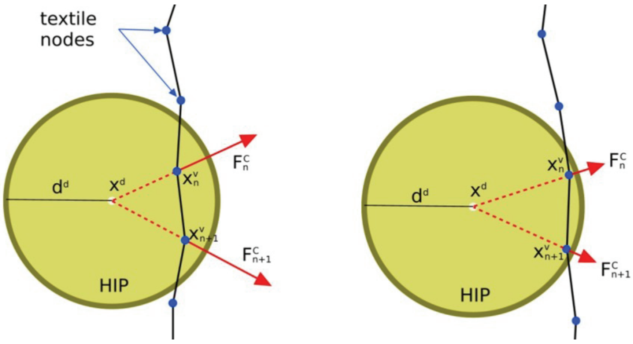

Fig. 5. Initial state (left) and final state (right) of penetration algorithm. See Color Plate 14.

3.2 Tactile rendering

During exploration of a virtual tactile environment a drive waveform is specified for each contactor of the stimulator array(s) – see section IV, below. A significant problem is the current lack of knowledge on the origin and nature of excitation patterns in real situations of tactile exploration of an object. The mechanical stimulation of a given receptor has a complicated relation to the mechanical properties and topology of the object's surface, to the mechanical properties of the skin and its local topology (especially skin ridges, i.e., fingerprints), and to the precise nature of the exploratory movement (speed, contact pressure and direction). Although it may be possible to produce an accurate software model of an object's surface, it is not at present possible to augment this with an accurate model of the skin/surface interaction. This situation may change in the near future: research is currently underway to develop an "artificial finger" with embedded transducers to mimic mechanoreceptors; improved finite-element models may also provide useful data.

For the particular case of the manipulation of textiles, the situation is more promising: Information on the nature of the mechanical input to the skin's mechanoreceptors is available from the Kawabata system for evaluation of textiles [5]. This provides a range of data on the textile sample under test, including surface roughness and surface friction profiles which are direct measures of the mechanical excitations produced when a probe is moved over the textile surface. The probe and associated instrumentation are designed so that the measured quantities correlate well with subjective assessment of the textile surface. Hence the Kawabata surface measurements provide an approximation to the "perceived surface", i.e., the surface after it has been "filtered" through the surface/skin interface. They thus provide a good basis for specifying drive signals for a stimulator array, in order to provide the tactile component for a virtual textile. Kawabata measurements have been used in this way by Govindaraj *et al.* [21]; they have also been used to provide source data for the tactile rendering developed within the HAPTEX project.

Fig. 6 outlines a scheme for tactile rendering, developed within the HAPTEX project [22]. For each digit, the tactile renderer generates 24 drive signals for the 24 contactors of the stimulator array. Input and output data specified in 25 ms time steps. The input data are:

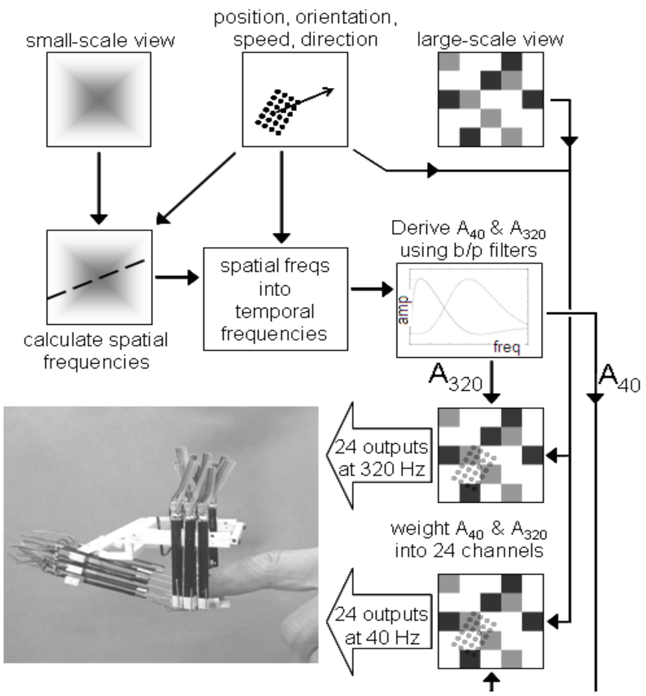

Fig. 6. A scheme for tactile rendering.

- a small-scale description of the object surface, represented as 2D k-space, derived from a pseudo-topology at 0.1 mm resolution over an area of a few mm^2;
- a large-scale description of the object surface: a representation of the non-uniformity of the surface, specified as pseudo-amplitudes at 1 mm resolution over an area of several tens of cm^2;
- position and orientation of the finger pad on the virtual surface;
- speed and direction of the movement of the finger pad over the virtual surface.

