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ORIGINAL ARTICLE

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Haptic modeling in the conceptual phases of product design

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Abstract The paper presents the results of a research project aimed at developing an innovative system for modeling industrial products based on haptic technology. The system consists of a Computer Aided Design (CAD) system enhanced with intuitive designer-oriented interaction tools and modalities. The system integrates innovative six degrees of freedom (DOF) haptic tools for modeling digital shapes, with sweep operators applied to class-A surfaces and force computation models based on chip formation models. The system aims at exploiting designers' existing skills in modeling products, improving the products design process by reducing the necessity of building several physical models for evaluating and testing the product designs. The system requirements have been defined observing designers during their daily work and translating the way they model shapes using hands and craft tools into specifications for the modeling system and the haptic tool. The system prototype has been tested by designers who have found it intuitive and effective to use.

Keywords Virtual prototyping · Product design · Haptics · Haptic modeling

1 Introduction

Virtual Prototyping (VP) is becoming a commonly adopted design and validation practice in several industrial sectors. Companies are moving from expensive physical models of designs to digital (virtual) models. Compared to physical models, virtual prototypes are in general less expensive, easily configurable and support variants, and allow for several simulations to run on a single model. Moreover, tests are repeatable, and the results of validation are often immediately available for product design review. Virtual prototypes often provide insights that physical testing would not reveal. Even if VP does not completely substitute physical models, it helps optimizing and eliminating redundancy in test facilities, accelerating life testing, and reducing the overall number of physical models used in the product lifecycle. Today, VP has its main focus on the late concept and engineering analysis stages of the product development process [1].

Recent trend aims at also using VP earlier in the concept stages, when product design is not too much detailed and changes do not heavily impact on the product development process. Used in the conceptual phase, VPs offer the possibility of evaluating as many concepts as possible, improving the product quality, and better exploiting designers' activities. For these reasons, this practice is rapidly catching on in engineering design as well as industrial design. Most advanced VP systems are based on Virtual Reality (VR) technologies. Visual techniques have rapidly evolved in the last decades, providing new devices supporting realistic rendering, stereo viewing, and immersive experiences [2]. Conversely, research and development of interactive devices have provided less innovative and effective solutions. The three dimensional (3D) devices, like 3D mice and joysticks, support a more realistic and intuitive interaction with 3D models [3]. Since a few years, some digital design tools allow users to physically get in touch with the design while working on a computer through haptic technologies. Haptic technology offers a revolutionary approach for combining physical and digital aspects to be exploited in various phases of product development. Haptics allow users to experience a sensation of touch and physical properties when they interact with virtual objects. Haptic devices can be used to interact intuitively with virtual models in 3D space by moving the 3D virtual model into the users' physical workspace, allowing hands and eyes to work together with the model. Integrating haptic technologies within applications combines the benefits of more natural ways of working. In fact,

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existing haptic technology allows combining the capabilities of computer systems with the traditional skills and working methods of modelers and designers. Hands and direct modeling become the means of interaction with digital models. Physical interaction with the new product is considered important because designers can explore the product's shape and style, and evaluate proportions. It is an intuitive modality for modeling new shapes, and for testing and evaluating product functionality and ergonomics [4].

New modeling systems are being developed which allow designers to use their existing manual skills while working in the virtual environment. The potential of such technologies that allow a less constrained, more natural and intuitive interaction with virtual models has increased the drive towards computer support for the whole design process, in particular for conceptual design [5, 6]. 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 exploit designers' skills is at the basis of the research work described in this paper.

This paper presents the results of the research project T'nD – Touch and Design (www.kaemart.it/touch-and-design) that aims at 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. The project 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 FCS-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). The most innovative aspects of the research concerns the development of designer-oriented haptic tools resembling craft tools like rakes and sandpapers, and of a physics-based shape modeling tool based on chip removal theories, and sweep operators computed on class A surfaces. The last feature allows us to use the sculpted digital model directly within the downstream design process activities without any further surface mathematic manipulation and reconstruction.

Section 2 presents the state of the art and related works concerning haptic technology, physics-based modeling, and haptic modeling. Section 3 describes how designers' existing manual skills have been captured and analyzed in order to translate them into interaction tools and modalities within the system. Section 4 describes the haptic modeling system developed, presenting its features, the haptic tools and the shape modeling operators, and the physics-based model. Section 5 presents the system prototype and testing results. Finally, section 6 draws some conclusions and describes future directions of the research.

