# Flexible touch sensor for evaluating geometric properties of virtual shapes through sound

## This paper reports a sonification approach to visualise geometric features that are missing in haptic display

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This paper describes the design and implementation of a system for rendering virtual shape through vision, haptic and sound. The system consists of a haptic strip that physically renders virtual curves. A flexible capacitive touch sensor (FCTS) is integrated with the haptic strip, and allows the system to track the position of the user's fingers on the strip. According to the position, the system renders curve properties such as curve shape, inflexion points and curvature through sound metaphors. The goal of this sonification approach is to strengthen the user's understanding of the shape of a virtual prototype, and to inform the user about geometrical attributes that could otherwise remain unseen. Such unseen attributes may either be a result of limitations in the visual and haptic display hardware or a result of limitations in human perception.

**Keywords**: haptic rendering; conceptual design; immersive virtual reality; product design; human-computer interaction

### 1. Introduction

Haptic devices allow users to perceive the shape of a virtual surface through the sense of touch, by using the fingers or the palm of the hand. Shape displays are among the diverse kinds of interfaces that have been developed for this purpose. These displays can modify their shape so as to mimic the form of the surface to be represented. In this way, they enable the users to freely explore a virtual surface through the sense of touch, as with a real object surface. These displays can be effectively used in several applications, such as product design, where there is a need to evaluate the quality of a new shape that is being designed. With these displays, designers can touch and explore the virtual model of a shape.

Our research group has been developing haptic devices which allow multimodal interactions with virtual products. In particular, in the context of the Sound and Tangible Interfaces for Novel Product Design (SATIN) Project (Bordegoni *et al.* 2010), we have developed a haptic interface which aims at replicating approaches that designers use for creating new shapes and for checking their quality. Two typical approaches used by designers are described in the following.

Designers sometimes create new shapes by using a mechanical spline, which is a thin strip of flexible material constrained to pass through several points with weighted implements (called 'ducks' or 'whales' due to their shape), but otherwise free. This strip naturally finds its minimal energy configuration (Levien 2009). Typically, designers locate the weights in two different ways. In the first method, the weight pushes against the side of the spline, and the spline is free to slide with fairly low friction. An example is shown in Figure 1a. Another common way to locate the weights is to place the point of the pin on the spline curve, as shown in Figure 1b. In this way, the weights effectively constrain the arc length as well as the position, leaving only rotation entirely free. A second approach uses a flexible strip, as can be seen in

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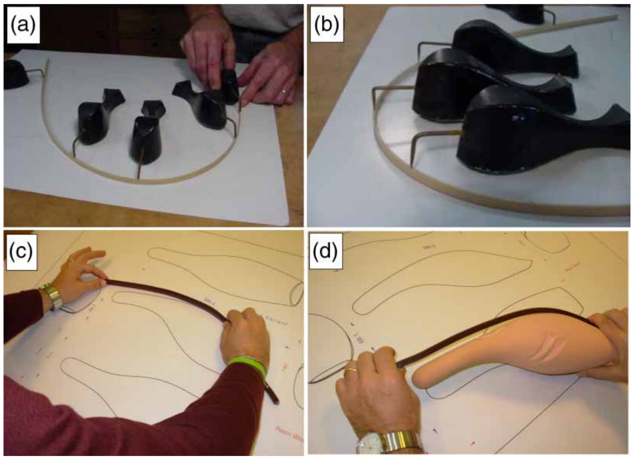

Figure 1. (a) and (b), representation of a real spline [2]; (c) and (d), flexible strip approach (courtesy of Alessi).

Figures 1c and 1d. This technique is often used to acquire shapes from a 2D template, and check the possible variants of the curve directly on the 2D drawings.

The new contribution of this paper is related to the design and implementation of the sound feedback through the Flexible Capacitive Touch Sensor (FCTS). The SATIN Project encompasses research on a new generation of multimodal and multisensory interfaces, supporting free-hand interaction with virtual shapes. The main goal of SATIN is to develop a system for 3D shape modification and exploration by means of free hands using the metaphor of tape sketching and the metaphor of bending along a curvilinear trajectory under the control of integrated and fused visual, audio and haptic feedback. The haptic feedback will guarantee the naturalness of evaluating a virtual shape and the intuitiveness of modifying an object. Furthermore, sound feedback will enhance the user's perception capabilities. Thus, the collaboration between different actors will be eased, reducing the time needed to represent the designer's ideas and reach the best result.

The SATIN project aimed at developing a system for shape design that mimics these ways of working, where designers easily and intuitively manipulate a physical strip for designing new shapes. The strip is handled and curved, and its curvature is checked by sweeping the hand fingers along it.

The SATIN system has been conceived as a multimodal virtual reality system whose aim is to allow designers to feel the shape of a virtual object using a combination of visual, haptic and sound feedback (Bordegoni et al. 2011, Covarrubias 2013). Figure 2c shows the SATIN system.

The system includes a haptic strip consisting of a flexible strip that can conform its curvature according to the curves on the shape's surface, obtained by intersecting a virtual plane with the surface. The shape of the strip is controlled and modified by means of a number of digital servos which have been selected so as to guarantee high reliability and

