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Human Centered System for Computer Aided Replication of Sculptures

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Abstract – The paper presents a technical solution for manually making replication of sculptures in real material from a numerical representation of the original work. This solution is based on a human centered system that provides an alternative to current techniques used in the art domain. This paper is focused on the presentation of the main capabilities of the system : functional and hardware characteristics, techniques for computer aided gesture.

I. INTRODUCTION

Making replication of original models is the common way used by museums for providing the general public with original and unique works of art. To make a replication, two steps are required: first, perform on the original the 3D measurements necessary to the realization of the replication, and second build a replication into a given material.

The first phase requires to physically manipulating the original model in order to measure fundamental characteristics that allow to completely specify the shape to be copied. This operation, still performed manually, is laborious and could cause damage to the original model. Most of museums in the world have banished the measurement techniques that require to touch the original model or to be in contact with it. Techniques allowing to digitalize 3D models without contact such as stereovision, laser plane with camera should be consequently preferred. In that case, measurements consist of numerical models (clouds of points, mesh, etc.) that contain a very important number of data and that do not necessary provide the specialist (sculptor for example) with relevant information for the realization of the replication.

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 paper suggests a technical solution for manually making replication of sculptures in a real material from a numerical model of the original work. The realized system provides the specialist with adapted sensorial feedback for a computer assisted gesture. The system has been designed both in order to be simple during its use and to be easily carried and installed in the place (workshop, quarries) where the material must be worked.

II. PREVIOUS WORK

Making replication of an original work based on a numerical model is currently performed in Art [9]. 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 disadvantages. Firstly, they do not allow to realize large work and they are limited to the work of certain materials. Secondly, they involve important investment 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.

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 [4, 6]. Virtual reality technology has played an important role in the developments described in this paper, specially in providing ideas for man-machine interaction [2, 5] and sensorial feedback synthesis [1, 7, 8]. However some techniques provided by virtual reality have been adapted to the specific problem that we have to be faced.

III. DESCRIPTION OF THE SYSTEM

A. Hardware description

The system presented in this paper provides the specialist with a technical solution for making a copy of the original work based on a numerical model. The system is mainly composed of the following devices (cf. Fig. 1):

- A cell defined by the frame R_C . It is mainly composed of a support receiving the bloc of material to be worked and the tool calibration system.
- A PC computer 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 associated with a frame R_A. It provides in real time the position (3 translations) and the orientation (3 Euler angles) of the tool in R_A. The current version of 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) is mounted on the measuring arm. It is associated with a frame R_T defined in R_A.
- A feedback stimuli generator that provides the user with relevant information for guiding the gesture according to the numerical model to be copied.
- A numerical model associated with a frame R_m. It represents the shape to be copied and the bloc of material to be worked.
- A bloc of material associated with a frame R_M and fixed in the cell.
- A tool calibration system associated with a frame R_{TC}. This system mainly composed of a set of reference planes is used to calibrate the tools before and during the work of the material bloc.

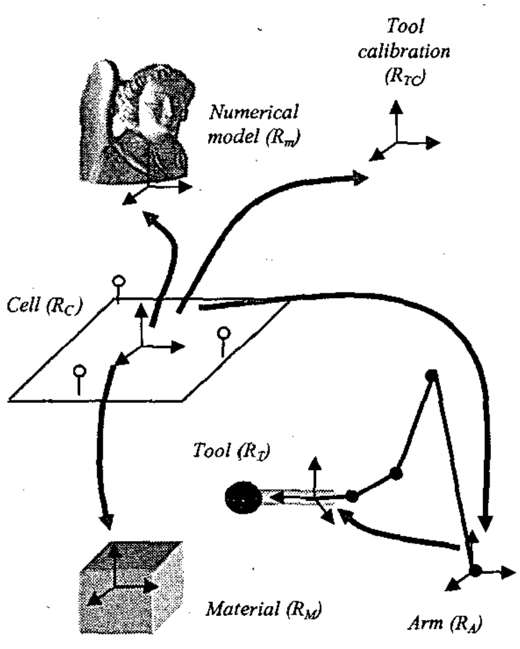

Fig.1 Main devices composing the system

The tool, that is manually manipulated by the specialist, is mounted on the measuring arm that provides the situation (position and orientation) of the tool in real time (cf. Fig. 2). This information is 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 feedback (visual and audio stimuli) that are sent to the specialist.

