

Visuo-tactile system for 3D digital models rendering

Alessandro Mansutti , Mario Covarrubias Rodriguez, Giandomenico Caruso, Monica Bordegoni  and Umberto Cugini

Politecnico di Milano, Italy

ABSTRACT

The product design process is based on a sequence of phases where the concept of the shape of a product is typically represented through a digital 3D model of the shape, and often also by means of a corresponding physical prototype. The digital model allows designers to perform the visual evaluation of the product, while the physical model is used to better evaluate the aesthetic characteristics of the product, i.e. its dimension and proportions, by touching and interacting with it. Design and evaluation activities are typical cyclical, repeated as many times as needed in order to reach the optimal and desired shape. This reiteration leads to an increase of the development time and, consequently, of the overall product development cost.

The aim of this research work is to develop a novel system for the simultaneous visual and tactile rendering of product shapes, thus allowing designers to both touch and see new product shapes already during the product conceptual development phase.

The proposed system for visual and tactile shape rendering consists in a Tactile Display able to represent in the real environment the shape of a product, which can be explored naturally through free hand interaction. The device is designed in order to be portable, low cost, modular and high performing in terms of types of shapes that can be represented. The developed Tactile Display can be effectively used if integrated with an Augmented Reality system, which allows the rendering of the visual shape on top of the tactile haptic strip. This allows a simultaneous representation of visual and tactile properties of a shape.

By using the Tactile Display in the initial conceptual phases of product design, the designers will be able to change the shape of a product according to the tactile evaluation, before the development of the physical prototype. This feature will lead to a decrease of the number of physical prototypes needed, thereby reducing, both cost and overall time of the product development process.

KEYWORDS

Tactile display; virtual prototyping; shape rendering; augmented reality

1. Introduction

The product design process is based on a sequence of phases where the concept of the shape of a product is typically developed through a 3D Computer Aided Design (CAD) model, and often also by means of a corresponding physical prototype. The design process of products, mainly for what concerns the shape and the aesthetic properties of a product, can be divided into five main phases:

- *Concept ideation*: this is the preliminary phase, where the designer creates the concept of the product that is represented by hand drawing and sketches;
- *Shape modeling*: where the shape of the product is modeled and represented by using a CAD software tool, which allows obtaining a 3D digital model of the product;
- *Visual evaluation*: in this phase, the designer evaluates the shape and the aesthetic features of the 3D digital

model. This phase is typically performed simultaneously with the shape-modeling phase;

- *Physical Prototyping*: in this phase, a physical prototype is created, which is based on the shape described by the CAD model. In this way, the designer can have a physical interaction with the model of the product;
- *Tactile evaluation*: owing to the development of physical prototypes, the designers can experience a physical interaction with the models of their in-progress products. The information provided by the tactile evaluation cannot be obtained by sole visual evaluation. This phase is fundamental for the designers, because it also allows them to evaluate how the shape of the future product will be perceived by the user.

The digital CAD model allows designers to perform visual evaluation of the shape, while the physical model is used to better evaluate the aesthetic properties, such as symmetry, roundness, of the product by touching and

interacting with it. If the new shape, either in its digital or physical form, does not satisfy the designer, it has to be modified. A modification of the digital model requires a new physical prototyping of the shape for further evaluation. These physical prototypes are often developed through a traditional manufacturing process or through modern rapid manufacturing techniques. Conversely, a modification of the physical prototype requires the consequent update of the digital model, which may imply the use of reverse engineering. In the traditional Product Design Process (Fig. 1-a) the design and evaluation activities are typically cyclical, i.e. repeated many times before reaching the optimal and desired shape. This reiteration leads to an increase of the time-to-market and also of the overall product development cost.

With respect to the traditional product design process of aesthetic shapes, the novel approach presented in this paper proposes to anticipate the tactile evaluation phase, as shown in Fig. 1-b. In this way, the designer will be able to check the shape of the model and perform the tactile evaluation directly during the shape modeling together with the visual evaluation phase. By means of this new approach, it will be possible to decrease the number of physical prototypes needed, and therefore reducing the development time and costs.

The aim of the research work described in this paper is to develop a novel system for enabling the simultaneous visual and tactile rendering of product shapes, thus allowing product designers to both touch and see new shapes during the creative initial conceptual phase of product development. The proposed system for visual and tactile shape rendering consists of a Tactile Display that is able to represent the shape of the CAD model of a product in the real environment. It allows designers to explore the rendered surface by touching continuous curves lying on a physical representation of the product shape. In order to physically represent these selected curves, a flexible surface is deformed by means of servo-actuated modules controlling a physical deforming strip. The device is designed so as to be portable, low cost, modular and high performing in terms of the types of shapes that can be represented. The developed Tactile Display

has been integrated with an Augmented Reality visualization system, which allows rendering the visual shape on top of the tactile haptic strip. This allows a simultaneous representation of visual and tactile properties of a shape.

