A Hand Gestural Interaction System for handling a Desktop Haptic Strip for Shape Rendering

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1. Introduction

Current practice in the design process of industrial products is to use digital tools even at the stage of concept generation. Particularly regarding the design of products with aesthetic value, the designers are typically in need of touching the shape being created in order to validate some of its properties such as overall dimension, proportions, symmetry, etc. This is typically done by using physical prototypes built with traditional production processes. Rapid prototyping techniques are also valuable for this purpose. This practice has some intrinsic limitations, since physical prototypes can be used solely as a display, and not as a full interface for both input and output handling of shapes. Besides, they do not allow the evaluation of variants of shape, color and material, and they do not support easy shape modification and immediate correlation with the corresponding digital model. In addition, the production of physical prototypes is costly and time consuming, especially with respect to the overall resources dedicated to the product design process.

For this reason, a research area in the haptics domain addresses the study of haptic devices allowing the physical rendering of virtual shapes [1]. A system named Desktop Haptic Strip for Shape Rendering (DHSSR) has been developed with this intention: it allows a continuous and smooth free hand contact interaction with a real and developable physical strip that is actuated by a servo-controlled mechanism [2]. This new haptic interaction modality, combined with traditional visualization means, aims to allow designers to evaluate new shapes through the sense of touch in addition to vision. In this way, the manual skills and sensitivity of designers can be exploited by offering them an operating modality which is very close to their habits and usual way of working.

The DHSSR system mimics the functioning of a mechanical spline, which is a thin strip made of flexible material constrained to pass through several interpolation points with weighted implements (called ducks or whales due to their shape) and otherwise free, which naturally finds its minimal energy configuration [3]. Typically, the designer positions the weights in two different ways. In the first one, the weight pushes against the side of the spline, which is free to slide with fairly low friction. An example is shown in Figure 1-a. An alternative common way to locate the weights is to place the point of the pin on the spline curve, as shown in Figure 1-b. In this way, the weights effectively constrain the arc length as well as the position, leaving only the rotation entirely free. The second approach instead mimics a flexible strip as can be seen in Figures 1-c and 1-d. This technique is often used for deriving the initial shapes from the 2d template, and then providing directly the simulation of possible modifications on the 2d drawings.

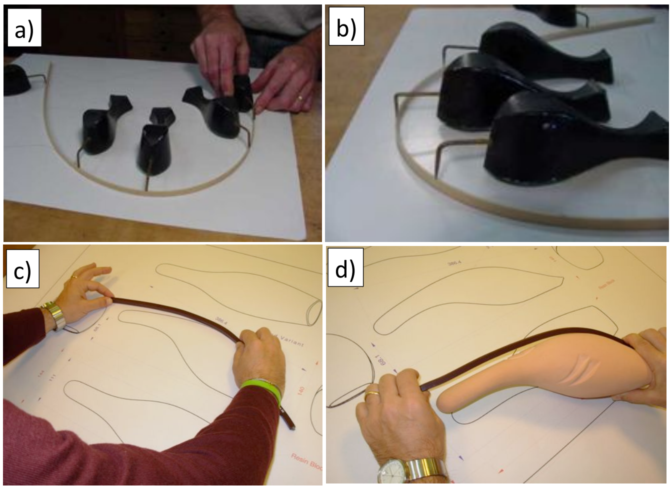

Figure 1: a) and b) Representation of a real mechanical spline [3] c) and d) Flexible strip approach (courtesy of Alessi).

The strip of the DHSSR system dynamically represents curves obtained by intersecting a virtual plane with the surface of a virtual object. Basically, there are two strips, one virtual and one physical in a 1:1 scale. Both the virtual strip and its kinematics are simulated in the virtual world, and the simulation data are used to control the servo-actuators deforming the physical strip.

The physical strip is at the moment an output display, and its shape can be changed by selecting a new curve in the virtual space. One of the issues we had to address concerned the interaction with the virtual curve, which should be easy and user friendly for the designer. One way to achieve this is by providing realism and naturalness in the interaction, and also creating a sense of presence in the virtual environment.

We have developed a visualization and interaction system integrated with the DHSSR system that visually renders the selected curve and also the user's virtual hand in real-time during the interaction with the curve, which is handled and deforms accordingly during the interaction. This functionality requires tracking the user's hands in the physical space. In order to provide a realistic immersiveness, the tracking and the representation of the user's hands in the virtual environment should be accurate and timely. In fact, some studies have shown that if the users are able to see the virtual rendering of their hands and their movements relative to the movements of other objects there is a much better chance that they feel that the virtual hands embody their intentions and actions [4].

This paper describes the hand gestural interaction system for handling the virtual curve that we have developed and connected with the Desktop Haptic Strip for Shape Rendering.

In designing the system we have considered the new generation of so-called 'natural user interfaces' (NUI) technologies [5], which track the user's hands, fingers, or entire body in 3D, without wearing any kind of invasive device. Free-hand gestures can provide effective and natural methods for 3D interaction with virtual shapes, which can provide fluidity in the interaction.

Traditional desktop interaction approaches, typically based on devices such as keyboard and mouse and touch pad interfaces, are often designed for 2D interfaces and consequently are less effective and usable for 3D interaction [6]. In addition, many of the techniques that are used for 3D interaction require the user to wear or hold 3D tracking devices and also require several markers attached to the user's hand or body. The use of markers can make the system more difficult to configure and is inappropriate for some scenarios. Reasonably precise 3D sensing techniques, which can recognize freehand movements, are now available at low cost (e.g. Microsoft Kinect, Asus Xtion, and Leap Motion). These types of devices do not require on-body attachments or hands-on tracked devices, thus enabling very low configuration interaction. In this way, users can interact with the system naturally through their hands or body movements, without using complex commands.

However, simply because the interface is based on 'natural' gestures, this does not reduce the need for careful interface design [7].

Taking this into account we propose two user interaction modalities for handling the virtual curve and the 3D object shape, which are described in the paper.

The paper is organized as follows. Section 2 presents an overview of related works. Section 3 presents the concept of the Desktop Haptic Strip for Shape Rendering (DHSSR). Section 4 describes the system architecture and the hardware components. Section 5 describes the gesture recognition module that has been developed using the Leap Motion controller. Section 6 presents the module for controlling the DHSSR servo-motors that have been implemented using the Arduino board. Section 7 presents the system prototype and its preliminary validation. Finally, Section 8 draws some conclusions.

