

Graduation Thesis Presentation

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Thesis Title

Virtual Dental Treatment Training System Using Haptic Device



Presentation Structure

Overall View

- **Reasons for choosing the thesis topic**
- **Scope and goal of the thesis**

Contents

- **Introduction**
- **Related work**
- **Method**
- **Implementation and Results**

Conclusion

- **Summary**
- **Future work**



Reasons for Choosing the Thesis Topic

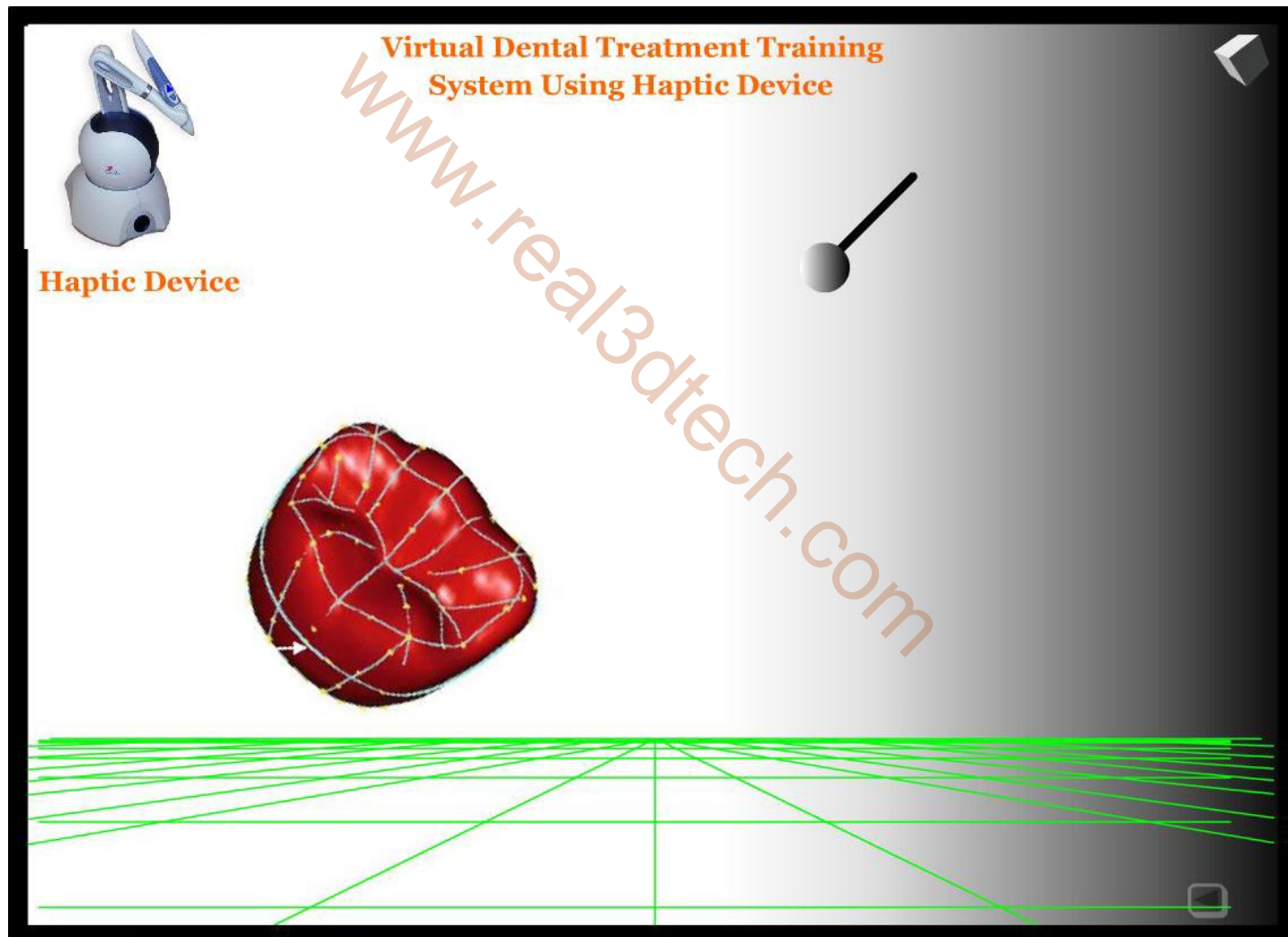
- **Interest Area**
- **To train dental students before proceeding the real patient.**
- **Much related work in dental treatment simulation but need precision and efficiency.**
- **Needs to further development in dental simulator field.**

Scope and Goal of the Thesis

- To develop a software package in which dental students can perform cutting simulation for cavity preparation and removing of other tooth tissues in Virtual Reality environment with the realistic sense of touch.

Introduction

Animation

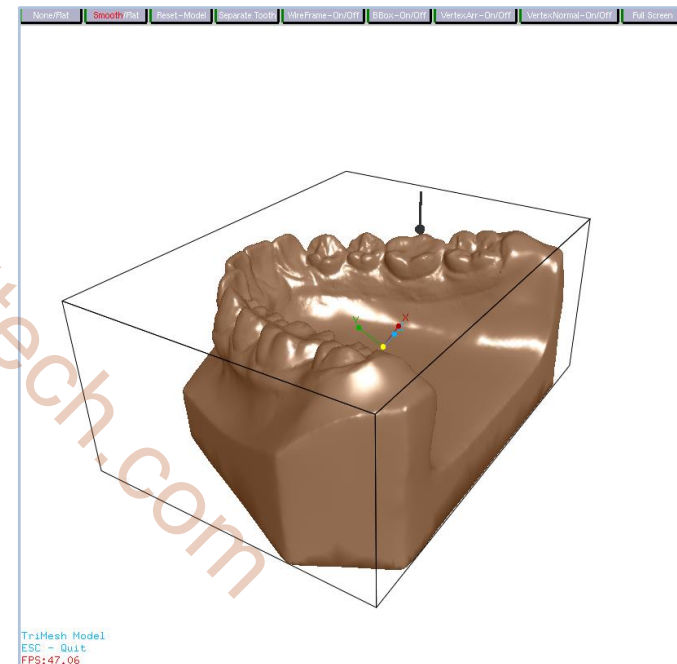


Introduction

Research is About...



If you can touch it and you can see it, it's **REAL**



If you can't touch it but you can see it, it's **VIRTUAL**



Introduction

Simulation:

The process of imitating a real phenomenon with a set of mathematical formulas.

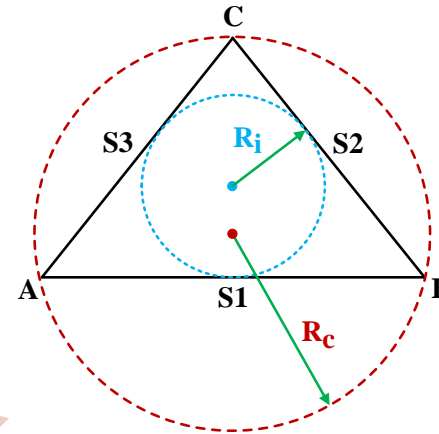
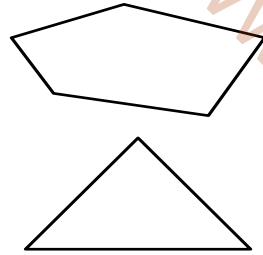
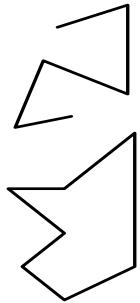
Advantages:

- Study the behavior of a system without building it.
- Results are accurate in general, compared to analytical model.
- Help to find un-expected phenomenon, behavior of the system.
- Easy to perform “What-If” analysis.

Disadvantages:

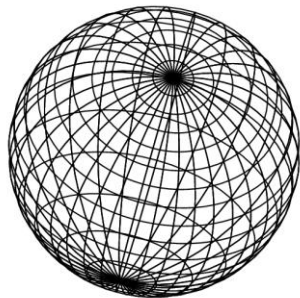
- Expensive to build a simulation model.
- Expensive to conduct simulation.
- Sometimes it is difficult to interpret the simulation results.

Introduction



- A, B, C - Vertices of triangle
- S1, S2, S3 - Triangle edges
- R_c - Circumcircle radius
- R_i - Incircle radius

Basic structures of 3D geometry



Sphere: $x^2 + y^2 + z^2 = r^2$

Basic triangle calculations

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha & 0 \\ 0 & \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \alpha & 0 & -\sin \alpha & 0 \\ 0 & 1 & 0 & 0 \\ \sin \alpha & 0 & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 & 0 \\ \sin \alpha & \cos \alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotation About
X Axis

Rotation About
Y Axis

Rotation About
Z Axis

$$\begin{bmatrix} Sx & 0 & 0 & 0 \\ 0 & Sy & 0 & 0 \\ 0 & 0 & Sz & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & Tx \\ 0 & 1 & 0 & Ty \\ 0 & 0 & 1 & Tz \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Scaling Matrix

Translation Matrix

Identity Matrix

Basic three dimensional matrices

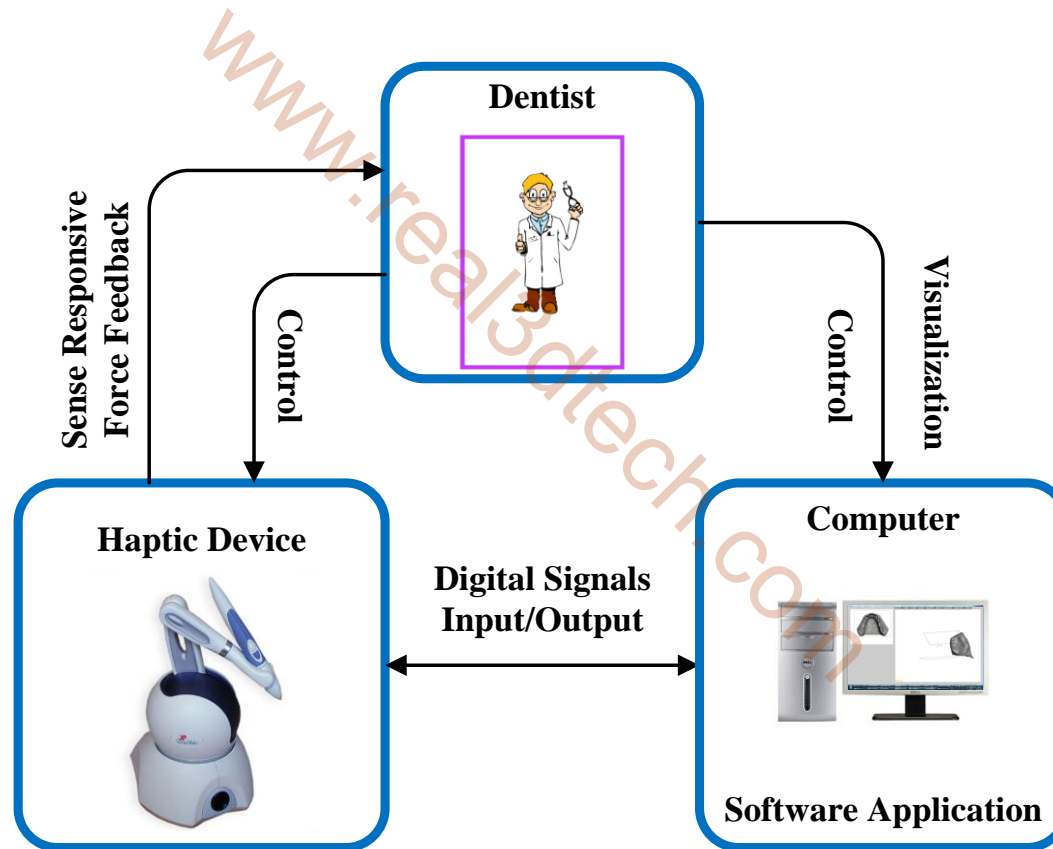
Introduction

Haptic device is a mechanical device that mediates communication between the user and the computer. It makes it possible for users to touch and manipulate virtual objects in virtual environment. We can feel the realistic sense of touch during the cutting simulation of 3D tooth model in 3D dimensional virtual environment.