2 Related works

2.1 Haptic technology

Haptic devices allow users to experience a sensation of touch and force feedback when they interact with virtual material. The sense of touch in virtual environment is provided by haptic devices [7]. Haptic devices are subdivided into force feedback devices and tactile devices. Within the context of our project, only force feedback devices were considered for the moment. A review of haptic literature can be found in [8]. A wide range of commercial force feedback devices is on the market today, but it is still an active research topic. In order to check if any force feedback device satisfies our system requirements, an overview of state-of-the-art haptic devices has been performed, also considering recent developments of haptics and applications [9]. Some benchmarkings have been performed on current available technology, considering haptic performance indicators such as workspace, position resolution, stiffness, nominal forces, and tip inertia, and also some non-dimensional performance indicators [10]. Details of the state-of-the-art analysis can be found in [11]. Several devices are for general purpose; others are developed for specific applications, for example for medical applications or video games. The latter types of devices seem to be more effective in that they resemble real physical tools that users are used to.

The PHANTOM® devices produced by SensAble Technologies, Inc. (www.sensable.com) are the first commercial haptic products and are still the most popular devices. They are point-based devices having from three to six degrees of freedom (DOF) and using stylus or thimble as haptic interface. The working space is rather limited, at least in the standard model, and the maximum feedback force is low (10 N). Some other similar devices have been developed, like the HapticMaster device developed at the University of Tsukuba actuating three fingers [12]. Rather recent, more industrial oriented point-based devices are the HapticMaster produced by FCS-CS (www.fcs-robotics.com) and the VIRTUOSE device produced by Haption (www.haption.com). The FCS-HapticMaster is a bi-directional three DOF I/O device. The feedback force supported is high (250 N) and its working space is much larger than the one supported by most of the competitors' commercial products. Thanks to these features, the device is used in industrial oriented applications like the welding application developed by FCS-CS in a research project (see www.fcs-robotics.com for details). A different class of devices includes exoskeletons, like the Sarcos Dextrous Arm Master (www.sarcos.com), the PERCRO device (www.percro.org), and actuated gloves like the

CyberForce device produced by Immersion Corp. (www.immersion.com). Actually, these devices are quite cumbersome, difficult to wear and to operate, and therefore little effective and seldom used in industrial applications. An interesting technology based on full hand contact has been recently developed. It consists of tactile devices, and haptic windows are at the moment only available as academic prototypes [13].

2.2 Physics-based modeling

In order for the haptic device to exert appropriate force in response to users' actions, the virtual object and its properties are simulated by means of a physics-based model. Various physics-based modeling techniques have been developed. Terzopoulous and Fleisher provide a basis for physics-based design supporting simple interactive sculpting using viscoelastic and plastic models [14]. Celniker and Gossard have developed a prototype system for interactive design based on finite-element optimization of energy functionals [15]. Celniker and Welch have investigated deformable B-splines with linear constraints [16]. Other methods implement dynamic sculpting with haptics spline models controlled by physical laws subject to various constraints [17]. Interactive sculpting framework based on subdivision solids and physics-based modeling has been proposed in [18].

2.3 Haptic modeling

Haptic modeling is concerned with modeling of virtual shapes using haptic technologies. Haptic modeling systems allow users to touch, feel, manipulate, and model objects in a 3D environment that is similar to a natural setting. Most of the applications are based on volume representation [19]. Some applications have been developed with the aim of providing haptic interaction with volume dataset, without actually providing realistic force feedback [20, 21]. Some other applications are more related to physics-based shape modeling. Some sculpting systems have been developed based on haptic force associated with dynamic subdivision of solids, which give users the illusion of manipulating semi-elastic virtual clay [17, 18]. They are both based on the use of the point-based PHANTOM® stylus for interacting with the virtual clay.

The only physically-based shape modeling system commercially available is the FreeForm® by SenSable Technologies Inc. (www.sensable.com/freeform/freeform.html), which is based on the PHANTOM® haptic device. Users work directly with the digital clay using the PHANTOM® stylus as a modeling tool. Hardness and surface smoothness of the clay can be varied, and different modeling tools can be selected. The material can be removed using some carving operators, but the user can also work from inside out pulling and deforming the shape. The main problem designers have reported concerns the difficulty in getting used to the tool and to the forces required for removing material with a constant depth. In addition, the fact that the application uses a voxel model does not allow them to have a high quality surface that can be immediately re-used in the downstream activities of product development.

