Integrating Force and Tactile Rendering Into a Single VR System

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***Abstract*—The EU funded RTD project "HAPTEX" addresses the challenge of developing a Virtual Reality (VR) system for the realistic and accurate rendering of the physical interactions of humans with textiles, through the real-time generation of artificial visual and haptic stimuli. This challenge concerns the development of both the SW and the HW components of the VR system, as well as it implies a substantial advancement in the understanding of the mechanisms underlying the human haptic perception of fine physical properties like those of textiles.**

This paper reports some important details relating to the technical implementation of the developed HW and SW components with special emphasis on the issues related to their integration into a single VR system. Furthermore some preliminary results relating to the functional tests carried out on the integrated system are also reported.

***Index Terms*—Force and Tactile Rendering, Haptic Interface, Tactile Actuators, Virtual Reality System.**

I. INTRODUCTION

TEXTILES are deformable objects characterized by very fine surface and bulk physical properties, indicated with terms such as stiffness, smoothness, softness, fullness, crispness, thickness, weight, etc. Taken as a whole they constitute the so called *Fabric Hand* (defined in [1]) of a specific fabric, which is the basis for assessing its quality in relation to a given use (for example for realizing a man's winter suit). These properties can be well distinguished and quantitatively evaluated by the human haptic sensorial system (related to sense of touch), with an important contribution given by the sense of sight. There is experimental evidence that the highly sophisticated mechanoreceptors located in the human skin have a predominant role in the evaluation, even if the signals generated by these sensors are combined in the brain with those generated by the kinesthetic sensors located in the physiological articulations and in the muscles. For example, when gently stroking the fingertip on a fabric to evaluate its smoothness, the kinesthetic sensors give to the brain information about the fingertip speed and the global force exerted on the fabric while the mechanoreceptors sense the small local fluctuation of the tangential force due to friction.

The EU funded RTD project "HAPTEX" addresses the challenge of developing a VR system intended for the visual-haptic realistic and accurate rendering of the complex physical interactions arising during the manipulation of textiles. Due to the limitations of the present technology, since the beginning it has been decided to focus the system simulation capability on the interactions that can be attained using only two fingertips: the ones of the index and the thumb (see Figure 1).

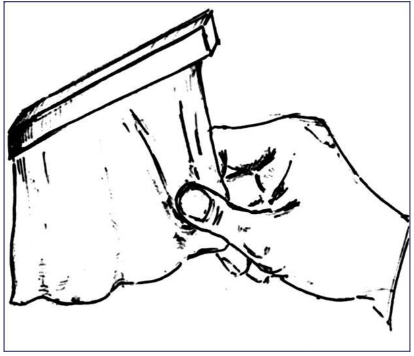

Figure 1 - Reference scenario of the HAPTEX project.

Taking into account the above considerations, the reference configuration for the development of the device responsible for generating the artificial mechanical stimuli to be delivered on the fingertips(named the *Whole Haptic Interface*, WHI), has been conceived as the combination of two independent force-controlled manipulators (Force Feedback Device, FFD), and two arrays of independently actuated pins (Tactile Actuator, TA). Each FFD is able to track the movements of the fingertip and to convey the global force of arbitrary direction on it, and each TA mounted on the end-effector of the corresponding manipulator is able to deliver to the surface of the fingertip skin specified spatial and temporal patterns, (see Figure 2).

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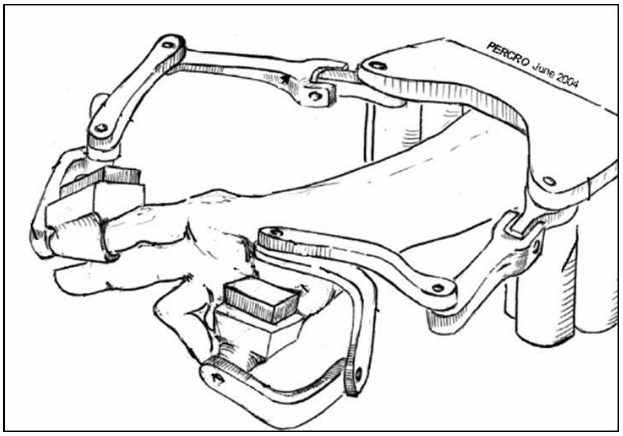

Figure 2 – Reference configuration of the Whole Haptic Interface .

