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Haptic and sound interface for shape rendering

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Abstract

This paper presents a system for the evaluation of the shape of aesthetic products. The evaluation of shapes is based on characteristic curves, which is a typical practice in the industrial design domain. The system, inspired by characteristic curves, is based on a haptic strip that conforms to a curve that the designer wishes to feel, explore and analyze by physically touching it. The haptic strip is an innovative solution in the haptics domain, although has some limitations concerning the domain of curves that can be actually represented. In order to extend this domain and make users feel the various curve features, for example curvature discontinuities, sound has been exploited as additional information modality.

Haptic and sound interface for shape rendering

1 Introduction

The process of product design comprises various activities that start from market analysis and conclude with product distribution and maintenance. Progresses in the product development process have been pushed by factors such as design costs, performances required and reduced time-to-market. We have seen progresses concerning methodologies, tools, and technologies for supporting the various phases of the product development in the last decades (Ulrich & Eppinger, 2008). Activities like product definition and conceptualization, aesthetic design, detailed design, testing and simulation, and manufacturing are today performed in a digital context.

The currently available CAD (Computer Aided Design) and CAS (Computer Aided Styling) systems provide an almost unlimited domain of shapes in terms of mathematical surfaces or solid models with a very high flexibility for modification and control of geometric characteristics, and in particular of continuities of various orders in the application domain of aesthetic objects.

During the development of new concept products, designers need to physically interact with the evolving shapes of the product they are designing (Yamada, 1997) so as to check and evaluate aesthetic features of their products. The satisfaction of this need requires the production of physical prototypes. Although physical prototypes are good means for product evaluation, they also show some limitations; for example, they do not allow variants of shape and material, as well as do not support easy shape modification and immediate correlation with the corresponding digital model. In addition, the production of the physical prototype is costly and time consuming, especially in respect to

the other product design phases. Just to give an idea of the size of the problem, Alessi - a well-known Italian company operating in the sector of household design- produces about 1200 physical prototypes per year, using Rapid Prototyping techniques, with respect to about 300 open projects and 50 products finally developed. Besides the cost and time of physical prototypes production, one major problem concerns the implementation of the effects of the aesthetic design review made on physical mock-ups into the digital model of the product. Sometimes, modifications performed on the physical mock-up are acquired through Reverse Engineering techniques, which again are costly and time consuming. We can reasonably affirm that reducing the number of physical prototypes would shorten the time-to-market and diminish costs. But a negative effect would be the deterioration of the quality of the final products, since fewer variants can be actually considered and evaluated.

On the basis of these considerations, and with the purpose of satisfying designers need about touching their products we have developed a new design system that integrates the best capabilities provided by CAD/CAS systems with the possibility to physically interact with the digital model of the product (Bordegoni and Cugini, 2006). The system intended to allow designers to evaluate the aesthetic quality of a product, thus providing a realistic visual representation and also a consistent physical rendering of its surface.

Haptic interfaces offer the possibility on one side of evaluating early in the design process components that do not exist already, and on the other side of better feeling components through physical interaction. This practice can be effectively used for rapid design evaluation and review of new products. The major benefit would be the reduction of the time required for the production of physical prototypes, and therefore the reduction of the total time-to-market, without affecting the quality of the final product.

The paper presents a design system developed within the context of the European project SATIN Sound And Tangible Interfaces for Novel product design (`http://www.satin-project.eu`) whose aim is allowing designers of aesthetic products to

use virtual prototyping techniques to shorten time-to-market, augmented with the possibility to touch and evaluate through the sense of touch the quality of a shape that exists digitally. The system (named SATIN system) allows designers to perceive, explore and evaluate the shape of an object along a curve by interacting with a haptic strip, to look in stereoscopy the visualization of the object, and also to hear sounds that represent the relevant geometric characteristics of the digital shape.

The paper is organised as follows. Section 2 presents an overview of related works. Section 3 provides a conceptual description of the SATIN system. Section 4 presents some interaction scenarios showing the system functionalities and operational modalities. Section 5 describes the system architecture and the hardware components, and section 6 presents the software framework. In section 7 we present the implementation of the system and the user testing results. Finally, section 8 draws some conclusions.

2 Related Works

Digital tools for the creation of shapes, CAD (Computer Aided Design) tools or CAS (Computer Aided Styling) tools, support the creation of shapes including their definition, representation and testing. Currently, they have reached very good performances in terms of graphical representation of the digital products. Conversely, their user interface, and then the usability of these tools, has not reached a good quality. This is particularly true for CAS tools that are mainly used by designers, who are creative people with a limited knowledge about the technical aspects related to the representation of surfaces. In fact, CAS tools include curves and surfaces manipulators that allow designers to control the shape of a surface, which underlines a mathematical representation. Although having little knowledge about mathematics of surfaces, designers have to model surfaces through the use of these manipulators. Actually, this may not be the most natural and effective way for designers to create new objects shapes while

expressing their creativity. For these reasons, still today several designers prefer using clay, wood and cardboard to create a physical representation of their idea of a new shape.

A very important task in the design of complex-shaped products is shape modification applied to fit local/global aesthetic requirements and/or engineering constraints. Shape modification involves different modeling aspects like fairing, local correction, global deformation, shape optimization, etc. The geometric models supported by most CAD and CAS systems are generally based on curves and surfaces represented by NURBS. Their shape generation and manipulation are obtained by acting on some low level parameters (control points and weights). Although it is still extensively used, this technique is neither sufficiently intuitive for the users nor definitively adapted for patchworks of trimmed entities (B-rep). Several alternative deformation techniques, based on the extension of feature capabilities to free form modeling, have been developed to provide users with an easier and more intuitive control of the surface shape: (Cavendish & Marin, 1992; Krause, Stiel, & Martini, 1998; Wyvill, Mc Robie, Haig, & McNaughton, 1996) and others.

The recent and fast evolution of technology has proposed some systems that attempt to provide better modeling techniques and more effective user interfaces oriented to design. Various research works have addressed style features of shapes that are the basis for modeling and shape evaluation systems (Martino, Falcidieno, Giannini, Hassinger, & Ovtcharova, 1994; Attene et al., 2006). These systems allow the creation and modification of shapes through the manipulation of aesthetic curves, which are anyway handled through traditional interaction modalities. Virtual Reality technologies are used for the implementation of these systems. The 3-Draw system (Sachs, Roberts, & Stoops, 1991) allows users to sketch a set of curves and use them to define the skeleton of a surface, as in a wireframe representation, but there is no possibility to create a surface with the curves drawn. JDCAD (Liang & Green, 1994) is the first VR-based tool that

gives the designer an integrated environment, where the creation of 3D primitives and Boolean operations are effectively performed through stereoscopic visualization. One of the first modeling applications using immersive Virtual Reality technology is 3DM (Butterworth, Davidson, Hench, & Olano, 1992), which is based on the use of HMD. Object modeling in performed in an intuitive way as well as experimentation with model shapes, although the use of HMD is not ergonomically fully satisfactory. The COVIRDS system (Dani & Gadh, 1997), tries to combine various multimodal technologies, such as speech input, gesture recognition as 3D input and output, and to develop new interaction techniques for creating and modifying free-form surfaces. The main limitation of this system is that it allows users only to manipulate surfaces by moving some control points, which is not an intuitive way for non-expert users. Perles and Vance (Perles & Vance, 1999) have developed a set of tools that allow users to change the shape of NURBS surfaces in a virtual environment. These shaping tools allow surface manipulations to be made using methods that match the shaping of real malleable objects. They consist of three- dimensional shapes that are controlled through a six degree-of-freedom tracking system that converts users hand motions into computer input.

Some other advanced modeling tools allow the creation of sketches of products. Particularly interesting are those applications using a physical tape (for example the ShapeTape by Measurand) as curve input device (`http://www.measurand.com/`). The manipulation of the tape allows the creation of 3D digital curves, but has problems regarding precisions in terms of absolute positioning of the starting point of the strip, and related position of the end point, and correct rendering of the 3D shape. More recently, haptic technology has been integrated into the design tools. Haptic modeling is a term used to indicate modeling of virtual shapes using haptic technologies. Haptic modeling systems allow users to touch, feel, manipulate and model objects in a 3D environment that is similar to a natural setting. Several examples of sculpting systems have been

developed based on haptic force associated with dynamic subdivision of solids that give users the illusion of manipulating semi-elastic virtual clay (Dachille, Qin, & Kaufman, 2001; McDonnell, Qin, & Wlodarczyk, 2001). These environments permit both expert and non-expert users to interactively deform virtual materials with real properties using force feedback overcoming conventional geometric modeling and design techniques that make use of popular splines that often require tedious control-point manipulation and/or painstaking constraint specification via unnatural mouse-based computer interfaces. These applications are based on the use of the point-based PHANToM stylus for interacting with the virtual clay.