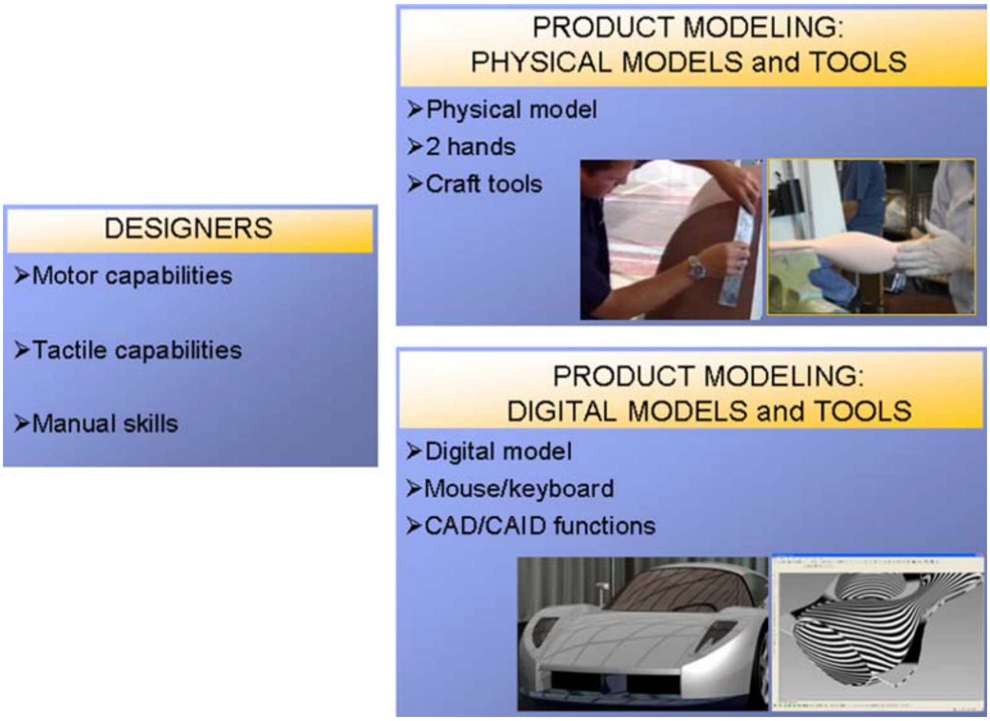
3 Users' skills analysis

The aim of the research work presented in this paper is to develop a system supporting ways of interaction that are easy, intuitive, and pleasant to use for product designers so as to convince them to adopt the system as a daily working tool. Therefore, great attention has been given to the usability and intuitive aspects of the interaction modalities with virtual models [3].

The target users of our system are designers who are used to modeling physical prototypes of product by hands, or designers with some experience using computer aided design (CAD) and Computer Aided Industrial Design (CAID) tools (Fig. 1). These users have motor and tactile capabilities that are well exploited during manual modeling of plastic materials. The existing skills they have in their hands allow them to intuitively create physical models from ideas, and to check surface quality by just passing their hands over the newly created shape. Physical modeling is a very common practice in the industrial design field, even if it shows some critical aspects. First, the physical models produced are often rough, not precise and of the right dimension, and not symmetrical. In addition, the digitalization of the physical models required for subsequent product development phases is complex and costly.

Computer-aided tools offer a nice set of functions that allow designers to perform on the digital model what is not possible to do in real world – such as undo, copy and paste, and mirror operations, and also the very useful "reflection lines" function that allows designers to test the surface quality. Several surveys demonstrate that designers are not fully comfortable using these tools since they often find them too technical and much more oriented towards engineers than creative people. Another major criticism concerns the lack of physical contact and continuous tactile interaction with objects that are being modeled.

The idea of this research work is to provide a system that offers all the good features of CAD/CAID tools with improved user interface and interaction modalities that preserve and exploit designers' existing manual skills. Different from other research works related to haptic modeling and virtual clay modeling [5, 17, 22], the aim of this work is to develop new haptic tools and modeling modalities that are dedicated to, and directly specified and evaluated by designers. Therefore, the initial activity of the research has consisted in observing designers while modeling physical prototypes of products in order to derive some specifications for the system user interface.



PRODUCT MODELING:
PHYSICAL MODELS and TOOLS

- Physical model
- 2 hands
- Craft tools

DESIGNERS

- Motor capabilities
- Tactile capabilities
- Manual skills

PRODUCT MODELING:
DIGITAL MODELS and TOOLS

- Digital model
- Mouse/keyboard
- CAD/CAID functions

Fig. 1 Physical and digital modeling of products

Cognitive psychologists participating in the research project have observed and analyzed the modelers while modeling physical prototypes using their hands and craft tools (Fig. 2). 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 material, etc.) with their hands and tools like rakes, sandpaper, templates, cutters. Subsequently, the collected data have been quantitatively and qualitatively analyzed in order to understand the advantages derived from operating manually when creating shapes, and to understand the modelers' skill that is in their hands. 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.

The analysis of the acquired data has lead to the identification and classification of the tools used (manual tools, machines) and of the gestures and hand motions performed (for shaping the object, for feeling the surface quality, etc.). From this analysis, we have pointed out the most recurrent, common, and effective users' hand operations. These are the actions that are

Fig. 2 Physical modeling tasks and tools (Images by courtesy of Alessi and Pininfarina)

going to be reproduced in the system: *scraping, surface quality testing*, and *finishing*. Scraping is usually performed using rakes, surface quality testing using hands directly, and surface finishing using sandpaper.