II. DESCRIPTION OF THE SYSTEM

A. *System Architecture*

Achieving a convincing virtual textile simulation requires a good compromise to be reached between the need of accuracy in the material representation and the need of speed for obtaining visually realistic 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. Two separate computation threads were implemented: The first is a low-frequency thread running a complex large-scale simulation of the whole cloth surface achieving quantitative accuracy of the difficult nonlinear anisotropic behavior of cloth in real-time. This simulation has to use nonlinear strain-stress functions related to the cloth being simulated. An efficient non-linear minimization method computing spline functions approximating the aforementioned non-linear strain-stress curves is presented in [20]. 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 the mechanical simulation.

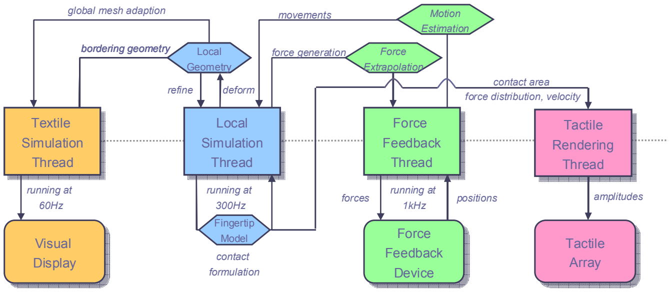

Figure 3 - Different threads within the HAPTEX system

Although the threads allow parallelizing of the computation, we also need some synchronization of the threads. Therefore, the synchronization works as follows. In the initial stage all threads are running at their dedicated update rates. 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, whereas the local simulation thread waits for any 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 Figure 3 shows the separation of the computational tasks into the different threads.

B. *Force Renderer*

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 [17] an effective point-based rendering algorithm was firstly introduced and constantly improved by others, i.e. [19][18].Ruspini et al. [15][16]extended the algorithm to support contacts of arbitrary shapes. In contrast to the well known proxy method a recent approach (see [14]) suggests to compute the contact forces by solving the Signorini contact problem employing finite elements. Although the latter method models the deformation of the fingertip at the contact appropriately, it is demanding of 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. The penetration- or penalty-force-model 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 a 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 a force equilibrium as depicted in Figure 4.

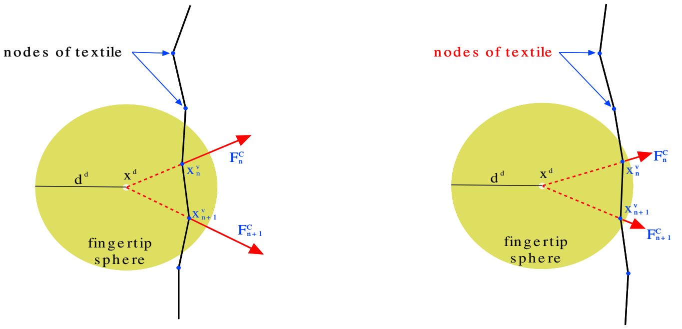

Figure 4 - Initial state (left) and final state (right) of the penetration algorithm

At this stage the bodies are still intersecting. In this strategy the fingertip is modeled as a rigid sphere being the first contact body. Due to its shape, a fast collision test with the textile can be made. The fingertip collides with a textile particle n with position x_n^v if $\left\| x_n^v - x^d \right\| < d^d$ holds.

Both fingers are in collision under the following condition:

$$\left\| x_0^d - x_1^d \right\| < 2d^d .$$

To distinguish between static and kinetic friction we separate the force resultant F_v^r into tangential f_v^T and normal f_v^N components applied to a textile particle *v*. The force F_v^r is the sum of the internal force F_v^V, penetration force F_v^C and friction force.