2. Related works

In the last decades, several systems have been developed for tactile interaction with digital models and in general for Virtual Reality applications, such as the Full-Shape Displays. These interfaces are able to communicate both tactile and kinaesthetic cues and allow for a whole-hand interaction. They are able to render a spatial continuous surface leaving the user free to choose where to touch the shape. One of the first Full-Shape Displays is the Feelex Project [7]. It is a 2.5D-formable crust concept that uses a linear actuator array that is able to deform a flexible membrane. In this way, Feelex allows the user to touch the surface and feel its shape. Relief [9], developed at the MIT Media Lab, is a pin-based device, which investigates direct manipulation of the control points and gestural input. These features enable interaction techniques that match the capabilities and potential of 2.5D shape displays. Sublimate [10] is based on a similar approach and it integrates actuated shape displays and Augmented Reality (AR) for co-located physical shapes and 3D graphics.

All these devices allow rendering a portion of a surface, and are based on a matrix of moving pins, which could be perceived by the user during the tactile evaluation. Moreover, the curvature radii that these devices can render are not appropriate for the evaluation of the typical shapes of products in the industrial design domain.

It has been observed [1] that designers slide their hands along a trajectory, while exploring a surface. Based on this observation, the authors have developed the SATIN system [2][3], which includes a device capable of rendering a curve that allows users to perform a continuous free-hand shape evaluation. However, the system has some drawbacks, as shown in Tab. 1. For instance, the high value of curvature radii that can be rendered, the dimensions of the whole system and the implementation costs.

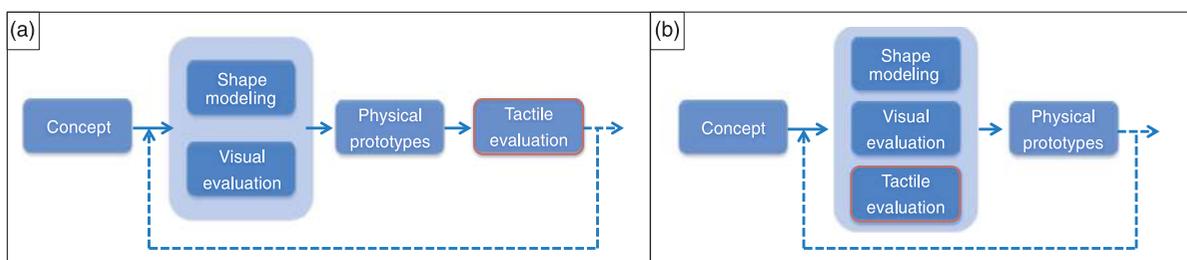


Figure 1. Phases of Product Design Process. (a) Traditional approach, (b) New approach.

Table 1. SATIN system main characteristics.

SATIN System	
Dimensions of the whole system	(2600 × 2100 × 1280) mm
Number of control points of the tactile interface	9
Distance among the control points of tactile interface	90 mm
Possibility to regulate in real time the distance among the control points	NO
Reached radius by the tactile interface	185 mm
Modularity	NO
Portable	NO
Implementation cost	High

To overcome these problems, a desktop version of the haptic strip has been developed. This haptic strip replicates the concept demonstrated in the SATIN system by using a desktop and portable mechatronic device [5][6]. However, these Desktop versions are capable of rendering only 2D sections. To extend the range of representable trajectory to the 3D domain also for the desktop version, the authors have developed a device based on a modular approach [11]. Also this interface was affected by some drawbacks, such as the positional errors of the actuation mechanisms and the impossibility to manage in real time the distance among the control points.

3. System specifications and working principle

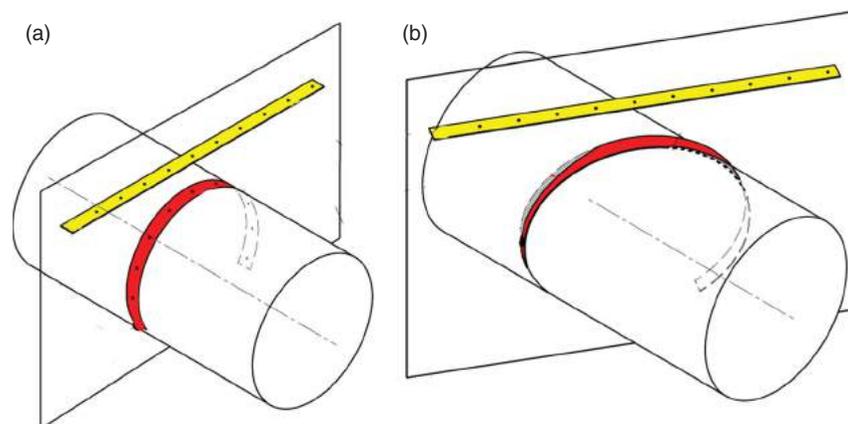
In order to obtain a system based on the strip approach able to overcome the described limits, the authors have developed a new system that has the following features:

