A Review of Virtual Surgical Object Modeling Technology Based on Force Feedback

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***Abstract*—The early virtual surgical system was only developed on the computer software, and users could only interact with the surgical model through the mouse. The disadvantage of this way was that users could not get tactile feelings. Therefore, with the development and progress of virtual reality technology, force feedback equipment has been introduced into virtual surgery, and has become a research hotspot in this field, in order to make efforts to feedback equipment in the research institute and higher and higher utilization rate. Researchers, teachers and students used force feedback devices to improve the immersion of virtual surgical system. This article mainly introduced the virtual modeling method in the operation, including geometric modeling and physical modeling, the geometric modeling of the two models are introduced, and summarizes their advantages and disadvantages, the physical modeling of soft tissue deformation modeling of three models are analyzed and compared, and the feedback force calculation model are introduced, finally, expounds some problems faced by modeling technology, virtual surgery The future development is also prospected.**

Keywords-Force Feedback; Virtual Surgery; Geometric Modeling; Physical Modeling

I. INTRODUCTION

With the development of science and technology in medical surgery, virtual surgery has become a hot topic and research direction, and a lot of research institute and hospital using computer simulation technology to reproduce the surgical scenario, it's a multidisciplinary cross area of research, including medical, computer graphics, math, mechanical, etc. [1]. In medical teaching, ever took the form of teaching material teaching theory teaching to students, but because of the limited resources, cannot guarantee that every student to practice the operation, cause the teacher cannot effectively guide students [2], as a result, virtual surgery have solved the problem of resource scarcity, provides students with a realistic operation environment, can undertake training over and over again, But because most of the virtual surgery can only provide the feeling on the vision [3], unable to bring in other senses, such as the sense of touch, leading to the doctor in the virtual environment to complete the operation effect of the operation and clinical surgery a greater difference between the effect of the environment, in order to allow users to get tactile perception, is gradually applied to the virtual force feedback devices [4] in the operation, Users by force feedback device control virtual surgery tool model and object model of operation environment interact [5], when the force feedback device access to the user's operation, the operation information for the corresponding calculation and feedback to the user of an appropriate size, thereby enhancing the user immersion in virtual surgery [6], the user in the process of training again and again, Having a comprehensive understanding of the entire surgical process and the structural characteristics of the surgical object saves resources and reduces costs.

The modeling of surgical objects and surgical tools in virtual surgery is related to the degree of reality of the virtual surgery system, and also has a great influence on the collision detection, feedback force calculation and deformation calculation. Therefore, geometric modeling and physical modeling are the focus of virtual surgery research. In clinical surgery, in the case of soft tissue, if for press operation, not only with focus on production, and its surface will with corresponding deformation pressure strength, but for this rigid body such as teeth, because the surface of the teeth will not happen with the touch of needle deformation, therefore in virtual surgery, the software not only need to consider the feedback force calculation model, Deformation models are also needed. The establishment of a good geometric model and physical model has an important impact on the real-time and authenticity of virtual surgery.

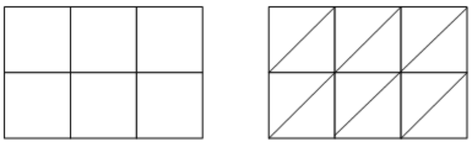
II. GEOMETRIC MODELING

Geometric modeling refers to drawing the geometric shape of the model in the virtual three-dimensional scene, and establishing an accurate geometric model of the surgical object, which can bring a realistic visual experience to the user, which is of great significance for the visual rendering of virtual surgery, such as in clinical oral cavity. In surgery, drilling operations are particularly common. Teeth are the main object of oral surgery. When the doctor drills the teeth, tooth debris will be generated. In the virtual oral surgery, certain structural changes must be made to the geometric model, so that the Users have a clear visual experience. Therefore, in virtual surgery, a reasonable geometric modeling method is a prerequisite to ensure the authenticity of virtual surgery.

There are two methods of geometric modeling: surface model based on surface mesh and volume model based on voxel.

A. Surface model based on surface mesh

Surface model based on surface mesh refers to many discrete particle by line connected together by the model, the model of topological relations between particle and particle, according to the topological relationship model can be further calculated the stress or deformation, therefore, choose the appropriate topology relationship is the premise of guarantee authenticity model deformation. Common topologies of face models include triangles, quadrangles, or other polygons, as shown in Figure 1. In the process of grid division, triangle structure is the smallest topological structure that can be divided. Compared with quadrilateral structure, there is no need to judge whether four points are on the same plane. Therefore, triangle structure is simple, flexible, easy to describe and efficient, and has been adopted by most scholars [7]. Early in virtual surgery system, most scholars use the surface of the triangular structure model to simulate the surgery simulation, for example, in 1994, Massie is simulated by the method, the operation objects in the virtual environment, and the operation object gives stiffness characteristics, force analysis through the spring model can calculate the size of the force feedback, and feedback to the user, The user can get a tactile feeling, but the model can not reflect the deformation characteristics. In 2017, Liao Denghong et al. used the grid deformation algorithm to realize the drilling operation of teeth, but the model could only reflect the changes of tooth surface, but could not reflect the structural changes inside the tooth model.



