A VIRTUAL REALITY TOOTH DRILLING SIMULATOR

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Abstract

A virtual teeth drilling system whose basic aim is to be used for the training of dental students in the handling of drilling instruments is presented in this paper. A 3D model of the face and the oral cavity is utilized by the application. This model can be adapted to the characteristics of a specific person and animated. Drilling is performed within the oral cavity, on realistic teeth models constructed from real data. A haptic device can be used to control the drilling operation. Results as well as intermediate steps of the drilling procedure can be saved for future use.

1 Introduction

Practicing dental drilling for cavity preparation and other similar tasks is an important part of a dental student training. In most cases students use artificial teeth and jaws (sometimes placed within a manikin head) and real instruments before proceeding to real patients. Lately, virtual-reality based cavity preparation training systems have been introduced. The DentSimTM system (Denx Corp, Jerusalem, Israel) [1] is such an example. The system comprises of a real dental unit, a manikin head, a tracking system and software that allows students to view the results of his/her cavity preparation in the manikin head on 3D models displayed on a computer monitor and compare them with the results of an optimal preparation. The systems in [2], [3] involve a 3D virtual tooth model and a Phantom haptic device (Sensable Technologies Inc., Woburn, MA) that enables the trainee to perform virtual drilling while receiving force feedback. The systems described in both these papers operate on standalone teeth and the focus is on providing realistic material removal simulation as well as realistic, haptically stable and computationally efficient force rendering. However such a simulation would be much more realistic if cavity preparation was performed on teeth placed within the oral cavity.

The virtual tooth drilling simulator presented in this paper allows the user to view and manipulate a 3-D head and oral cavity model constructed using anatomical data, adapt the model to the characteristics of specific patient using facial photographs, animate it using an MPEG-compatible facial animation player and use a Phantom haptic device to perform virtual tooth drilling within the oral cavity.

Drilling is performed on 3D teeth models using a dual volumetric/surface representation. These models have been obtained from cross sections of real teeth. The final results, i.e. the drilled teeth models, as well as intermediate steps of the drilling procedure can be saved for future use. Apart from being used for training students, the system can also assist experienced dentists in planning a real tooth drilling intervention i.e., getting familiar with the anatomy of a certain patient, planning the approach and deciding upon the preferable target position of the actual drilling operation.

This paper is structured as follows. The construction of the head/oral cavity model is described in Section 2. Model adaptation/personification and animation is described in Sections 3, 4, whereas virtual tooth drilling is presented in Section 5. Conclusions follow.

2 Modeling of the Head and the Oral Cavity

A head/oral cavity model comprised of anatomically meaningful 3D points taken on the various head tissues was constructed by using manual modeling techniques at the cost of increased modeling time [4]. The 3D surface model consists of 1392 3D points and 2209 triangles that model 11 different anatomical entities (nodes) (Figure 1). The publicly available anatomical (cryosections) and CT data of a male cadaver originated from the Visible Human Project (National Institute of Health (NIH), USA) [5] have been used for this purpose.

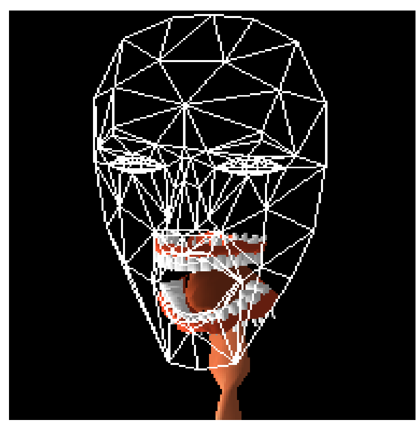

Figure 1: The oral/head cavity 3D model utilized in the virtual tooth drilling simulator.

The model incorporates the external face area and gums, palate, teeth, tongue, lips, cheeks, larynx and uvula. All formations are represented as triangular meshes. For modeling the face, we have used the CANDIDE – 3 [6] face model and adapted it to the NIH data. The constructed model provides an MPEG-4 compliant extension of the CANDIDE-3 that incorporates both the oral cavity's internal tissue surfaces (which are important for dental applications) and the head - neck outer surface.

