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An Haptic based Immersive Environment for Shape Analysis and Modeling

Abstract Currently, the design of aesthetic products is a process that requires a set of activities where digital models and physical mockups play a key role. Typically, these are modified (and built) several times before reaching the desired design, increasing the development time and, consequently, the final product cost. In this paper, we present an innovative design environment for CAD (Computer-aided design) surface analysis. Our system relies on a direct visuo-haptic display system, which enables users to visualize models using a stereoscopic view, and allows the evaluation of sectional curves using touch. Profile curves are rendered using an haptic device that deforms a plastic strip, thanks to a set of actuators, to reproduce the curvature of the shape co-located with the virtual model. By touching the strip users are able to evaluate shape characteristics, such as curvature or discontinuities (rendered using sound), and to assess the surface quality.

We believe that future CAS(Computer-aided systems)/ CAD systems based on our approach will contribute in improving the design process at industrial level. Moreover, these will allow companies to reduce the product development time by reducing the number of physical mockups necessary for the product design evaluation and by increasing the quality of the final product, allowing a wider exploration and comparative evaluation of alternatives in the given time.

1 Introduction

The design process of aesthetic products includes a typical sequence of activities where physical prototypes and digital models are both used and modified several times in an iterative loop, until the shape is fully satisfactory or

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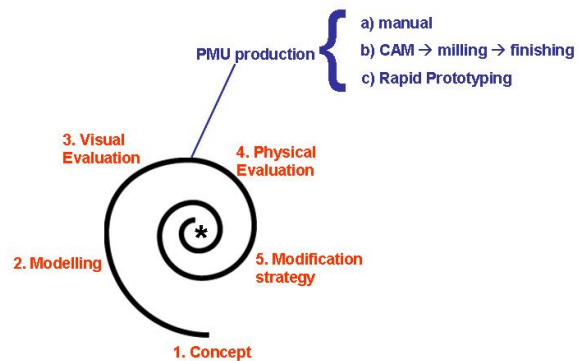
Fig. 1 Typical Design Process Phases and the Physical Mockup Phase

the time available to design expires. While digital models usually focus only the shape visual aspects, physical mockups allow a better perception of the shape quality. However, moving from one representation (digital model) to the other (physical mockup) is not straightforward. In fact, the physical mockup cannot be immediately derived from the digital model, requiring a specific production phase (see Figure 1). This can be performed manually or through a technological process including CAM, milling and finishing activities or through Rapid Prototyping (for small objects).

Before reaching a final satisfactory product representation, several loops are carried out and, therefore, several physical prototypes are developed during the design process. Moreover, each time a physical mockup is required for evaluating the product, the design process halts, waiting for the construction of the physical prototype. However, while the other phases of the design process only take a few minutes or hours, the physical mockup production requires more time that can range from days to weeks, causing a bigger impact in the design process.

While in the engineering domain it is possible to reduce the number of physical mockups to just one, be-

cause the evaluation is based on quantitative criteria and all the analysis and simulations can be performed with virtual prototyping, in the aesthetic domain, the evaluation is more subjective, vague and multisensorial. In fact, the final result is not necessarily within the initial domain concerning the object shape and defined by the requirements that are approximated and not well defined. In this case requirements evolve during the design process and are increasingly focused and defined during the iterative evaluation phase, making physical mockups more crucial and essential for any kind of evaluation.

To solve this, we developed an innovative design environment for CAD surface analysis and modification, called SATIN. The system allows users to visualize models using a stereoscopic view and the assessment of sectional curves using touch over an haptic strip, complemented with sound to convey information about the quality of the surface. Aesthetic design process analysis has revealed the importance on the usage of curves, either characteristic or aesthetic, in the creation and manipulation of tridimensional (3D) shapes. We followed this idea by proposing a new CAS tool with an haptic strip as interface in an augmented virtual environment. The concept of curve as a basis for shape generation and modification is used not only in digital models, but also in physical models, such as, those in Figure 2, where we can see the usage of tapping. For what concerns shape evaluation, the haptic strip can be seen as a tool for shape analysis. Functionalities of CAS/CAD tools for shape analysis have been developed over the years: functionalities for representing and checking sections, functionalities for representing and checking curvature of surfaces, reflection lines, and porcupine diagrams. Each of these functionalities has been introduced to simplify the perception of class A surfaces' quality and are, in general, oriented to the evaluation of a single aspect. Therefore, several functionalities are used together for a better and overall evaluation of the shape. The SATIN strip adds an additional and innovative modality for shape evaluation where the perception of the quality of the curve is not based on mathematics or visualization, but is based on touch, something that is new to the field of tools oriented to design. Concerning modification, users' typical actions also start from a characteristic curve belonging to the surface that is pulled, pushed, stretched, in order

to reach the desired shape. Of course, that is achieved by manipulating the mathematical description of the curve or by modifying a physical maquette (that implies acquisition of the digital model of the shape through reverse engineering procedures). In our solution, users can manipulate the haptic strip to change the shape of the surface, and the result is reflected in the digital model being visualized.

The haptic-based immersive environment that we propose here, will reduce the number of physical mockups during the design process and will shrink the design time by allowing the evaluation of the product shape and surface earlier. On the other hand, our system will allow designers to perform all the phases of the product design process (concept, modeling, visual and physical evaluation, and modification) continuously and without any interruption. By doing so, we will reduce the need of necessary physical mockups allowing a wider exploration and comparative evaluation of alternatives in the given time. For designers, this would definitely increase comprehension of the shape under development and contribute to improve the product quality and reduce dramatically the development time.

In summary, by providing an haptic-based immersive environment, we can expect the following main benefits:

– Reduce time of the design process and gain time within the development process
– Allow more time for designers to research on styling issues, so as to obtain better quality of results
– Increase aesthetic perception of shape (by touching the object besides seeing it)
– Provide possibility of producing variations of style in a very short time
– Produce many more virtual models in the same time stamp that is allocated today to conceptual design
– Allow people with different skills (model makers, designers) to work directly on the digital model of the conceptual shape.

The remaining of this paper is organized as follows: Section 2 provides an overview of related work in immersive environments for shape design and modeling techniques; in Section 3 we present a set of functional requirements collected from users and we also describe a set of interaction scenarios; Section 4 describes an overview of the different components of the current prototype; in Section 5, we present details about the immersive environment, putting the focus on the visualization component and the calibration issues; Section 6 describes the haptic interface and the strip device; Section 7 describes an example application developed using our approach and Section 8 presents some results achieved during tests with target users; finally, Section 9 presents conclusions and directions for further research.

Fig. 2 Shape analysis and modification expressed using curves in industrial product design: left) a vacuum cleaner mockup and right) a car being reviewed

2 Related Work

During the last decade, several researchers have proposed new 3D tools for shape design based on curves in virtual environments. Several research works have focused on providing sketch based modeling interfaces allowing to build up 3D shapes based on the sketching of 2D curves (Zeleznik et al (1996); Igarashi et al (August 1999); Shesh and Chen (2004); Nealen et al (2005); LEVET et al (2006)). Most of these approaches resulted in 2D editors for desktop computers or tabletPCs taking advantage of 2D gesture recognition or sketch analysis. These techniques were extrapolated to other environments such as large scale displays, common to the automotive industry (Buxton et al (2000)) mimicking the usage of tapes in the surface design process or other tools such as French curves (Singh (1999)).