Haptic Device PHANTOM Omni

The System



The Setup

Haptic Device



Research Purposes

Users:

- Dentists
- Dental students

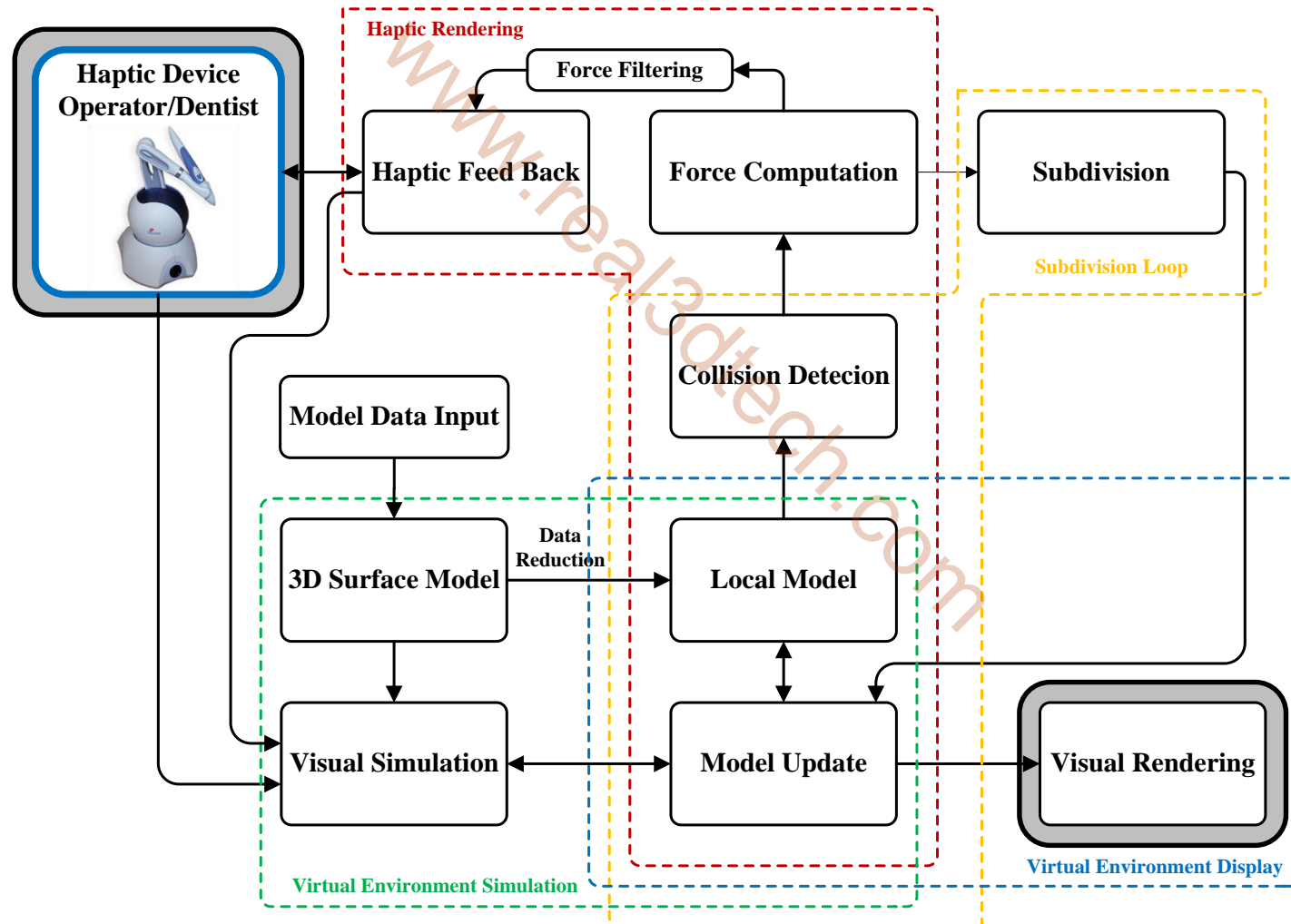
Provide:

- Convenient work environment
- User friendly interface
- Repetition
- Stable haptic force feedback system

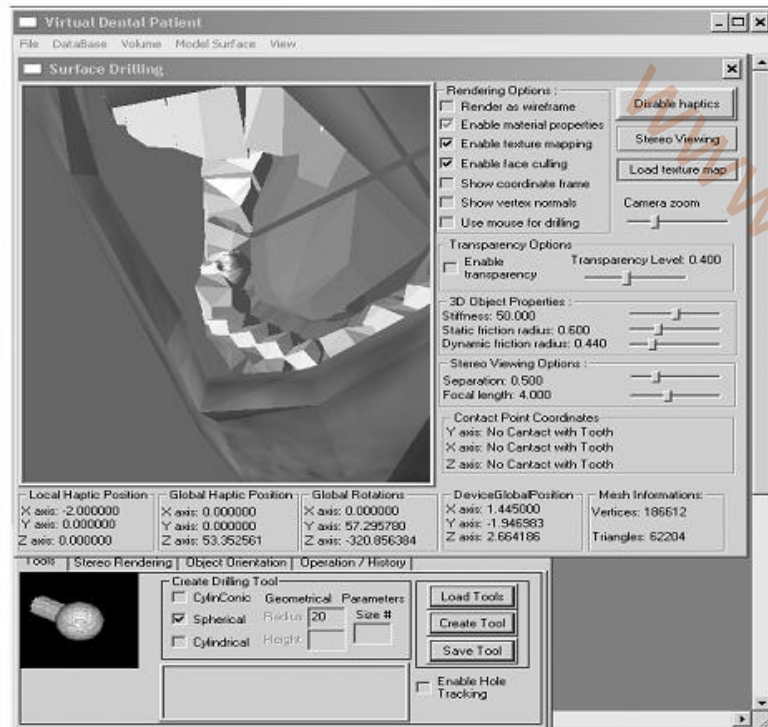
Characteristics:

- Fast and smooth visual rendering
- Efficient collision detection between tooth and tool
- Enhanced haptic sensation (sense of touch)
- Smooth and precise cutting simulation in VR
- Efficiently model update
- Improvement in skills

System Architecture

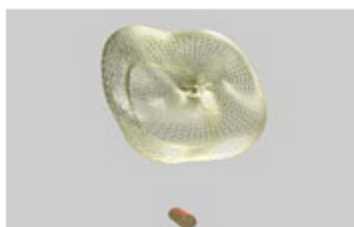


Related Work

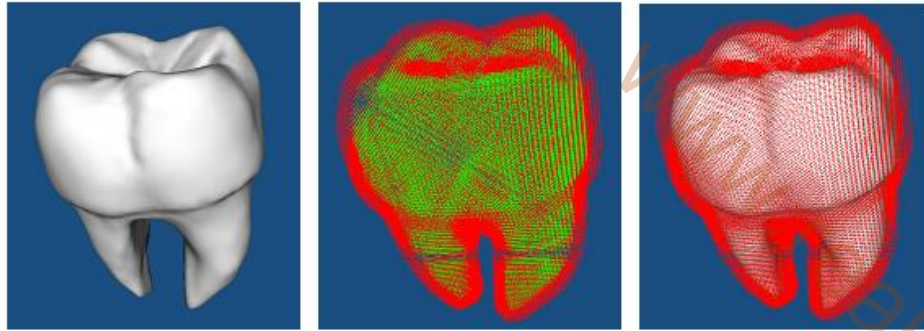


Virtual Reality Based Dental Treatment Simulation Systems:

- Ranta et al. introduced a concept design of a Phantom based dental training system to practice cavity preparation [1].
- Novint is developing a VRDTS (Virtual Reality Dental Training System) prototype [2].
- Thomas et al. developed a dental surgical simulator system; they also explain the software and implementation of the prototype system [3].
- Hong-Tzong and Chien-Yu present a dental training system which uses surfel (surface elements) models and carries out realistic cutting simulation using a haptic device [4].
- Cutting on the clay using different shaped tools has been supported by the Freeform system [5].



Related Work



Work of Voxel based Dental Training Systems:

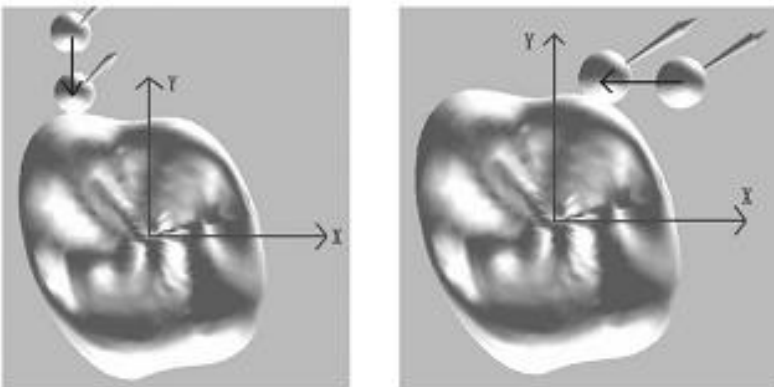
(Voxel, a shortcut for Volumetric piXEL)

- Barentzen proposed an Octree based volume sculpting to reduce the memory requirement [6].
- Galyean and Hughes introduced a voxel-based approach to volume sculpting that used the marching cube algorithm to display the model [7].
- H. T. Yau et al. also presented octree-based virtual dental training system with a haptic device [8].