The only physically-based shape modeling system commercially available is FreeForm by SenSable Technologies Inc. (`http://www.sensable.com/`) which is based on the Phantom haptic device. The FreeForm modeling system uses an internal volumetric representation and associated techniques, so it appears rather difficult and time-consuming to create smooth surfaces and smooth sharp edges or tense shapes on models. More recently, the ClayTools has been released by Sensable Technologies Inc., where the Phantom haptic interface has been integrated into the modeling applications 3ds max, Maya and Rhino. The integration of haptic devices into commercial CAS systems may be effective because it is possible to simulate tools that users are familiar with, by changing the traditional input device (the mouse) with a more intuitive and natural one. An additional benefit is the fact that the new interaction tool is also an output device, which returns to the users hands the contact with the shape A new step towards the use of hands to create shape is offered by the T'nD project, which has developed a haptic system based on a haptic scraping tool and sweep operators for digital material removal (Bordegoni & Cugini, 2006). In this tool the users for the first time do not modify geometries with a generic end effector mounted on a commercial point-based haptic system, but with a replica of a tool (a clay scraper) they are used to work with.

3 Conceptual description of the system

The context of use of the SATIN system is the design review of newly conceived products. In the process of creating new shapes, designers often need to touch the surfaces of their products, in order to check and evaluate their aesthetic quality. In fact, some important local and global continuity aspects may be very difficult to perceive or appreciate using only a computer screen, and images -even presented in a stereoscopic view- may be misleading. The ability to touch and feel the objects that designers produce during the design process allows them to better evaluate the shapes in terms of their geometric properties.

The idea of proposing a new design tool having a novel interface based on haptic technology was generated by the observation that designers of aesthetic products create and manipulate shapes on the basis of curves: characteristic curves, aesthetic curves, etc. The concept of curve as basis for shape generation and modification is not only used in digital modeling, but also in physical modeling.

In order to clarify the role and importance of curves in typical industrial design processes, we report some examples of use of physical profiles typical of some of the end-user companies participating to the SATIN project: Italdesign-Giugiaro (`http://www.italdesign.it`) a well-known company for car design, and Alessi (`http://www.alessi.com`) a well-known company for the design of household products.

Currently, during styling activities at Italdesign-Giugiaro, the evaluation of a model is made taking into account the fundamental styling curves of the object. Designers use a physical bendable spline on the drawing to modify a sketch in a virtual room (Figure 1-a), but also to check/modify a physical model (Figure 1-b). So, even if a designer deals with 3D shapes, it is clear that the evaluation and modification of those shapes is done basing on fundamental curves.

PLACE FIGURE 1 HERE

Another example addresses the use of a physical flexible profile in a traditional Alessi design process. After the acquisition of a specific shape from 2d drawings to build first the CAD model and then the physical prototype - the physical profile is used for checking the shape of the physical prototype of the product (Figure 2-a). Some potential modifications of the shape of the physical prototype can be simulated by bending differently the physical profile, as shown in Figures 2-b and 2-c. The appreciation of the new profile is done visually as well as physically (by touch). Satisfactory profiles may then be inserted into the original 2d drawings and then transformed again into a CAD model.

PLACE FIGURE 2 HERE

On the basis of these observations and considerations, the SATIN system has been conceived as based on a haptic interface that is a haptic strip, which is coherent with the methodology used in the industrial design domain. The SATIN system is built on the concept of a mixed reality environment where the user, typically a designer, interacts with virtual 3D objects. The user is able to see the object and to explore the shape of the virtual object through the use of touch. As shown in Figure 3, the SATIN system consists of a haptic strip that mimics the tape placed by designers on physical mock-ups for evaluating characteristics and style lines. In addition, a 3D visualization of the shape is super-imposed onto the haptic strip interface by means of a stereoscopic display system. The system also plays sounds for communicating some geometric characteristics of the curve during the exploration.

PLACE FIGURE 3 HERE

4 Interaction Scenarios

The SATIN system functionalities have been defined and initially described through some interaction scenarios. The scenarios present two typical design tasks: visualization, exploration and analysis of the aesthetic shape of a digital model of an object, and

modification of the object shape. The haptic strip is the interface used to interact with shapes: it is an output device used to represent the shape, and an input device used to modify the shape. The two scenarios are detailed in the following. The rest of the paper presents the strip used for rendering and evaluating digital shapes.

4.1 Haptic strip for shape representation

The haptic strip is a tool for the representation and analysis of product shapes; it adds an additional and innovative interaction modality where the perception of the quality of a curve is not based on mathematics and visualization alone but is also based on touch. The strip has been conceived in a way that it can be used to handle the virtual object (rotation and translation) or as a haptic interface. A switch command allows us to change between the modalities.

When a digital model is loaded, the user may explore the shape of the object. By moving the strip the user moves a virtual plane. The strip continuously adapts its shape for representing the curve given by the intersection of the virtual cutting plane with the digital object surface. The user can decide (using a menu command) to associate the strip with the object instead of with the virtual plane. So, when the user moves the strip he is actually moving the object. In this mode, the strip form is not updated. By switching the modality again the system goes get back to the exploration mode. The possibility of switching between the two modalities (1. exploration mode, and 2. positioning and rotation of the object) offered by the strip, allows us to avoid using any additional input device, which would be necessary to rotate and position in space the virtual object.

The system also plays specific sounds in correspondence of some geometric properties of the curve, such as curvature discontinuities and inflection points. For example, a specific sound is played when discontinuities are encountered during the exploration of the haptic strip.

4.2 Haptic strip for shape modification

We have seen that typical designers actions start from a characteristic curve belonging to the surface that is pulled, pushed, stretched, in order to reach the desired shape; the SATIN haptic strip uses the same approach for applying modifications to shapes. The strip for shape modification, and related modalities are addressed in more details in (Bordegoni, Cugini, Covarrubias, & Antolini, 2010), and only shortly mentioned hereafter.

After exploring the shape of an object, the user may select a specific curve whose shape he wants to modify. After entering the modification modality, the position of the strip is frozen and information related to the curve edition, such as the curve and the area of influence for the edition, is presented. The user edits the shape by applying forces to the extremities of the strip, that are force sensitive, in order to modify the general curvature of the object. During the shape editing, a preview of the modified shape is shown. When the user is happy with the changes, he releases the strip, causing the system to update the shape of the 3D object.

5 System Architecture

The SATIN system architecture consists of a set of hardware and software components to control the haptic-based environment, the 3D visualization system and the sound system. The system architecture is shown in Figure 4, and consists of the following hardware components, which are detailed in the next sections:

- *Visualization system*, consisting of a rear-projected system providing the stereoscopic visualization of virtual objects, and of an optical tracking system for tracking the user point of view;
- *Haptic system*, consisting of two MOOG-HapticMaster (HM) systems to control the strip, each with its controller plugged to a TCP/IP network switch, and the haptic

strip that is mounted onto the HM. On the haptic strip is glued the hand position tracking system, that is used to detect the user's hand/finger position;

- *Sound module*, consisting of a set of speakers. This module makes use of the information coming from the position tracking system integrated with the haptic strip for rendering through sound the geometric characteristics of the curve.

Table 1 provides an overview of the technical features of the system.

PLACE FIGURE 4 HERE

5.1 User working space

The system allows users to operate in a standing position and in a working space where the visual and haptic representations of the object are co-located. The virtual representation overlaps the physical representation of the haptic strip, which conforms to the virtual shape. The co-location of the haptic and visual spaces provides a realistic working environment, and a good visual perception of the shape (Figure 5).

PLACE FIGURE 5 HERE

One of the main requirements of the SATIN system is offering an adequate working space that is equivalent to human manual operations, and that corresponds at least to the minimal working space of a standing person. This requirement motivates the choice of the haptic system architecture, consisting of two MOOG-HapticMaster systems that provide a wide working space and appropriate force feedback (Lammertse, Frederiksen, & Ruiter, 2002), on top of which the strip is mounted.

For what concerns the system layout, two working spaces need to be considered: one related to human interaction and manipulation operations, and a second one defined by the operational area of the haptic device. To achieve that, the system should offer a precise coincidence of the visual and hand operational working spaces, which are typically required in mixed reality environments (Haller, Billinghurst, & Thomas, 2007), and that

need appropriate calibration procedures in order to reach a perfect co-location.