Taping techniques have fostered the design of several tangible interfaces focusing on the usage of virtual taping as the essential modeling paradigm (Balakrishnan et al (1999a); Bae et al (2004); Cao and Balakrishnan (2003); Grossman et al (2001, 2002)). Balakrishnan et al (1999b) were the first to propose a dedicated shape device as an input to a sketching program. Grossman et al (2003) expanded this interface with a simple gesture language for performing actions like curve selection, zooming and scaling, and "dropping" curves in space. Other similar devices (Llamas et al (2003, 2005); Geiger and Rattay (2008)) were proposed, however they just use the tape device as a tangible interface to introduce modification operators and cannot be used as real physical representation of the curve or the surface. Other modeling techniques preferred to follow the sculpting paradigm (Ishii et al (2004); Sheng et al (2006)). The "illuminating clay" (Ishii et al (2004)) presents a virtually augmenting hands-on design in malleable materials like sand or clay for landscaping and architectural circles. Sheng et al (2006) expanded this idea into a handheld "clay block" sculpting interface for virtual sculpting. They use a sponge as a proxy for the clay, and attach a screen widget called "PropWidget" to it for display. User fingers are tracked optically, and both the tabletop and the sponge prop contain a number of virtual buttons, "pushed" by optically tracked gestures. This idea was also followed by Smith et al (2008), however they proposed deformable input device enriched with pressure sensors to describe a 3D shape instead of using optical tracking.

Along the years, several immersive environments were proposed for modeling tasks mixing different configuration of displays based on projection systems. Agrawala et al (1997); Ullmer and Ishii (1997); CHU et al (1998); Kuester et al (2000) present immersive solutions based on the usage of one projection surface using a stereoscopic rendering. In Agrawala et al (1997), a workbench is described where the user can manipulate 3D objects using gloves on top of an horizontal stereo display. Ullmer and Ishii (1997); CHU et al (1998) place the screen in an oblique way in front of the user, allowing to interact with tangible objects on top of the surface or also using glove devices respectively. More immersive displays, such as CAVEs, joint up to six displays to provide a complete immersive system which can also be used to manipulate and visualize 3D shapes such in Hill et al (1999) for architectural visualization. On the other hand,one projection based system can be extended with mirrors and create a mixed reality scenario such as Bimber et al (2000) where the user can visualize and interact with virtual content mixed with physical objects. Regarding interaction most of these visualization systems rely on 3D input devices such as gloves or tracked objects. Tangible interfaces and hardware devices (Hachet and Guitton (2002); Wesche and Seidel (2001)) were combined to the workbench metaphor to support the interaction with virtual content. Fleisch et al (2004); Amicis et al (2004) proposed a different immersive setup using head-mounted displays (HMD) and allowing the user to create 3D shapes by sketching 3D curves in the space using a tracked artifact. However, none of these approaches present a real representation to evaluate and perceive the real surface, and still follow the usage of the device as a proxy to modify the shape. Several experiments (Brederson et al (2000); Tarrin et al (2003); Fischer and Vance (2003); Ortega and Coquillart (2005)) have been performed combining the usage of haptic devices with these immersive environment such as the workbench or CAVE displays in order provide a physical representation of the virtual content. These solutions constraint user movements and only provide a one force feedback dimension just enabling point based exploration which is not adequate to perceive and analyse the shape by touch. Unlike existing modeling environment, our SATIN strip will enable the user to explore the shape physically along a curve using booth hands instead of feeling just one position. Combining the usage of an haptic device with a projection based environment, we will allow the user to have a physical representation of the 3D object that is being seen in the virtual scene. By doing so, we expect to increase the perception since we will use an immersive environment similar to (Bimber et al (2000); Luciano et al (2005)) which provides co-location between the virtual and the physical object combining projection based displays with mirrors. Unlike the ShapeTape (Balakrishnan et al (1999b)) interface, the SATIN strip will not adapt its shape to the user's hand gestures but it will be activated to represent the shape in real time. However, it will also behave like a device in order to control the object in the space and to perform deformations over the 3D virtual object by using the strip.

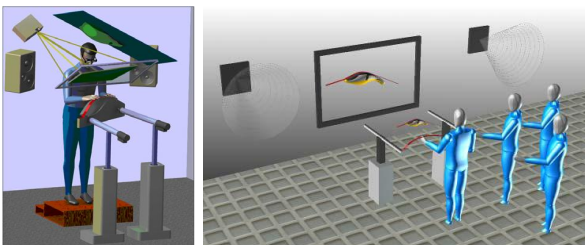## 3 SATIN Requirements and User Scenarios

Before developing the SATIN system, we performed task and requirements analysis in order to identify the poten-

tial users, tasks they want to perform and their needs. Based on the collected information and on the study of the state of the art solutions, we enumerate in the next subsections a set of user requirements, identify some functional requirements, to satisfy users needs, and describe three interaction scenarios to illustrate a possible solution.

3.1 User Requirements

During task and requirement analysis we identified the following user needs:

- Evaluation of shape features through assessment of a curve (e.g. curvature and discontinuities)
- Modification of a shape by modifying a curve
- Evaluation of aesthetic smooth shapes (1mt curves or mid size objects)
- Exploration of the curve using free hand motion
- Realistic perception of shapes through common senses (e.g. touch, sound and vision)
- Interaction with familiar graphical user interfaces (GUI) for input command
- Ergonomic technologies, not too invasive for the user
- Data exchange with in use CAS/CAD tools
- Integration with in use visualization systems (e.g. power walls)

Fig. 3 SATIN scenarios, for one user (left), and several users (right).

3.2 Functional Requirements

From the user requirements, and from all application contexts investigated within the SATIN project, we noticed that the definition and perception of shapes is mostly based on reasoning on characteristic curves. Therefore, the curve is the means (and metaphor) used for evaluating and controlling the shape of objects.

Taking this into account, we devised a solution using an haptic deformable strip to approximate curves with splines and a framework based on a stereoscopic visualization system to show virtual 3D models co-located with the haptic device. As the strip cannot represent G2

discontinuities (CAD modelers use geometrical continuity to define the level of smoothness of curves or surfaces Barsky and DeRose (1989)) and edges, we will use multimodality (haptic illusion and sound) to render G2 discontinuities and the strip physical edges to represent object edges. Additionally, we will also use the strip as a mechanism to deform the curve of 3D objects.

To satisfy the user's requirements, we defined the following functional requirements for the SATIN system:

The visualization of the 3D model is provided using a projection-based technology where the user sees the virtual object, the haptic interface (strip) and his hands, all co-located and calibrated. This solution overcomes problems demonstrated by head-mounted displays, such as the reduced field of view and the uncomfortable use.

Regarding 3D navigation and object manipulation, our system will allow users to change the point of view of the model or to change camera position and orientation, by tracking the users head (point of view) and consequently re-computing and displaying the 3D model. This way, users can get a better view of the mathematical characteristics of the shape.

Shape analysis should be offered using the haptic strip. To that end, we should provide a sectioning plane, that is manipulated using a 3D interaction device, to select the curve of the digital object to explore and evaluate. The selected curve of the CAD model should be rendered using the physical strip, which will mimic (in an approximate way) the shape of the digital curve. Imperfections, discontinuities or other mathematical characteristics that are invisible through other senses, will be rendered using sound providing more information about the curve and the surface. Specifically, sound will help to render properties that the strip cannot mimic. Sound will be generated according to the user's finger position over the strip, during exploration of the curve.

Shape and curve modification will be provided through the manipulation of the strip. From user requirement analysis, we identified two types of modifications required by the users: local and global. The former are related to changes made to the curve associated to the sectioning plane, while the latter refer to changes to the overall object. To apply (local or global) changes to the surface users could bend and twist the strip to define the desired curvature or shape. After that, the CAD model will be updated taking into account the modification parameters specified by the user using the strip.