- *Modularity*: to be customized according to the needs of the designers;
- *Portability*: to provide flexibility and usability in the everyday working life;
- *Low-cost*: to be affordable for a large number of design studios or for single designers;
- *High performance*: to overcome the limits of the previously developed solutions.

In order to obtain a system that allows designers to perform a tactile and visual evaluation of the digital models of the products they are designing, the authors have developed a Tactile Display integrated with an Augmented Reality visualization system. The Tactile Display working principle is based on the attitude of the designers, who typically explore the shape of products along trajectories as it usually happens when they use flexible curvilinear strip [1]. Considering a generic shape, in order to obtain a continuous trajectory similar to the one that would be explored by a user touching the corresponding shape, it is possible to use the cutting plane metaphor. To understand the concept it is useful to consider a simple shape, such as a cylinder, as shown in Fig. 2. If the cutting plane is perpendicular to the axis of the cylinder, the obtained trajectory is a circumference in the form of a 2D curve, as shown in Fig. 2-a. On the contrary, if the cutting plane is tilted, the trajectory generated by its intersection with the cylinder generates a 3D entity (Fig. 2-b).

This curve can be physically represented by the centerline of a flexible strip and in the first case it is sufficient to bend the strip without twisting it. On the other hand, for a generic 3D trajectory, it can be observed that the behavior of the strip changes: it has to be bended and twisted in order to respect the correct envelope.

As shown in Fig. 3, the data provided by the CAD model can be processed so as to control the Tactile Display and obtain the information needed for the visual rendering. The user can select the cutting plane, and the system computes the 3D curve obtained by the intersection of this plane with the surface of the CAD model. Then, in order to control the elastic deformation of the strip, a variable number of control points are identified on this curve. This control points and the deformation of the strip are managed by a modular system, which will be described in the following section.

**Figure 2.** Cutting plane metaphor

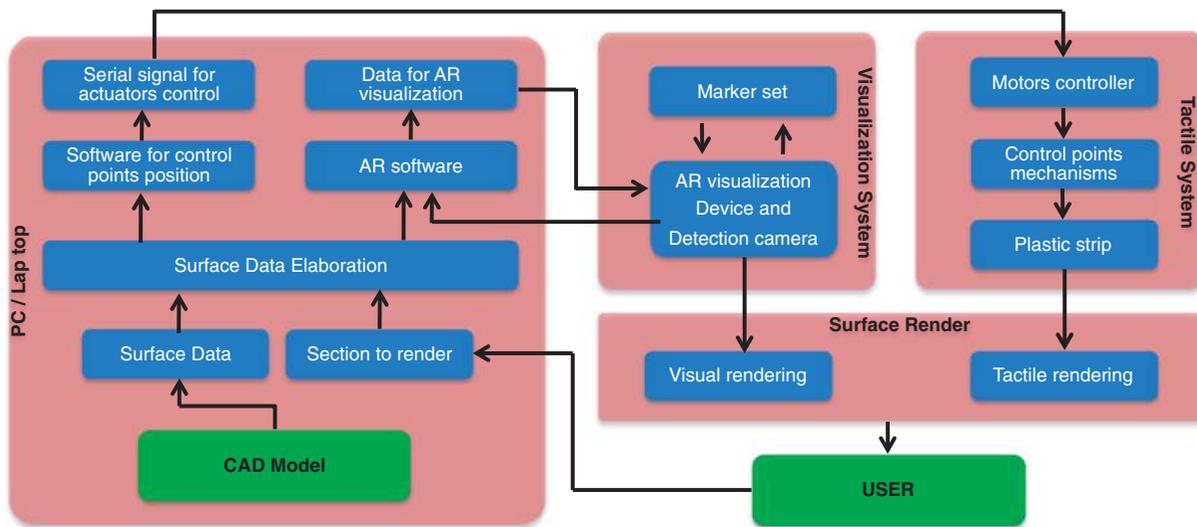


Figure 3. System working principle.

