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# Replication of sculptures: from virtual to real world

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**Abstract.** The paper presents an application for manually making replications of sculptures in a real material from a virtual representation of an original work. The application contributes to closely link the virtual and the real world. The technical solution uses virtual reality techniques for the guidance of gesture and constitutes an efficient alternative to current techniques used in art domain. The paper is focused on the presentation of the main capabilities of the system (hardware and functional description, techniques for computer aided gesture).

## 1 Introduction

Making replications of original models is the common way used by museums for providing the general public with original and unique works of art. Usually, making of the replication is performed by a specialist. A first step of the work consists in reporting manually on the material the measurements performed on the original model. A second step consists in sculpting the material with a tool. Depending on the nature of the material, different tools may be used. For example, electrical rolling mills are frequently used for cutting and drilling operations in hard material such as stone or marble. The recent introduction of Virtual Reality in Art offers new technologies for visiting Museum: interactive 3D visualization, guided visits with comments on the history of the works, etc. Many projects are currently in progress to constitute databases of 3D objects that provide today the specialists, and in the future the general public, with complete information on the original works. The use of such database by specialists, especially for the replication, constitutes a solution that avoids to manipulate the original work, but requires the manipulation of virtual representations of the original models. Today, most of the models are based on 3D geometrical descriptions (clouds of points, STL files, meshes) of the objects resulting from 3D digitalization, sometimes completed with the description of the colors.

Making replication of an original work based on a numerical model is currently performed in Art [8]. Some of the techniques consist in using a CNC-sculpting machines, directly controlled from the numerical model. Others techniques resulting from rapid prototyping are based on stereo lithography. However these approaches present several drawbacks. Firstly, they do not allow to realize large work and they are limited to the work of certain materials. Secondly, they involve important invest-

ment for a result whose quality of the finish does not necessary satisfy the specialists. Finally, they could not be exploited in site for the restoration of works of art.

The paper suggests an application for manually making replication of sculptures in a real material from a numerical model of the original work. In fact, the application contributes to closely link the virtual and the real world. The realized system provides the specialist with adapted sensorial feedback for a computer assisted gesture. Our approach aims at realizing a human centered system, that provides the specialist with facilities for guiding his gesture during the work of a real material from a virtual representation. In the domain of sculpting, as far as we know, it does not exist similar systems even if different approaches are suggested for sculpting virtual material [3, 5]. Virtual reality technology has played an important role in the developments described in this paper, especially in providing ideas for man-machine interaction [2, 4] and sensorial feedback synthesis [1, 6, 7]. However some techniques provided by virtual reality have been adapted to the specific problem that we have to be faced.

## 2 Presentation of the system

The system has been designed in order to take into account the following set of requirements imposed by the specialist:

- To be adapted to the use of standard tools such as those currently employed by the specialists (see Fig. 1). They allow to perform cutting or drilling operations in different material. There are equipped with diamond blades or drills. For each type of tool, a mechanical support has been designed in order to adapt the tool to the system and also to limit the mechanical stress.
- To take into account a set of constraints inherent in the replication of the sculptures: definition of the bloc of material, position of the shape to be replicated into the material, scale of the shape.
- To be able to make a replication according to a user-defined tolerance. Absolute tolerance is set to 1mm in all the workspace.
- To be simple during its use and to be easily carried and installed in the place (workshop, quarries) where the material must be worked.