3.3 Interaction Scenarios

Considering the user requirements and the functional requirements to be supported by the SATIN system, we defined a set of interaction scenarios describing all the steps that users are to follow to perform typical tasks. The three tasks selected and described in the interaction scenarios below are: loading of a model and initialization

of the strip; exploration and visualization of the shape and curvature of the model; and modification of the object shape.

3.3.1 Starting and Loading a Model

The user arrives to the SATIN room for a review session and switches on the system which automatically starts all the components. The haptic device sets itself in a straight line in the foreground of the workspace. The "initial menu" is unrolled over the strip, a bit like a piano keyboard, showing the available options. To load the model, the user selects the loading option of the menu by moving his finger over the strip.The list of models is presented over the strip and the user selects the desired model, sliding along the menus. After the selection, the menu is automatically rolled back and the model is loaded by the system. The model appears (on the default position or on the last position saved). A virtual cutting plane representation appears attached to the strip, while this safely adapts to the surface crossed by the plane. The user can now proceed with the exploration, visualization or edition of the shape.

3.3.2 Shape Exploration

With the model loaded, the user now wants to explore the shape of the object. The strip is adapted to the shape, and exploration can be done at any time without the need of any special activation. The user moves the virtual plane to select the profile to be rendered (haptic and sound rendering) by moving the strip, which continuously adapts to the surface. During exploration, the user pressed the "anchor switch", and now the strip is no longer associated to the virtual plane, but to the object. So, when the user moves the strip he is moving the object. In this mode, the strip form is not updated since it is an anchor relationship. By switching the "anchor switch" again, the user gets back to the exploration mode. To explore shape features, the user touches the strip, and to turn on the sound rendering, he activates the menu option to render C0 discontinuity of the curve using sound. To perceive the shape haptically and to evaluate the shape discontinuities guided by sound, the user moves his hand on top of the strip.

3.3.3 Modification of the Shape

After exploring the shape of the object, the user places the strip and the object as he wants and entered in the modification mode, by using a switch or pronouncing the voice command "edit shape". After entering this mode, the position of the strip is frozen and information related to the edition, such as the highlight of the curve and specific virtual markers describing the area of interest for the edition, are presented. The user uses two fingers over the strip, to delimit more precisely the area of interest for

the manipulation. The user edits the shape by pushing and pulling on top of the strip, changing the physical profile of the strip. To change the global shape of the object, the user switches the modification mode and now apply forces to the strip to edit the general curvature of the object. During edition, a preview of the edited shape is shown, and when the user is happy with the changes, he releases the strip, causing the system to update the shape of the 3D object. After performing the changes, the user saves the new model, by selecting the "save" option from the piano menu. The system will also save the current position of the haptic device, so the next time the user loads the model the strip will be positioned in the last used position.
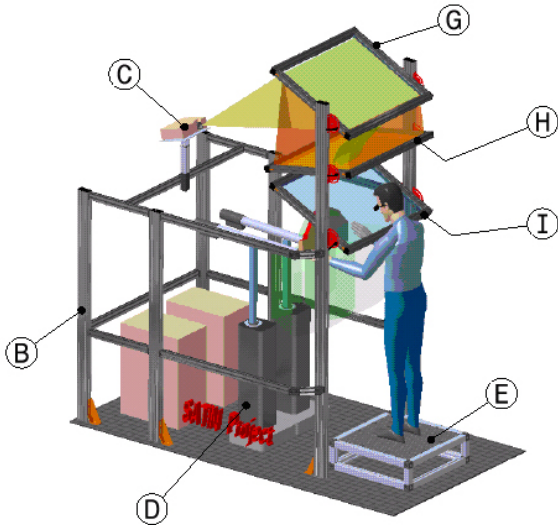
4 SATIN Mockup System

Current augmented reality solutions for product design are divided in two categories: front-projection and rear-projection. Solutions based on front-projection have the advantage of easily increasing/controlling the visual space by just acting on the position and focal length of the projector. However, they have the disadvantage of creating the 3D view of the projected image far away from the user's reachability. In rear-projection systems the real world objects always lie between the observer and the projection plane, thereby occluding the projected graphics and consequently obstructing the virtual environment.

To overcome these problems, we designed a solution named Direct Visuo-Haptic Display System (DVHDS), based on mirrors and screens for projecting an image over the users haptic working space. Compared to existing approaches such as the ImmersiveTouch(Luciano et al (2005)), our system relies on the usage of projector instead of a CRT display which provide a diagonal viewing area greater than 40". The DVHDS provides an adequate working space able to host the haptic system based on two FCS-HapticMaster devices, in a parallel configuration, which control the strip and cover an interacting volume of 100 liters. The visualization system is designed to support the co-location of the visual and haptic working space (as shown in Figure 4), allowing users to see their hands superimposed onto the virtual object being manipulated. Additionally, we paid attention to ergonomic issues, such as reduction of eye fatigue - by having a low inconsistency of accommodation and convergence (typical in mixed reality solutions based on see-trough HMD).

In this section, we present the SATIN mockup, created to validate our solution, describing its main components, namely, the visualization part, the haptic interface and the sound rendering module.

Fig. 4 Overview of the SATIN Mockup system

ID	Component
A	Haptic Workspace
B	Main frame
C	DLP Projector
D	FCS-HapticMaster
E	Support
F	SATIN Strip
G	Mirror
H	Rear-projection Screen
I	Half-silvered Mirror
L	Virtual image plane

Table 1 Components of our Mockup system

4.1 Direct Visuo-Haptic Display System

Our Direct Visuo-Haptic Display System consists of a projector, a mirror, a half-silvered mirror and a rear-projection screen as depicted by Figure 4. This configuration 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. Both Figures 4 and 5 show the operational principle of the DVHDS, and Table 1 lists the system components. In the isometric view it is possible to see the position of the haptic device and its workspace. The two haptic devices (D) 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 then 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).

This setup uses concepts similar to the Immersive-Touch(Luciano et al (2005)) and Paris(Johnson et al (2000)) devices. However, the haptic device is able to render a curve instead of just providing a point based exploration of the surface. The designed system has several DOFs related to:

– position and rotation of the projector;
– 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 used to achieve the co-location between virtual and physical object as we will describe in Section 5. In addition, by controlling the height of the support(E), users with arbitrarily height can stand and interact with our system.

4.2 Haptic overview

The haptic interface of the SATIN system consists of a deformable strip connected to a 6DOF platform based on two FCS-HapticMaster devices operating in a parallel configuration. The basic concept is to use as main user interface a force sensitive tangible strip, suspended in space in the position of a section of a simulated virtual object. The user manipulates a virtual cutting plane for selecting a section, which is a curve, on the virtual model of a product. The strip actively shapes and places itself in the appropriate position and orientation in the workspace. The tangible strip is an output device in that it is an exploration device that can be touched by the user's fingers; 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 designed as a continuous physical spline that is actuated
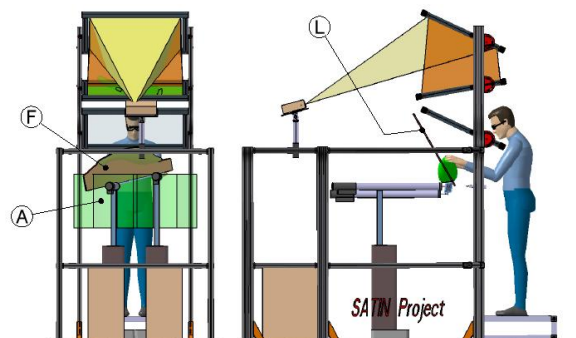
Fig. 5 Orthogonal views of the Direct Visuo-Haptic Display System and its components