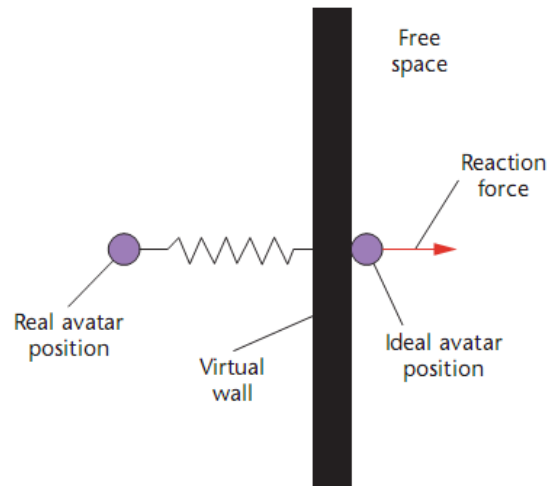
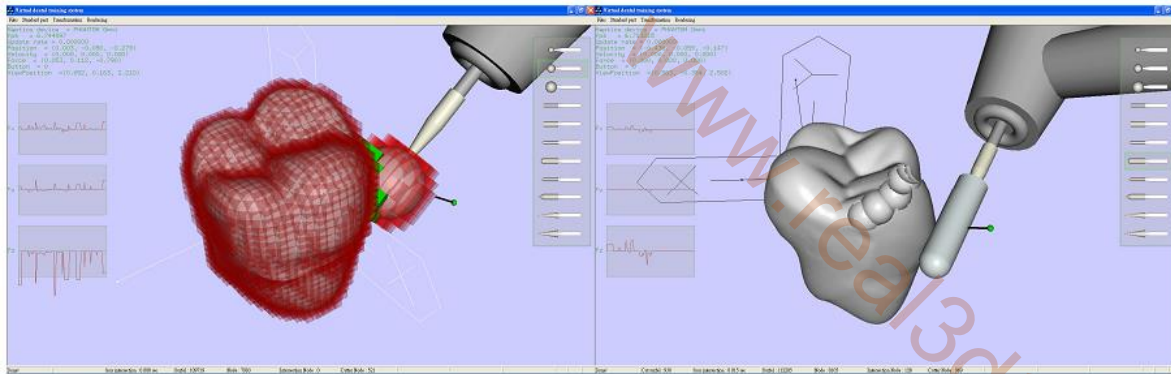
Work of Surfel based Dental Training Systems:

(Surfel, a shortcut for SURface ELement)

- Hong-Tzong Yau and Chien-Yu Hsu, used surfel model with Octree algorithm for the development and improvement of dental training system [4].
- Wang et al. described the cutting on surface model by using haptic display in virtual reality environment [9].



Related Work



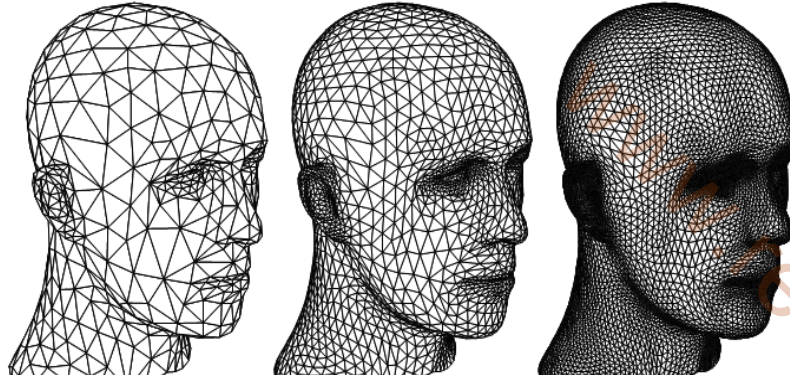
Haptic Interface in VR Environment:

- Many researchers are interested in using haptic feedback devices to enhance their virtual environment research because simulating touch in virtual worlds has led to increased performance in training simulators [1], [2], [3], [4], [9].
- Adams and Hannaford discussed the basic stability and performance of haptic interface [10].
- A more accurate examination of the stability problem was performed by Colgate et al. [11]

Force Rendering:

- Foskey et al., uses spring-based force established between the initial contact point on the surface and tool tip position [12].
- Hervé Delingette et al. proposed a tensor-mass force model similar to the spring-mass model [13].

Related Work



Compute hybrid hierarchial representation

offline

online

Input last position and current position / SCP

Check contact witness

false

Find segment's bounding grid cell(s)

Query cell's OBBTree(s)

Check potential triangles for intersection

return FALSE or intersection point / SCP

true

Subdivision Approach:

- Hui Zhang et al. introduce novel algorithms to subdivide the surface and generate interior structures for the simulation of the virtual cutting operation [14].
- Kup-Sze Choi described an interactive cutting simulation approach based on mass-spring system. He used subdivision of triangle algorithm during interactive cutting of deformable objects [15].

Collision detection:

- A. Gregory et al. presented a fast and accurate collision detection algorithm for haptic interaction with polygonal model[16].
- The haptic toolkit developed by SensAble Technologies, also has a collision detection library which is useful for interaction of objects [17].



Challenges

Graphic User Interface:

- OpenGL with Visual Studio C++

Realistic 3D modeling:

- Physical properties: colors, size, etc.
- Clear visualization

Realistic sense of touch:

- Haptic (1kHz) & graphic (30Hz) update rate [11].
- Reduction in vibration: Haptic device force & update rate
- Precise collision detection
- Tactile feelings at different regions
- Deformation of soft tissues (Removal of material from tooth surface)

Accuracy in calculation:

- The specific surfaces of contact (efficient collision detection)
- Timing
- Efficiently subdivision of triangles
- Efficiently model update after every sculpting action

Procedural Assessment

- Detailed evaluation



Process

Programming language:

- C
- C++

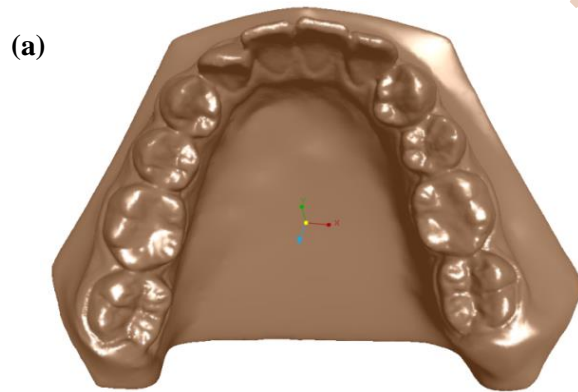
Rendering techniques:

- HLAPI / HDAPI – OpenHaptics library
- OpenGL – graphic rendering library
- GLUT – auxiliary library handles window creations, mouse movement, button and keyboard functions, callbacks, etc.

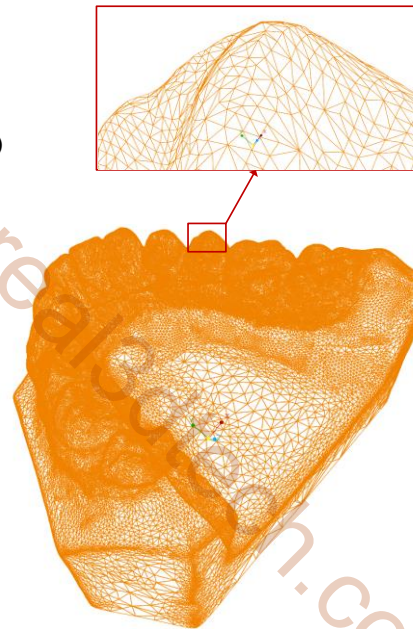
Method

Data Representation

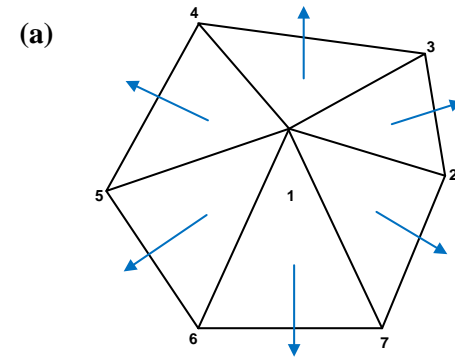
3D Sculpture Model Representation:



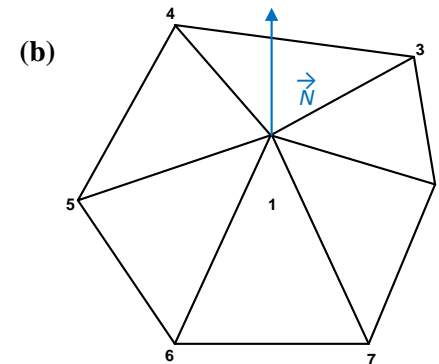
(a)



(b)



(a)

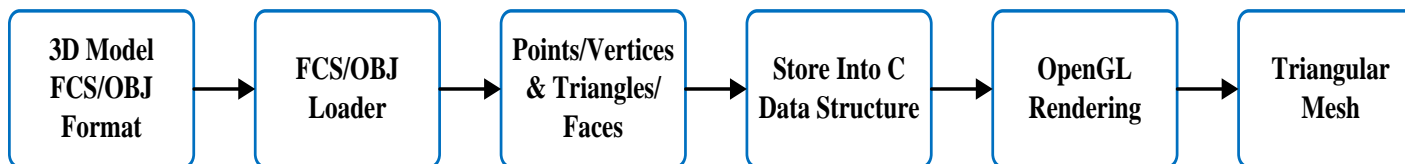


(b)

Facet Normal: (a) Face normal vector of each triangle (b) The normals of six adjacent faces are averaged to compute the vertex normal in N

Model Representation, Scanned from Digital 3D Laser Scanner (a) Surface-Based 3D Jaw Model having 6001 vertices and 119995 triangles with Average Vertex Normal Vector.

(b) Wireframe model of (a).



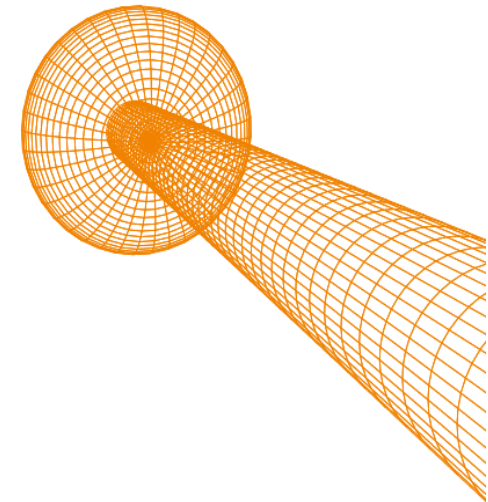
Rendering of virtual 3D object from FCS data file format.

