Architectural Design of the Haptex System

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Abstract

This paper reports the preliminary results of the architectural design of the HAPTEX system that will be developed in the framework of the IST FET (Future and Emerging Technologies) initiative. The aim of the EU funded RTD project is to realize a virtual reality system able to render, visually and haptically, the behavior of fabrics. The integration of force-feedback devices with tactile arrays is foreseen to reproduce both kinesthetic and tactile stimulations. A multilayer-multithread architecture has been selected in order to optimize the computational speed and to achieve a sufficient refresh rate for real-time applications.

1. Introduction

The assessment of the *Fabric Hand* of a cloth or a garment, i.e. its overall quality as perceived by the humans through their tactile sensors in response to actions like touching, squeezing, rubbing, or otherwise handling a fabric [1], is central in the selection-for-purchase process of every consumer.

Therefore, pursuing the online marketing and commerce of new garments, beside the technical means for the real time rendering of their appearance, also suitable technologies have to be developed for the haptic rendering of the textiles.

HAPTEX (HAPtic sensing of the virtual TEXtiles) is a visionary research project, funded by the European Union (EU) in the scope of the 6th Framework Program, whose final goal is the development of a complete Virtual Reality (VR) System for the visual and haptic rendering of the textiles. Looking at the requirements of the possible final applications (as said above online marketing and commerce of garments), the accuracy of the rendering, i.e. the accordance between the sensations perceived in the real world and the corresponding ones perceived in the virtual world, is the main metric by which the success of the project will be assessed. For this reason a physical based modeling of the virtual scenario is mandatory. This set the terms of the technical challenge: to identify suitable implementations able to render in real-time the mechanical behavior of the fabric using appropriate physically based models that have to be simplified enough to be run in real-time but not too much to affect the realism of the rendering. Beside this technical challenge, the project will address some other issues of fundamental nature: which are the physical properties of a fabric that we can measure with a suitable equipment that directly correlate with the Fabric Hand? Which are the underlying mechanisms that make the humans perceive these properties through their haptic sensorial system? To give answers to these questions the HAPTEX system will be used as a test bed on which experimentation on human perception will be carried on.

This paper will only deal with the architectural issues of the HAPTEX system, aiming at identifying possible solutions for addressing the technical challenge set above.

2. Background

To the author's knowledge, there are solely two other research projects having a final goal similar to the one of HAPTEX, [2] and [3]. The most advanced between the two, from the technical point of view, is the one coordinated by Prof. Muthu Govindaraj of the School of Textiles and Materials Technology, Philadelphia University. The project envisages the use of a tactile pin array attached to the end-effector of a force-feedback device for the haptic rendering of the fine mechanical properties of virtual fabrics. At present the research is mainly focused on finding the best strategies for the stimulation of the mechanoreceptors of the skin in response of the kinesthetic exploration of the textile performed by the user, displaying at the same time the resistant forces due to the friction between the finger and the fabric. At present the implemented modality of the interaction is limited to the rubbing of a virtual fabric laid down on a plain surface with one finger. The authors reckon that this represents a considerable restriction to the natural way to handle a fabric for quality assessment and for this reason they plan to develop a new haptic device with 2 points of interaction.

From the architectural point of view, the requirement for a real time response having a certain degree of accuracy makes the problem of the visual and haptic rendering of the virtual fabric very similar to the one of developing computer based simulator for surgery procedures.

Huge amount of research activities has been carried out in this field trying to identify suitable physical based models and related computational techniques. Extensive surveys of these researches can be found in [4] and in [5]. From these works emerges that is commonly accepted that for the visual rendering an update frequency of the virtual scenario greater than 20-30 Hz is required, while for the haptic rendering response frequencies in the range of 300-1000 Hz are needed in order to guarantee the stability of the interaction, depending on the stiffness of the simulated environment. As far as the physical models are concerned, the most used ones are the particle models (mass and spring) and the finite element models. These two approaches have complementary computational characteristics, the particle models allowing faster response but less accurate evaluations with respect to the finite element method.