into the desired shapes by nine equidistant actuators positioned along its length. Figure 6 shows a conceptual image of the strip mechanism.
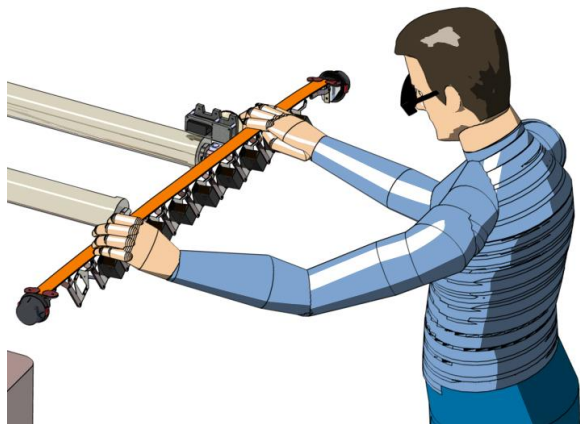
Fig. 6 Conceptual image of the strip mechanism.

4.3 Sound rendering

The haptic interface that we are developing is a major advance in 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. 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. 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. The movement and the position of the users' fingers on the strip is tracked by means of a flexible sensorised strip (I-CubeX Infusion (2008)) that is attached to the top of the plastic haptic strip. The sensorised strip allows us to detect the position of contact between the user's finger and the haptic interface. We have considered three distinctive aspects of curvature data for sonification: the absolute value of the curvature that indicates how strongly curved the surface is; the sign of the curvature that indicates whether the surface is concave or convex; the discontinuities in the curvature. These parameters are mapped to different acoustic variables used to control or modify a sound source.

5 Immersive Environment

The visualization system is one of the main elements of our design environment since it allows the user to visualize the 3D model of the shape to be evaluated and modified. We design our environment to provide a mixed reality scenario where virtual representation overlaps the physical representation of the SATIN strip which conforms to the virtual shape. In this section, we describe how the mixed reality scenario is achieved using the mockup presented previously (Figure 4) explaining how the stereoscopic view was configured to provide a good visual perception of the shape and which are the calibration procedure employ to achieved such result.

5.1 Mixed Reality Working Space

As described in the previous section, the user is looking to an half-silvered mirror enabling to see the reflection of the projection screen, the physical SATIN strip and its own hands at the same time. This configuration creates a mixed scenario where virtual and physical elements are co-located, which foster a natural interaction with virtual content. Angular positions of the screen and mirror are defined to place the virtual screen in the middle of the working space of interaction. The user's head is tracked and the stereoscopic view presents the virtual object on top of the haptic device as depicted by the Figure 7. The mixed reality scenario avoids the need of an avatar representation of the user, since both hand are visible in the working space.

Our DVHDS system relies on a main frame using standard aluminium profiles in a similar manner to the PARIS(Johnson et al (2000)) system combining a screen, a mirror and a half-silvered mirror with a DLP projector. Our setup is designed to guarantee maximum stability, robustness and flexibility to control the orientation of the mirrors and the screen to provide a stereoscopic virtual plane as depicted by Figure 8. To optimize the virtual plane location in the working space, we have developed a parametric CAD model of the system to compute its location based on the angular valued of the frame structure joints.The parametric CAD model allows us to study all the possible configurations so as to locate the virtual image plane at the center of the haptic workspace.We used a XGA DLP projector displaying at 90Hz combined with stereographic shutter glasses that are worn by the user. In order to enhance the realistic perception of the 3D mixed image, the glasses worn by the user as well as its point of view- are tracked in order to guarantee a real-time adjustment of the stereoscopic image.
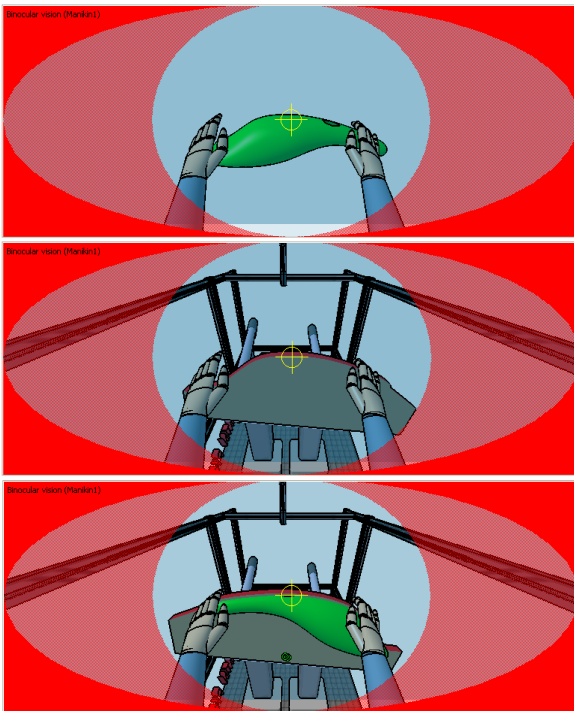
Fig. 7 User view when looking to the half-silvered mirror: top) shows the virtual object; middle) shows the real world that is seen by the user when the projection system is switched off; and bottom) shows the mixed image perceived by the user with a collocation of the virtual object and the real haptic device.

5.2 Requirements to enable stereoscopic haptic co-location

As depicted by Figure 8,the 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. In order to compute the mirrored screen position, firstly, we have to compute the world coordinates of the half-silvered mirror using an established global coordinate system origin and then we have to compute those of the rear-projection screen as well.

Using this global coordinate system, the calibration process has two goals:

1. defining the orientation of the semi transparent mirror and the position and orientation of the screen, i.e. we need to know the four 3D points in global coordinate of the extremities of the virtual plane
2. defining the location and orientation of the user point of view based on the position and orientation of the camera in the global coordinate system

These data will be inserted into our OpenGL based visualization software as configuration parameters regarding the virtual plane definition for the stereoscopic definition

and as tracked stream data for the 6DOF information of the camera.

5.3 Calibrating DVHDS using tracking system

We used initially a tracking system (VICON) to gather the user point of view and calibrate the mirror based visualization system. To determine the point of view, four rear-reflective markers were attached to the user's shutter glasses tracked by 3 cameras. The tracking system was able to deliver the tracking data according to the tracking area origin which was defined arbitrarily in the DVHDS space. Then using the same reference, we defined a calibration process in order to define the position of projection screen and the half-silvered mirror in order to compute the location of the virtual screen for the stereoscopic visualization.

The positions of the user's head and of the mirrored image of the rear-projection screen are known thanks to the VICON tracking optical system. In this way we can calibrate the visualization set-up with the assumption of using the reflected image of the rear-projection screen as a real stereo screen. In order to compute the virtual plane position, we measured the world coordinates of both the half-silvered mirror and the screen mirror using a known calibration object with four reflective markers to track their center and orientation as depicted by Figure 8.