2. Related Works

Gestural interaction techniques have been investigated for a long time and several types of gestures have been designed and evaluated. For example, a finger has been used for the selection of occluded targets on small touch screens [8]. Also, the use of gestures has been explored to select distant targets on large displays [9]. Early freehand interaction systems needed fiducial markers on the users or data gloves in order to track the user's gestures. For example the authors in [10] used the fingers movements to simulate "mouse-clicking" and also to investigate freehand gestural interaction with ambient displays [11]. Bimanual marking menu selection presented in [12] uses a Kinect device at close range to track the fingers' pose and movement to select from a marking menu. However, this method requires setting up the camera under the desktop at a specific angle, so losing the convenience of free hand interaction. Freehand gestural input has also been explored for virtual object manipulation [13] including on curved surfaces [14] and projected directly on to everyday objets [15]. In this research it is illustrated the importance and immediacy of freehand gestural interaction in daily life use cases. The freehand interaction approach has been compared to other interaction techniques for multimedia control [16]. Participants felt that freehand pointing is intuitive but needs more precision. Their feedback suggests that, with the improvement of pointing precision, freehand interaction could be a better candidate than the mobile phone as an interface device for remote interaction. There is a great amount of previous research on object and option selection in both 2D and 3D interfaces. However, most previous research used hand-held tracked devices or fiducial markers to enable camera-based tracking [6].

Regarding the specific problem of physically representing shapes, several research works in the field of haptics have addressed the problem of representing correctly curves and curvature information, overcoming the limits of point-based devices, and providing cutaneous information to the fingers. In [1] is presented an attempt to give the illusion of touching a haptic shape solely through the communication of the local tangency of the curve on one or more fingertips. This device does not provide enough kinesthetic cues, especially for large curves. [17] describes a haptic device that is the combination of a point-based device providing kinesthetic cues, and a fingertip haptic device providing cutaneous cues. In [18] it is described an attempt to communicate curves and curvature information through a contact location feedback on the fingertips.

The main limitation of these research works is that users interact with the shape using only a part of the hand, mainly one or a couple of fingers, and not with the whole hand. In the application domain of product design that we address, the possibility of touching and exploring a surface with the whole hand is of primary importance. With this regard, some research activities have addressed the limits of human perception and discrimination of curvature in a whole-hand exploration like those reported in [19, 20]. These studies are of great utility in the development of new full hand haptic devices because they provide several guidelines, on the basis of haptic curve discrimination and haptic shape perception.

The problems of computer-controlled shaping, even in real-time, of a strip made of metallic material were addressed by several researchers in the past. They focused on a kind of free shaping of a heated cutting blade for free form cutting of rigid plastic foam slabs for layered object manufacturing [21, 22, 23]. These researchers have developed the mathematical/technological fundamentals and process of free-form cutting based on heated flexible blades. The shape and the relative positions of the flexible blade are controlled continuously as needed by the normal curvatures of the front faces of the layers. They based their computation on the Kallay-algorithm [24], but they did not manage to reduce the elapsed computational time below a threshold, which is acceptable for direct free hand interaction.

Some research activities have addressed the limits of human perception and discrimination of curvatures in a whole-hand shape exploration manner, as for instance those reported in [19, 20].

The haptic strip developed by our group in the context of the European project IST-FP6-SATIN [25], is an example of a haptic shape display for rendering virtual shapes. This device tries to reproduce the shape of a curve, by deforming a physical continuous strip, in order to provide the users with the full-hand contact of the virtual surface. In this way, the device is able to communicate both tactile and kinaesthetic cues through a whole-hand interaction. This haptic interface is held in space in front of the user by means of two MOOG-Haptic Master systems [26].

The strip consists of a series of nine equidistant relative actuators, which allow the strip to actively shape itself in order to match the curve of the virtual object along a geodesic curve. This set up allows for six degrees of freedom in the movement of the haptic strip. The first version of the haptic strip [27] has been developed with the main objective of integrating the various mechanical components and validating the concept at the basis of the strip, so as to allow users to explore a shape along a trajectory through full-hand contact. However, this version was able to represent only planar curves that do not allow us to represent the whole domain of curvature of curves.

For this reason a more performing version of the haptic strip [25, 28, 29] has been subsequently designed. The final version is based on a geodesic approach, allowing the representation of curves in 3D space, thus increasing the domain of curvature of curves that can be represented.

The system includes a hand tracking system in order to play metaphoric sounds while the user interacts with the system. However, there is no a visualisation of the virtual hands. The SATIN system set up, in its entirety, is expensive, with limited possibility of scaling and it is not portable. To overcome these problems, it has been developed a desktop version of the haptic strip, which replicates the concept demonstrated in the SATIN system by using a desktop and portable mechatronic device, as described in [2, 30, 31, 32].

Another haptic device for full-hand hand contact is the FEELEX mechanism [33], a 2.5D-formable crust concept, which uses a linear actuator array. Each actuator drives a rod located under a rubber membrane. A drawback of this concept is that it is equipped with a bulky actuator arrangement and it is not possible to display shapes with undercuts.

The interface developed by the MIT Media Lab [34] uses a similar approach for the haptic display but integrates it with an Augmented Reality visualization system. This allows the Media Lab researchers to analyze how the users can interact with digital models, handles and controls, which are perceived as virtual 3D graphics or dynamic physical shapes. The Digital Clay developed at Georgia Institute of Technology [35] is based on a multiple collocated spherical joints, and it has been developed by Bosscher *et al.* [36]. A formable crust is obtained by combining the spherical joints into an array. It can be easily manufactured in a very small scale. Nonetheless, the actuation of the Digital Clay is an unsolved problem.
In [37], the authors presented a virtual prototype with a matrix of nine nodes, which are 35 mm distant from each other. This concept is interesting because the system is able to render a full surface.

A comparison of the characteristics of these systems is shown in Table1, and is based on the following five parameters: number of nodes, node distance, reached radius, output shape and possibility for tracking the users' hands. These represent the main characteristics, which are used in our research work to evaluate the performances of the systems. The number of nodes and the distance between them represent the resolution of the device. The value of the reached radius allows evaluating the range of curvatures that the system can represent. The output shape indicates the possibility to represent 2D or 3D curves.

