DESIGN PRODUCTS WITH YOUR HANDS

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Abstract: The paper presents the initial results of a research project aiming at developing a shape modelling system that take advantage from both virtual and physical prototypes oriented to conceptual design of industrial design products. The system allows designers to easily create, modify and evaluate shapes of products by interacting with a virtual model through a haptic tool operated with their hands, as well as they do in reality using physical craft tools. Differently from hand-made prototyping techniques used in reality, the system allows users to obtain at the end of the modelling phase a digital model of the product that can be directly used in the downstream phases of the product development process.

Key words: product design, virtual prototyping, haptics, shape modelling, hand-made prototyping.

1- Introduction

The product design phase is today well supported by CAS (Computer Aided Styling) and CAID (Computer Aided Industrial Design) tools that allow designers to produce and release digital descriptions of products that are re-used in subsequent product development phases. In recent years, several tools supporting virtual validation and simulation of products have been developed [1]. The spreading of these tools has been also supported by increasingly powerful hardware enabling the execution of complex simulations. The practice based on digital product generation and simulation is named "virtual prototyping".

Virtual Prototyping is becoming a commonly adopted design and validation practice. Compared to physical prototypes, *virtual prototypes* are in general less expensive, allow for not one but several simulation runs on a single model, are easily configurable and support variants. Furthermore, tests are repeatable, and results of validation are often immediately available for product design review. One can say that virtual prototypes often provide insights that physical testing would not reveal. Anyway, if digital prototyping does not completely substitute physical tests, they help optimizing and eliminating redundancy in test facilities, accelerating life testing, etc.

Virtual Prototyping mainly focus in the late concept phases and engineering analysis phases of the product development process. The industrial design sector – mainly focusing on early concept phases- is still characterized by physical prototypes extensively used for creating and testing the conceptual design of new products [2, 3]. That is due to two main reasons. First, modelers are used to test product characteristics like shape, surface continuity, etc. by physically touching a real object with their hands. Second, they find CAS/CAD tools too technical, too oriented to users skilled in engineering, and therefore they privilege physical prototypes to virtual ones [4].

The paper presents the results of the research project T'nD – Touch and Design (www.kaemart.it/touch-and-design) that aims at bridging the gap between physical and real, by developing a system that allows the generation of digital shapes in a natural and intuitive way for the modelers by manipulating haptic tools that closely resemble the physical tools they use in everyday work. The project is financially supported by FP6 IST Programme of the European Union. It is coordinated by Politecnico di Milano (expert in shape modeling, haptics and system integration), and involves two technology providers think3 (provider of shape modeling technology) and FCS-CS (provider of HapticMaster system), two academic partners Universitè Aix-Marseille I (expert in cognitive ergonomics) and Universitat de Girona (expert in product design sector), and three end-users Pininfarina (end-user operating in car design sector), Alessi and Eiger (end-users operating in the domestic appliances and household articles design sector).

Section 2 of the paper describes typical types of design processes in the industrial design sector, pointing out critical aspects and problems.

Section 3 presents the conceptual characteristics of a new system developed for integrating the benefits coming from virtual and physical prototypes. The system specification starts from the analysis of hand-made prototyping practice and human hand-skill. The section also discusses the improvement expected for the product design process when using the new system.

Section 4 presents an overview of the system architecture, its functionalities and the study of the haptic tools resembling the real ones used by modelers.

Finally, section 5 draws some conclusions on achievements and future developments.

2- Product Design Process in Industrial Design

In order to understand how to innovate and improve the performance of the product design process in the industrial design sector, current practices adopted by the industrial partners of the T'nD project have been analyzed. The design processes have been described collecting information, existing documents, and through interviews to the end-user partners of the project that represent two industrial sectors (automotive and domestic appliances) and are of different industrial dimensions (large, medium and small). The analysis of the collected information has highlighted a list of issues that need to be addressed in order to improve the performances of the whole design process.

