Using observations of real designers at work to inform the development of a novel haptic modeling system

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ABSTRACT
Gestures, besides speech, represent the mostly used means of expression by humans. For what regards the product design field, designers have multiple ways for communicating their ideas and concepts. One of them concerns the model making activity, where designers make explicit their concepts by using some appropriate tools and specific hand movements on plastic material with the intent of obtaining a shape. Some studies have demonstrated that visual, tactile and kinesthetic feedbacks are equally important in the shape creation and evaluation process [1]. The European project "Touch and Design" (T'nD) (www.kaemart.it/touch-and-design) proposes the implementation of an innovative virtual clay modeling system based on novel haptic interaction modality oriented to industrial designers. In order to develop an intuitive and easy-to-use system, a study of designers' hand modeling activities has been carried out by the project industrial partners supported by cognitive psychologists. The users' manual operators and tools have been translated into corresponding haptic tools and multimodal interaction modalities in the virtual free-form shape modeling system. The paper presents the project research activities and the results achieved so far.

Categories and Subject Descriptors
I.3.6 [**Computer Graphics**]: Methodology and Techniques – *interaction techniques.*

General Terms
Human Factors

Keywords
Haptic modeling, haptic interaction, virtual prototyping

1. INTRODUCTION
Keyboard and mouse for many years have been the mostly used interaction interface between user and computer independently from the task that has to be performed. It has been made possible because of the wide range of applications supported by those simple devices. The advent of new applications, like 3D simulation, modeling, etc., requires different and more appropriate interaction tools and modalities. The current trend is not the development of a generic tool able to respond to all various requirements of applications, but instead the definition of new interaction modalities that satisfy specific requirements. For example, some highly specific interaction tools have been developed for medical applications, for fine electronics manipulation or general computer aided modeling [2]. Specifically, in the field of computer aided product design, more performing and powerful interaction modalities are being required. For what concerns the development process of stylistic products, in general, the creation of physical mock-ups is still the mostly widespread practice for validating several product design aspects like ergonomics, proportions, shape and style, etc. [3]. With the relatively recent digitalization of the process activities, gradually, it has been possible to approach differently the assessment of a product such as its appearance (by means of photo-realistic rendering techniques), its physical properties (for example, using some Finite Element Analysis methods), etc. Besides, physical mock-ups can be easily and rapidly generated using computer numeric control machines and most recently using some rapid prototyping techniques [4]. Nevertheless, each evolution involves some contradictory issues. It has been reported that because of the heavy digitalization of the process, people who used their practical knowledge in manual modeling, are loosing their role in the product development process and a long lasting modeling heritage is inevitably disappearing hauling a dramatic loss of this kind of knowledge. In addition, the *lack of physical interaction with the virtual product* is a main issue designers are concerned with [5].

A solution addressing the problem related to the lack of physical interaction with the virtual model can be provided by developing *multimodal user interfaces* with virtual prototypes that allow users to see with high realism and also "touch" virtual objects. This can be achieved today by means of stereoscopic visualization devices combined with force-feedback and tactile devices, named haptic devices, which provide the user the sense of touch [6]. For what concerns haptic interaction, one of the most popular solutions commercially available is provided by the PHANToM haptic device by SensAble Technologies Inc. (www.sensable.com). The FreeForm application is integrated with the PHANToM device and is aimed at supporting sketching shapes in 3D using a haptic stylus. The application provides designers with an easy approach in modeling shapes based on intuitive interaction modality that renders force feedback during the modeling of the material. Nevertheless, for what concerns its usability, some aspects have resulted to be not as effective and predictable as reported in [7]. The application, at a first glance, looks immediate in its use and extremely intuitive. However, some problems arise when it is necessary to increase the control over the tool. In fact, it is quite difficult to orient the pen-like tool towards precise directions in respect to the virtual surface. This can cause some possible miscomprehension of the relative positioning in the virtual environment of the tool (rotation around the tool's relative Z axis) which can produce some unexpected results while modeling. In addition, the proposed desktop-based environment may produce results that are ergonomically not correct for long period of working; the distortion between the vision and the movements involves some perceptive problems because of the lack of parallax continuity.