The objective of our research is to obtain a system with high level of performance compared with the other state-of-the-art solutions. In this paper we describe the interaction modality implemented for handling the interaction with the virtual shape.

Table 1: Comparision of some systems for physical shape rendering

System	Number of nodes	Node distance [mm]	Reached Radius [mm]	Output shape	Tracking hands
FEE* [33]	36	48	n/a	3D	No
Digital Clay [35]	≥ 100	13	n/a	3D-2D	No
SATIN [25, 27, 28, 29]	9	90	185	3D-2D	Yes
Desktop Strip [2, 32, 38, 39]	7	10-45	30-60	2D	No
Formable Object [37]	9	35	60	3D-2D	No

3. The Desktop Haptic Strip for Shape Rendering (DHSSR)

The DHSSR device consists of a servo-actuated developable metallic strip physically representing geometric curves laying on the surface of a 3D model. The haptic interaction occurs through a 2D cross-section curve of the virtual object surface, which is obtained by intersecting the virtual 3D object with a virtual cutting plane. The basic concept is to use the virtual cutting plane as a tool for interacting with the virtual object. Figure 2-a shows an example of a 2D cross-section curve of a virtual vacuum cleaner. Figure 2-b shows the real vacuum cleaner and a tape attached on its surface, which is a practice typically used by designers in the conceptual phase of a new product design for highlighting style curves. The approach based on the 2D cross-section curve of the virtual object surface intends to mimic this practice. A portion of this 2D cross-section corresponds to the target curve on which the strip has to be located. The physical strip, represented by the blue curve in Figure 2-c, is initially in its nominal position and is defined by a set of equidistant elements. Then the strip is bent as a Minimal Energy Curve (MEC) spline, and the spline interpolation points are positioned in the same place of the joints of the equidistant elements.

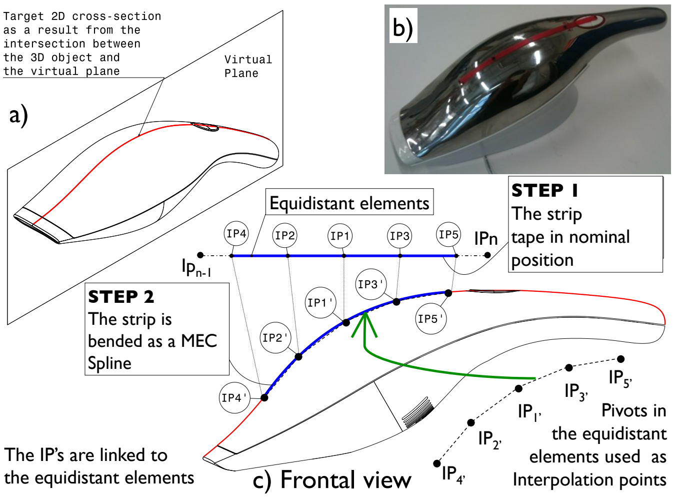

Figure 2: MEC spline approach for representing the 2D cross-section curve.

In order to better approximate the virtual 2D cross-section with the real metallic strip, we decided to use the Minimal Energy Curve (MEC) Spline approach. This approach simplifies the conformation of the metallic strip on the virtual shape. In practice, the physical strip is able to approximate the shape of the virtual object surface by adopting the shape of a MEC spline, i.e. the strip can only morph itself into a twice continuously differentiable function constructed of piecewise third-order polynomials, which pass through a set of several equidistant interpolation points. The main idea behind the MEC spline is based on the designer's tool used to draw several and smooth curves crossing a number of points. This spline consists of interpolation points attached to a flat element at the endpoints. The mechatronic device we have developed adopts this approach in which the flexible strip is bent across each of these interpolation points, resulting in a pleasingly smooth curve. The interpolation points are numerical data driven by their position and orientation on the virtual model. In fact, these data are used to control the actuators.

These interpolation points 'bend' the strip so that it passes through each point without any erratic behavior or break in continuity. Note that the quality and precision of the MEC spline depends on both the number of the Interpolation Points, and the distance between them.

4. System Architecture

The system architecture consists of a set of hardware and software components to control the Desktop Haptic Strip for Shape Rendering (DHSSR). Figure 3 shows the components and the data flow between the components. The user is the first element in the diagram, which interacts with the system. Unity3D is an engine for interactive 3D content generation, which provides the scene simulation of the virtual strip that is used to sense the position of the interpolation points, and the visualisation of the user's virtual hands that are tracked by means of the Leap Motion Sensor. Unity3D is also connected to an Arduino Leonardo board for controlling in real-time the six servo actuators of the DHSSR, which is used to provide a physical output of the virtual shape.

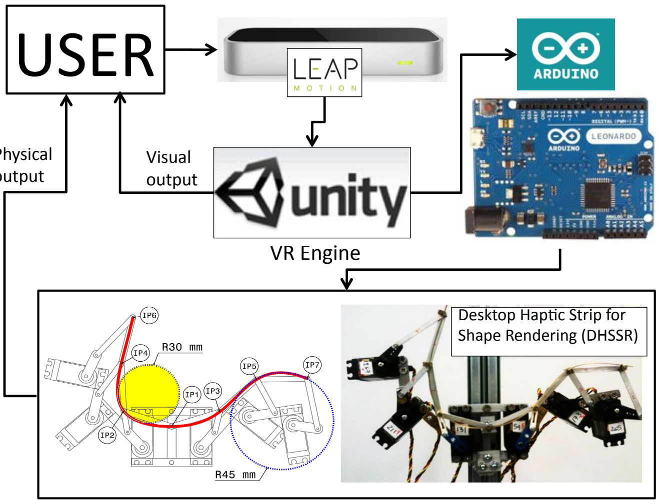

Figure 3: DHSSR system components and data flow between the components.

4.1. Visual feedback and interaction with the virtual shape and curve

After comparing several Virtual Reality engines, Unity3D has been selected for the implementation of the visualization and interaction with the virtual shape and curve. The main reason is that Unity3D has a powerful interface that allows visual object placement and property modification during the interaction. The application is also easily customizable and provides a simple environment for project deployment to use with multiple platforms, with no need for additional configuration.