2.1 – Typical Product Design Process

The information collection and interviews done to end-users have pointed out three types of product design processes (As-Is processes) that are typical of the industrial design sectors. More details about process modeling and analysis carried out are reported in [5].

2.1.1 – As-Is Process 1

Three users are involved in the process (Figure 1): designer/stylist, modeler and engineer. The designer produces sketches, 2D renderings and 2D technical drawings for describing his ideas. After a comparative analysis and evaluation, a few of them are selected and given to the modeler who makes physical models (PM) by interpreting the sketches content. PMs are made with different malleable materials (clay, foam, or other) according to the type of product and the company practice. Each physical model is then given back to the designer/stylist for evaluation and validation. The designer might require some modifications that are communicated to the modeler using informal and not codified descriptions. The number of loops required for product style improvements might be several. The physical model is accepted by the designer when it reflects at best his initial design intent. At this point, the physical model is passed to the engineer for producing the CAD model. This last activity is frequently performed using Reverse Engineering (RE) techniques that allow the reconstruction of the object shape, or at least of the main shape features of the object (styling curves). The RE model is an approximate polygonal model that require to be further elaborated in order to obtain high quality CAD surfaces (usually NURBS) required by downstream product design phases. Once the high quality virtual model is ready, it has to be tested in respect to initial designers' ideas regarding the product. This is often done by making a physical prototype of the virtual model using some Rapid Prototyping (RP) techniques (stereolitography, LOM, multi jet printing, etc.) or CNC techniques, which allow designers to evaluate and check the final representation of the product [1]. It is often the case that the RP model is very close to the initial designer's intent. However, if there are modifications requested by the designer, these are not formally described with reference to the RP model, and have to be implemented into the CAD model, and tested again. This is a very critical step that at the moment has not be given optimal and consolidated solutions. The output of the overall process is a CAD model that has been validated and finally accepted by the designer.

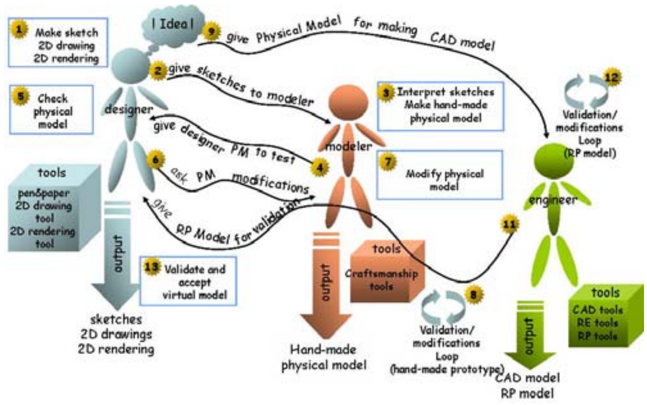

Figure 1 – As-Is process based on hand-made prototypes made by a modeler and evaluated by a designer.

2.1.2 –As-Is Process 2

Two users are involved in the process (Figure 2): designer/stylist and engineer. The designer produces sketches, 2D renderings, 2D technical drawings and also physical models for describing his ideas. The physical models are directly evaluated and modified if necessary by the designer himself in order to satisfy at best the design concepts. Once the physical model is accepted, it is passed to the engineer for producing the CAD model, and the subsequent activities are the same of the *As-Is Process 1* previously described. Also in this case, the output of the overall activity is a CAD model that is validated and accepted by the designer.

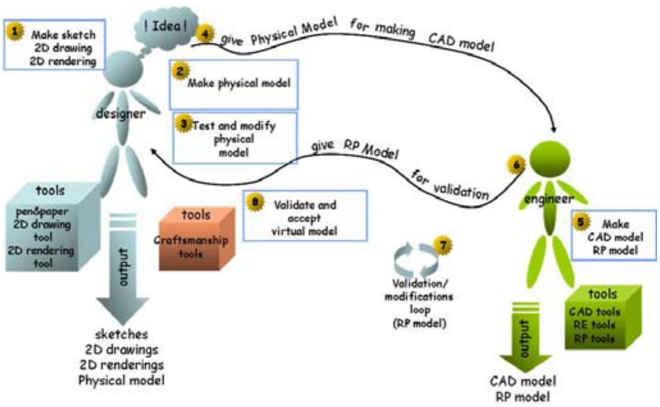

Figure 2 – As-Is process based on hand-made prototype made and evaluated by the designer.

