VIRTUAL DRILLING - SCULPTURING IN 3-D VOLUMES

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Abstract— **In this paper we propose a virtual drilling - sculpturing algorithm applied on 3-D objects. The 3-D objects can either be simple geometrical shapes such as cubes and spheres or more complicated objects as teeth. In the second case, we consider that we are provided with a sparse set of parallel and equi-distant slices of the 3-D object. With that set of slices we reconstruct the 3-D object using a volumetric interpolation method. On the created volumes, we simulate the drilling action as a 3-D erosion operation. The proposed technique is applied for virtual drilling of teeth considering various bur tools of different shapes as erosion elements. Furthermore, the algorithm has been extended as a virtual sculpturing method that can be applied in many 3-D objects, simulating the action of chisel tools.**

Keywords: shape-based interpolation, drilling, virtual sculpturing, simulation, user-friendliness

I. INTRODUCTION - METHOD DESCRIPTION

Virtual surgery using 3-D data visualization and human interaction has lately attracted a lot of attention due to its potential use in surgical intervention planning and training [1]. In that framework, a virtual dental drilling environment was developed and it is proposed in this paper. Drilling is applied on 3-D tooth images and is simulated by a set of successive 3-D morphological erosions. This application can be used for training and educational purposes helping dental school students and young dentists to acquire the necessary drilling experience, as well as for testing purposes, i.e. simulating a drilling operation before applying it, in real environment. Since the application is intended to people that might have limited familiarization with computers, user - friendliness was one of the principal goals.

At the beginning of the application , a window containing a 3-D volume, representing a tooth, appears on the screen. The user may select between a spherical, a cylindrical or a cylinder-conical dental burs, as those than can be seen in Figure 1 and determine its radius and height, whether it is necessary. A set of standardized bur tools with fixed dimensions is also provided as a user - friendly interface service.

Having selected an appropriate tool, the user proceeds with drilling operation. The 3-D tooth image may be rotated, to achieve a better perspective view in order to select the point where drilling will be applied. Rotation is realized either by using the mouse or by entering the right perspective angle for more accuracy using the appropriate edit dialog box that it is provided by the application. Then, drilling is implemented by putting the cursor of the mouse at the appropriate point of tooth's volume and clicking the mouse button. Drilling is simulated by a volumetric erosion operator with a 3 - D morphological structuring element.

The structuring element of the erosion operator has a changeable size which is proportional, each time, to the dimensions of the used bur. Therefore, drilling effects are generated by creating a hole in the size and shape of the tool, at the cursor's location. For the visualization of drilling, each time that the mouse is pressed in tooth's surface, volume rendering is applied locally onto the area of the hole, where rotation means that the whole volume of the tooth is rendered in order to view volume under the new perspective angle.

For improved visualization of the drilling effects red/green or red/blue stereo images that can be viewed with stereo glasses are generated. Stereo effects are produced by composing two different images, one from the red and one from the blue or green canal, of an RGB type image of the same 3-d object slightly transposed one from the other. The user can recall (undo) a previous operation or save the partial results of drilling in order to recall them later either for demonstration reasons or continuing drilling. For the saving purposes, the appropriate parameters, such as view angles, dimensions of bur tool, drilling point, that are needed, are maintained in a linked list data structure.

For tooth volumes construction, tooth slices acquired by mechanical slicing were used. These slices were digitized and the tooth was segmented from its background. Automatic or semi - automatic alignment of the slices was then performed. Usually the pixel size within a slice is different from the spacing between two adjacent slices. In such situations it is necessary to interpolate additional slices in order to obtain an accurate volumetric description of the tooth. For that reason, we have devised a shape based interpolation method using morphology morphing.

The drilling method that is proposed in this paper can be also used in virtual sculpturing, simulating the whole process of the creation of a sculpture.

The paper is organized as follows. Section 2 describes the interpolation algorithm, and the drilling simulation al-

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gorithm is presented in Section 3. Section 4 outlines how the drilling algorithm can be extended to a virtual sculpturing tool and Conclusions are drawn in Section 5.

II. Shape based interpolation using morphology morphing

Several interpolation methods exist in the literature [2], [3], [4]. Our approach relies on erosions and dilations for morphing consecutive 2-D sets into one another. Let us assume that we are provided with two aligned sets X_i, X_{i+1} sharing at least one common point. Also, consider $X_{i,m}$ an element (pixel in 2-D or voxel in 3-D) of X_i, where m denotes an ordering number and $X_i^c = E - X_i$ is the complement (background) of the set X_i. Each element $X_{i,m}$ in one set has a corresponding element with the same coordinates in the other set either as a member of $X_{i+1,m} \in X_{i+1}$, or as a part of its background $X_{i+1,m}^c \in X_{i+1}^c$.

