



Design of a Desktop Haptic System driven by CAD and Multi-body Systems Associativity

Mario Covarrubias¹ and Monica Bordegoni²

¹Politecnico di Milano, mario.covarrubias@polimi.it

²Politecnico di Milano, monica.bordegoni@polimi.it

ABSTRACT

This paper describes a Desktop Haptic System, which supports designers in the evaluation and modification of aesthetic virtual shapes. This System includes the advantages of using the associative data to both CAD and multi-body tools and thus maintaining the parametric dependencies between them. In this way, as the parametric data model gets modified according with the designer's needs in the CAD system, the changes are consistently reflected in the multi-body system. Modifications on the virtual shape can be done by using a global approach or by using a CAD drawing, then the data model in the multi-body system is used to render a real 2D cross-section of the aesthetic virtual shape through a Desktop Haptic Interface (DHI), which allows a free-hand interaction with the aesthetic virtual object. The DHI is linked to the multi-body system by means of using MATLAB and Simulink in order to control their servo-actuators. We also present the results of the validation process specifically carried out to evaluate the accuracy and the effectiveness of the DHI while rendering 2D cross-sections of a virtual shape.

Keywords: CAD associativity, multi-body interaction, desktop haptic system.

1. INTRODUCTION

During the development of new concept products, designers need to physically interact with the evolving shapes of the product they are designing so as to check and evaluate aesthetic features of the products. The satisfaction of this need requires the production of physical prototypes.

Although physical prototypes are a good means for product evaluation, they also show some limitations; for example, they do not allow variants of shape and material, nor they support easy shape modification and immediate correlation with the corresponding digital model. In addition, the production of the physical prototype is costly and time consuming, especially with respect to the other product design phases. In particular, for building a physical prototype a design engineer has to work with two or even more software tools for modeling and analysis at a time in order to check all the constraints applied throughout the engineering processes. In fact, there are several commercial CAD, CAE and multi-body software tools, which are widely used in the design industry.

Currently, a CAD tool provides the geometric model of the object to physically produce in standard formats such as STL, STEP or IGES, which can be used as input in CAE or/and in multi-body analysis tools. Some of the major problems associated with CAD-CAE and multi-body integration are information losses, breakdown of the parametric properties of the CAD model, loss of design expertise, difficulties in automation of the design process, and unacceptable time associated with the total design process [4].

The research described in this paper proposes a methodology for the design and evaluation of new aesthetic shapes that is based on the integration of digital modeling tools and a Desktop Haptic Interface (DHI), allowing designers to physically touch the shape. The method is based on CAD modeling and multi-body associativity between several commercial software tools in order to maintain the parametric constraints while the aesthetic shape is created; then through MATLAB/Simulink the DHI renders the 2D cross-section of the digital shape. The DHI allows a continuous and smooth free hand contact interaction

on a real and developable metallic strip, which is actuated by a servo-controlled mechanism.

The objective in designing the Desktop Haptic Interface is to reproduce a 2D cross-section with a consistent physical rendering. The desktop interface consists in a servo-actuated metallic strip that has been devised and implemented using seven interpolation points. In fact, by using the MEC (Minimal Energy Curve) Spline approach a 2D cross-section is rendered taking account of the CAD geometry of the digital shape. By using this device, the designer can control the design process according to the well-defined engineering concepts and technical drawings.

2. RELATED WORK

Considerable research has been done on CAD, CAE and multi-body integration and associativity in previous years. In [11] the problems associated with CAD and CAE interoperability are described while in [6] suggest the incorporation of feature-based modeling and analysis for CAD and CAE integration, including all geometric and non-geometric ones. In [12] is described an intelligent hybrid system to integrate various CAD, CAE and CAM tools in the design process using artificial neural networks, genetic algorithm into a single environment using the parametric approach for model generation.

However, their work did not investigate the automation mechanisms to reapply engineering constraints in the design process as for example, geometric features and distances constraints.

At the KAEMaRT group all the previous mechatronic devices related to the haptic strip have been developed in the context of the SATIN project [3]. The haptic interfaces, described in detail in our previous papers, consists of a plastic flexible strip that is held in space in front of the users using two Moog Haptic-Master systems [9]. This set-up allows for six degrees of freedom in the movement of the haptic strip. The haptic strip consists of a series of nine equidistant relative actuators, which allow it to actively shape itself in order to match the curve of the virtual object along a geodesic curve.

The strip is inspired by the deformable tape that designers use for creating and modifying aesthetic shapes. The first version of the haptic strip [1] has been developed with the main objective of just integrating the various mechanical components in order to validate the concept at the basis of the strip, which is related to the cutting plane metaphor. Subsequently, a higher performing version of the haptic strip [2,5] has been designed, with the aim of extending the domain of curves that can be haptically rendered. This second strip is capable of rendering geodesic trajectories in addition to planar ones. The mechanical configuration of both releases of the strip achieves a minimum-bending radius of 180 mm, which directly limits the total curves that the haptic

strip is able to represent. Obviously, the smaller the bending radius of the haptic strip, the higher is the domain of virtual shapes that is possible to render. In both configurations of the haptic strip (planar and geodesic), the device is able to reproduce curves that lie on the virtual object.