2.1.3 – As-Is Process 3

Two users are involved in the process (Figure 3): designer/stylist and engineer. The designer produces sketches, 2D renderings and 2D technical drawings for describing his ideas. In addition, he produces a digital model (virtual model) representing the product using a CAS or CAID tool. Some variants of the product may be directly evaluated through the 3D virtual model. Once the model satisfies the design concepts, it is passed to the engineer for detailing. RP techniques are used for producing PMs used for validating the product design. As in the previous cases, the output of the overall activity is a CAD model that is validated and accepted by the designer.

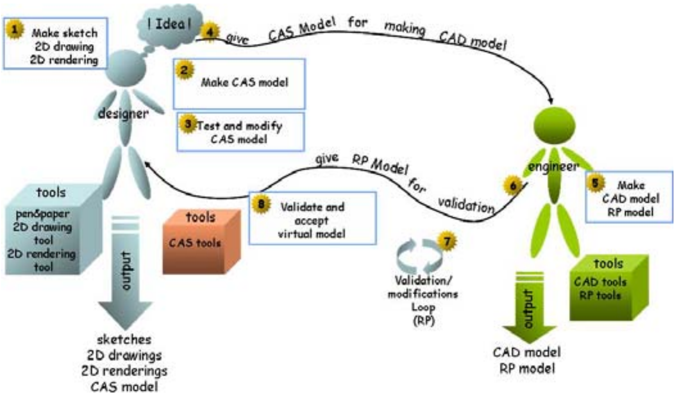

Figure 3 – As-Is process based on virtual model.

2.2 – Critical aspects of the processes

The analysis of end-users' processes and the evaluation of their performances points out that the third process is more efficient than the other two. This is mainly due to the fact that it is efficient having a digital model resulting from the conceptual phase of product design ready to use in the product development downstream phases, and a larger number of solutions may be evaluated.

However, also this process has some critical points. For example, since designers interact with digital models, they have not the possibility to fully evaluate the design intent, since some aspects (like ergonomics and usability aspects, as well as styling aspects) still require physical models to be properly addressed. Besides, some physical prototypes are in any case requested by designers at the end of the conceptual design process, in order to evaluate the full correspondence of 3D product representations with the initial design intent, since they are not able to check this aspect through the 3D virtual model.

In summary, the following major issues, which require to be addressed and improved have been identified in the three As-Is processes:

- The designer makes several sketches and technical drawings representing his product concepts, but for economical reasons only a few are selected for physical prototyping and subsequent product development activities.
- There is a cognitive load in the modeling activities performed by modelers since they have to interpret the designers' sketches that most of the times are incomplete, ambiguous, and vague for making physical prototypes. These activities are often subject to errors and misunderstandings that require interactions and several subsequent modifications.
- Requests made by designers to modelers for styling modifications to implement onto the physical prototype are difficult to communicate, and are expressed in an informal and not codified way. Therefore, modification loops for style improvement might be several, and the iterations often cause delays, since the evaluation and modification activities are performed by different actors, at different times.
- Several CAS/CAID tools use "mesh" representations that are low quality, and require to be translated into high quality surfaces used by CAD tools. Surface reconstruction is often critical and produces errors and inaccuracy in the final representation of the surface.
- Not many designers are used to, or are willing to use CAS/CAID modeling for representing their ideas since they are not intuitive to use and far from their way of operating.
- After the engineer details CAD models starting from RE or CAS/CAID digital models, the designer has to check the CAD resulting model in respect to the initial product concepts. This activity is often done by producing additional physical prototypes (often using RP techniques), which are given to the designer for testing. Again, requests for styling modifications are difficult to communicate, and are expressed in an informal and not codified way. Besides, practices for importing and implementing requests for shape modifications into the digital model are not consolidated yet, and often require the use of RE techniques.