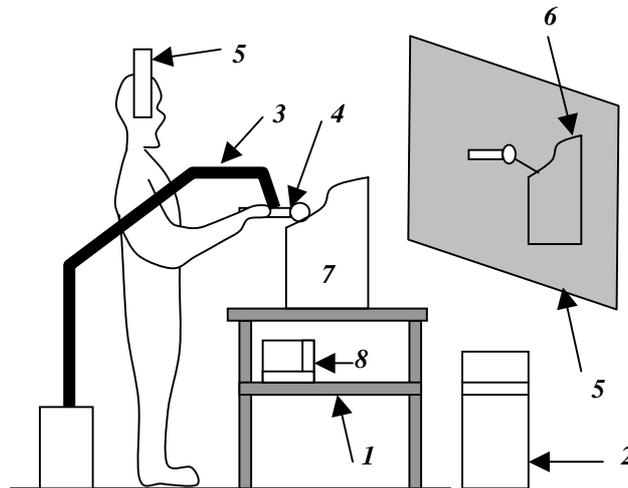


**Fig. 1:** Two types of standard tool are currently used.

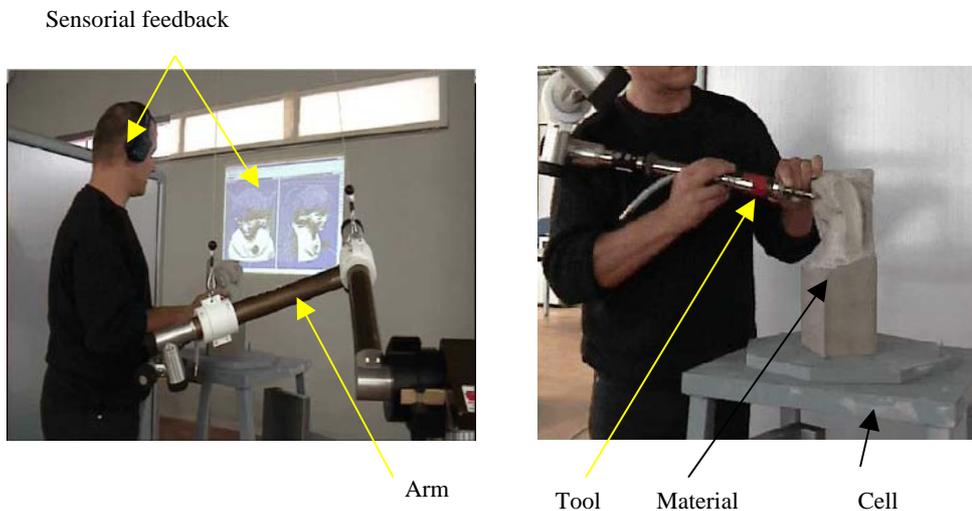
## 2.1 Hardware description

The system is mainly composed of the following devices (see Fig. 2 and 3):

- A cell (1) composed of a support receiving the bloc of material to be worked and the tool calibration system.
- A PC computer (2) that collects the position and orientation of the tool provided by the measuring arm and that calculates the data used for guiding the gesture of the specialist.
- A measuring arm (3) provides in real time the position (3 translations) and the orientation (3 Euler angles) of the tool. The current version of the system uses a 7 joint arm (Faro Arm, Gold 2.4 m). The system is equipped with a compensation in order to balance the gravity effects induced by the bodies of the arm and of the tool.
- A tool (pneumatic or electric millstone) (4) is mounted on the measuring arm.
- A feedback stimuli generator (5) that provides the user with relevant information for guiding the gesture according to the numerical model to be replicated.
- A numerical model (6) represents the shape to be replicated and the bloc of material to be worked.
- A bloc of material (7) fixed in the cell.
- A tool calibration system (8) composed of a set of reference planes is used to calibrate the tools before and during the work of the material bloc.



**Fig. 2:** Main devices composing the system.



**Fig. 3:** Work of the material by the specialist.

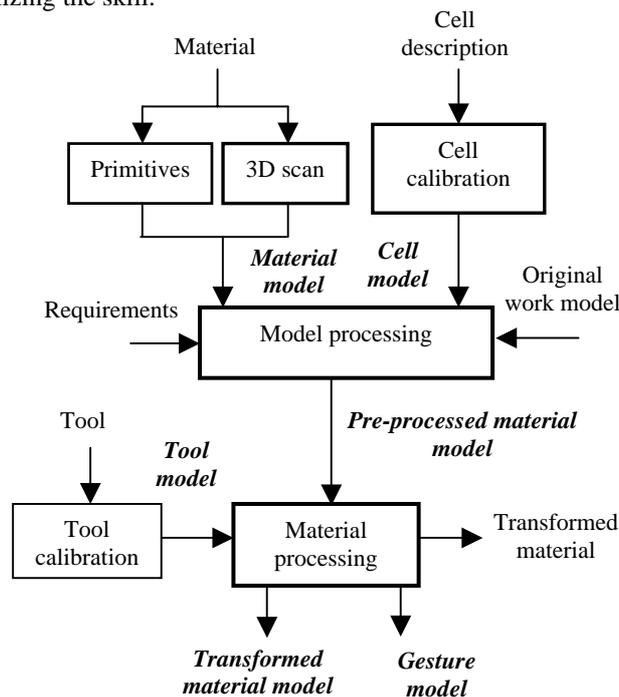
During the replication, the tool, mounted on the measuring arm, is manually manipulated by the specialist (see Fig. 3). The situation (position and orientation) of the tool is captured and sent to the PC computer that performs its treatment taking into account the numerical models of the original work and the material. This treatment consists mainly of two steps : compute the collisions between the tool and the numerical model, calculate a set of information used to generate sensorial feedbacks (visual and sound stimuli) that are sent to the specialist.