The required features of Unity3D for the development of our system are as follows:

- 3D rendering of virtual shapes;
- Graphical User Interface (GUI);
- Physics engine (used for handling collision detection);
- Collision detection;
- Integration with the Leap Motion Sensor (used for user's gesture recognition);
- Interaction with Arduino Leonardo board (used to control the mechatronic system);

Figure 4 shows the visual feedback which is seen by the user while interacting with the DHSSR system. Basically, the user can see his/her virtual hands, the virtual strip with the seven interpolation points, and the 3D model.

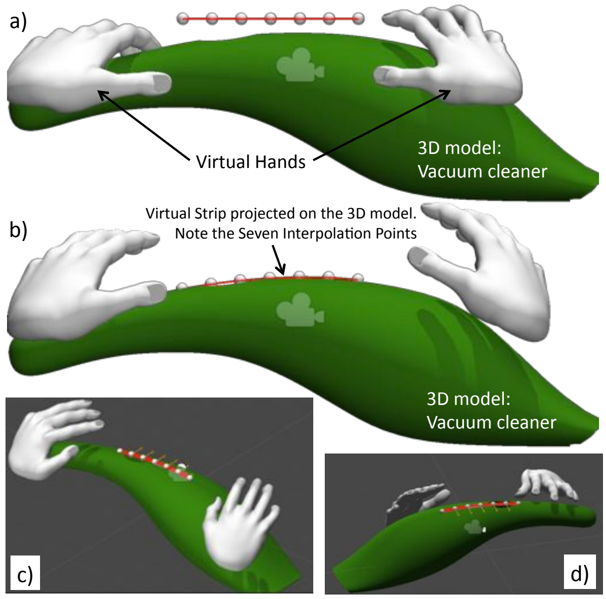

Figure 4: Visual Feedback of shape and curve implemented using Unity3D.

Figure 4-a shows the scene with the virtual strip in the nominal position, without gravity effect. Figure 4-b shows the instant in which the interpolation points of the virtual strip are projected on the 3D model. It is possible to detect the rotation on each interpolation point in order to control the servo actuators of the DHSSR. Figures 4-c and 4-d show some other views on the 3D scene during interaction.

5. Gesture recognition module

The DHSSR device has been integrated with a visualization and interaction system that allows users to see the virtual shape, and select curves to render physically. The system provides two user interaction modalities for handling the virtual curve and the 3D object shape. The DHSSR system provides the following interaction modalities:

1. Positioning modality in which the user moves the virtual strip or the virtual object through a hand pinch gesture. In this modality the 3D object is fixed on the ground and the physical strip (DHSSR) is the movable mechanism. The virtual hands moving in space are graphically rendered and both the virtual curve and the physical strip are updated according to the virtual shape;
2. Positioning modality in which the user moves the virtual 3D object through a hand gesture. In this modality the virtual strip is floating in the air and the 3D object is the movable part. The user's hands are not graphically rendered because according to this metaphor the 3D shape rotations are blocked and only translations are allowed. Therefore, this modality does not require tracking the orientation of the hand or the position of the fingers.

The exploration modality is used in the two previous interaction modalities. The user 'touches' the virtual 3D object for evaluating its shape along a curve by touching the real DHSSR representing it.

In this way, the user has the possibility to properly set the DHSSR or the 3D model position in space, for the evaluation of the shape. The hand gestural interaction system has been developed using state-of-the-art, low cost and open hardware and software technology, combining an engine for interactive 3D content generation (Unity3D), a motion capture sensor (LeapMotion) and the Arduino Leonardo board, as described in the following sections.

5.1. Moving the DHSSR through the pinch gesture

The DHSSR is moved and properly positioned onto the virtual shape through a specific hand gesture, that is a pinch gesture. The virtual hand visually represents the pinch gesture. A Magnetic Pinch feature is activated, where the virtual hand is attached to one of the Interpolation Points of the virtual strip (represented as spheres) located at the extremities of the virtual strip.

Once the virtual hand is linked to the Interpolation Point, the user can drag the virtual strip until reaching the desired position. Figure 5-a shows the instant when the Magnetic Pinch feature has been enabled by the pinch gesture performed by the user's hand. Figures 5-b and 5-c show two different locations of the virtual strip. Currently, the system allows the virtual strip moving only along the 'X' axis.

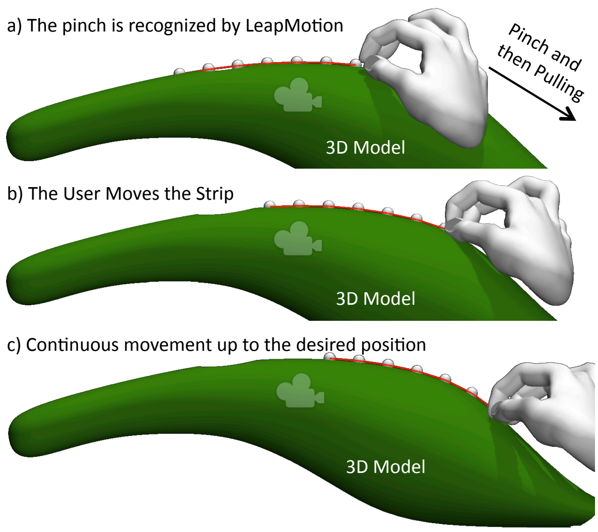

Figure 5: Moving the virtual strip through the Pinch gesture detected by means of the Leap Motion controller.

5.2. Moving the 3D object trough the hand/finger recognition

With this approach the virtual curve is floating in the air, and the 3D model can be moved by the user. As explained in the introduction of this paper, the user's hands are not graphically rendered. The 3D model is translated up to the virtual curve. Therefore, this modality does not require tracking the hand orientation or the position of multiple fingers. Figure 6-a shows the scene including the 3D model and the virtual strip.

