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Haptic technologies for the conceptual and validation phases of product design

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Abstract

The paper presents two applications of haptic technologies to demonstrate how they can increase human computer interaction during different steps of design process. The first application aims at developing a system to generate digital shapes by manipulating haptic tools that resemble the physical ones that the modelers use in everyday work. The second is focused on the use of haptic interfaces to evaluate ergonomics of virtual products control boards. We designed and developed the mentioned haptic devices; the first uses two FCS HapticMaster equipped with a innovative strong and stiff 6 DOF device carrying simulated clay modeling tools. The second is an ''ad hoc'' mechatronic device able to simulate some controls with rotary motions (knobs). The described haptic devices are integrated in more complex virtual reality applications; the paper describes their architecture and the methodologies proposed to simulate material shaping and ergonomic validation. The main aspects of haptic modeling and rendering are also discussed.

Keywords: Virtual prototyping; Product design; Haptics; Haptic modeling

1. Introduction

Virtual Prototyping is becoming a commonly adopted design and validation practice in several industrial sectors. Companies are moving from expensive physical models to the direct realization of digital models. Compared to physical models, *virtual prototypes* are in general less expensive, are easily configurable and support variants, allow for not one but several simulation runs on a single model. Furthermore, tests are repeatable, and results are often immediately available for product design review. Virtual prototypes often provide insights that physical testing would not reveal. Digital prototyping does not completely substitute physical models. Anyway, it helps optimizing and eliminating redundancy in test facilities, accelerating life testing, reducing the overall number of physical models used in the product lifecycle. Virtual Prototyping has its main focus today in the late concept stages and engineering analysis stages of the product development process [1]. Recent trend aims at using this practice also earlier in the concept stages in order to evaluate several concepts, improve the product quality, and better exploit designers' activities.

Most advanced Virtual Prototyping systems are based on Virtual Reality 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. 3D devices, like 3D mice and joysticks, support a more realistic and intuitive interaction with 3D models [3]. Till few years ago, some of the commonly used digital design tools (Computer Aided Design—CAD and Computer Aided Industrial Design—CAID) allowed users to physically get in touch with the design while working on a computer. 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. They exert force in response to users' action.

Haptic devices can be used to interact intuitively with virtual models in 3D space allowing hands and eye to work

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together with the model. Integrating haptic technologies within applications combines the benefits of more natural ways of working. In fact, 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.

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 [4,5].

The idea of bridging physical and virtual modeling is at the basis of the research work described in this paper. The aim is maintaining the effective and performing aspects of digital modeling and enriching tools with some new modalities of interaction more oriented to exploit designers' skills.

Haptic technologies can also play an important role in Virtual Prototyping for what concerns the validation of ergonomics aspects. Haptic interfaces between virtual prototype and real testers let them touch parts of the virtual product, evaluate the right dispositions of controls such as knobs, buttons, and simulate operations such as the opening of a door. In the last few years, great effort has been spent to investigate how to replace traditional approaches based on recursive testing performed on physical mock-ups with more innovative ones, which rely on virtual prototyping and digital mock-ups. In various research activities, an innovative approach based on simulations realized by integrating virtual prototyping and virtual models of human beings has been proposed. Software tools like Jack, Ramsis, Sammie, Safework, and some others allow users to model complex scenes where virtual humans interact with digital products [6]. However, the interaction is limited to "macro" aspects such as hazardous postures during shop-floor activities, or it is related to configuration and size of workstations or visibility of parts [7,8]. Today, when "fine" aspects such as tactile sensations are involved, a physical prototype is required. The goal of one of our research activities is to investigate the possibility to simulate the "fine" interaction by using haptic devices.

The paper presents the results of two research projects. The first is the T'nD —Touch and Design[1] project 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 second is the VeRVE[2] (Virtual Reality system for Validation of Equipment controls) project, which is focused on use of haptic interfaces to evaluate ergonomics of boards of control of virtual products.

Section 2 of this paper presents the state-of-the-art and related works concerning haptic technology and their application in product modeling and validation. Sections 3 and 4 describe methods and results obtained in the two mentioned research projects. Finally, Section 5 draws some conclusions and present future developments.

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 in virtual environments [9]. Haptic devices are subdivided in force feedback devices, and tactile devices. A review of haptic literature can be found in [10]. The past five or ten years have seen a considerable increase in the number of force feedback systems. 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 [11], also considering recent developments of haptics and applications [12]. Some benchmarking has 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 [13]. Several devices are general purpose; others are developed for specific applications, for example for medical applications or video games. The later types seem to be more effective since they resemble real physical tools that users are used to. The PHANTOM devices produced by SensAble Technologies, Inc.[3] have been the first commercial haptic products and are still the most popular devices. They are point-based devices having from 3 to 6 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 [14]. Rather recent more industrial oriented point-based devices are the HapticMaster produced by FCS-CS[4] and the VIRTUOSE device produced by Haption.[5] The FCS-HapticMaster is a bi-directional 3 DOF I/O device. The feedback force supported is high and its working space is much larger than the one supported by most of the competitors' commercial products. That allows using the device to develop industrial oriented applications. A different class of devices includes exoskeletons, like the Sarcos Dextrous ArmMaster,[6] the

[1]T'nD project: www.kaemart.it/touch-and-design.