For computation of the reflection, only the plane in which the half-silvered mirror lies is important. In order to correctly match both the virtual plane and the half-silvered mirror, a calibrating rectangle was created corresponding to the measurement of the rear-reflective screen. The screen transformation is then computed reflecting this rectangle along the Up-Axis of the half-silvered mirror in the tracking reference coordinate system. Since the user head is tracked using the same reference system, we use the tracking system reference system as our global coordinate system in this scenario.
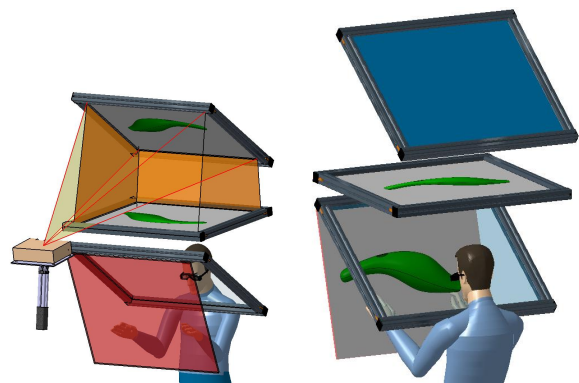
Fig. 8 Creation of Virtual Plane (L) and User view: left) Projection of the stereo image onto the mirror and its reflection correspond to the virtual plane right) The user sees the image created by the reflected image on a virtual plane
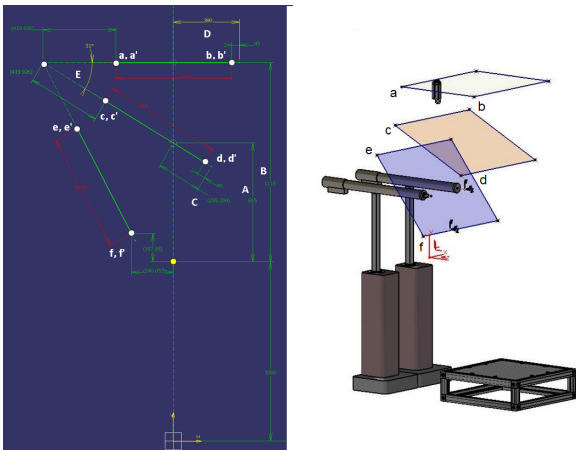
Fig. 9 left) Parametric assembly used to compute calibration points and right) calibration points defining the screen, mirror and virtual plane extremities into the SATIN environment.

### 5.4 Simplification of the calibration system

The calibration process defined above requires the usage of a costly tracking system to compute the position of the virtual stereoscopic screen and the point of view of the user. As an alternative solution, we implemented a new process based on the usage of the parametric model of our aluminium frame structure. First, we defined a Global Coordinate system as a fixed point in frame structure to easy the precise measurement from this reference point as shows Figure 9.

Then using a CAD application, we have created a parametric assembly to compute all the 3D points required in the calibration of the screens. Firstly, precise 3D models including all the components used in the mock-up were designed; second, position restrictions were assigned as equal length, mirroring, and equal angles in order to always maintain symmetry and finally some considerations regarding the coordinate system were established. The inputs in the parametric assembly are A, B, C, D and E and the outputs are the twelve points a, a', b, b', c, c', d, d', e, e', f, and f' defining screens and mirror extremities (Figure 9). All the measurements were taken using the CAD application which reproduced precisely our visualization setup.
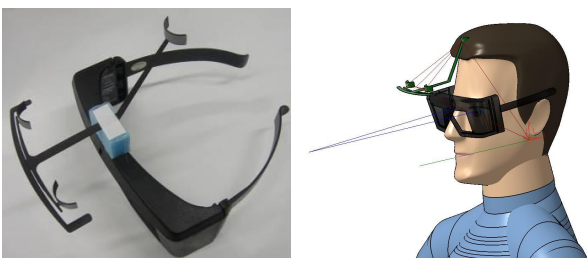
Fig. 10 Clamping the TrackIR marker onto the shutter glasses

Regarding the head user tracking, we replaced the VI-CON tracking system by a more simple tracking system exclusively used to track the shutter glasses. We use a NaturalPoint TrackIR camera which is able to track position and orientation of a predefined tracking artifact. The camera was attached to the aluminum frame in a rigid way located in the midpoint of the furthest edge of the half silvered mirror. Combining the physical and virtual measurement, we compute a precise location of the camera in the Global Coordinate system. We tested several way to attached the reflective marker on top of the shutter glasses defining the correct offset to apply to the tracking data in order to recover the position of the user head instead of the center of the marker as depicted by Figure 10. Combining this correction with the position and orientation of the camera in the global coordinate system, we were able to define the configuration in order to feed our Visualization application with the correct user view point in the global reference system as the one used to define the virtual plane configuration. Thanks to this change, we are able to create a cheaper and effective solution to provide a DVH Display system as shown in Figure 11. In this image, we can also observe the virtual image seen by the user. In this case, we can only observe the representation of the structure in the virtual world but, from the user's position, he can see the virtual shape representation matched with the physical strip underneath.
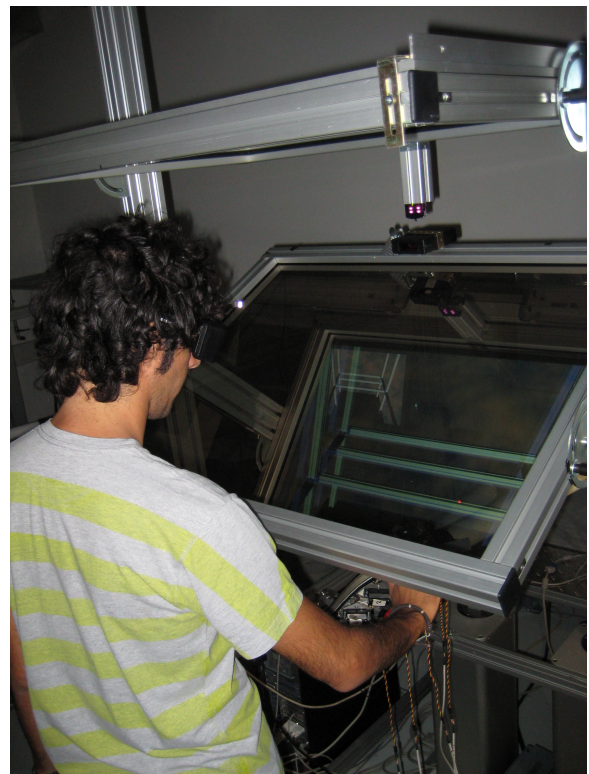

Fig. 11 User mixed reality view of the SATIN environment with head tracking

6 Haptic Interface

This section describes the mechanism designed to actuate the haptic strip and the architecture of the haptic strip used in shape exploration mode. The deformable haptic strip control mechanism has been developed from a specification derived by observing typical design operations performed during the evaluation and modification of physical product prototypes. Thus, we have created a virtual haptic strip prototype with the aim of having a flexible configurable model to maximise our freedom during the design phase and, at the same time, to be suitable for practical use, during the modification phase. In this section, the final configuration of the haptic interface is presented and discussed.