The SATIN system set-up in its entirety is not portable, and because of its relative expensive set of components only one prototype has been built. The main idea in the design and construction of the haptic device described in this paper consists in replicating the concept demonstrated in the SATIN system by using a desktop and portable mechatronic device

3. THE STYLE PRODUCT PROCESS

The first phase of the design of a new style product concerns the conception of the shape of the product, which is carried out by stylist and designers [13]. They have a shape in their mind, and translate this shape into a visible representation using various means: paper and pencil, physical mock-up, computer-based tools. Currently, the most effective way of representing the mental model of a shape is still the physical mock-up, since it well represents the object, which can be seen and also touched [10].

The main activities performed by designers during the conceptual phase of a new product are:

- Creation of a new shape,
- Evaluation of the shape and
- Modification if necessary.

However, the process of a new product design often follows a horizontal structure, which can be seen as a sequence of steps, if the new product is relatively simple to develop, but with continuous recall at the previous phases if the object is more complex to develop. In order to give some examples: if a tray will be developed (usually it is a simple object to understand and produce), the designer exactly knows the sequence of tasks in order to achieve the final product; but if is necessary to develop a handled vacuum cleaner (not very simple object to understand in terms of style, ergonomics and engineering) the proceed to produce it is well known, but the typical sequence of tasks cannot be used, because is necessary to merge some of them at different levels (i.e., the designer cannot think about a new shape without taking into account some standard engineering solution, and vice versa the engineer is free to work on styling aspects without the designer's approval). Therefore, when is required to work on a complex new project, it is also required to introduce several loops of iteration between all the actors involved in the process. The result is that the stylist must think back at the shape of the object, marketing must explore what the competitors are doing, and the engineer must think again what the best solution is, in terms of time and cost, in order to achieve

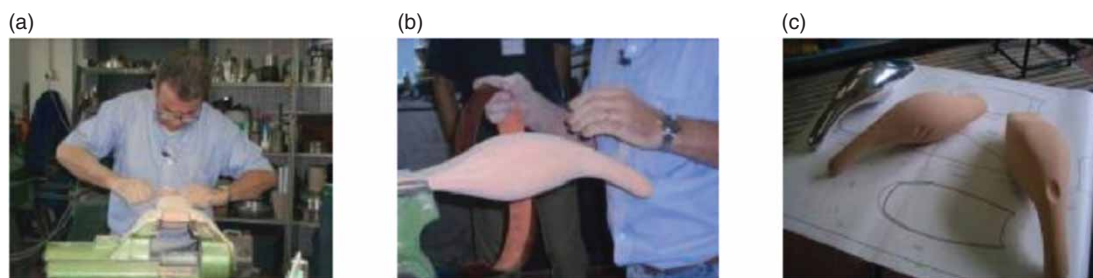


Fig. 1: Hand made prototyping (a) Sculpting, (b) Surface finishing through sand paper, (c) Final prototype.

the final product. Of course, there are a lot of tools at a different level in order to finalize a new product: rendering and graphics tools and CAS for styling, CAD for engineering, CNC for moulding and prototyping, Rapid Prototyping. However, still today there are many companies which use a hand made model, built directly by the stylist, usually in malleable materials and low quality of execution (this sample just aims at showing us the design intent of the product), or built by a modeler, usually in rigid resin and high quality of execution. In this case the modeler generally has to understand through not very accurate sketches what the stylist really wants. Figure 1 shows a modeler while produce a hand made prototype. During the physical modeling process, modelers and designers work together. The modelers modify by hand the physical model by adding and sculpting out material. They can be working on big surfaces like the bonnet of the car or on smaller parts like the door handle. For modifying the model, modelers can use different materials and tools; each material needs to be prepared and modeled with a specific tool. The shape can be evaluated from an aesthetic point of view and also by touching the surfaces. Although starting from a predefined concept, this technique allows the stylist/modeler to modify his model while he is working the material with hands.

This direct interaction that the designer, modeler or stylist have with physical interaction is not available within computer-based design tools whose interfaces are based on traditional interaction paradigms (based on mouse and keyboard), then limiting their possibility of exploiting their creativity and manual skills. Additionally, this way to produce physical models is usually more expensive than rapid prototyping, both in terms of time and people involved to prepare all the materials needed, like drawings, sections, dimensions, etc. The activity to produce 2D drawing (performed by CAS/CAD users) is always skipped when from the 3D model, the prototypes are directly printed by rapid prototyping machine. Furthermore, the hand-made prototyping approach makes the whole process more expensive, due to the necessity of putting in the design process the reverse engineering activity and makes a new 3D model suitable for the engineering steps. The idea of proposing the Desktop Haptic System, which supports designers in the evaluation and modification of aesthetic virtual

shapes, takes advantage of the combination and integration of commercial software, which are used to control the whole system. This set of software tools provide the user with an efficient approach for designing test, measurement, and control. It can also be seamlessly connected to equipment such as the DMX Servo-12 controller board that is used as the interface between the computer and the servo actuators. The desktop haptic device performs as the human interface module, through which people can feel the corresponding virtual shape. The selected software both permit full user control of model geometry, inertial properties, have extensive libraries of existing dynamic elements for modeling constraints, allow the user to construct complex constraint equations and allow the user to input complex forcing functions.