If both forces satisfy the stick condition equation for static friction as seen below.

$$f_v^t < \mu_S f_v^N$$

Then we have

$$f_v^N = n_v F_v^r$$

$$f_v^T = \left\| F_v^r - f_v^N n_v \right\|$$

In this state the particles are not moving relatively to the fingertip. The position is set according to the fingertip movement. Forces of the remaining free particles of the textile have to be recomputed. Otherwise, if the stick condition is not met, the kinetic friction is added to the particle.

The force sent to the force feedback device is determined by the reaction force of the contacting particles and the second fingertip F^D. This leads to the following equation

$$F^d = F^D - \sum_{v} F_v^C - \sum_{v_S} \mu_S f_{v_s}^N \frac{v_{rel}}{\left\| v_{rel} \right\|} - \sum_{v_K} \mu F_{v_K}^N \frac{v_{rel}}{\left\| v_{rel} \right\|}$$

where v indexes the particles being in contact with the fingertip and v_S and v_K defining the particles respective to their friction state.

C. *Tactile Renderer*

The tactile renderer is based on vibrations that play an important role in the tactile exploration of fine surfaces. To produce appropriate excitation patterns we use an array of vibrating contactor pins as described in Section II-E.

The tactile renderer generates 24 drive signals for the individual contactors of a single tactile stimulator, on the basis of the following inputs:

- small scale description of the textile surface: a single “tile” of the textile weave pattern, specified as a pseudo-topology at 0.1 mm resolution over the 2D surface of the tile (derived from Kawabata measurements of roughness and/or friction);
- large-scale description of the textile surface: a representation of the non-uniformity of the textile surface, specified as a pseudo-amplitude at 1 mm resolution over the 2D surface of the 200 mm × 200 mm sample of virtual textile (derived from optical imaging);
- position and orientation of the finger pad on the virtual textile;
- speed and direction of the movement of the finger pad over the virtual textile.

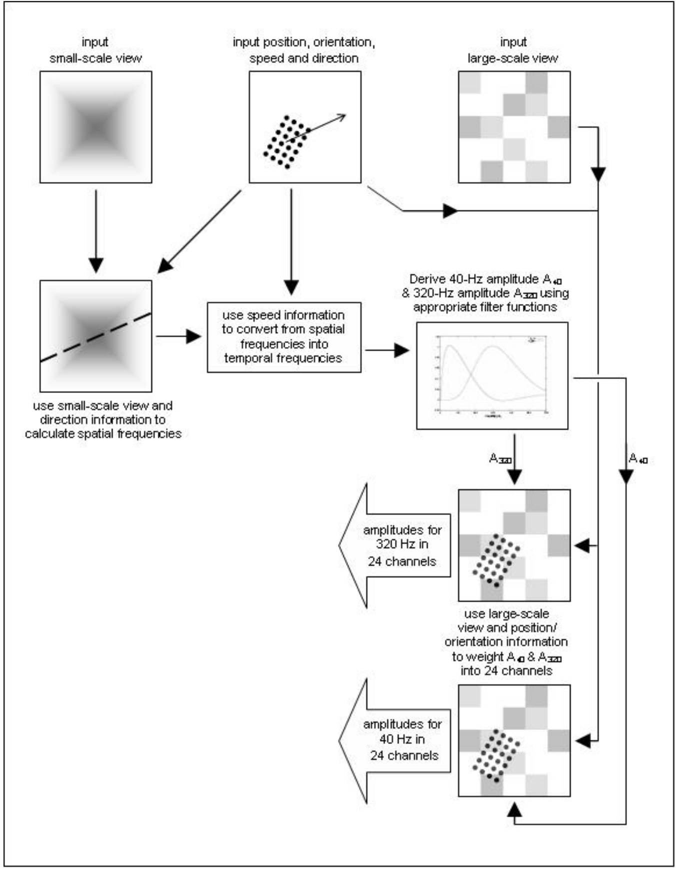

Figure 5 - The tactile renderer. Input and ouput data are specified in 25 ms timesteps.