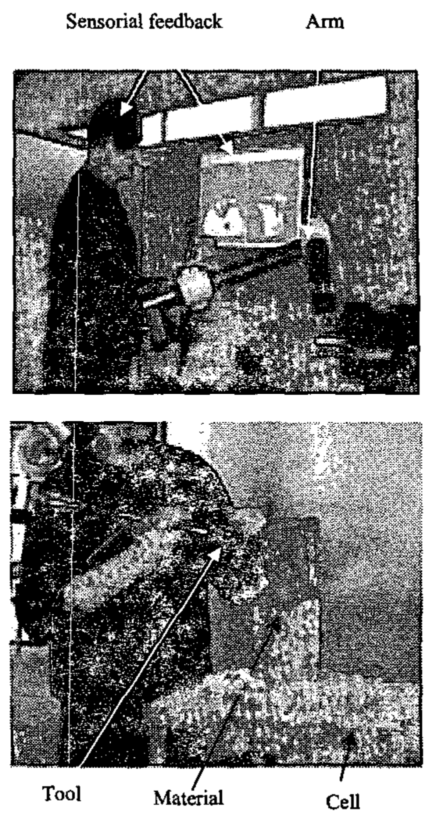

Fig.2. Hardware description of the system

B. Functional description

The different steps of the process leading to the work of the material are presented on Fig. 3. The system uses the following models:

- *Cell model*: it contains the descriptions (transformation matrix, state of calibration) of the elements composing the cell.
- *Material model*: it contains a numerical description of the geometry of the material to be worked. This description is based on a boundary representation. It 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. On the other hand, this model contains some physical features (type, milling parameters) associated with the material.
- *Original work model*: it represents the reference for the copy. It consists of the complete and valid descriptions (B-Rep, spatial decomposition) of the 3D geometry of the original work.
- *Preprocessed material model*: this model establishes 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 that is function of 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 feedback.

- *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 preprocessed 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.

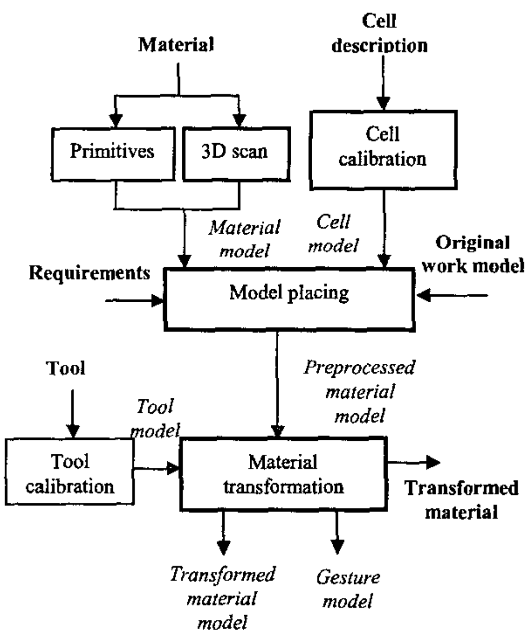

Fig.3. Functional description of the system

The process is decomposed into the following steps.

1) Cell calibration: this step manually executed by the operator aims at defining the parameters that specify the position and orientation of the measuring arm and of the calibration tool system. The position of the measuring arm results from of procedure that consists in fingering (with calibrated strobe) at least three calibrated spheres mounted on the cell. The center of each fingered sphere is computed into the arm frame R_A , and then, the homogeneous transformation ${}^{C}T_{A}$, that specifies the position of the arm into the cell frame R_C, is computed. 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 ${}^{C}T_{A}$. The tool calibration system consists of a structure composed of a set of five reference planes. 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.

2) Material definition: 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 position and the orientation 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.

3) Model placing: 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. This operation allows the operator to choice the way he wants to realize the copy of the original work model into the material. This step uses the material model as support for inspecting the final result of the model placing. On Fig. 4 (left hand) are displayed the material model in wireframe and the original work model. Fig. 4 (right hand) shows the result of the placing that illustrates the transformations performed on the original model: translation, rotation and adjustment of the scale factor ($\cong$ 0.6) in order to fit the original model on the material. The technique allows to realize replication either identical with the original, with enlargement or with reduction. The output of the placing step leads to a new model (preprocessed material model) that consists mainly of a 3D cell decomposition of the material model calculated from the placing of the original work model.

4) 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.

5) Material transformation: 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 preprocessed material model the position and orientation 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.

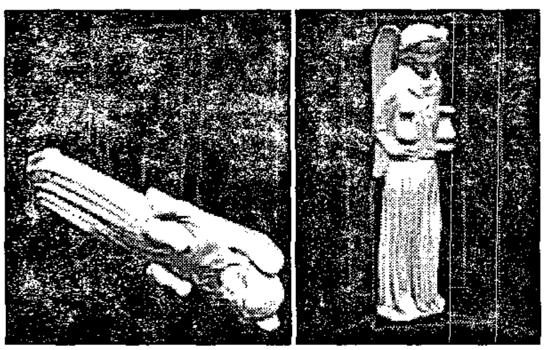

Fig.4. Model placing

All the results coming from each step of the process are stored into a project file.

IV. COMPUTER AIDED GESTURE

A. Introduction

The guidance of the gesture constitutes for this application a real problem because the gesture during sculpting must be controlled along the six degree of freedom associated with the tool. On the other hand, the copy of sculptures must be performed with a good precision (the difference between the original and the copy must be less equal than 0.5 mm on each point of the copy).