4. THE CONCEPT USING THE MINIMAL ENERGY CURVE (MEC) SPLINE APPROACH

The basic concept in using the Desktop Haptic Interface is related to mimic (in an approximate way) the evaluation process of shape features in a physical prototype. Figure 2-a shows a case study concerning the real vacuum cleaner and the tape attached on its surface mimicking this approach. In fact, in the intersection of the virtual cutting plane with the virtual object there is a 2-D cross-section curve as can be seen in Figure 2-b. A portion of this 2-D cross-section curve is the target curve on which the tape will be located. The physical strip represented by the blue line is blended as a MEC Spline in which several interpolation points have been used (Figure 2-c).

In order to better approximate the virtual 2D cross-section with the real tape, we decided to use the Minimal Energy Curve (MEC) Spline interpolation approach to control the mechatronic device. This approach simplifies the conformation of the real strip on the virtual one. In practice, the physical tape is able to approximate the shape of the virtual objects surface by adopting the shape of a MEC spline, which passes through a set of several interpolation points. The main idea behind the MEC Spline Interpolation is based on the designers' tool used to draw several and smooth curves through a number of interpolation points. It is important to notice that the distance between the interpolation points is the same only

when the strip is flat. Once the strip is bended as a MEC spline the distance between the interpolation points change in order to reach the virtual shape.

4.1. Quantity and Distances of the Interpolation Points

A porcupine curvature analysis has been performed taking 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 porcupine analysis has been done with a parameter of density equal to 30. With this parameter, the shape curve has been divided in various equally spaced segments. Five different radii have been used in this analysis (80, 100, 120, 140 and 160 mm) in order to render a convex and a concave shape with the same radius. For each single radius value, the interpolation point distance has been modified from 45 mm to 25 mm. These distances have been assigned while the strip is in nominal position (completely flat). In total, for each curve we have measured the radius curvature value for the 30 points. We decided to perform several analyses changing also the number of interpolation points in which the tape is bended firstly by using three interpolation points, then by using five and finally by using seven interpolation points. We can conclude that the number of IP's and the distance between them have an important influence factor on the curvature radius error on the extremities of the spline. A second conclusion on this analysis suggests

the use of at least seven interpolation points in order to have an 'ideal zone' of curve representation. Having 5 interpolation points instead of seven reduces the number of servo-motors required to bend the physical strip. In fact, if 7 interpolation points are used for the spline, six servo-motors will be required to bend the strip. Conversely, if 5 interpolation points are used for the spline, only four servo-motors will be required. The position of the interpolation points changes based on the geometry of the virtual object. The interpolation points require to be correctly positioned while in contact with the virtual surface. The algorithm that drives this continual computation of contact location is based on the control of the seven interpolation points using the MEC Spline approach. Figure 3 shows the concept of the transmission system of the device; Figure 3-a shows the instant in which a concave surface is performed.

Figure 3-b shows the instant in which a convex surface is reached. As required for the MEC Spline approach, the device guarantees not only rotation, but also provides a slot constraint in order to allow a free conformation by the strip while reaching the virtual shapes. In other words, the strip is passing through a sequence of constraints, each of which rotates freely and allows the strip to slide freely through it. Note that the spline segments between the interpolation points are not equally separated while reaching the virtual shapes. The interpolation point 1 (IP1) is linked to the ground through a revolute joint constraint. Actuators 2 and 3 (A2 and A3) are also fixed to the ground allowing the absolute

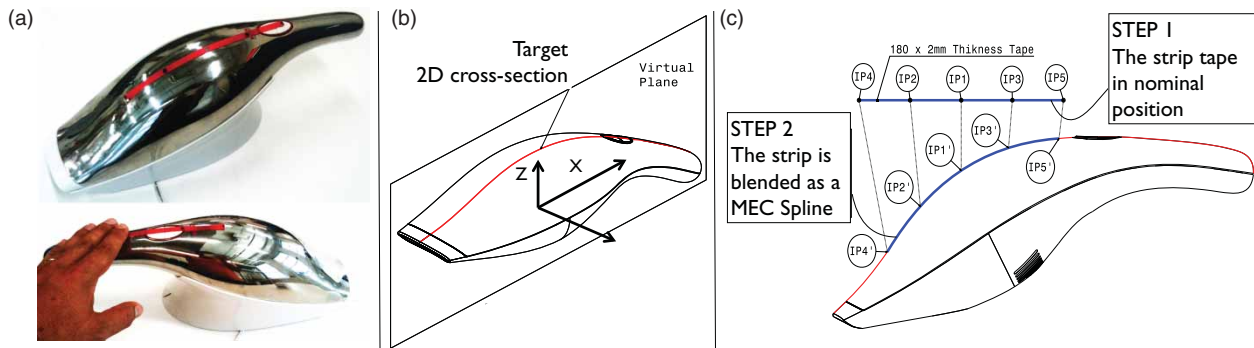


Fig. 2: The concept (a) Physical Vacuum Cleaner, (b) A target curve, and (c) The 2D cross-section process in which the tape is bended as a MEC spline.