The operation of the renderer is as follows: Taking account of the direction of movement, a spatial-frequency spectrum is calculated from the 2D *k*-space of the small-scale description of the virtual surface. Information about the speed of movement of the finger pad is used to convert spatial-frequency components into temporal-frequency components. The resulting temporal-frequency spectrum is reduced to only two amplitudes, A_{40} and A_{320}, by application of appropriate band pass filter functions, corresponding to the 40-Hz and 320-Hz channels. (It should be noted that the signal-processing operations to this point may be performed only once per 25-ms time step, i.e., they may be common to all 24 output channels.) Amplitudes for the 40-Hz component in the drive signals for each of the 24 channels are obtained from A_{40} by weighting according to data from the large-scale description of the virtual surface, for the 24 locations on the finger at which the contactors of the tactile stimulator are positioned. Similarly, amplitudes for the 320-Hz component in the drive signals for each of the 24 channels are obtained from A_{320} by weighting according to data from the large-scale description of the virtual surface.

IV. TACTILE STIMULATION

To excite the skin mechanoreceptors, an array of contactors on the skin may be used to provide spatiotemporal patterns of mechanical input to the skin surface. Encounters with virtual objects, during active exploration of the workspace by the user, produce appropriate patterns of tactile stimulation on the fingertips. The resulting sensations can provide information about the surface texture of the virtual object and about the contact between object and skin (contact area and position of edges/ corners). When presenting the tactile aspects of a virtual object, the intention is not to reproduce the significant features of the small-scale surface topology of the object in terms of a virtual surface. Instead, the intention is to reproduce the perceptual consequences of small-scale features of the surface topology, i.e., appropriate excitation patterns over the various populations of touch receptors in the skin.

4.1 Design of a stimulator array

The optimal spacing of contactors in a simulator array is determined by the spatial acuity of the sense of touch – around 1 mm on the fingertip [23]. However, a contactor spacing of 1 mm equates to around 100 contactors over the fingertip, each of which requires independent control. This is realistic for a passive (non-moving) device [24, 25] but is difficult to implement in an active device, for which a spacing of around 2 mm (i.e., around 25 contactors on the fingertip) may be a better choice. (There is some evidence [26] that perceptions available from an array with 2 mm spacing are not very different than those from an array with 1 mm spacing.)

In order to produce "realistic" touch sensations, a working bandwidth of around 10 to 500 Hz is required for the drive mechanism of each contactor, corresponding to the frequency range over which the various mechanoreceptors are sensitive [27]. Pacinian receptors are expected to respond most strongly to frequencies in the upper part of this frequency range (100 to 500 Hz, say); stimulation at lower frequencies is expected to stimulate mainly non-pacinian receptors. "Comfortable" sensation levels are produced by amplitudes of a few microns at frequencies around 300 Hz and a few tens of microns at frequencies around 50 Hz.

Design requirements for contactor spacing, working bandwidth and output amplitude may be satisfied by a variety of electromechanical drive mechanisms. Hafez and colleagues [28, 29] have developed arrays of drivers, based on shape-memory alloy or moving-coil technology, which apply normal forces to the skin. Hayward and colleagues [30, 31] have used piezoelectric-bimorph actuators to apply tangential forces. Summers *et al*.[32] have used similar actuators to apply normal forces, as have Kyung *et al*. [33].

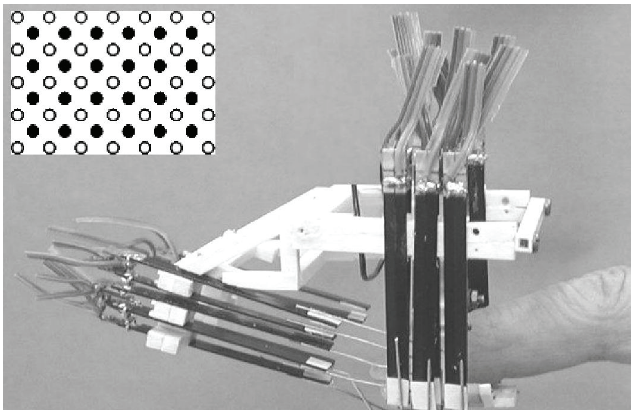

Fig. 7. Stimulator array developed for the HAPTEX project. The contactor surface lies under the finger – contactors are driven by piezoelectric bimorphs (appearing as black rectangles). The inset shows the arrangement of 24 moving contactors, interspersed between fixed contactors.