B. Tool modeling and calibration

In the present system, two types of standard tool are defined (cf. Fig. 5). 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 on the measuring arm (see Fig. 2) and also to limit the mechanical stress on the arm.

Each tool is represented by a set of parameters. On Fig. 6 is illustrated the set of parameters associated with a drilling tool : diameter d, offset δd, length l, center ${}^{T}c$ defined in the tool frame R_T, the error σ on the position of the tool center. For each situation (position and orientation) of the measuring arm, the center of the tool in the workspace is computed. This center is then exploited for computing the collisions and the swept volume generated by the displacement of the tool into the material [3]. The offset δd is a user-defined parameter that specifies the tolerance admitted between the original work model and the worked material. A the beginning of the work, the value of δd is chosen large enough (drilling operation : δd =3mm for d=12mm). This value is progressively decreased as the work progresses and the worked material becomes closer to the original work model.

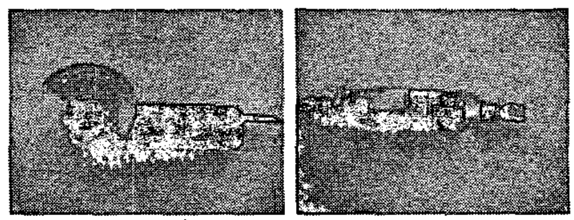

Fig.5. Illustration of standard tools

The tool calibration consists in placing the tool on the tool calibration system in contact with the reference planes and in moving the measuring arm as specified by the calibration procedure. During the operation, the operator stores a set of situations that are used to compute the parameters of the tool model.

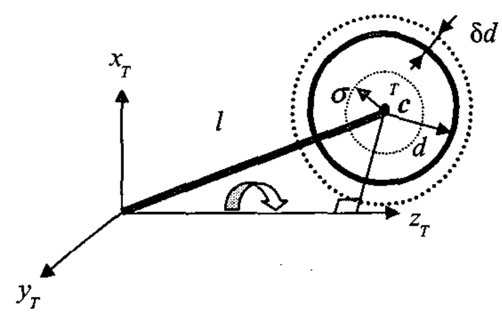

Fig.6. Tool parameters

C. Sensorial feedback

The computation of collisions allows to locate the position of the tool with respect to the original work model. It provides in real time the minimal distance between the center of the tool and the boundary of the original work model. The sensorial feedback used for computer assisted gesture is decomposed into visual and audio information.

1) Visual feedback: it is obtained by a projection, on a large screen, 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 offset δd, 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. Fig. 7 illustrates the information composing the visual feedback for the two types of tool.

Fig.7. Visual feedback

2) Audio feedback: the operator is equipped with wireless headphones and receives an audio signal whose frequency F is variable and function of the minimal distance D_{min} between the tool and the original work model expressed in number of offsets δd. The function $F = f\left(\frac{D_{min}}{\delta d}\right)$, represented on Fig. 8, outlines two different zones. For the distances greater than δd, the frequency linearly evolves in function of D_{min}. When the distance becomes less equal than δd, the signal returned to the operator is switched to an aggressive signal meaning that the admitted tolerance is reached.

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 parameter δd 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 δd 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.

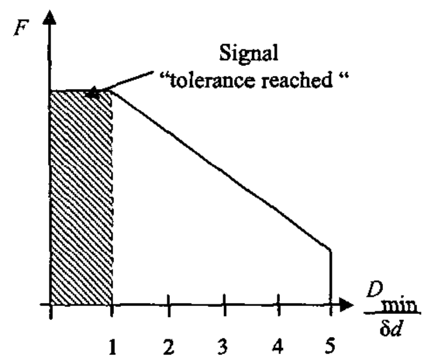

Fig.8. Frequency function

D. Tool-material interaction

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. Fig. 9 shows the result obtained with a drilling tool.

The transformed material model can be viewed as a way to capture the skill of the specialist and it can used to analyze the result for training. But it constitutes another input for creation of new original models. Given a bloc of material, it is possible to store and visualize the effects of the gesture. The result can be used afterwards as input (original work model) to the system.

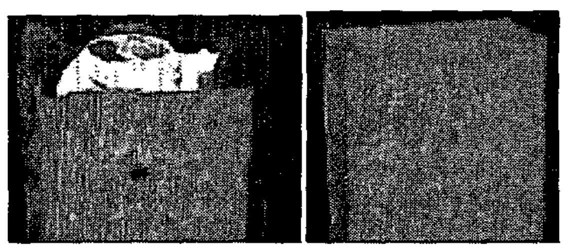

Fig.9. Tool-material interaction

V. 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.

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.

The next steps of the developments concern evolutions of the man-machine interfaces. Attention will be given to the need for some form of force feedback.

VI. REFERENCES

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