When using the system, the user sees the 3D graphical representation of the object, the physical strip and its own hands at the same time. This configuration creates a mixed scenario where virtual and physical elements are co-located, this fostering a natural interaction with the virtual content.

5.2 Haptic system

As previously anticipated, the haptic system for surface rendering consists of an actuated strip that conforms to a selected curve on a shape. The basic concept is to use as main user interface a tangible strip that detects the contact position with the human hand/finger exploring it, positioned in space in the position of a section of a simulated virtual object. The strip can actively shape and place itself in the appropriate position and orientation in the workspace. The psychophysical requirement to satisfy is to be able to explore and modify this part of a virtual object by means of touch. Being a haptic device, the tangible strip is an output device in that the strip is an exploration device for the human hand and fingers to touch; and it is an input device, in the sense that the strip behaves as a physical item, which can be shaped by hand like a physical bending spline. The haptic strip is implemented by means of continuous physical spline that is actuated into the desired shapes by six equidistant relative actuators along its length. The deformable strip is connected to a 6 Degree of Freedom (DOF) platform consisting of two MOOG-HapticMaster devices (MOOG-HapticMaster) operating in a parallel configuration. The number of actuators depends on the length of the strip. The positioning of the strip is controlled by defining the target position of the end point of each MOOG-HapticMaster (HM) and the value of the pitch angle (controlled by digital servos). Figure 6 schematizes the haptic system. An inverse kinematics algorithm has been implemented for positioning the strip. The algorithm takes as input the parameters

of the plane on which the curve lies on (normal vector N) and two points, named anchor points A_1 and A_2, which have the characteristic of laying on the curve plane and having a position that does not depend on the curve shape (Cugini, Bordegoni, Covarrubias, & Antolini, 2009). These data are enough to compute the inverse kinematics of the strip in order to obtain the position of the end points of the HM devices and the pitch angle α of the haptic strip. The curvature of the strip is controlled by a number of control points, each one actuated by a servo. The curvature of the strip is the same of the curvature of the surface. In fact, the strip assumes exactly the shape of the curve obtained by the intersection of a cutting plane and the virtual surface.

PLACE FIGURE 6 HERE

The computation of the shape of the haptic strip is based on an algorithm that takes as input the relative angles of each control point, from which, using a linear algorithm, is possible to compute the angle to impose to the arm of each servo controlling the haptic strip. In fact, the curvature of the strip on each control point depends on relative angle of previous, current and next control points. The resulting algorithm has a linear complexity $O(n)$ where n is the number of servos used in the strip. Figure 7 shows a curve describing the strip shape by means of 6 control points.

PLACE FIGURE 7 HERE

In this way, the new position of the cutting plane is completely specified. These data are sent to a geometric modeling module, which computes the new anchor point located on the surface of the object, and the new U and N (respectively U' and N') vectors that at best fit to the object surface. The strip conforms its shape according to the new values: the new anchor point, the recomputed vectors U' and N', the position of the six control points of the haptic strip and the six angles describing the shape of the planar curve. Concerning the haptic control and the force-feedback behavior of the device, the target position of each HM device is controlled using directional springs. For the HM device on

the left, defined as master, three springs are set: one for each vector U, N and D. For the HM device on the right, defined as slave, only two springs are set in directions U and N. Along direction D, the slave HM will follow the master, in order to avoid resonance problems between the devices. The springs with direction U are ten times stiffer than the others in order to give the feeling of being hardly snapped over the object surface.

The haptic strip is implemented by means of a continuous physical spline that is actuated into the desired shapes by equidistant relative actuators along its length. The strip has been designed according to a modular structure. The bending of the strip is controlled by a serial assembly of bending modules. The number of bending modules depends on the final length of the strip. Figure 8 shows schematically the geometry of a single bending module, described by the following parameters:

- O: center of rotation of servo arm
- C_0, C_1, C_2: control points of the part of the curve controlled by the module
- SC_0, SC_2, SO, OC_1: constant-length segments
- α: angle $S\hat{O}C_1$

PLACE FIGURE 8 HERE

Given α, it is possible to compute the square distance:

$$SC_1{}^2 = L^2 + D^2 - 2LD\cos\alpha \tag{1}$$

from which we can compute:

$$\cos\beta = \frac{SC_1{}^2 + C_0C_1{}^2 - P^2}{2 \cdot SC_1 \cdot C_0C_1} \tag{2}$$

The magnitude of the curvature in C_1 follows the relation:

$$K = \frac{\pi - 2\beta}{C_0C_2} \tag{3}$$

PLACE FIGURE 9 HERE

Figure 9 shows the implementation of the bending module: it consists of the servo **(1)** connecting the lever and the control points **(IP1)**, **(IP2)** and **(IP3)** through two pushrods **(2)**. Each bending module has one servo making the length of the link carrying it longer and shorter, and the two pushrods ending on its lever forming the V-shaped mechanism controlling the bending of that section of the plastic strip **(3)** symmetrically. The pushrods are linked through spherical joints to the lever and the shafts attached on each single control point. The bending servo makes exactly 180 degrees turn between making the distance from the lever end to the hanging pivot minimal and maximal, i.e. straight up the hanging link and straight down. The component **(4)**, which carries on the servo for bending, actuates as a pendulum. The single module for bending has been designed taking into account some important considerations related to the use of sheet metal components: low inertia, light weight parts and low friction. The union of these components with the servo frame guarantees the structural rigidity of the entire module. This solution provides a lighter and rigid module for bending.

PLACE FIGURE 10 HERE

Figure 10 shows the prototype of the final haptic strip. The prototype consists of a plastic strip laying on six bending modules. The plastic strip is made of flexible PVC, its cross section is 50 mm x 2 mm with a total length of 600 mm. The haptic strip has been evaluated by some industrial designers participating to our research project in order to assess the conceptual design of the system. The designers appreciated the use of the continuous strip for evaluating the quality of the shape curvature. The only limitation concerned the impossibility of exploring those curves that are not planar. This stimulated the development of an extended version of the haptic strip, which consists of a geodesic version of the strip, which is described in details in (Cugini et al., 2009).

5.3 3D Visualization system

The main requirement of the visualization system is to provide an adequate working space in order to host the haptic system based on two MOOG-HapticMaster devices, and to support the co-location of the visual and haptic working spaces. In particular, the system is required to allow users to see their hands when operating the haptic interfaces, as well as observing the virtual shape being manipulated. In order to obtain the co-location of the virtual scene and the haptic device, the main problem we had to address was having a projection path that was not occluded by the haptic device in the whole working space. Several solutions have been studied and tested both in simulation and through real tests, before reaching the final configuration (Bordegoni, Cugini, & Covarrubias, 2008).

The final solution, named Direct Visuo-Haptic Display System (DVHDS), is a display system based on mirrors and screens for projecting an image over the haptic working space. The DVHDS system consists of a DLP projector, a mirror, a half-silvered mirror and a rear-projection screen.

The projector used for the system implementation is an active stereo DLP projector, which supports high-quality flicker free stereoscopic visualization. It has a native resolution of 1024 x 768 @ 120 Hz. The images are refreshed at 85 fps, or at 42 fps for each eye synchronized with stereographic glasses that are worn by the user. The half-silvered mirror size is 700 mm x 500 mm, and the pixel density is 58 pixels per inch.

The projector is located in a position that is above and on the back in respect to the haptic system. This position allows the user to stand in front of the visualization system without the problem of creating a shadow with his head, thus occluding the image projected by the projector. The display system is also designed in a way that its components do not interfere with the haptic workspace. So, the user can freely move his hands within the interaction space, and is able to interact with the system by grabbing and manipulating the physical interface that is positioned under the half-silvered mirror or

using other specific input devices to control the application.

PLACE FIGURE 11 HERE

Figure 11 shows the operational principle of the DVHDS. In the isometric view it is possible to see the position of the haptic device and its workspace **(A)**. The two MOOG-HapticMaster robots **(D)** holding the physical strip **(F)** are positioned under the visualization system. The stereo image coming out from the projector **(C)** is reflected on the mirror positioned on top of the layout **(G)**. The image is projected straight to the overhead projection plane, which is a rear-projection screen **(H)** that has been previously angled in order to correct the distorted image. The user sees the mirrored image in the virtual plane where the 3D image is created thanks to the half-silvered mirror **(I)**. The half-silvered mirror through which the user looks at reflects the image projected on the rear-projection screen, creating the impression that the stereo image is located in front of him (on a virtual plane) behind the half-silvered mirror.