[2]VeRVE project: www.media.unisi.it/verve.

[3]SensAble Technologies: www.sensable.com.

[4]FCS Control Systems: www.fcs-robotics.com.

[5]Haption: www.haption.com.

[6]Sarcos: www.sarcos.com.

PERCRO[7] device and actuated gloves like the CyberForce device produced by Immersion Corp.[8] 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, and are at the moment only available as academic prototypes [15].

2.2. Haptics for product 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 [16]. Some applications have been developed with the aim of providing haptic interaction with volume dataset, without actually providing realistic force feedback [17,18]. 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 [19,20]. 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 FreeForm by SenSable Technologies Inc.[9] 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.

2.3. Haptics for product validation

In the VeRVE project we limit the domain of investigation to ergonomics of controls mainly used in automotive and home appliances fields. Some commercial haptic tools can be used to simulate the interaction between a user and the controls. Devices like PHANTOM may be used to simulate controls with rotational (knob) or translational (slider, button) DOF. Fig. 1 shows the use of two PHANTOM devices for simulating a knob. However, the characteristics of this type of device (particularly for what concerns the control), make it of difficult integration in complex environments. For complex environment we intend, for example, Virtual Reality systems developed to increase the design of car interiors as described in [21]. In such a context, a haptic device integrates visual information and increases realism. To this purpose ‘‘ad hoc’’ devices are more suitable to accurately simulate the behavior of push-buttons, door handles and so on; in [22] a specific purpose haptic interface which simulates hand grips has been described. The interface has been used to simulate controls of some consumer goods such as stoves, ovens, washing machines. We have adopted a similar approach to develop a specific device for the evaluation of the ergonomics of control boards based on buttons, slide-bars and knobs. The device can be considered an innovative virtual prototyping approach where common Virtual Reality techniques are enhanced with haptic interaction.

[7] PERCRO: www.percro.org.

[8] Immersion Corp.: www.immersion.com.

[9] www.sensable.com/freeform/freeform.html.

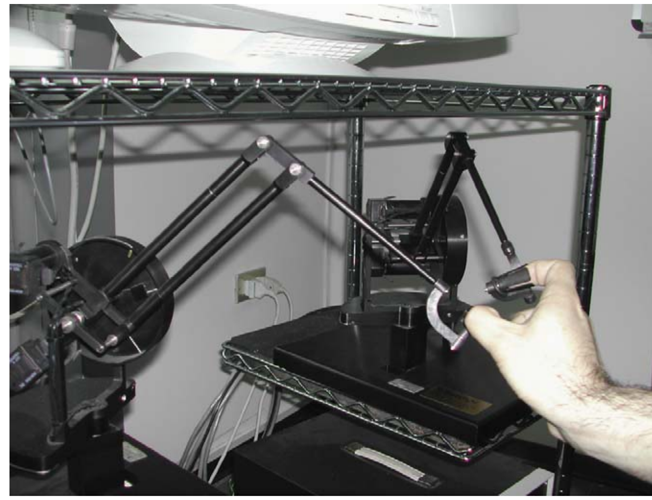


Fig. 1. Two PHANTOMs utilized to simulate manipulation of a knob

3. Haptic system for the conceptual phase of product design

This section presents the results of the research project T’nD—Touch and Design aiming at developing an innovative system for modeling industrial products based on haptic technology. The system consists of a CAD system enhanced with intuitive designer-oriented interaction tools and modalities. The system integrates innovative 6-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 to build 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. Modelers of

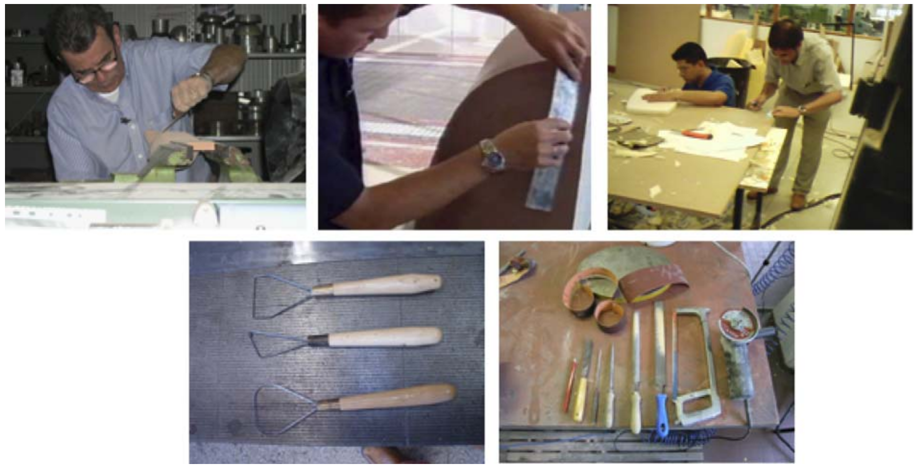


Fig. 2. Physical modeling tasks and tools.

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 and foam material) using their hands and tools like rakes, sandpaper, templates, cutters (Fig. 2). 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 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 going to be reproduced in the system: scraping, surface quality testing and finishing. Scraping is usually performed using rakes, surface quality check using hands directly, and surface finishing using sandpaper.