Figure 5 shows an overview of the process using the input data are used to specify the output drive signals. Taking into account of the direction of the movement, a spatial-frequency spectrum is calculated from the pseudo topology of the small-scale description of the virtual surface. Information on 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 applying appropriate bandpass filter functions (see [21]), corresponding to the 40-Hz and 320-Hz 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 where 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.

D. *Force Feedback Device*

In the scope of the HAPTEX project the Force Feedback Device (FFD) is responsible for 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. In order to allow early integration of the different components of the HAPTEX system, it has been decided to develop two different types of FFD, the first one derived from an existing device (named "FFD in configuration A") and the second one designed from scratch (named "FFD in configuration B").

Although the two configurations use very different basic solutions and hardware implementations, they have quite similar functionalities, even if the related performances are substantially different. In both cases, one of the main requirements in their development has been the achievement of a highly accurate force feedback. This requirement derives directly from the stated goal of allowing the discrimination of the fine mechanical properties of the textiles. 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.

To address this challenge, a new explicit force control has been developed making use of purpose-designed highly sensitive multi-component force sensors, placed directly in contact with the user's fingertips.

The following paragraphs describe in detail the two configurations and report some experimental data relating to their performances.

1) *FFD in Configuration A*

The FFD in configuration A has been derived from the GRAB system (a detailed description is reported in [2]), developed by the PERCRO Laboratory in the framework of the homonymous European RTD Project. The system is composed of two identical robotic arms, each having 6 DOF of which the first 3 translational DOF are instrumented and actuated, while the remaining 3 orientational DoF are only passive. Each robotic arm is functionally equivalent to the well known Phantom® [3] haptic interface but has larger workspace.

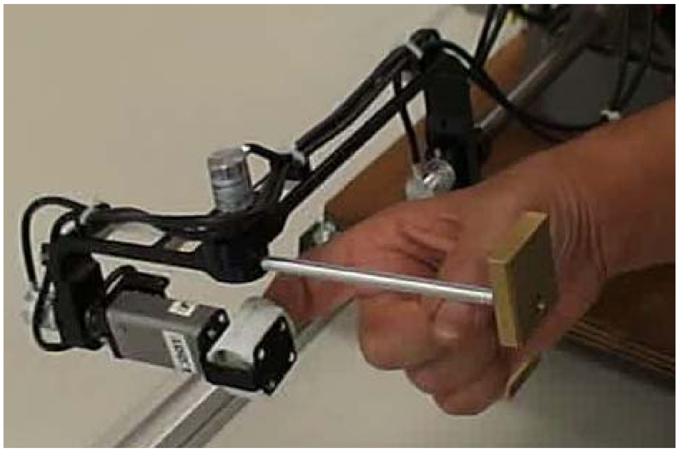

Figure 6 - Picture of the sensor-equipped gimbal.

With respect to the original GRAB system, the FFD in configuration A uses new gimbals (see Figure 6) mounted on the robotic arm, each equipped with 3 rotational position sensors (encoders) for the measurement of the fingertip orientation and with a 3 component highly sensitive force sensor specifically conceived for the application, and an explicit force control making use of the said force sensor.

Explicit force control algorithm consists of an inner velocity loop-outer force loop scheme (see Figure 7). The mechanical model of the device and the criteria for the dimensioning of the controller are described in detail in [5] and in. [6] Due to the presence of elasticity in the transmission of the force from the actuator to the moving mass, the bandwidth of the force controller has been limited to 3 Hz in order to ensure the stability of the system.