This configuration offers good image visualization and also allows us to control the sense of depth. If the rear-projection screen is collocated near to the half-silvered mirror the user perceives the virtual object near as well; conversely; if the rear-projection screen is collocated far from the half silvered mirror the user perceives that the virtual object is far as well.

The designed system has several DOFs related to:

- position (x, y, z) and rotation (α) of the light source;
- position and orientation of the reflection mirror **G**;
- position and orientation of the half-silvered mirror **I**;.

The modification of these parameters allows us to easily relocate and adjust the position and orientation of the virtual image plane **L**.

The construction of the main frame of the system **B** is made of standard aluminium profiles in order to guarantee maximum stability and robustness. A platform **E** is used to

adjust the user's height. The relative position of the projector, mirror, half-silvered mirror and rear-projection screen is computed in a way that the image on the rear-projection screen has no keystone distortion and is fixed during normal operation of the system. A parametric CAD model of the system is used for providing values for setting the correcting projector angular values, and therefore for correctly projecting the image. The parametric CAD model allows us to study all the possible configurations so as to locate the virtual image plane **L** exactly at the center of the haptic workspace. If the positions of the user's head and of the image mirrored by the rear-projection screen are known, we can calibrate the system with the simplified assumption of using the reflected image of the screen as a real stereo screen.

Figure 12 shows the various views as seen by the user: image a) shows the virtual object; image b) shows the real world that is seen by the user when the projection system is switched off; and image c) shows the mixed image perceived by the user with a co-location of the virtual object and the haptic device. The DVHDS system allows users to see both their hands and the virtual object. What happens usually in Mixed Reality applications is that virtual information sometimes occludes the real one. This is due to the difficulty of knowing exactly when real objects are ahead or behind virtual ones, and so to represent the virtual information only when ahead of the real one. The DVHDS system solves partially this problem of occlusion being designed in a way that allows user to see his hand and the virtual object with a tiny light source under the half-silvered mirror and in case of absence of this light, to represent the real hand with an avatar in the virtual environment (the arrow represented in Figure 16) indicating the contact point between the user's hand and the strip.

In addition, we have paid attention to ergonomics issues of the technical solution: the system reduces eye fatigue because of low inconsistency of accommodation and convergence typical of mixed reality solutions based on see-trough HMD.

PLACE FIGURE 12 HERE

5.4 Calibration of visuo-haptic system

A tracking system based on optical technology has been integrated into the system for two reasons: tracking the user's point of view, and calibrating the system for aligning the virtual representation with the physical strip. The optical tracking system used is the OptiTrack developed by NaturalPoint (`http://www.naturalpoint.com/`). It consists of three cameras attached to the system structure. The cameras have been placed above the user's head; they are placed at the left, right and center of the frame, at least one meter from the tracked artifact. Figure 13 shows the tracking system setup.

PLACE FIGURE 13 HERE

In order to enhance the realistic perception of the 3D mixed image, the stereoscopic glasses worn by the user as well as his point of view are tracked in order to guarantee a real-time adjustment of the generated image. The images are refreshed at 85 fps, synchronized with the stereographic glasses. A new artifact has been attached to the stereo glasses (as shown in Fig. 13). The artifact is made of 6 asymmetric reflective spheres that improve considerably the tracking results. With this setup the artifact appears beyond the user's head so there are no occlusions even if the user is leaned over the mirror.

The collocation of the real strip and virtual model is not only depending on the head tracking for the correct perception of the stereo viewing but also on the location of the visualization device i.e., the location of the display. Since the visualization system uses reflective and semi-transparent surfaces to merge the virtual space with the physical space, a calibration process has been defined to correctly compute the location of the virtual plane in respect to the physical working space. A user sees the reflected image of the rear-projection screen in the half-silvered mirror. If the positions of a user's head and

of the mirrored image of the rear projection screen are known, we can calibrate the system with the simplified assumption of using the reflected image of the screen as a real stereo screen.

5.5 Hand/finger position tracking

The aim of the haptic strip is to allow designers to explore a curve, which corresponds to an object section, and feel its geometrical properties. Because of the limitation of the strip, that is continuous in its nature, some geometric properties like discontinuities cannot be represented by the strip. For example representing position discontinuities is impossible without cutting the strip in two separate parts. Tangency discontinuities would require a part of the strip to be permanently deformed. The rendering of this kind of properties has been implemented through the use of sounds. The system plays sounds during the user's exploration of the haptic strip: different sounds are played according to the type of local geometric characteristics of the curve corresponding to the current position of the user's hand/finger. Specifically a continuous sound represents the local curvature value of the curve, while some localized sounds represent the discontinuities.

In order to detect the user's hand/finger position, we have integrated a tracking system into the strip. The hand/finger tracking system has been implemented using capacitive sensors. This solution has several advantages, including the fact that the user does not need to apply strong pressure to activate the tactile sensor as it happened with other technologies we have tested (for example, resistive tactile sensors).

The capacitive sensors detect a change in capacitance when something approaches or touches the sensor. Integrated circuits specifically designed to implement capacitance sensing in human-machine interface applications are today available from Analog Devices (`http://www.analog.com/`). As shown in Figure 14-a and Figure 14-b we have analysed

two sensor patterns in order to better track the user's hand/finger. Between the receiver and the transmitter trace an electric field is formed. Most of the field is concentrated between the two layers of the sensor. The electrical environment changes when an object (user's hand/finger in our case) invades the fringe field, with a portion of the electric field being shunted to ground instead of terminating at the receiver. The resulting capacitance decrease is detected by the converter.

We have decided to use four QProx E1101 development boards distributed by ATMEL (`http://www.atmel.com/`), which provide excitation to the capacitance sensor, sense the changes in capacitance caused by the user's proximity, and provide a digital output. The first board uses the metal traces *a1*, *b1*, *c1* and *d1* to track the user's hand/finger, the second board uses the metal traces from *a2* to *d2*, and so on. In this way we have designed a flexible multi touch strip. The metal traces are located in between the two plastic strips, like a sandwich, preventing any damage to the metal traces, and are free of pressure and tension stresses.

PLACE FIGURE 14 HERE

5.6 Sound Interface

The haptic interface that we have developed is a major advance with respect to the state of the art in the haptic domain, since it is the first device proposing a continuous contact along a line. But the strip interface has some limitations in representing geometric shapes. Specifically, it does not allow representing the entire domain of curvature of curves. We have addressed this problem by considering multimodal interaction (Jaimes & Sebe, 2007). Several research works have shown that multimodality helps in compensating, integrating and enhancing information.

We have investigated how sound can be used for providing information about the surface that cannot be rendered through the other senses, given the actual technological

limitations, and that can be perceived during the surface exploration. An example of this information is a discontinuity in the curve (Bordegoni, Ferrise, Shelley, Alonso, & Hermes, 2008).

Sound has been used in a metaphoric way to communicate quantitative values about some curve geometrical parameters, for example the degree of a discontinuity. The system plays sounds during the users' exploration of the haptic strip; different sounds are played according to the type of local geometric characteristics of the curve (see `http://www.youtube.com/SATINproject`). The movement and the position of the users' hand/finger on the strip is tracked by means of the sensorized strip described in the previous section. We have considered three distinctive aspects of curvature data for sonification: the absolute value of the curvature that indicates how the surface is strongly curved; the sign of the curvature that indicates whether the surface is concave or convex; and the discontinuities in the curvature. These parameters are mapped to different acoustic variables used to control or modify a sound source.

The sign of the curvature is mapped to the stereo panning of the sound output in the following way. If the data are negative, the output is weighted to the left channel. Similarly, if the data are positive, the output is weighted to the right channel. Between these two reference points, the output is linearly cross-faded between the two channels and a curvature value of zero is mapped to a sound reproduced from the middle between the two loudspeakers. As we said the sound is also used to represent information that is not possible to represent with the haptic device, as for example discontinuities and inflection points. In this way sound is used to substitute touch, or to create illusory tactile cues. In order to signify discontinuities in the curvature data, two different modulations are applied to the sound. When the hand/finger is moved across a discontinuity position on the surface, the amplitude of the audio output is rapidly increased and then decreased, resulting in a click-like sound played in synchrony with the hand/finger's movement across

the discontinuity. This sound is easily distinguished from the pure tones associated with ordinary curvature values and gives the user initial feedback about the presence and the approximate position of the discontinuity. In order to allow a precise exploration of the position of the discontinuity, a specific sound is reproduced if the hand/finger rests on the exact position of the discontinuity. This sound is made by rapidly alternating between the two frequencies which correspond to the curvature values on either side of the discontinuity. Further details of the design of the sound interface and the choice of the specific sounds to represent different geometrical information are described in (Shelley et al., 2009).