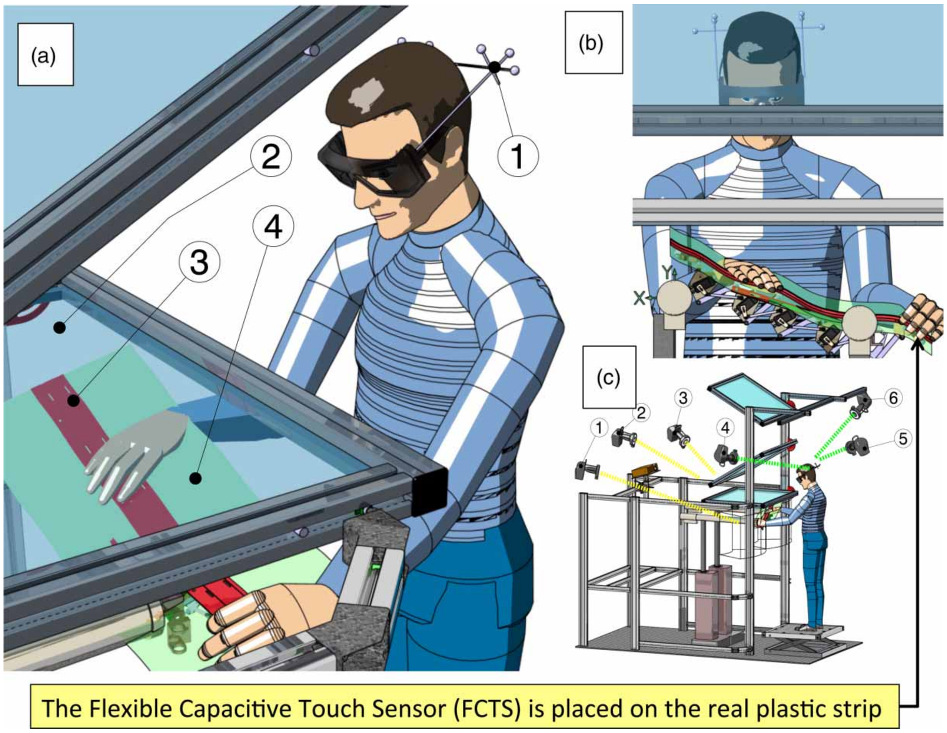

Figure 2. The SATIN system, including a stereoscopic visualisation system, a head-tracking system and the haptic strip.

continuous torque (HS-5955TG, manufactured by HITEC Servos 2013). In order to be located in space, the haptic strip is attached to two MOOG-HapticMaster systems (Lammertse 2002), which allow six degrees of freedom in the movement of the strip.

A 3D visualisation system has been integrated with the haptic strip in order to allow users to simultaneously see and touch the shape in a unique and coexisting space (Figure 2c). The visualisation system consists of a rear projection screen, creating an effect of a virtual plane (2) where the user sees the stereoscopic projected image (4) on top of the physical strip (3). Usually when a person looks at an object while exploring it with the hand or fingers, vision and touch both provide useful information for estimating the object's shape and properties. Frequently, vision dominates the integrated, visual-haptic percept such as when judging size, shape, or position – but in some circumstances, the percept is clearly affected by haptics. In this way, designers operate the system in several application fields for creating and modifying 3D shapes with free-hand interaction under the control of integrated and fused visual, audio and haptic feedbacks. The virtual environment supports intuitive creation, manipulation and evaluation of shapes exploiting sound as a new dimension. This objective is challenging since the simulation has to balance the complexity of realistic tangible physics and the real-time constraints of geometric modelling. A stereoscopic view is also required in order to correctly perceive both the real and the virtual worlds. The necessity to interact with a virtual object and the real hand requires tracking both the user's point of view and the user's hand. In order to allow this interaction, the system also includes a head-tracking system for real-time detection of the user's point of view (1).

The user can stand in front of the system, move his or her head, and see the shape from different points of view, while touching the surface along a selected curve by using his or her hand.

A software framework has been developed for managing the intercommunication of all hardware components and software modules (Antolini *et al.* 2010). In particular, the geometric engine of thinkCore has been used to manage the 3D models of the shapes (Think3 Inc. 2014), while a visualisation system, Open5 (Open5 2014), has been developed and used to manage the visualisation of a 3D model, its stereoscopic view, and the user interaction with the model.

The haptic strip includes a continuous plastic strip, which is the part of the system the users physically interact with. The plastic strip is intrinsically a continuous surface, which allows us to represent continuous curves. However, shapes created by designers often have discontinuities which need to be identified and handled. Since the haptic strip cannot directly represent some curve properties, such as discontinuities, we have decided to use other modalities for representing these kinds of information. In particular, sounds have been used as metaphor for representing geometric properties of the curves. Various kinds of sounds can be used to render different properties. In particular, FCTSs are integrated with the plastic strip in order to detect the interaction of the users' fingers with the strip and produce sounds accordingly (Figure 2b).

This paper is organised as follows. Section 2 presents the properties of curves that can be sonified, and the sonification metaphors defined for rendering these properties. Section 3 provides a general overview of the architecture of the SATIN systems and of its components. Section 4 describes the sound module, its architecture and its implementation details, and section 5 provides details about the tactile sensors integrated with the haptic strip and used for implementing the sound module. Section 6 presents some preliminary user tests and section 7 concludes the paper.

## 2. Geometry sonification

The main objective of a sonification application is to provide information using non-speech audio, as discussed in Scaletti (1994) and Hermann (2002). There are several related studies about sonification of geometrical data of surfaces in scientific and engineering applications. For example, Minghim and Forrest (1995) present a synthesiser for mapping surface data to frequency, timbre, volume and tempo using the Musical Instrument Digital Interface (MIDI) protocol. Since the visualisation of high-dimensional data is particularly complex, the authors propose new approaches for using audio to display the shape and connectivity of these data sets and so replace or supplement the traditional graphic approaches proposed in Axen and Choi (1996) and Hege and Polthier (1997). An interactive representation of complex geometry through sound is presented in Gossmann (2005) in order to render non-visible properties of fractal structures. Kamel et al. (2001) use a 2D sound plane to represent geometric shapes. The finding of this work indicates that the users were able to precisely identify the interrelation of simple geometric shapes, thus assisting them in the comprehension of the images presented. In literature there are several related studies with a sonification aim similar to that described here, but in a variety of different contexts and with different goals. However, they are not suitable for use in the SATIN system, where the data are produced dynamically and in real time by the interaction of the user with the haptic strip.

The geometry sonification proposed in our research aims at using sound metaphors to expose users to the geometric properties of virtual objects that would otherwise remain 'unseen', such as curvature properties, inflection points and discontinuities.

### *2.1. Sound metaphors*

This section presents the sound metaphors that have been studied in the SATIN system for communicating the geometric properties of 3D digital curves during the user's interaction with the haptic strip.

