VIRTUAL DRILLING IN 3-D VOLUMES

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ABSTRACT

In this paper we propose a virtual drilling algorithm which is applied on 3-D objects. We consider that we are provided with a sparse set of parallel and equi-distant slices of a 3-D object. With that set of slices we reconstruct the 3-D object using a volumetric interpolation method. On the reconstructed volume 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.

1. 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]. A virtual dental drilling environment 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 to acquire the necessary drilling experience, as well as for testing purposes, i.e. simulating a drilling operation before applying it, in real. Since the application is intended to people that might have limited familiarization with computer, user-friendliness was one of the principal goals. When the application starts, a window containing a 3-D volume, representing a tooth, appears on the screen. The user can select between a spherical, cylindrical or cylinder-conical tool and determine its radius and height. A set of standardized bur tools with fixed dimensions is also provided.

Having selected an appropriate tool, the user proceeds with drilling operation. The 3-D representation of the tooth can be rotated, to achieve a better perspective view and 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. Then, drilling is implemented by putting the cursor of the mouse at the appropriate point of tooth's volume and pressing the button of the mouse. Drilling is simulated by a volumetric erosion operator whose morphological structuring element is three dimensional. Drilling effects are generated by creating a hole in the size and shape of bur tool, at the point where the cursor was pressed. For improved visualization of the drilling effects red/green or red/blue stereo images that can be viewed with stereo glasses are generated. The user can recall (undo) a previous operation or save the partial results of drilling.

For the construction of tooth volumes, we use tooth slices acquired by mechanical slicing. These slices are digitized and the tooth is segmented from its background. Automatic or semi-automatic alignment of the slices is performed next. 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 our purposes, 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, Section 3 the drilling simulation algorithm. Conclusions are drawn in Section 4.

2. SHAPE BASED INTERPOLATION USING MORPHOLOGY MORPHING

Several interpolation methods exist in the literature [2], [3], [4]. Our approach uses 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}, which are sharing at least one common point. Also, consider $X_{i,m}$ an element (pixel in 2-D or voxel in 3-D) contained into the set X_i, where m denotes an ordering number and where $X_i^c = E - X_i$ is the complement (background) of the set X_i. Each element $X_{i,m}$ in one set will have a corresponding element that has the same coordinates in the other set either as a member of $X_{i+1,m} \in X_{i+1}$, or 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. One situation occurs when the border region of one set corresponds to the interior of the other set. In this case we dilate the border elements :

$$\begin{array}{cc} \text{If} & X_{i,m} \in C_i \wedge X_{i+1,m} \notin C_{i+1} \\ \text{then} & \text{perform } X_{i,m} \oplus B_1 \end{array} \quad (1)$$

where $\oplus$ represents dilation and B_1 is the structuring element for the set X_i. A second case occurs when the border region of one set corresponds to the background of the other set. In this situation we have erosions of the boundary elements :

$$\begin{array}{cc} \text{If} & X_{i,m} \in C_i \wedge \exists\, X_{i+1,m}^c \\ \text{then} & \text{perform } X_{i,m} \ominus B_1 \end{array} \quad (2)$$

where $\ominus$ denotes erosion. No modifications are performed when both corresponding elements are members of their sets boundary :

$$\begin{array}{cc} \text{If} & X_{i,m} \in C_i \wedge X_{i+1,m} \in C_{i+1} \\ \text{then} & \text{perform no change} \end{array} \quad (3)$$

By including all these local changes we define the following morphing transformation applied on the set X_i depending onto the set X_{i+1} and on the structuring element B_1 :

$$f(X_i|X_{i+1}, B_1) = [(X_i \ominus B_1) \bigcup ((X_i \bigcap X_{i+1}) \oplus B_1)] \bigcap (X_i \bigcup X_{i+1}) \quad (4)$$

A similar operation as in (4) is defined onto the set X_{i+1}. 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 extremes. Eventually this processing will lead to the idempotency of the resulting sets. This set will represent the resulting interpolation. The interpolation operation is applied to all pairs of slices that form a 3-D volume.

3. DRILLING SIMULATION ALGORITHM

After reconstructing the 3-D object as mentioned in section 2, we can simulate 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 O produces a drilled volume, denoted as O', and can be presented as a succession of erosions:

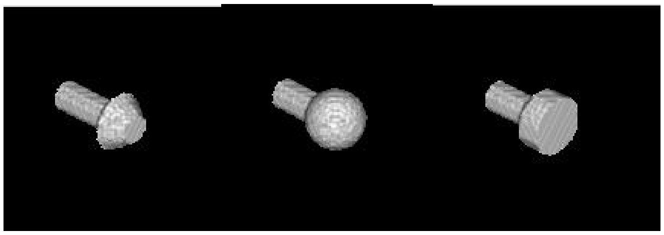
$$O' = O(x, y, z) \ominus B^{(3)} \quad (5)$$

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:

$$\begin{aligned} x(i) &= x(i-1) \pm d\cos(\theta)\cos(\phi) \\ y(i) &= y(i-1) \pm d\cos(\theta)\sin(\phi) \\ z(i) &= z(i-1) \pm dsin(\theta) \end{aligned} \quad (6)$$

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 coor-



(a) (b) (b)

Figure 1: (a) Cylinder-Conical (b) Spherical (c) Cylindrical tool

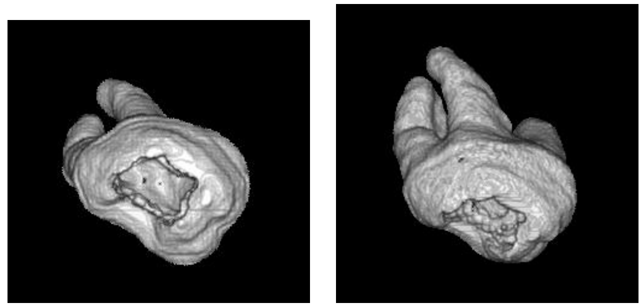
dinates of the starting drilling point.
The volumetric erosion element B^3 is implemented using three basic shapes: spherical, cylindrical and cylinder-conical, as can be seen in Figure 1. The region of the volume O, where drilling was applied, is assigned the value of the background. So, for the case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

$$(x, y, z) \in O',$$
$$(x - x_{IM})^2 + (y - y_{IM})^2 + (z - z(j))^2 < d^2 \in O'^c \quad (7)$$

where d is the radius of the spherical erosion element, O'^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 2a,b where we can se a premolar from two different points of view.

4. 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. This application is intended for training dentistry students, but can be extended to perform virtual sculpturing.



(a) (b)

Figure 2: 3-D views of an interpolated premolar, drilled with the proposed algorithm.

5. REFERENCES

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