3- A new paradigm: Virtual Hand-made Prototyping

In order to improve the design process performances, and to involve to a greater extent the designers in the digital modelling since the early conceptual phase of the product design, a possible solution is an innovative design environment that integrates the benefits coming from the use of physical prototypes (possibility to evaluate the conceptual representation of the product using hands) and those coming from the use of virtual prototypes (quick modifications and re-use, digital models ready to use in product development downstream activities). The solution proposed by this research work consists of a system based on the concept of *virtual hand-made prototyping*. The system is meant to take advantage of hand-made prototyping practice, and human hand skills. This practice and way of working are at the basis of the interaction interface supported by the system, which replicates the physical hand contact with objects in the virtual world by means of haptic interaction modalities. Differently from other research works related to haptic modelling and virtual clay modelling [6, 7, 8], the aim of this work is to develop haptic interaction and modeling modalities that are dedicated and specified and evaluated by designers. For this reason, the first activity of the project has concerned the analysis of typical hand-made modelling practices.

3.1 – Hand-made prototyping

The design process analysis has shown that the hand modeling practice is still frequently used in the initial conceptual phases of the product design [2, 3]. Cognitive psychologists participating to the research project have observed and analyzed the modelers' activities and skills while creating physical prototypes using their hands. Modelers of industrial partners of the project have been video recorded and interviewed while creating physical models of some selected objects (a vacuum cleaner and a car C-pillar) by working malleable materials (like clay, foam, etc.) with their hands. Subsequently, the collected data have been quantitatively and qualitatively analyzed in order to understand the advantages derived by using hands when creating shapes, and to capture the modelers' knowledge and skills. The analysis of the acquired data has produced the identification and classification of the tools used (manual tools and machine tools) and of the gestures and hand motions performed (for shaping the object, for feeling the surface quality).

The analysis of hand gestures has highlighted the fact that visual, tactile and kinesthetic feedbacks are equally important in the shape creation and evaluation process. The skilled hand motions performed by the modelers allow for a precise creation of the shape; the tactile interaction with the object helps in comparing adequacy of the physical prototype with the drawings, in providing early clues about shape features, and in improving the 3D mental representation of the shape. From this analysis we have pointed out the most recurrent, common and effective users' hand operations. These are the actions that are going to be reproduced in the system: *scraping, surface quality testing and finishing* (Figure 4).

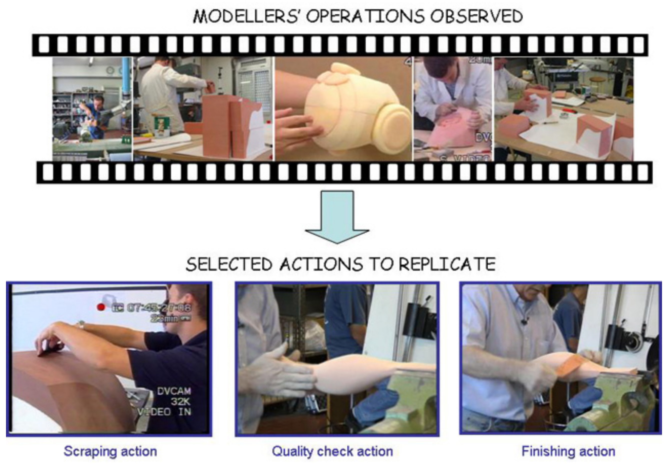

Figure 4 – Observation of modelers' operations and selection of actions to reproduce into the system.

3.2 – Haptic tools for virtual prototyping

The interaction modalities suitable for the system require to provide an environment and a set of tools for modeling object surfaces by removing material from an initial shape, and for finishing the surface and testing its quality by hand. The sense of touch in virtual environments is provided by haptic devices [9, 10].

