Designer-Centered Haptic Interfaces for Shape Modeling

Monica Bordegoni and Umberto Cugini

Politecnico di Milano, Dipartimento di Meccanica,
Via G. La Masa 34, 20158 Milano, Italy
{monica.bordegoni,umberto.cugini}@polimi.it

Abstract. This paper presents some results of a research project aiming at developing haptic tools for virtual shape modeling resembling the real tools like rakes and sandpaper used by modelers and designers in the real workshop. The developed system consists of a CAS (Computer Aided Styling) system enhanced with intuitive designer-oriented interaction tools and modalities. The system requirements have been defined on the basis of the observation of designers during their daily work and translating the way they model shapes using hands and craft tools into specifications for the modeling system based on haptic tools. The haptic tool and the interaction modality developed for exploring and sanding a surface is presented in the paper.

Keywords: Haptic interfaces, designer-centered user interface, 3D interaction techniques, shape modeling.

1 Introduction

The conceptual design phase of new products having aesthetic value presents several critical issues that contribute in making the overall design process costly and time consuming. Two main practices are used for representing concepts of new products: hand-made prototypes and 3D digital models. Hand-made prototypes are created by skilled modelers by modeling malleable materials with their hands, and/or using very basic tools [1]. This practice is expensive and requires long time of execution. Besides, some reverse engineering techniques are required for building the digital model of the physical prototype for subsequent manufacturing activities. The other practice consists of designers making digital models using CAS (Computer Aided Styling) or CAD (Computer Aided Design) tools. In general, designers consider these tools too technical, and lacking intuitive user interfaces. Furthermore, there is the subsequent necessity to physically build the prototype for evaluating the most important qualities of the model: aspects such as proportions and quality of surface are evaluated by observing and touching the object. In order to create physical prototypes, some expensive and time consuming rapid prototyping or milling techniques are used, which needs 3D digital models as starting point.

The idea of bridging physical and virtual modeling by maintaining the effective and performing aspects of digital modeling and enriching tools with some new modalities of interaction more oriented to exploiting designers' skills is at the basis of the

research work described in this paper. The research activities have been carried out in the context of the research project T'nD - Touch and Design (www.kaemart.it/touch-and-design) funded by the FP6-IST Programme of the European Union. The project intends to define free-form shape modeling tools based on novel haptic interaction techniques that can be easily used by designers in their activity for incrementing their performances, and by modelers who are able to preserve their manual skillfulness and at the same time be integrated into the digital process for the development of new industrial design products [2].

The paper presents the novel shape modeling system developed within the context of the T'nD project. The system is based on a designer-cantered approach, is friendly and intuitive to use for designers, and couples the effective functionalities of current CAS tools with user friendly modalities which allow designers to make use of ways of working and tools similar to the ones used in the real workshop.

Section 2 presents the users' requirements defined on the basis of observing designers' ways of working. Section 3 describes the overall architecture and components of the developed shape modeling system based on 3D haptic tools, and section 4 describes the sanding tool used for shape refinement and exploration. Finally, Section 5 includes conclusions and a discussion about future development activities.

2 Users' Requirements

In order to achieve the goal of proposing an intuitive and easy-to-use shape modeling system, the research activity supported by the cognitive psychologists involved in the project has focused on the observation and analysis of modelers' activities performed in the real workshop [3]. The intention was to gather information about the different modeling techniques used by modelers and designers at work, their gestures, the used tools, and the modalities used for checking the quality and characteristics of the in-progress models. Therefore, practices and hand modeling activities performed by modelers of the project industrial partners (working in the car design and domestic appliances design sectors) have been observed and analyzed. During some study case sessions modelers have been asked to create the physical model of an object using different techniques, in order to gather information about the various approaches used in relation to different materials and tasks: some modelers were asked to create a hand-hold vacuum cleaner using hard resin, other modelers were asked to make the same object using foam material and clay.

Video recordings of the modeling sessions have been tabulated in a process chart, including: timing, duration of events, activities and tools, and target of the actions. Subsequently, a quantitative analysis of gestures for each session (characterized by the kind of material used, the modelers' or designers' skills, the expected level of accuracy and the overall complexity of the mock-up) has been performed. Finally, main gestures have been selected and described on the basis of qualitative and quantitative information, such as: aim and modus operandi of the tool, tool movements, hands movements, shape evaluation tasks, similarity with other tools, etc.

Concerning the gestures performed by the modeler, they are influenced by several factors. We can identify two main types of gestures: ergotic gesture which is performed by the modeler when working on the shape, and exploratory gesture which is

performed for evaluating the quality of the shape. The analysis of ergotic gestures also provides hints about how the tools are used. Conversely, exploratory gestures occurred without the use of any tools.

