Surface-Based Virtual Dental Surgical Simulator using Haptic Display

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ABSTRACT

This research work presents a surface-based virtual dental surgical simulator in which dentists can perform dental procedures using various cutters with realistic feelings of touch. Generating realistic smooth tactile feelings during drilling, grinding, or scrubbing is a critical issue in triangular sculpting simulators. Therefore, a stable haptic rendering algorithm is required to generate realistic touch feeling. In this simulator, the force feedback is realized using a spring damper force model and a force filter is proposed to make the force feedback smooth. Fast and efficient collision detection is used using vertex deformation technique for the sculpting process. In addition, the simulator is not designed for the one specific surface-based tooth model but rather the sculpting simulation can be carried out on any scanned model from a commercial 3D dental scanner.

Keywords: haptic display, smooth force feedback, surface-based dental model.
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1 INTRODUCTION

Simulation is an important feature in CAD/CAM systems or any engineering system that involves many processes. Currently, in the medical area, simulators are applied to research and development of tools for new therapies, treatments and early diagnosis in medicine. Medical simulation in dental treatment systems and surgery training systems, etc. is the area of major applications in computer graphics and virtual reality. Different methods were presented to sculpt the triangular models, these methods could be applied in medical surgery simulations [1],[2],[3],[4]. Thomas et al. developed a dental surgical simulator system in which they also explained the software and implementation of the prototype system [5]. Compared with the volumetric based approach, the surface based approach is more complex and difficult to handle but costs lesser amount of computer memory. Hong et al. used surfel model with Octree algorithm for the development and improvement of dental training system [6]. Wang et al. described the cutting on a surface model by using haptic display in the virtual reality environment [7]. Dachille introduced a novel haptic-based interface and sculpting system [8]. Kim et al. used a hybrid surface representation for haptic display [9]. In recent years, many haptic force feedback simulators based on volumetric and surface-based have been proposed for virtual simulation and visualization of medical training [10],[11],[12],[13],[14],[15],[16],[17]. In real dental treatment, tissues will be removed according to the interaction between the moving tool and tissues. This feature involves haptic sensation by computation of force rendering. For realistic haptic sensation the dental

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training system must have the ability to efficiently compute the repulsive force feedback and realistic tool interaction with the virtual tooth, which all based on efficient collision detection. In this system, many virtual tools of different shapes are used for the material removal processes. The virtual tools have a bounding box (Bbox) that minimizes the computation time for the fast rendering.
The computation of the force feedback depends on efficient interaction between the virtual tool and the surface of the tooth model. For this purpose, the Hooke's Law is used for the calculation of the repulsive force. In this law when the force is applied to a spring, the spring will be compressed from one position to another and the displacement during this compression can be computed. Therefore, the spring force can be computed using this method with different factors that are involved in the compression. However, accurately measuring the repulsive force from the deformed surface, fidelity, stability, and smooth haptic sensation are problems that still need to be resolved. To handling these problems, a force filter is proposed. Fig. 1 dictates the system architecture of the virtual system that consists of collision detection, force computation, haptic rendering, and simulation processes.

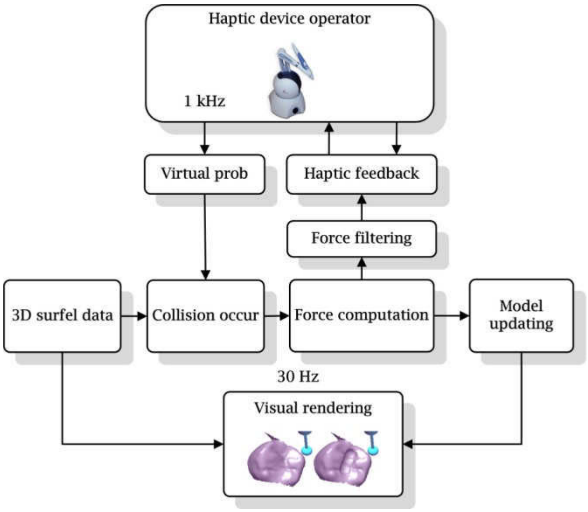

Fig. 1: Framework of the system.