There are very few haptic systems developed for sculpting virtual shapes. At the moment, the most popular is FreeForm by SensAble (www.sensable.com). Using the system, users can see and feel the shape of the product they model, and can also have a feeling of the type of material they are molding (clay, foam material, hard material, etc.). This system simulates a spherical sculptor's tool used to remove or add "matter" from/onto an initial block of matter. Its major limit is that the high aesthetic quality level required by several industrial design sectors (like, the car industry or high-end customer products) –named class A surfaces- is not reached since the spherical tools provided by the system are not sufficient for complex models. This technique is anyway promising and it would be interesting combining this innovative user interface with a more aesthetic intent driven process.

Since the objective of the T'nD project is to create an interface that allows designers to interact haptically and graphically with virtual models of products including a true size car body, purely point-based haptic interaction that is provided by most of the haptic devices is not sufficient to appreciate and modify the surfaces in an intuitive way. Designers wish to interact either with the full hand, or with a virtual version of typical material modelling tools. Satisfactory full hand interfaces (haptic gloves) have not been built so far, despite a number of attempts and one commercial product (the Immersion CyberGlove). This is probably a bridge too far at the current state-of-the-art.

On the basis of an overview of haptic devices [11], also carried out within the project [12], the final conclusion is that an extended version of the FCS HapticMaster (www.fcs-robotics.com) is the most appropriate hardware solution for the project. In fact, the device provides an adequate workspace (66 litres) and rendered force (250 N). Currently, the device provides from 3 to 4-d.o.f. (degree of freedom). Within the context of the project, the FCS HapticMaster is planned to be used as basic platform, equipped with a strong and stiff 6 d.o.f. device carrying simulated clay modelling tools.

3.3 – Expected improvements of the design process

In order to overcome the problems of the design processes listed in § 2.2, a system satisfying the following requirements has been conceived. The system is expected to:

- be very intuitive and easily usable by designers;
- allow designers to create, modify and evaluate a shape using a display for seeing the product, and some haptic tools for touching it;
- provide shape modeling operators that are intuitive to use, and provide in output high quality surfaces (class-A surfaces) immediately re-usable within CAD tools.

The conceptual design process based on the use of the T'nD system is shown in Figure 5. The system is used by designers for creating, modifying and evaluating the product concept. They operate using vision and touch for creating shapes starting from initial ideas and concepts. The system generates models that are physical and digital (high quality surface). To note that in the proposed process physical models are always the results of virtual prototyping.

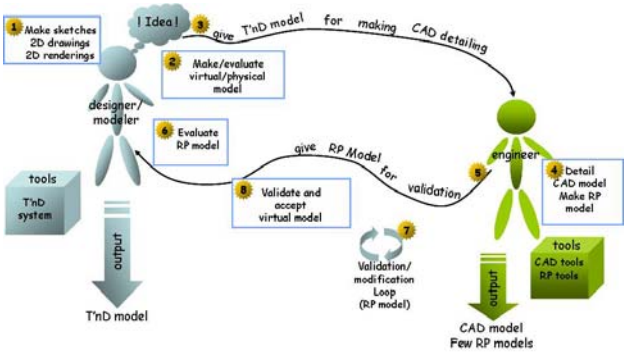

Figure 5 – Improved product design process using the T'nD system.

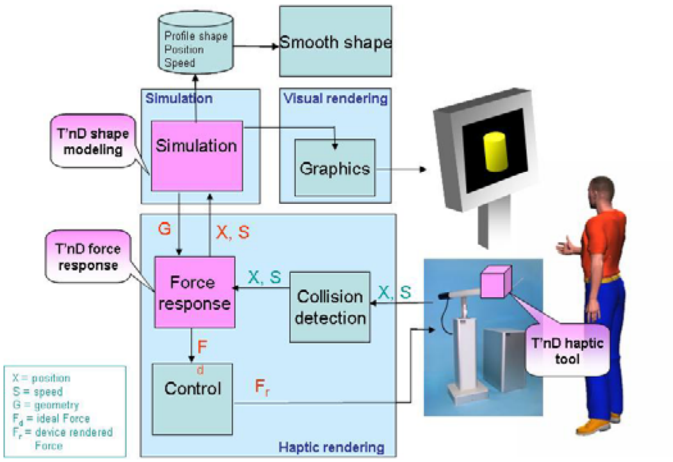

Figure 6 – System Architecture.