Several model simplifications and computational strategies have been proposed. Using finite element models in the simulation of bulky organs (like for example the liver), the assumption of a linear behavior is generally considered acceptable for the finality of surgery training, even if the deformation can be in some cases large and the behavior of the material is visco-elastic [6]. The adoption of linear model makes it possible to exploit computational strategies like offline pre-calculation and condensation of the stiffness matrix [7],[4]. Further improvement of the response time can be achieved deciding from the beginning the portion of the organ surface that will be in contact with the surgical tool and the one that has to be visualized [5]. By transforming the evaluations deriving from the adoption of linear models with suitable functions, it is possible to recover the non-linear behavior of the material, as proposed in [4]. Multi-resolution computation is another possibility to reduce the time response. In [8] a two layer hierarchical meshing has been proposed, the coarser mesh being used for the evaluation of the deformation of the virtual body in regions which are far from the part interested by physical interaction with the tool, while the finer one for the part in contact with it. The mechanical connection between the two meshes is achieved by means of equivalent springs (impedance in the general case) representing the mechanical behavior of the coarser meshes and attached to the nodes of the finer one. Also in [6] an adaptive resolution is proposed and different implementations (h-method and p-method) are compared. The use of a multi-resolution approach for the reduction of the computation complexity should take into account the perceptual aspect of the haptic rendering. Because of the limitations in the accuracy of the haptic perception it is possible to exploit algorithms that use a coarser model [14]. Nevertheless, it has to point out that the simulation of virtual clothes has its own specificity with respect to surgery. Indeed, the large displacement exhibited by the fabric even under the action of relatively small forces, makes mandatory to formulate the resolution of the problem taking into account the non-linearity due to the macroscopic change of the geometry (geometric non-linearity). Non-linearity, such as visco-elasticity and hysteresis, is also exhibited by the material itself in the stress strain characteristic and, in general, cannot be neglected for a realistic rendering. This makes it impossible to pre-calculate the stiffness matrix before the simulation, because it is deeply dependent on the ever changing geometry. For this reason it is advisable to use particle models that are more suitable for a non-linear formulation, even if this is at the expense of the overall accuracy. Furthermore, with respect to surgery, in the case of cloth simulation is important to take into account the dynamic effects (inertial and viscous forces) as well as the effect of gravity. Finally the eventuality of self-collision of the fabric with itself must be considered. While on one hand all these elements make cloth simulation a more complicated problem to tackle, on the other hand the fact that the cloth is a bi-dimensional object (differently an organ is a 3D object) helps, in part, to reduce the computational burden. In computer graphics, cloth objects are approximated as thin 2D surfaces, typically represented by polygonal meshes. During cloth animation, the vertices of the cloth mesh are driven the laws of the underlying physical model. The resulting equations are solved using numerical methods such as the semi-implicit Backward Euler method, which was first introduced by the groundbreaking work of Baraff and Witkin [17]. Since then, semi-implicit integration has been widely used for cloth animation, as it provides better results in terms of stability and speed compared with other integration schemes [22]. An exhaustive overview

of the state of the art in cloth animation research is given by [23].
In recent years, several research activities have been carried on in the field of cloth simulation, focusing on different aspects ranging from physical based models [15],[16] to integration schemes [17],[18] and collision response [19],[20].
However, despite the big advances in all related fields, accurate cloth simulation is still a very resource consuming task, and real-time requirements additionally increase the computational cost. Due to performance reasons it is unavoidable, when designing VR Systems for real-time cloth simulation, to introduce suitable simplifications (e.g. neglect possible self-collision) and address specific target scenarios.

3. Setting the target scenario

In order to steer the research and development activities to a clear focus, it has been decided to set, since the beginning of the project, the most demanding scenario that the HAPTEX system would be able to simulate.

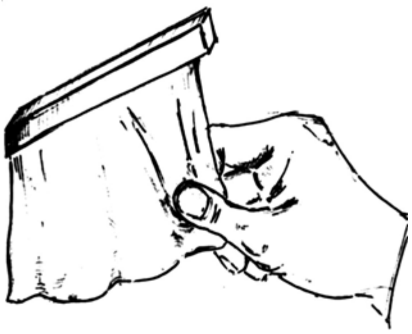

Fig. 1 - HAPTEX Scenario.