3.1. System overview

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

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

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. 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 l) and rendered force (250 N). The FCS-HapticMaster is used as basic 3 DOF platform, equipped with a strong and stiff 6 DOF device carrying simulated clay modeling tools. For what concerns the mathematical model of shapes approximated models like voxel-based techniques [23] do not satisfy the second requirement concerning high precision representation of the created shape. Therefore, a technique has been developed based on tessellated model representations used during the material removal operations, and generic sweeping motions of profiles operators applied 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, such as 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 (around 1 kHz) to obtain realistic force feedback. The update rates of the physical objects being simulated is normally of the order of 20–150 Hz. Therefore, in order to satisfy the haptic simulation rate, the system architecture is based on decoupled haptic and simulation computation loops, and we have developed force computation algorithms based on data interpolation and prediction.

3.2. System architecture

The architecture of the system is shown in Fig. 3. 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. Moreover, 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.

3.3. Haptic tools

The design of the haptic tools has started from the collected users and technical requirements. The haptic tool interface developed in the project is a dedicated one that physically simulates the 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 3-DOF haptic interfaces [24]. Actually, complex interaction modalities require 6-DOF object manipulation 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. The system is used as the basis for a 5-DOF powered 6 DOF moving virtual tools interface.

The first tool implemented is a scraping tool resembling a real rake (Fig. 4a). The tool consists of a strip of metal, which is typically handled by the user by gripping it

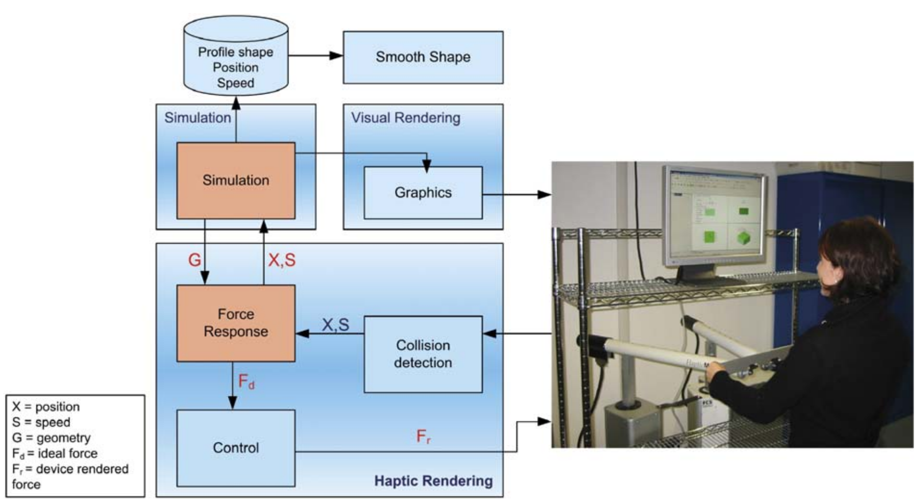


Fig. 3. System architecture.

Fig. 4. Haptic virtual rake: (a) real rake used by designers for clay modeling; (b) virtual rake; (c) rake mounted on a 6 DOF haptic system.

between the thumb and fingers in two places, with both hands, as shown in Fig. 4b). The scraping tool requires 6 DOF. The solution currently implemented consists of two 3 DOF HM devices that are (conceptually) connected to the scraping tool by means of spherical joints as shown in Fig. 4c). 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. The scraping tool is equipped with some buttons on its back side that allow the user to change some physical parameters of the models, like the stiffness and the resistance of the material when scraped.

3.4. Shape modeling methods

For what concerns the mathematical model of shapes, approximated models like voxel-based techniques [23], do not satisfy the requirement for high precision shape representation. Therefore, our research has focused on the study of generic sweeping motions of profiles [25]. 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 and the action performed;
- visualization of the resulting scraped surface, using the above tessellations to render in the graphic module.

3.5. Cutting forces computation

This section describes the algorithms developed for computing forces to apply when a collision between the tool and the model is detected. The computation of forces is based on the well-known theory of chip removal based on the Merchant model [26]. There are a wide range of different tools used in clay modeling, but almost all of them can be modeled as a blade hence the cutting process is mainly dependent on three specific angles (Fig. 5): 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. 6 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 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 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. 6).

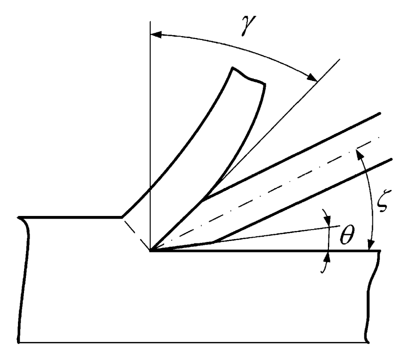


Fig. 5. Tool angles: setting angle ζ, rake angle γ, clearance angle θ.

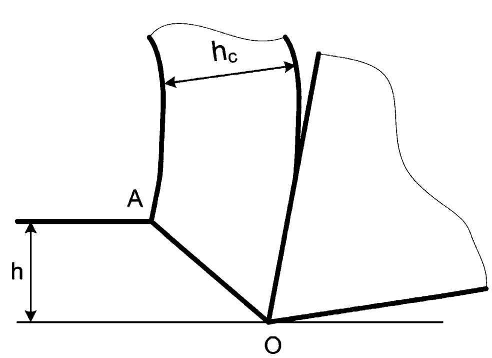


Fig. 6. Depth of cut h and chip thickness h_c.