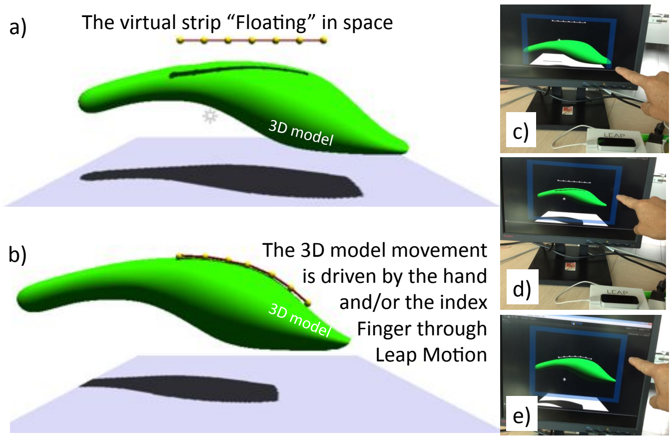

Figure 6: Moving the 3D model through the hand and/or the index finger detected by LeapMotion.

Once the user's hand or a single finger is detected, the 3D model is immediately connected, and the 3D model is then translated according to its movements, as shown in Figure 6-b. Figures 6-c, 6-d and 6-e show the sequence in which the user moves the 3D model.

This interaction modality has several advantages:

- it does not require precision in performing the gestures in order to be recognized (as the pinch);
- it is easy for the user to get a feedback of the interaction with the system;
- it does not require tracking the hand orientation or the position of multiple fingers because the 3D model rotations are disabled.

6. Control of the DHSSR servo-actuators

The orientation data required to rotate the servo-actuators is captured inside Unity3D because the position of the interpolation points changes on the basis of the geometry of the virtual object. The interpolation points require to be positioned correctly while in contact with the virtual surface. The approach that drives this continual computation of contact location is based on the control of the seven interpolation points through the Arduino Leonardo board.

Figures 7-a and 7-b show that for each single interpolation point it is required an α**s** angle (which is captured by the Unity3D library). The α**s1** angle required by the servo motor is exactly the same α**1** angle computed while the strip takes the shape of the virtual object (these data is used by the Arduino board in order to drive each servo motor). The mechatronic device requires the combination of seven interpolation points to reproduce both convex or concave surfaces, and a combination of those.

The shapes that can be represented exactly with the developable strip driven by side force actuators have been analyzed. The servo motors **A2** and **A3** (Absolute actuators) are clamped to the Interpolation Point 1 (IP1). The IP1 is linked through a rigid joint on slot constraint with the virtual environment. This constraint guarantees the sliding motion on the "Z" axis. The servo motor **A2** is responsible to change the position and orientation of the Point 2 (**IP2**), the servo motor **A3** is responsible to change the position and orientation of the Point 3 (**IP3**), and so on. Note that the servo motor **A4** is relatively linked to the servo motor **A2** and in the same way, the servo motor **A5** is relatively linked to the servo motor **A3**.

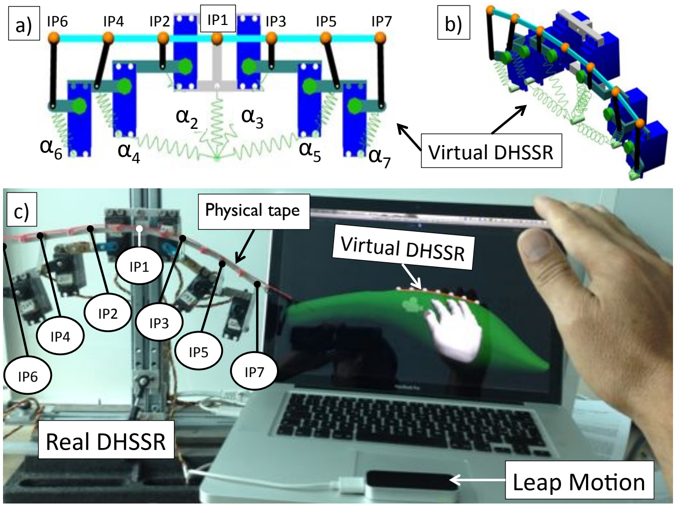

Figure 7: Control of the Real DHSSR through the Virtual DHSSR.

Figure 7-c shows the main system components. The real DHSSR device which renders the curve from the virtual DHSSR and the hand gesture interaction through the leap motion controller.

7. System Prototype

A physical prototype of the system based on the studies previously described has been developed taking into account some important considerations related to the use of sheet metal components that implies: low inertia, light weight parts and low friction. Regarding the haptic strip a critical concern is the component stiffness while reaching the target surface. In order to provide this stiffness, the links have been designed as beams or shell structures. This solution provides a lighter and rigid module for bending. Furthermore a Finite Element Analysis (FEM) has been carried out in order to verify both the displacements and stress in the critical components of the strip mechanism. Finally, the mounting arrangement of the set of actuators housing has been designed to accommodate manufacturing tolerances. Figure 8-a shows the frontal view of the prototype of the desktop mechatronic device with the absolute and relative actuators.

Figure 8-b shows the top view, in which the metallic strip is located on the seven interpolation points. This configuration has been considered in order to prevent collisions between the components. Figure 8-c shows the desktop-mechatronic prototype. It consists of a combination of the transmission system and the interface linked to the multi-body analysis tool.

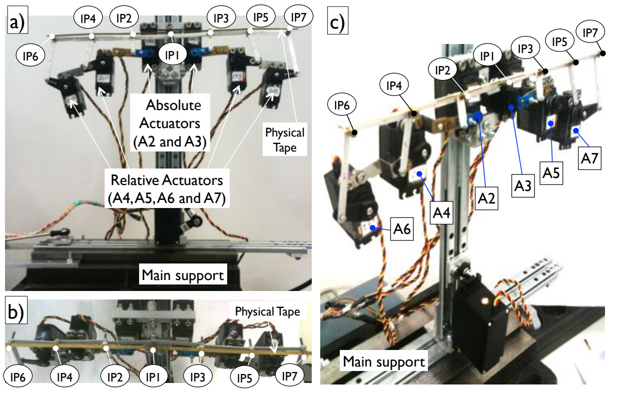

Figure 8: Prototype of the Desktop Haptic Strip for Shape Rendering (DHSSR)

7.1. Limits of the strip while bending

Figure 9 shows different instants of the physical rendering process in which the system displays a combination of convex and concave shapes without having any collision between the servo actuators and the mechanical components.