The T'nD -Touch and Design project – performs research in the context of shape modeling based on haptic interaction (www.kaemart.it/touch-and-design). Specifically the intent is focused on the study of an innovative system based on new multimodal interaction modalities and modeling operators oriented both to designers and modelers in order to support their model making activity within the digital design context, still maintaining their ordinary gestures and way of working. The project is funded by the European Union under the Sixth Framework Programme and involves academic partners: Politecnico di Milano (Italy) coordinator of the project, Université de Provence (France) expert in cognitive psychology, Universitat de Girona (Spain) with the Industrial Design Department; industrial partners: Pininfarina (Italy) operating in the car design sector, Alessi (Italy) dealing with household products, and Eiger (Spain) a product design company; and finally two technology providers: FCS-CS (the Netherlands) providing haptic technology, and think3 (France) providing 3D modeling applications. In order to achieve the goal of proposing to the final user an intuitive and easy-to-use shape modeling system, the research activity supported by the psychologists involved in the project has focused on the observation and analysis of modelers' activities. Our intention has been gathering data about the various modeling techniques used by modelers at work, their gestures, the used tools, and the way of checking the quality of the in-progress models based on visual and tactile modalities. These data have been subsequently used for designing and developing the interaction modalities and tools of the modeling system. Some test cases have been conducted in order to verify the correctness of the initial hypothesis (i.e., re-conducing real world gestures for creating virtual models) and the intuitiveness of use of the developed system.

The paper includes a section regarding the methodology used for modelers' and designers' skill capture and the analysis of gathered data. The subsequent section presents the system architecture and the studied haptic tools and interaction modalities. Finally, the results of the evaluation of the first running prototype of the T'nD system are reported.

2. METHODOLOGY AND ANALYSIS FOR CAPTURING USER'S MODELING MODALITIES

The virtual simulation of specific actions needs to refer to real world metaphors in order to be truly exploitable by users. Within the T'nD project we intend to propose to final users (modelers and designers) a novel system including multimodal interaction based on real world's clay modeling gestures and shape modeling modalities and tools. To achieve this, we conducted some test cases on users at work at the project industrial partners' workshops (Alessi, Eiger and Pininfarina). In those test case sessions, modelers and designers were asked to produce the physical model of an object starting from simple 2D blueprints or 3D sketches. The selected objects were a household appliance for Alessi and Eiger, and the C-pillar of a car for Pininfarina.

Modelers and designers were video recorded while modeling malleable materials like clay and resins using their hands directly or some modeling tools. Their activities were tabulated in a process chart including timing, activities, tools and frequency of use (Table 1). Subsequently, a quantitative analysis of gestures for each partner's session was performed. It has to be noticed that analysis results have been merged for each test case separately because main factors like the kind of material used, the modeler's and designer's skills, the expected level of accuracy and the complexity of the physical model are controlled in each test case separately. The elements taken into account for describing the users' gestures were mainly the following: aim and modus operandi of the tool, tool movements, hands movements, kind of information gathered while modeling with each tool, similarity with other tools.

At first it is necessary to point out that the users' gestures are influenced by several factors. The first one is related to whether the modeler is working on the shape (performing ergotic gestures) or exploring the shape by hand (performing exploratory gestures). Ergotic gestures were very dependent on the tool used. This means that analyzing gestures is equivalent to analyzing how tools are used, and therefore our study has concentrated on this side. We have analyzed the five most important tool families. In order to define which tools were more important than others, we decided to cluster them on the basis of the comparison between working time and frequency of their use. In fact it is possible to affirm that if a certain tool is used more often in terms of time, it does not intrinsically confirm its value, but, instead, the significance can be provided by a direct comparison between the total amount of time of its use and the frequency of use.

In general terms, we found that the most important tools were the ones belonging to the "*small material removal*" family including several tools like sandpaper, hand-drill and the rake, all of them used for detailing the model and providing a first finishing of the surface. These tools are used quite differently according to the kind of material for which they are used. Some similarities like the achieved shape and the tools orientation of use can be found.