2.1 Ergotic Gestures and Tools

The analysis of the recorded modeling sessions have highlighted that approximately 75% of the object modeling actions are done using five tools. In order to define which tools are more effective and useful than others, we have decided to classify the tools on the basis of the comparison of the total time of usage, and the number of times they were used. In fact, we noticed that if a tool was used for a longer time, it did not necessarily demonstrate its importance.

Concerning the tools, we can state that the movement performed for scraping material is representative enough of most of the gestures families occurring during the process. This type of action is rather qualitative, and we can affirm that the same gesture is used both for shaping and finishing a surface, and is also used either for large surfaces or for details. Concerning the type of tools, rakes are used for removing thick layers of material, while sandpaper is used for finishing the surface and eliminating small defects. Both hands are often used in order to work with strength and accuracy. A single stroke allows obtaining a wide curved surface, instead of a number of small flat surfaces, which have to be refined further.

2.2 Exploratory Gestures

After working the piece of material with the tools, the modeler had the necessity to check whether the physical mock-up had the expected proportions and quality of shape. Different approaches were used for assessing the correctness of the work regarding the various aspects. For example, modelers checked the object dimensions and the profile and the curvature continuity through the use of both vision and touch. These evaluations depended on the expected level of accuracy, on the scale and size of the mock-ups, and on the strategy used by the modeler. For instance, in the case of car design, the expected level of accuracy was very high: several measurements were done, many marks were placed on the mock-up, and the outcome dimensional precision of the mock-up was in the order of tenth of millimeters. According to our observations, the most commonly used validation modalities were based on the use of touch and surface contact. These validations occurred during the sculpting activities as well as during the finishing activities and affected an average of 5% of the whole object modeling time. They were used to test the final shape (sculpting steps), and to ensure the obtaining of high quality surface (finishing steps).

Concerning tactile verifications, they were carried out in different ways, and each of them had different goals. Rapid sweeps on surface appeared often while sculpting or finishing the mock-up and more particularly when the modeler had to remove dust. This action carries information not exactly about the precise curvature of the shape, but rather about the detection of irregularities or variations on the curvature. For example, a bump or a hole can be detected very quickly. Thus, a curvature variation is detected and not the curvature itself; this method allows to detect features otherwise unrecognizable just by visual observation.

Another method is based on long sweep performed along the surface, that are iterative movements, back and forth or from side to side, through which the modeler gets information about curvature variations more than curvatures themselves. In addition, a long sweep movement was performed with both hands encompassing the mock-up; it was used for exploring the symmetry of the mock-up. The information was slowly and hardly treated, and it was necessary to repeat this movement several times in order to integrate the information acquired in the various steps more precisely.

It has to be pointed out that the work was made all the time under visual control and that the very first and intuitive way to check shape was through its visual observation. For doing this, the modeler stopped working and started observing the mock-up. In this way two aspects were mainly observed: the object curvatures and its symmetry. The mock-up cannot be evaluated in a global way that is all its aspects at the same time. Therefore, the modeler generally performs local checks. The user holds the mock-up at the eyes level, orients it in order to observe the contour only, and turns it to observe different aspects sequentially. Another common technique is based on the use of the reflection lines of light and shading, which has been extensively simulated in computer aided design systems.

In conclusion, tactile and kinesthetic inputs seem to complete visual information, still ambiguous about the three dimensions, and help to construct a more precise 3D mental representation of the concept [4].

2.3 Analysis and Conclusions

The gestures and tools analysis has shown that the most common actions are scraping, surface quality check and finishing actions, and the related tool, which are respectively: rakes, hands and sandpaper. Figure 1 shows some typical actions performed by modelers and tools used during the manual modeling sessions.

The results of this study have been used for designing and developing the interaction modalities and tools of the system.

Fig. 1. Typical actions performed by modelers while modeling objects manually, and related tools

3 Shape Modeling System Based on 3d Haptic Tools

The design and development of the innovative modeling system developed within the context of the research has started with the definition of its requirements. From a human-computer interaction and usability perspective, the system intended to provide

haptic tools and modeling operators for scraping and finishing surfaces which support a way of working for users which is very much similar to the one used in their daily physical work. Therefore, the system should allow users to generate digital shapes using a CAS tool integrated with interaction devices and modalities which are similar to the ones supported by rakes and sandpaper tools used for modeling and finishing the object surfaces in real life.