An initial kinematical solution has been created based on two FCS-HapticMaster (HM) devices. This setup has been used for positioning and controlling the 6-DOF of the platform supporting the mechanism for the strip deformation. The simulations performed on the virtual prototype have shown that this configuration provides six degrees force feedback (roll, pitch, yaw, X, Y and Z), but in order to rotate the strip of 30 degrees around the pitch axis at least one of the HM devices must rotate of 1 degree (around Z axis). This solution was not considered adequate, that is the tilt control provided for the two HM devices was not suitable mainly because of the poor relationship between the tilt orientation and the rotation of the two HM devices. The following and final configuration of the 6-DOF mechanism is an improvement of the previous one and is displayed in Figure 12. This solution uses two servo drives to control tilting. It provides five force feedback degrees (X, Y and Z of the strip anchor point, and roll and yaw). The tilt angle control is provided by the two servos. In this way, we get 90 degrees forward and backward rotation without any collision between the components. This value related to the pitch is optimal in relation to the functionalities required by the SATIN system. The right HM carries a block consisting of a roll link, and a yaw link which carries the tilt servo on it, which drives the lever on the pitch link via a reduction gear system. Also, the left HM device carries a roll link and a yaw link which carries the second tilt servo on it. A linear rail guide has been introduced to connect the two servos: this solution enables simultaneously accomodating the changing distance between the HM devices and the lengthening/shortening of the distance between the strip support points while the strip is conforming. One reason to use the linear rail guide is to prevent the unnecessary stress on the strip mechanism in case the HM devices misbehave, or one of them does not follow the other. Furthermore, using two servos to control the tilt permits direct and stiff connection between the HMs. This allows us to get high stiffness and load capacity even when the user is applying pressure while exploring the strip.
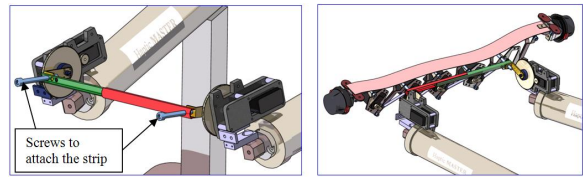
Fig. 12 Tilt angle provided by the reduction gear system.

6.1 Deformable Haptic Strip

The deformable haptic strip allows us to render the form of a target curve. The curve is obtained from the intersection of the object surface and a virtual cutting plane. Several constraints were considered in the design process: first, was to have a minimal local bend radius of 80mm; second, the length of the plastic strip should be of about 1 m. These parameters have been derived by the study cases provided by the end-users (Italdesign-Giugiaro's cars, Alessi's household items and Steklarna Hrastnik's glass products). Another important design issues addressed in the haptic strip design were: low friction and inertia, adequate force ranges, static balancing, large workspace while the strip is conforming and regular spacing of the deformable joints. The haptic strip has been designed incrementally, from a preliminary version with one degree of freedom to a second version with four degrees of freedom. The aim of the second version has been to study the behaviour of a modular version of the device, investigating the angular limitations and the interferences between the various components. Figure 13 shows the modular components used in the strip. Each module is attached through revolute joints (pins A and B), using a pushrod (E) attached on a lever (D); each module is able to rotate the adjoining module.
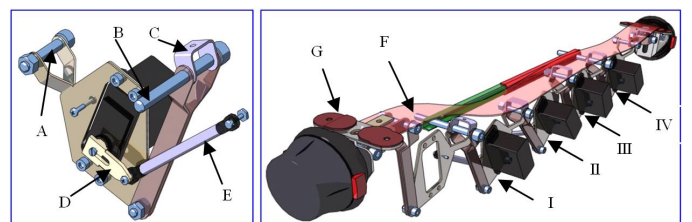
Fig. 13 Modular components used in the strip.

The plastic strip (F) is attached by means of five bolts on the component (C) of each single module. This configuration guarantees that the plastic strip behaves as a spline. While manipulating the system, the user may need to interact with the virtual scene, e.g., to move the object, position the cutting plane, and activate a functional menu. As extra input devices would be unsuitable when both hands are engaged in handling the strip, we attached two 6DOF mice (3D connection space mice) at the extremities of the deformable strip. They are used as

sensors in addition to those provided by the HMs for manipulating the virtual scene. All the components (G) required to attach each 3D mouse to the plastic strip allow slide motion maintaining the rigid join on slot properties in order to always guarantee tangency in the plastic strip. The goal of the SATIN haptic interface is to allow designers to feel and modify a curve, which corresponds to an object section. When the system is used to represent the curve, the virtual object and the physical strip are located in a fixed position in space and keep still until the user selects another curve to explore. In this case, the two HM devices are used as ordinary robots, and therefore, they have to be fairly robust and stiff, but they do not actually need to be force sensitive. Conversely, in the modification phase, the strip needs to become force sensitive. In fact, when pushed by the user, the strip should react by deforming in a way that is constrained by previous actions, and by the overall geometry of the designed object. Therefore, when the system is used in deformation mode, the HM devices provide the required force feedback.

6.2 Physical Shape Approximation

The control of haptic device is split in several tasks:

1. 6DOF positioning of the strip (inverse kinematics)
2. Conformation of the strip
3. Haptic control while moving the section plane
4. Haptic control while moving the object

The positioning of the strip is controlled by defining the target position of the end point of each FCS-HapticMaster and the value of the angle of pitch (controlled by the digital servos). The inverse kinematics algorithm takes as input the parameters of the plane the curve lies on (normal vector N) and two points, we name them anchor points $A1$ and $A2$, that have the characteristics to lie on the curve plane and have a position that doesnt depend on the curve shape. The direction A1A2 is parallel to vectors D and $D0$. These informations 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 a of the haptic strip (Figure 14).

Concerning the computation of the shape of the haptic strip, the algorithm takes as input the relative angles of each control point (Figure 15), from which, using a linear algorithm, it is possible to compute the angle to impose to the arm of each servo composing 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.

The haptic control loop continuously conforms the strip to the shape of the curve defined by the geometric CAD kernel (Think3 (2009)) while the user moves
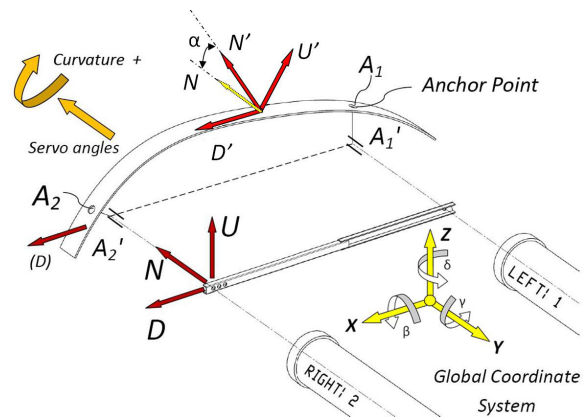
Fig. 14 Representation of reference systems and parameters used for computing the inverse kinematics.

the strip with his hands. When the user moves the cutting plane to a new position, the system computes the new coordinates of the anchor point on the haptic strip (translation and rotation from the current position) and new vectors U (up face of the strip) and N (normal to cutting plane) (see Figure 14). In this way, the new position of the cutting plane is completely specified. These data are sent to CAD kernel, which computes the new anchor point located on the surface of the object, and the new U and N vectors that at best fit to the object surface. The geometric kernel sends to the inverse kinematics block 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 (Figure 15). At this point, the strip conforms itself according to these values. Figure 16 shows the strip approximating a physical 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
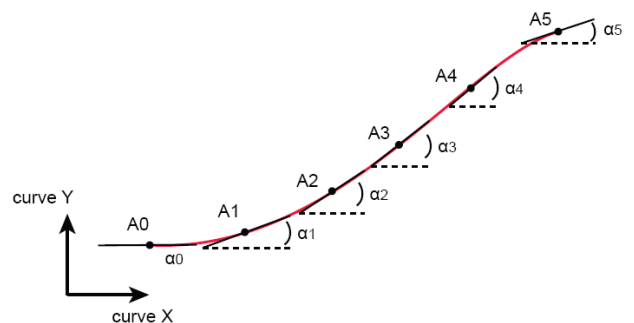
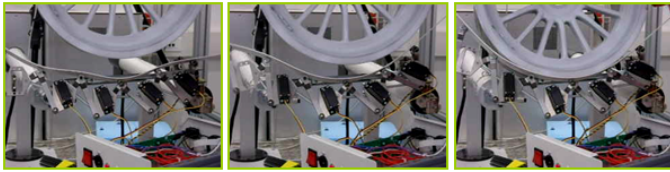**Fig. 15** Representation of the six angles describing the shape of the curve.