2 3D REPRESENTATION

2.1 Sculpture Model

Surface-based modeling costs less computer memory than volumetric representations. However, it is more complex and difficult to handle. In this paper, a realistic surface-based 3D human jaw model is used based on standard geometric references and parameters. The original jaw model data is extracted from a commercial 3D dental laser scanner, which defines the boundary surface of the human jaw as illustrated in Fig. 2(a). It is not mandatory to use only one specific surfel model but rather any scanned surfel model can be used in this system. The graphical user interface provides dentists to visualize the 3D model from any point of view or angle selected by the dentist.

2.2 Virtual Tools

In the real world, dentists use different kinds of cutter shapes to sculpture teeth according to several requirements. In this system, many dental tools with different shapes are included as shown in Fig. 2(c). All dental tools are surface-based modeled with good visual quality. Dentists can change the size and the shape of a cutter any time during the real-time sculpting simulation. The ability to change the size and shape of the virtual dental tool makes the simulator a functional sculpting system. The tooth is supposed to be still in the world coordinate system, but the virtual cutter can move around the 3D tooth model freely along with the translation of the haptic stylus.

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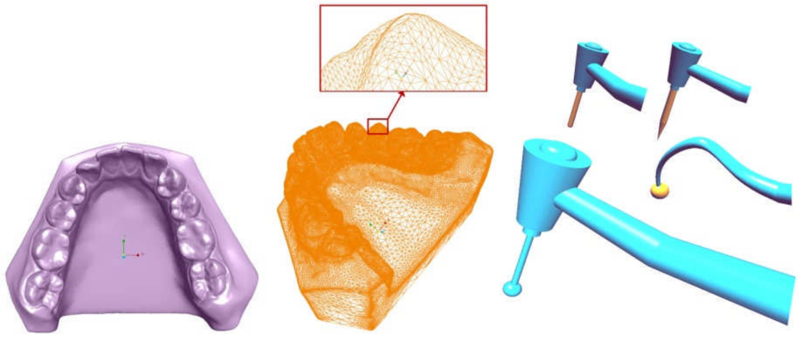

Fig. 2: 3D representation: (a) Surface-based 3D human jaw model extracted from a commercial 3D dental laser scanner, (b) Wireframe model of (a), and (c) Virtual dental tools of different shapes.

3 COLLISION DETECTION AND SCULPTING PROCESS

A realistic dental treatment system with haptic interaction requires natural and real-time interaction between a cutter and a tooth surface. In this paper, many dental tools are used with different shapes according to different dental requirements. In order to consider a haptic computation frequency of 1 kHz, a Bbox detection method is used to accelerate the collision detection between the virtual tool and the surface of the tooth. Bbox is used to minimize the vertices data computation during the real-time collision because it is necessary to complete all computations in one loop for the stability of the haptic device. For the removal of the tooth material, a vertex deformation method is used because of its simplicity and reduced computation costs. During the collision, the bounding box intersects the surface of the tooth before the virtual tool does, and when the collision happens between the tooth surface and the Bbox, we check how many vertices penetrate the Bbox. We only consider those penetrated vertices for the second check between the tool and the penetrated vertex for the deformation calculation. In order to calculate the updating position of the penetrated vertex for the material removal, we simply extend that penetrated vertex to the cutter's surface by computing the surface coordinates of the cutter. After that a new look of the surface can be realized based on the penetrated vertices. The collision between the spherical tool and the tooth vertex is demonstrated in Fig. 3(a) and the final shape of the tooth surface after sculpting can be seen in Fig. 3(b). The cylinder and cone tools are restricted to be aligned with respect to the model coordinate system due to an axis-aligned bounding box (AABB). AABB is adopted due to its simplicity and less computation cost than the oriented bounding box (OBB).

