Dental Training System using Multi-modal Interface

Laehyun Kim[1], Yoha Hwang[2], Se Hyung Park[3] and Sungdo Ha[4]

Korea Institute of Science and Technology
{laehyunk[1], yoha[2], sehyung[3], s.ha[4]@kist.re.kr}

ABSTRACT

We present a dental training system through multi-modal interface such as visual, auditory and haptic sensations. The system allows dental students to learn dental procedures and handling dental instruments with realistic feelings and evaluate their performance. To implement this system, it requires stable and fast haptic rendering algorithm, visual model deformation techniques on the virtual tooth being deformed, and sound rendering to simulate contact sound between the virtual tool and tooth. We enhance previous volume-based haptic modeling systems for haptic dental simulation. Collision detection and force computation are implemented on an offset surface rather than the implicit surface to simulate physical interactions between the virtual dental tool and tooth model. To bridge the gap between fast haptic process (1 KHz) and much slower visual update frequency (~30Hz), the system generates intermediate implicit surfaces between two consecutive physical models being deformed resulting in smooth force rendering. The volumetric tooth model is visualized as a geometric model which is adaptively polygonized according to the surface complexity. Volumetric material properties are used to simulate the resistance and texture information depending on anatomical tissues. Finally, we developed a multi-modal workbench to register visual, auditory and haptic sensations so that the user see, hear, and feel the virtual environment in the same space.

Keywords: Dental simulation, Human Computer Interaction, Haptic interaction, Sound rendering, Volume-based sculpting, Multi-modal workbench.

1. INTRODUCTION

Dental students usually use artificial teeth (plastic model) along with real dental instruments to practice cavity preparation and other procedures. However, these plastic models lack the level of detail and material properties needed to accurately simulate real teeth and procedures. As an alternative to current training procedures, haptic dental simulation allows students to perform virtual dental procedures by providing realistic touch sensations in the same way that they do in the real world. Novint is developing the VRDTS (Virtual Reality Dental Training System) prototype [17]. In this system, a student holds the PHANToM's stylus (PHANToM is a haptic device from SensAble) and then use it to probe a decayed virtual teeth, or to prepare the tooth using a virtual drill for cavity repair. However, this paper does not describe how to implement the VRDTS since Novint does not provide further information.

Dental training system using haptic interface requires two basic techniques: Haptic rendering to generate force feedback and volume-based sculpting to simulate material removal. Typically volume-based approach is used for drilling simulation since it provides direct and intuitive modeling without topological constraint unlike geometry-based one. In recent years, many haptic modeling systems based on volumetric data have been proposed for virtual design, art, or surgical training. *FreeForm* [15] is the first commercial haptic modeling system from SensAble. However, they have many limitations for realistic dental simulation. In this paper, we propose volume-based haptic dental simulation techniques to address these limitations as follows:

- Maintaining sharp features of volume model being sculpted using an adaptive polygonization method in which the generated mesh is adapted to surface complexity
- Collision detection and force computation on an offset surface for simulating realistic tool interaction with the virtual tooth

- Smooth force rendering by directly simulating intermediate implicit surfaces created by interpolating potential values between two consecutive physical models being sculpted
- Simulating internal material properties including stiffness and color information which are saved into a volumetric representation

Our system consists of several basic parts: visual, sound, haptic rendering, simulation and sound rendering processes (see Fig. 1). The first four processes run on a PC with dual Intel Xeon 3.0-GHz CPUs, 1 G Byte of RAM, and NVida FX 3000 video card. Sound rendering runs on a separate PC with DSP board. The visual rendering is implemented based on OpenGL. A 3-DOF PHANToM Premium 1.5 is used for haptic display.