In order to evaluate the shear angle it is generally used a method 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 calculated the thickness of chip, we can directly evaluate the shear angle, given the rake angle and the cutting ratio. The magnitude of the *force in the cutting direction* ($\mathbf{F}_1$) is the following:

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

From Eqs. (1) and (2) 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).

3.5.1. *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 formulas chosen to compute them. According to (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 to use 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 (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, thus 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 2D shape (the rake) intersecting the solid. Referring to Fig. 7 the intersecting area can be considered to be approximated by a discrete number of thin slices.

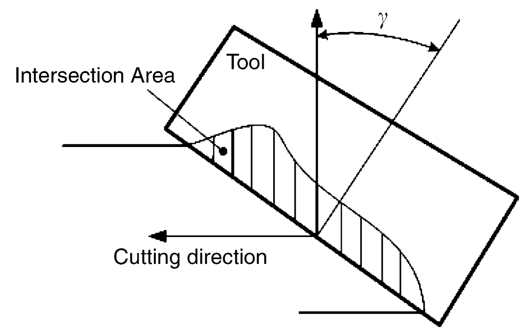


Fig. 7. Tool during cutting operation.

For each slice, the cutting process is orthogonal to the sweep trajectory, allowing the computation of the elementary cutting force $\mathbf{F}_i$, as previously described. The sum of the forces $\mathbf{F}_i$ is equivalent to a force $\mathbf{F}_{tot}$ applied in a particular point of the surface. The tool is actuated by means of the two HapticMasters as described previously; they exert a system of two forces, each positioned in correspondence of the HapticMaster end-effector, equivalent to $\mathbf{F}_{tot}$. In order to analytically solve the problem, it is then necessary to perform the following steps (Fig. 8):

1. calculate the forces along the cutting surface to find the resultant force $\mathbf{F}_{tot}$;
2. approximate this force with a force ($\mathbf{F}_{ch}$) that lies to the bottom line of the tool where the HMs are jointed;
3. decompose this force into two forces $\mathbf{F}_{HM1}$ and $\mathbf{F}_{HM2}$. In this way we do not simulate the torque due to the fact that the center of gravity of the area (and than the application point of $\mathbf{F}_{tot}$) does not belong to the bottom line of the tool. The approximation due 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 HapticMaster devices in an appropriate way in order to make them exert these forces to the user.

Steps 1–4 need to be continuously computed at a frequency high enough to be suitable for haptic rendering ($\sim$1 kHz).

Being the force for every slice proportional to the area (A) of the slice itself, the magnitude of $\mathbf{F}_{tot}$ can be

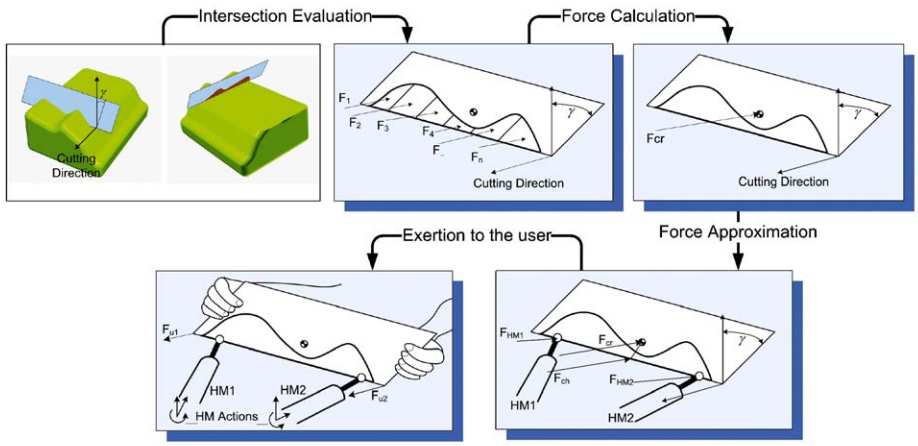


Fig. 8. Force computation algorithm.

computed as follows:

$$F_{tot} = \int_{AREA} k_p \, \mathrm{d}A = k_p \int_{AREA} \mathrm{d}A = k_p \cdot Area. \tag{4}$$

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 FCS-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 are 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.

3.6. Haptic rendering

As we have seen in previous sections, the forces to exert to 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 the system includes an internal loop—named haptic loop—which operates in such a way 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:

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 HapticMaster has an internal high frequency loop (2500 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.

3.7. 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 very important testing the concepts and interaction modalities proposed by the research. 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 (Fig. 9). 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.

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. At the moment, testers do not see the possibility to replace 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 agree 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.

4. Haptics in ergonomics validation

Ergonomic analysis can be performed at the initial phase, or at later phases of product design. In the first case, simplified models or drawings are realized using traditional procedures and tools. In case a physical mock-up of the product is built, mannequins based on linkages or real human testers can be involved in the validation process. This practice is usually complex and time consuming.