Let us denote the elements located on the boundary set by C_i. We can identify three possible correspondence cases for the structuring elements of the two aligned sets, that are described by the following equations :

$$\begin{array}{cc} \text{If} & X_{i,m} \in C_i \wedge X_{i+1,m} \notin C_{i+1} \\ \text{then} & \text{do } X_{i,m} \oplus B_1 \\ \text{If} & X_{i,m} \in C_i \wedge \exists\, X_{i+1,m}^c \\ \text{then} & \text{do } X_{i,m} \ominus B_1 \end{array} \tag{1}$$

$$\begin{array}{cc} \text{If} & X_{i,m} \in C_i \wedge X_{i+1,m} \in C_{i+1} \\ \text{then} & \text{do no change} \end{array} \tag{2}$$

where $\oplus$ represents dilation, $\ominus$ denotes erosion and B_1 is the structuring element for the set X_i. Including all these local changes we define the following morphing transformation applied on both sets X_i, X_{i+1} :

$$\begin{aligned} f(X_i|X_{i+1}, B_1) = \; & [(X_i \ominus B_1) \\ & \bigcup((X_i \bigcap X_{i+1}) \oplus B_1)] \\ & \bigcap(X_i \bigcup X_{i+1}) \end{aligned} \tag{3}$$

The morphing operation is applied iteratively onto the sets resulting from the previous morphing. The succession of these operations creates new sets starting from the two initial extreme points . The interpolation operation is applied to all pairs of slices that form a 3-D volume.

III. Drilling Simulation Algorithm

After reconstructing the 3-D object as mentioned in Section II, may be simulated drilling operation onto this object. The drilling of the 3-D volume proceeds along a certain direction. If we have a spherical coordinate system then the drilling direction is given by two angles (θ, ϕ), where θ is the angle between the drilling direction and the image plane *(x,y)* and ϕ is the angle between the projection of the drilling direction on the image plane and the horizontal axis x. The drilling of a volume V produces a drilled volume, denoted as V', and can be presented as a succession of erosions:

$$V' = V(x, y, z) \ominus B^{(3)} \tag{4}$$

where $B^{(3)}$ is the volumetric structuring element and (x, y, z) the point where drilling is applied. By keeping a log of the tooth's parts that have been removed, one can easily implement the undo action.

In conclusion the simulation of the drilling or undo action is achieved by successively eroding or adding 3 - dimensional structuring elements from or on the volume respectively, in a certain direction. The drilling direction is given by the following equations:

$$\begin{aligned} x(i) &= x(i-1) \pm d\cos(\theta)\cos(\phi) \\ y(i) &= y(i-1) \pm d\cos(\theta)\sin(\phi) \\ z(i) &= z(i-1) \pm dsin(\theta) \end{aligned} \tag{5}$$

where " $-$ " corresponds to the drilling - eroding action, " $+$ " corresponds to the undo - adding action, d is the width of the drilling element in the direction of the drilling, and $(x(0), y(0), z(0))$ the coordinates of the starting drilling point.

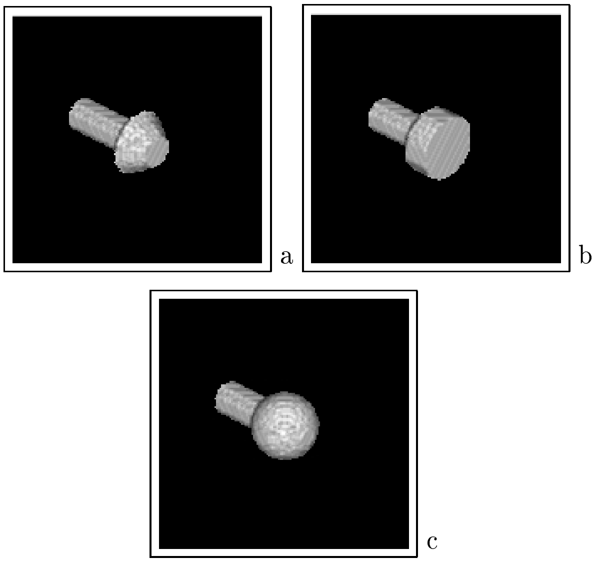

Fig. 1. *The three types of bur tools that are used.* **(a)** *Cylinder-Conical Tool.* **(b)** *Cylindrical Tool.* **(c)** *Spherical Tool.*

The volumetric erosion element B^3 is implemented using three basic shapes: spherical, cylindrical and cylinder-conical, as can be seen in Figure 1. The region of the volume V, where drilling was applied, is assigned the value of the background. So, for the case of the spherical element, we have at the j-th iteration:

$$\begin{aligned} & (x, y, z) \in V', \\ & (x - x_{IM})^2 + (y - y_{IM})^2 + (z - z(j))^2 < \\ & d^2 \in V'^c \end{aligned} \tag{6}$$

where d is the radius of the spherical erosion element, V'^c the background and (x_{IM}, y_{IM}) the coordinates on the image where the erosion takes place. In exactly the same way we can define the erosion procedure with a cylindrical and cylinder-conical structuring element. Results of drilling simulation can be seen in Figure 2.