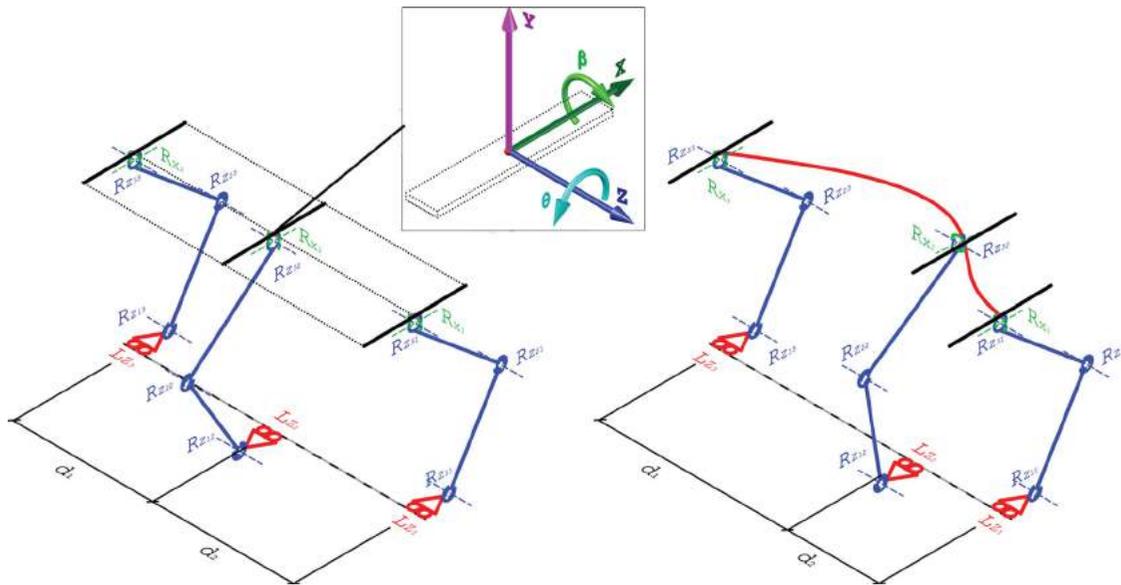


Figure 4. Kinematic of the system with modular approach.

4. Tactile display

4.1. Concept of the system

To control the elastic deformation of the strip so as to physically represent the curve that has to be rendered, the authors have developed an interface based on modules with absolute actuation system (Fig. 4). It is possible to control the behavior of the strip by controlling the position and the rotation of those sectors of the strip where the modules are connected (called control sectors). The modules are replicated and placed in the space alternately. This characteristic avoids collisions between two adjoined modules, thus decreasing the minimum distance needed between them, which is the resolution of the system. The designed kinematic will also allow us to

slide the control sector on the strip. With this feature, it is possible to place the control sector in a given point of the trajectory, such as inflexion points. This allows us to choose in real time the best configuration of the system according to the characteristics of each trajectory that has to be rendered.

Each control sector and, therefore, each module is equipped with 5 Degrees of Freedom:

- X, Y and Z define the absolute position of the point on the trajectory acting as reference for the control sector in the space, thus allowing the bending of the strip;
- θ defines the torsion;
- β allows handling the tangency of the trajectory to the control point.