Used tools		Test Case # 1	%	Test case # 2	%	Test Case # 3
Small material removal tools	2-fingers use sand paper	02:45,0	8,29%	00:00,0	0,00%	02:08,0
	Palm-used sand paper	02:36,0	7,84%	01:18,4	9,69%	00:00,0
	Thumb-used sand paper	05:17,4	15,94%	03:12,9	23,85%	00:55,4
	Edge-use sand paper	05:30,3	16,59%	01:40,0	12,36%	01:00,5
	Band-use sand paper	00:00,0	0,00%	07:27,4	55,31%	06:31,7
	Index-finger sand paper	00:00,0	0,00%	01:32,3	11,41%	00:23,5
	4-fingers sand use paper	00:00,0	0,00%	00:28,0	3,46%	04:10,2
	Block-use sand paper	00:00,0	0,00%	00:00,0	0,00%	00:00,0
	Sponge-use sand paper	00:00,0	0,00%	00:00,0	0,00%	00:00,0
	Flexible steel plate straight	00:00,0	0,00%	00:00,0	0,00%	00:00,0
	Flexible steel plate curved	00:00,0	0,00%	00:00,0	0,00%	00:00,0
	Clay tool small	00:00,0	0,00%	00:00,0	0,00%	00:00,0
middle range material removal tools	Hand-hold milling machine	09:03,0	27,28%	00:00,0	0,00%	03:20,0
	Small size grind	07:19,8	22,09%	00:00,0	0,00%	05:49,3
	Clay tool large	00:00,0	0,00%	00:00,0	0,00%	00:00,0
	Cutter	00:00,0	0,00%	00:00,0	0,00%	00:00,0
Detailing tools	Chisel	00:00,0	0,00%	05:13,5	38,76%	00:00,0
	Rasp	09:36,0	28,93%	03:28,3	25,75%	06:51,5
Large material removal tools	Grinder	00:00,0	0,00%	00:18,0	2,23%	00:00,0
	Hand saw	00:00,0	0,00%	00:26,0	3,21%	00:00,0
	Band saw	07:12,0	21,70%	00:00,0	0,00%	03:18,0
	Hot wire	00:00,0	0,00%	00:00,0	0,00%	00:00,0
Sander	Sand belt	00:00,0	0,00%	02:00,0	14,83%	00:22,0
	Cirucular sander	00:00,0	0,00%	00:00,0	0,00%	02:48,0
	Single-hand-use sanding machine	00:00,0	0,00%	00:00,0	0,00%	00:00,0
	Two-hand-use sanding machine	00:00,0	0,00%	00:00,0	0,00%	00:00,0
Peculiar tools	Slice	00:00,0	0,00%	00:00,0	0,00%	00:00,0
	Self made tool	00:00,0	0,00%	00:00,0	0,00%	00:00,0
Marking tools	Tape	00:00,0	0,00%	00:00,0	0,00%	00:00,0
	Pencil	00:00,0	0,00%	02:03,1	15,22%	00:00,0
	Summatory	**0.33.11**	100,00%	**0.13.29**	100,00%	**0.22.29**

Table 1: Table reporting data concerning hand modeling gestures and tools.

In the second stage of the analysis, we have focused on the relative orientation of the tools, as each tool is used following a preferential axis. If one defines the X axis parallel to the body of the user, the Y axis orthogonal to it, the Y axis looks like being the most frequently used one. By an anthropometric point of view, this is due to the fact that the operator can apply forces more effectively, and, therefore, remove a larger amount of material. However, this orientation axis does not permit a fine control over the movement. For this scope the X axis is preferred.

2.1 Quality control

During the physical model creation process, the modeler has to continuously check whether the model is attaining the expected shape. For doing that, the modeler applies different methods for assessing the correctness of the result, considering different aspects such as the dimensions, the profile, the symmetry and the curvature continuity which are obtained by means of visual and tactile testing. Since the physical model cannot be evaluated in a global way, the user generally performs local checks. Regarding the visual control, checks are done in two ways: according to orthogonal observation and prospective observation. Regarding the first one, the operator, generally, holds the model at the eye level and orients it in order to observe just the profiles and turns it to observe different aspects sequentially. In this way the correctness of measurements is verified. In case of prospective observation, the operator basically observes the model in its totality and gets a general feedback about proportions.