3 Model Adaptation

Within the simulator presented in this paper, the user can adapt the generic facial mesh model so that it matches the characteristics of a specific person, using a semi-automatic approach. This procedure relies on two photographs of the person obtained from two perpendicular directions, i.e. a frontal one and a side one (Figure 2). The adaptation is supported by a 2D FEM (Finite Element Model). This approach has been selected because of its speed and reliability and because it requires only a limited amount of interaction with the user. The two steps of the adaptation process are explained below.

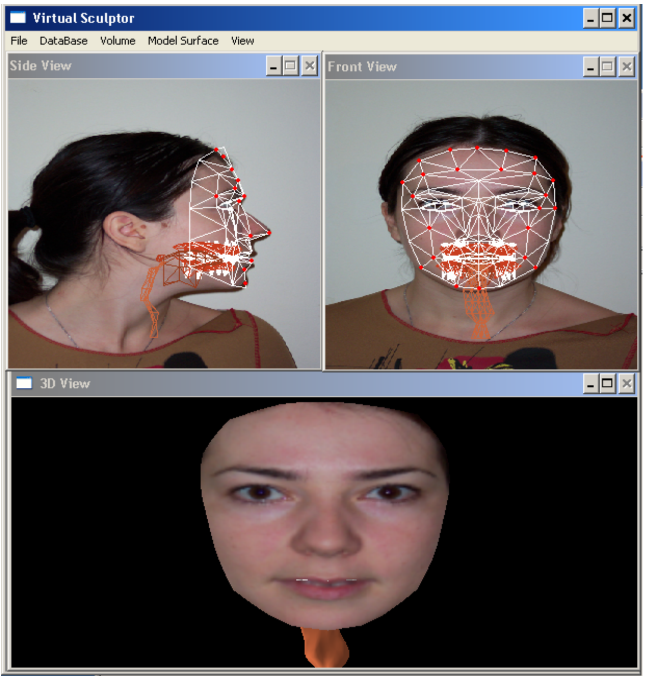

Figure 2: Model adaptation using two facial photographs.

In the first step, the user performs global translation and scaling on the facial model which is overlaid on the two photographs. The models of the internal, oral cavity, structures are scaled and translated automatically in the same way as the facial model.

For a detailed adaptation of the mesh on the photographs, user interaction along with a 2D FEM [7] method is used in the second step. Essentially the model's mesh is represented as a system of springs that can be deformed through user interaction. The user moves (by using the mouse) a certain number vertices of the model's mesh, to the corresponding points in the picture. Subsequently, the FEM moves the remaining vertices of the mesh (i.e. those that have not been displaced by the user). This operation is executed in real time so that the user can see the results of the interactive adaptation.

The interactive FEM-based adaptation is applied only on the facial model. The models of the oral cavity structures are translated and scaled in real time according to the position of the model's mouth. More specifically, after each deformation of the facial mesh, the translation of the centre of the mouth (evaluated using FDPs 8.3 and 8.4) is calculated and the models of the internal structures are translated by the same amount. Moreover, the oral cavity models are scaled on the basis of the jaw width which in turn is evaluated using the centers of the cheeks (FDP 5.1 and 5.2).

At the final stage of the model adaptation/personification the user can select through a graphic representation of the teeth the ones that he wishes to remove from the model. This is useful in cases of persons that lack some of their teeth. Furthermore, the user can control which parts of the model (e.g face, gums, tongue) will be visible.

In addition, the user can replace within the 3D oral cavity model the limited resolution prototype of a certain tooth where virtual drilling will be performed with a more detailed model. In order to do so, the user provides the volumetric model of the tooth in the form of a series of slice images where the structures of interest (external tooth surface and root canals) have been segmented. A database of volumetric models for all types of teeth (canines, molars, premolars etc) is provided along with the application. The database has been constructed by digitizing and post-processing (i.e., aligning and segmenting) physical cross sections of extracted teeth, which are viewed through an optical microscope.