PLACE TABLE 1 HERE

6 Application Framework

The application framework consists of various software modules, which are distributed on different computers and are synchronized by a main loop component. The following list presents an overview of the several software components of the system which are described in the next sections:

- *Main Loop module* is responsible for the communication and synchronization of all SATIN modules in order to provide a consistent overall state;
- *OpenIVI framework* is responsible for the 3D visualization system as well as handling tracking devices in order to provide a stereoscopic view, interaction techniques and graphical user interfaces;
- *Haptic module* is controlling the haptic rendering which is performed using both MOOG-HapticMaster systems and the strip;
- *CAD module* provides all the support to load 3D CAD models, identify their surfaces and access to a complete Class A surfacing CAD kernel. This module is also responsible for generating the data required to render the curve using the strip, and to

generate the curve data for the shape characteristics sonification;

- *Sound module* is responsible for rendering, using sound, all shape characteristics using the curve data when the user is interacting with the touch sensor, which is placed on top of the strip device;
- *Graphical User Interface*, is responsible for giving the user the possibility to choose among all the different functionalities implemented in the SATIN system, by means of easy and intuitive menus, sub-menus and icons.

6.1 Main Loop Module

As mentioned above, the SATIN application is composed by a set of modules that are communicating and sharing data representing the full status of the SATIN system. This is performed by the Main Loop module (Satin Main Loop SML) that is responsible for the communication and synchronization of all SATIN modules in order to provide a consistent state of the system. The Satin Main Loop (SML) is a publish-subscribe event manager that easily permits communications between SATIN modules, taking advantage of XML communications over TCP/IP network interface. Each module can send and receive messages in an asynchronous way (see Figure 15). The stable bandwidth of the SATIN system is about 15 Hz, which is calculated taking into account all the software/hardware components and their integration.

PLACE FIGURE 15 HERE

6.2 The OpenIVI framework

The OpenIVI framework is the basis of the SATIN visualization system and provides support for the development of virtual reality and mixed reality applications. OpenIVI relies on both OpenSG (`http://opensg.vrsource.org/`) and OpenTracker (Reitmayr & Schmalstieg, 2005) technologies to provide an integrated solution with a powerful 3D scenegraph and support for tracking devices.

The SATIN visualization system uses the OpenIVI framework to define the stereoscopic viewing based on user head position that is gathered using the OptiTrack camera system and supported by the OpenIVI Tracking Module, implemented using the OpenTracker framework. The visualization module gives access to a full 3D SceneGraph functionality implemented on top of OpenSG SceneGraph. A simple graphical interface has been implemented using the OpenIVI WidgetModule, which enables the user to select the model to load and to change visualization setting during the use of the SATIN system. Regarding the application loop and its state machine, which interacts with other SATIN modules an OpenIVI like module was created connecting the visualization framework as a client of the SATIN Loop. This module is responsible to handle all the messages from the haptic device, in order to present a synchronized haptic and virtual representation of the 3D surface explored using the SATIN application.

6.3 CAD Module

The SATIN system architecture include think3 CAD tool as geometric modeling module (`http://www.think3.com/`). In particular, it is based on the thinkCore API, which is a subset of the think3 COM Application Programming Interface. This API allows the programmer to manage think3 documents and to create or modify modeling geometry and topology objects and to apply the Global Shape Modeling paradigm, which basically allows the modification of shapes based on a set of defined constraints that define the extent to which an existing model cannot change and a set of objectives, which define what the desired shape needs to look like.

6.4 Haptic Module

The MOOG-HapticMasters are accessible through the HapticAPI. While the HapticMaster is actually composed of a separate controller server machine, the HapticAPI is running on the client machine to hide any details of communication between the

controller and the client machine. This module is also synchronized with the main loop.

6.5 Sound Module

The sound application has been developed using the Max/MSP software (`http://www.cycling74.com/`). Data relating to the characteristics of, and user interaction with the physical strip are handled in real-time, requiring communication with the other components of the system. The OpenSound Control protocol is well suited for this application, and allows optimal communication with other modules of the SATIN setup representing the haptic and visual components. These components can run on the same system, or on different systems connected in a network. The sound application receives input from other components of the SATIN system, as the position of the user's hand/finger, input from HapticAPI, shape data (curvature, tangency, etc.) from the physical prototype, and direct user input (selection of the specific characteristic to render audible (curvature, tangency, etc.), selection of sound source. The sound application generates multi-channel auditory feedback that can be directly rendered to transducers (loudspeakers).

6.6 Graphical User Interface

A graphical user interface (GUI) has been implemented, including some functions for the traditional management of models (open an existing model, save e new model, activate reflection lines, etc.). These functions are assessed through a menu, which is activated through some buttons located at the extremities of the strip (see Figure 18). In addition, the GUI renders the virtual model in the working space and provides visual feedback about the user's hand/finger position during the exploration of the curve through the rendering of a virtual arrow on the virtual strip (Figure 16). This virtual arrow act as an avatar of the user's hand/finger when there is not enough light under the half-silvered mirror and so problems of visibility of the user's hand occur.

PLACE FIGURE 16 HERE

7 System Implementation and User Testing

Figure 17 shows the final system. The user stands in front of the system, wears 3D glasses and manipulates the physical strip for positioning it on a style curve of the object; the user can evaluate the quality of the curve through touch and sounds. Figure 18 shows a detail of the strip being used for shape evaluation. Figure 16 shows the Graphical User Interface of the system. The visualization of the virtual model is superimposed onto the physical strip. Figure 16 shows the virtual object by means of the zebra lines modality. A virtual representation of the strip is also shown on top of the object model, as well as an arrow indicating the position of the user's hand/finger during the strip exploration.

PLACE FIGURE 17 HERE

PLACE FIGURE 18 HERE

7.1 User's Testing

In order to test the system usability, functionalities and performances we have organized some evaluation tests, which are described in detail in (Sharples et al., 2009). Hereafter we report the most relevant parts of the testing procedure and of the results.

Testing Modality Sixteen users participated to the testing of the SATIN system, all designers, thirteen males and three females (see Figure 19) aged between 25 and 50. Fifteen participants were used to work with physical prototypes and CAS systems, while one of them was not able to use any CAS tool. All the experiments were videoed, including the recording of views of the screen, participant hand movements and head movements. In addition, still shots were taken to enable a view of the participant's whole body posture. During the experiment a short symptom checklist was administered to all participants both immediately before use, and immediately following the experiment, to

check that symptom levels were not excessively high.

All participants were asked to perform a task, which involved using a combination of visual, haptic and sound functions in order to carry out explorations of a selected model of a product. It was important to run the tests in multimodality, instead of testing separately vision, sound and touch because the aim of the test was to judge the combined effect of information coming through different sensory channels. Specific tests performed on single modalities are reported in (Bordegoni, Ferrise, et al., 2008; Shelley et al., 2009).

Specifically, the participants were required to explore the 3D model along a given curve and to determine the points of maximum and minimum curvature, and the point(s) of discontinuity. Before starting the task, the participants were allowed to use the system for around 10 minutes in order to get acquainted with the interaction modalities and the system functionalities.

After the completion of the tasks, participants were asked to fill a questionnaire, including three sub-parts:

- **Symptom questionnaire**. The first part of the questionnaire was a standard questionnaire - the Simulator Sickness Questionnaire (SSQ) - that has been used during the evaluation of a number of different systems worldwide (Kennedy, Lane, Berbaum, & Lilienthal, 1993). It is an excellent benchmarking tool consistently used in much research on simulator use, and also widely applied in Virtual Reality research (Cobb, Nichols, Ramsey, & Wilson, 1999; Witmer & Singer, 1998). The SSQ consists of a self-report measure and contains a list of thirty separate symptoms. Participants are asked to indicate whether or not they are experiencing each symptom and, for some symptoms, the severity experienced on a scale from 0 (not at all) to 3 (severe). Analysis of the data produces an index of symptom experience on three subscales: nausea, oculomotor, and disorientation (Cobb et al., 1999).

- **Post evaluation questionnaire**. The questionnaire includes combined

questions from previously applied usability and presence questionnaires with specific questions relating to particular aspects of the SATIN system.

- **Workload questionnaire**. This questionnaire follows the NASA TLX protocol (Hart & Staveland, 1988), and is used to assess workload across a number of dimensions, including mental demand, physical demand, temporal demand, performance, effort and frustration.

The object exploration was assessed in terms of the overall time taken to detect the minimum and maximum point of curvature, and the time taken to detect a point of discontinuity.