To this aim, a good balance has been searched between the complexity of the scenario and its usability for the assessment of the fabric hand.
In Fig.1 the target scenario of HAPTEX is depicted. When un-deformed, the sample of the virtual cloth has a simple geometry (rectangle) and it is attached to a fixed stand by one of its edges. The physical interaction can be attained solely through the fingertips of the index and of the thumb (interaction with the other fingers, phalanxes or limbs won't be simulated). The user can touch, squeeze, rub and stretch the fabric, feeling the corresponding global forces on the fingertips arising from the deformation of the textile and the tactile stimulation due to the relative motion of the finger with respect to the deformed surface. As a step forward in the direction to allow the user to handle the fabric in a more natural way, it has been decided to develop enabling haptic technologies suitable for the simulation of a whole hand interaction.

4. Architectural considerations

Even if the selected target scenario at a first sight could seem simplified enough to be feasible with the present technology, if a realistic rendering is pursued, it has still to be considered highly demanding for at least the following reasons:

- The physical interaction with the fingertips can occur in every part of the cloth, so it does not make sense to conceive a mesh with a statically predefined resolution;
- The interaction occurs through two independent fingertips, so the relative position between them can be variable within large limits. In particular it is possible for the fingertips to be far separated as well as overlapped;
- To make the simulation realistic, it is important to render also the local deformation of the fingertips and to calculate the corresponding contact pressure especially when one fingertip is pressed against the other. This is the case if the friction of the fabric is to be assessed;
- The curvature as well as the deformation of the fabric in the proximity of the fingertip can be very high;
- Once the contact between the fingertip and the fabric has occurred, the fabric can slip with respect to the surface of the fingertip or not depending if the local tangential force exceeds or not the static friction threshold, that in turn depends on the pressure normal to the contact surface;
- The stimulation of the mechanoreceptors of the skin depends on the local fine characteristics of the fabric but also on the operating conditions in which the contact occurs (relative velocity and pressure).

From these considerations it can be observed that in proximity of the fingertips a large number of different mechanical variables have to be evaluated (deformation of the fingertips and of the cloth, normal pressures acting on the contact surface, tangential forces and slip velocities) on a relatively small area. These variables may change very rapidly from point to point due to the high curvature of the surface in contact. On the other hand, for the portion of the cloth far from the interaction points, it is needed to evaluate only the internal forces and the corresponding displacements of the cloth surface. These variables have a lower spatial rate of change (gradient), but they have to be calculated for a relatively larger area.
This observation suggests the adoption of a two layer architecture, using two different interconnected models, as proposed in [8]; one model with coarser resolution (named Large Scale Model) is devoted to the evaluation of the cloth dynamics in the region far from the contact points

while the second (Small Scale Model) is specialized for the evaluation of the contact variables.

The two models are mechanically interconnected by means of impedance representing the mechanical equivalent of the portion of the cloth around the fingertips.

This basic solution allows to differentiate the time response requirements for the two models; for the large scale model, whose output is mainly used for the visual rendering, the requested update frequency has to be greater than 20 Hz, while for the small scale model an update frequency greater than 500 Hz, at least for the evaluation of the interaction forces, is needed in order to guarantee the stability of the interaction.

Furthermore the two models can have completely different structures (for example the Large Scale Model can be based on particles, while the Small Scale Model can be based on specialized finite elements).