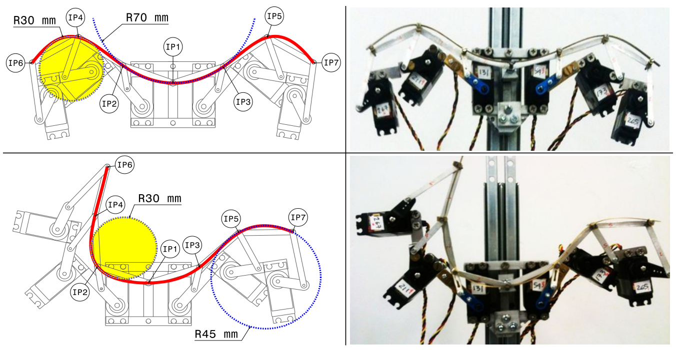

Figure 9: Limits in radius curvature.

The minimum bending radius is 30 mm when representing a concave shape, and 20 mm when representing a convex shape.

7.2. Validation of the accuracy of the DHSSR

This section presents the results of the validation of the Desktop Haptic Strip for Shape Rendering (DHSSR), whose aim is to give rigorous, valid and practical conclusions about the accuracy of the device. In this research we were interested in evaluating the DHSSR device in terms of accuracy while representing a 2D cross-section.

Figure 10 shows the experimental setup used for the evaluation. Three different 2D cross-sections (named target curves) laying on a target object (a vacuum cleaner) have been rendered and measured in order to know the accuracy error computed in millimeters.

Figure 10-a shows the location of the three target curves, one on the left, one in the middle and one on the right hand side of the object. The three curves have been chosen because they differ in both curvature and inflexion points that might be expected for judgements involving high and low curvatures. In

this way, Curve A presents a low level of curvature, Curve B presents a high level of curvature and Curve C presents one inflexion point with two different curvatures. Principal curvatures help to form the shape of objects. Shapes are assessed in relation to these curvatures and these curvatures may be adapted to form more pleasing or exact shapes. Usually this is normally not only achieved through manipulation of CAD models, but also in relation to physical prototypes. Figure 10-b shows the device while reaching the target Curve A, and the user's hand while exploring the real vacuum cleaner. Figure 10-c shows the Unity3D interface and the device while reaching the target Curve B, and Figure 10-d shows a visual comparison of the real vacuum cleaner and the device while reaching the target curve C.

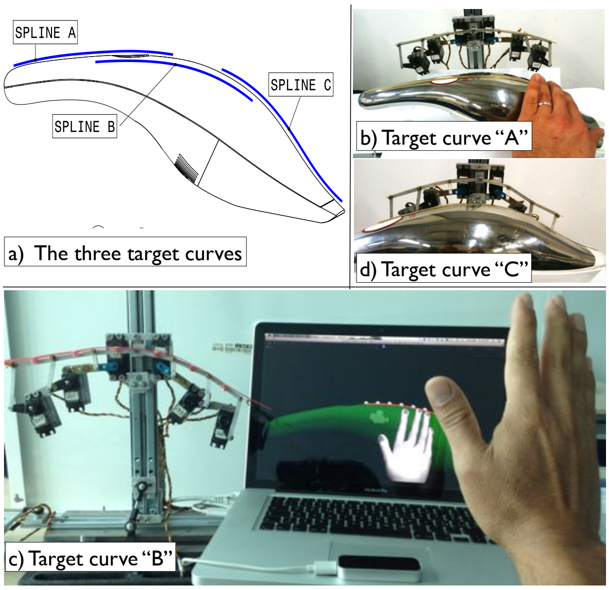

Figure 10: Experimental setup.

In order to determine the accuracy of the desktop strip we have compared the real strip and the virtual 2D cross-section curves. A set of measurements has been performed using the Konica Minolta 3D scanner device [40]. This scanner has an accuracy of 50 μm enabling 3D measurements. The data have been exported in STL file format, and used to compare those with the CAD surfaces. Therefore, we have been able to measure the error present in the physical strip spline.

7.3. Porcupine Curvature Analysis

A porcupine curvature analysis has been performed by considering as geometry references both convex and concave shapes. The porcupine plot is a visual curvature analysis technique for curves and surfaces, which places visual 'quills' at points along a curve. The Frenet frame of the curve determines the direction that the quill displays at that point on the curve, while the relative length of the quill reflects the curvature and/or the radius at that point. The greater the curvature of the curve at the quill point, the longer the length of the quill. Figure 11-a shows the position of the Target Curve A, the theoretical and the physical strip curvature radius and the positional error.

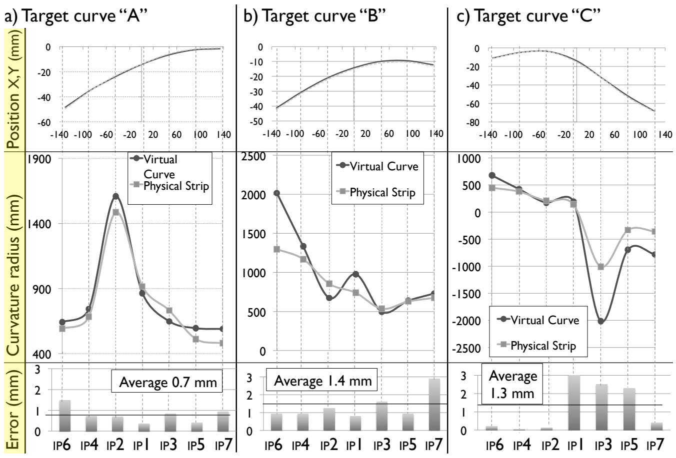

Figure 11: Vacuum cleaner 2D cross-sections.

The positional error is the distance between the theoretical spline and the physical one. In this case, the maximum error value is reported in the interpolation point 6 (IP_6), which is 1.4 mm. However, the average error value along the total trajectory of the spline is only 0.7 mm.

The same analysis has been performed for the target Curve B as can be seen in Figure 11-b, in which it is also reported the curve position (theoretical and physical), their curvature radius and their positional error. In this case, the highest error value is located on the interpolation point 7 (IP_7) which is 2.9 mm with an average value along its length of about 1.4 mm.