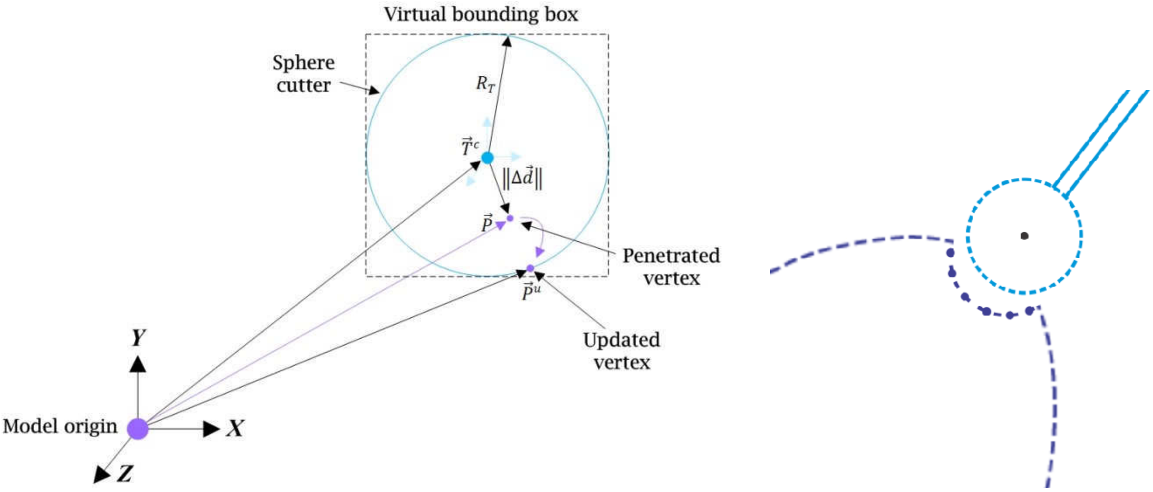

Fig. 3: (a) Collision between the spherical tool and the tooth vertex, (b) Final shape of the tooth surface.

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3.1 Spherical Tool

The surface coordinates of a sphere can be calculated as follows:

$$\begin{cases} \vec{P}^{u} = (R_T \cdot \frac{\Delta\vec{d}}{\|\Delta\vec{d}\|}) + \vec{T}^{c} & 0 < \|\Delta\vec{d}\| < R_T \\ \vec{P}^{u} = \vec{P} & \|\Delta\vec{d}\| \geq R_T \end{cases} \tag{3.1}$$

$$\Delta\vec{d} = \vec{P} - \vec{T}^{c} \tag{3.2}$$

where R_T is the radius, $\Delta\vec{d}$ is the distance from the penetrated vertex position to the center, $\vec{P}(P^x, P^y, P^z)$ is the position of the original mesh vertex, $\vec{P}^u(P^{ux}, P^{uy}, P^{uz})$ is the updated position of the penetrated vertex, and $\vec{T}^c(T^{cx}, T^{cy}, T^{cz})$ is the center of the sphere.

3.2 Cylindrical Tool

In order to calculate the surface coordinates of a cylinder, the cylinder can be subdivided into two parts. The first part is the lower half disk of the sphere and the second part is the vertical cylinder. The surface coordinates of the lower half disk can be computed by the spherical tool, and the surface coordinates of the vertical cylinder can be calculated as follows:

$$\begin{cases} P^{ux} = \left(R_{\dot{T}} \cos\theta\right) + T^{c'x} & \\ P^{uy} = \left(R_{\dot{T}} \sin\theta\right) + T^{c'y} & 0 < d' < R_{\dot{T}} \\ P^{uz} = P^{z} & \end{cases} \tag{3.3}$$

$$\theta = \tan^{-1}\left(\frac{P^{y} - T^{c'y}}{P^{x} - T^{c'x}}\right) \tag{3.4}$$

$$d' = \sqrt{(P^{x} - T^{c'x})^{2} + (P^{y} - T^{c'y})^{2}} \tag{3.5}$$

where $R_{\dot{T}'}$ is the radius, d' is the distance from the penetrated vertex position to the center axis, $\vec{T}^{c'}(T^{c'x}, T^{c'y}, T^{c'z})$ is the center point of the bottom, and θ is the angle between the center axis and the outer edge of the cylinder.