5. Architecture of the HAPTEX system

5.1. Overview

With reference to Fig.2 the Physical Engine (PE) of the HAPTEX System is composed by two different models: a coarse model (Large Scale Model) for the whole fabric and a fine model (Small Scale Model) for the portion of the fabric that is close to the fingertips. The Large Scale Model (LSM) represents the whole simulated piece of fabric and, being composed by a large number of nodes, it can achieve a relatively low refresh rate (>20Hz). The Small Scale Model (SSM) is connected to the Large Scale Model through a Norton Equivalent Impedance and, being constituted by few nodes, is able to achieve a high refresh rate (>500Hz). The SSM evaluates the reaction forces that have to be exerted on the user by the Force Feedback Device (FFD) and the operational conditions of the contact (relative velocity and pressure) to be sent to the Tactile Renderer that in turn generates the driving signals for the Tactile Feedback Device (TFD). The runtime positions and orientations of the two fingertips are acquired by the FFD and passed to the two models with different purposes: the LSM uses this information to decide which portion of the cloth has to be substituted by the SSM, while this one places in space the geometry of the fingertips according to them. In order to guarantee the fidelity of the force and visual feedback, the parameters of the two models are derived by measured properties of real fabrics that have been stored in a Fabric Database. Lastly the visualization of the scenario is performed trough a specific software component (Scenario Viewer) that receives the updated geometries of the cloth and of the fingertips from the SSM and the LSM.

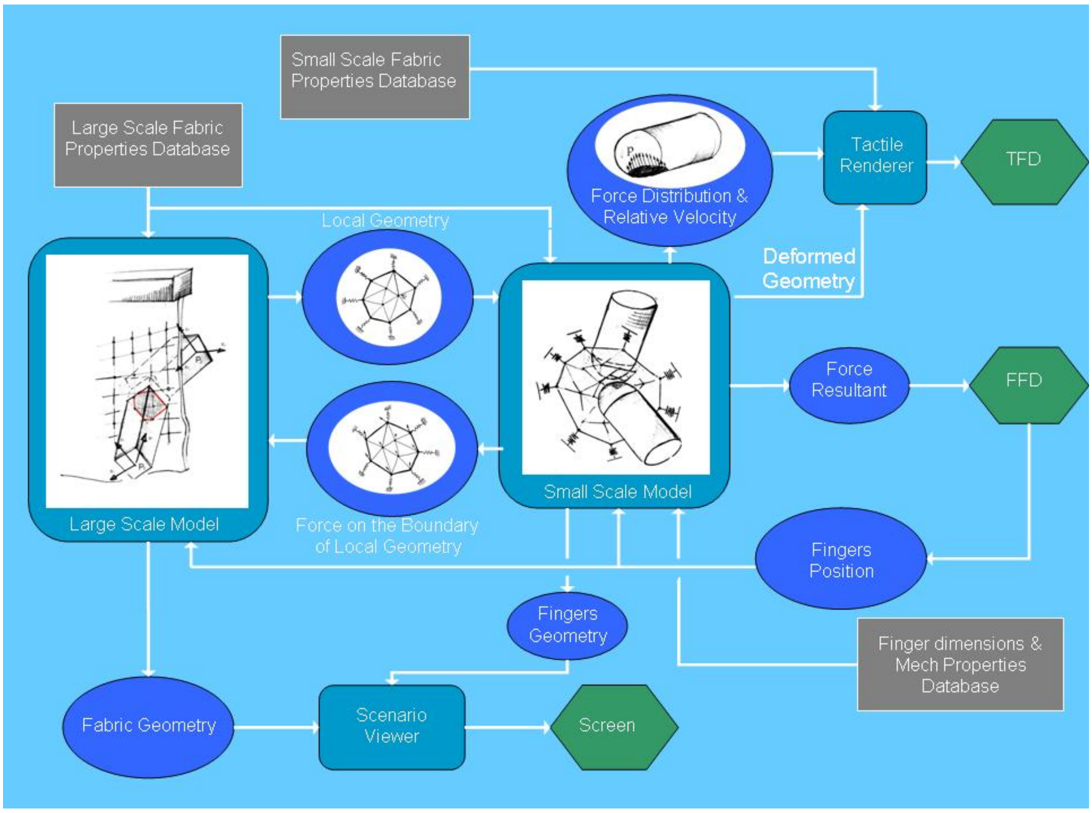

Fig. 2 - Scheme of the architecture of the HAPTEX system.