We propose an alternative approach based on the use of Virtual Prototypes augmented with the possibility of physically interacting with some of the product components. The study case developed is aimed at evaluating the ergonomics of control boards consisting of buttons, slide-bars and knobs like those shown in Fig. 10 used in products like cars and home appliances.

Traditionally, control boards are designed making use of experimental data [27,28], obtained by anthropometric studies, which report useful information like the best distances between commands, the dimensions that best fit human hands, movement range etc. In the following we show some of these data (Figs. 11 and 12) used for solving

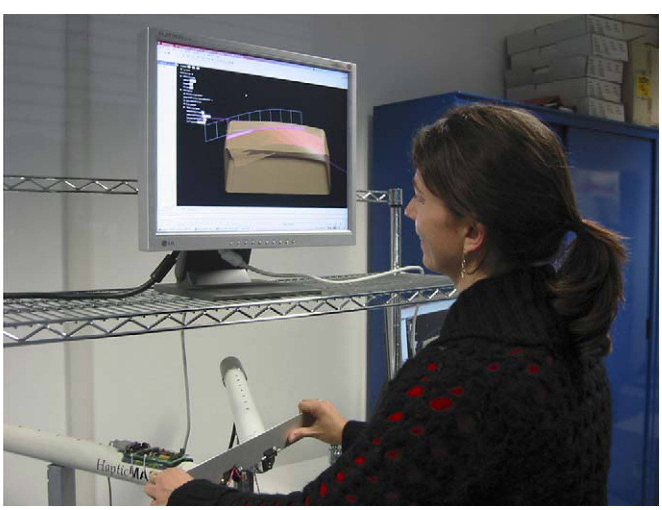
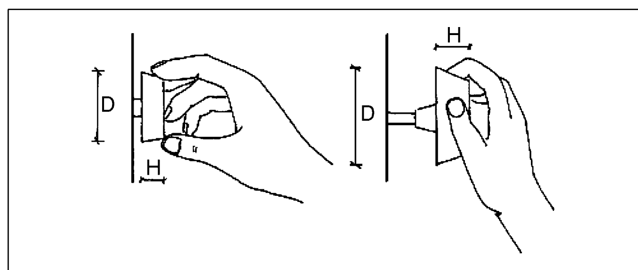


Fig. 9. System prototype tested by a user.

Control device	Operation method	Distance (in mm)	
		min	recommended
PushButton	with a finger	20	50
Lever switch	with a finger	25	50
Main switch	with an hand	50	100
	with both hands	75	125
Ridge Knob	with both hands	75	125
Knob	with an hand	25	50

Fig. 11. Distances between control devices [27].



Parameters	Recommended dimensions
Precision handling with two or more fingers :	
Diameter D	10-100 mm
Minimum diameter for slow rotations	6 mm
Depth H	12-25 mm
Palm grasp:	
Diameter D	35-75 mm
Minimum depth H	15 mm

Fig. 12. Knobs recommended dimensions [28].

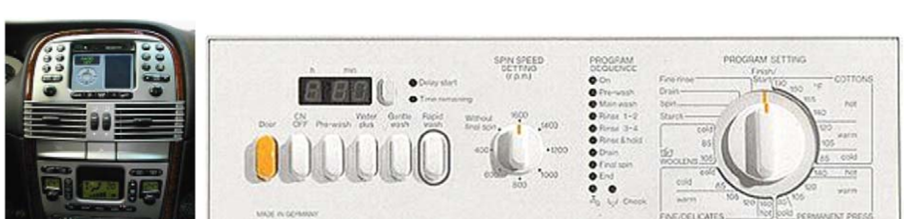


Fig. 10. Examples of control boards in the automotive and home appliance fields.

dimensioning problems. In the last few years, the results of dimensioning are tested by means of digital mock-up techniques and 3D visualization, which is also useful for aesthetic evaluations. The usability of controls is analyzed also by means of some human modeling software, which allow users to visualize possible ergonomics problems due to a wrong dimensioning or positioning of a particular control. The quantity of data available, and the high capabilities of virtual prototyping software, permit users to consider the dimensioning and geometrical design of controls a quite easy to solve problem.

However, controls are characterized also by an activation force or torque, which influences the user's perception of the product quality as well as their aesthetic appearance and degree of usability. It is common practice to tabulate these features [29], by gender and age of the user, for a large number of different regulation device shapes. A first dimensioning of dynamic behavior of controls relies on this data, but this information is not appropriate when a deeper analysis is meant to be performed. It is a well known fact in industry that sometimes quality level of a product is associated with factors not directly tied with it, and one of these factors refers to tactile sensations and force-feedbacks of controls. Whilst advanced software are available for geometrical evaluation, very poor tools are available for investigating haptic sensations conveyed by controls.

Another very important aspect related to the definition of controls regards the psychophysical sphere. Some studies stated that the sensibility and accuracy of the regulation strongly depends by the position and orientation of controls in respect to the effects of the regulation itself [30]. For instance, the effect on a gauge is generally better estimated by a user when he/she turns a knob positioned just beside the gauge rather than when he/she actuates a knob not in the same field of view of the gauge and, in addition, with the axe incident with that of the gauge. Data related to the above mentioned feature is scarcely available. Moreover, in case some hints, which are useful during product design, come from digital mock-ups, there are no suitable tools to treat these ergonomics aspects of control devices.