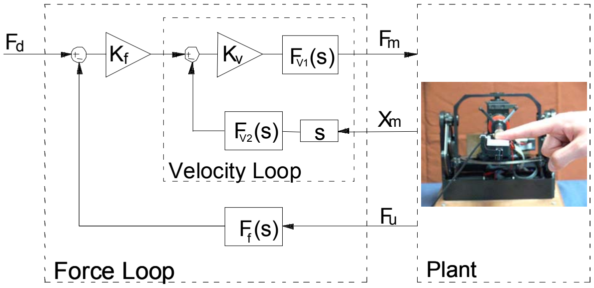

Figure 7 - Scheme of the force control

Furthermore, investigations on the attachments of the device with the fingertips have been carried out. Indeed, during the natural handling with the textiles the interaction forces can be of the order of few grams. This implies that the attachment of the fingertip with the device has to be so to not hinder the high sensitivity of the human mechanoreceptors located in the skin. From this point of view the thimble-like attachment, commonly used by the existing haptic interface, is not well suited because it produces a pre-stress of the skin reducing the sensitivity of the mechanoreceptors. In order to address this issue, different alternative solutions for the fingertip attachment have been investigated (a bare plate, a plate with elastic strip, a plate with eccentric thimble). As expected the experimental test demonstrated that the human sensitivity is at best when the bare plate is used, even if this solution is the worst for the transmission of the torques required for the orientation of the gimbal.

Finally a field test investigating the system capability to track the finger motion with minimal resistance force has been carried out. The subjects were asked to move their fingers at constant velocity and the system was set to display no forces. The maximum module of the acquired resistant force was about one tenth of a Newton (10 grams force), as it can be observed in Figure 8.

2) *FFD in configuration B: development of the hand exoskeleton*

The FFD in configuration B consists of a Hand Exoskeleton (HE) expressly conceived for the accurate generation of light forces.

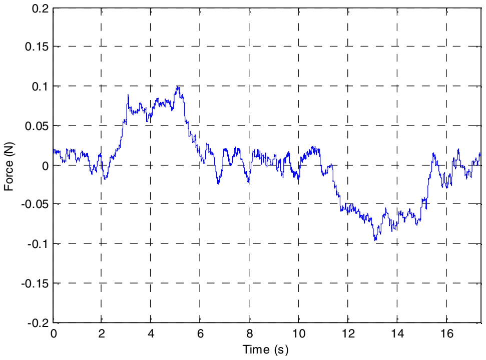

Figure 8 - Plot of the resistant force versus time during finger tracking at constant velocity

Several works (for example [4], [7] and [8] 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 the 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.

A scheme of 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 completely extended.

In Figure 9 a CAD model of the HE is shown. 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 implement 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 steel cables working in tension.

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

The purposely developed electronics for the sensor acquisition and the driving of the motors have 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.

A further development will be the integration of the dorsal tactile array described in Section III on the dorsal side of the last phalanx of the exoskeleton.

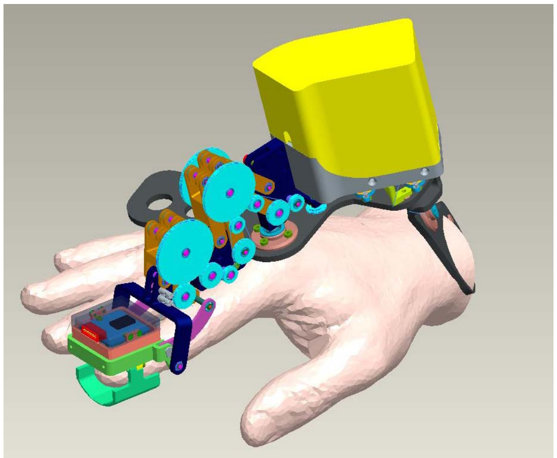

Figure 9 - CAD model of the Hand Exoskeleton.

E. *Tactile Actuator*

Two designs of stimulator array have been developed as the tactile component of the HAPTEX system, hereafter referred to as configurations "A" and "B". Both configurations use identical actuators and have the same contactor layout, and each has been designed to be used with the FFD.