Finally, Figure 11-c shows the target Curves C (theoretical and physical), their curvature radius and the positional error. In this case, the highest error is reported at the interpolation point 1 with 2.9 mm. The average error while reaching this curve is 1.3 mm. The positional errors are probably occurring due to manufacturing and assembly tolerances. However the physical curvature rendering process follows the same trajectory of the target curves.

7.4. Validation of the user interaction

In order to test the usability, quality and effectiveness of the interaction modalities implemented in the system, we have performed a set or preliminary tests with users. The test consists of two parts. In the first part of the test, all participants were asked to carry out three tasks, consisting of using a combination of visual and haptic functions in order to carry out the manipulation of the virtual DHSSR through hand gestures, and the exploration of the model of a vacuum cleaner.

Fifteen participants (10 male and 5 female) have been selected ranging between 22 and 35 years of age, five of them were experts coming from the Industrial Design sector or from the Virtual Reality field, and ten were postgraduate students. They were all right-handed and had some experience of gestural interaction, such as using a Wii remote or Microsoft Kinect for playing games. For what concerns the manipulation task,

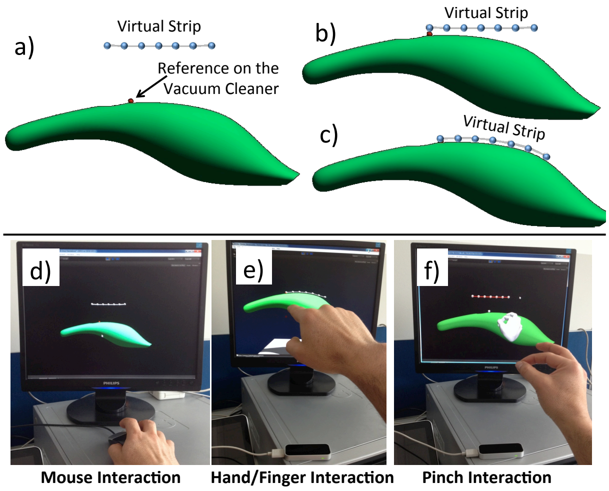

Figure 12: 2D task

the model of a vacuum cleaner has been loaded. Then, by using three different interaction modalities (by using: a mouse, the hand/finger and pinch approaches) each user started to move the virtual vacuum cleaner from an initial position (e.g. home position) up to the virtual strip (Figures 12-a, 12-b and 12-c). In this way, the Curve A, Curve B and Curve C were used as curve references, which have been described in Section 7.2.

Figures 12-d, 12-e and 12-f show the different interaction modalities, by using a mouse and the two interaction modalities proposed in this research work: hand/finger and pinch recognition.

Table 2 shows the user's time performance while using the different interaction modalities during the test (in seconds). The time required to reach the Curves A, B and C through a mouse are listed on the MCA (Mouse Curve A), MCB (Mouse Curve B) and MCC (Mouse Curve C) columns. Then, the time required to reach the same curves through the hand/finger recognition modality are listed on the HFCA (Hand/Finger Curve A), HFCB (Hand/Finger Curve B) and HFCC (Hand/Finger Curve C). Finally, the time required to reach these curves through the pinch approach are listed on the last tree columns, PCA (Pinch Curve A), PCB (Pinch Curve B) and PCC (Pinch Curve C).

Figure 13 summarizes the results of this first part of the test. Figure 13-a shows the comparison between the user's task by using the mouse, the hand/finger and pinch recognition while reaching the Curve A, Figure 13-b shows the comparison of the three modalities for the Curve B, and finally Figure 13-C shows the comparison results for the Curve C.

No statistically significant differences were found, all interaction modalities exhibit about equal good performances. We expected that the hand/finger interaction would be easier to use than the pinch approach and, hence, would lead to better performance. This is due to the fact that in the pinch modality, the user's needs to perform the pinch gesture in order to activate the magnetic constraint which is responsible to attach the hand's movements to the virtual vacuum cleaner. This operation takes more time than the time required in the hand/finger recognition,

Table 2: Time results while reaching the Curve references through: mouse, hand/finger and pinch gesture recognition. p-value* results for comparing Mouse vs Hand/Finger and Mouse vs Pinch interactions

User	MCA	MCB	MCC	HFCA	HFCB	HFCC	PCA	PCB	PCC
1	1.11	1.32	1.52	1.25	1.52	1.71	1.62	1.89	1.91
2	1.23	1.41	1.54	1.21	1.48	1.53	1.52	1.73	1.72
3	1.12	1.22	1.67	1.14	1.31	1.57	1.61	1.25	1.49
4	0.82	0.95	1.23	0.92	0.87	1.32	1.13	1.12	1.38
5	0.93	0.96	1.34	0.98	0.92	1.35	1.24	1.21	1.67
6	1.41	1.75	2.01	1.52	1.52	1.98	2.03	1.57	2.02
7	1.32	1.43	1.99	1.31	1.42	2.03	1.92	2.31	2.41
8	1.49	1.73	1.85	1.30	1.58	1.97	1.76	1.67	2.31
9	1.41	1.54	1.79	1.35	1.62	1.82	1.56	1.75	1.76
10	1.72	1.85	2.01	1.65	1.78	1.92	1.73	1.98	2.03
11	1.33	1.42	1.92	1.45	1.43	1.87	1.68	2.12	2.10
12	1.67	1.76	1.89	1.72	1.52	1.93	1.85	2.23	2.35
13	1.78	1.94	2.05	1.67	1.96	1.94	1.92	2.51	2.78
14	1.35	1.43	1.87	1.31	1.35	1.98	1.78	2.21	2.33
15	1.31	1.39	1.92	1.45	1.34	1.93	1.98	2.15	2.21
Median	1.33	1.47	1.77	1.35	1.44	1.79	1.69	1.85	2.03
STD	0.27	0.30	0.26	0.24	0.28	0.24	0.26	0.43	0.38
p-value*				0.56	0.49	0.67	0.99	0.98	0.99

which automatically attaches the hand/finger movement to the virtual vacuum cleaner. Furthermore, we expected that using the two gesture interaction modalities presented in this research would result in a more natural interaction, and thus in a better performance. It is important to point out that the mouse interaction is used in 2D tasks, that means that the user moves the virtual vacuum cleaner on the XY plane (the screen plane) while in our two gesture recognition approaches, the user can also move the virtual vacuum cleaner on the Z axis (normal to the screen plane). Only one user had the necessity to try twice the pinch modality to get the virtual vacuum cleaner move up to the target curves. Wilcoxon Rank-Sum test did not show any difference between the three modalities with respect to user completion time at the 5% significance level (p-value$\geq$0.5). This result is encouraging because it suggests that there is no exceptional loss of performance when the gesture interaction modalities were used instead of the mouse.