4.1. System architecture

This section describes the architecture of a workstation for ergonomics tests on virtual products (Fig. 13). The architecture has been aiming at providing high level realism and immersion, and according to experiences and results derived from previous virtual reality research [31]. The virtual scene is created by a virtual reality engine which visualizes virtual products and humans, modeled using products and human modeling tools. The first tool updates the geometric model of the product on the basis of the position information coming from the haptic device. The second one builds a geometric human model based on the kinematics information acquired by a motion tracking system that captures the posture of the tester. This is done because the reproduction of the tester within the virtual scene is fundamental to achieve a good level of immersion. It is also important to recreate the gesture of the hands of the tester, since they directly interact with the virtual board. For this reason we propose the adoption of two separate tracking systems, one (optical for instance) for the "gross motion" of the tester and another one (like a virtual glove) for the "fine motion" of the hand. The virtual scene, created and rendered by the virtual reality engine, is then presented to the user by means of a head mounted display (HMD) in form of stereoscopic images to create depth cues and 3D visualization. HMDs are occlusive displays, and almost completely prevent the visualization of the real world creating a good immersion into the virtual scene.

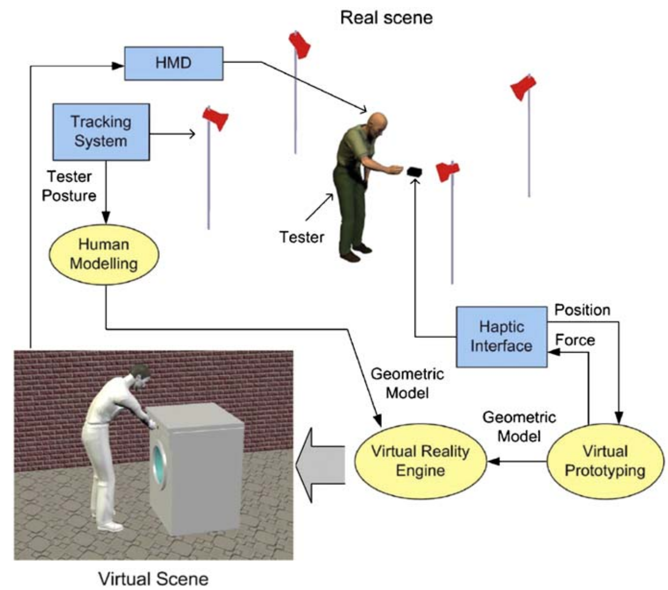


Fig. 13. Architecture of the ergonomic workstation.

Application software estimates the forces or torques associated with the position of the control device and transmits them to the haptic interface. These forces are computed on the basis of a physical model of the specific regulation device that is directly derived from the geometric model of the device itself by means of a dynamic simulation. The haptic device should render realistic sensations, be completely reconfigurable and have a certain degree of modularity.

4.2. Haptic device for the simulation of controls

A main objective of the VeRVE project is the development of an haptic interface for the simulation of controls used in automotive and home appliance domains. Designing a haptic interface is not a simple task, since it is directly in contact with the user that cannot be represented with a simple model or transfer function. This causes several problems that concur to make the device unstable [32].

First, we developed a 1 DOF active mechatronic system able to simulate the behavior of a real knob. In this case the device must exert a torque function of the position (and the velocity) of the knob itself. The architecture of this device is reported in Fig. 14. The user handles a knob joined with a DC brushed motor that exerts the requested torque. An optical encoder measures the angular position of the knob. This information is read by a digital controller that, on the basis of the haptic model, generates a tension which is passed by the power driver to the motor, and conveys the correct torque to the user. The controller, which is a programmable digital microcomputer with analog interfaces, communicates via a serial link with the virtual prototyping application.

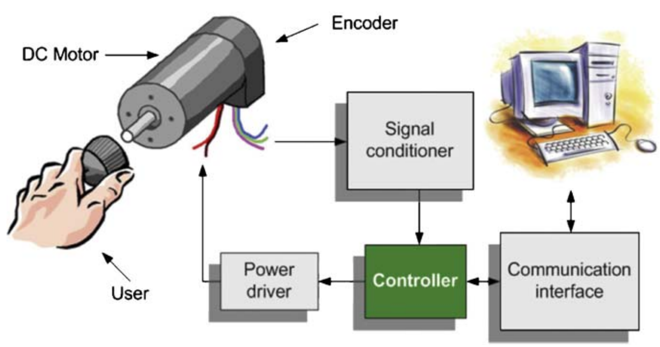


Fig. 14. Architecture of the haptic device.