Method

Data Representation

Virtual Dental Tool Representation:

In real world, dentist use different kind of cutter shapes for sculpture the teeth according to the several requirements. In this system virtual dental round cutter tool is used which has a specified standard radius for cutting simulation. Dentist can change the size of round cutter tool any time during the real time cutting simulation.

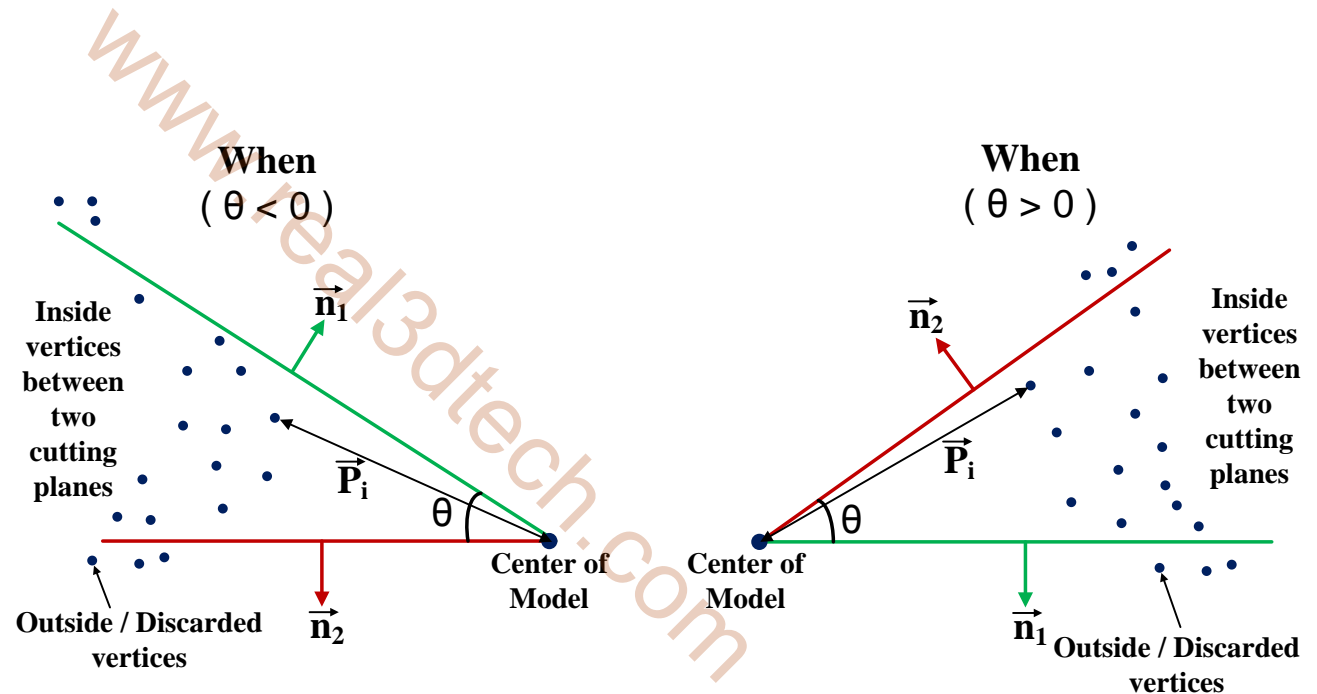
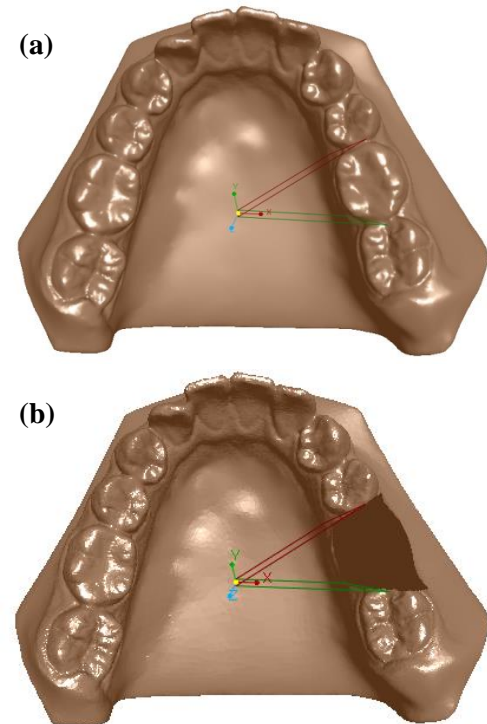


Virtual dental round cutter tool that constructed from a polygon based sphere.

Method

Algorithms

Data Reduction Algorithm



(a) Surface-based 3D jaw model having 60001 vertices and 119995 triangles with two cutting planes. (b) After applying Data Reduction Algorithm, the black portion shows the removed tooth area.

Method

Algorithms

Data Reduction Algorithm

if ($\theta > 0$)

if ($\vec{P}_i \cdot \vec{n}_1 < 0$ && $\vec{P}_i \cdot \vec{n}_2 > 0$)

V_j = ID number of i^{th} vertex

if ($\theta < 0$)

if ($\vec{P}_i \cdot \vec{n}_1 > 0$ && $\vec{P}_i \cdot \vec{n}_2 < 0$)

V_j = ID number of i^{th} vertex

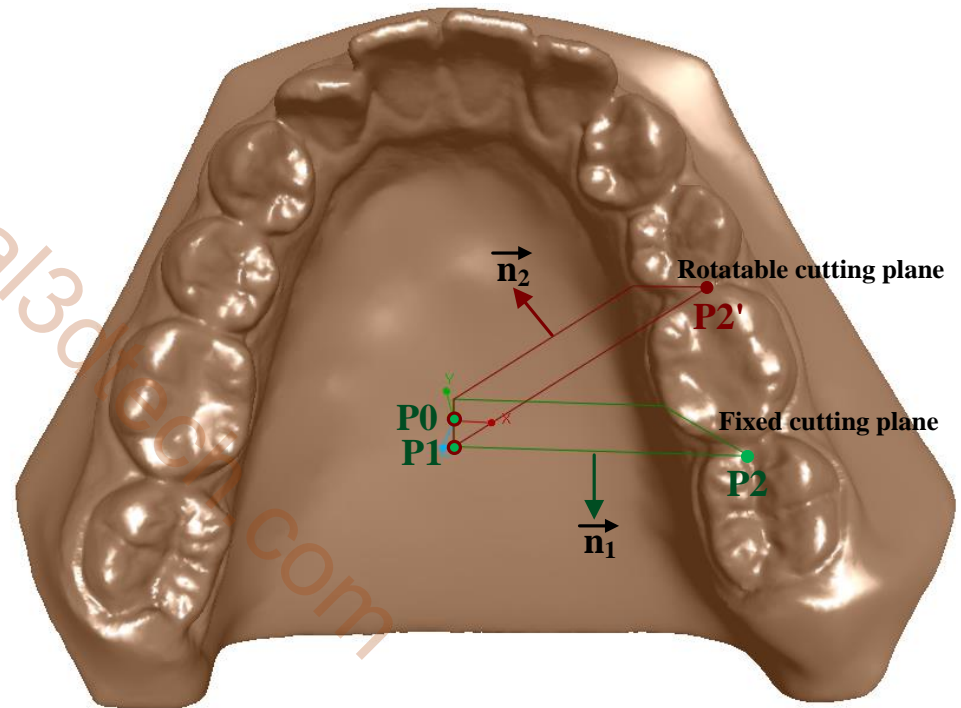
$$\vec{n}_1 = \frac{(\vec{P1} - \vec{P2}) \times (\vec{P0} - \vec{P2})}{\|(\vec{P1} - \vec{P2}) \times (\vec{P0} - \vec{P2})\|}$$

$$\vec{n}_2 = \frac{(\vec{P1} - \vec{P2}') \times (\vec{P0} - \vec{P2}')}{\|(\vec{P1} - \vec{P2}') \times (\vec{P0} - \vec{P2}')\|}$$

$\vec{P0}$ = Centroid of the 3D model

$\vec{P1}$ = Corner position of cutting planes along "Z" axis

$\vec{P2}$ = World coordinates at the desired position by mouse click



$$\begin{bmatrix} x^o_i \\ y^o_i \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix}$$

Method

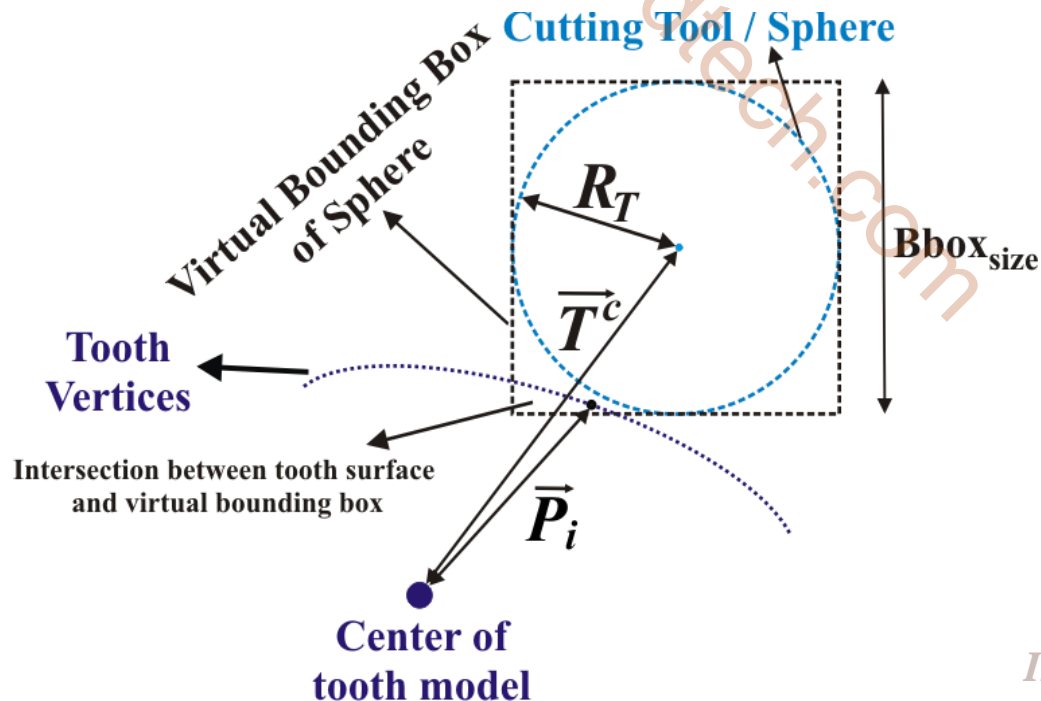
Algorithms

Collision Detection Algorithm with Cutting Process

(Intersection between virtual Bbox and tooth surface)

$$\text{if } (\vec{P}_i < \vec{T}^c + \frac{BboxSize}{2} \quad \&\& \quad \vec{P}_i > \vec{T}^c - \frac{BboxSize}{2})$$