The sound interface of the SATIN system offers the ability to play metaphoric sounds during the user's exploration of the haptic strip in order to represent different properties of the curve that represents the virtual object. The geometric properties to render are those that cannot be perceived through a physical interaction with the haptic strip but which are particularly meaningful to product designers for the task of evaluating the quality of a surface. Specifically, information about curve shape and curvature is of special interest for designers. In fact, a smooth surface that is continuous in terms of curvature is often considered to be highly desirable.

A list of properties of curves that can be sonified are listed below:

- *Curvature*: this is a discrete series of values representing the curvature calculated for a planar curve, i.e. a 1D function. The sign of the curvature is also considered. Curvature is a function of the position along the curve and is closely related to the second derivative of the curve shape as a function of position. An optional specific sonification has been provided at points when the concavity sign changes, known as inflection points, or when the curvature is zero.
- *Tangency*: this is represented by a series of values providing the angle between the tangent at discrete points on the plane curve and a reference direction, i.e. a 1D function. We consider tangent to be the first derivative of the curve shape as a function of position.
- *Curve shape*: this is a discrete series of values describing the curve shape of the actual model (rather than the shape realised by the haptic interface). Again this is a 1D function.
- *Discontinuities*: there is audible marking for the discontinuities found in the curve shape, curvature and tangency.
- *Errors*: this is the displacement occurring between the theoretical curve shape and the actual curve shape rendered by the haptic strip. This error is also a function of position and a result of the physical limitations of the haptic strip being capable of only rendering curve shapes limited to splines. In this sound rendering mode the size of the error is indicated. Note that this is a sonification mode that is primarily intended to be used by developers, although it might also be made available to the general end user.
- *Discrepancies*: this is the difference between the haptic strip and fluctuations, holes or irregularities belonging to the theoretical shape. Note that these discrepancies are specifically small in scale relative to the size of the curve.

Table 1. Sonification properties.

| Geometrical properties | Continuous | Discrete |
|---|---|---|
| Curvature | ★ | |
| Tangency | ★ | |
| Curve shape | ★ | |
| Discontinuities | | ★ |
| Inflection points | | ★ |
| Errors | ★ | ★ |
| Discrepancies | ★ | ★ |

Table 1 summarises the several properties that can be sonified during the user's interaction with the shape. The properties being sonified are classified as continuous data and discrete data. Continuous data are associated with performing continuous sound feedback. Nevertheless, there are indications that continuous sound is difficult to perceive, or conflicts with the perception of some properties that are sonified. This led us to consider more effective modalities for offering sound feedback for shape properties. Some tests were carried out and demonstrated that auditory presentation can be performed by discrete data, which can be more easily perceived by the users. This is related with the ability to produce two tones that can be compared and discriminated by users.

### 2.2. Sonification of 'curve shape' and 'curvature'

Typically, in computer aided design (CAD) tools the orientation of quills representing the curvature may be reversed, i.e. positive curvature quills are drawn on the top instead of on the bottom of the curve, and negative curvature quills are drawn underneath instead of on top.

Unlike some curves which have a fixed curvature, most curves in reality have a changing curvature. In fact it is these changes in curvature that make a line curvy. High curvature produces tight curves, and low curvature gives more open curves, until a straight line is obtained at zero curvature. It is important to note that we cannot see curvature, for it is a mathematical construct. However we can experience curvature as we observe changes in the curve of a shape. Even so, it is difficult to fully appreciate these changes in curvature as we can only imagine them as we see or feel fluctuations in a curve. As previously mentioned, for product designers these changes are of great importance – and in fact they have devised a means for visualising curvature, through the use of the porcupine plot.

In our research we initially considered rendering two shape properties using sound: *curve shape* and *curvature*. In order to do this, certain sound frequencies are associated with curve properties. For representing *curve shape*, sound frequency is associated with a shape through the specific position on that shape. With regard to *curvature*, sound frequency is associated with the curvature value. Effectively, this means that two pieces of information are conveyed to users via sound: the first concerns the shape of the curve, and the second concerns the mathematically defined curvature of the curve.

Figure 3 shows the concept of the sonification approach developed in the SATIN system. Figure 3a shows the virtual object that is seen by the user while interacting with the SATIN system. Figure 3b shows the haptic strip that is handled by the user. Figure 3c shows the user's finger while