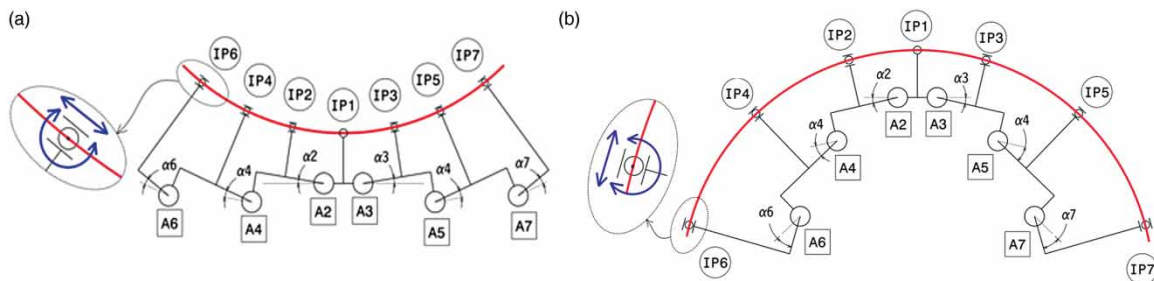


Fig. 3: Transmission System (a) While reaching a concave shape and (b) While reaching a convex shape.

approach in the transmission system. A2 through the proposed array of elements is responsible to rotate (while rotates α_2) the IP2, and then A4 is linked to A2 allowing the relative transmission required to locate IP4 through α_4 and so on. We have performed several simulations with MSC.VisualNastran 4D in order to test the influence of different parameters in the curvature radius of the final spline. These parameters are directly related to the best fitting of the ideal curve the number of interpolation points and the distance between them.

5. ARCHITECTURE OF THE SYSTEM

The positioning system and the desktop haptic interface (DHI) are part of the desktop haptic system conceived for the evaluation and the modification of digital prototypes. Actually, the interaction modality provided by the desktop strip permits the inspection and exploration by touching the physical strip while the modification of the virtual object is performed through the CAD software.

The Desktop Haptic System involves multiple hardware and software tools and is divided into two main devices. The first is related to the servo-controlled haptic interface, which renders a physical 2D cross-section. The second device regards the use of a positioning system, which carries on the servo-controlled haptic interface. The following hardware has been used:

1. Three servo-actuators to control the positioning system, each with its controller plugged to the multi-body software tool.
2. The strip and its servos are plugged to an embedded system controller, which is connected to the multi-body software tool using a serial interface (RS-232 port). In fact, the strip uses six servo-actuators in order to bend the strip according to the CAD geometry and using the Minimal Energy Curve (MEC) spline approach.

6. DESKTOP HAPTIC INTERFACE POSITIONING SYSTEM

According with the user's needs, the DHI is moved on the virtual shape through the positioning system.

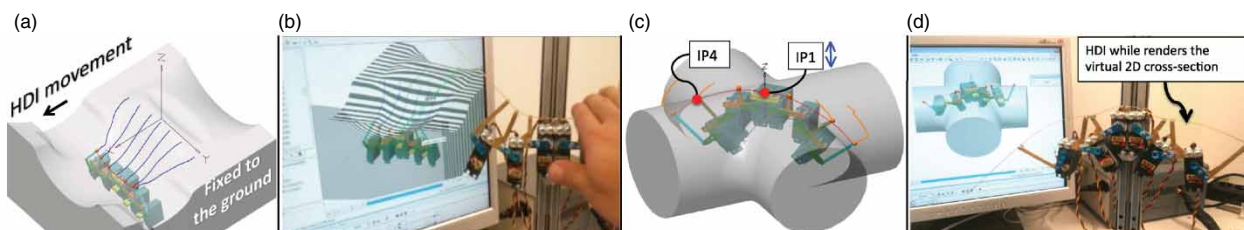


Fig. 4: User interaction with the system. (a) The haptic interface while moving along “X” axis, (b) User’s hand while touching the strip, (c) The 3D object while rotating around “Z” Axis and (d) The haptic interface while rendering the 2D cross-section.

In fact, the positioning system includes a 3-DOF platform and a combination of virtual DOF’s, which are linked to both, the DHI and the 3D model. The workspace of the positioning system includes consideration of regions of limited accessibility where the physical 3-DOF platform itself may experience movement limitations. The user interaction is performed by the positioning system through several sliders depending on the modality adopted.

The Desktop Haptic System provides the following modalities:

1. **Moving the DHI on the 3D Object:** In this positioning modality, the user moves the DHI on the virtual shape through a physical 3-DOF platform. In fact, when this modality is enabled, the 3D model is linked to the ground, completely fixed and the user can move the DHI through three servo-actuators. In this way, the DHI is located on the 3D model according to the user’s needs as can be seen from Figures 4-a and 4-b. It is important to notice, that, while the DHI is moving to the new position, at the same time the 2D cross-section process is enabled allowing the strip to render its shape.
2. **Moving the 3D Object:** This positioning modality allows the user to move the virtual object through a virtual platform, which is also used to increase the working volume that is limited by the physical 3-DOF platform. Figures 4-c and 4-d shows an instant of the simulation in which the user moves the 3D object instead of moving the DHI. In this modality, the DHI remains linked to the ground through a rigid joint on slot constraint and the translation on the vertical axis is driven by central interpolation point (IP1).