According to our observations, the most used checking methods are the tactile ones. They occur during the sculpting activities as well as during finishing activities. In particular for tactile verifications, different methods with different goals are used. One method consists of rapid sweeps over the surface. This movement is often used while sculpting or finishing a mock-up and more particularly when the modeler has to remove dust. This control gesture does not directly lead to acquire precise information about the curvature of the shape, but, rather, allows for the detection of irregularities or variations on that surface otherwise unrecognizable just by visual observation. Another recurrent movement regards long sweeps on the surface through which the modeler acquires more detailed informations about the curvature differences along one direction. However, it depends on the expected level of accuracy of the final model both in terms of measurement and surface quality.

It is clear that the modelers acquire information related to shapes by exploring specifically some aspects of the volume, such as variations of a given surface or global symmetry, with different kinds of strategies integrating and exploiting information. On the basis of our analysis we realize that exploratory gestures have a primary role in checking the shape but, on the contrary, vision is still the most immediate modality. Tactile and kinesthetic inputs seem to complete visual information, often ambiguous about the spatial dimension, and help to construct a more precise 3D mental representation of the object.

2.2 Implementation

Once gathered all necessary data about users' gestures and modeling modalities, it has been necessary to cluster them and select which modalities were interesting and feasible to implement into the system. For what regards the modeling operators (and therefore the gestures) it has been considered that thick-material-removal tools have not to be taken into account, because they can be replaced by other standard CAD (Computer

Aided Design) operators and their use is not of primary importance. Conversely, we decided that it could have been interesting to study and implement medium to fine material removal tools. The rake used for clay modeling (see Figure 1) appeared to be the most effective one since intuitive in its use (referring to the common metaphor of material removal) and able to produce high surface quality. Furthermore, by our analysis it resulted that the sanding operation is a quite important activity to be considered. By sanding, the operator makes an action of refinement over the model, and, at the same time, acquires direct information about the surface quality.

On the basis of the data analysis, we have decided to implement thin-material and sanding operators and modalities within the T'nD system. In this way, a new metaphor which is based on the combination of two different practices in shape modeling will be available to the final user.

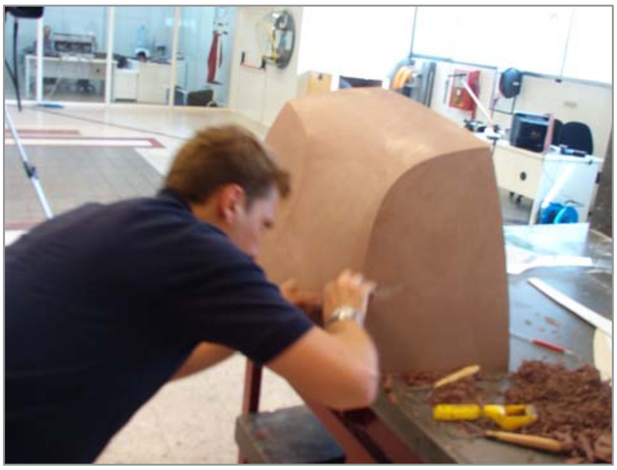

Figure 1: Clay modeling performed by a designer

3. CLAY MODELLING SYSTEM

On the basis of the analyzed users' operations and tools to be reproduced the architecture of the T'nD system has been conceived and its functionalities have been defined. The system has to provide tools like rake and sandpaper that allow the users to feel, touch and model the object surface. The sense of touch in virtual environments is provided by haptic devices [6]. The first step has dealt with the study of which haptic device would have at best satisfied our requirements. Besides the already mentioned SensAble haptic technologies (www.sensable.com), some other similar devices have been developed like the HapticMaster device developed at the University of Tsukuba [8] actuating three fingers. 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).

Since the objective of the project is to create an interface that allows designers to interact haptically and graphically with virtual models of products (including a true-size car body), a purely point-based haptic interaction provided by most of the haptic devices is not sufficient to appreciate and modify the surfaces in an intuitive way. Designers and modelers wish to interact either with the full hand, or with a virtual version of a standard modeling tool. Concerning full hand interaction, satisfactory full hand interfaces (haptic gloves) have not been built so far, despite a number of attempts and one commercial product (the Immersion CyberGlove). This is probably a bridge too far at the current state-of-the-art. Therefore, the solution proposed in the project bases on dedicated haptic tools resembling rakes and sandpapers.