Then store i^{th} penetrated vertex into Bbox;



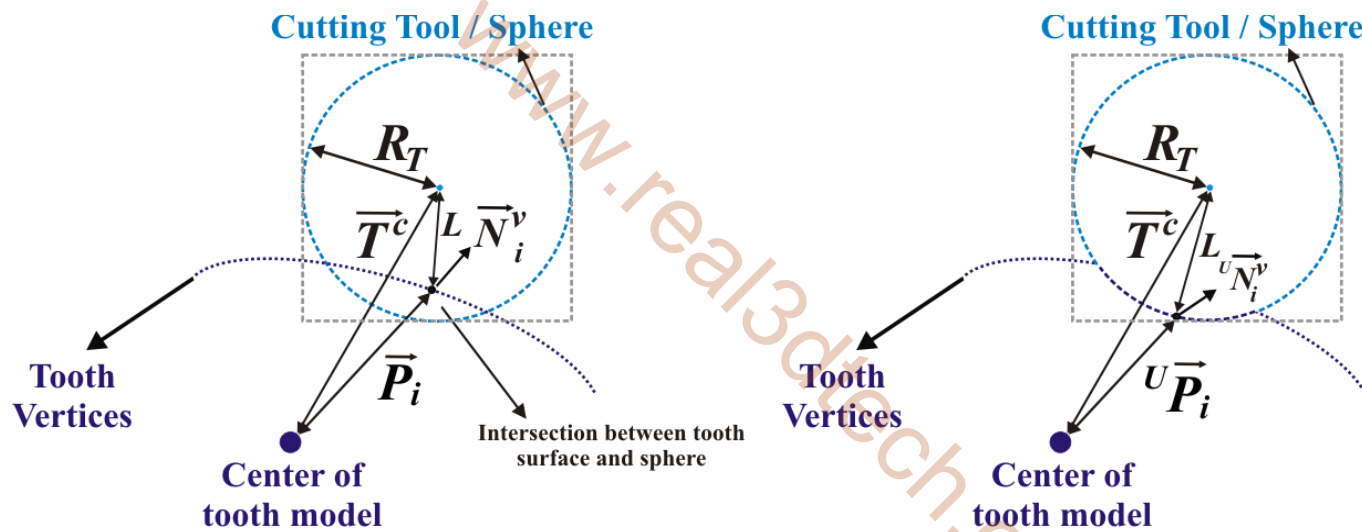
$$\vec{T}^c (T_x^c, T_y^c, T_z^c)$$

$$\vec{P}_i (P_x, P_y, P_z)$$

Method

Algorithms

Collision Detection Algorithm with Cutting Process



$${}^u\vec{P}_i = (R_T \cdot \vec{N}_i^v) + \vec{T}^c \quad L < R_T$$

$${}^u\vec{N}_i^v = \frac{\vec{P}_i - \vec{T}^c}{L}$$

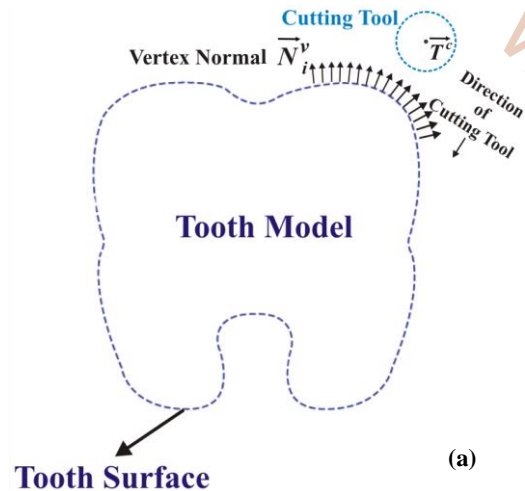
$$L = \|\vec{P}_i - \vec{T}^c\|$$

$$\vec{N}_i^v = \text{Vector Normalize} \left[\sum_{i=0}^m \vec{N}_i \right]$$

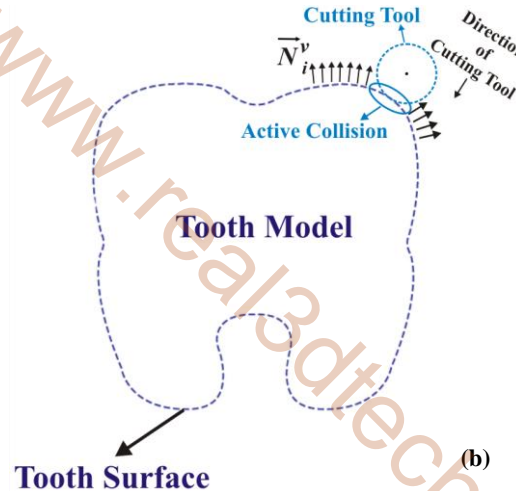
Method

Algorithms

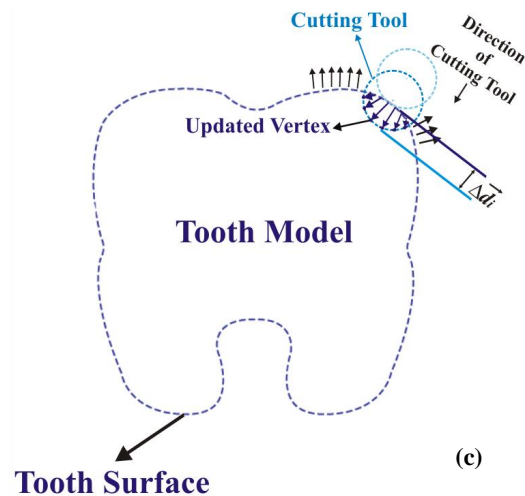
Collision Detection Algorithm with Cutting Process



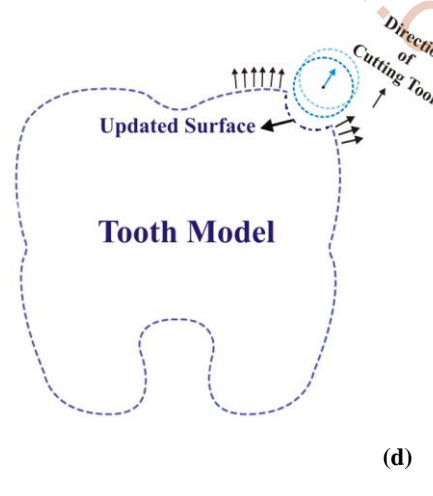
(a)



(b)



(c)



(d)

- (a) No collision between virtual tool and tooth surface.
- (b) Intersection between virtual tool and tooth surface.
- (c) After intersection, the vertices deformed from original tooth surface to the virtual tool surface.
- (d) After cutting, final tooth shape

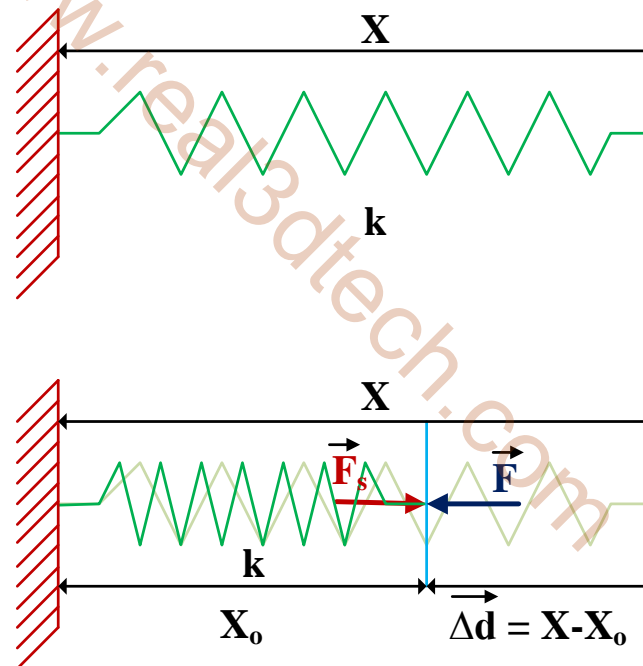
Method

Algorithms

Generally graphics applications in real time virtual environment have display update requirement almost between 20 to 30 frames per seconds. But for the sense of touch, the update rate of haptic simulations must be as high as 1 kHz frequency in order to maintain a stable force feedback system.

Haptic Rendering Algorithm

The spring damping model for the computation of responsive force feedback



(Hooke's Law for spring force computation)

$$\vec{F}_s = k \cdot \Delta \vec{d}$$

Where F_s is the force exerted by the spring, k is a spring stiffness/constant and Δd is the change in displacement from original spring position.

Method

Algorithms

Haptic Rendering Algorithm

After summation of all forces of all penetrated vertices, the total force vector by apply the spring-damping model can be computed by following Eqn.