Fig. 16 Physical curve approximation

follow the master, in order to avoid resonance problems between the devices. The springs with direction U are 10 times stiffer than the others in order to give the sensation of being hardly snapped over the object surface. The strip is used also to rotate the object: in this modality every spring has the same stiffness.

The linear haptic interface that we are developing is a major advance in respect to the state of the art in the haptic domain, since it is the first device proposing a continuous contact along a line. Figure 17 presents several different possible approximations represented by the haptic strip. As described before, the usage of metaphoric sounds allow to complement the haptic representation with additional surface quality information and overcome the continuous limitations of the strip representation such as its non-ability of rendering sharp edges and discontinuities.
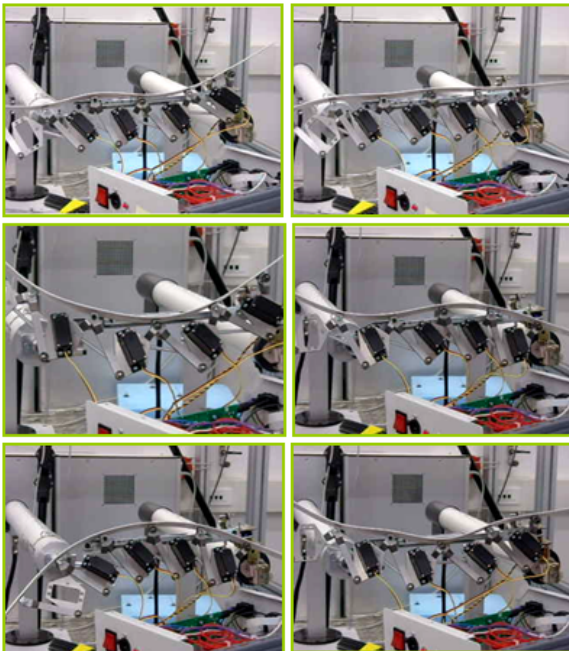

Fig. 17 Different curve approximation examples

7 Application

The SATIN Application features a set of hardware and software components in order to control our haptic based immersive environment. Two scenarios were deployed depending on the tracking system used by the setup. The first prototype was based on VICON tracking system usage which is not longer required considering the current frame structure.The following hardware was used to complement the aluminum frame and mirror based visualization structure:

1. two FCS Haptic Masters to control the strip, each with its controller plugged to a TCP/IP network switch;
2. the strip and its servos are plugged to an embedded system controller which is connected to the haptic module using a serial interface (RS-232 port);
3. the TrackIR camera system is connected by a USB interface to the computer running the visualization;
4. the 3D mouse which is attached to the strip device and is connected via USB to the computer running the haptic module;
5. the touch sensor and speakers are controlled by the sound module and the sensor is connected using a MIDI interface.

Regarding the software components, we designed several modules, which can operate on different computers due to the SATIN Loop component. However, the current setup and functionalities enable us to run all the software components on the same computer. The following list presents an overview of the several software components described on the next subsections:

– SatinLoop 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 in the SATIN scope;
– Haptic module is controlling the haptic rendering which is performed using both haptic masters and the strip, as well as the 3D mouse attached to it (in order to control the haptic device);
– 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 generateing the data required to render the curve using the strip, and 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 the top of the strip device.

7.1 System Architecture and SatinLoop Coordinator

As mentioned above, the SATIN application is composed by a set of modules which are communicating and sharing data representing the full status of the SATIN system. This is performed by Satin Main Loop module which is responsible for the communication and synchronization of all SATIN modules in order to provide a consistent state of the Satin 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. Each module can be debugged by sending test messages, application sessions may be recorded (and played back) and modules can be easily plugged and unplugged.

7.2 The OpenIVI visualization 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. It is a new Open Source Initiative launched to support fast prototyping of new applications with advanced 3D visualization techniques combined with innovative interaction techniques. OpenIVI relies on both OpenSG (2007) and OpenTracker (Reitmayr and Schmalstieg (2001)) technologies to provide an integrated solution with a powerful 3D scenegraph and support for tracking devices. OpenIVI proposes a flexible event loop management to fit any VR/MR/AR setup and to support multi-input configurations. This framework enables customized visualization devices usage such as Head-Mounted Displays, Tiled display systems or traditional Desktop monitors. Due to flexible XML based configuration files, it enables customized prototyping and fast integration mechanisms with a complete separation of inputs, interaction and functionality. OpenIVI is implemented using C++ as a set of dynamic libraries relying on cross platform technologies such as OpenGL, OpenSG, Glut, OpenTracker and ACE and can be compiled using Windows, Linux and Mac OS.

OpenIVI is organized into a set of internal modules (EventModule, VisModule, TrackingModule, WidgetModule, InputModule, InteractionModule, SchedulerModule) with different responsabilities which are managed by a kernel component. Each module provides its functionality trough a service interface which can be access by other module thanks to the kernel where all modules of the running application are registered. Each module is implemented as a separate thread which can also communicate with other modules using events which it has previously subscribed using the Event Module. OpenIVI allows to be extended by implementing new modules to be plugged to the OpenIVI Kernel. The following description presents modules that are already provided and part of the OpenIVI Framework.

EventModule: Module allowing event publication and subscription using flexible filters in order to enable a module to be alerted when a given event type is available. Events description is customizable allowing to place any basic C++ types, vectors and maps combinations.

VisModule: Main module for the visualization which provides access to a full 3D SceneGraph functionality implemented on top of OpenSG SceneGraph. This module supports several visualization setups: traditional Mono Display, Tiled Display (mono and stereo), Head-Mounted Display or any stereo projection configuration. The visualization is customizable using XML based configuration files to define the type of visualization (multi-viewport, mono, stereo, cluster) and the initial content of the 3D scenes organized into identifiable nodes which can be referenced using the visualization module service. Thread and synchronization support is provided to enable other OpenIVI modules to manipulate the scene-graph in a parallel way using a technique similar to the one used to support cluster based visualization.

TrackingModule: Module responsible to handle 3D input devices such as tracking systems (optical, magnetic or ultra-sound), 3D space mouse or other 3D input devices. This module is implemented using the OpenTracker framework which is extensible, already supports a rich set of devices and relies on a generic event description which enable multi-modal events. The OpenTracker XML configuration was extended by OpenIVI allowing to easily map tracking data to existing scene node such as objects or even cameras to control the view.

WidgetModule: This module is responsible for the management and design of the graphical user interfaces. Traditional 2D Menus and buttons are supported but also 3D representations which can be easily extended to offer new 3D manipulators or widgets. Several menu layouts are available and can be configured using an XML file which defines the layout and content of existing widgets but also what kind of events need to be generated when an action is performed over a widget.

InputModule: Traditional keyboard and mouse events gathered from the operating system are provided by this module. It is also possible thanks to the Input Module service to register callbacks to receive inputs' information.

InteractionModule: Interaction concepts and manipulators are implemented by the Interaction Module such as navigators using 2D, 3D mice or devices, the Nintendo's WiiMote or 3D object manipulators. Several Widget interaction metaphors are provided by this module and can be selected using the XML definition. This module is designed in an extensible way

in order to enable the implementation of new multi-modal interactions.

SchedulerModule: This module is responsible to provide a cross platform access to timer events based on the ACE framework. Several timers can be created to synchronize the different activity of existing module using the Scheduler module service.