4 Haptic modeling system

4.1 System overview

The system has been designed considering the following three main requirements:

- The system should provide haptic tools and modeling operators for scraping, finishing a surface, and for checking its quality.
- The system is oriented towards the creation of industrial design models; therefore, it should support the generation of high quality class-A surfaces.
- The system should render real-time forces that simulate contact and force response with plastic materials like clay.

According to the first requirement, the system is expected to provide an interface that allows designers to interact haptically and graphically with virtual models of products including a true size car body. Therefore, 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. Satisfactory full hand interfaces, such as haptic gloves, have not been built so far, despite a number of attempts and the commercial product Immersion CyberGlove (www.immersion.com). On the basis of the force feedback devices overview reported previously, the final conclusion we draw is that an extended version of the FCS-HapticMaster is the most appropriate hardware solution for the project. In fact, the device provides an adequate workspace (66 litres) and rendered forces (250 N). Currently, the device provides from three- to four-DOF. Within the context of the project, the FCS-HapticMaster is used as basic platform, equipped with a strong and stiff six DOF device carrying simulated clay modeling tools.

For what concerns the mathematical description of products, approximated models of shapes, like the ones supported by voxel-based techniques, do not satisfy the second point requiring high precision representation of the created shape. Therefore, we have developed a technique that is based on tessellated model representations used during the material removal operations, and that uses generic sweeping motions of profiles operators at the end of the removal operation in order to compute a precise high-quality surface.

Finally, the system is required to compute and render the geometric and haptic model of the sculpted object in real-time. Virtual objects must behave credibly, and interaction must take place in real-time. Therefore, the system should be able to simulate properties and behaviors, and at the same time satisfy the real-time constraints. For what concerns the physics-based model used for computing and rendering the forces in accordance to the type of plastic material simulated, we have adopted a solution based on the well-known theory of chip removal.

Several problems arise in haptic applications supporting interaction with deformable objects: costly computational time, numerical instability in the integration of body dynamics and collision detection, time delays, etc. It is well known that haptic systems require high simulation rates (about 1 kHz) to obtain realistic force feedback. The update rates of the physical objects being simulated are normally of the order of 20–150 Hz. In order to satisfy haptic simulation rate, we have designed a system architecture based on parallel computation loops, and we have developed force computation algorithms based on data interpolation and prediction.

4.2 System architecture

The architecture of the system is shown in Fig. 3. It consists of the following main components:

- The FCS-HapticMaster that is operated by the user. The device has been equipped with innovative haptic tools that are oriented towards 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 (i.e., 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 into a smooth shape at the end of the interactive session.

4.3 Haptic tool

The design of the haptic tools has started from the collected users and technical requirements. Given the target products and the modeling functions addressed by the project, the haptic tool interface developed in the project is a dedicated tool that physically simulates one or more

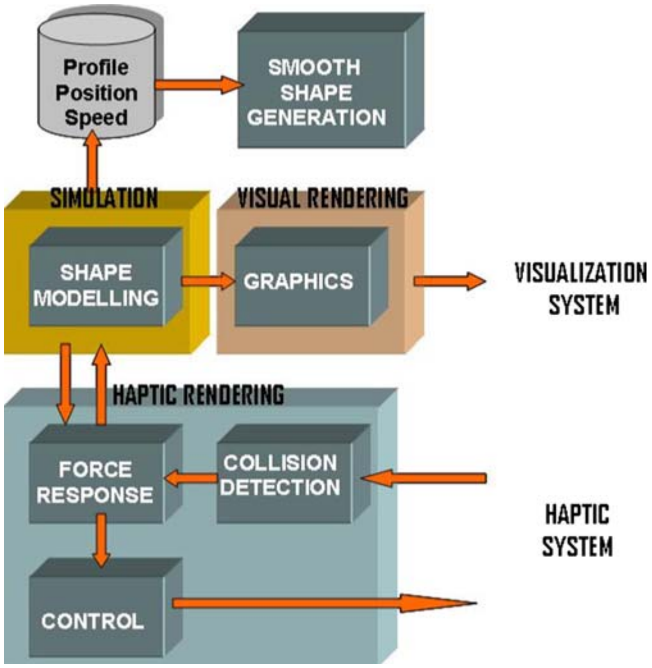


Fig. 3 System architecture

of the craft tools used in actual clay work. Two tools have been studied: a scraping tool for material removal, and a sandpaper tool, which allows virtual sanding of a gently curved surface with touch feedback of the curvature achieved.

Much of the existing work on haptics has focused on three-DOF haptic interfaces [23]. Actually, complex interaction modalities require six-DOF object manipulation capabilities with force-and-torque feedback. In this type of operation, the interaction generally cannot be modelled by a point-surface contact, which is typically supported by available point-based force feedback devices. 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-HapticMaster (HM). The HM is used as the basis for a five-DOF powered six DOF moving virtual tools interface.