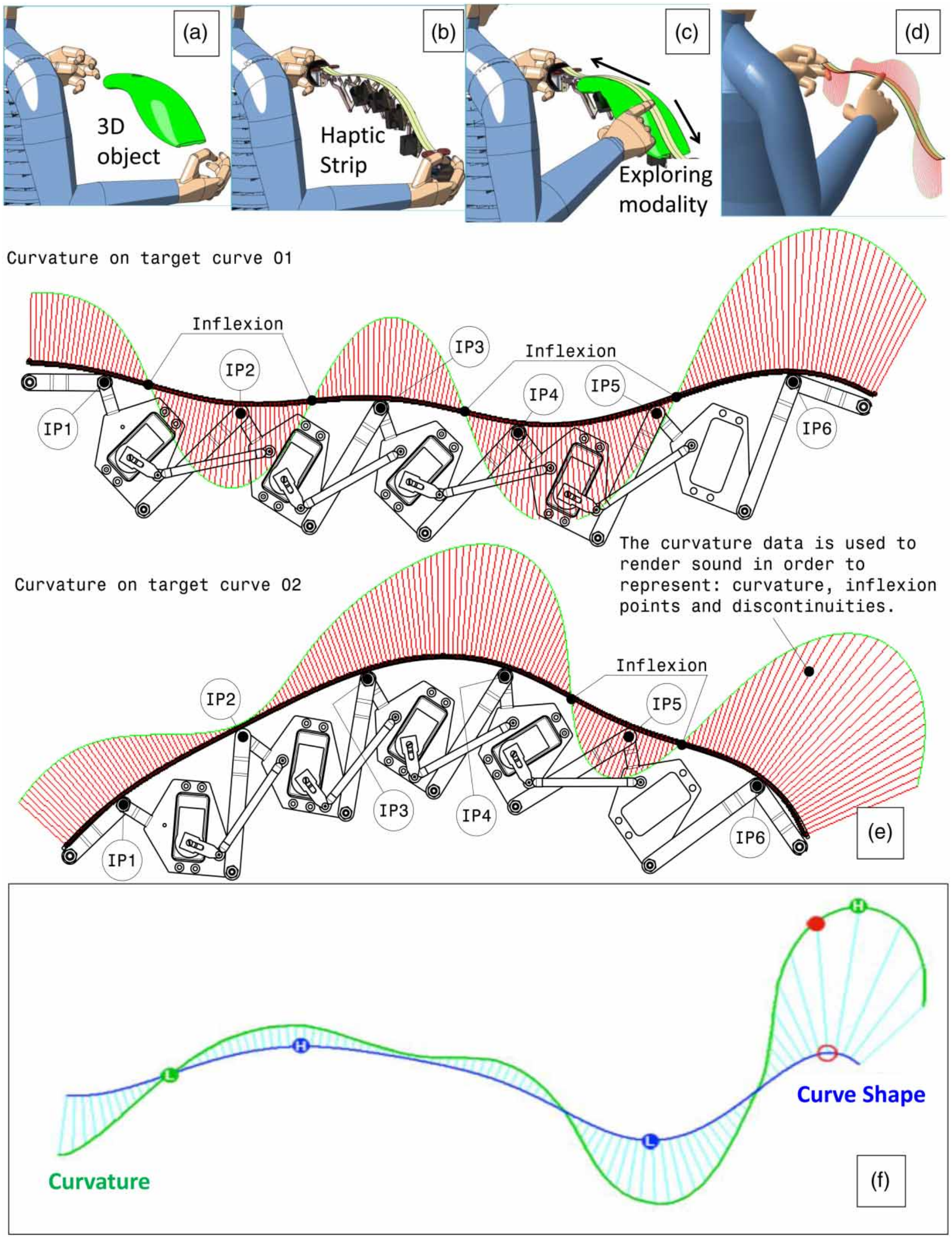

Figure 3. Sonification approach developed in the SATIN system.

exploring the virtual object: the haptic strip renders the shape of the virtual object, and at the same time the user is able to hear some geometric properties of the virtual object. Metaphoric sounds are played according to the type of local geometric characteristics of the curve, e.g. curvature, curve shape, discontinuities and inflexion points.

In particular, the correlation of the geometric properties concerning curvature and sound has been made by using a technique based on the porcupine plot. This is a visual technique for curvature analysis applied to curves and surfaces which places visual ‘quills’ at points along a curve (examples are shown in Figure 3e). The Frenet frame of the curve determines the direction that the quill displays at a specific point on the curve, while the relative length of the quill reflects the curvature and/or radius at that point. The greater the curvature of the curve at the quill point, the longer the length of the quill. For a given curve $C$, the curvature at point $q$ has a magnitude equal to the reciprocal of the radius of the osculating circle, i. e., the widest circle that shares a common tangent with the curve at the contact point. For a 2D curve defined explicitly as $C = f(q)$, the curvature K is given by the following equation:

$$K = \frac{\frac{d^2c}{dq^2}}{\left(1 + \left(\frac{dc}{dq}\right)^2\right)^{\frac{3}{2}}} \tag{1}$$

During the interaction with the SATIN system, the CAD tool (thinkCore) extracts a set of characteristics of the curve. This set consists of the interpolation points (nodes) of the selected curve, which is approximated with a cubic spline, and other characteristics such as curvature data and discontinuities (computed from Equation 1). Figure 3f shows the curve shape and curvature sonification. In this example, two mappings were used; curve shape and curvature. For both mappings the frequency ranges from 100 Hz to 400 Hz, which is approximately a two-octave range. For the curve shape sonification the minimum frequency is mapped to the lowest point of the curve, and the maximum frequency is mapped to the highest point. Thus, as the curve is explored, the emitted sound rises and falls dependent upon the position along the line of the curve. For the curvature sonification the mapping is similar; the minimum point produces the minimum frequency and the maximum point produces the maximum frequency. However, this time the sonification relates to the curvature value at a given point. The curve shape sonification is produced as the participant explores along the line of the displayed curve (blue line) with the SATIN system. The maximum frequency (400 Hz) is heard at the highest position of the curve (blue H), and the minimum frequency (100 Hz) is heard at the lowest position of the curve (blue L). The curvature sonification is again produced as the participant explores along the displayed curve (blue), however this time it is the curvature value (green line) which is heard at this point. So if the curve is touched at the point marked by the red circle, then the curvature value marked by the red dot is heard. The maximum frequency (400 Hz) is heard at the point of highest curvature (green H), and the minimum frequency (100 Hz) is heard at the point of lowest curvature (green L). For the curvature sonification, what is heard is very different to what is seen, as illustrated by the blue and green lines above.

## 3. SATIN system: architecture and components

The SATIN system consists of several components for handling user interaction with shapes, through visualisation, haptic and sound modalities. The main components are:

- *Viewer*: stereoscopic visualisation system including the head-tracking system;
- *Haptic module*: haptic strip;
- *Tactile sensors*: sensors positioned on the haptic strip to detect user input used for sound rendering;
- *Sound module*: system for rendering sounds;
- *Geometric engine*: engine for handling the shape geometry.

The SATIN system architecture permits asynchronous communication among the components based on appropriate interfaces. Each component has been implemented by using the most appropriate language and tool. Specifically, the *geometric engine* is implemented using thinkCore (Think3 Inc. 2014), which exposes a COM (communication port) interface. The *haptic module* is developed in C.NET v. 1.1. The *sound module* is written in C and uses Max/MSP (MAX/MSP 2014) plugins, which are written in ANSI C. Consequently, it is necessary to decouple as much as possible the system components, and provide the specifications for both the interfaces and the behaviour of each component. This has been done by defining a state-machine for each module, where state transitions are performed after the reception of specific messages (some of them carrying optional payload data).

Several possibilities have been examined in order to find a suitable solution for the inter-communication of such heterogeneous components. The communication between the modules and the definition of the finite-state machines has been used primarily for controlling the interaction flow of the application with the user and among the system components, and secondarily as a channel for sensor data. Figure 4a shows the point-to-point communication between different modules.