Therefore, in order to satisfy the requirements, the system consists of the integration of haptic interfaces into a digital design tool. Haptic technology supports the possibility of touching virtual objects and perceiving their physical properties [5]. In this way besides the usual visual perception of the object, a kinesthetic knowledge of the object can also be achieved defining a more comprehensive perception of it.

The analysis of the state of the art of technology available showed that an extended version of the FCS-HapticMaster (www.moog-fcs.com/robotics) haptic technology would have been the most appropriate hardware solution for the implementation of the system [6]. In fact, the device provides an adequate workspace and rendered force (250 N), appropriate stiffness and supports from 3 to 4 degrees of freedom (DOF). The FCS-HapticMaster technology has been used as basic platform for the system development, equipped with a strong and stiff 6 DOF device carrying simulated modeling tools.

Fig. 2. Haptic modeling workstation set-up

The haptic modeling workstation consists of several hardware and software modules [7]. They include commercially available components and custom components that have been developed as part of the research project. Figure 2 depicts the hardware

configuration of the system. The visible components are two FCS-HapticMasters (A, B) complete with their controller boxes (1, 2) and mounting hardware (3, 4), a suspended display (5) with its mounting rack (6) and a computer workstation (7). The configuration of the system is based on the use of two FCS-HapticMasters (A, B) as each device does not provide a sufficient number of DOFs useful for supporting the simulation of the movement and of the exertion of reaction forces as required by the scraping and sanding tools.

Ad-hoc end-effectors meeting the application specifications have been developed. Users' activities that the project aims to simulate include scraping a piece of clay, check the surface quality and sand the surface. Therefore, two tools have been developed: scraping tool for material removal, and the sanding tool for surface quality check and surface finishing operations. The configuration of the haptic system is such that the two tools can be easily replaced so that the user can switch between the various actions he intends to perform. The application must also change its behavior accordingly by switching between different operational modes. The end-effector shown in the picture is the scraping tool (8). The second end-effector for surface finishing has been developed and is described in details in the following section.

4 Haptic Tool for Exploring and Sanding a Shape

As previously said, the system was expected to provide a tool for checking the surface quality and sanding the surface. Therefore, a sanding system has been developed consisting of a sanding tool that allows the simulation of a piece of sandpaper, where the curvature actually follows the curvature of the virtual surface to be sanded. Since the device is new, it required psychophysical research into the difference perceived between a single curvature ("cylindrical" curvature) piece of paper, or a double curvature ("spherical" or "saddle" curvature) piece of paper which would in practice have to wrinkle in real life. It is considered that even an interface which would only have plane motion and single curvature would yield important information on the degree of fidelity needed to convincingly emulate the feeling of actually sanding a virtual surface. Even such a simple setup would allow experiments with completely virtual experiences with tools not available or indeed possible, in real life, such as adding instead of removing material by virtual sanding. The rotational workspace of the tool is the same as that of the human hand. It is usually limited to $\pm 30^\circ$ in fore-aft tilt relative to the human arm, but the freedom in roll is at least 120° , and in fact more than that if the extra roll at the elbow joint of the human arm is taken into account. In order to accurately and realistically representing the surface shape, the implementation of the sandpaper tool supports double curvature.

4.1 Hand Interface for Rendering the Surface Curvature

Surface curvature can be rendered to the human hand by presenting the proper alignment of the surface at all places of contact between the hand and the surface. Conceptually, the surface can be subdivided into patches for some or all fingers or groups of fingers, and the palm of the hand (Figure 3 a). This gives great flexibility in the type of surface curvature to render, and the maximum deflections possible. However, it

would imply that every patch needs actuation in depth, and possibly also in two degrees of rotational freedom. Since it was our aim to present surfaces of G2 (geometric curvature continuity) complexity only, it has been decided to create an interface which is itself a contiguous surface of exactly this complexity. This will typically take the form shown in Figure 3 b, with the number of degrees of freedom discussed in the following.

Fig. 3. a) Surface curvature rendering. b) DOF representation of surface curvature interface.

A piece of sandpaper, or rather the underlying surface of the work piece contacted, has curvature in addition to orientation. Our system is limited to the G2 curvature, which is the degree of "roundness" of the surface, similar to the second derivative of a curved line on a flat surface. From mathematical theory, we know that the curvature has three degrees of freedom:

- Orientation of the first principal direction.
- Curvature in the first principal direction.
- Curvature in the second principal direction, which is at right angles to the first.