(a) Square structure (b) Triangular structure

Figure 1. General surface model surface topology.

Surface model based on surface mesh has certain advantages in displaying the surface structure of the model, and the modeling speed of the surface model is faster than that of the volume model, which can fully display the topological relationship between each particle on the surface of the surgical model. The model of single tooth surface based on triangular plane is shown in Figure 2.

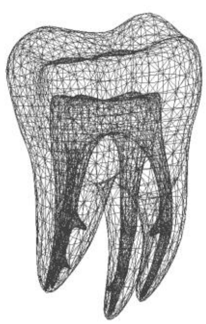
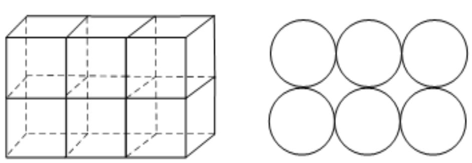


Figure 2. Single tooth surface model based on triangular plane.

B. Volume model based on voxel

Volume model based on voxel refers to contain internal structure information of three-dimensional data model, the model consists of a number of individual element, voxel volume element, namely the voxel is through the body to a space according to certain size and manner of dividing, similar to the pixels, each individual element are closely linked and has its own location information, and fully displayed the model the internal organization of the information, Therefore, the selection of voxels is of great significance to the authenticity of model deformation. Common voxel structures include cubes, spheres or other shapes, as shown in Figure 3. Because cube is the easiest method for structure division, researchers mostly use cube structure to divide voxels and generate corresponding volume models [8, 9]. In 1997, Stijn Oomes applied Scale-space Theory to achieve voxelization of the model. In 1998, Roni Yagel et al. voxelized the model using a function of a normal vector. In 2000, Jones et al. used Distance Fields and Distance Transform to realize the voxelization of the model. Although these voxel methods can generate voxel models faster and better, they all need graphic workstations to participate in and have high requirements on hardware. Therefore, in 2004, Wu Xiaojun et al. proposed a method to voxelize the mesh model by using the structure of the octree. This method calculates the distance from the triangle to the center of the voxel. If the calculated distance is less than the preset threshold, it is considered that the voxel unit intersects with the triangle, and finally voxelization is realized. Although this method does not require the participation of a graphics workstation and only requires a computer, it consumes a lot of computing resources in the calculation process, and the threshold is difficult to determine, resulting in inefficient voxelization and incomplete voxel search. In 2010, Mu Bin et al. proposed a new voxelization method based on the octree structure. By calculating the projected volume, it is judged whether the voxel intersects the triangle, and the adjacency relationship is used to fill the interior of the model with voxels. , and finally realize the voxelization process. This method projects the 3D to the 2D plane, and then returns the 2D data to the 3D space to realize the voxelization. Although the speed is improved, the processing process of this method is relatively Complicated, returning from 2D to 3D will cause errors to cause incomplete voxel search errors. In 2017, in order to improve this shortcoming, Duan Weiwei et al. proposed a new voxelization method based on the octree structure. First, the octree was used to subdivide the model, and then the model was scanned from multiple directions. This method Although it can quickly determine the surface voxels and internal voxels of the model, it is not suitable for the case where the model contains holes, and it will treat the internal holes as internal voxels. Therefore, the voxelization method still needs to be further improved.

Compared with the surface model, the volume model based on voxel can show the structure of the internal information, for example in the oral cavity in virtual surgery, voxel model can according to different physical properties of the internal structure of simulated teeth of layered internal structure, such as enamel, dentin and dental pulp, etc., thus brings the user in the process of the whole operation and clinical surgery similar visual and tactile sensation. Therefore, the body model is used by most scholars to build the virtual surgical object model. The single tooth volume model based on cube is shown in Figure 4.



(a) Cube structure (b) Sphere structure

Figure 3. General volume model topology.

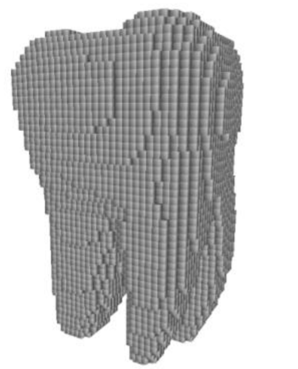


Figure 4. Single tooth volume model based on cube.