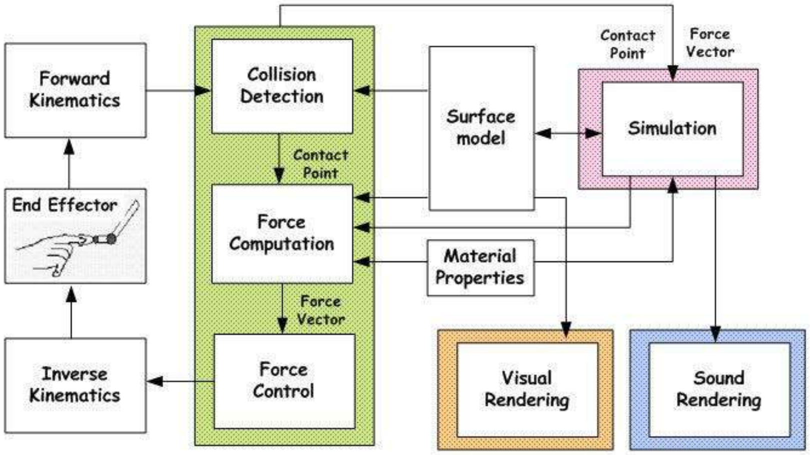

Fig. 1. System architecture of the dental training system.

We proceed with a discussion on previous related work in Section 2. Section 3 discusses our haptic model and section 4 describes our volume-based haptic sculpting techniques. Sound rendering and multi-modal workbench are discussed at Section 5 and 6 respectively. We conclude in Section 7.

2. RELATED WORK

2.1 Haptic Rendering for Stiff Objects

Traditional haptic rendering methods can be classified into roughly two groups according to the surface representation used such as geometric, or volumetric (including implicit) surface. One approach for the geometric models is the constraint based method. Zilles and Salisbury [19] introduced a constraint-based “god-object” method in which the movement of a god-object (a virtual contact point on the surface) is constrained to stay on the object's surface. Ruspini et al. [14] proposed a more general constraint based method and simulating additional surface properties such as friction and haptic texture. In the haptic rendering for volumetric data, the force field is computed directly from the volume data without conversion to geometric model. A haptic rendering algorithm for volumetric data was introduced by Avila and Sobierajski [1]. They used the gradient of the potential value to calculate the direction of the force and the amount of force was linearly proportional to the potential value. Kim et al. [7] used a hybrid surface representation which is a combination of geometric model for visual rendering and implicit surface for haptic display to take advantage of both data representations.

2.2 Force Rendering on 3D Model being sculpted

While sculpting, typically, visual frequency (~30 Hz) is much slower than haptic update rate (1 KHz). This performance gap leads is continuity in both the force direction and amount if the force is computed directly on the physical surface being sculpted. In order to smooth the force rendering, Foskey et al., uses spring-based force established between the initial contact point on the surface and tool tip position [4]. The user can move the tool tip freely and force computation is independent of the surface. Another method is "proxy blending" [13] which smoothly interpolates the goal point from old proxy point constrained on the old model to the new proxy point on the new surface. During the blending period, the user can not adjust the blending speed and direction since the new surface should be defined when the blending starts.

2.3 Volume-based Modeling System

Galyean and Hughes [5] introduced a voxel-based approach to volume sculpting that used the marching cube algorithm to display the model. Barentzen [2] proposed an octree-based volume sculpting to reduce the memory requirement. However, these approaches have limitation such as low resolution due to the data size of the volume, or the large number of triangles for the displayed surface. In order to address these limitations, multi-resolution [6] and adaptive approaches [11] have been suggested resulting in high image quality with less number of triangles. Mouse-based computer interface in the 3D sculpting system is unnatural and inefficient inherently. Avila and Sobierajski [1] introduced a volume-based haptic sculpting system which allows the user to intuitively sculpt a volumetric data using a haptic interface.

3. HAPTIC MODEL

3.1 Data Representation

In our algorithm, volumetric implicit surface is used for surface modeling and haptic rendering while sculpting. In the volumetric representation, only potential values close to the implicit surface (see Fig. 2) are involved in the computation. The potential values inside the close neighborhood of the surface range from -1 to 1 according to the proximity to the closest point on the surface. The values inside the surface are negative and positive outside. The values out of this narrow band are nothing to do with the surface modeling and haptic rendering. Therefore, to reduce the memory requirement, we use an octree-based data structure, avoiding the representation of empty portions of the space.