3.3 Cone Tool

A cone can also be subdivided into two parts: a vertical cylinder and a cone. The surface coordinates of a cone can be calculated as follows:

$$\begin{cases} P^{ux} = \left(h_p \frac{R_{\ddot{T}}}{h_c} \cos\theta\right) + T^{c'x} & \\ P^{uy} = \left(h_p \frac{R_{\ddot{T}}}{h_c} \sin\theta\right) + T^{c'y} & 0 < d' < (h_p \frac{R_{\ddot{T}}}{hc}) \\ P^{uz} = P^{z} & \end{cases} \tag{3.6}$$

$$h_p = \sqrt{\left(P^{z} - T^{c'z}\right)^{2}} \tag{3.7}$$

where $R_{\ddot{T}'}$ is the radius, h_c is the height of the cone, and h_p is the distance from the penetrated vertex to the apex of the cone along z-axis.

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4 FORCE RENDERING

In order to render the haptic force feedback, the spring force model is commonly used to transform the motion of the haptic tip to the virtual force. Therefore, the spring damping approach is adopted to compute the force feedback. The general force vector equation $\vec{F}(F_x, F_y, F_z)$ is as follows:

$$\vec{F} = K_s . \Delta\vec{x} - K_d . \vec{v}_p \tag{4.1}$$

where K_s and K_d are the spring stiffness and the damping coefficient respectively, $\Delta\vec{x}$ is the displacement of the spring, and $\vec{v}_p$ is the velocity of the virtual tool. For the smooth and stabilize force feedback, several different methods have been implemented in surfel dental simulation systems. All of those methods tried to develop a stable haptic interface system with haptic devices with higher frequencies. Here, a new method is proposed to increase the fidelity, reduce the vibration, and obtain the smooth force signal. The details are described as follows:

$$\Delta\vec{x} = \vec{P}_{last} - \vec{P}_{current} \tag{4.2}$$

where $\vec{P}_{last}$ is the last position and $\vec{P}_{current}$ is the current (updated) position of the penetrated vertex. Thus, the resultant force $(\vec{F}_r)$ is the summation of all forces:

$$(\vec{F}r)_{current} = \sum_{i=1}^{m} \left((K_s)_i \Delta\vec{x}_i - (K_d)_i \vec{v} \right) \tag{4.3}$$

$$\vec{v} = \vec{n} \, (\vec{n} \bullet \vec{v}_p) \tag{4.4}$$

$$\vec{n} = \left(\sum_{i=1}^{m} \vec{N}_i \right) \Big/ \left\| \left(\sum_{i=1}^{m} \vec{N}_i \right) \right\| \tag{4.5}$$

where $\vec{n}$ is the average normal vector, $\vec{N}_i$ is the vertex normal vector, and m is the total number of vertices penetrated by the virtual cutter. The non-linear mapping of the virtual tool motion to the mesh vertex is a critic issue.

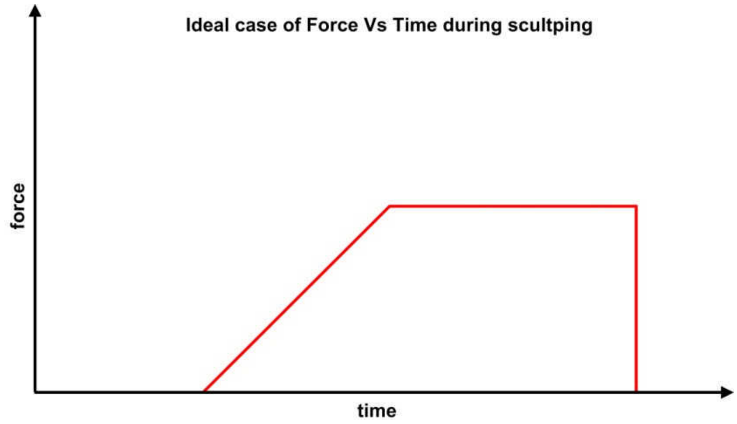

Fig. 4: Ideal case of the force feedback signal verses time.