As part of the validation of the user interaction of the whole system, we have decided to organise some additional questionnaires with the same users with the aim to show the concept related to the new technologies developed for supporting product design, and also to gather opinions about the use of the system and collect feedback about it.

The charts on Figure 14 show the results of these questionnaires. The score system proposed has a scale from 1 (which is

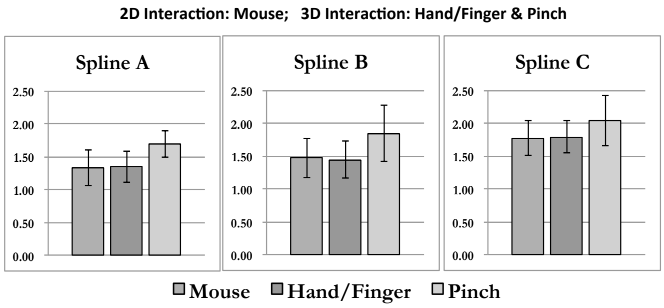

Figure 13: Validation of the user interaction.

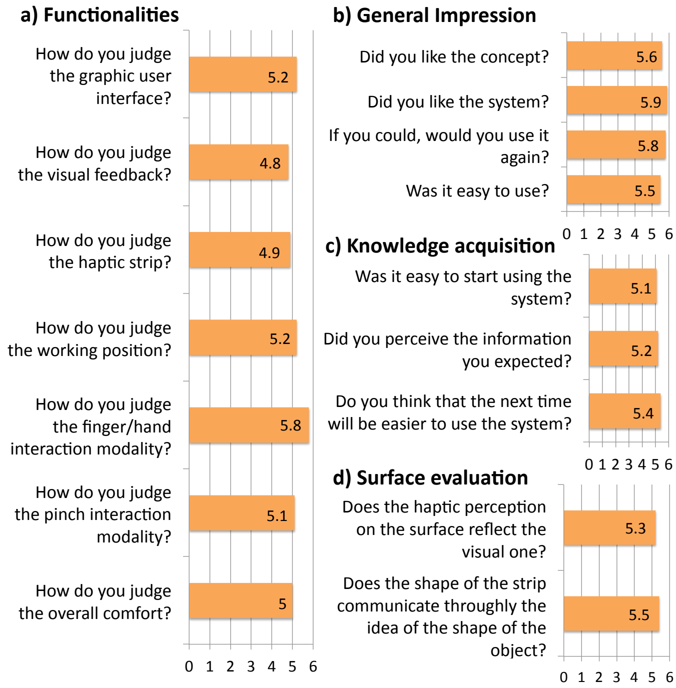

Figure 14: General results of the users' evaluation

the most negative value) to 6 (which is the most positive value).

As it is possible to observe from chart **a** on Figure 14, the participants have judged interesting the gesture interaction modalities proposed (pinch and finger/hand gestures), and the use of the haptic strip. A positive evaluation has been given also to the visual feedback coherent with the user's interaction. The users have stated that they felt an overall comfort, and in general they have assigned high scores also to the working position.

The system achieved a high evaluation rate relatively to the aspects concerning the system in general, a quite positive evaluation to the easiness in using it as a whole, and in using it for evaluating the shapes (chart **b** on Figure 14).

The *knowledge acquisition* part of the test has intended to go more in details into the understanding and evaluation of the system by the user's perspective. Chart **c** on Figure 14 shows the results. Overall the results show a positive evaluation from users. Only one user has assigned a very low rate for what concerned the easiness of using the system the first time. But the same user was convinced that the next time it would have been easier and more natural to use the system.

The scores assigned to the two questions related to the *surface evaluation* have been very high as reported on chart **d**. Thus, the users have particularly appreciated the possibilities of exploring the surface by means of the haptic strip. Actually, the users have asserted that the perception of the surface reflects the visual one. In addition, the users have recognized the effectiveness of the strip in communicating thoroughly the idea of the shape of the object that they were seeing.

Detailed information of the specific questions and answers and other human factor aspects of the evaluation can be found in [41]. In this paper, we intend to highlight that users considered the gesture recognition interaction helping them to move and interact with virtual objects in order to render the real curve through the Desktop Haptic Strip for Shape Rendering (DHSSR).

8. Conclusion

In this paper we have presented gesture interaction modalities implemented for interacting with a Desktop Haptic Strip for Shape Rendering (DHSSR) system aimed at physically rendering virtual shapes. The system consists of a mechatronic device that allows a continuous and smooth, free hand contact interaction with a developable real strip actuated by a servo-controlled mechanism, which is controlled by seven interpolation points. Through the DHSSR, industrial designers can physically explore the surfaces of virtual objects directly with their hands.

We have performed some preliminary tests in order to prove the concept and identify the improvements of the precision and quality of the representation of an aesthetic surface offered by the DHSSR, as well as of the usability aspects. The test results reported in the paper are positive for what concerns the quality of the rendering of the surface, and of the interaction modality proposed. These results are based on the pinch gesture recognition. On this basis, we conclude that the hand gestural interaction system for handling DHSSR provides users with an effective and natural method to manipulate both the virtual DHSSR or the 3D virtual object according to the modality selected.

The main innovations and contributions of the research presented in this paper, with respect to the state of the art, include the following:

- Design of a free-hand gesture interface based on two modalities (pinch and hand/finger recognition);
- Implementation of a system controlling in real-time the servo-actuators of the real DHSSR;
- Implementation of a strategy avoiding the limitations of the LeapMotion device while still enabling interaction that is perceived as natural and fluid.

As future work, the authors intend to continue improving this work by exploring different free-hand gesture metaphors and tools, by including the integration of the DHSSR with a 3D visual rendering system, based on an Augmented Reality approach.

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