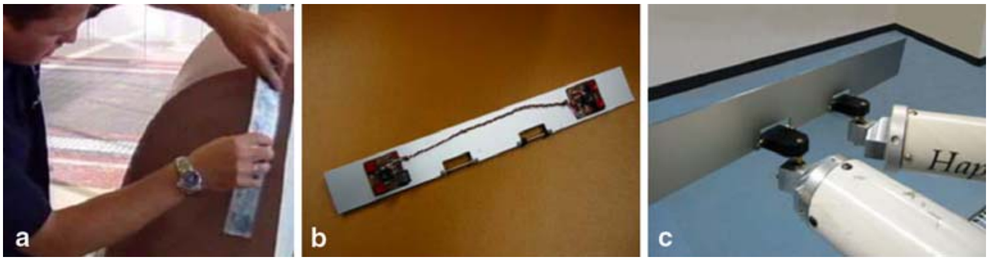
The first tool implemented is a *scraping tool* resembling a real rake (Fig. 4). The tool consists of a strip of metal, which is typically handled by the user by gripping it between the thumb and fingers in two places, with both hands. Movement and force feedback on the tool is needed in at least all the three translational 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 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 are as light as possible.

Since the scraping tool requires six DOF, a single HM device that supports three DOF is not enough. A higher number of DOF requires more than one HM. The solution currently implemented consists of two HMs that are (conceptually) connected to the scraping tool by means of spherical joints as shown in Fig. 4c, with the joints axis coincident to the lower tool edge. The scraping tool has five fully measured and actuated DOF (three translational plus two rotational). It also has 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. The scraping tool is equipped with some buttons on its back side that allow the user to change some physical parameters of the models, as shown in Fig. 4b. The two buttons placed on the right hand side of the tool allow users to set the stiffness of the material. The two buttons on the left hand side allow changing the resistance of the material when scraped.

To summarize, in this “5 + 1 DOF” configuration the tool can reach any position in its workspace and can be rotated by a certain extent. Relative to the scraping simulation purpose, it can be considered a reasonably good approximation of a full six-DOF device, which is simpler to implement both on hardware and software side.

The project is also developing a *sanding tool*, which is more appropriate to finish a surface. Sanding tools 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 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.

Fig. 4 Haptic virtual rake: (a) real rake used by designers for clay modeling; (b) virtual rake; (c) rake mounted on a six DOF haptic system



4.4 Shape modeling methods

As already mentioned, for what concerns the mathematical model of shapes, approximated models like voxel-based techniques do not satisfy the requirement for high precision shape representation. Therefore, our research has focused on the study of generic sweeping motions of profiles [24]. Six meaningful motions used in the shop floors by modelers when scraping clay using shaped templates have been considered: "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 users' 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 product development activities.

The shape tessellation supports high frequency rendering loop (around 50 Hz) required by the real time interaction of the users with the virtual 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 [25] and the action performed.
- Visualization of the resulting scraped surface, using the above tessellations to render in the graphic module.

Figure 5 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.

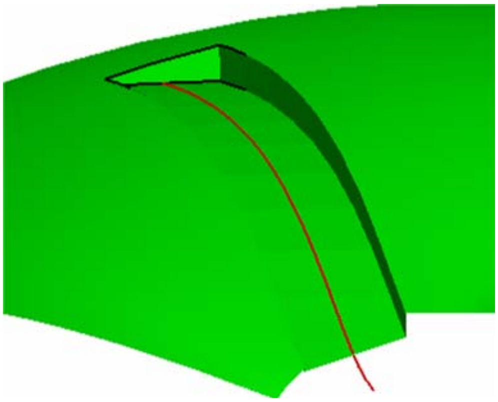


Fig. 5 Model representation of a scraped surface (computed by the think3 system)

4.5 Cutting forces computation

This section describes the theory and issues related to the computation of forces to be applied when a collision between the tool and the model is detected. The computation of forces is built on the well-known theory of chip removal based on the Merchant model [26].

4.5.1 Cutting forces theory and issues

Despite the fact that there is a wide range of different tools used in clay modeling, almost all of them can be modeled as a blade. Hence, the cutting process is mainly dependent on three specific angles (Fig. 6): the rake angle (γ), the clearance angle (θ), and the setting angle (ζ).

There are three regions of interest in the cutting process. The first area, shown in Fig. 7, extends along the shear plane, and is the boundary between the deformed and non deformed material or the chip and the work. The second area includes the interface between the chip and the tool face, while the third area includes the finished surface and the material adjacent to the surface. Cutting forces are dominated primarily from what happens in the first area, and secondarily from the friction and wear between the tool and the work in the second area. The third area basically influences the roughness and integrity of the worked surface.