On the basis of the haptic devices overview, the final conclusion we have drawn is that an extended version of the FCS HapticMaster is the most appropriate hardware solution for the project. The HapticMaster is a bi-directional 3 D.O.F 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, supporting the development of industrial applications. In fact, the device provides an adequate workspace (66 litres) and rendered force (250 N). Currently, the device provides from 3 to 4 D.O.F (Degree Of Freedom). The HapticMaster will be used as the basis for the development of 5-DOF powered 6-DOF moving modeling tools.

3.1 System architecture

The architecture of the T'nD system consists of a hardware component that is controlled by a software module that computes and renders the geometrical model of the object, and also the response forces to be actuated by the haptic device (Figure 2). The system architecture consists of the following main components:

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

3.2 Modeling tools

The first virtual haptic modelling tool developed consists of an aluminum blade vertically positioned. The blade is typically handled by the user with both hands by gripping its lateral edges between the thumb and the other fingers. This haptic interface allows users to scrape the surface of a virtual clay block with the same gestures and responses like it is commonly done in real world.

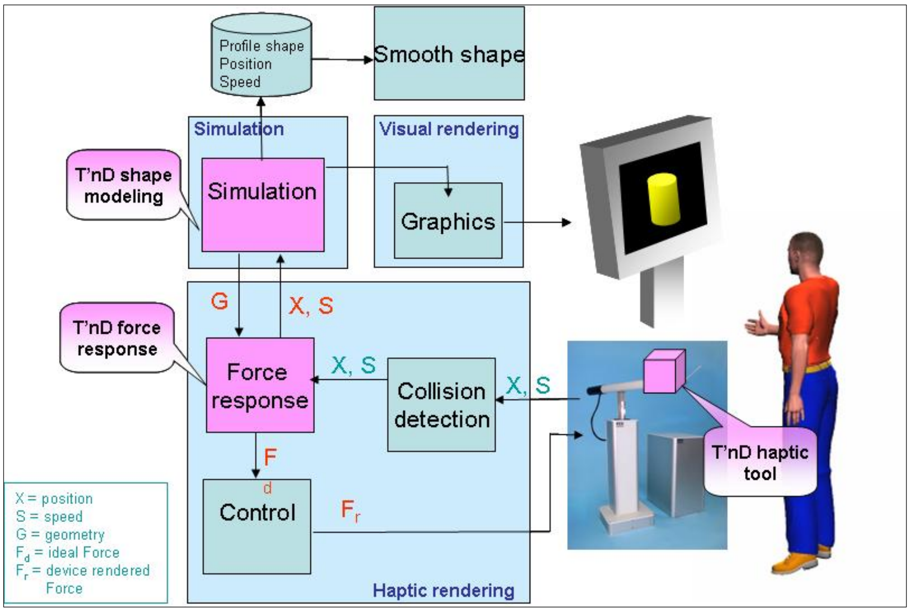

Figure 2: System Architecture

Since the FCS HapticMaster is a 3 DOF device, it is necessary to increase its DOFs, in order to provide an appropriate interface for the scraping haptic tools. An easy way for getting a higher number of DOFs is using two HMs connected together. Several solutions have been considered for connecting the scraping tool with two HMs using different kinds of joints. The assessed solution is based on two HMs connected by the aluminium blade with two spherical joints coincident to the lower edge of the tool. The scraping tool developed in this first development step has 5 actuated DOFs (three translational plus two rotational). The tool is also provided with one further DOF, which is free, but, due to the way the tool is used, it can produce a torque feedback consistent with the simulation.

In this last "5+1 DOF" configuration the tool can reach any position in its workspace and can be rotated by a certain extent. Relatively to the scraping simulation purpose, it can be considered a reasonably good approximation of a full 6-DOF device and it is simpler to implement concerning both the hardware and the software aspects. Concerning the resistance of the tool that is perceived by the user, it must be either the same as using the actual physical tool on real clay or the differences must be acceptable and easy for the user to accustom to.