## 2.2 Functional description

The functional description of the system is illustrated by Figure 4. The process is based on the use of the following set of models:

- *Cell model*: it contains the descriptions (transformation matrix, state of calibration) of the elements composing the cell.
- *Material model*: it contains numerical descriptions of the geometry (B-Rep, voxel) of the material to be worked. This description can be generated either from a library of simple shapes (like blocs for example) whose dimensions are adjusted on the real material, or from the 3D digitalization of the material. This model is completed by some physical features (type, milling parameters) associated with the material.
- *Original work model*: it represents the numerical reference for the replication. It consists of the complete and valid descriptions (B-Rep, spatial decomposition) of the 3D geometry of the original work.

- *Pre-processed material model*: this model realizes a link between the original work model and the material model. It results from a placing operation of the original work model inside the material model using as inputs the requirements (position and orientation, scale factor) defined by the specialist. This model is used as a reference during the milling operations, especially for collision detection and the computation of the sensorial feedbacks.
- *Tool model*: it describes the parameters of the tool that are necessary for locating the tool with respect to the original work model and for simulating milling operations. This model depends on the tool type and results from a calibration procedure.
- *Transformed material model*: based on the tool model and the pre-processed material model, the system reports the gesture of the specialist and computes in real time the effects of the tool on the material for the milling operations. The result is used to build a 3D representation of the material being worked that is stored into the transformed material model.
- *Gesture model*: it contains the description of the gesture performed by the specialist. This model, mainly composed of the tool trajectory, may be used for training and capitalizing the skill.



**Fig. 4:** Functional description of the system.

The process leading to the material transformation is decomposed into the following steps.

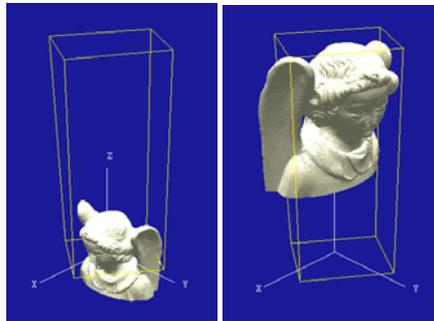
**Cell calibration:** this step manually performed by the operator aims at defining the parameters that specify the situations of the measuring arm and the calibration tool system. The position of the measuring arm is obtained by fingering with calibrated strobe at least three calibrated spheres mounted on the cell. From the computation of the center of the spheres, it is possible to establish the homogeneous transformation that specifies the position of the arm into the cell frame. This technique allows to move the arm into the cell, and consequently, provides a solution for increasing the workspace of the arm. After the displacement of the arm, the calibration procedure is run again in order to compute the new transformation matrix. The calibration procedure consists in fingering three reference points on each plane and computing its position and its normal in the cell frame. In the same time, an homogeneous transformation defining the position of the tool calibration system into the cell frame is computed.

**Material modeling:** this step leads to the definition of the material model. Two aspects are resolved during this step. The first one allows to specify the shape of the material and the second one consists in defining the situation of the material into the cell frame. The shape of the material is specified either from a simple shape selected from a library or from an imported file containing the description of the geometry. The adjustment of the geometry for simple shapes and the position is then computed from a set of fingered points on the real material using the measuring arm.

**Model processing:** this step manually performed by the operator aims at placing the original work model into the material. The original work model, that is imported, is defined in its own frame. The system provides the operator with graphical facilities for manipulating the original work model in order to adjust its position, its orientation and its scale with respect to the material (Fig. 5). This operation allows the operator to choose the way he wants to realize the replication of the original work model into the material. This step uses the material model as support for inspecting the final result of the model processing. The technique allows to realize replication either identical with the original, with enlargement or with reduction. The output of the model processing step leads to a new model (pre-processed material model) that consists mainly of a 3D cell decomposition of the material model calculated from the placing of the original work model.