SATIN visualization system uses the OpenIVI framework to define the stereoscopic viewing based on user head position which is gathered using the TrackIR camera system and supported by the OpenIVI Tracking Module. The WidgetModule was configured in order to provide a simple graphical interface that enables the user to select the model to be loaded and change visualization setting during the usage of the SATIN system. Regarding the application loop and its state machine, which interacts with other SATIN modules, using the SATIN Loop coordinator, a 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 and 3D mouse, in order to present a synchronized haptic and virtual representation of the 3D surface explored using the SATIN application.

7.3 ThinkCore CAD Kernel API

Think3 produces a set of software CAD applications offering a wide variability of modelling, visualization and modification capabilities. thinkCore API is a subset of the think3 COM Application Programming Interface. This API allows the programmer to develop applications working with Think3 products and to extend the Think3 products functionality, while the thinkCore API focuses on writing standalone applications to embed the ability to manage think3 documents and to create or modify modelling geometry and topology objects. The Think3 API COM architecture is based on a modern platform-independent, distributed, object-oriented system framework: standard Component Object Model (COM). Benefits of the Think3 COM API are encapsulation, modularity and independence of components at compile time, but also at run-time, in addition programmers can use different languages, including C++ and scripting languages. ThinkCore API is well suited to develop the SATIN system, since in addition to the COM standard itself, it provides a rich set of functionalities, in particular the Global Shape Modeling.

7.4 Haptic API

The HapticMaster is 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.

7.5 Sound application and Sound API

The sound application has been developed to run on a computer with the operating system Windows XP and the Max/MSP software installed (version number 4.6.3 cycling74 (2009)). Data relating to the characteristics of, and user interaction with the physical prototype will be loaded or received in real-time, requiring communication with other components of the setup. 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 reveives input from other components of the SATIN system (position of the user's finger,pressure applied by the user, input from haptic API, shape data (curvature, tangency,...) from the physical prototype), and Direct user input (selection of the specific characteristic to render audible (curvature, tangency,...), selection of sound source (realistic, abstract,...). The sound application generates multi-channel auditory feedback which can be directly rendered to transducers (loudspeakers or headphones, for example). In addition, a visual feedback providing information related to user's finger position and physical prototype shape is under consideration.

8 Preliminary Tests

A first functional ptototype of the SATIN system was developed in order to perform user tests with the target group. This prototype includes all the elements described in this document featuring the presented physical setup, haptic strip, sound feedback and visualization environment. With this prototype, the user is able to explore a shape's curves as well as moving the object. All of this is achieved while still maintaining the matching between physical and virtual representations. Figure 18 shows the virtual and real views of the prototype while navigating a shape.
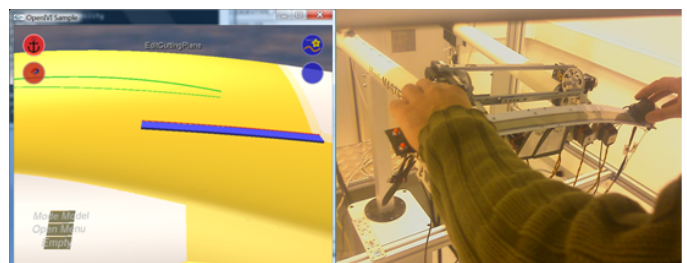
Fig. 18 Virtual and real snapshots of the SATIN system.

We carried out two test sessions to assess the conceptual design of the system and to validate the system,

first from the ergonomic point of view, and then to test the multimodal approach. Tests were performed by end-users, namely CAS designers and model makers, with the support of human factors experts.

In the remainder of this section, we first describe the evaluation process and give a brief description of the tasks performed by users, and then we present the achieved results and some considerations.

8.1 Evaluation Procedure

The experimental evaluation focuses on the integration of sound, vision and haptic feedback, and was composed of several stages. We started by presenting a pre-experiment questionnaire, to collect information about participants. Then, we explained the main components of the SATIN system, its main functionalities and what could be done with it. While users were performing the task, we observed and collected information, such as, errors, need for help, expressions of frustration, indications that they were experimenting sickness symptoms, etc. The goal of the task was to interact with the system, using the haptic strip and the sound effects (see Figure 19), to identify points of interest on the represented curve shape, e.g. points of inflexion, discontinuities, points of maximum and minimum curvature. Additionally, we evaluated the expressiveness of different ranges of sounds to convey curvature information. Finally, and after performing the requested task, we asked users to fill a post-experiment questionnaire to obtain information about participants' opinions and experiences while using the system.

This preliminary tests were conducted with only four users, representatives of the user population, namely, modellers, designers and CAD technicians. Due to the small number of users involved in the experimental evaluation, we focus our interpretation of the results more on observational and qualitative data rather than statistical analysis of objective measures. To overcome this, we plan to perform, in a near future, tests with a larger number of participants (e.g. 20).

8.2 Results

Experimental results from the test reveal that the memorability of point sounds (inflexion and discontinuity) should be improved and that point sounds should be clearly distinct from continuous sounds (curvature), since users had some difficulty in remember and distinguish them. In addition, the efficiency of simultaneous presentation of sound information (e.g., curvature plus inflexion/discontinuity points) should be further evaluated, because users get confused about the type a information being conveyed through sound. Although, the evaluation of the different ranges of sounds was not conclusive, requiring further evaluation work, we observed that the

Fig. 19 The SATIN interface used during the evaluation tests.

least efficient setup was when there is no sound at all, suggesting that the addition of sound is beneficial.

Regarding the effects of the system on users, a generally low level of symptoms was reported - only half of the participants reported any symptoms at all, and some of these symptoms were present before the evaluation. Disorientation symptoms predominated to some extent. The symptoms mainly reported were difficulty focussing and blurred vision - these are likely to be an artefact of the prototype stage of the visual element of the system, or the presence of reflection on the screen. Another drawback mentioned by users is the discomfort cause by the system during long periods of use due to postural issues.

On the other hand, participants rated the ability to control events within the system and manoeuvre objects within the environment as the factors that contributed most for the feeling of realism. Although, sometimes sound distracts users from the visual and haptic information, participants considered the use of sound positive, and results indicate that the SATIN approach is effective in helping designers appreciate the curve, discontinuities and other information related to the surface quality. Since the use of sound for long periods can be uncomfortable, we will study alternatives to determine the appropriate sounds, durations and information to sonify.

As a final comment, from users' answers we identified that what contributes to a sense of realism was the possibility of mixing the three different senses while interacting - sound, vision and haptic.

9 Conclusion

In this paper we presented an innovative immersive environment that reduces the need for creating several physical mockups. It combines haptic interfaces, 3D stereoscopic visualization and sound to convey information about the curvature of 3D objects and about the quality of the surfaces.

The visualization is done in an augmented reality scenario, where users can interact physically with the virtual model though the haptic strip. This can be used not only to explore the shape of the object by touching it (output device), but also to change the surface of the 3D model by pushing or twisting it (input device). Users can also move a finger over the strip to analyze the quality of the surface, which is rendered using sound.

Preliminary tests with users revealed that the use of sound is beneficial. However, the way it should be used, or what type of sound to use is not very clear yet. On the other hand, users considered very positive the use of different output modalities (sound, vision and haptic) to convey information about the virtual object being analyzed.

To overcome some of the drawbacks identified during the preliminary tests with users, we plan to improve our mechanism of sonifying information about the surface, change the physical prototype to reduce problems with posture and improve visualization. Finally, we plan to perform test with users using a larger number of participants to get information suitable to be processed statistically.

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