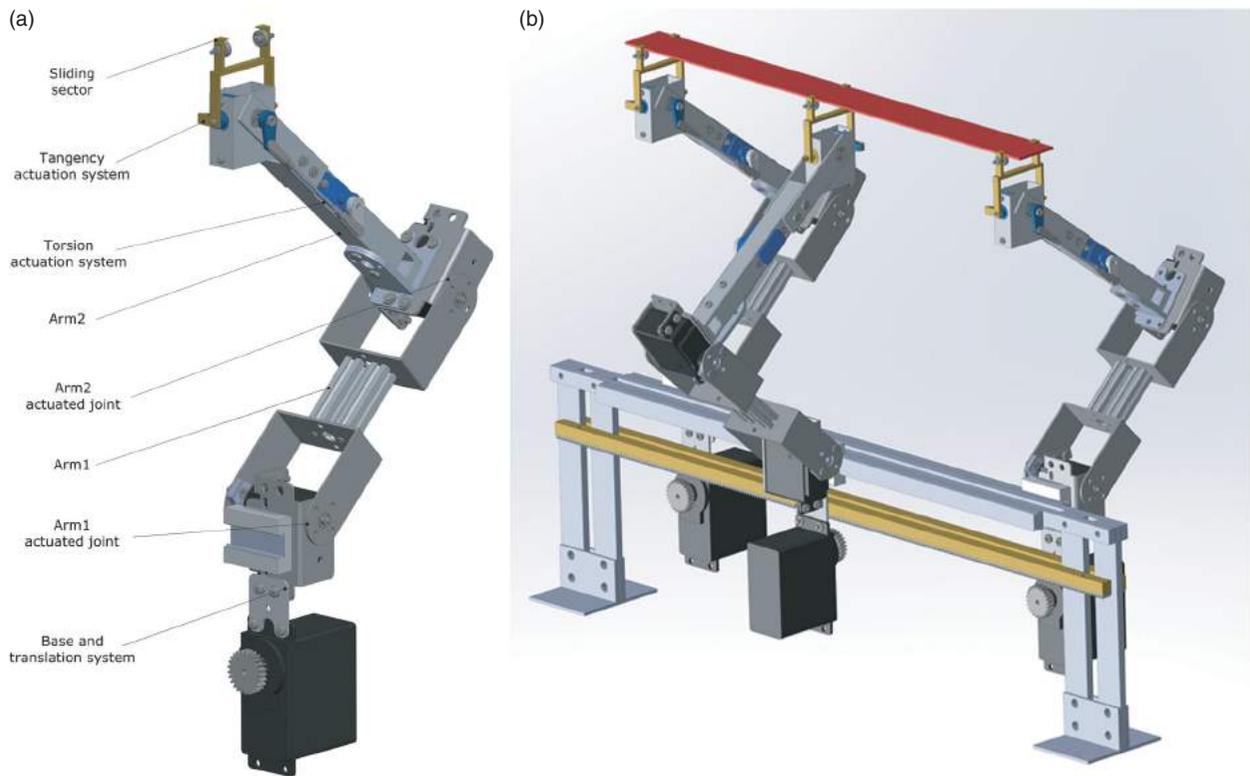


Figure 5. The tactile display. (a) Architecture of the module, (b) Tactile Display with 3 modules.

The actuation of the Degree of Freedom β is a novel feature in the architecture of tactile interfaces. In fact, currently there are no similar devices able to control the local curvature.

4.2. Design of the module

The positioning of the control point on the transversal plane (X-Y), as shown in Fig. 5, is provided by the planar articulated system, which is obtained by actuating the element *Arm1* and *Arm2*. The third displacement needed to place the control point in a specific position is provided by a translational system obtained by means of a rack-pinion system. With regards to the rotation in charge of controlling the torsion, the upper end of the element *Arm2* is equipped with a tilting system, which allows the rotation needed. It is controlled by a twisting servo by means of a four-bar linkage. Inside the tilting system, there is a frame that hosts the tangency servomotor. This servo controls the rotation of the contact element between the module and the strip. It is equipped with two miniaturized bearings, which enable the sector to slide on the strip. This feature allows us to dynamically change the distance between the control points. In this manner, it is possible to place each control sector in a specific point by selecting the best position for each trajectory. On the upper side of the contact element there

are two ultra-thin plates, which guide the tangency of the strip in the correct direction. The position of the bearings is adjustable in order to allow us to use strips of different thickness.

To test the real performance of the designed device, a prototype (Fig. 6) made up of three modules has been built. To obtain an isotactic system, the central module was not to be equipped with sliding sector but with a component that does not allow the strip to slide. To develop this component, the bearings are substituted with miniaturized profiles that prevent the longitudinal sliding of the strip. According to the functional process previously shown in Fig. 3 the 3D CAD model is imported and analysed by the developed software for the surface data analysis. The user can choose the position and the orientation of the cutting plane to obtain the trajectory that the strip has to represent. Once the trajectory is defined, the user can choose the position of the central point, which is the fixed one of the device. In the meanwhile, the software manages the position of the other control points and the intervals to place them. The limits of the intervals have been defined in order to prevent the collision between two adjoined modules and they are based on the length of the strip. Moreover, it is also possible to manually define the value of these intervals by selecting a constant value. After that, the software will verify if these ranges respect the conditions needed