**Tool calibration:** this step aims at identifying the parameters of the tool model. For each tool, a model and a specific calibration procedure have been established. Our approach has been guided by one goal: to be able to work with the standard tools that are currently used by the specialist. The calibration procedure must be performed the first time before starting milling operations, periodically during milling operations in order to check the wornness of the tool, or when the operator changes the tool.

**Material processing:** during this step, the specialist operates on the real material with the tool. The gesture of the operator is guided in real time to guarantee that the tool does not affect the part of the material representing the shape of the final copy. The process is based on an interactive action/feedback loop. First, it reports into the pre-processed material model the situation of the tool measured at each sample time by the arm and computes the distance between the tool and the original work model. Then, it synthesizes a sensorial feedback for the operator. The effect of the tool on the material can be simulated in real time and stored into the transformed material model. The different positions and orientations of the tool are stored into the model gesture. At any time, the operator can stop the process, for example to change visualization viewpoint or to recalibrate the tool.



**Fig. 5:** Placing the original work model (shaded) into the material (wireframe).

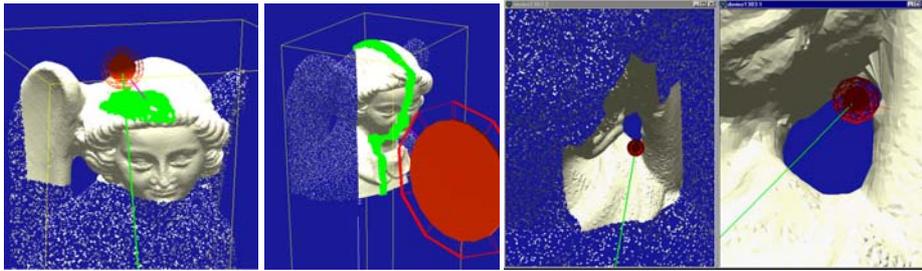
### 3 Sensorial feedbacks for gesture guidance

#### 3.1 Introduction

The guidance of the gesture consists for this application in generating a feedback for the operator that provides him with information on the relative position of the tool with respect to the original model. Techniques resulting from Virtual Reality, especially input devices and output devices, can be applied in that case. However, sculpting induces drawbacks (large workspace, dust, noise) that must be taken into account for the synthesis of sensorial feedbacks. Among the different solutions for sensorial feedback synthesis, the choice has been done to rely sensorial feedbacks on two channels: visual and audio. Sculpting with standard tools consists in performing movement along a limited number of directions, for example one direction when drilling. The solution of haptic feedback has been dismissed because of the large workspace required by the application, and also because of the cost.

### 3.2 Visual feedback

The solution retained for the application is the use of large projection of a set of 3D views representing the original work model and the material. Each view is manually adjusted by the operator before starting the work of the material and a remote control of these views is also available from the measuring arm. During the work of the material, the tool is continuously visualized on each view and the spatial effects of the tool on the original work model are reported on the views. In a first step, the whole original work model is visualized in degraded shading mode and a passive influence zone (square or spherical bounding box) of the tool, computed from the user-defined tolerance  $\tau$ , is highlighted by locally improving the resolution of the visualization. This technique provides the operator with a solution to easily locate in 3D the tool with respect to the original work model. In a second step, an active influence zone, which depends on the geometry of the tool, represents the effect of the tool on the original work model. Finally, the minimal distance of the tool with respect to the original work is visualized. Figure 6 illustrates the information composing the visual feedback for the two types of tool.