The stimulator array developed for the HAPTEX project is shown in Fig. 7. Piezoelectric bimorphs are used to drive 24 contactors in a 6 × 4 array on the fingertip, with a spacing of 2 mm between contactor centers. It can be seen that the drive mechanism is placed to the side of the finger and ahead of the finger, rather than below the contactor surface (which, at first sight, appears to be the mot convenient location). With one such array on the index finger and one on the thumb, this positioning of the drive mechanism allows the finger to move close to the thumb so that a virtual textile can be manipulated between the tips of finger and thumb. The contactor surface delivers to the fingertip the small forces associated with touch stimuli, but it must also deliver the larger forces associated with the overall mechanical properties of the virtual object, represented by the output of the force-feedback system. However, the moving contactors which provide touch stimuli are driven by delicate piezoelectric mechanisms and so they are unsuitable for delivering the force-feedback output, which may involve forces of considerable magnitude. Consequently, the contactor surface includes an additional set of contactors (“fixed” contactors – see inset to Fig. 7) which deliver the force-feedback output, in parallel with the tactile stimulation from the moving contactors.

4.2 Drive signals for a stimulator array

During active exploration of a virtual tactile environment it is necessary to generate in real time a drive waveform for each contactor of the stimulator array(s) which are in contact with the user’s fingertip(s). The amount of data which must be generated “on the fly” is thus considerable. For example, the HAPTEX system has 24-contactor arrays on finger and thumb, requiring 48 analogue drive signals, in principle each with a bandwidth of around 500 Hz. However, because of the limited temporal resolution, frequency resolution and phase sensitivity of human touch perception [34, 35, 36, 37, 38], there are possibilities for a significant reduction in the data flow. For example, each drive signal may be reduced to the sum of a limited number of sinusoidal components, distributed across the working bandwidth (10 to 500 Hz – see above). The drive signal can be simply specified in terms of the amplitudes of these components, which require an update of approx. 20 ms.

In the HAPTEX project, a cut-down version of this scheme has been used, in which the drive signal to each contactor is the sum of components at only two frequencies: 40 Hz and 320 Hz. Following the suggestion of Bernstein [39], the higher frequency was selected (at 320 Hz) to target pacinian receptors and the lower frequency was selected (at 40 Hz) to target non-pacinian receptors. Each drive signal is specified by the amplitudes A_{40} and A_{320} of the two signal components. These are updated every 25 ms. A virtual tactile surface is specified in terms of an amplitude map for each of the two frequency components that make up the stimulus.

4.3 Discussion

When using stimulator arrays and rendering schemes as described above, the intention is to present time-varying spatial patterns of tactile stimuli which have two perceptual dimensions: one relating to intensity and one relating to spectral distribution. In order to establish the potential for such a system, it is necessary to determine whether a two-dimensional perceptual space can indeed be created in this way – it is very likely that the intensity dimension is available to the user, but less obvious that the spectral dimension is available. However, recent results from Kyung *et al.* [40] demonstrate that test subjects can detect changes of frequency when stimuli are presented via a stimulator array in an active task, so it seems that spectral information is indeed available in such a scenario.

Initial evaluations of the HAPTEX system (Fig. 6) also suggest that a 2D perceptual space can be achieved. For uniform stimuli (i.e., stimuli with no spatial variation over the skin), the spectral dimension appears relatively weak-changes in spectral balance at constant subjective intensity tend to be less noticeable than changes in subjective intensity at constant spectral balance. (There are perhaps 4 to 5 discriminable steps of spectral balance along an equal-intensity contour.)

Perhaps the most interesting observation when using the HAPTEX system is a strong interaction between the perceived spatial aspects of the texture and the stimulation frequency. If the stimulation frequency is changed from 40 Hz to 320 Hz, the perceived sensation during active exploration changes much more if the texture is spatially non-uniform than if it is spatially uniform. It is clear that the spectral dimension provides a significant enhancement to the available range of tactile sensations.

Using physical data from a selection of real fabrics (obtained with the Kawabata system), the HAPTEX system has been used to simulate the tactile aspects of those fabrics. Given the apparent mismatch between the real situation (fingertip touching a textile) and the virtual situation (fingertip touching the metallic contactors of a stimulator array), results are surprisingly good – in some cases test subjects are able to match real and virtual textiles in terms of their tactile qualities.

V. FORCE-FEEDBACK DEVICE

In the scope of the HAPTEX project the Force Feedback Device is in charge of tracking the global movements of the user's index and thumb fingertips, delivering controlled forces on them as evaluated by the Force Renderer Module and holding the Tactile Actuators.

A device allowing the haptic discrimination of the fine mechanical properties of the textiles requires a highly accurate force feedback. From the technical point of view this implies the accurate generation and control of forces that can be of the order of few grams (0.01 N), as they arise during the natural manipulation of textiles.