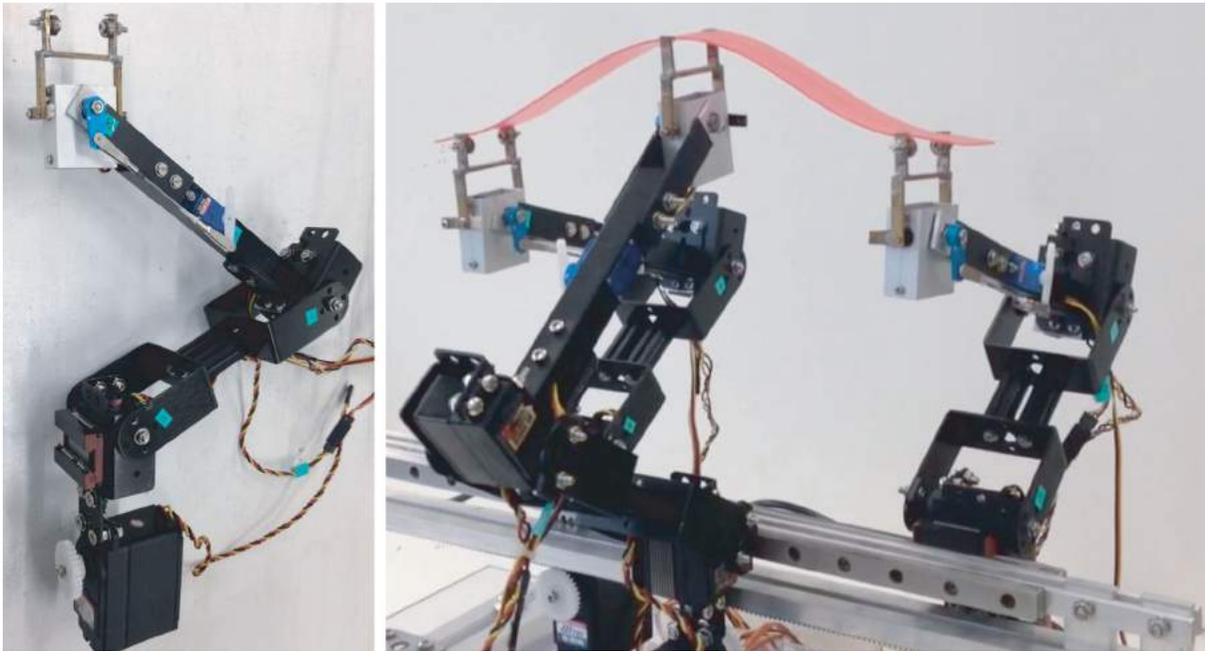


Figure 6. The prototype of the Tactile Display.

for avoiding the collision and related to the length of the strip. Once the intervals and placement of the control points have been determined, it is possible to perform a functional analysis that allows us to identify the presence of:

- Inflection points;
- Relative minimum point;
- Relative maximum point;
- High values of curvature variation.

These kinds of points are the best solution to place a control point in order to manage the rendered trajectory. Once the positions of the points are defined, it is possible to calculate the normal vectors to the surface in the

obtained points needed for the torsion and the tangency control.

By defining the position of each control point and by identifying the orientation of each relative normal vectors, it is possible to state that all the parameters needed to place and orientate each control sector in the space (X, Y, Z, θ and β) are available. Therefore, the position of the end effector of each module is defined. Through an inverse kinematic analysis, the developed control software calculates the angular position that each servomotor has to assume in order to perform the rendering. Then, each angular position is converted from an angular value to the appropriate millisecond value, which



Figure 7. Different configurations during the rendering process.

is obtained according to the RC PWM communication protocol, and it is sent to the 15 servomotors. Fig. 7 shows the prototype in four different configurations during the rendering process.

4.3. Discussion on the obtained results

As mentioned in Section 3, in order to obtain a system that allows designers to perform simultaneously tactile and visual evaluation of the digital models of the products they are designing, the authors have developed a system that is high performance, modular, portable and low cost. The following analysis compares the proposed system with the SATIN system in order to highlight the improvements obtained:

- Performances, number of control points and their distance:** The prototype has been developed by integrating three modules with direct actuation system. This is the minimum number of modules that are needed to control the deformation of the strip. Thanks to the modular configuration of the system, it is possible to add a higher number of modules. Actually, there is no maximum limit to the number of modules, since this value depends on the length of the longitudinal rail, which can be selected according to the kind of the surfaces to be rendered. The developed system allows the control sectors to slide on the strip. Thanks to this feature, it is possible to place the control sector in a given point of the trajectory, such as the maximum points, minimum points or inflexion points. This allows us to select in real-time the best configuration of the Tactile Display, according to the characteristics of each trajectory that has to be rendered. The modules can be organized with alternately disposition. Thanks to this feature, the distance between two adjoined control points only depends on the width of the upper extremity of the element *Arm2*. Therefore, the minimum value of the nominal distance between two control points is 35 mm.
- Performances, curvature radius:** The short distance between control sectors and the possibility of modifying this distance in real-time allow a minimum curvature radius of 30 mm to be obtained. This value corresponds to the resolution of the system, and allows users to render a large range of smooth surfaces.
- Modularity:** As explained, the minimum number of modules required to obtain a properly working interface is equal to three. Therefore, it is possible to adapt the length of the rail and the rank, required to perform the longitudinal translation, so as to obtain the space needed to increase the number of modules. In any case, the number of modules can be decided to increase with the aim of obtaining two

different results: increasing the length of the rendered trajectory or/and increasing the resolution of the system. Regarding the first case, increasing the rail length and the number of modules, and maintaining similar the nominal distance between the sectors allow an increase in the total length of the trajectory that can be rendered. Otherwise, maintaining the same rail length, while increasing the number of modules, implies that the nominal distance between the modules has to be reduced. This feature increases the resolution of the system.