The advantages of using the positioning system are:

1. It allows placing the haptic strip in any realistic location and orientation in the users workspace.
2. It allows rotating the 3D model according to the user’s requirements.

- It keeps open the option of actively moving the Desktop Haptic Strip to display a larger working volume than the metallic strip's own length.

7. 2D PHYSICAL RENDERING PROCESS

This section presents the motivations underlying the conceptual development of the Desktop Haptic Interface and its control through commercial CAD and multi-body tools. The 2D physical rendering process is arranged in such a manner that its flexibility follows the conventional, integrated and parametric design product process. The entire 2D physical rendering process takes place in several stages as can be seen from Figure 5. It begins with the 3D model and the technical drawing construction (step 1), in which, the user models the 3D object by means of using any commercial software (Autodesk Inventor, Pro/Engineer, Solid Edge, SolidWorks, etc.), then the model is directly imported into the multi-body tool.

The CAD Integration simulation and control (step 2), in which the dynamic modeling with the multi-body software is extended, also includes the control system with the integration of Simulink. The multi-body software is used to construct the dynamic model, while Simulink is used to design the control system. A multi-body library is inserted as a block (vNPlant) into the Simulink model, allowing feedback between the control system and the dynamic model.

Then, the 3rd step shows the integration with the Desktop Haptic Interface (DHI), whose main objective is to reproduce a 2D Cross-Section of a 3D model, allowing a continuous and smooth free hand contact. The relationships obtained preserve the identities of the CAD components and the corresponding imported components of the multi-body simulation system. The multi-body exporter defines these unique identities from the CAD assembly components and embeds them in the exported model i.e. STEP, STL or IGES formats.

In the 4th step of the methodology, if the user's evaluation of the 2D cross-section through the DHI is positive the 3D final shape is ready (step 5). If not, the user is able to perform some modifications (step 6) by using the technical drawing or by using a

global approach. The link between the CAD software with the multi-body software allows the possibility to maintain the parametric constraints assigned by the user in the creation of the 3D model. If a modification is required, the user is able to perform the change in the CAD software (step 7). This modification is automatically incorporated into the multi-body motion simulation (step 2). In this way, the Desktop Haptic Interface renders the new 2D cross-section (step 3) and the user is able to evaluate with the hand its physical shape.

7.1. CAD, Multi-body Associativity and Physical Rendering Process

The multi-body models generated from its exporter retain the associativity. In fact, this associativity is a mapping between the parts and their constraints in the CAD assembly and the corresponding body and joint blocks, coordinate systems, and subassemblies in the multi-body system generated from the CAD assembly. In other words, it captures the identities of the CAD components through their topology. However, this associativity is not completely symmetric between the CAD and the multi-body system, because the translation process moves in only one direction, from the CAD system to the generated multi-body model. If the designer requires modifying some data in the main model i.e. a parametric distance, by updating the model in the CAD system allows reusing an existing multi-body model previously translated from the same CAD assembly. The updates do not disturb the existence and identity of the multi-body model components corresponding to the original CAD assembly components.

For proofing the CAD and Multi-body associativity concept, a case study was chosen to design an aesthetic shape. Figure 6-a shows the parametric dimensions of the aesthetic shape and Figure 6-b shows the multi-body system with Matlab/Simulink and the rendering physical 2D cross-section process through the Desktop Haptic Strip. At this stage of the methodology, the user is able to feel with the hand the physical strip, which represents the 2D cross-section of the virtual object.

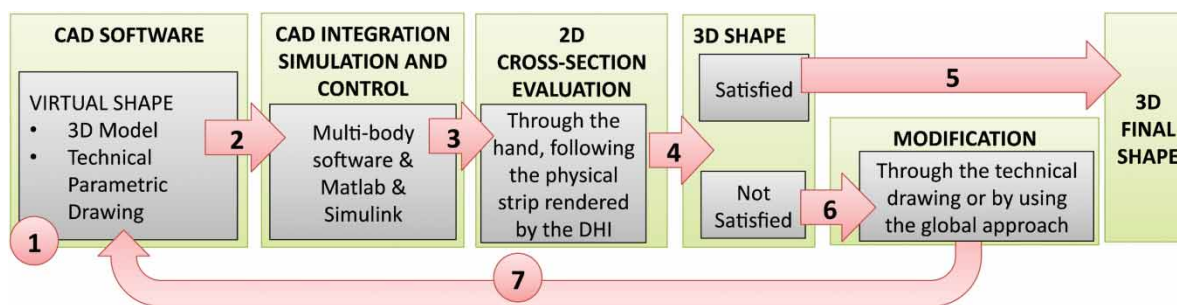


Fig. 5: Methodology to include the Desktop Haptic Interface in the Style Product Design Process.