The cutting process involves concentrated shear along a rather distinct shear plane. As the material approaches the shear plane, it does not deform until the shear plane is reached. It then undergoes a substantial amount of simple shear as it crosses a thin primary shear zone. There is essentially no further plastic flow as the chip proceeds up the face of the tool. The small amount

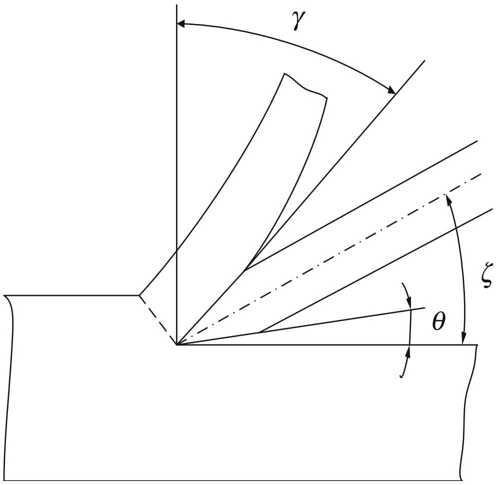


Fig. 6 Tool angles: ζ, setting angle; γ, rake angle; θ, clearance angle

of secondary shear along the tool face is generally ignored in a first study of the cutting process, and we do the same, and the motion of the chip along the tool face is considered to be similar to that of a friction slider of constant coefficient from A to O (Fig. 7). In order to evaluate the shear angle, generally a method is used that relies on the experimental observation that there is no change in density; hence being l and L, respectively, the length and the width of the chip before the separation from the work, and l_c and L_c, the length and width of the chip after the separation we can write:

$$lLh = l_c L_c h_c. \tag{1}$$

Once the thickness of chip is calculated, we can directly evaluate the shear angle, given the rake angle and the cutting ratio.

The expression of the *force in the cutting direction* (F_1) is the following:

$$F_1 = Lh\tau_0 \frac{\cot\varphi + \tan(Cost - \varphi)}{1 - \xi \tan(Cost - \varphi)}. \tag{2}$$

From this, it is possible to draw some considerations:

1. The cutting force is proportional to the cutting area.
2. The properties of the material directly affect the value of the cutting force.
3. An increase in the friction coefficient (tied to μ) is associated with a decrease in the shear plane angle (ϕ), hence leads to an increase in the cutting force.
4. An increase in the rake angle γ also leads to an increase in the shear plane angle, hence the cutting force decreases.

The material characteristics require to be computed experimentally. In many cases, the dependence of the force from the material is concentrated in a single coefficient called *cutting pressure* (k_p) defined as follows:

$$k_p = \frac{F_1}{s}, \tag{3}$$

where s is the area calculated as the width (L) of chip times its thickness (h).

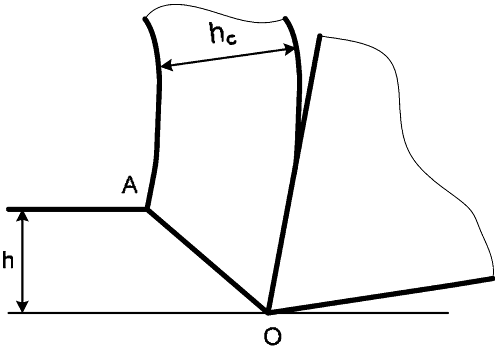


Fig. 7 Depth of cut (h) and chip thickness (h_c)

4.5.2 *Cutting forces computation algorithm*

According to the previous discussion, it follows that in order to simulate the forces exerted during clay cutting operations, several levels of accuracy can be adopted depending on the formula chosen to compute them. According to Eq. 2, it is necessary to know the values of material constants ξ, τ_0, Const that can only be obtained experimentally. The effort required to separately evaluate the values of these three constants is repaid by the possibility of using a more accurate model that allows us to assess the difference in force due to variations in the rake angle or in the magnitude of friction. Conversely, using the cutting pressure, as from Eq. 3, it is possible to simplify the experimental activity of material characterization with the penalty of having a less accurate model that does not take into account variations of tool angle and friction. Since the aim of our system is to obtain a global good level of correspondence between real and virtual clay modeling experience, this simplified method based on cutting pressure is used. The advantage of this choice is that it requires a simpler experimental phase and reduces the computational time. Also, since human capability in force discrimination depending on kinesthetic perception is not very accurate, a "precise" model is not required.

The implemented algorithm works as follows. The scraping operation consists of the tool cutting away material from the clay model. In geometrical modeling terms, it is represented as a sweeping operation along a trajectory of a two dimensional (2D) shape (the rake) intersecting the solid. Referring to Fig. 8, the intersecting area can be considered to be approximated by a discrete number of thin slices.