The controller embedded software implements the state machine reported in Fig. 15. In particular, it is designed to permit two different simulation methods. In the first one, the haptic model of the knob is entirely loaded into the device (so called "local model"). This means that at the beginning of the simulation the virtual prototyping application sends to the haptic device the desired value of torque in every possible knob position. The controller, during simulation, has just to read the knob position and send the corresponding torque, available in its memory, through the power driver to the motor. This method is completely implemented into a single machine state, than it is repeated with high rate because of the absence of any state transitions. The position of the knob is send to the virtual prototyping application with a predefined frequency. Thus, the execution of the cycle is speeded up because it does not use wasting time polling mechanism. Conversely, in the second simulation method instead, the haptic device does not know the entire model, which is totally managed by the virtual prototyping application. This implies that during the simulation the controller has to read the position from the encoder, communicate it to the application and receive from this the desired torque value. These methods have both pros and cons. Using remote model, since the heavy use of the communication channel and its limited throughput, it is not possible to achieve high refresh rate of the control variable (proportional to the torque), it permits the realization of

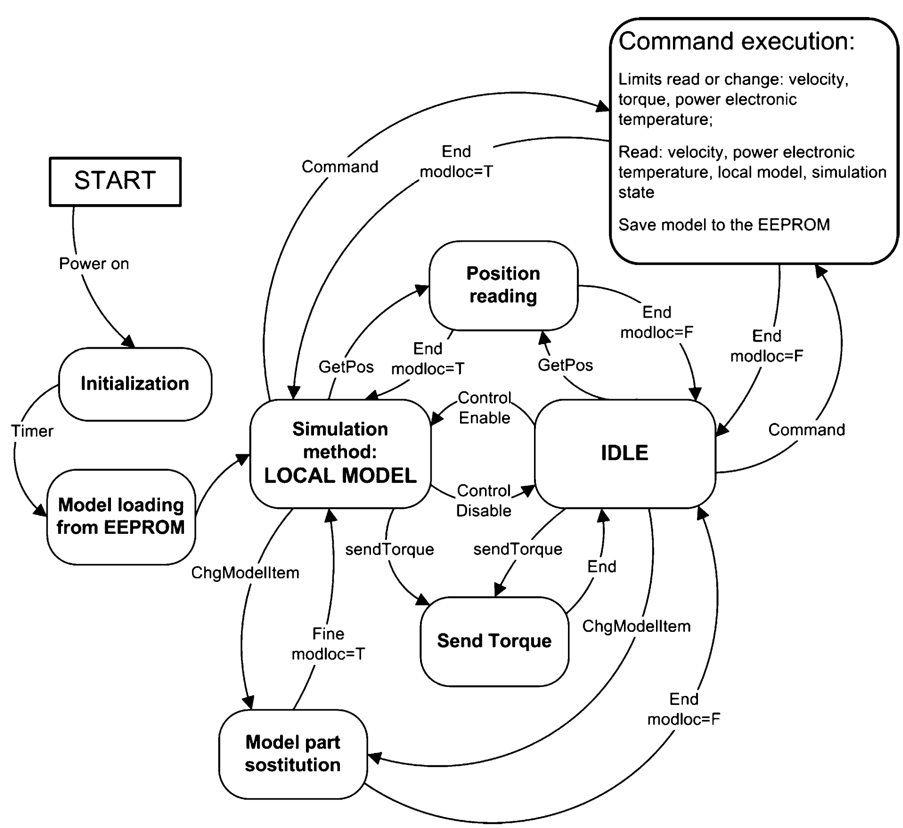


Fig. 15. Architecture of the haptic device.

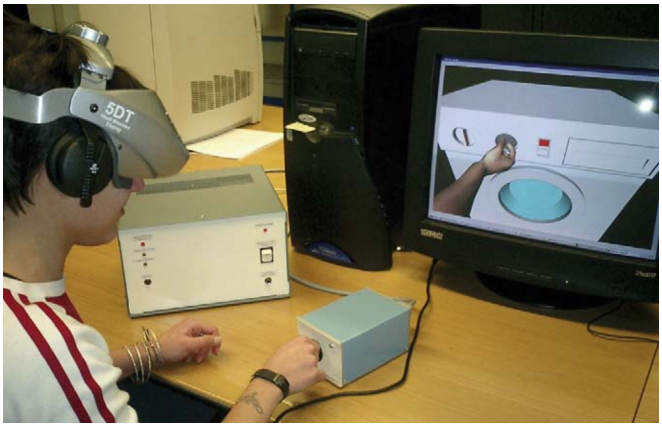


Fig. 16. A first prototype of the ergonomic workstation.

very complicated haptic models that cannot be reproduced in a local model because of the bounded device memory availability. Local model, instead, is characterized by higher refresh frequencies, which provide better haptic sensations.

As reported in [33–35], the maximum virtual stiffness exerted by the device depends from the refresh rate hence, for a given stiffness, the stability of the device itself depends on it. It is then noteworthy to observe that the obtained refresh rate is about 8000 Hz using the local model and still 1000 Hz when using the remote model. As said, the torque also depends from the velocity of the knob that is evaluated differentiating the position. Ii is then clear that an increase in refresh rate, if positive for the quality reproduction of positional torque, is detrimental for the velocity depended components. In fact, the velocity resolution lowers, while the refresh rate increases. To solve this problem we implement a digital filter applied to the calculated velocity, this preserves the advantages related to high refresh rates and increases the available resolution in velocity measures. This, at the end, permits to recreate good sensations of both step knobs (in which torque is mainly proportional to position) and continuous knobs (in which the friction component is predominant).