The configuration "A" actuator has been designed to display a 2D tactile pattern on a single fingertip. In contrast, the type "B" actuator (pictured in figure 10) is suitable for use in a pair, displaying tactile information to both the finger and thumb in a grasp configuration.

In an ideal device, the fingertip would be completely covered with contactors. The spacing of these would be around 1 per square millimeter, matching the spatial acuity of the mechanoreceptors in the skin [9]. In reality, the number of actuators is limited by the space available and the complexity of the drive electronics and the wiring. A pin spacing of 2 mm has been used, as it is believed that for many tactile tasks this is indistinguishable from a 1 mm spacing [10]. 24 pins are arranged in 6×4 grid, with fixed pins in interstitial positions to localise the stimulation sites on the skin, and to transfer forces from the FFD to the finger. The height of the active pins is set such that they indent slightly into the skin when the finger pad is gently pressed into the fixed pins and the surround.

Both designs are driven by piezo-electric bimorphs, chosen for their simplicity, ease of assembly and low cost. The dimensions of the bimorphs were selected by numerical modelling and experiment.

The free-length of the bimorphs was chosen such that their resonant frequency (100 Hz, rising to 120Hz when loaded by the skin) lies between the two working frequencies of the renderer (40 Hz and 320 Hz), and such that the first anti-resonance (450 Hz) is not too close to the upper working frequency. The response is designed such that the roll-off above resonance counteracts the increase in sensitivity of the human fingertip [11]. This balances the perceived intensity at a given drive signal, and reduces the dynamic range required from the drive electronics.

The width of each bimorph is a compromise must be struck between the amount of force the actuator could deliver and the overall size of the device. A pair of commercially available 2.1 mm wide actuators (APC International), arranged in parallel, was chosen. This gave a width of 4.2 mm and a static blocked force of ~0.5 mN/volt.

The design of the type "A" is a logical development of earlier systems [12],[13], with the piezoelectric actuators located below the palmar surface of the fingertip. It is suitable for use with a single finger in a 2D environment, and has been used to develop the drive electronics and software, and for testing the tactile renderer.

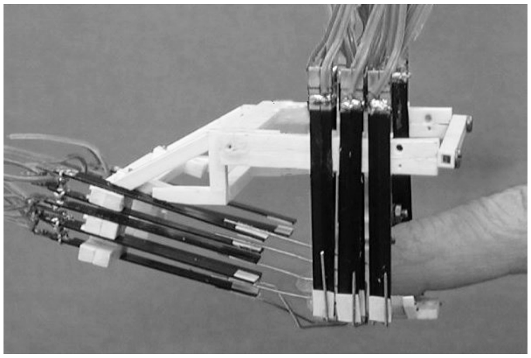

Figure 10 - Early prototype of the configuration "B", showing the two different orientations of the piezo-beams

The design of the type "B" actuator TA was constrained by the need to move the actuators out from underneath the fingertip to reduce the depth of the device below the fingertip, and so allow for a grasp configuration. In addition, the device had to accommodate and integrate with the force sensor for the FFD, and to fit the FFD mechanism.

In the type "A" configuration, the fingertip rests on a planar surface. The contactor pins are arranged to be perpendicular to this plane. The type "B" configuration uses a curved contact plate which follows the shape of the finger pad. Contactor pins are approximately normal to the contact plate (illustrated in Figure 11), with different orientations of the drive mechanism for different rows of pins. As a result, some of the drive links have to follow relatively complex paths. Subjective tests of this configuration have shown that the performance is good.

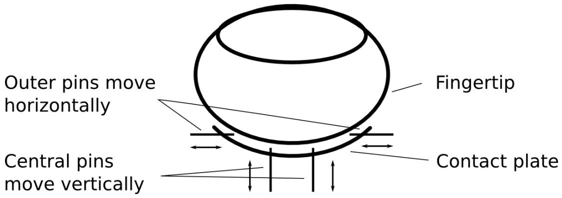

Figure 11 - This end on sketch of the fingertip shows the orientation of the contactor pins and the direction in which they are driven.