- Portability and implementation costs:** The whole interface, which consists of the desktop station and the modules, has approximately the following dimensions: 500 mm of width, 350 mm of height and 400 mm of depth. Regarding the device weight, it is approximately 6 kg. All the modules can be easily removed from the rail so as to ensure safe and compact packaging. To use the interface on a common workstation it is sufficient to connect its power supply to the electricity grid, thus providing the system with power. Then, it is possible to connect the device to a PC/laptop by means of a USB cable. After that, it is possible to start the software, thus making the interface ready to work. All these characteristics ensure portability and the possibility to use the Tactile Display as a desktop device. With regards to the development costs, it is difficult to make an accurate estimation. All the elements have been built by using commercial profiles and commercial components. The material and components needed to develop the prototype have required less than 1.000 Euros. Therefore, it is possible to assume that the proposed solution is less expensive than similar devices developed in research Labs.

In order to analyse the improvement in terms of performances of the developed Tactile Display, it is useful to compare it with the SATIN system as shown in Tab. 2.

The main limitation of the developed system is its inability to represent trajectories with curvature radii

Table 2. Comparison between the SATIN system and the proposed solution.

	SATIN System	Proposed System
Dimensions of the whole system	L 2100 mm H 2600 mm D 1280 mm	L 500 mm H 350 mm D 400 mm
Number of control points of the tactile interface	9	≥ 3
Distance among the control points of tactile interface	90 mm	≥ 35 mm
Possibility to regulate in real time the distance among the control points	No	Yes
Reached radius by the tactile interface	185 mm	30 mm
Modularity	No	Yes
Portable	No	Yes
Implementation cost	High	Low

lower than 30 mm. However, considering the currently available tactile devices, which allow for a free hand and continuous surface exploration, the proposed system can be considered as a major improvement in terms of range of curvatures that can be rendered. Another limit of the developed system is the fact that it is not capable of representing discontinuity. Notwithstanding, it is worth mentioning that at the moment there are no free-hand shape displays that are able to represent discontinuity. Usually, this kind of evaluation is performed by using a point-based force feedback device. The representation of the shape of products by means of trajectories could be considered as a limit of the proposed solution. But it is important to keep in mind that the Tactile Display has been developed with the aim of supporting designers in a typical modality that they use for exploring and evaluating the quality of surfaces. Specifically, it has been observed that designers during the exploration of the shape of a product slide their hands along a trajectory. So, the limitation regarding the use of trajectories for shape rendering is not related to the operational principle, but to the modality implemented for selecting the appropriate cutting plane, which is the new starting reference point, required for obtaining the trajectory. Whenever the designer intends to change the trajectory to explore, he/she needs to select a new cutting plane. To overcome this limitation, it will be studied, as mentioned in Section 6 related to the future works, a solution based on the same operational principle proposed by the Tactile Display, but able to render spatial 3D surfaces.

5. Augmented reality visualization system

Augmented Reality (AR) visualization technologies have demonstrated to be effective in the development of applications for design review [8][12], since it allows evaluating 3D virtual models in a real context. This feature creates more realistic and engaging users interaction with the virtual models. Several devices can be used to provide AR visualization but surely the use of AR Head Mounted Display or glasses represents the most suitable solution for our system. The benefits of this visualization solution have been proven in several research works [13], and the authors themselves have developed and tested a specific visualization system for design review [4].

In the context of this research, a commercial AR visualization device has been used. The device is the Vuzix Wrap 920 AR [12], which is a AR Video See-Through glasses. Vuzix Wrap 920 AR consists of twin high-resolution 640×480 LCD displays and two VGA video cameras. The AR visualization is obtained by merging the video streams coming from the two cameras with the 3D virtual model representing the shape, which the user can touch by means of the tactile display. The two video streams were also used to allow the calculation of the relative position and orientation of the point of view of the user, the position of the virtual object and the position of the tactile display. In particular, a multi-marker tracking approach was used for this scope. Four markers have been fixed onto the tactile display. The position of these markers was defined in order to have always at least a marker visible during the user's interaction.