III. PHYSICAL MODELING

Physical modeling refers to adding some physical characteristics, such as weight, surface roughness, suction, adhesion and deformation characteristics, on the basis of the geometric model, so that the model in the virtual environment is more consistent with the object in the real world. Therefore, the establishment of physical model is closely related to the authenticity and real-time of the system.

For tissues and organs, soft tissues will be deformed when pressed. In order to achieve this visual deformation effect, a deformation model of soft tissues needs to be established [10]. When pressing, not only the visual deformation effect will be produced, but also the tactile force feedback will be accompanied. In order to realize the tactile feedback, the feedback force calculation model needs to be established.

A. Soft tissue deformation model

At present, common modeling methods for soft tissue deformation include Mass Spring Method (MSM), Finite Element Method (FEM) and Boundary Element Method (BEM) [11]. The analysis and comparison of soft tissue deformation modeling methods is shown in Table Ⅰ.

TABLE I. COMPARISON OF THREE MODELING METHODS

Modeling method	Instantaneity	Complexity	Computational accuracy	Robustness
Mass Spring Method	best	simple	general	general
Finite Element Method	general	complex	best	better
Boundary Element Method	general	more complex	better	better

1) *Mass Spring Method*

Mass spring method refers to the use of some discrete particles to describe the object, the particles and particles are connected through the spring, the force of the particle meets Newton's laws of motion, the spring meets Hooke's law. The mass spring model is shown in Figure 5.

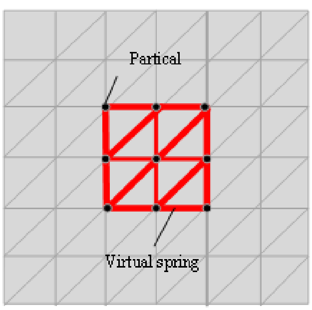


Figure 5. Mass Spring Model

2) *Finite Element Method*

Refers to a continuum of finite element method is used to solve the domain of discrete into several units, each unit through the certain way of interconnecting approximation instead of the original system, and then within each unit, with the assumption of approximate function to piecewise said the whole solution domain and the unknown variables, finally through with the original problem, the mathematical model of the equivalent variational principle or weighted method, The equations of ordinary differential equations are established to solve the basic unknowns, and then numerical analysis is used to solve the equations, and finally the solution of the original problem is obtained.

3）*Boundary Element Method*

Boundary element method refers to discretely solving the boundary of the solution domain by piecewise functions. This method is also a numerical analysis method, but it requires less computation than the finite element method. The boundary element model is shown in Figure 6.

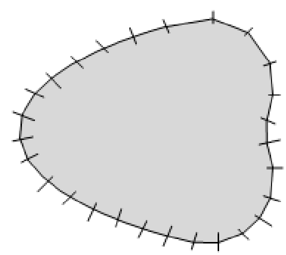


Figure 6. Boundary Element Model

B. *Feedback force calculation model*

In order to enable users to get tactile feelings in virtual surgery, that is, users can obviously feel the contour, stiffness and other characteristics of the model surface through force feedback equipment [13], so as to make the experience more real, it is necessary to add mechanical properties to the geometric model and establish an appropriate feedback force calculation model for tissue and organ models. At present, the most commonly used force feedback model is the mass-spring-damper model. However, for rigid body models, such as teeth and human bones, their surfaces will not deform with the contact of the surgical tool model, so damping force is not needed to be considered.

The tactile feedback of the mass-spring-damper model is rendered by the relative position of the surgical tool model, In order to prevent the "piercing" phenomenon, that is, when the surgical object model is touched with the surgical tool, the surgical tool is prevented from being embedded inside the surgical object model. Therefore, for the situation where the visual and tactile positions of the surgical tool model are inconsistent, 1995 In 2008, Zilles and Salisbury proposed a point-based three-degree-of-freedom force feedback calculation method, also known as the God-Object method. This method saves two position information, one is the force contact point, which refers to the position where the surgical tool does not receive any resistance during the movement process, that is, the ideal position; the other is the God-Object point, when the surgical tool is in contact with the position of the collision point when the model object collides. When the surgical tool touches the surgical object in the process of moving, the force contact point will penetrate the surgical object, and the God-Object point will stay on the surface of the surgical object, and the feedback force can be obtained by calculating the distance between the two points. . However, this method has a disadvantage. It is easy to cause the God-Object point to fall into the gap due to the error, resulting in discontinuity of force. Therefore, in 1997, Ruspini proposed a Virtual-proxy method based on this method. The Object point is replaced by a small ball without weight, which improves the disadvantage of falling into the gap and realizes the feedback effect of friction [14].The idea of this method is the same as the God-Object method, require the force feedback Device to store two location information in the virtual surgical scene, one is the actual terminal location of the force feedback device, the other is the proxy location of the surgical tool model. In the initial state, the tool model has not collided with the object model. Therefore, the proxy and device overlap at this time. When the collision between the tool model and object model is detected, the proxy of the tool model will always be on the surface of the object model where the collision occurs. The device "pricks" into the object model as the force feedback device applies varying amounts of force. That is, visually, the tool model is on the surface of the object model, but tactile, the tool model is already deep inside the object model, as shown in Figure 7.