4.3. Initial testing results

Some prototypes of the ergonomics workstation have been built in order to test the concept with users. The prototypes are characterized by different levels of complexity, and by assembling different system components. The first prototype realized consists of three main hardware and software components: 1. HMD; 2. haptic device; 3. modeling and rendering software. Fig. 15 depicts the workstation during the tests. The HMD used is a commercial device produced by 5DT Inc.[10] and is composed of two displays, one for each eye, and guarantees a 32 field of view on the diagonal at 800x600 resolution.

[10]www.5dt.com.

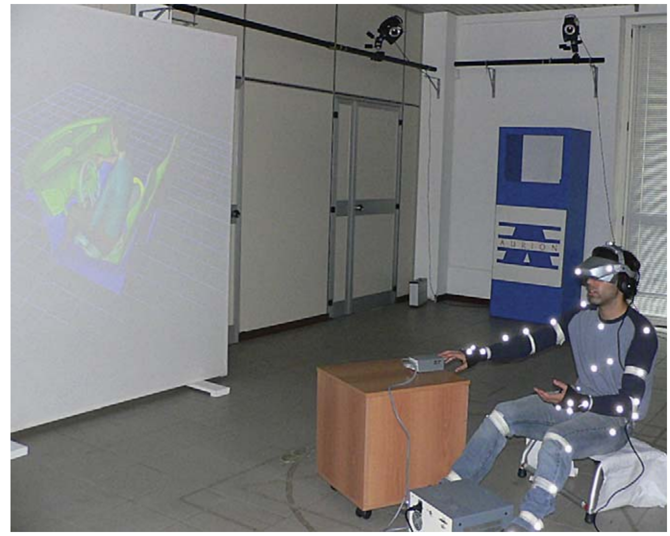


Fig. 17. Test with the first prototype of the complete ergonomic workstation.

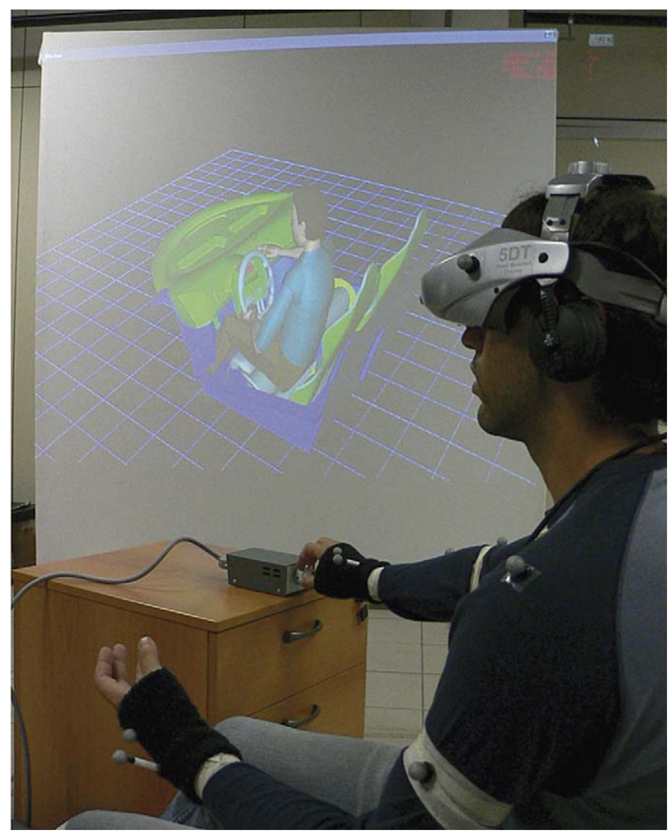


Fig. 18. A more detailed view.

The electronic interface of this device permits users to address different images to the two eyes. Hence stereoscopic techniques can be used to convey depth cues to the user and spatialization. Fig. 16 depicts the first prototype implemented of the ergonomic workstation.

A tracking system has been integrated in order to detect "gross motion" of the tester. The tracking system used is the optical system Vicon M2-460 based on infrared cameras (www.vicon.com). Figs. 17 and 18 depict tests realized by using this "extended first prototype" of the ergonomic workstation.

5. Conclusions

The paper has presented the research works related to haptic technology for supporting the conceptual phase and the ergonomics evaluation phase of product design carried out at the KAEMaRT (Knowledge Aided Engineering and Manufacturing and Related Technologies) Group of Politecnico di Milano. Recent advances in haptic technologies have proven to be very effective in supporting various phases of product design since the first evaluation tests with users. The first part of 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 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, improving design quality, while preserving valuable skills of operators. The second work presented consists of an immersive virtual reality system developed for ergonomics evaluation of product designs based on the integration of a customized haptic system and commercial tools for Virtual Reality. We presented a first haptic system realized, that is a 1 d.o.f. mechatronic device which exerts torques suitable for the simulation of knob controls. The system is integrated into a virtual simulator of products (like car dashboards, ovens, washing machines, etc.) and allows designers to physically evaluate the behavior, usability, and ergonomics aspects of control devices, like knobs. This application augments the commonly available visual representation of the products, which is performed through a stereo HMD, with the possibility to physically touch, operate, and also change the behavior of a real knob. The system has been tested by some users who have appreciated and evaluated positively the level of immersion provided by the system, and the realism of the haptic rendering of the knob. Future activities include the development of other customized haptic devices for the simulation of control devices like slider and button controls and a better tracking of the tester including "fine motion" of the hand.

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