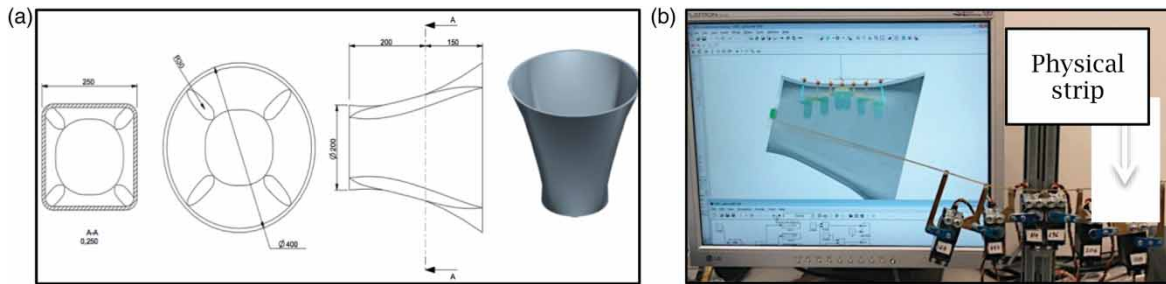


Fig. 6: CAD and multi-body associativity a) Technical drawing, b) Multi-body system with Matlab/Simulink and the rendering physical 2D cross-section process through the DHI.

8. EXPLORATION OF THE VIRTUAL OBJECT THROUGH THE PHYSICAL STRIP

With this modality the DHI remains static allowing a stable evaluation of the virtual curve represented by the physical strip. Lets consider the case in which the user has positioned the DHI as can be seen from Figure 7-a, by means of using the positioning system. Once this position is reached, the user is able to feel the shape of the virtual object using the dominant hand. This operation is performed in the same way than in the real world.

Figure 7-b shows the case in which the haptic strip has been rotated on the 'Z' axis; during this operation, the DHI is also rendering the new shape in real-time. Figure 7-c shows the real user's hand while exploring a concave shape.

8.1. 2D Cross-section Validation

This section presents the evaluation of the haptic desktop interface whose aim is to reach rigorous, valid and practical conclusions about the accuracy of

the device. In our research we have been interested in two main aspects. The first was related to evaluate the haptic desktop interface in terms of accuracy while represents a 2D cross-section; the second was to re-design the device and provide guidelines for the design of future devices by using the evaluation results.

Three different curves of the vacuum cleaner have been rendered and measured in order to know the accuracy error in terms of millimeters. The measurement process has been performed using the Konica Minolta 3D scanner [8] device, which has an accuracy of 50 μm enabling 3D measurements. These data have been exported into STL format in order to compare it with the CAD surfaces.

Figure 8-a shows the position of the three target curves. Figure 8-b shows both, the Desktop Haptic Strip while rendering this curve and the multi-body system, which is connected with Matlab/Simulink. Figures 8-c and 8-d show the physical rendering process performed by the Desktop Haptic Interface while rendering the Spline B and the Spline C respectively.

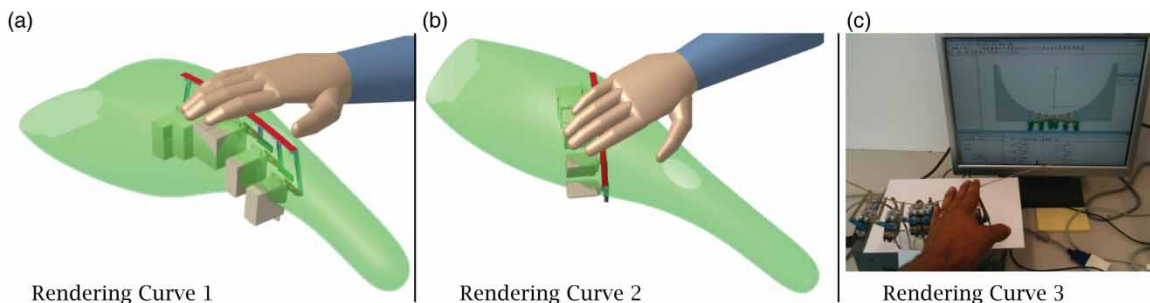


Fig. 7: Different target curves during exploration.

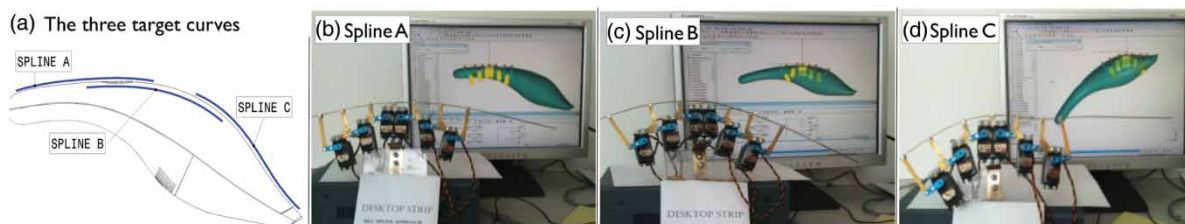


Fig. 8: Experimental setup for the accuracy validation. a) The target curves, physical rendering process for the b) target Spline A, c) target Spline B and d) target Spline C.