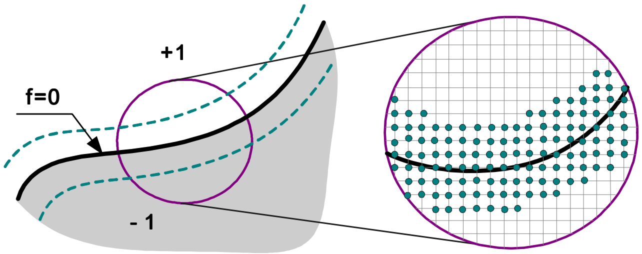

Fig. 2. Data representation for surface modeling and haptic rendering.

A volumetric implicit surface representation (Fig. 3(b)) is created from a geometric tooth model (Fig. 3(a)) by Mauch's fast closest point transform (CPT) algorithm [8]. The algorithm computes the closest point to a surface and its distance from it by solving the Eikonal equation using the method of characteristics.

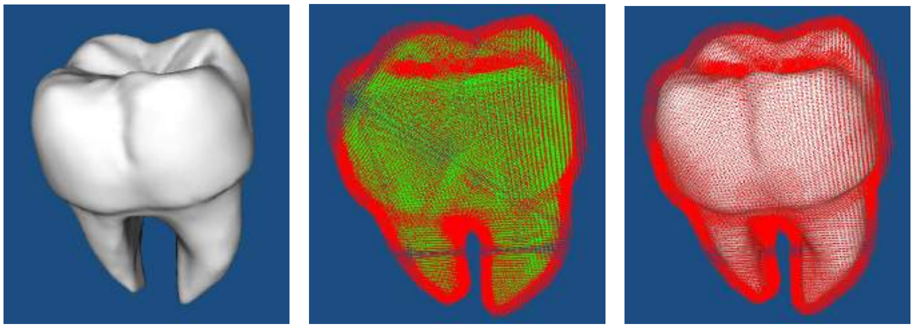

Fig. 3. Model conversion. (a) Geometric tooth model. (b) Volumetric implicit surface (128x128x128) converted from (a) by CPT. (c) Geometric model extracted from (b) using an adaptive polygonization method.

3.2 Collision Detection

Most haptic rendering algorithms use only one point of the virtual tool for collision detection and force computation. However, the visual contact interaction between the virtual tool and model surface may not correspond with the haptic feeling on complex models with shape edges or small holes. To address this problem, Persik [12] uses multiple points distributed on the virtual tool to detect collision and calculate the force in a porous bone surgery simulator. However, whenever the number and position of the points involved in force computation are changed, the force rendering may lose continuity in haptic sensation.

In our system, we still use a single point of the virtual tool but collision detection and force computation are performed on an offset surface rather than the implicit surface. The offset value from the implicit surface is determined by the radius of bounding sphere of the tool. The center point of the bounding sphere becomes the single point (Fig. 4(a)). If the point collides with the offset surface, the system computes the force vector based on the offset surface (Fig. 4(b)). This approach can match both visual and haptic sensation and provides stable force rendering.

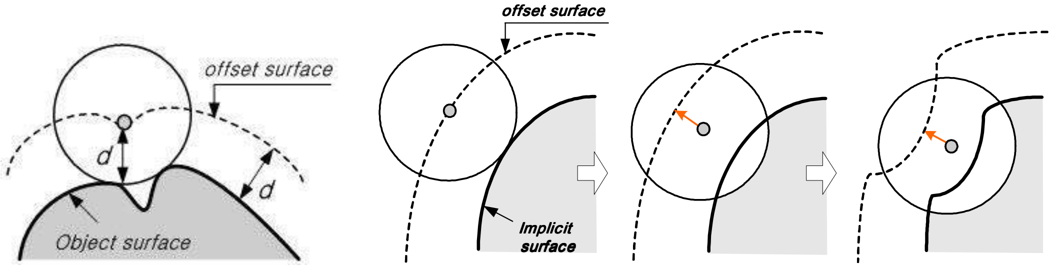

Fig. 4. (a) Collision detection. (b) Force computation based on an offset surface.