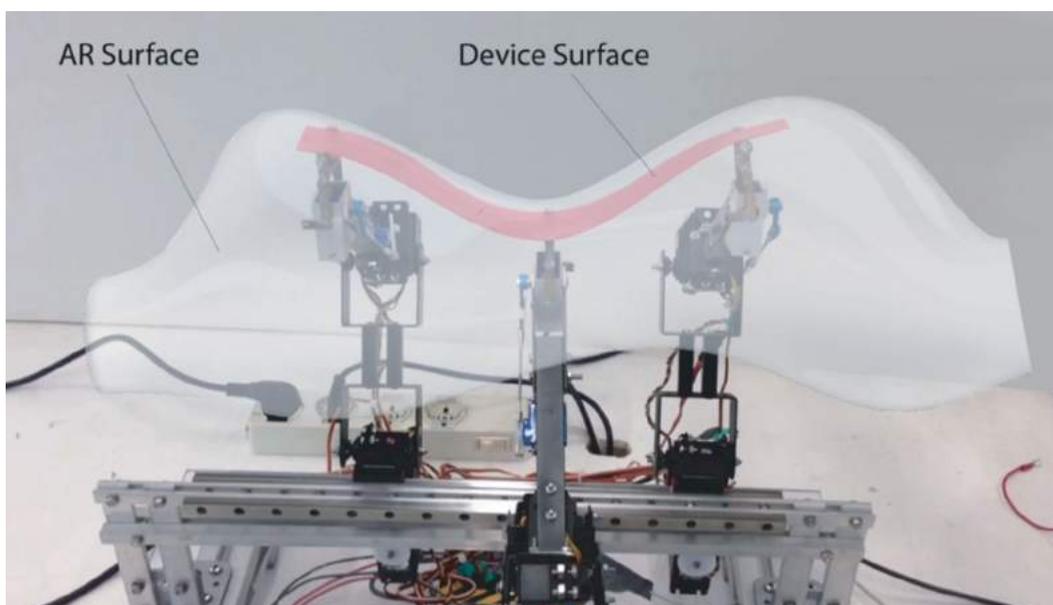


Figure 8. Augmented Reality visualization system.

In this way, the user constantly visualizes the 3D virtual model coherently with the tactile display (Fig. 8). The AR software application has been developed by using osgART [14], which is an open-source AR library, in order to maintain the low-cost feature, as required by the specifications of the system. The application manages both the visualization of the 3D virtual model and the tracking of the user's point of view.

The AR application is the first attempt to integrate AR visualization with the tactile display and several issues have to be solved. Firstly, the visualization of the 3D virtual model is always in foreground and the hand of the user is hidden. To reduce this effect the 3D virtual model is visualized transparently. In the future, this problem could be overcome by using an algorithm that recognizes the hand and automatically hides the part of the 3D virtual model. Other further implementations will aim at increasing the interactivity of the application, by enabling the user to change in real time shape parameters and the interaction area.

6. Conclusions

The aim of this research work was to design and develop a novel Tactile Display integrated with an Augmented Reality visualization system. The aim of this device is to allow designers to perform tactile evaluation of CAD models of the products they are developing directly during the shape-modeling phase. In this way, the designer will be able to change the shape of the model according to the tactile evaluation before the creation of the physical prototype. This feature would benefit the design process, since the number of prototypes to develop for testing the product concept would decrease, thus reducing, as a consequence, both cost and overall time needed for the whole product development process.

In order to obtain a strong improvement over currently available devices, the authors have designed a system that is *low cost* so as to be affordable for a large number of design studios, *desktop-based and portable* so as to be used in their everyday working life. In addition, the device is *modular* so as to be customized according to the kind of surfaces with which the designer and/or the design studio usually deals with, and *performance* in terms of the capability of representing a surface. In order to increase the usability of the device and specifically the relation between the visual and the tactile interaction, the Tactile Display is integrated with Augmented Reality technology, which allows the superimposition of a 3D visual representation of the digital model directly onto the tactile interface.

Making a comparison with the devices developed up to date, in particular with the SATIN system (as shown

in Tab. 2) it was observed that the designed tactile display presents better performance. All these results have been demonstrated by means of the development of the reliable and high performance tactile display, which allows the user to touch and feel the shapes. In general, all these features give the possibility of reducing the time needed in the design process.

In order to analyse the accuracy of the device, the authors will perform the evaluation of the maximum error between the virtual surface and the surface rendered by the device. Furthermore, a test session with users will be organized so as to evaluate the usability of the system and its effectiveness also from a perceptual point of view.

A possible line of investigation as future work could be to extend the representation domain of the device from the current 3D trajectories to full 3D surfaces. The idea is to develop a full-shape display based on a frame made up of four systems developed within this research work, which will have the aim of rendering the boundaries of a surface. The rendering of the internal part will be obtained by means of an innovative active structure based on a mesh of flexible elements. This solution could innovate the research in the field of surface rendering by allowing the rendering of virtual surfaces with high accuracy.

ORCID

Alessandro Mansutti  <http://orcid.org/0000-0002-9787-1464>

Monica Bordegoni  <http://orcid.org/0000-0001-9378-8295>

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