Subjective results Participants reports of sickness were collected using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) and short symptom checklist (Nichols et al., 2000). The SSQ allows symptom scores to be calculated for three sub-scales: nausea, oculomotor and disorientation. The second part includes a short checklist that was valuable for monitoring, and has also been used on a number of different systems.

As the SATIN task does not involve participants being exposed to a high level of optic flow, it was not anticipated that high symptom levels would be experienced, as participants were using the system for approximately 10-15 minutes. The majority of participants were able to complete the specified tasks; time taken to complete the task varies considerably between participants.

Global results In summary participants were generally pleased with the ease with which they were able to explore the virtual models. The overall response to the experience was positive. Table 2 reports the results of the questionnaires, including the median and the mean for each question. Note that only two median have negative values.

PLACE TABLE 2 HERE

Positive points Everyone considered the concept to be a good one, with terms such as good, intuitive, interesting, valid and innovative being recorded on the post-evaluation questionnaire. Participants liked the potential that the system promised and the idea of being able to touch and feel the virtual surfaces with the hands, and appreciated the enhancements of sound and vision.

The system was considered to be an advance on current available systems, as the multi-modal approach provides an increased sense of reality to the user. The use of sound was very well received as an aid to exploring curvature. Most were impressed with the use of sound to represent curvature, although one person did not like this and another thought it useful but unpleasant. A couple of people commented that more initial user training/experience would be helpful.

Overall, participants believed that the SATIN system would be a useful tool for designers in the future, since they appreciated the opportunity to manipulate virtual objects using their hands. The facility for exploring curvature and shape was liked.

Areas of improvement Participants valued the multi-modality of the system but it was generally felt that improvements needed to be carried out in order to provide greater control and in particular, precision and accuracy, perceived as an important requirement for designers.

There seemed to be difficulties with the visualization of the object on the display as a number of users wanted to change the view perspective in order to understand which part of the object they were viewing.

In terms of ergonomics (see Figure 19), comfort was highlighted by a couple of people. One person was uncomfortable using the system in a standing position and suggested it might be better to work sitting down. Another participant was disturbed by the glasses blinking when looking outside the virtual field.

Regarding the symptom scores for the SATIN system, calculated with the SSQ, disorientation symptoms appear to predominate and closer examination of the data reveals that the particular symptoms that were reported within the disorientation score were difficultly focussing and blurred vision.

PLACE FIGURE 19 HERE

The participants liked the stereoscopic/3D visualization, although one person commented that he had some problems, in some situations, related to the deflection of the display. They suggested that the user interface and the menu selection needs improvement.

When asked what changes participants would make to the system to make it more useful to them, there were a range of responses which included improvements to the display (as well as solving the light reflection issue with the glasses) and a more comfortable working position.

8 Conclusions

This paper has presented a multi-modal system for shape rendering and evaluation based on the combination of vision, touch and sound. The system is oriented to industrial designers, who are expected to be able to evaluate the aesthetic features of new products in a natural, intuitive and rapid way. The implementation of the system as well as some users' tests have been described in the paper.

The benefits of the SATIN system concern both the design process and the designers' practice and way of working. The use of the system in the concept design phase would primarily impact on the number of physical prototypes required for the concept validation and testing. In fact, the possibility of physically evaluating the quality of the product shape would reduce the number of physical prototypes to few of them, which are produced at the very end of the product design phase for the final checking of product features.

In addition, our work has demonstrated how the combination of natural interaction with the capabilities of traditional design tools can lead to a design environment that allows the designers to express their ideas through physical interaction with objects, which is a natural way of working for them. The system developed fully satisfied the initial specifications including the realistic visual representation of a product, which is obtained through the 3D stereoscopic visualization of the digital model, as well as a consistent physical rendering of its surface, which provided through the haptic conformable strip.

From the discussion with the participants to the users' tests it emerged that it would be desirable to have the possibility of rendering the full surface, instead of a single curve, as well as to make the system lighter and portable. These improvements would allow us to expand the domain of application of the SATIN concept to different fields (as for example the medical or entertainment fields). In addition, at the current development stage, the system is a prototype that requires to be engineered. This would improve the performance of some components, and also significantly reduce the cost of the overall system, that would make it a marketable product. The improvement of the system in these directions will constitute our future work.

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Table 1

Technical specs of the system

Device	**Variable**	**Value**
Capacitive Touch sensor	Resolution	0.47 mm
	Number of sensors	4
	Total length	480 mm
Platform supporting the strip	Working Volume	0.160 m^3
	Max rotation angles (Roll, Pitch, Yaw)	$\pm 80, \quad +90 \quad -55,$ ± 62 *degrees*
Strip	Min curvature radius	160 mm
	Dimensions	$2 \times 40 \times 600$ mm
	Number of servos	5
Visualization System	Tracked Volume	0.212 m^3
	Dimensions (Width×Depth×Height)	$0.85 \times 0.5 \times 0.5$ m
	Refresh	85 Hz

Table 2

Results of the users' tests

Question	**Median**	**Mean**
It was comfortable to touch and explore the physical strip	1	0.82
I found it difficult to learn how to use the system	1	0.47
The sound helped me to understand some hidden information about the shape of the curve	1	0.65
The sound helped me to perceive discontinuities on the curve	1	0.53
What I heard matched my expectations of curvature based on what I saw	1	0.71
What I heard matched my expectations of curvature based on what I felt by touch	1	0.47
I understood what the sound meant	1	0.59
I had to concentrate very hard in order to understand what I was hearing	1	0.65
When listening to the sound I did not attend to what I was touching	1	0.65
When listening to the sound I did not attend to what I was seeing	1	0.76
The sound was pleasant	0	0.29
The sound improved my performance when examining the quality of the curve	1	0.71
It was comfortable to listen to the sound for a long period of time	-1	-0.29
The sound representing curvature distracted me from the visual/haptic information	1	0.94
I would like to be able to customize the sound	-1	-0.71

Figure Captions

Figure 1. Model evaluation using a physical bendable spline on the 2d model and on a physical model (courtesy by Italdesign-Giugiaro).

Figure 2. Use of a physical flexible profile for simulating some modifications of a shape of a product (courtesy by Alessi).

Figure 3. Conceptual image of the SATIN system used for aesthetic shapes evaluation.

Figure 4. System architecture.

Figure 5. System configuration.

Figure 6. Representation of reference systems and parameters used for computing the inverse kinematics.

Figure 7. Representation of the six angles describing the shape of the planar curve.

Figure 8. Bending module schema

Figure 9. Bending module

Figure 10. Physical prototype of the haptic strip

Figure 11. Operational principles of DVHDS.

Figure 12. a) virtual object; b) real world from the user's point of view; c) mixed image of virtual object co-located with the physical haptic device.

Figure 13. Tracking system setup.

Figure 14. Strip equipped with capacitive sensors

Figure 15. a) Communication among the modules of the SATIN system b) Communication of the modules with the Main Loop

Figure 16. The GUI shows the virtual object, the virtual representation of the strip and an arrow indicating the position of the user's hand/finger during the strip exploration

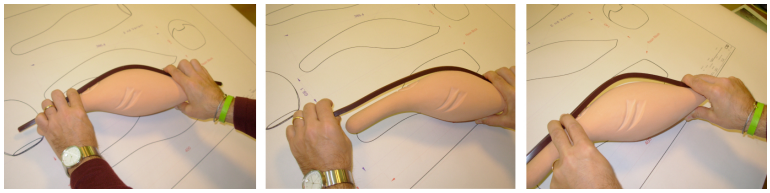
Figure 17. Final system

Figure 18. Haptic strip used for shape evaluation

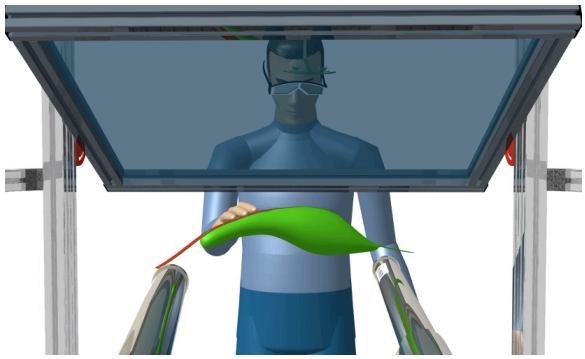
Figure 19. Posture of the participants of the tests, while using the SATIN system