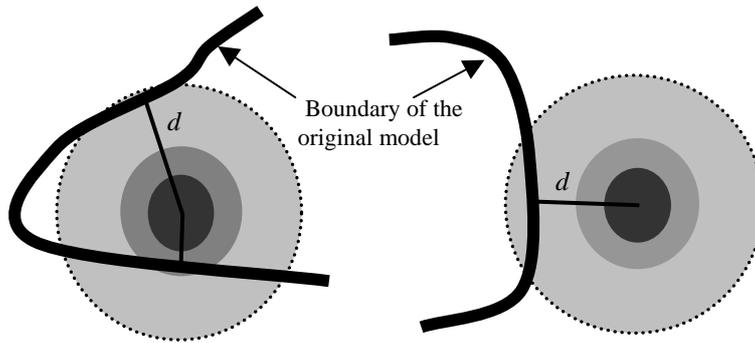
**Fig. 6:** 3D visualization of the spatial effects of the tool associated with the user-defined tolerance (left and left middle). 3D visualization of the active influence zone and the minimal distance (right middle, right).

### 3.3 Audio feedback

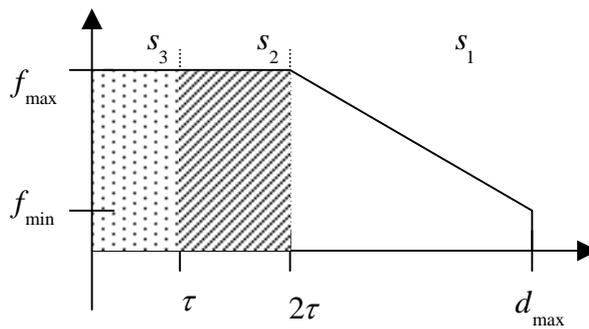
The operator is equipped with wireless headphones and receives an audio signal. The computation of collisions in real time allows to locate the position of the tool with respect to the original work model. It provides the minimal distance  $d$  between the center of the tool and the boundary of the original work model. The frequency  $f$  and the nature of the feedback signal are variable and function of the minimal distance  $d$ . The function  $f = F(d)$  is represented on Figure 8. For the tool reduced to a point, the influence zone of the tool is decomposed in three different zones (Fig. 7). The zones are defined from the user-defined tolerance  $\tau$  that depends on the dimension of the tool. Depending on the position of the collision point associated with the distance  $d$  with respect to the zones, a specific signal is generated.

- if  $0 < d < \tau$ , the signal  $s_3$  is generated at the frequency  $f_{\max}$ . This situation is critical for the replication and it must be avoided.
- if  $\tau \leq d < 2\tau$ , the signal  $s_2$  is generated at the frequency  $f_{\max}$ . This situation is not critical and constitutes a transition before the critical case. Working at the limit between  $s_2$  and  $s_3$  leads to make a replication with an offsetting equal to  $\tau$ .
- if  $2\tau \leq d \leq d_{\max}$ , where  $d_{\max}$  is a user-defined parameter, typically  $d_{\max} = 5\tau$ . The signal  $s_1$  is generated at a frequency  $f$  that linearly varies in function of the distance between the tool and the model as follows:

$$f = f_{\max} - a[d - \tau] \text{ where } a = \frac{f_{\max} - f_{\min}}{d_{\max} - \tau} \quad (1)$$



**Fig. 7:** Influence zones associated with the tool.



**Fig. 8:** Frequency response.

The exploitation of the sensorial feedback by the operator depends on the state of the work. At the beginning of the work, the task aims at removing a large amount of

material until reaching the first shapes of the original model. During this phase, performed with adjusting the tolerance  $\tau$  to a large value, visual feedback plays a key role because it provides the operator with facilities for navigating inside the real material. On the other hand, during the phase that consists in refining the shape of material with small tools, the parameter  $\tau$  is set to a small value, and only the audio feedback is exploited by the operator for guiding the gesture because it provides the user with a precise solution to localize the tool with respect to the original work model.

## 4 Conclusion

The system presented in this paper constitutes an other alternative for the specialists of the art domain for creating new works and also for making replication of existing sculptures. It has been designed to fulfill several requirements: to be human centered by choosing adapted man-machine interfaces, to be simple in its use, to be easily carried and installed in the place where the material must be worked. In the current version of the system, a simple model representing the removal of material by the tool has been developed. This model is based on voxel representation of the material and exploits the swept volume generated by the tool during its movement to update in real time the transformed material model. Today, the system allows to make replications with a precision evaluated to 0.5 mm and a large saving of time (roughly 10 times faster) compared to the traditional sculpting techniques. The system can be used also to perform training of specialists and constitutes a solution for the capitalization of the skill.

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