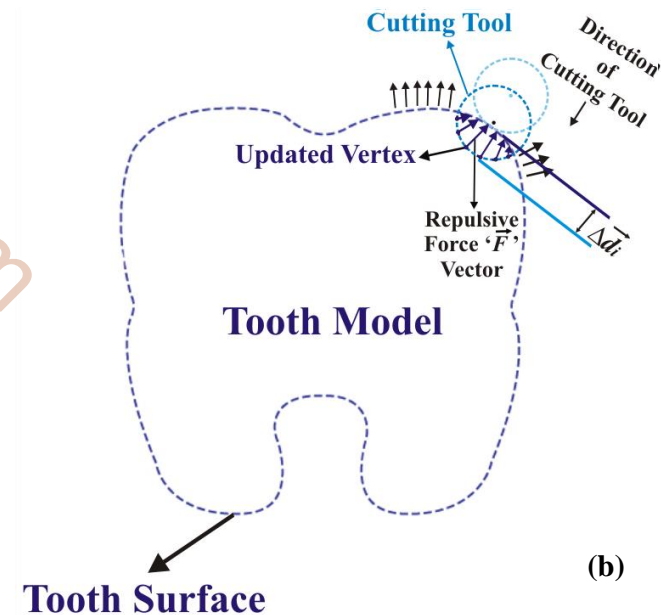
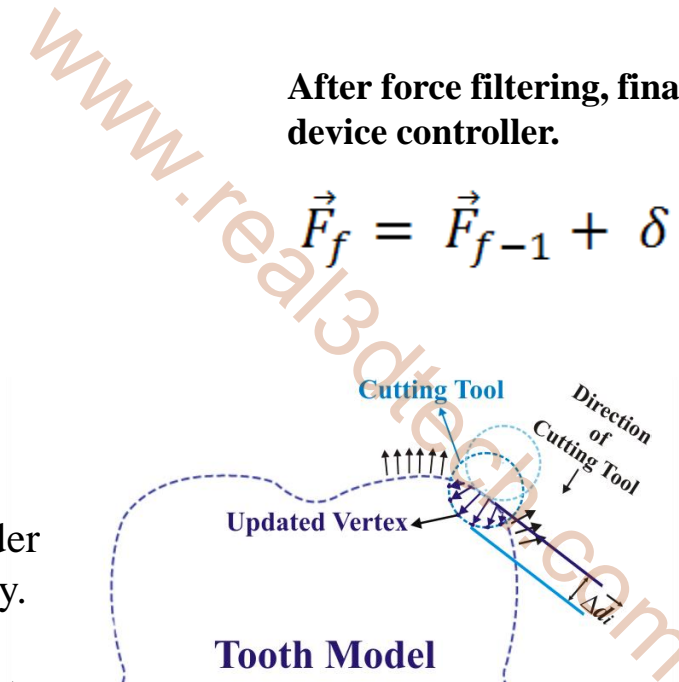
$$\vec{F}^t = k \cdot \sum_{i=0}^m \Delta \vec{d}_i$$

It must be necessary to consider material properties i.e. viscosity. Following Eqn. for the computation of overall resultant force before sending to the haptic device controller.

$$\vec{F}_R = k \cdot \sum_{i=0}^m \Delta \vec{d}_i \cdot \vec{n}_i - b \cdot \vec{v}_i$$

After force filtering, final force vector that send to the haptic device controller.

$$\vec{F}_f = \vec{F}_{f-1} + \delta \cdot \frac{\vec{F}_R}{\|\vec{F}_R\|} \quad \|\vec{F}_R\| > \delta$$

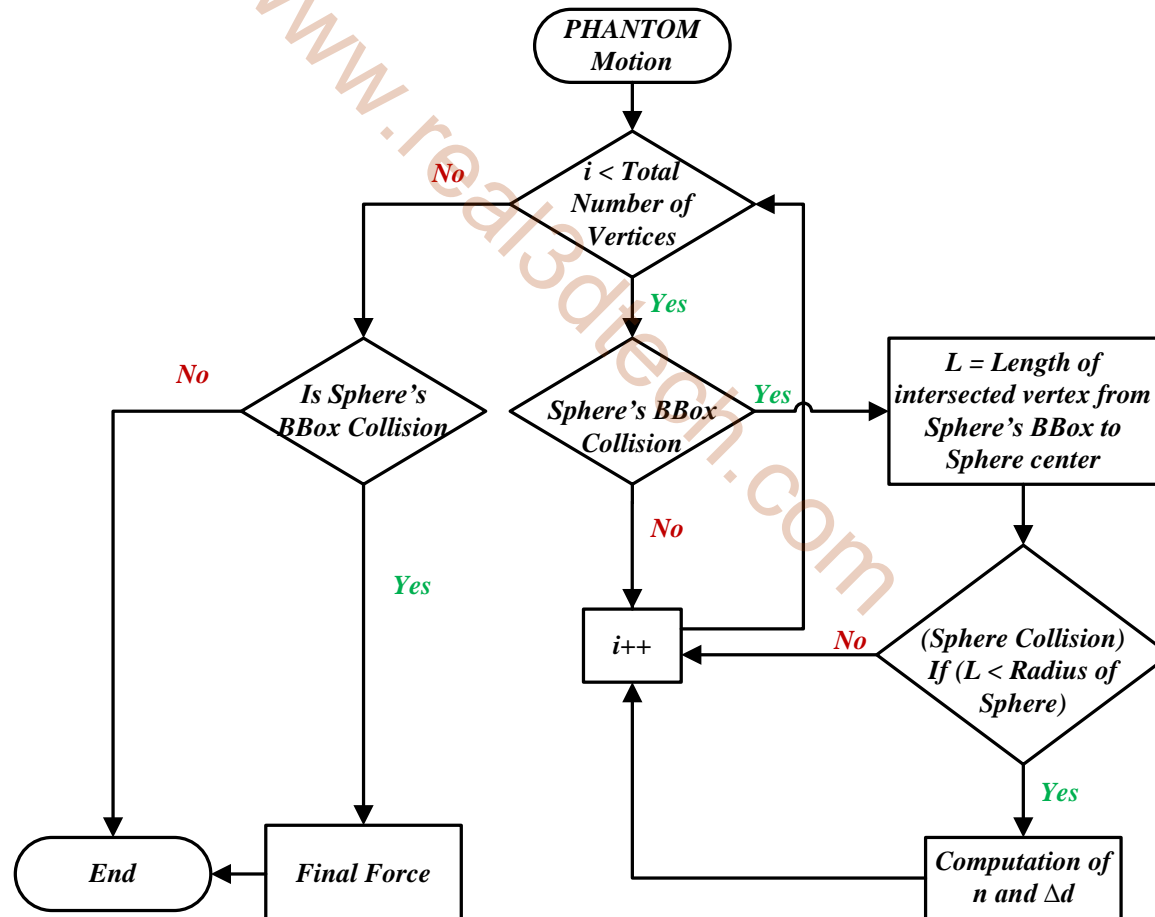


Method

Algorithms

Haptic Rendering Algorithm

Force computation flowchart

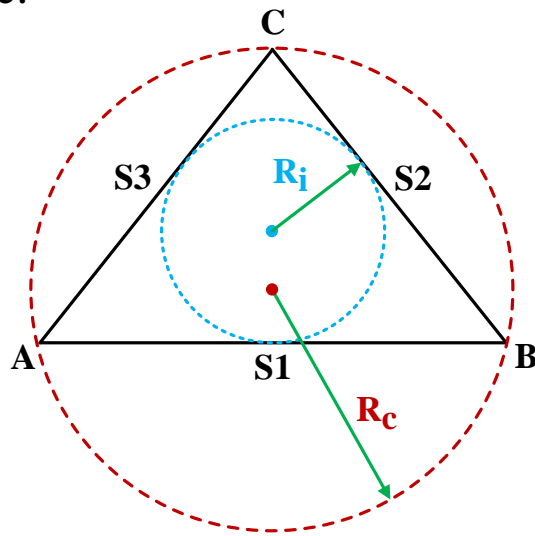


Method

Algorithms

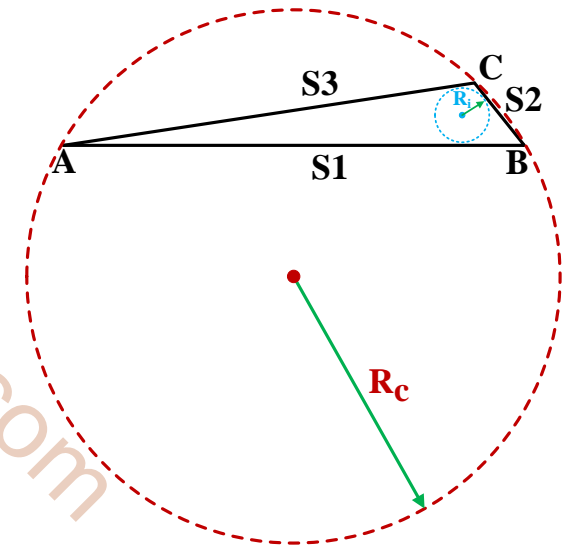
Triangle Subdivision Algorithm

Abnormality of triangles happen during continues deformation of tooth vertices by cutting tool, such as long and thin triangles which will affect the stability of force computation and tooth shape.



(Regular Triangle)

- A, B, C - Vertices of triangle
- S1, S2, S3 - Triangle edges
- R_c - Circumcircle radius
- R_i - Incircle radius



(Irregular Triangle)

if $\left(\frac{R_c}{R_i} > U \ \&\& \ ((S1 > L) \ OR \ (S2 > L) \ OR \ (S3 > L)) \right)$ (U and L are the magnitudes of user defined criteria.)

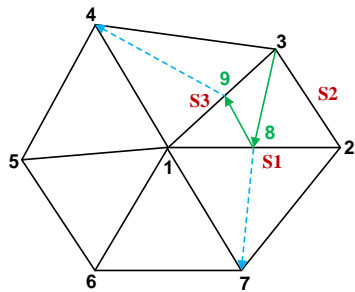
Then active subdivision;