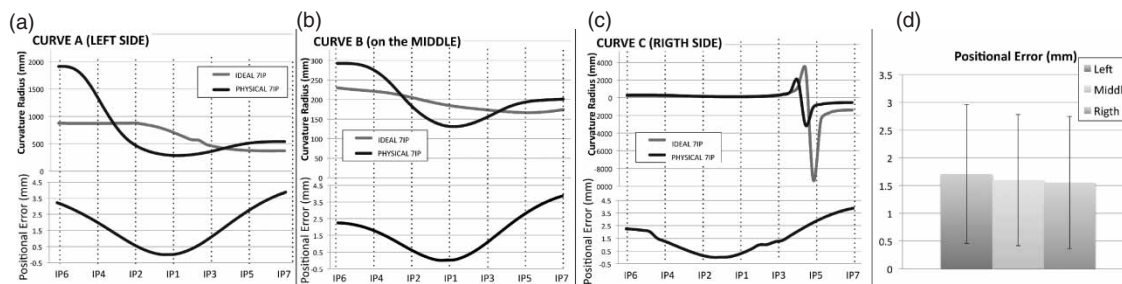


Fig. 9: Accuracy validation results.

Figure 9 shows in detail the error in terms of millimeters reported for each position on the three different 2D cross-sections that have been rendered. It is also reported the measurement results, according with the minimal distance between the position of each interpolation point that lies on the real strip and the curve of the virtual object. It can be noticed that the simulation and the measurements are quite close and that the higher discrepancy between the real strip and the 2D cross-section relies on the extremities.

This is most probably because with the physical strip is not possible to control the tangency in the extremities through the interpolations points 6 and 7. However, the errors are quite consistent and the worst-case error reports an average of 2 mm. The accuracy offered by the device is good enough according to [7]; their results showed that the minimum variation in the radius necessary to make the subjects able to detect a discontinuity in the surface curvature was roughly a variation of 25% of the base radius.

9. MODIFICATION MODALITIES

Modifications on the virtual shape can be performed by using a global approach or by using a CAD drawing, and then the new data model in the multi-body system is used to render a real 2D cross-section of the aesthetic virtual shape through the Desktop Haptic Interface (DHI).

9.1. Modification through a Technical Drawing

A technical drawing is used in order to maintain all the parametric features of the 3D model. Obviously,

if a modification is performed, the result is reached once the user updates the model option link that is located in the drawing system. Each modification takes only a couple of seconds for the updating process, from the CAD modification up to the multi-body system. Then, through Matlab and Simulink the 2D cross-section rendering process begins. Figure 10-a shows the instant in which the parametric distance between the second and third sections has been modified (from 150 to 300 mm). Figure 10-b shows the user's hand while exploring the new physical shape. Figure 10-c shows the modification of the third section's diameter, from 400 to 600 mm with its physical rendering process.

By adopting this step in the methodology the user has an easy and immediate way of seeing and evaluating the modifications up to have the final 3D shape. These features could improve the quality of modelers' work and the collaboration between the modeler and the designer.

9.2. Global Modification

The global modification refers to changes to the overall object by means of using a mesh in which the grid points are used to modify the global shape of the 3D object as can be seen from Figures 11-a and 11-b. In typical interactive mesh editing, the user first selects the region to be modified, and then the vertices to be used as the manipulation tool. When the user drags the positions of the vertices on the screen, the 3D object is deformed according to the users requirements. Then, the DHI renders the 2D cross-section (Figure 11-c). In this way, the designer

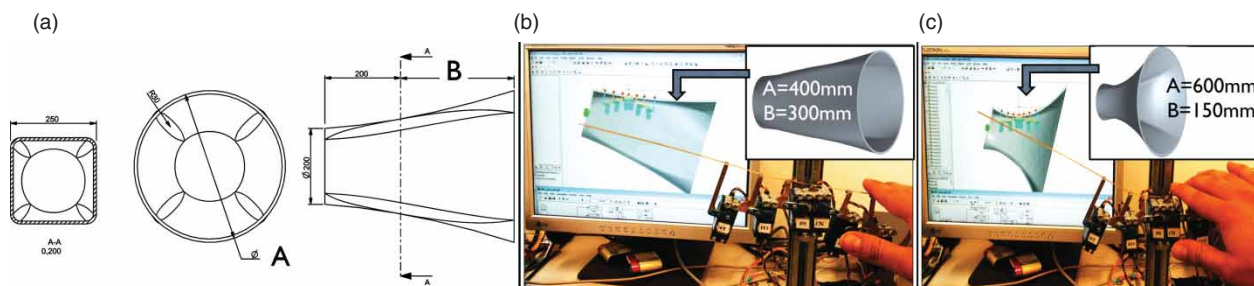


Fig. 10: Modification modality through a technical drawing.