4 – T'nD system overview

The T'nD system is based on the use of haptic technology and interaction for replicating the physical tools used by modellers in real life for modeling malleable material. The following sections present the system architecture, the haptic tools designed and the shape modelling operators, and the implemented prototype.

4.1 – System architecture

The architecture of the system is shown in Figure 6. It consists of the following main components:

- The FCS HapticMaster is operated by the user. The device is going to be equipped with innovative haptic tools that are oriented to design and modeling operations. In response to the collision with the virtual object the device renders appropriate contact and reaction forces. The rendered forces depend on the type of collision and on the type of material being simulated.
- The haptic rendering system includes a collision detection module for detecting contacts between the virtual representation of haptic interface (avatar) at position X and the virtual object; a force response module that returns the interaction force between the avatar and the virtual object; and the control module that returns a contact force to the user (that is the ideal interaction force approximated to the haptic device capabilities).
- The simulation system updates the geometric and haptic model of the object on the basis of the shape, position and speed of the haptic tool. The simulation engine operates on a simplified geometry that is converted in a smooth shape at the end of the interactive session.

4.2 – Haptic tool for virtual modelling

The aim of the project is to create a dedicated virtual reality tool for interacting with virtual clay on car body models or any other shaped objects using such manual process. The newly designed haptic tool interface physically simulates one or more of the tools used in actual clay work. Two tools under investigation are: a scraping tool with two handles, and a virtual sandpaper tool which allows virtual sanding of a gently curved surface, with touch feedback of the curvature achieved. The only device available at the moment which can render the forces required in a workspace similar to the reach of the human arm is the FCS Haptic Master (HM). The HM is used as the basis for a 5-DOF powered, 6 DOF moving scraping tool plate interface.

The first tool selected for implementation is a scraping tool. The tool is a strip of metal, which is typically handled by the user by gripping it between the thumb and fingers in two places, with both hands. Hence the first requirement on the human interface to the virtual scraping tool is that the tool has to be physically handled by the user by gripping it with two hands, while scraping the surface of the (virtual) clay.

Movement and force feedback on the tool is needed in at least all the 3 translational degrees of freedom (DOF) that a body has fore-aft, left-right, and up-down. The workspace needed is on the order of the reach of the human arm, or the size of a quarter (say, the front left side) of a 40 % car model. Movement and force feedbacks are preferably available also in one or more of the three rotational DOF that a body in space has. The tool needs to be powered in only two of the three axes of rotation available to any body in space, provided the correct order of rotations is chosen. The resistance of the tool perceived by the user must be either the same as using the actual physical tool on real clay, or the differences must be acceptable and easily accustomed to. Tool forces presented to the user when moving free of the virtual clay surface must be as light as possible.

The scraping tool (in this case, a small plate blade) has 6 degrees of freedom (DOF). A single Haptic Master is instead a 3 DOF device; a higher number of DOF requires more than one HM. A variety of solutions can be thought by connecting to the scraping tool more than one HMs using different kind of joints.

A first solution implemented for proving the haptic tool design concepts with designers consists of two HMs that are (conceptually) connected to the scraping tool by spherical joints, as shown in Figure 7, with the joints axis coincident to the lower tool edge. The scraping tool has 5 fully measured and actuated DOF (3 translational plus 2 rotational). The tool has also one further DOF, which is free, but, due to the way the tool is used, it can produce a feedback torque consistent with the simulation. To summarize, in this last “5+1 DOF” configuration the tool can reach any position in its workspace and can be rotated by a certain extent; relatively to the scraping simulation purpose, it can be considered a reasonably good approximation of a full 6-DOF device and it is simpler to implement both on the hardware side and the software side.