3.3 Force Vector

Interpolation function leads the system to avoid the force discontinuity. In order to determine the amount of force, we first find the virtual contact point (VCP) on a surface which is the intersection point between the surface and a ray along the computed force direction. The amount of force is proportional to the distance between the VCP and the tool tip. After the VCP is determined, a spring-damper model is used to compute the final force vector in Eqn. (1).

$$\vec{F} = (P_c - P_t) * k - (\dot{P}_c - \dot{P}_t) * b \qquad (1)$$

Where, $\vec{F}$ is the force vector, P_c and $\dot{p}_c$ are the coordinate and velocity of VCP in 3D space, P_t and $\dot{P}_t$ are the coordinate and velocity of the virtual tool respectively. k is spring constant and b is viscosity. Spring stiffness has a reasonably high value and viscosity is to prevent oscillations.

4. VOLUME-BASED HAPTIC MODELING

4.1 Adaptive Polygonization Method

Model modification during sculpting is implemented by updating the local potential values around the sculpting tool, depending on the shape and size of the tool, operation type (carving or adding) and the applied force by the user. The volumetric model is converted into the geometric model every graphical frame for the visual rendering. Many sculpting systems [3],[5] use a uniform polygonization method such as Marching cube which suffers from large triangle count and a resolution limited by a fixed sampling rate.

In order to address these limitations, we employ the adaptive polygonization method suggested by Velho [16]. This adaptive method consists of two steps. In the initial polygonization step, a uniform space decomposition is used to create the initial mesh that serves as the basis for adaptive refinement. In the second step, for adaptive polygonization, the mesh is refined adaptively according to the surface curvature until the desired accuracy is achieved and then projected onto the implicit surface. The resulting mesh effectively represents sharp edges with a smaller number of triangles and does not introduce cracks. The volumetric implicit surface and generated mesh are saved into separate octree-based data structures to locally manage both data.

4.2 Drilling operation

The system typically could not update the physical model at a rate sufficient for haptic rendering (at least 1 KHz). Due to this performance gap, most previous haptic sculpting systems could not directly simulate physical models being deformed. Instead, a virtual spring-based force [9] (Fig. 5(a)) established between the current tool tip and the initial position is used to provide feedback. However, the user cannot directly feel the physical surface being deformed and is not allowed to move the tool tip along the surface being deformed without retouching the surface.

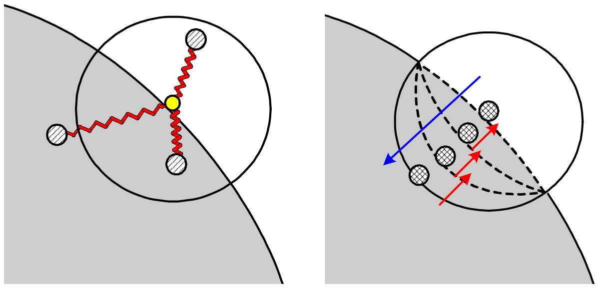

Fig. 5. Collision Spring-based approach (a) and our method (b). The blue arrow indicates the moving direction of the tool and the red arrow does the responsive force).

To bridge the gap between the update rate of the visual and haptic rendering, we introduce an intermediate implicit surface smoothly transiting between discrete old model and target models in haptic process. The target model is defined by CSG (Constructive Solid Geometry) point-set operation based on the old model and sculpting tool. The intermediate surface is animated from the old surface toward the target surface. The speed of animation changes with time according to the force the user applies, local material stiffness, and contact area. Note that the force computation is implemented on the intermediate surface instead of physical models in the haptic loop (see Fig. 5(b)). In the next visual frame, the system updates the physical model based on current intermediate implicit surface. If the user continues to drill, the system computes the next target surface by CSG operation which is fast enough to avoid the impact in haptic sensation and then animates the intermediate surface for smooth transition. Dust and debris generated by the dental burr is simulated by particle system. Each particle has a mass, a position, and a velocity, and a simple dynamic behavior. Fig. 6 shows a drilling simulation process.