Conversely, Figure 4b shows the publish/subscribe framework, through which each module needs only connect to the server component and send and receive messages, being aware of which modules are sending or receiving messages. This framework, described in detail in Antolini et al. (2010), is responsible for the communication and synchronisation of all SATIN modules in order to provide a consistent system state. The framework is a publish/subscribe event manager that easily permits communication between the SATIN modules, taking advantage of XML (Extensible Markup Language) communication over the TCP/IP network interface. Each module can send and receive messages in an asynchronous way. The stable bandwidth of the SATIN system is about 15 Hz, which is estimated by taking into account all

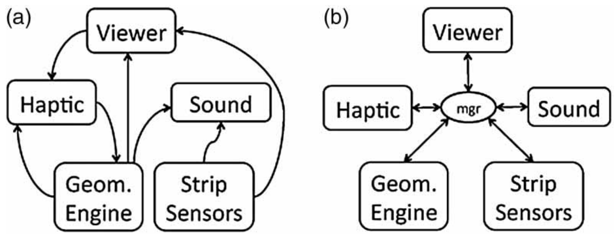

Figure 4. Conceptual schema of the SATIN modules (a) without publish/subscribe manager (b) with publish/subscribe manager.

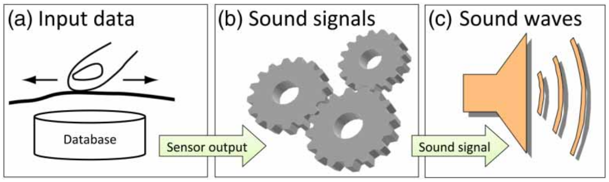

Figure 5. Sound module blocks: (a) input data, (b) sound signals, and (c) sound waves.

the software and hardware components, along with their integration.

## 4. Sound module: architecture and implementation

The sound module consists of three major blocks, as illustrated in Figure 5. The first block (a) represents the inputs to the sound module. Specifically, it provides information about the user's finger positions detected by sensors placed on the haptic strip, and data describing the shape properties of the virtual object, e.g., curvature, tangency and discontinuities. This information is passed to the second block (b) which computes the curvature properties in the exact position of the curve touched by the user, and then maps these data onto values that are used in a sound synthesis algorithm. The resulting output of the second block is a digital signal that is converted to sound waves in the third block (c).

Actually, data handled in block (a) are generated by the SATIN system main loop, which deals with the overall handling of the user's interaction. Block (c) consists of hardware elements able to convert a digital signal into an analogue electrical signal, which in turn is transduced into sound waves. In practice, this task is carried out transparently using a sound board of a standard PC. The tasks performed by block (b) require a flexible software tool that allows the execution of real-time signal processing algorithms. In fact, the tool connects the user interaction and the sound produced as a feedback effect, and obviously this has to be provided in real time.

The sound module has been implemented using the Max/MSP software, which is a graphical development environment for music, sound synthesis and multimedia, developed and maintained by Cycling '74 (MAX/MSP 2014). It has been used for over 15 years by composers, performers, software designers, researchers and artists interested in creating interactive audio applications. The Max/MSP program itself is highly modular, with most routines existing in the form of shared libraries, and an API allows third-party development of new routines (called 'external objects'). Max/MSP has been selected for implementing the sound module mainly because of its extensible design and graphical interface (which in a novel way represents the program structure and the graphical user interface (GUI) as presented to the user simultaneously), which makes this tool an environment for quickly developing interactive audio software applications. Specifically, an external object has been developed for Max/MSP which acts as an interface between the main SATIN system application and the sound synthesis engine of the sound module.

In this case the carrier sound is generated using a modal synthesis approach. Modal synthesis is a physical modelling technique for sound rendering, with theoretical roots in modal analysis. The aim of modal synthesis is to mimic the dynamic properties of an elastic and damped structure in terms of its characteristic modes of vibration. A physical structure has an inherent set of modes of vibration, determined by its material, its dimensions and the conditions at its boundaries. Each mode can be defined by its resonant frequency, damping factor and mode shape (eigenfunction). In modal analysis, the goal is to separate the equations of motion of a structure so that they can be solved separately and individual modes can be calculated. By adding together these respective modal responses, the frequency response of the entire structure can be found. Detailed information of the sound system algorithm can be found in Alonso-Arevalo et al. (2012).

## 5. Tactile sensor

In order to correlate sounds with the user's interaction with the haptic strip, it was necessary to track the user's fingers when moving on the strip surface. Solutions such as data gloves have been considered too invasive for designers, who are used to freely interacting with shape surfaces. Therefore, two other solutions have been considered: the resistive tactile flexible sensor (RTFS) and the flexible capacitive tactile sensor (FCTS), described in the following sections.

### *5.1. The resistive tactile flexible sensor (RTFS)*

The movement and position of the user's fingers on the strip can be tracked by means of an RTFS, which is attached onto the top of the haptic strip. The RTFS allows us to detect the point of contact of the user's finger with the haptic interface. The RTFS has a resolution in the order of 3 mm and is 1 mm thick. Because of its thickness, it is not possible to glue the sensor directly to the haptic strip without the creation of folds (see Figure 6a). This deformation is even greater when the strip is bent. Obviously, these irregularities generate errors when tracking the finger position.