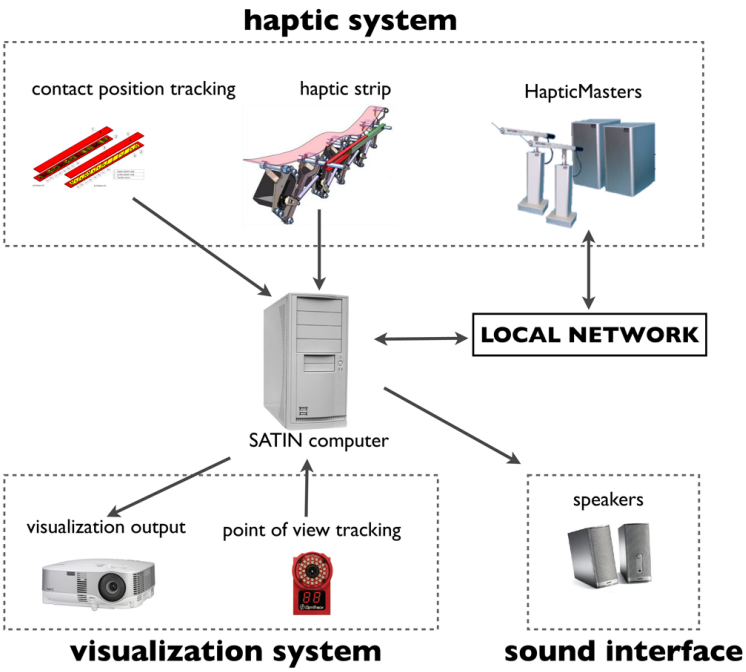
a)

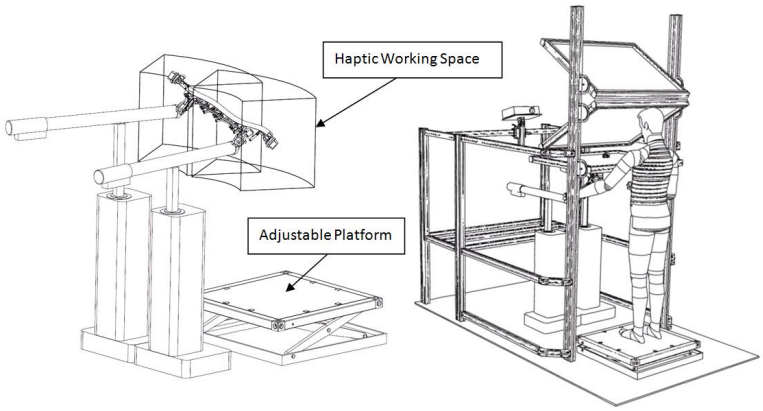
b)

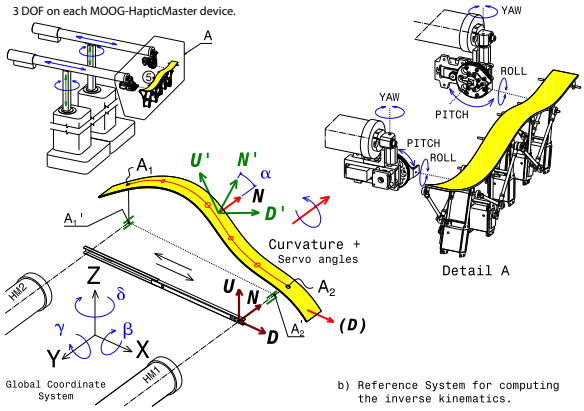


a) b) c)

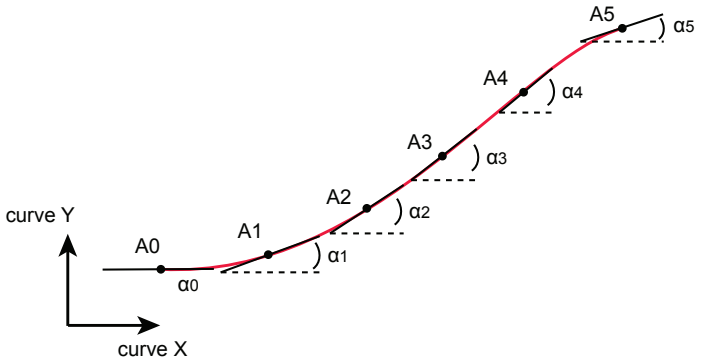


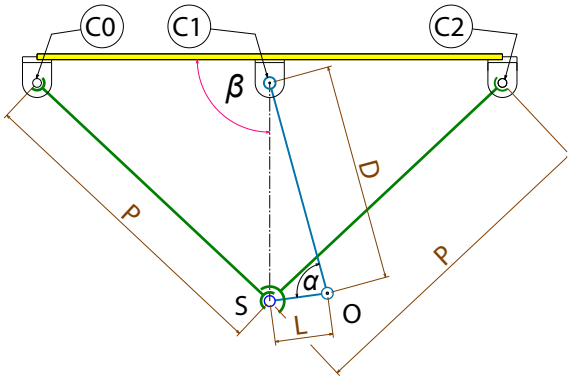

haptic system
contact position tracking
haptic strip
HapticMasters
LOCAL NETWORK
SATIN computer
visualization output
point of view tracking
speakers
visualization system
sound interface

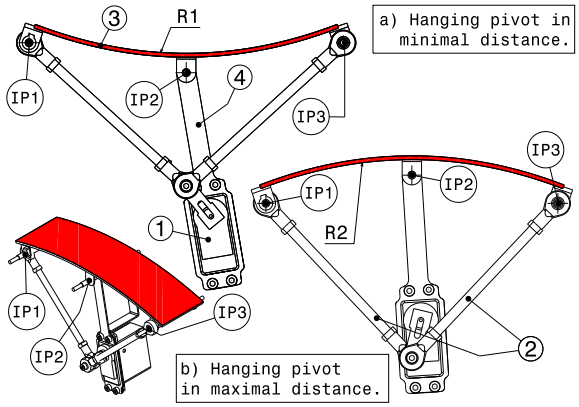

Haptic Working Space
Adjustable Platform

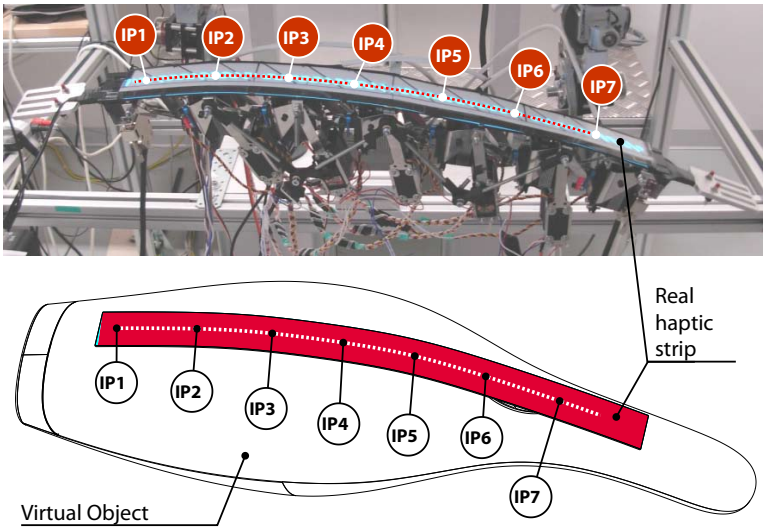


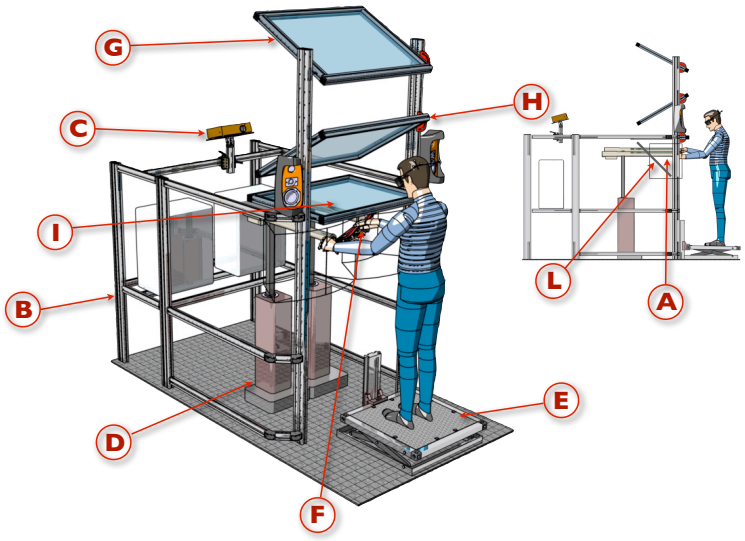
b) Reference System for computing the inverse kinematics.