In the context of the HAPTEX Project, a novel haptic interface is being developed, consisting of a Hand Exoskeleton (HE) expressly conceived for the accurate generation of light forces.

Several works (for example [41] and [42]) can be found in the literature addressing the development of HEs.

According to their type of functionality, the existing HE can be grouped in two different categories:

- Multi-phalanx HEs: they can generate forces on each phalanx of the finger along a fixed direction with respect to phalanx (e.g. normal to the phalanx);
- Fingertip HEs: they can generate forces only on the (the fingertips along arbitrary direction in 3 D space.

Considering the application addressed by the HAPTEX project, the second type of functionality has been selected.

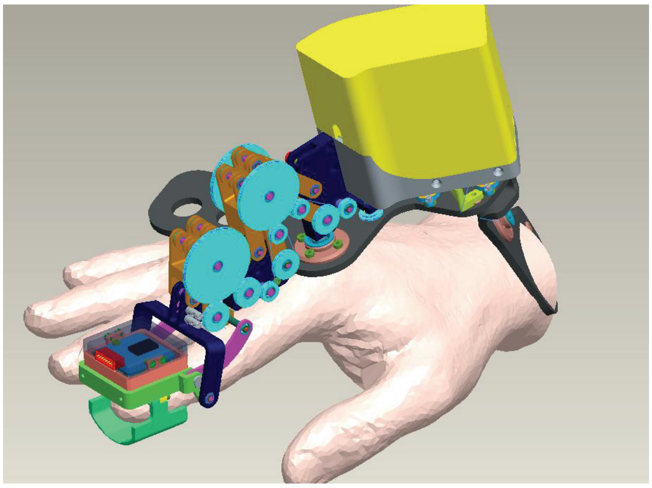

Fig. 8. CAD model of the Hand Exoskeleton. See Color Plate 15.

A quasi-anthropomorphic kinematics has been selected for the implementation of the finger exoskeleton. This solution allows exploiting the benefits of anthropomorphic kinematics, like the maximum ratio of the available over the needed workspaces and minimum encumbrance of the linkages, while avoiding at the same time the singularity that would occurs when the finger is all extended.

Fig. 8 depicts a CAD model of the HE. It can be noticed that the encumbrance of the device has been mainly located in the dorsal side with the aim of allowing the complete closing of the hand. This has been achieved through the use of Remote Centre of Rotation Mechanisms that implements rotational joints having the axes located outside the linkages. The whole mechanism has 4 Degrees of Freedom (DoF), even if it is actuated with only three motors, thanks to the coupling of the last DoF (end-effector joint) with the previous one. The coupling is acceptable because also in the human hand the last phalanx can be rarely moved independently from the middle phalanx during natural movements. The HE is equipped with three electrical motors with low speed reduction ratios (1:14). The actuators are placed at the base of the finger exoskeleton in proximity of the dorsal side of the palm. The joints are actuated through in tension steel cables.

For the position sensing common incremental encoders located on the axis of the motors have been used while for the force sensing a compact high sensitive 3 component force sensor, placed directly in contact with the user's fingertip, has been expressly conceived for the application.

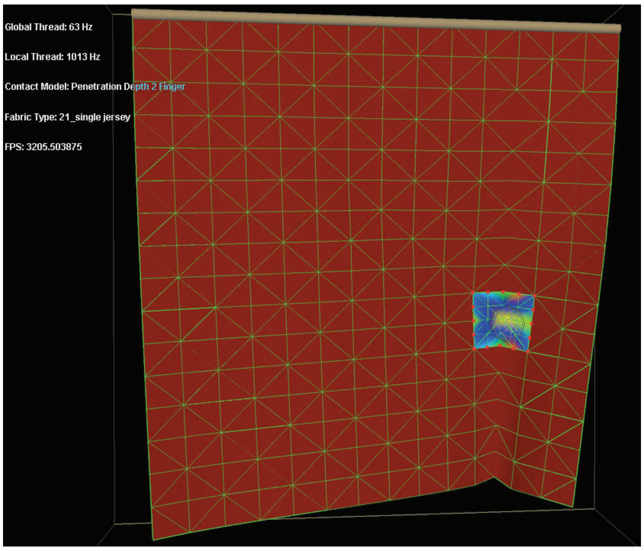

Fig. 9. Screen shot from the HAPTEX System. See Color Plate 17.

A purposely developed electronics for the sensor acquisition and the driving of the motors has been located inside the motor box. The communication with the control PC takes place through standard RS-232 serial cable.