5.2. Fabric Database

In the first selection process, a broad range of fabrics (32 samples) was chosen for the objective assessment of fabric hand. The measurements were performed with the KES-F system (Kawabata's hand evaluation system for fabrics) [24], which is the most common method for objective evaluation of fabric hand. According to this method fabric hand is based on parameters obtained from the measurements of bending, tensile, shearing, compression, friction and roughness.

Several tests were performed along both machine and cross directions and the resulting data were collected in table format (digitalization). In bending test the sample is bent according two directions: firstly towards the reverse side of the fabric and then towards the face side. The recorded data columns are values of curvature and bending moment. In tensile test force and strain values and in shearing test force and angle values are recorded. In the fourth test the sample is compressed and the corresponding value of pressure is recorded. In surface measurements data are collected about friction and surface roughness.

5.3. Large Scale Model

Our "Large Scale Model" is designed to be an efficient mechanical model for simulating the large-scale behavior of cloth, i.e. to represent its anisotropic nonlinear mechanical behavior accurately. In the HAPTEX system, cloth is approximated by thin, curved surfaces, represented by triangular meshes. The model describing its mechanical behavior takes as input elastic strain-stress curves derived from the weft and warp elongation of the real fabric.

We have defined a particle system model that simulates the viscoelastic behavior of actual surfaces over any arbitrary cloth triangle through simultaneous interaction between the three particles which 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. Our cloth simulation makes use of a semi-implicit numerical integration method with a parametric handle for adjusting the compromise between stability and accuracy according to the simulation and interaction requirements. The model is described in detail elsewhere in these conference proceedings in the paper "Haptic Rendering of Mechanical Surfaces".

Due to constraints for real-time performance, self-collision detection on the cloth object is ignored. The only task in this field is to detect collisions between solid objects and the cloth surface. This task is performed through an adapted bounding-volume hierarchy algorithm, which uses a constant Discrete-Orientation-Polytope hierarchy constructed on the mesh [20] [21]. The solid object is itself embedded in a polytope, and collision detection is done through traversal of the colliding nodes of the hierarchy.

5.4. Small Scale Model

The Small Scale Model is the link between the Large Scale Model and the haptic devices depicted in Fig.2. Due to the requirement of sending forces at a high rate to the force feedback device, the Small Scale Model cannot make use of the physical concepts underlying the Large Scale Model. Besides the trade-off in simulation accuracy, a reduction of the geometry to be considered for the interaction is necessary. Hence it is reasonable to focus on the area which is of high interest. The latter one contains only a part of the virtual fabric being inside a bounding region which is determined on the basis of the position of the fingertips sent by the Force Feedback Device.

This part is described by a triangular mesh where the vertices are containing the relevant information of Large Scale Model, e.g. mass, velocity and internal force of the representing particle. Within the low latency haptic loop, running at least at 500Hz, the Small Scale Model has to detect collisions between the fingertips and the local mesh.

In case of a collision, the Small Scale Model computes the force to be sent to the user, the deformation and the contact area between the fingertips and the local mesh with the pressure distribution. Instead of an immediate transmission of the reaction force, the relevant data for the tactile rendering is collected in a buffer. This buffer contains the area, the orientation and the pressure distribution on the fabric at the last time steps. It is requested by the tactile renderer to compute the drive signals for the tactile array at a rate of 40Hz. Moreover, an update of the global mesh has to be made by returning the deformed local mesh to the Large Scale Model. Afterwards a new local geometry is received for the new contact computations.

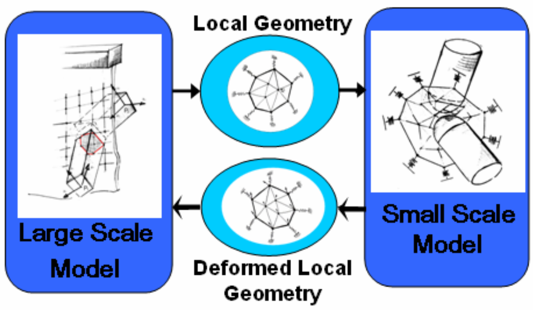

Fig. 3 – Communication between LSM and SSM.