Therefore, Eqn. (4.4) is introduced to modify the virtual tool velocity in which $\vec{v}$ is the value of $\vec{v}_p$ projected onto $\vec{n}$. However, even after computing the resultant force, low fidelity and vibration of the haptic stylus are issues that still need to be resolved. So, in order to resolve these issues, it can be assumed from experiments that the relationship between the force feedback signal verses time during sculpting is approximately the same as the curve shown in Fig. 4. However, using Eqn. (4.3), the vibration of the haptic stylus can be realized by the dentist's hand and noise of phantom motors occur. Therefore, to achieve the ideal case of Fig. 4, the force signal is modified as described in Fig. 5.

In Fig. 5, $\vec{F}_{const}$ is considered as the constant force in the current stroke, λ is the maximum force capability of the haptic device, and ξ and ζ are the force thresholds. The values of the constants (ξ and

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ζ) are based on the non-linearity of the tooth surface. The parameters used in this filter can be easily adjusted to the dynamic properties of the haptic device, without changes in the algorithm. Finally, the filtered force signal $(\vec{F}_f)_{current}$ is sent to the haptic device controller for haptic rendering at 1 kHz.

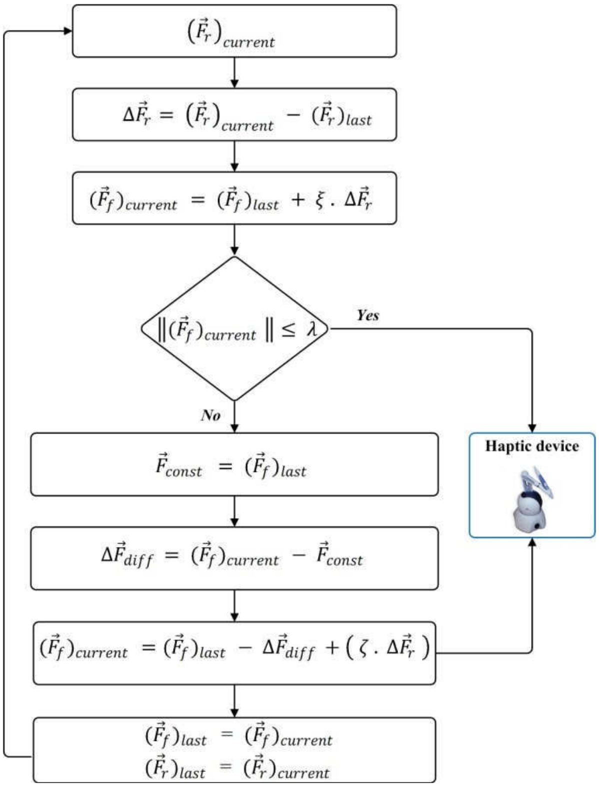

Fig. 5: Block diagram of the force filter.

The specifications of the adopted hardware setup includes a 2.0 GHz Intel Core™2 CPU, 2 Giga Bytes of RAM, simulation rendering based on Nvidia GT220 GPU with 512 MB memory, a 22” monitor, and windows based operating system Microsoft Windows Vista. The Phantom Omni™ is used as a haptic device which offers three degrees of freedom output capabilities and was provided by SensAble Technologies [18]. The proposed system has been implemented on a PC using OpenGL graphics library to visualize 3D models and OpenHaptics toolkit to render force signal. The programming environment is Microsoft VS C++ 2005. All predefined coefficients are selected according to the maximum stiffness and force capability by Phantom Omni™. The martial removal result in the real time drilling and scrubbing operation using a spherical tool can be visualized in Fig. 6.

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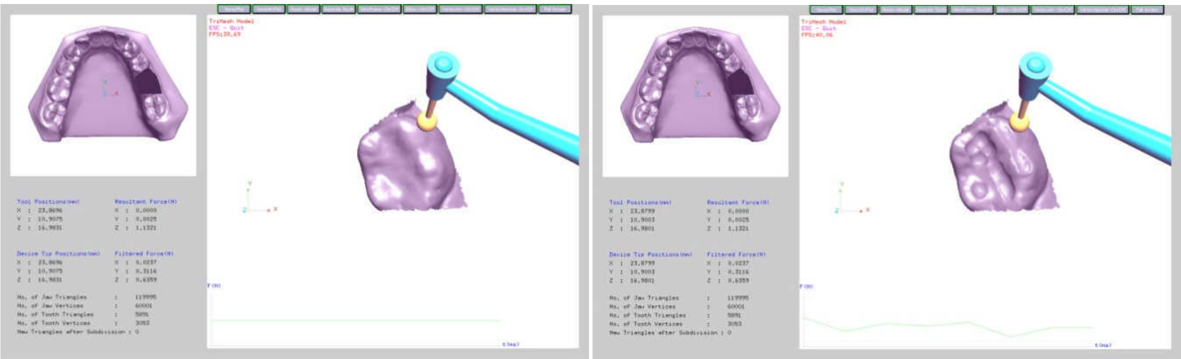