To solve this problem, we have successfully developed and implemented a flexible mechanism that prevents the creation of folds in the RTFS. Figure 6b shows the way in which the flexible sensor is attached to the haptic strip in order to always guarantee perfect adhesion to it. The RTFS is glued to the two thin steel components; each steel component has five wire parts that freely move inside the ten slots created in the haptic strip. There is a relative movement between the two thin steel components and the two slots in the lengthwise

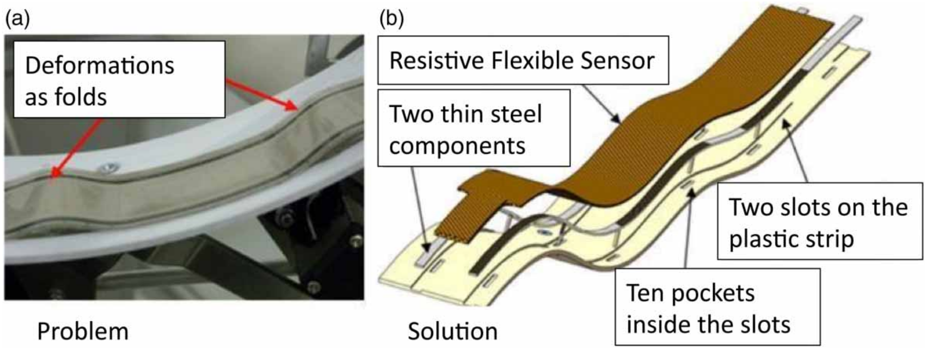

Figure 6. Resistive tactile flexible sensor (RTFS) attached to the haptic strip.

direction of the haptic strip mechanism. In this way we have created a flexible joint on slot constraint. However, the pressure required to activate the resistive sensor is quite high, and this is uncomfortable for the user. For this reason, we have investigated an alternative solution, as described below.

### *5.2. The flexible capacitive tactile sensor (FCTS)*

The FCTS is a more convenient solution because, unlike with the RTFS, the user does not need to apply any pressure to activate the tactile sensor. In fact, the FCTS detects a change in capacitance when something approaches or touches it.

Integrated circuits specifically designed to implement capacitance sensing in human–machine interface applications are now available from Analog Devices (2014). As shown in Figures 7a and 7b we have analysed two patterns (Pattern 01 and Pattern 02) in order to better track the user's finger. Figure 7c shows the prototype of Pattern 02. 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 invades the fringe field, with a portion of the electric field being shunted to ground instead of terminating at the receiver. The resultant decrease in capacitance is detected by the converter (see Figure 7d).

We have used four QProx E1101 development boards distributed by ATMEL (QProx touch sensors by ATMEL 2014) which provide excitation to the capacitive sensor, sense the changes in capacitance caused by proximity of the user's finger, and provide a digital output.

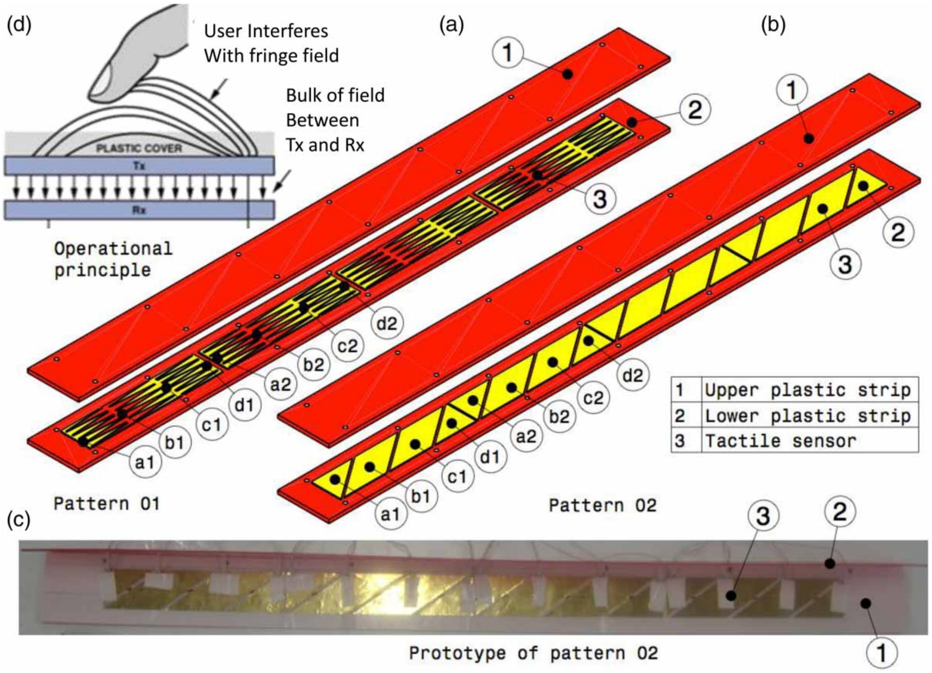

Figure 7. Flexible capacitive tactile sensor (FCTS) integrated with the haptic strip.

The first board uses the metal traces a1, b1, c1 and d1 to track the user's finger (see Figures 7a and 7b), the second board uses the metal traces from a2 to d2, and so on. In this way we have obtained a flexible capacitive touch sensor. The resolution of the FCTS is 0.47 mm with Pattern 01 and 0.82 mm with Pattern 02. The resolutions are good enough for the scope of the device that is used for detecting the user's finger position. The metal traces are located in between the two plastic strips, like a sandwich. This arrangement prevents any damage to the metal traces, which are located in the neutral fibre, free of pressure and tension stresses.

This solution based on the FCTS performs demonstrably better with respect to the previous one based on the RTFS, and therefore has been selected for implementation in the SATIN system.

### 5.3. *System for lighting the strip*

When users interact with the virtual object through the haptic strip, it is necessary to see where their hands are positioned in space in order to see where the haptic strip is positioned and where the fingers are located with respect to the strip. For this reason, it seemed necessary to illuminate the strip. To do this, we have used lighting stripes technology (Lighting Stripes device, Elshine Inc. 2014) which is completely dimmable for great lighting effects, as well as very appealing for backlit displays. The lighting stripes device is driven by an AC inverter, which depends on the total light surface required to illuminate the strip. Of course, high surfaces can be lit, but the limit is set by the driver's size. Figure 8a shows the first configuration of the lighting stripe integrated with the FCTS. The capacitive sensor was positioned under the lighting stripe, and the lighting stripe was positioned on the red plastic strip.

This solution allows us to see a continuous light of 10 mm width. Nevertheless, we found a critical problem related to the use of the capacitive sensor. The lighting stripe generates an electric field that interferes with the electric field of the capacitive sensor. In other words, the electric field of the lighting stripe completely blocks the electric field of the capacitive sensor, and obviously the hand tracking system remains blocked as well. In order to solve this problem, the lighting stripe was moved under the capacitive sensor, and some cutting patterns were investigated. Figures 8c and 8d show the cutting patterns, and Figure 9 shows the final configuration.