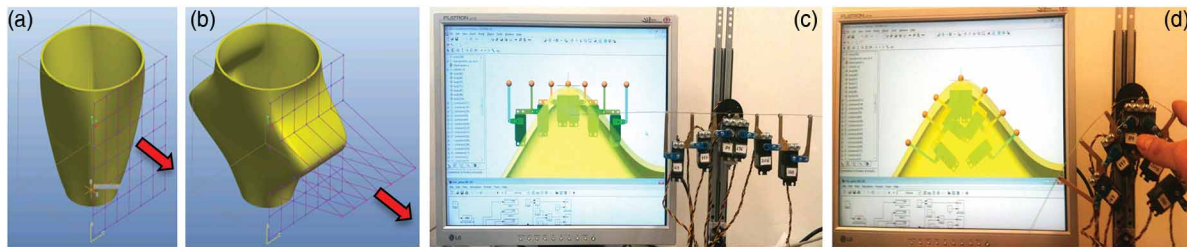


Fig. 11: Modification modality through a global approach. a) and b) Global modification using the CAD software tool, c) The multi-body interface and the DHI in nominal position and d) The DHI while reaching the 3D shape and the user's hand while exploring the metallic strip.

has an immediate feedback about the modified shape (Figure 11-d).

As in the modification option, which is driven by a technical drawing, in the global modification modality, the result is also reached once the user updates the model option link that is located in the CAD system. In this way, these modifications are directly updated to the multi-body system and finally through the Desktop Haptic Interface the new 2D cross-section is rendered.

10. CONCLUSIONS

In this paper we have presented a successful methodology to physical render a 2D cross section of a virtual object. The methodology and the Desktop Haptic Interface that we propose here reduce the number of physical prototypes during the design process and shrink the design time by allowing the evaluation and modification of the product shape and surface earlier. On the other hand, our system allows designers to perform several phases of the product design process (concept, modeling, visual and physical evaluation and modification) continuously and without any interruption. In this way, the system permits to rapidly evaluate the 3D shape variants until reaching the optimum model.

REFERENCES

- [1] Bordegoni, M.; Ferrise, F.; Covarrubias, M.; Antolini, M.: A linear haptic interface for the evaluation of shapes, in ASME 2009 International Design Engineering Technical Conferences (IDETC) and Computers and Information in Engineering Conference (CIE) San Diego, CA, USA, 2009.
- [2] Bordegoni, M.; Ferrise, F.; Covarrubias, M.; Antolini, M.: Geodesic spline interface for haptic curve rendering, IEEE Transactions on Haptics, 4(2), 2011, 111-121. <http://dx.doi.org/10.1109/TOH.2011.1>
- [3] Bordegoni, M.; Ferrise, F.; Covarrubias, M.; Antolini, M.: Haptic and sound interface for shape rendering, Presence: Teleoperators and Virtual Environments, 19(4), 2010, 341-363. [doi:http://dx.doi.org/10.1162/PRES_a_00010](http://dx.doi.org/10.1162/PRES_a_00010)
- [4] Cao, B.-W.; Chen, J.-J.; Huang, Z.-G.; Zheng, Y.: CAD/CAE integration framework with layered software architecture, in Proc. of 11th IEEE International Conference on Computer-Aided Design and Computer Graphics, Huangshan, pp. 410-415, China, 2009.
- [5] Cugini, U.; Bordegoni, M.; Covarrubias, M.; Antolini, M.: Geodesic haptic device for surface rendering. Joint Virtual Reality Conference of EGVE - ICAT - EuroVR (2009), 2009.
- [6] Deng, Y.-M.; Britton, G.A.; Lam, Y. C.; Tor, S.B.; Ma, Y. -S.: A feature-based CAD-CAE integration model for injection molded product design, International Journal of Production Research, 40(15), 2002, 3737-3750. <http://dx.doi.org/10.1080/00207540210141643>
- [7] Gatti, E.; Re, G.; Ferrise, F.; Bordegoni, M.: Curvature Discontinuities Discrimination During Dynamic Exploration of Surfaces, 27th Annual Meeting of the International Society for Psychophysics in Herzliya, Fechner Day, Israel, October 24th-27th 2011.
- [8] Konica Minolta Sensing Americas, Inc., <http://sensing.konicaminolta.us/applications/3d-scanners>, accessed 25 January 2013.
- [9] Lammertse, P.; Frederiksen, E.; Ruiters, B.: hapticmaster, a new high-performance haptic interface, in Proceedings of Eurohaptics 2002, Edinburgh, UK, 2002.
- [10] Lawson, B.: How Designers Think, Fourth Edition: The Design Process Demystified, 4th Edition. Architectural Press, London, 2005.
- [11] Peak, R.S.: Characterizing fine-grained associativity gaps: a preliminary study of CAD-CAE model interoperability, in Proc. of the ASME Design Engineering Technical Conference, 1A, 2003, 573-580.
- [12] Su, D.Z.; Wakelam, M.: Intelligent hybrid system for integration in design and manufacture, Journal of Materials Processing Technology, 76(1-3), 1998, 23-28. [http://dx.doi.org/10.1016/S0924-0136\(97\)00310-5](http://dx.doi.org/10.1016/S0924-0136(97)00310-5)
- [13] Ulrich, K.; Eppinger, S.: Product Design and Development. McGraw-Hill, New York, 2008.