Fig. 6: Material removed from the tooth by implementing real-time drilling and scrubbing operation: (a) Before sculpting, (b) After sculpting.

For demonstrating the force signal, the magnitude of the virtual force vector was recorded. Fig. 7(a) gives the interaction force between the virtual cutter and the tooth surface in the real-time drilling without force filtering. In this case, the computed force proportional to the summation of the spring lengths of penetrated vertices by the virtual cutter. The vibration of the haptic stylus can be realized by the dentist's hand and noise of phantom motors occur. In Fig. 7(b), the smooth and stable force signal can be realized during the same drilling operation with force filtering at $\xi = 0.001$N/mm and $\zeta = 0.10$N/mm. The maintained force fidelity can also be observed in this illustration. It can be observed from experiments that the stability of the device decreases with the increase of ζ. The dentist feels the brittle surface with the higher value of ζ and feels soft with the lower value. The illustrations, verify that the signals of force feedback from deformed vertices are as expected for a surface-based 3D mesh model.

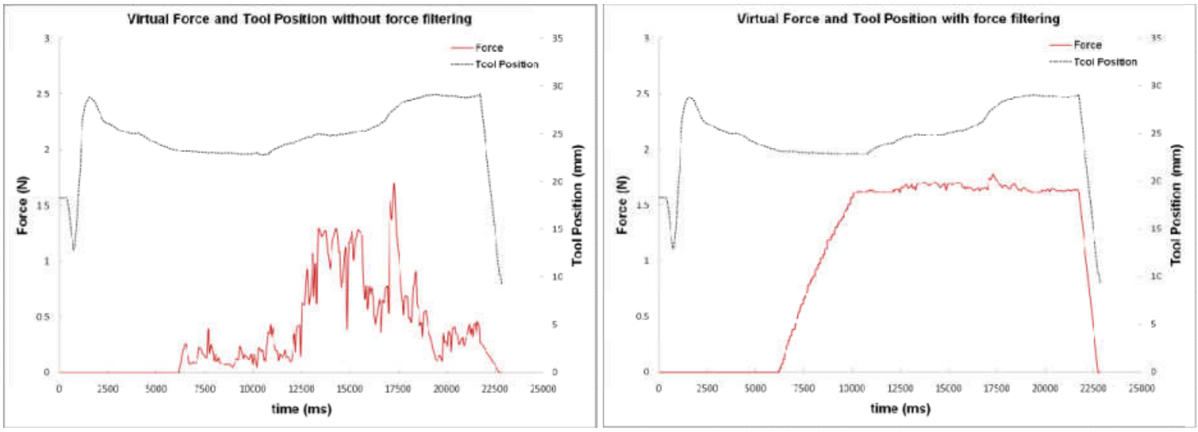

Fig. 7: Signal of the virtual force and the tool position: (a) Without force filtering, (b) With force filtering.

5 CONCLUSION

In this paper, a surface-based virtual system is presented with many virtual tools of different shapes. The simulator can be helpful for dentists to learn surgical procedures and gain experience of using dental instruments. Different dental treatment procedures in this simulator could help dentists to perform safer operations before entering to the real operation task. A vertex deformation technique is used to simulate the removal of tooth tissues. It is concluded that for the smooth haptic rendering, an optimal collision detection is important as well as the consideration of nonlinearity of the deformed

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surface. Experiments were carried out using a Phantom Omni™ haptic device; these experiments involved the three-dimensional cutting of a tooth model using a proposed force filtering method. The experiment operations verify that the force stability can be easily maintained under the specified operation criteria.

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