Method

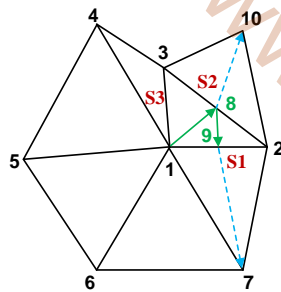
Algorithms

Triangle Subdivision Algorithm

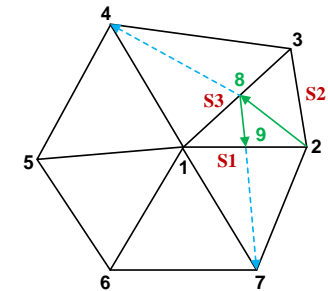
Case # 1 - $S2 < S3 < S1$



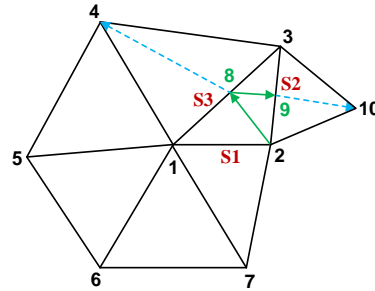
Case # 4 - $S3 < S1 < S2$



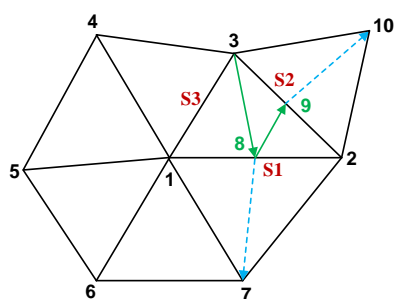
Case # 2 - $S2 < S1 < S3$



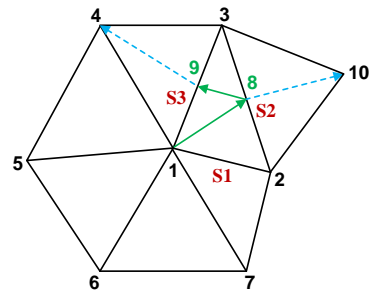
Case # 5 - $S1 < S2 < S3$



Case # 3 - $S3 < S2 < S1$



Case # 6 - $S1 < S3 < S2$



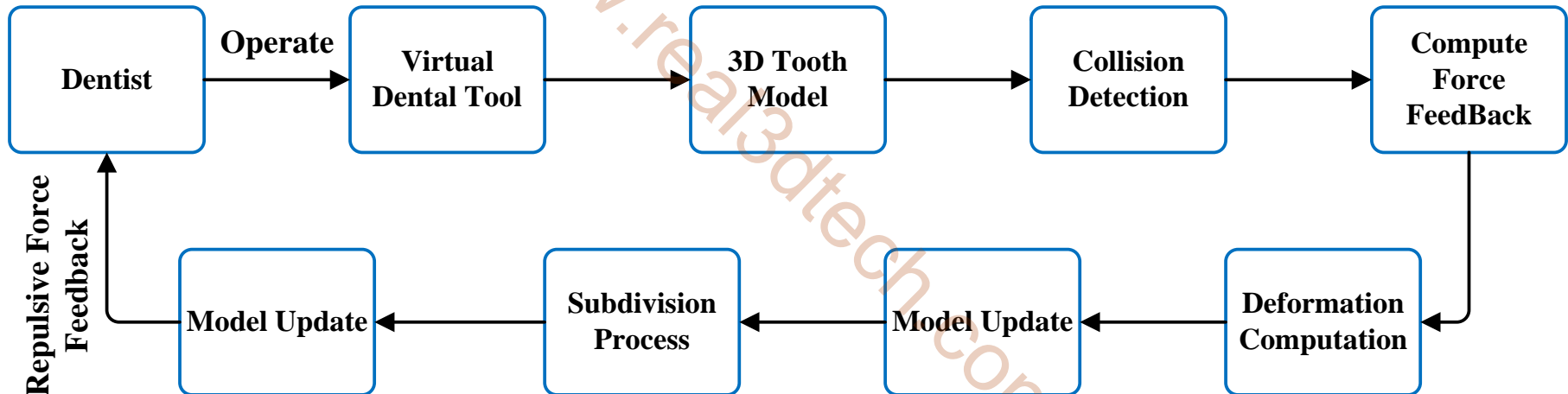
**Tri-Division Method,
6 possible cases of
subdivision of triangle**

- Tri-Subdivision
- - - Bi-Subdivision
- 1,2,3... Triangles Vertices
- 8,9- New Vertices
- S1,S2,S3- Triangle Edges

Method

Algorithms

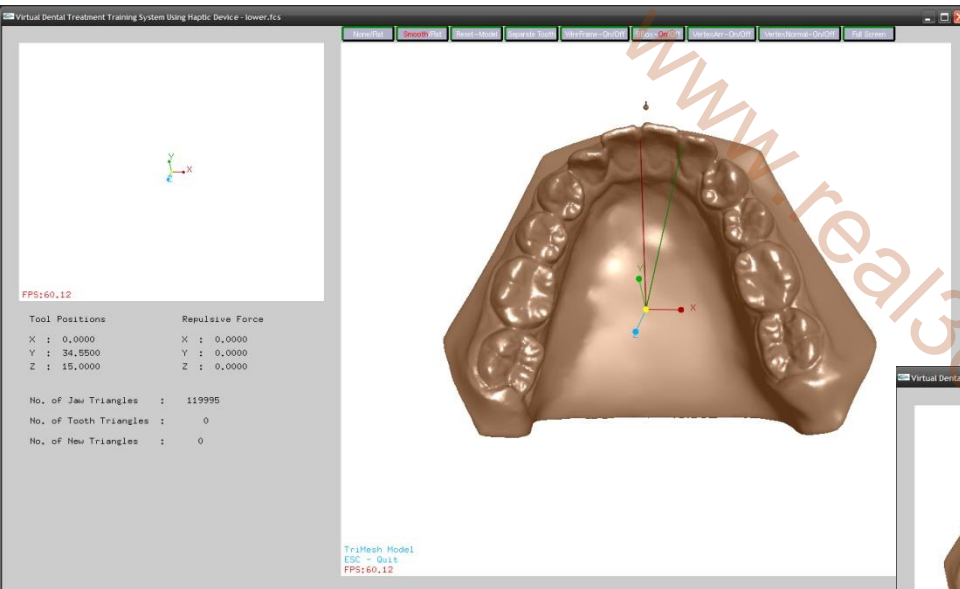
Local Updating



Process flow of virtual dental treatment training system with realistic sense of touch.

Implementation and Results

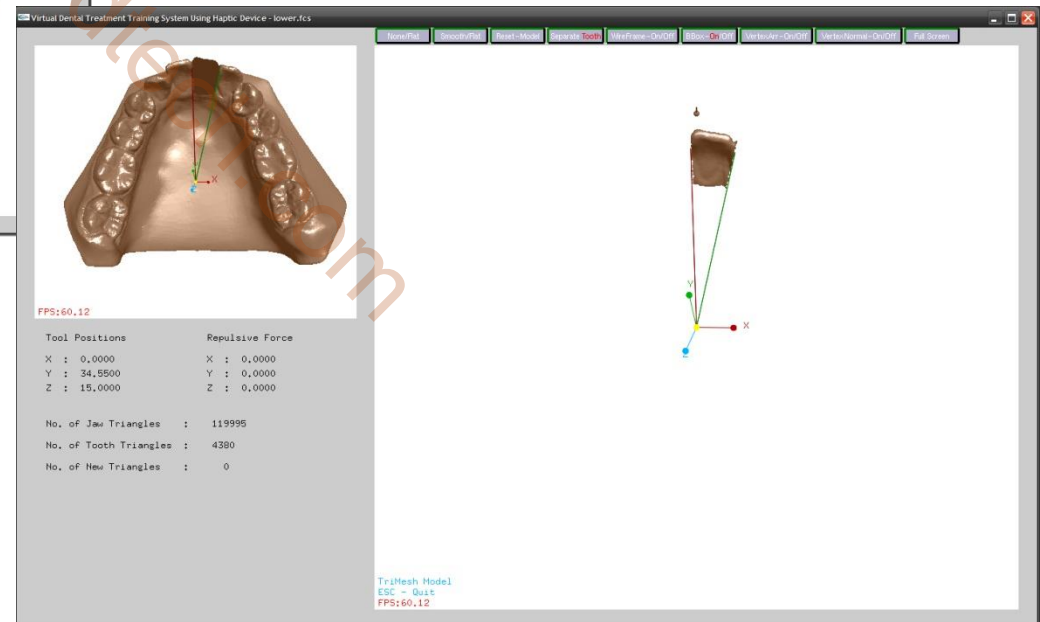
Implementation of data reduction algorithm



After Implementation of data reduction algorithm

No. of triangles = 4380

Percentage of remaining data = 3.65%



After Implementation of data reduction algorithm

No. of triangles = 119995



Implementation and Results

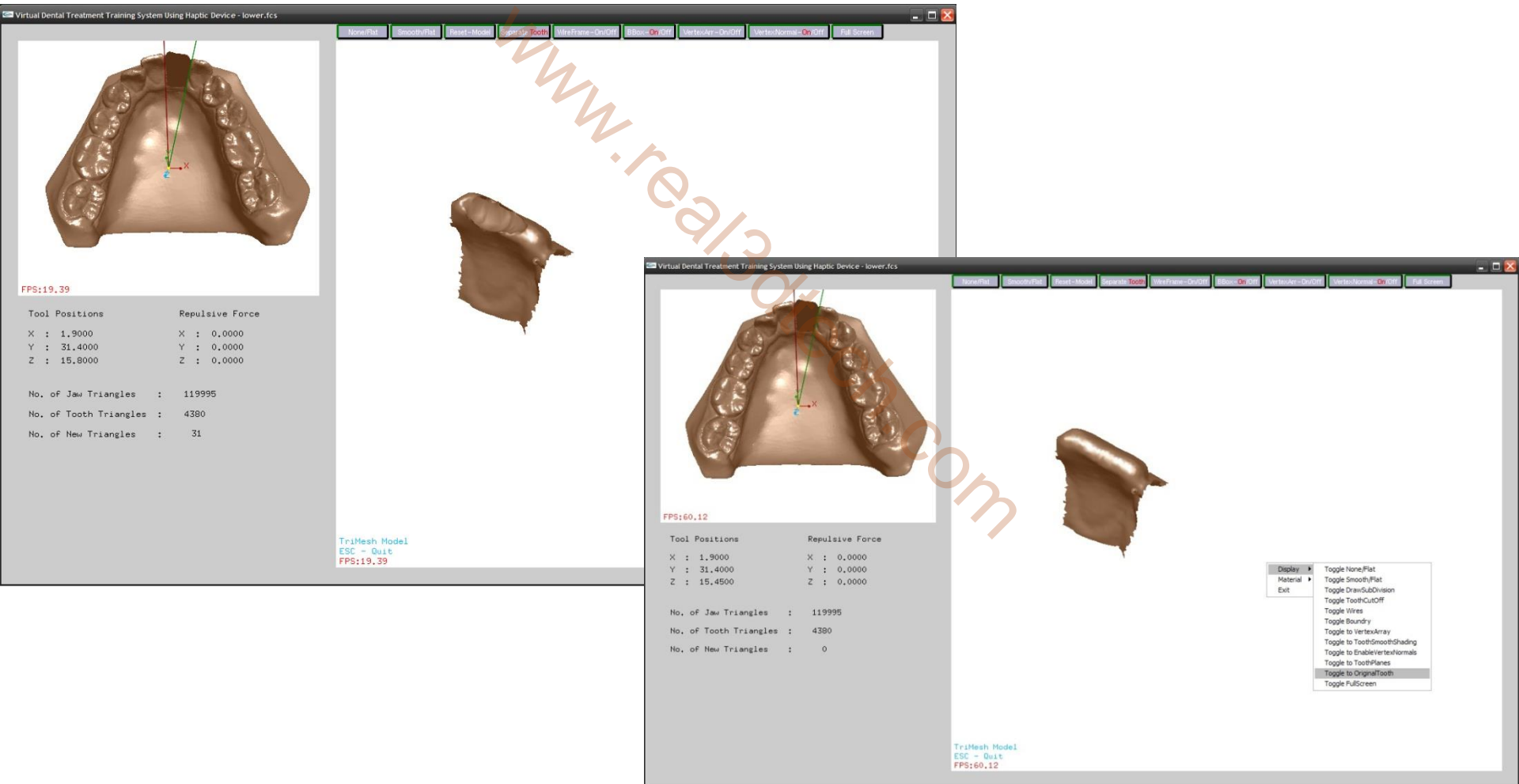
Implementation of real time cutting simulation