### 5.4. *SATIN system set-up*

Figure 10 shows the operating modality of the SATIN system. The user touches the strip and sees the virtual object and a virtual avatar (an arrow) indicating the contact point. The data for tracking the position of the finger is provided by the FCTS. These data are used for computing the curve parameters to be displayed both graphically and audibly, and to display a virtual avatar in the graphical scene (see Figure 10b).

## 6. User test

The SATIN system was developed with a user-centred approach whereby the evaluation of an interactive system is performed several times in order to ensure that usability issues are properly addressed during development (Hassenzahl and Tractinsky 2006). Therefore, users tests have been performed throughout

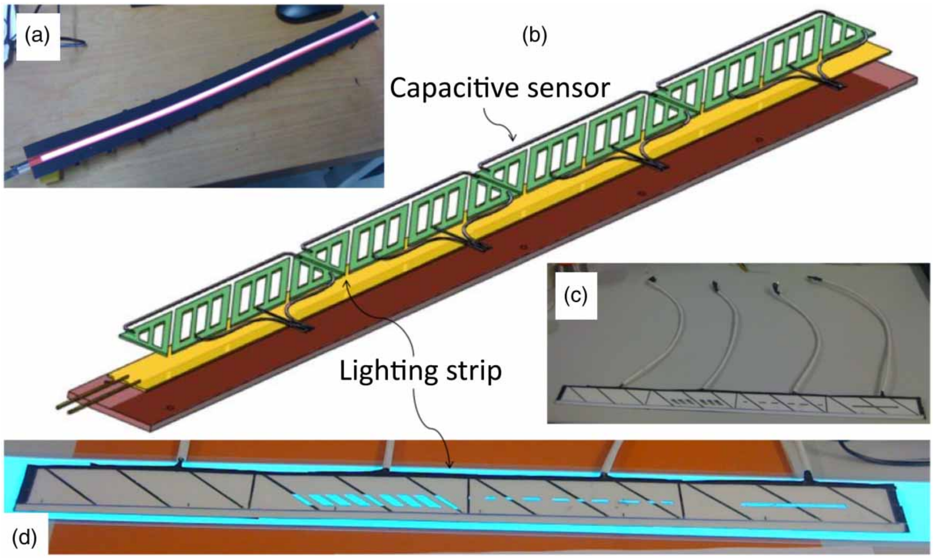

Figure 8. Flexible capacitive tactile sensor (FCTS) and the lighting stripe.

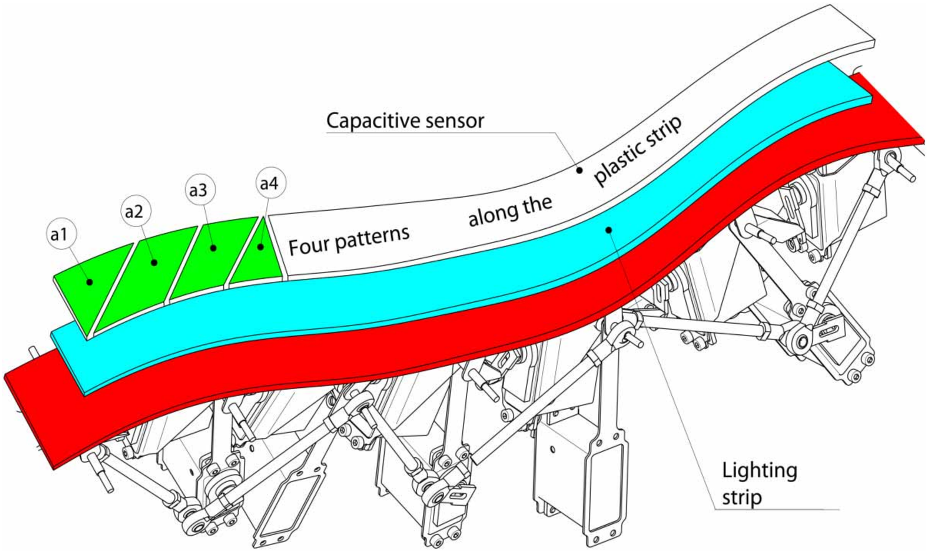

Figure 9. Final configuration of the haptic strip including the FCTS and the lighting stripe.

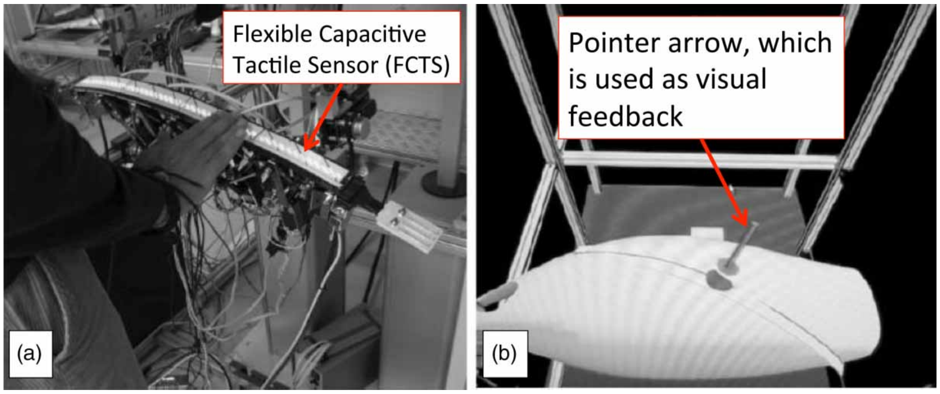

Figure 10. Visual feedback provided by tracking the user's hand/finger through the FCTS sensors.

the evolution of the project in order to assess the conceptual design and validate the system. Tests were performed by end users, both CAD designers and model makers, with the support of experts in human factors. Participants were asked to stand in front of the system and wear the stereo glasses. Looking through the glasses enabled participants to see the 3D virtual model of the virtual object selected for the tests: a table vacuum cleaner. By touching and rubbing their fingers along the physical strip, participants were able to receive sound information representing the curvature of the curved shape.