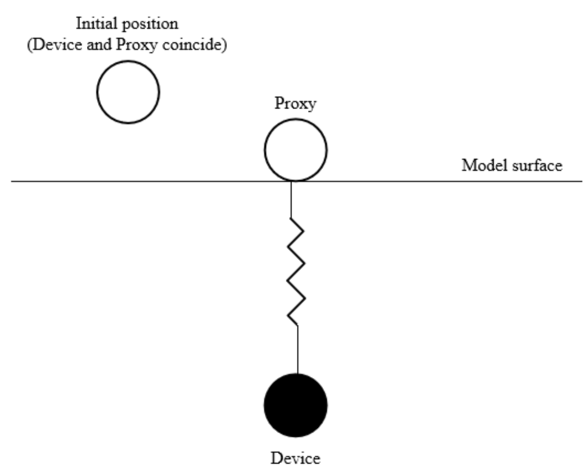


Figure 7. Mass-spring-damper Model

When there is no collision in the moving process of the tool model, the feedback force is 0. When a collision occurs, the spring will stretch with the force applied by the force feedback device. The coordinate of the collision point should be found according to the line between the target position of the tool model and the position of the previous moment and the intersection of the object model surface. Then hooke's Law is used to calculate the size of the feedback force. Its feedback force can be described as formula (1).

$$F = (k\Delta x + d\Delta x)\vec{n} \quad (1)$$

Where k represents the elastic coefficient of the virtual spring, the distance between the device and the proxy of the surgical tool model, and d represents the damping coefficient, and $\vec{n}$ represents the direction vector of the normal vector of the action point [15]. By adjusting k and d values, the mechanical properties of the surgical object in the actual operation can be accurately simulated, so that doctors can feel the feedback force in the real operation.

After a good model is established, if you want to get the tactile feeling in the virtual surgical system, you need to introduce force feedback devices. Now there are many force feedback devices on the market. Examples include Phantom Omni (Geomagic Touch) from Sensable, 3D Touch from Novint Falcon, Omega.6 and Omega.7 from Force Dimension, as shown in Figure 8. Phantom Omni force feedback device supports 3-Dof position and 3-Dof force feedback, 3D Touch force feedback device supports 6-Dof position and 3-Dof force feedback, Omega.6 force feedback device supports 6-Dof position and 3-Dof force feedback, Omega.7 force feedback equipment supports seven degrees of freedom position and three degrees of freedom force feedback. User through the manipulation of the force feedback device control handle control surgical tools and operation model to interact, the force feedback device access to the user by controlling the control handle to the operation model of the force f a state information, the state information including the tool position or size of the force, and then through the establishment of good physical model, Calculate the size and direction of the reaction force generated by this force, so as to generate force control signal, and then calculate the feedback force through the actuator in the force feedback device, and transmit it to the user through the control handle, so that the user can get the tactile feeling in the virtual environment.

(a)Phantom Omni

(b)3D Touch

(c)Omega.6

Figure 8. Common force feedback devices

IV. CONCLUSIONS

The introduction of force feedback virtual surgery system, for users with visual perception at the same time, also gives the user more true feelings in the sense of touch, and establish a precise surgical object model is the basis and important part of virtual surgery training, to the visual rendering of virtual surgery and feedback force calculation has important influence. This article mainly introduced the virtual modeling method in the operation, after introducing the force feedback include geometric modeling and physical modeling, the geometric modeling of the two models are introduced, including physical modeling of soft tissue deformation model and the feedback force calculation model, the soft tissue deformation model of the three common models are introduced and compared, the feedback force calculation model and force feedback algorithm are introduced. In this paper, by analyzing a variety of geometric model and physical model for the visual rendering of force sensing and rendering in virtual surgery training provides the theoretical basis, although the present modeling technology can provide users with visual and tactile feeling good, but its real time needs to be improved, the need to improve the model to improve the real-time performance of the system, bring a good sense of immersion.

ACKNOWLEDGMENT

This work is partially supported by Science & Technology Program of Shaanxi Province with project “2021GY-005”. In addition the authors would like to thank Prof. Liu Baolong for his contributions and suggestions.

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