5.5. Tactile Actuators and Rendering

The tactile display will consist of vibrotactile arrays at the tips of the thumb and index finger. The displays will have minimal extent beyond the fingerpad, allowing the user to experience a pinch-type interaction with the virtual textile, and will be an integral part of the end-effector of the force feedback device. Actuation of the pins will be accomplished using piezoelectric bimorph elements. A possible configuration for the device is shown in Fig.4.

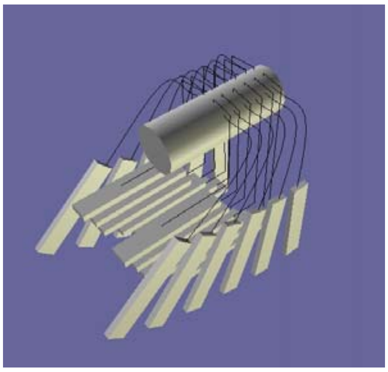

Fig. 4 –Schematic diagram of the tactile array. The finger is represented by the cylindrical element. The mechanism is at the back of the finger.

Rendering of the virtual surface will be based on a two-channel model of tactile perception, assuming a channel which primarily stimulates Pacinian receptors and a channel which primarily stimulates non-Pacinian receptors. The intention is not to use the array to reproduce the topology of "real" surfaces, but instead to create an excitation pattern over the various populations of mechanoreceptors within the skin which matches that caused by feeling real fabric. The drive for each contactor will consist of a mixture of two sinewaves whose frequencies (40 Hz and 320 Hz) are chosen to selectively stimulate the different mechanoreceptor populations. The amplitude distributions of the two sinewaves over the contactor array will be generated by signal processing techniques from the Small Scale Model. A more detailed description of the tactile rendering is given in [25].

5.6. Force Feedback Device

Within the HAPTEX project two different custom Force Feedback Devices will be developed: a Two Point Interaction Device (TPID) and a Whole Hand Interaction Device (WHID).

The TPID (Fig.5) will be able to exert two 3-components independent forces on the fingertip of user's thumb and index. Each force will have an arbitrary orientation and magnitude in 3D space. The device will be able to provide to the PE the position and the orientation of each fingertip.

Fig. 5 – Forces generated by TPID.

The WHID (Fig.6) is a more complex device and it is able to exert 11 1-component forces, one for each phalanx of all the fingers of a hand (excluding the little finger). Each of such forces will lay in the sagittal plane of the finger and it will be normal to the longitudinal axes of the corresponding phalanx. The WHID will provide also the kinematics configuration (posture) of the user's hand.

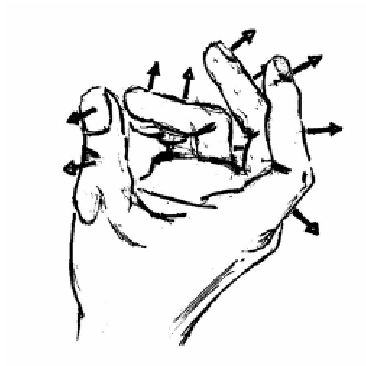

Fig. 6 - Forces generated by WHID.

6. Conclusions

The design of the architecture of the HAPTEX system is a very challenging task for at least the following reasons:

- The requirements relating to the real-time rendering are very strict especially for what concerns the haptic feedback;
- The displacements/deformations of the surface of the cloth are so large that they make the use of non-linear model formulations mandatory;
- The rapidly changing mechanical variables in proximity of the contacts with the fingertips require a high spatial resolution;
- From the hardware point of view, an integrated kinesthetic plus tactile stimulator device has to be developed allowing at least 2 points interaction.

A dual thread architecture has been selected in order to make a rational use of the computational resource, complying with the two different time constraints of the visual (low refresh rate) and haptic (high refresh rate) rendering.

The computational burden has been well distributed using a dynamically variable spatial resolution. To this aim two mechanically linked models of the fabric have been used having different spatial resolution.
The development of this project is still in a very early stage and the details of the various software and hardware components will be defined in the future.

7. Acknowledgments

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