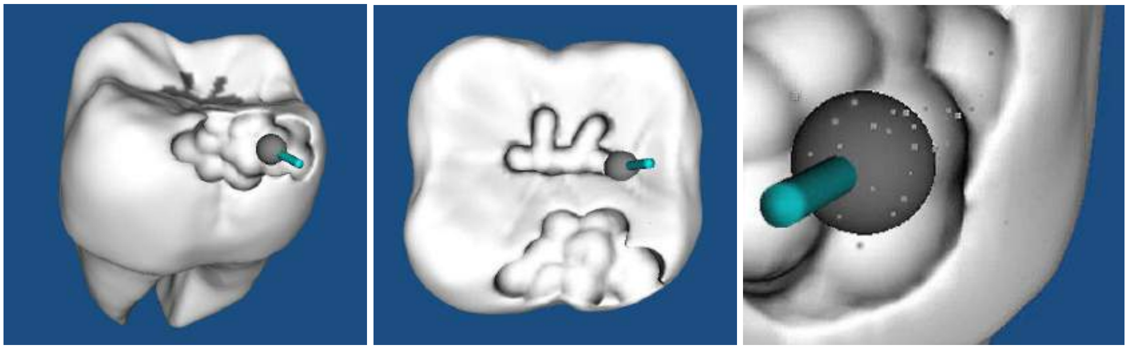

Fig. 6. Dental simulation. Drilling operation and dust simulation by the dental burr

4.2 Volumetric material properties

Human tooth has multi-layered structure consisting enamel (hard tissue, outer surface of the tooth), dentin (hard but porous) and pulp (soft tissue containing blood vessels and nerves) in Fig. 7(a). While sculpting, internal material properties such as stiffness have influences on the resistance.

In our system, volumetric properties including stiffness and color are saved into the volumetric representation and are simulated while sculpting. The system calculates the local stiffness at the tool position by averaging stiffness values of the grid points within the sculpting tool. In addition to controlling the sculpting speed, local stiffness can be used to simulate dental probing process for the diagnosis of carious lesions (see Fig. 7(b) and (c)). For advanced lesions, the haptic sensation is similar to poking soft cheese which can be simulated as material with low stiffness. The system allows the user to directly paint on the virtual tooth (Fig. 8(b)). Different colors often indicate different material or anatomical part. To make the color boundaries clear, the mesh is adapted to the color complexity as well as surface complexity using the adaptive polygonization method (Fig. 8(c)).

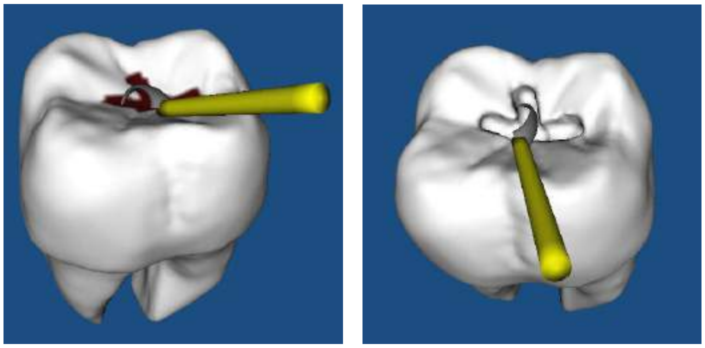

Fig. 7. Simulation of tooth material properties and dental probing to diagnose carious lesions. (a) Multi-layered tooth tissue. (b) Initial probing before a preparation. (c) Detecting if all caries has been removed.

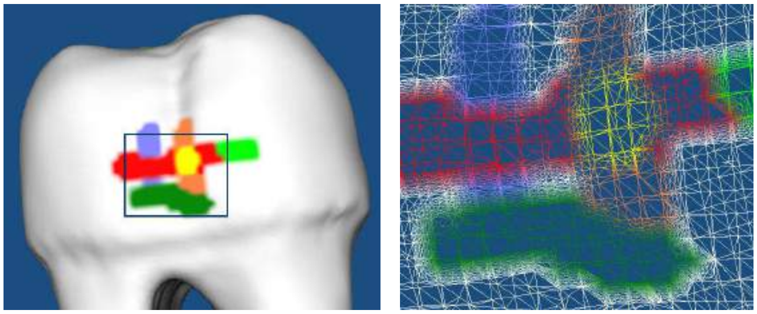

Fig. 8. Adaptive polygonization with the color complexity. (a) Painting on the tooth model. (b) Mesh model.