The user will move the surface patch over the virtual surface, when exploring or virtually sanding a surface. It has been noticed that in most of the cases it is sufficient to continuously adapt the G2 curvature of the patch symmetrically, to the local curvature of the surface under exploration, instead of providing higher derivatives. If the hand is relatively large in relation to the radii of curvature of the surface under exploration, and if the curvature of the surface is changing rapidly, then human users may well extract a cue about the nature of the surface, from the longitudinal changing of the curvature under the moving hand, i.e. by feeling the traveling bumps passing under the hand. Emulating this moving curvature would require higher orders of derivatives of the surface than G2, starting with the third derivative. Third derivatives indicate a linearly changing G2 curvature, if nonzero in a certain direction. Actuating certain third derivatives would allow users to feel how they are approaching and passing corners first feeling the increase of the curvature under the hand when approaching the corner, then feeling the symmetry of the curvature when at the most curved point of the corner, and then feeling the decreasing curvature under the patch when moving away from the high point of the corner.

The hardware device consists of a structure that is covered by a tactile patch. The patch is supported and controlled from the centre, where the G0 location, G1 attitude

orientation and G2 curvature of the patch are defined. The tool is based on a ting structure consisting of a plane structure based on semi-stiff radial ribs placed at 120° intervals, forced by the actuators to the desired cross-sections of the surface to the desired curves, and with the webs between the radial ribs filled in by some form of semi-stiff concentric webbing. The resulting structure looks like an umbrella. The important difference to a foil umbrella is that the area between the radial ribs will be stiffened by circular elements. These need to be fairly stiff in out of plane bending, but at the same time variable in length to accommodate the compression and stretching of these concentric perimeter curves. Figure 4 shows a closer look of the device, complete with the custom elastic surface that was made from thin plastic sheet. The numbers in the figure identify the components of the device. In particular, the picture shows the following main components:

- flexible spokes made of harmonic steel. There are three spokes spaced at 120° degrees from each other (number 1);
- guy wires used to transform the traction force exerted by the servo motors via the nylon cables, into a torque (number 2);
- the elastic surface, driven by the flexible spokes (number 5);
- hexagonal stud that serves as the base component supporting all the other components (number 6).

Fig. 4. Detailed view of the sanding tool device structure

This combination of stiffness can be achieved by making the rings out of sheet material such as stiff paper or plastic, placed on end to give out of plane bending stiffness, and folded into a zig-zag or concertina pattern to accommodate length changes. The resulting rings look like a cookie cutter, or like certain table placemats (Figure 5 a). Depending on the coarseness of the webbing of the supporting structure, the final surface is smoothed to the touch. The tool has a smooth, stretching surface. This consists of a number of layers of lycra pre-stretched to avoid wrinkling when "compressed". The number of layers and the thickness of the material can be adapted to the smoothness required. The system computes information about the surface curvature according to the haptic tool position. This information is used for shaping the tool according to the surface curvature (Figure 6 b).

Fig. 5. a) Views of the sanding tool device without the cover; b) area explored using the sanding tool

The sanding tool is easily manipulated by the user as it was a real piece of sandpaper. The user is free to move and rotate the tool around the three axes in order to feel the surface curvature of the object. When the user moves the hand the device deforms according to the surface curvature (Figure 6 b). The same device is used for adding material to a shape by means of an inflating operator. When the system is operating in this modality, the user exerts some forces over the surface, and a proportional layer of material is added.

Fig. 6. a) T'nD system equipped with the sanding tool; b) The sanding tool device deforms according to the surface curvature

For what concerns the evaluation of the sanding tool, the users who tried the system reported that the force feedback provided by the device was good. The current device allows the perception of convex shapes with a minimum radius. The perception of these types of shapes is good. Additional research activities are required for

extending the application to a broader range of surfaces. The evaluation of the inflating operation reported that the users appreciated the fact that at the end of the modification action the overall quality of the modified surface was always guaranteed and maintained.

5 Conclusions

The paper has presented the results of the research project T'nD funded by the European Union. The paper has described the motivations that justify the project, the objectives and relevance of the research topics in the industrial design sector, the requirements collected by interviewing and observing designers at work, and the analysis performed for designing the system. Furthermore, the paper has presented the achieved results that consist in the identification of the system functionalities resembling ways of operating of designers and modelers, in the study and implementation of the haptic tools. In particular, the paper has presented the haptic tool developed for exploring and sanding a surface. The tools have been tested by end users who have reported easiness of use, fidelity of the force feedback provided. The perception about the effectiveness of the system was quite positive, despite the fact that the kinds of surfaces that can be rendered are currently limited. One of the major problems concerning the system usability reported in the users' tests is related to the lack of co-location of the haptic and visual perceptive spaces. In this sense, a better visualization system, based on stereo viewing, would certainly improve the overall users' perception, and consequently the system usability aspects.

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