The application loads the volumetric representation of the tooth (required for the drilling procedure as will be explained later) and applies the Discrete Marching Cubes algorithm [8] in order to obtain the tooth surface and embed it in the face/oral cavity model. The user can control several options of the surface extraction procedure (merging of coplanar triangles that will result from the triangulation, smoothing of the surface by applying Laplacian smoothing, etc) through an appropriate interface. The insertion of the selected tooth in the face/oral cavity model is performed in two steps:

- Coarse automatic placement of the tooth on the gums. This step utilizes information about the size of the teeth models and the alveole.
- Optional manual adjustment (global rotation, translation scaling).

After the adaptation, the 3D model of the face can be texture mapped using the facial photographs in order to achieve additional realism.

4 Animation

Animation of the models is performed in an MPEG-4 compatible way. More specifically, the application incorporates a FAP (Facial Animation Parameters) player that reads FAP files from disk and animates the model by moving the corresponding MPEG-4 FDPs. The user can select to save the model configuration at a certain frame of the animation in VRML format.

The movements of the internal structures, i.e., the ones that are not covered by the MPEG model, should be also defined. More specifically, the movement of the lower jaw which is a rotation around an axis should be defined. In order to do so, the user specifies this axis during the model adaptation procedure. The movement of the vertex that represents the chin, i.e., FDP 2.1 is then used to define the angle of rotation of the jaw around this axis. The lower teeth, gum and tongue are also rotated along with the jaw. In order to implement the horizontal motion of the lower jaw, the influenced models (teeth, gums, jaw, etc) are translated in the x axis at the same distance and direction as the vertex that defines the tip of the chin (FDP 2.1).

Real-time surface subdivision is used during the animation in order to improve the visual quality of the models and obtain smooth surfaces. A technique that leaves the original model vertices unaffected is required in this case. After experimentation, the curved Point-Normal triangles (curved PN triangles) technique [9] has been selected.

5 Tooth Drilling Simulation

After loading a detailed tooth model on the application the user can proceed in performing virtual drilling on this tooth. Both the volumetric (voxel-based) and surface representation of the tooth are available to the application, since in the proposed approach, removal of material during drilling is implemented as a series of morphological operations on the volumetric representation of the object. More specifically, the drilling operations in the virtual drilling approach that has been developed are simulated using successive erosions that involve 3-D structuring elements representing the shape of drilling tools (dental burs) [10]. This approach can be used to implement almost any kind of drilling tool shape. Four basic tool shapes, namely a spherical, a cylindrical, a cylindrical-conical and a conical tool have been implemented using 3-D mathematical morphology decomposition. The user can select the appropriate drilling tool and control its shape parameters (e.g. the radius for the spherical tool). The parameters of a tool can be saved for future use. Moreover, the application is accompanied by a database of virtual dental burs whose dimensions have been obtained from real burs.

At this stage the user can perform on the volumetric tooth model two additional operations:
1) Add material on the surface of the volume, an operation that has been implemented by using 3D dilations.
2) Perform local smoothing of the volume, by using the mouse and by selecting an appropriate smoothing window.

The dental drilling operation can be performed directly on the standalone volumetric model of the tooth using the mouse. However, a more realistic simulation can be achieved by performing drilling on the surface model of the inserted tooth, within the full face-oral cavity model, using either the mouse or a haptic device to control the operation (Figure 3). The Phantom Desktop six degrees of freedom positional sensing force-feedback haptic device has been used for this purpose.

With the use of the haptic device, the user can perform drilling while sensing contact/resistance forces. Currently, a constant force model is utilized. The force value is determined by the properties (stiffness, static and dynamic friction) of the object, which are set by the user. The stylus of the haptic device controls the position of the dental bur [11] which is also visible as a simple surface model in the scene. During the material removal operation, the application utilizes the internal dual surface/volumetric representation of the tooth. This dual representation is necessary since the GHOST SDK (Sensable Technologies Inc. Woburn, MA) is used for handling the tool-tooth physical interaction (e.g. collision detection). GHOST requires that the object is represented by its surface whereas the proposed mathematical morphology-based material removal algorithm operates on the volumetric representation of the tooth. More specifically, the position of the tip of the drilling tool on the surface representation of the tooth (obtained through collision detection) is used to find the corresponding position on the volumetric representation. Subsequently, 3D erosions with the appropriate structuring element are performed at this position of the volumetric model and the haptic device scene graph is updated with the altered surface model. Reduced update time is achieved by performing local updating of the surface model through a local application of the Discrete Marching Cubes algorithm on the area of the volumetric representation that has been affected by the drilling.