- **Enable haptic device**
- **Load models**
- **Draw models**
 - Graphically
 - Haptically
- **Determine proxy point**
- **Force calculation**
- **Local based collision detection**
- **Cutting process in real time**
- **GUI builds on top of virtual environment**
 - Menu
 - GUI



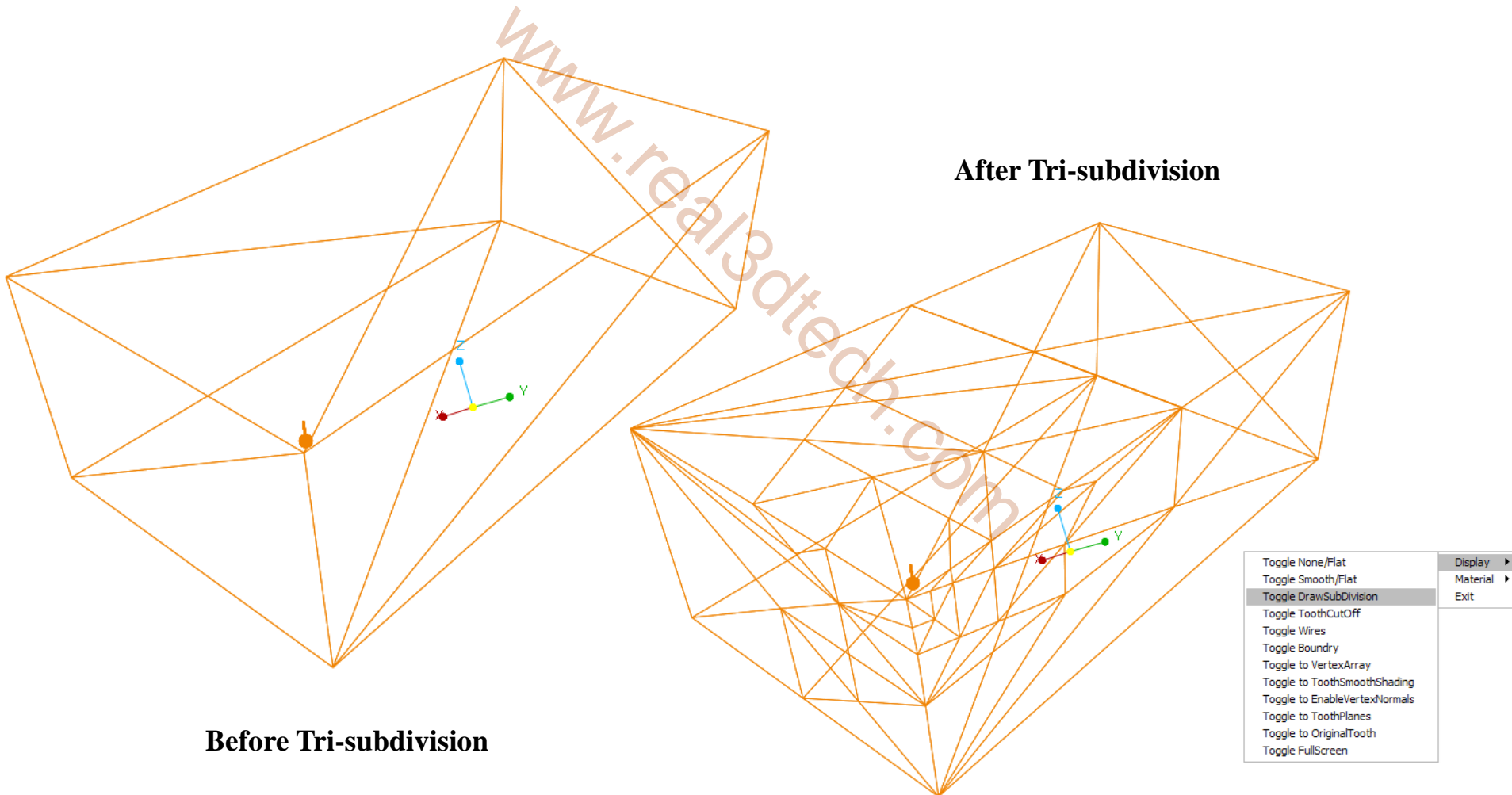
Implementation and Results

Implementation of real time cutting simulation



Implementation and Results

Implementation of subdivision of triangle algorithm

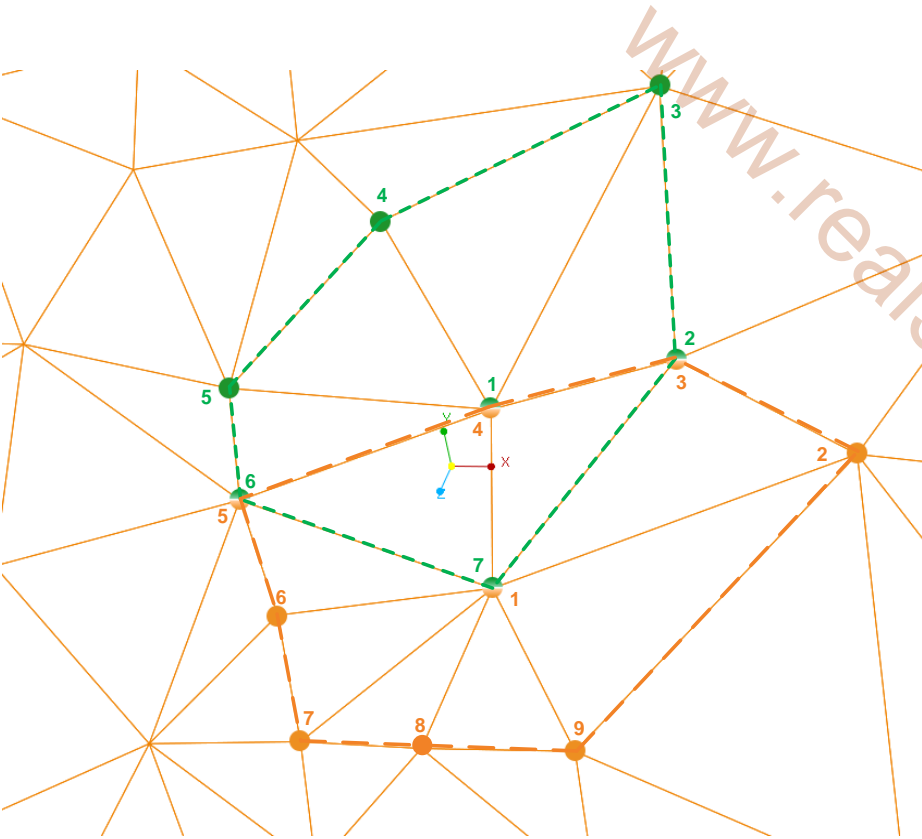


Before Tri-subdivision

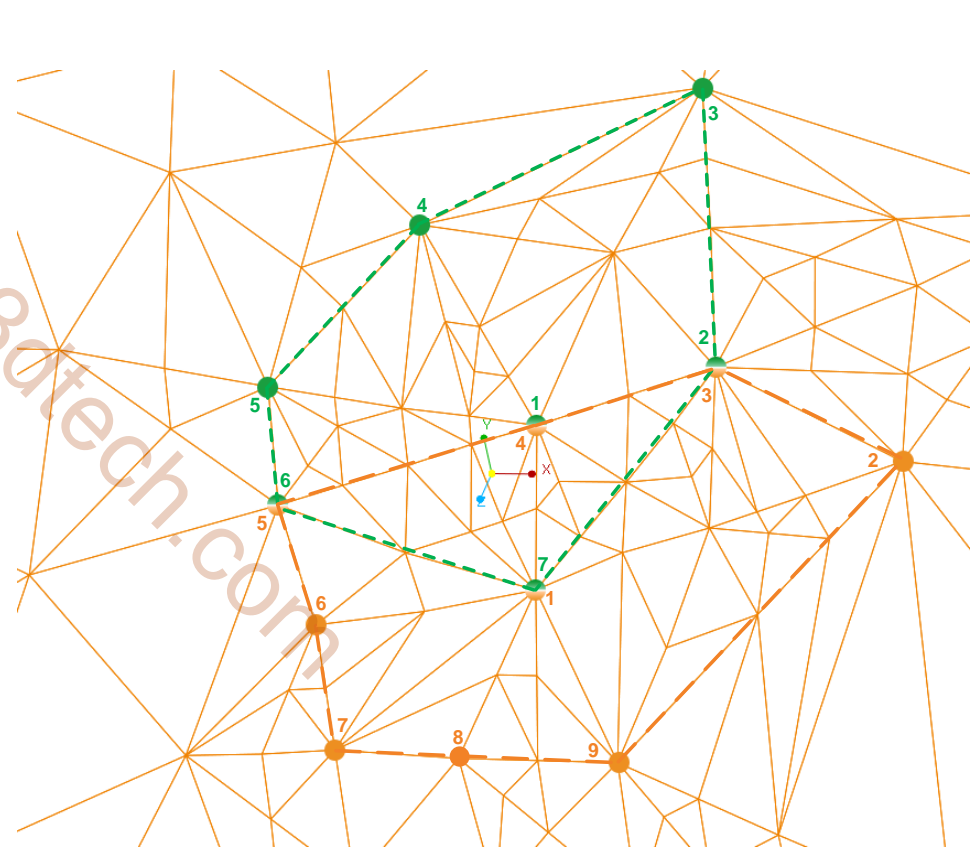
After Tri-subdivision

Implementation and Results

Implementation of subdivision of triangle algorithm



Before Tri-subdivision



After Tri-subdivision



Conclusion

- Surface based virtual dental cutting simulation is performed using haptic interface.
- Using Surface based model costs less memory than using volumetric representation.
- It is concluded that the mapping from haptic tool tip to the virtual tool is critical for designing the force computation model.
- Data reduction algorithm is proposed for the fast rendering of cutting simulation.
- Vertex deformation method is used for the removal of tooth tissues, and for the prevention of abnormality of triangles, tri-subdivision method is utilized.
- Improved stability and fidelity in responsive haptic force feedback.
- Enhanced model updating by using local based updating algorithm.



Future Work

- It is necessary to include friction force into the force model for better sense of touch during cutting simulation.
- Stability and fidelity need to improve.
- Material removal from tooth surface needs to improve when the continues deformation occur.
- Future improvement in overall system.
- Enhanced system by adding various dental tools and visual effects
- Different visual effects can be add for better understanding of dental students.



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THANKS