For each slice, the cutting process is orthogonal to the sweep trajectory, allowing the computation of the cutting force F_i, as previously described. The sum of the forces F_i is equivalent to a force (F_{tot}) applied in a particular point of the surface, and a torque corresponding to two forces positioned at two different lines of action. The tool is actuated by means of the two

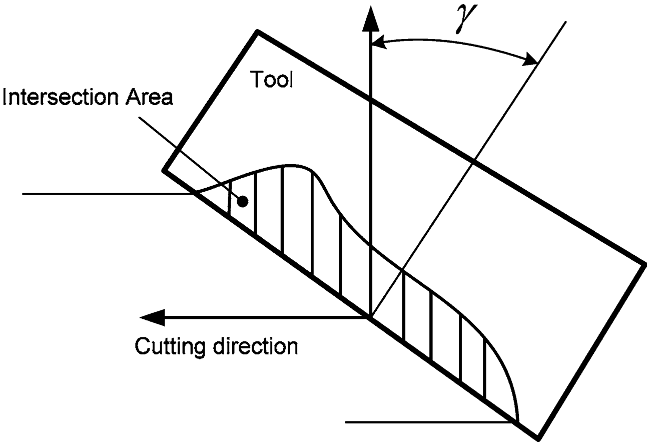


Fig. 8 Tool during cutting operation

FCS-HapticMaster devices as described previously. Therefore, it is convenient to transform the force system in the equivalent system made of two forces, each positioned in correspondence of the FCS-HapticMaster end-effector. In order to analytically solve the problem, it is then necessary to perform the following steps (Fig. 9):

1. Calculate the forces along the cutting surface to find the resultant force (F_{cr}).
2. Approximate this force with a force (F_{ch}) that lies to the bottom line of the tool where the HM devices are jointed.
3. Decompose this force into two forces F_{HM1} and F_{HM2}. In this way we do not simulate the torque due to the fact that the center of gravity of the area (and then the application point of F_{cr}) does not belong to the bottom line of the tool. The approximation due to this simplification has negligible effects on the realism of the simulation due to the fact that the distance between the center of gravity and the bottom line is generally irrelevant if compared with the height of the tool.
4. Control the two HM devices in an appropriate way in order to make them exert these forces on the user. Steps 1–4 need to be continuously computed at a frequency high enough to be suitable for haptic rendering (~1 kHz).

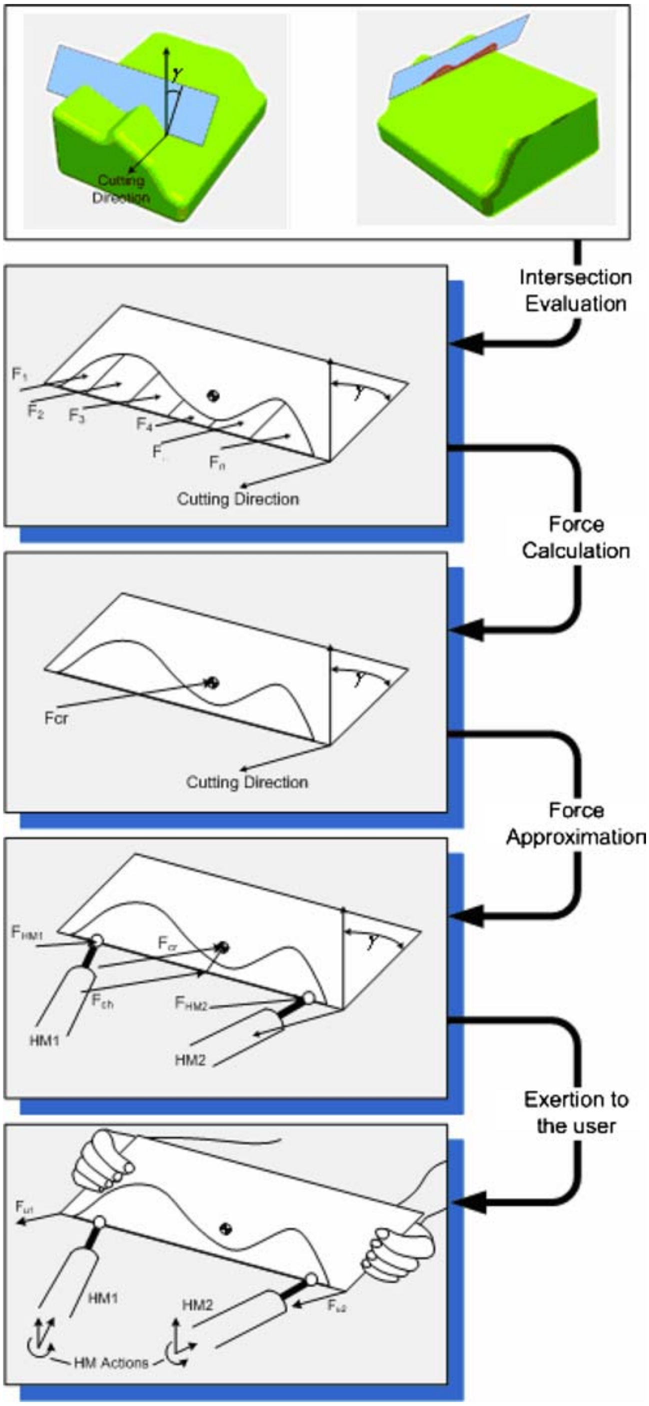


Fig. 9 Force computation algorithm

Being the force for every slice proportional to the area (A) of the slice itself, F_{tot} can be computed as follows:

$$F_{tot} = \int_{\text{AREA}} k_p \, dA = k_p \int_{\text{AREA}} dA = k_p \cdot \text{Area}. \tag{4}$$

In other words, the system corresponds to just one force if the origin of the reference frame corresponds to the center of gravity of the intersection area. Moreover, the intensity of this force is proportional to the value of the area itself. In order to compute the two forces applied in correspondence with the two HapticMaster end effectors, it is then sufficient to use the lever principle referred to the center of gravity of the area. In this way we just take into account the force component in the cutting direction. The same consideration can be done for forces orthogonal to it. The only necessary information other than material characteristics is the value of the intersection area and the position of its center of gravity referred to a known frame. It is also necessary to know the rake angle and the direction of cutting, but it is possible to directly measure it.

4.6 Haptic rendering

As we have seen in previous sections, the forces to exert on the user are computed on the basis of the geometrical data provided by the collision detection module. These data are provided with a relatively slow rate (between 5 and 30 Hz) because of the complexity of the computation. If the haptic forces were updated at the same rate, haptic simulation would not be very realistic, and the user would experience a very bouncy surface and abruptly changing forces. To mitigate this phenomenon due to low forces refresh rate, we have decoupled the haptic and the simulation loops. The system includes an internal loop – named *haptic loop* – that operates in such a way as to compensate the effects of data provision delay.

The haptic loop operates at a frequency in the range 50–700 Hz and performs the following steps (Fig. 10):

1. It receives intersection data from the geometric modeling module in an asynchronous way.
2. It applies to these data a time delay compensation algorithm that allows the system to reconstruct, with a certain degree of uncertainty, geometrical data between two consecutive intersection steps. In this way, the system is able to compute forces with a higher rate compared with the one of the geometric module. The FCS-HapticMaster has an internal high frequency loop (2,500 Hz) that continuously adapts the force to the actual end-effector position.
3. It sends to the haptic system the appropriate parameters to exert the computed forces.

Step 2 of the haptic loop includes a time delay compensation algorithm, which computes the missing data (between two consecutive geometrical intersection computations) by linearly interpolating the already known ones. In this way, it is possible to avoid the problem of step changes in the exerted forces, and then partially solve problems related to the low rate of the geometric modeling loop.

5 System prototype and testing

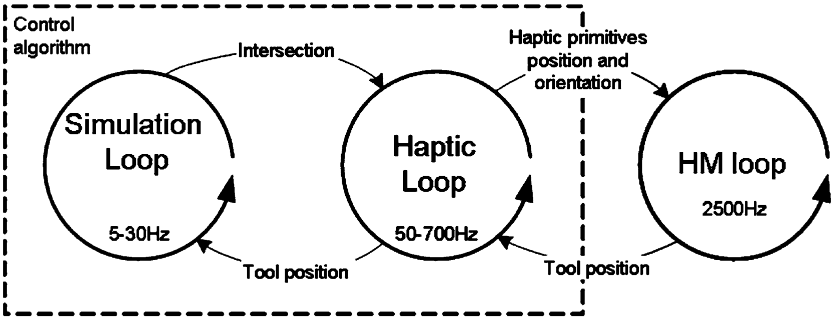
The idea of using a haptic tool for modeling shapes in the industrial design field is quite new. Therefore, we have considered as very important testing the concepts and interaction modalities proposed by the research with designers in order not to build a system that users will not like, and consequently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

Fig. 11 System prototype tested by a user

The system set-up consists of an initial version of the scraping haptic tool driven by two integrated FCS-HapticMaster devices of the product (a car body in the example), and a monitor showing the object virtual model (Fig. 11). 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 backside that allow the user to change the stiffness of the material and the resistance of the material when scraped.

About ten 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 on the possibility of integrating this new tool with other modeling tools within the design process. At the moment, testers do not see the possibility of replacing 2D sketching or 3D CAID 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.

Fig. 10 Loops for forces computation and exertion



6 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 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, the first system prototype has been presented. 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 integrated. Besides, the visualization capabilities of the system are going to be improved integrating stereo viewing provided through a stereo Head Mounted Display. The system is expected to be a major improvement for industrial design companies that will be able to shorten product design lifecycle, improve design quality, while preserving valuable skills of operators.

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