5. SOUND RENDERING

While drilling operation, physical contact sound between the virtual drill and tooth can enhances realism significantly. In our system parametric modeling techniques and vibration theory are used to simulate artificial and natural contact sound. The AR modeling [10] is used to simulate small drill sound for dental simulator. Separate computer equipped with DSP is used for simulation sound calculation and TCP/IP is used for communication with simulator computer to get information on power switch on/off, contact, and contact area. Drilling sound at idling and working is sampled and modeled as the AR model as in Eqn. (2).

$$y(t) = a_1 \cdot y(t-1) + \cdots + a_M \cdot y(t-N) + e(t) \tag{2}$$

where, M is model order, a_1 , $\cdots$, a_M are AR coefficients, and $e(t)$ is Gaussian noise. AR(300) model is selected and volume of drilling sound is adjusted according to contact area information to enhance reality. Fig. 9(a) shows the spectrum of real and simulated sound at idling and working condition. Solid lines show spectrum of real sound and dotted lines show spectrum of simulated sound. The spectrums of simulated sound show very similar characteristics. Fig. 9(b) shows dental simulator under development.

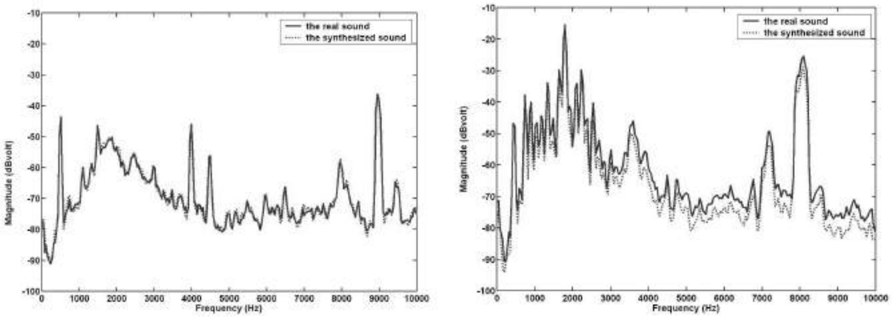

Fig. 9. (a) Sound spectrum of idling condition. (b) Sound spectrum of drilling condition.

6. MULTI-MODAL WORKBENCH

We developed the Multi-Modal Workbench (MMW) which incorporates a stereo-visual display (viewed in a mirror), a PHANToM haptic device, a SpaceMouse as a 6 DOF position device and an auditory display. Thomas et. Al., first suggested a similar system for near-field virtual environment system [18]. The system is designed to register three sensory modalities such as visual, haptic and auditory sensation. The user views the images on a mirror reflecting the monitor mounted on the MMW (see Fig. 10). This configuration allows the user to see, hear, and touch virtual objects in the same time and space.

For the stereoscopic view, we use GL_STEREO quad buffering on a stereo-ready graphics card such as NVidia FX 3000. A common approach is to rotate the cameras and point at the center of the object. However, once the cameras are rotated, their axes of projection become different introducing vertical parallax which requires the stereo "point of focus" to be constantly adjusted if the viewer is moving through the scene. To address this limitation, the system skews each camera's view frustum so that the view volume contains the object. This approach is known as the "parallel axis asymmetric frustum perspective projection". By increasing or decreasing the frustum asymmetry, the scene will appear to be moved with respect to the screen plane.

Fig. 10. Multi-modal Workbench. The user views images on the mirror.

7. CONCLUSION

We introduced a dental training system which allows the dental student to learn dental procedures and how to handle dental instruments with realistic tactile feeling and visual and sound display. Haptic rendering is implemented based on a volumetric representation which contains implicit surface and material properties. Based on this idea, collision detection and smooth force computation are implemented based on the offset surface and surface properties such as stiffness and color are simulated. The virtual tooth model being deformed is generated by an adaptive polygonization method for better visual quality and performance. In addition to haptic interface, simulation of physical contact sound is implemented to enhance haptic realism significantly. In the future, we plan to enhance the dental training system by adding various dental tools and visual effects to deliver more realistic feeling to the user.

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