The device is capable of exerting a continuous force on the fingertips of 5N with a resolution of 0.005 N. At present several parts of the device have been realized and other ones are being manufactured.

VI. THE FINAL HAPTEX DEMONSTRATOR

The final HAPTEX demonstrator integrates all developments achieved in the context of the HAPTEX project and is used for testing, validation and dissemination purposes.

5.1 Graphical User Interface

Fig. 9 shows the graphical user interface of the HAPTEX system. On the lower right of the fabric the local geometry reflecting the contact is shown. The resulting forces are represented in false color to illustrate the force distribution under the fingertip. At the top of the screen the update rates of the concurrent simulation threads are displayed. The fabric's material properties can be changed at runtime and are instantly reflected by the physical simulation.

5.2 Hardware Integration

A preliminary integration of force-feedback device and tactile arrays has been successfully achieved. The resulting interface is capable of rendering forces and tactile stimuli at the same time (see Fig. 10).

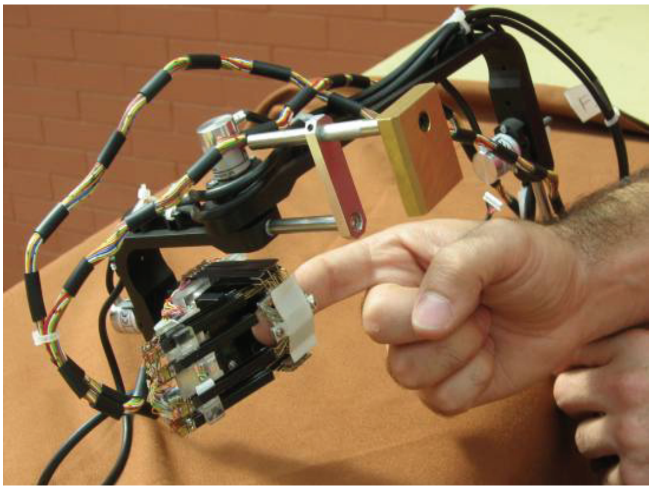

Fig. 10. Integrated force-feedback and tactile components. See Color Plate 18.

Extensive tests have been performed to assess the mechanical and electrical disturbance induced by the vibration and the electrical noise generated by the TA on the measure of the interaction force. The tests evidenced that the effect of the vibration is predominant with respect to the electrical noise. Furthermore a system test has been also performed in order to assess the global consequence of the induced noise on the accuracy of the force feedback. No meaningful effects have been detected due to the low bandwidth of the force feedback. The final HAPTEX Demonstrator will consist of the Hand Exos described in Section V with integrated dorsal tactile arrays described in Section IV on the dorsal side of the last phalanx of the exoskeleton.

5.3 System Validation

The planned evaluation of the complete HAPTEX system involves comparison of results from a subjective evaluation of real fabrics and a subjective evaluation of virtual fabrics. (The virtual fabrics are intended to replicate the real fabrics.) Experiments will be carried out in two variants: with and without vision. The experimental scenario is the same for the real and virtual cases, involving manipulation of a fabric sample (200 mm × 200 mm square) hanging from one edge, secured to a horizontal bar. The sample sits within a workspace of dimensions 400 mm × 400 mm × 400 mm. Manipulation involves the thumb and forefinger of one hand. The experimental task involve a rating procedure, with separate experiments for each of the various fabric properties (tensile, shear and bending properties, surface roughness, surface friction, compressibility, weight, drapeability). Each fabric is rated on an absolute scale, which the evaluator has learned in advance, from reference to some "standards" (e.g., 1 = very smooth; 5 = very rough). Manipulation procedures are specified for evaluation of each property: for example, to evaluate surface roughness the evaluator is asked to grasp halfway up the sample and slide the thumb and finger downwards.

As mentioned above, encouraging preliminary results have been obtained from a comparison of real and virtual fabrics, in terms of their tactile aspects only. (In this case the experimental scenario involved exploration of real and virtual samples stretched on a horizontal table, using only the index finger of one hand.) A preliminary evaluation of the visual system has also provided good results [43]. Evaluation of the full functionality of the whole HAPTEX system is planned for the coming months.

ACKNOWLEDGEMENTS

We would like to thank Christiane Luible, Harriet Meinander, Minna Verhenmaa for the textile measurements and evaluation; Pierre Davy and Guido Boettcher for the work on the force-feedback rendering, Dennis Allerkamp, Alan C. Brady and Jianguo Qu for the tactile hardware and rendering, Marco Fontana, Federico Tarri and Simone Marcheschi for the force-feedback hardware and the integration with the tactile component; finally, all the people involved in the HAPTEX Project.

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