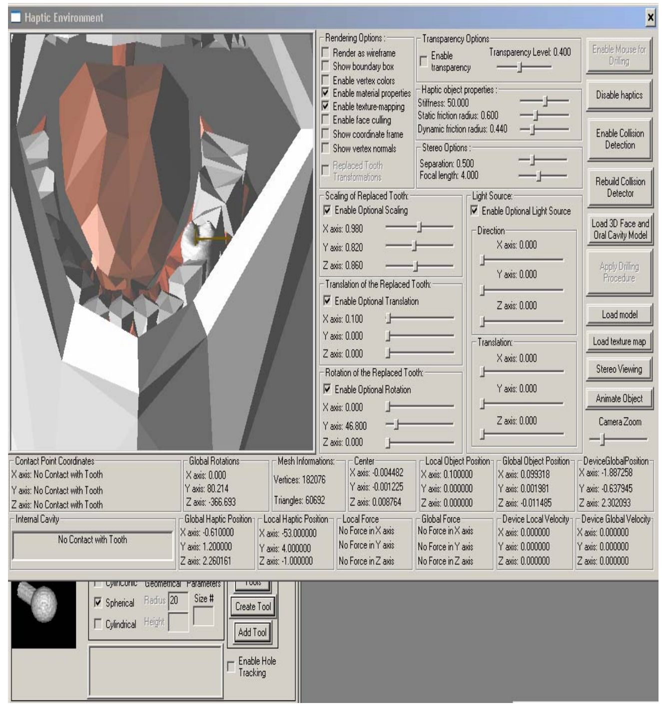

Figure 3: Virtual drilling on the face/oral cavity model.

The user can select to keep track of the performed drilling operations on the tooth model, i.e., keep the "history" of the performed operations. If the user chooses to keep track of these operations he can undo a certain number of them. Furthermore, he can save the sequence of operations on a file and re-apply them on the current tooth. Thus, an experienced dentist can perform the operation and then "replay" in order to train dental students.

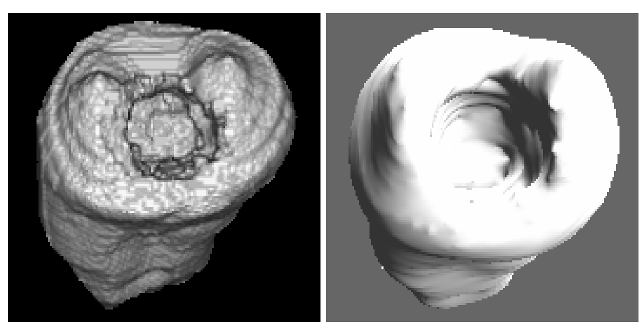
Figure 4: Volumetric (left) and surface (right) representation of a tooth that has been subject to virtual drilling.

The tooth that has been subject to a drilling operation can be saved either in volumetric representation (i.e. as a series of slices) or as a triangular mesh (in VRML2, DXF and STL formats). An example of a tooth that has been drilled with the developed application can be seen in Figure 4. During drilling, the user can enable stereo viewing through active shutter glasses. In addition, transparency options are provided.

6 Conclusions-Future Work

A novel virtual tooth drilling simulator has been described in this paper. The application allows the user to practice virtual tooth drilling for cavity preparation and similar tasks on detailed teeth models that are placed within an animated 3D head and oral cavity model. The models can be adapted to the characteristics of a specific patient. During the operation, a Phantom haptic device is used to provide force feedback. So far the focus was on developing the "visual" part of the application with sufficient realism. In the future, realistic and physically accurate material removal and force models that will take into account all the involved factors will be pursued. Usability tests involving dental students will be also performed.

7 Acknowledgements

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