III. SYSTEM INTEGRATION

A. Mechanical Integration of TA with FFD

The integration of the FFD with the TA requires the resolution of non-trivial problems that have implications for the most appropriate mutual mechanical arrangement of the different parts constituting the two devices. This arrangement should be so to allow, on one hand, the delivery to the fingertip of the mechanical stimulations that each device can generate and on the other, to comply with the specific capabilities and requirements of the devices. In particular the TA pins can produce dynamic indentation of the skin, but the forces (normal to the surface) that they can deliver are relatively small (in the range of few grams).

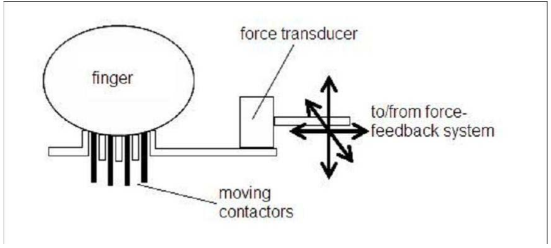

Figure 12 - Scheme of the force transmission between fingertip and plate

Furthermore they cannot withstand lateral forces acting on the pin because these forces would produce their deflection. In short the mechanical arrangement has to be so to prevent the loading of the pins with relatively high forces. Vice versa the FFD can deliver to the skin relatively high force in every direction, but in order to guarantee a high accurate force feedback these forces must be sensed by the 3 component force sensor (see scheme in Figure 12).

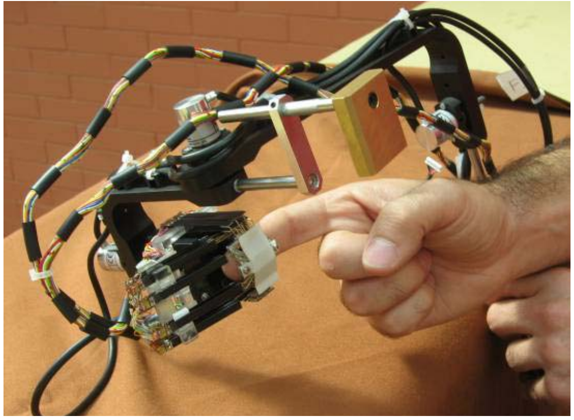

Figure 13 - Mechanical Integration of FFD and TA

The FFD in configuration A and the TA in configuration B have been successfully integrated in order to realize the development level 4 (DL4) of the HAPTEX system (see Figure 13).

B. Integration of the Force and Tactile Renderer

For the computation of the force-feedback the haptic renderer already requires among others the contact point, the velocity of the fingertip relative to the fabric and the normal force (cf. [20]). Instead of a single contact point the tactile renderer requires a contact area to decide which contactor pins have to be activated. Also a single normal force is not sufficient for a convincing tactile simulation. Rather a distribution of the normal force over the whole contact area is needed by the tactile renderer.

For each contactor pin, the geometry of the tactile actuator determines the point on the fingertip where the stimulation caused by that pin occurs. These points have been included in the model of the fingertip. Employing the contact model the position (in local coordinates of the fabric) and the normal force at each point is computed. The velocity is computed by applying a discrete differential operator.

The tactile renderer is called every 25 ms, i.e. it runs in a 40 Hz loop. However, the contact data is computed by the haptic renderer every millisecond and the data needs to be resampled. To avoid aliasing the data is passed through a digital antialiasing filter that suppresses frequency components above 20 Hz.

In the stand-alone version of the tactile renderer the fabric was assumed to be planar. Furthermore the finger was assumed to always being in contact with the plane of the fabric (see [9]). However, in the integrated case the fabric may have folds and wrinkles, resulting in a more complex contact geometry. The fingertip deforms due to the contact pressure, also influence the shape of the contact area. As a consequence not all pins of the tactile actuator should be activated, only those inside the contact area. The shape of each finger's contact area is provided by the force-feedback renderer. Note that a contact area may not exist, i.e. in that case the finger does not touch the fabric.