4. SYSTEM PROTOTYPE

A first prototype of the system has been developed in order to verify the initial hypotheses and validate its functionality and usability. The system prototype is made of a metal plate simulating the scraping haptic tool which is driven by two integrated HapticMaster devices and a monitor displaying the virtual model. In this first implementation the system makes use of a simple geometrical shape for simplicity reasons. The user handles the haptic tool with two hands like in the real world when using a scraping tool and clay, and moves it in the space for removing material. When the haptic tool gets in contact with the virtual object, it provides to the user a force feedback. The tool is equipped with some buttons on its back side that allow the user changes the stiffness of the material, and the resistance of the material when it is scraped.

4.1 Prototype testing

Some users (designers and CAD engineers) have been invited to test and evaluate the prototype (Figure 3). From the testing sessions we have mainly acquired some qualitative data about the feeling the users get about the system use and some quantitative and mote technical data about stiffness and damping parameter values in order to properly tune the system for future developments. Hereby, we intend to provide a general overview regarding the questionnaires we carried out. Testers have all agreed on the fact that the system is suitable for rough shape creation, more specifically they all have expressed the feeling that the system might be a very helpful tool both for modelers (expert in hand-made prototyping) and designers (experts in virtual prototyping). They all seemed quite positive about the possibility of integrating this new tool with other modeling tools within the design process. At the moment, testers did not see the possibility to replace 2D sketching or 3D CAID (Computer Aided Industrial Design) tools, but rather they have confirmed the effective potentiality of this tool for substituting the physical model making. The testers agreed in confirming the intrinsic naturalness of the kind of hand gestures supported by the system, and on the high degree of intuitiveness offered by the multimodal interface for creating new shapes. An important achievement to be noted is that all participants considered the motion they were making and the forces exerted by the system of extreme good quality and fully similar to what is done and perceived during physical clay model making.

Some discussions have been arisen by the haptic steel plate mounted on the HapticMaster. It has been demonstrated that in 3D user interaction, the shape of the tool strongly influences the choice of 3D manipulation and interaction modality [2]. During the testing session we came across some unexpected considerations about the physical interaction with the haptic system. For example, the tester have noted that the position with which they griped the tool varied depending on the task to be performed (i.e. rough shape definition or fine shape definition) and on the applied forces. For instance we noticed that when the user wanted to remove a large amount of material for creating the initial overall shape of the object, the pulling force was mostly located in the whole hand and the plate was grasped with strong forces over the whole length of the fingers. Conversely, when a fine and precise scraping action was requested, just three fingers were used and the plate was hold just with the finger tips and in some case it also happened that the tool was held on the top edge instead of the usual side edges. These kinds of observations lead us to think that different modeling operations, even when performed with the same tool, involve different grasping modalities. That definitely implies that physical variations in terms of size and geometry of the plate are required in order to allow a correct ergonomics use of the system. In this sense it is justified to take into consideration for further developments the development of different rakes to be mounted onto the HapticMaster interface.

Figure 3: System prototype tested by a designer.

5. CONCLUSION AND FUTURE DEVELOPMENTS

In this paper we have presented part of the research activities carried out in the context of the European project Touch and Design - T'nD concerning users' skills capture, analysis and implementation. As we have seen, in order to define a new virtual modeling system, we have started our activities from the analysis of modelers and designers' gestures performed while modeling real physical products. In this way, we have obtained information about the types of gestures and tools mostly used during hand modeling activities. After an appropriate clustering of the gathered data we have finally designed the tools and the interaction modalities for virtual clay modeling to implement into the T'nD system. We have designed and developed a new system architecture based on two FCS-HapticMaster devices working simultaneously able to reproduce the real rake tool functions for the shape definition. At the moment we are developing another haptic tool that we have highlighted during our preliminary research, consisting of a sanding tool able to satisfy the requirements for shape refinement and tactile verification of the virtual model. The first testing sessions have proved the effectiveness of the simulation of forces, and the quality of the system in resembling the interaction with real clay.

The T'nD project is still in progress. Future activities include the development of the shape modeling software and the related haptic simulation in order to support an appropriate interaction as close as possible to real world clay-modeling activities. For what regards interaction modalities we are working on several clay modeling haptic tools and we are planning to improve the perception of immersion in the virtual environment by integrating immersive stereoscopic visualization devices.

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