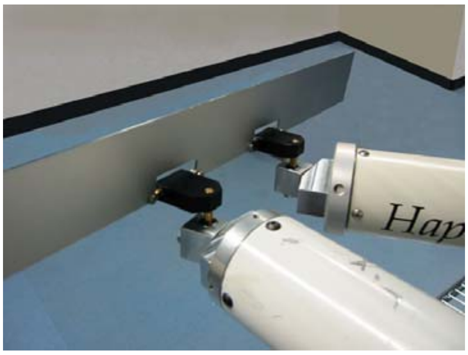

Figure 7 - End-effectors built by FCS-CS

The project will also develop sanding blocks which are more appropriate to foam models than to clay models. Sanding blocks or rather freehand sandpapering may require more DOF in the tool handle, because the curvature of the surface can be felt through an unsupported piece of sandpaper. The haptic device will be a versatile platform for these kinds of tools, ideally with a higher haptic quality than current haptic technology, and will perform better especially in the range of forces and torques that can be rendered faithfully and without introducing artifacts such as spurious frictional and mass forces on the simulated tool.

4.3 –Shape modelling methods

For what concerns shape modeling methods, the project has focused on the study of generic sweeping motions of profiles [13]. Six meaningful motions used in the shop floors by modelers when scraping clay using shaped templates have been studied. The motions considered are the following: “constant”, “constant axis”, “Frenet”, “enhanced Frenet”, “along a plane” and “surface based”. These motions are independent from the profile and cover several cases of actual sweeping. The user’s haptic based motions are supported by a tessellated model for flexibility reasons. In fact, tessellation is used in several contexts where the treatment of such elementary elements makes computation faster than other mathematical representations. The shape representation is then translated into NURBS data so as to be used straightforward for downstream engineering activities.

The shape tessellation supports high frequency rendering loop (around 50 Hz) required by the interactive simulation of the users’ interaction with the shape. The computational loop consists of the following tasks:

- detection of collision, computed as intersection between the tessellated shapes and the tessellated tools
- computation of the resulting haptic forces, using geometric computation of the collisions based on tessellation (scraped volume, area of collision); the system provides contact feedback to the users according to the physics-based model simulating the real clay [14] and the action performed.
- visualization of the resulting scraped surface, using the above tessellations to render in the graphic module.

Figure 8 shows the resulting scraped surface obtained when the tool follows the shown curve. The scraped surface is computed by cutting and updating only a tessellated model of the surface. The bold segments are the intersections of the tool displacement between two subsequent positions.

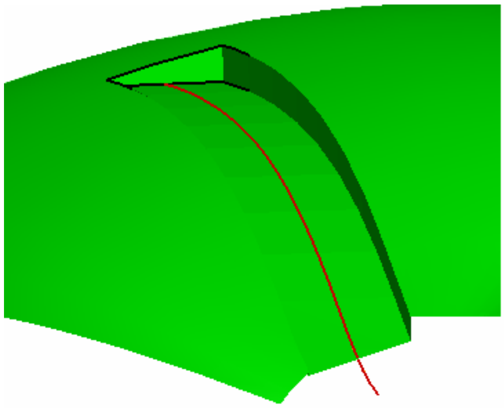

Figure 8 - Scraped surface.

4.4 –System prototype

The idea of using a haptic tool for modeling shapes in the industrial design field is quite new. Therefore, we have considered very important testing the concepts and interaction modalities proposed by the research with designers in order not to build a system that users won’t like, and consequently won’t use. Therefore, in order to test the concept of haptic “scraping” in the virtual environment, we have developed a prototype that can be evaluated by end-users.