### *6.1. Participants*

Four users participated in the tests. All participants were male, and the ages ranged from 25 to 38. All participants had previously used CAD and 3D graphics, though none had previously used sound software. Table 2 describes the users' demographics and experience.

### *6.2. Tasks*

During the experiment, participants were asked to interact with the system and identify points of interest on the represented curve shape in order to identify:

(1) The point(s) of maximum curvature;
(2) The point(s) of minimum curvature;
(3) Point(s) of inflexion;
(4) Point(s) of discontinuity.

A range of sounds were tested during this phase. They were assessed on the successfulness of their responses and the time

Table 2. Evaluation participants' demographics and experience.

| **Participant data** | **P1** | **P2** | **P3** | **P4** |
|---|---|---|---|---|
| Age | 34 | 25 | 36 | 38 |
| Gender | Male | Male | Male | Male |
| Occupation | Tec | Tec | Des | Des |
| Have you used a CAD/graphics system before? | Yes | Yes | Yes | Yes |
| Have you used software to develop or record sounds before? | No | No | No | No |

Table 3. Summary of performance for all tasks.

| Sound type | ***n*** | **Time (s)** | **Effectiveness (%)** | **Efficiency (%)** |
|---|---|---|---|---|
| Points only (C) | 3 | 28 | 72.23 | 2.58 |
| Frequency (A) | 3 | 25 | 62.50 | 2.48 |
| Kinaesthetic (B) | 3 | 38 | 73.61 | 1.95 |
| None | 4 | 31 | 51.04 | 1.67 |

Table 4. Sonification properties.

| Statement | Mean | Median |
|---|---|---|
| The sound helped me to understand the shape of the curve. | 4 | 3.75 |
| The sound helped me to perceive discontinuities on the curve. | 4 | 4 |
| What I heard matched what I saw. | 4 | 3.75 |
| What I heard matched what I felt by touch. | 4 | 3.5 |
| I understood what the sound meant. | 3.5 | 3.25 |
| The sound was pleasant. | 3.5 | 3.25 |
| It was comfortable to listen to the sound for a long period of time. | 2.5 | 2.75 |
| The sound representing the curvature distracted me from the visual and haptic information. | 4 | 3.5 |

taken to complete tasks. Subsequently, participants were asked to draw a graph of the curvature information. This task was repeated in four conditions:

(1) No sound
(2) Sound A: Sinusoidal Wave simple pure tone
(3) Sound B: Sampled Cello harmonic frequencies
(4) Sound C: Modal Synthesis realistic complex noise

Due to the low number of participants, the results have no statistical value. However, they may be seen as providing some indication of the relative efficiency of the sounds evaluated.

The efficiency here is according to ANSI NCITS 354-2001 (2001), which is calculated by dividing the mean time on task (time) by the success rate (effectiveness). Table 3 shows an indication of the most efficient sound across all tasks.

The most efficient sound is Sound C, closely followed by Sound A. The least efficient is no sound at all, which suggests that the addition of sound is beneficial. However, the results also suggest that the effect may not be straightforward, and further evaluation work needs to be undertaken in order to elucidate some open issues.

### *6.3. Questions about sound: key findings*

After the participants had completed the evaluation assignments they were asked to answer a questionnaire about their experience. Table 4 shows the responses to a questionnaire aimed at discovering more information about the participants' experience of the sounds used in the prototype. The score system proposed uses a scale from 1 (bad) to 5 (excellent).

Detailed information on the specific questions and answers and other human factors aspects of the evaluation can be found in Alonso-Arevalo et al. (2012). In this article we only wish to highlight that participants considered that sound helped them to understand the unseeable curvature information and to better examine the quality of the curve shape:

- Participants responded generally positively towards the use of sound, and results indicate that the SATIN approach is effective in helping designers appreciate the properties of the curve, discontinuities, and so on. Note that subjective responses are inconsistent with task performance.
- Participants felt the sound distracted them from the visual and haptic information.
- Participants responded neutrally when asked if the sound was pleasant, and indicated that it may not be comfortable to listen to for long periods.

The scores are encouraging for the SATIN concept, with positive indications that the sound aided understanding of the curve shape, aided the perception of discontinuities, was understood and was consistent with the visual and haptic information. However, this data should be considered in parallel with the actual performance. Previous research has suggested that, for complex tasks, subjective measures of task performance are insufficient in isolation for usability studies, and should also incorporate measures of the completeness and correctness of user performance, as we have done (Howard 2008).

## 7. Conclusion

The paper has presented a novel sonification approach for providing sound feedback which represents numerical data related to the geometrical properties of virtual objects, as for example curve shape, inflexion points and curvature. This work has been carried out in the context of the SATIN Project, which aims at developing a multi-modal interface exploiting auditory, visual and tactile senses to convey information about virtual shapes. The SATIN Project aims at developing a system for shape design that mimics some typical designers' ways of working, where they easily and intuitively manipulate a physical strip for designing new shapes. The system includes a haptic strip consisting of a flexible strip that can conform its curvature according to curves lying on the shape surface, obtained by intersecting a virtual plane with the surface. Since the strip is continuous, some features of curves, which are particularly important for designers, cannot be represented. Therefore, we have proposed using sound to render those features. Some metaphors have been created for sounds in order to render the different kinds of curve characteristics. Sounds can be dynamically associated with the interaction of the user with the strip, and this requires detecting the position of his or her finger on the strip. This is accomplished through the use of FCTSs, which have demonstrated a good performance in terms of precision of finger detection. In order to evaluate the idea of rendering curve properties through sound, and to evaluate the types of sounds used, we have performed some preliminary tests with users who are CAD designers and model makers. In general, the users reported a strong appreciation of the concept proposed by the sonification approach and the intrinsic possibilities of such technology.

Future research activity includes the integration of the FCTS with a desktop and portable version of the SATIN system, as described in Covarrubias et al. (2013) and Covarrubias and Bordegoni (2014).

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