IV. Virtual Sculpturing

The virtual drilling algorithm presented in Section III has been extended to be part of a virtual sculpturing ap-

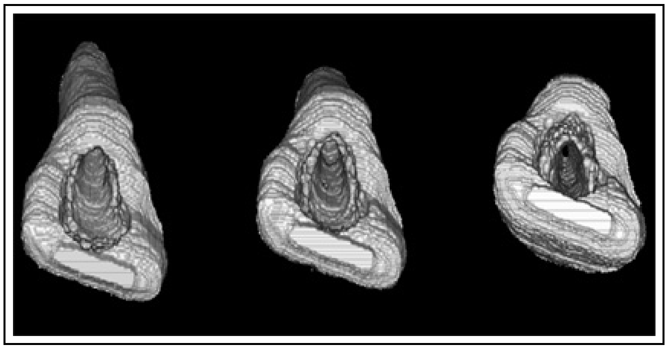

Fig. 2. *Different views of a maxillary incisor after drilling.*

plication. Many efforts have been made in this field either based on a surface or volumetric models for the 3 - D representation and the interactive computer editing [5], [6], [7], [8], [9]. Although, surface models have the advantage of a realistic 3- D representation of an object, with a low cost in storage and computer overhead, there are complications applying interactive editing on such models because of the nature of the surface, as the interior of the object is left hollow and information exists only around an infinitely thin skin on the exterior of this object. On the other hand, volume models have the advantage that they describe explicitly three dimensional object through an axis - aligned grid of voxels, sacrificing matters as resolution and needs in memory and storage. But the fact that within this approach a model is treated as a solid, filled object in space makes modeling tasks, such as sculpturing, much easier in the usage than that of surface models. Volumetric sculpturing was initially introduced in [7]. In this system a user could move a tool in 3D space and locally edit the volumetric information. Volume sculpturing was significantly extended with the usage of specific haptic devices as those proposed in [10], [11]. Common characteristic of all methods is the usage of a specific input device like haptics.

Our drilling - sculpturing algorithm follows the volumetric approach but without using any specific/dedicated input device. The sculpturing operation is achieved with only the usage of the mouse, a device that exists on any computer, and with real interactive response times. As in the tooth drilling application, volume rendering is locally in the region where the virtual chisel tool is applied and only the rotation function requires rendering of the whole volume. For instance, our application supports two types of chisel tools, a spherical and a cylindrical, and also two types of objects, cube and sphere, where sculpturing can be applied. The user can determine both the dimensions of the chisel and the size of the 3 - D object, and after can proceed with the 3 - D sculpturing operation whose function is the same as in tooth drilling. Saving, undo and redo are capabilities that offered as services of a user - friendly interface taking under consideration that a sculptor has similar needs with these of a dentist. In Figure 3 we can see the Virtual sculptor's menu where in Figure 4 it is presented the cubic and spherical 3 - D object where sculpturing can be applied.

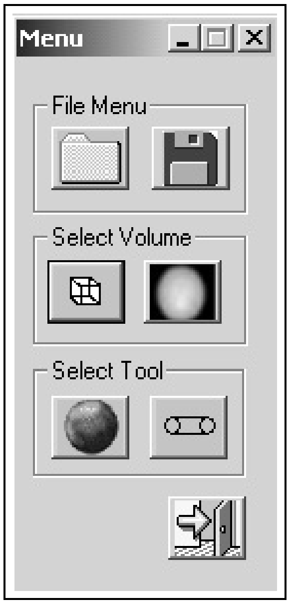

Fig. 3. *The sculp menu.*

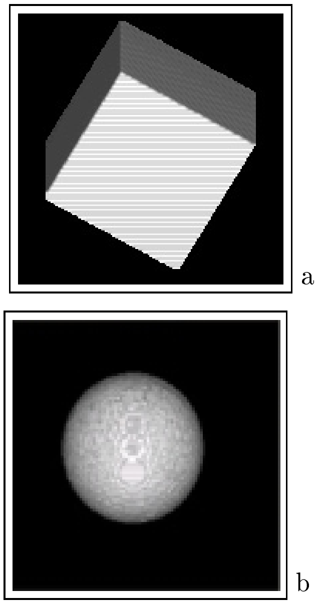

Fig. 4. *The 3-D sculpturing objects.***(a)** *The Cube object.* **(b)** *The Sphere object.*

V. Conclusions

We have proposed an algorithm for drilling 3-D objects reconstructed from a set of slices using an intermediate interpolation step. Interpolation is performed using a morphological shape-based approach. Virtual drilling is simulated by a succession of erosions, and includes capabilities such as rotation, undo and stereo display. The proposed algorithms are applied on 3-D teeth models, where three different erosion elements are considered as bur tools: spherical, cylindrical and cylinder-conical. We have also extended the algorithm to consider virtual sculpturing application. Further improvements can be done in the field of a more user - friendliness interface.

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