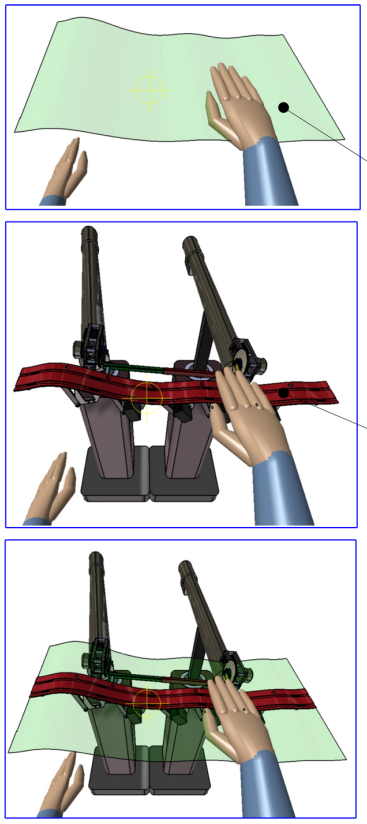

A5
α5
A4
α4
A3
α3
A2
α2
A1
α1
A0
α0
curve Y
curve X

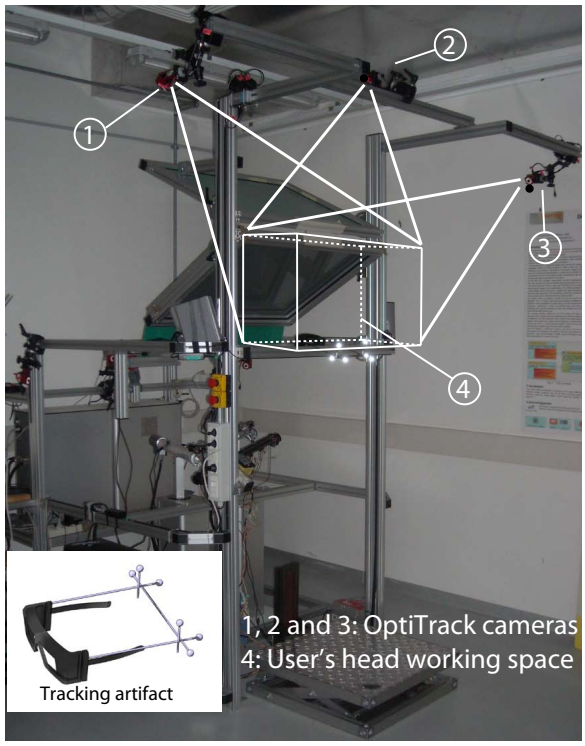

C0
C1
C2
β
D
P
P
α
S
O
L

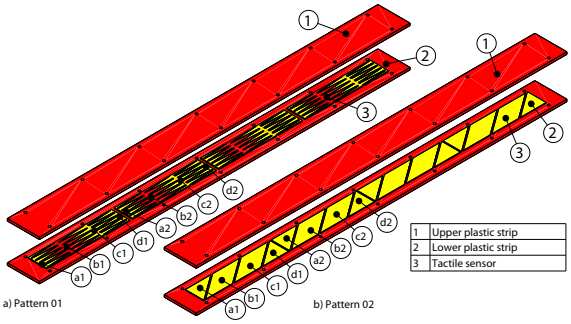

3
R1
a) Hanging pivot in minimal distance.
IP1
IP2
4
IP3
IP3
IP1
IP2
R2
1
IP1
IP3
IP2
2
b) Hanging pivot in maximal distance.


IP1
IP2
IP3
IP4
IP5
IP6
IP7
Real
haptic
strip
IP1
IP2
IP3
IP4
IP5
IP6
IP7
Virtual Object


G
C
I
B
D
F
E
H
L
A

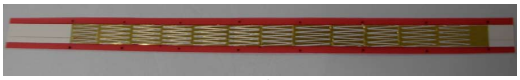

a)
Virtual
Object
b)
Real Haptic
Strip
c)
Mixing
Virtual
and Real
worlds


1
2
3
4
Tracking artifact
1, 2 and 3: OptiTrack cameras
4: User's head working space



a) Pattern 01

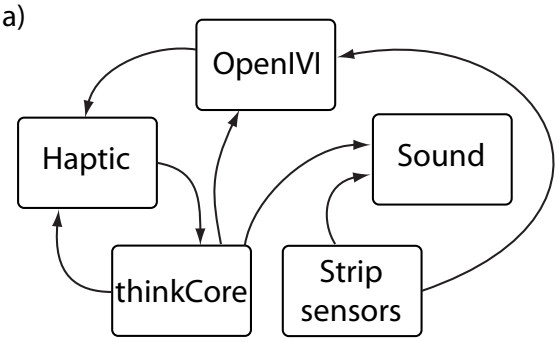
b) Pattern 02



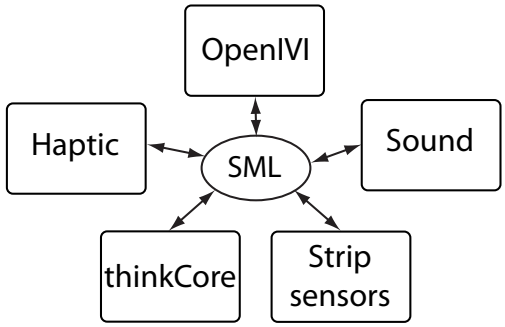
c) Prototype of pattern 01

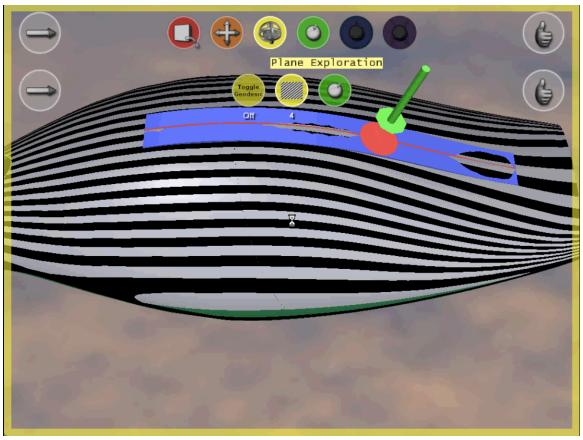
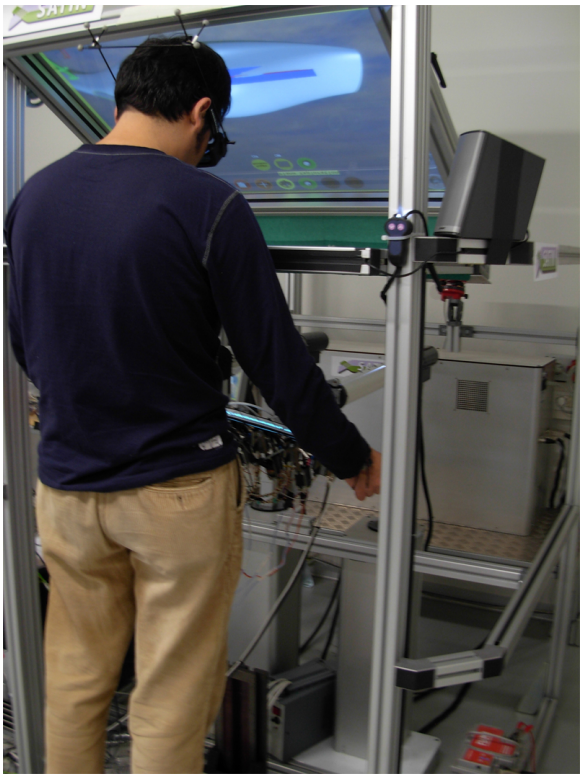
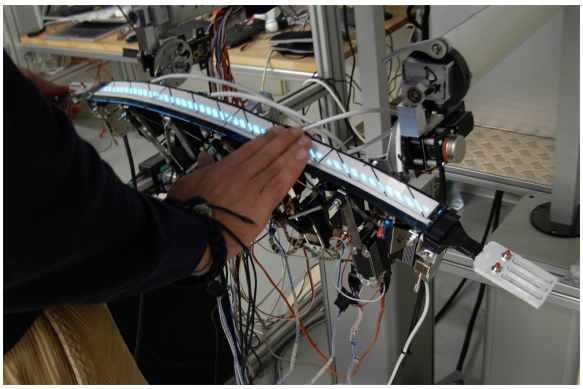
d) Prototype of pattern 02

a)


OpenIVI
Haptic
Sound
thinkCore
Strip
sensors

b)


OpenIVI
Haptic
SML
Sound
thinkCore
Strip
sensors


Plane Exploration
Toggle Geodesic
Off
4