While moving a fingertip over a rough surface we experience a tactile sensation. Its intensity also depends on the force with which the finger is pressed against the fabric. For relatively small forces a linear dependency between the force and the sensation seems to be reasonable. Therefore the amplitudes computed by the tactile renderer are multiplied by $k_F \cdot F$ before they are transmitted to the tactile actuator. F denotes the force between the finger and the fabric and k_F is a constant relating the force to the intensity. Previous to the integration there was no possibility to assess the contact pressure between the fingertip and the fabric. Therefore a constant force normal to the fabric was assumed implicitly by the tactile renderer.

IV. PRELIMINARY TESTS

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, because of its potential negative impact on the accuracy of the force feedback. The tests have been performed activating only one specific pin of the TA array at a time and acquiring the resulting measured force signal. The frequency spectrum of the signal has been then evaluated using the Discrete Fourier Transformation (see Figure 14). The disturbances produced by 4 different pins, having different locations in the TA array and mechanical coupling conditions (free-moving or in contact with the force plate hole) have been investigated. The tests evidenced that the disturbance produced by the vibration is predominant with respect to the electrical noise and that free-moving pins produce about 10 times less disturbance than produced by pins in contact. The magnitude of the disturbance on the excitation frequency (40Hz and 320 Hz) is about 200 times greater for the free-moving pin with respect to the base noise than when the pin is not activated. 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 (about 3 Hz).

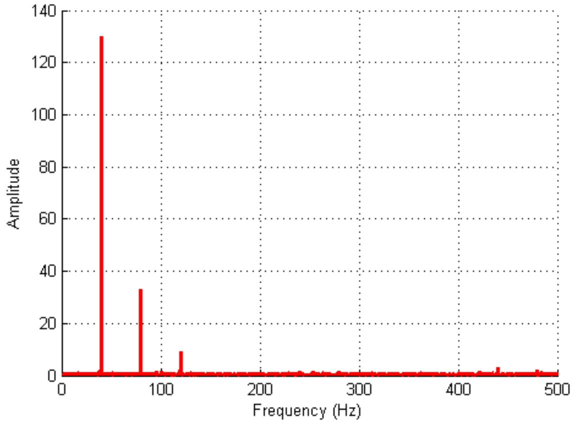

Figure 14 - Typical Discrete Fourier Transform of the disturbance produced by one TA pin vibrating at 40Hz on the force measure.

V. CONCLUSIONS AND FUTURE WORK

In this paper we have reported the preliminary work performed towards the realization of a system able to simulate the visual and haptic interaction with fabrics.

The manipulation of fabrics is a very complex perceptual experience that is associated with a lot of stimuli that are very hard to simulate and to reproduce virtually.

The system that has been realized integrates two kinds of stimulation devices: a Tactile Array (TA) for the tactile stimulation of the fingertip and a Force Feedback Device (FFD) for delivering the interaction forces. In this work we focused on the issue of the integration of these two devices from the software and the hardware point of views.

From the software point of view the main issue is to generate simultaneously the signals to be provided to the FFD and the TA complying with real time specifications. To achieve this two separate software components called the Force Feedback Renderer and the Tactile Renderer, were realized and integrated.

For what concerns the hardware, the real challenges consist of realizing a device able to convey both the delicate and fine interaction forces that are involved with the manipulation of textiles and deliver the associated tactile stimulus. It has been shown that the integration of these two devices can raise several issues like the electrical and mechanical cross-talk between the two feedback devices and the issue of how to deliver the force to the user's fingertip whilst not transmitting it to the pins of the array. This has lead to the design of a purposely developed haptic-tactile integrated device.

The preliminary tests on the integrated system have shown that the global performances of the device are acceptable and the major issues associated with the integration have been successfully overcome.

In the near future we will set up the complete system for two finger interaction and perform several tests.

The next step will be the realization of a portable wearable FFD and to integrate it with the tactile array.

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