The system set-up consists of an initial version of the scraping haptic tool driven by two integrated HapticMaster devices of the product (a car body in the example), and a monitor showing the object virtual model (Figure 8). The developed example aims at just validating the general idea. The user handles the haptic tool with two hands like in the real case when using a scraping tool, and moves it for removing material. When the haptic tool gets in contact with the virtual object, it gives back the user a haptic feedback. The tool is equipped with some buttons on its back side that allow the user to change some physical parameters of the models. The two buttons placed on the right hand side of the tool allow the user to set the stiffness of the material. The two buttons on the left hand side allow changing the resistance of the material when scraped.

Some designers and CAD engineers have been invited to try and evaluate the prototype. They all agree on the fact that the system is suitable for rough shape creation. In general, all the testers have expressed the opinion that the system might be a very helpful tool both for modelers and designers. They all seem quite positive in the possibility of integrating this new tool with other modeling tools within the design process. At the moment, testers do not see the possibility to replace 2D sketching or 3D CAS tools, but rather they confirm the effective use of this tool for substituting the physical model making. Concerning the system usability, they all agreed in confirming its extreme intuitiveness for creating shapes, also because of the intrinsic naturalness of the hand gesture. An important achievement to be noted is that all participants considered the motion they were making and the forces implied of extreme good quality, absolutely similar to the ones of the physical clay model making.

Figure 8 – System prototype tested by a user.

5- Conclusions

The paper has presented the first 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 and modelers at work, and the analysis performed for designing the system. Furthermore, the paper has presented the first achieved results that consist in the identification of the system functionalities resembling ways of operating of designers and modelers, the study of the haptic tools and of the shape modeling techniques, and the system architecture. Finally, a prototype that has been implemented for proving the system conceptual basis is presented.
The system under development is expected to be a major improvement for industrial design companies that will be able to shorten product design lifecycle, improving design quality, while preserving valuable skills of operators. On the basis of the evaluation results carried out on the system prototype a new version of the system is being developed, and a sandpaper tool is going to be developed and integrated.

6- Acknowledgement

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7- References

[1] Lee K., Principles of CAD/CAM/CAE systems, Addison-Wesley Pub Co, 1999.

[2] Yamada Y. Clay Modeling: techniques forgiving three-dimensional form to idea, San'ei Shobo Publishing Co., 1997.

[3] Romer et. Al., Effort-saving product representations in design – results of a questionnaire survey. Design Studies 22, 2001, pp. 473-491.

[4] Wiegers T., Vergeest J.S.M., Extraction if CAD tool requirements from industry and from experimental design projects, Proc. ASME DETC'01/DAC, 2001.

[5] Bordegoni et. al., Deliverable D6 "Definition of scenario and test cases", T'nD project, www.kaemart.it/touch-and-design.

[6] Cheshire D.G., Evans M.A., Dean C.J., Haptic modeling – An Alternative Industrial Design Methodology?, Proc. EuroHaptics 2001, Birmingham (UK).

[7] Dachille F., Qin H., Kaufman A., A novel haptics-based interface and sculpting system for physics-based geometric design, Computer-Aided Design, vol. 33, 2001, pp. 403-420.

[8] Dewaele G., Cani J.-P., Interactive Global and local Deformations for Virtual Clay, Proc. Pacific Conference on Computer Graphics and Applications, 2003, pp. 131-140.

[9] Burdea G.C., Virtual reality technology. John Wiley, ISBN: 0-471-36089-9, 2003.

[10] Burdea G.C., Force and touch feedback for virtual reality, John Wiley & Sons, Inc., 1996.

[11] Hayward V et al. Haptic Interfaces and Devices, Sensor Review 2004, 24 (1): 16-29.

[12] Bordegoni et. al., Deliverable D1 "Hardware and software technology and cognitive ergonomics update, T'nD project, www.kaemart.it/touch-and-design.

[13] Abdel-Malek, Blackmore D., Joy K., Swept Volumes: Foundations, Perspectives, and Applications, International Journal of Shape Modeling, 2002.

[14] Baraff D., Witkin A., Anderson J. Kass M., Physically-Based Modeling, ACM SIGGRAPH'03 Course Notes, n. 12, 2003.