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Construction of Virtual Dense Elastic Object from Medical Image Data and Deformation with Haptic Device

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Abstract: In recent years, there have been various problems in medical treatments, of which human error by the surgeon in an operation. Therefore, the simulation of a medical operation with a sense of reality, as in a real operation, is required. Our objective in this research is to construct the training system of a medical operation which gives the haptic sense of operation, and an inexperienced surgeon can try operation again and again to improve his skill by using the system. We construct a virtual dense elastic object which considers inner tissue from medical image data such as computed tomography (CT) or magnetic resonance imaging (MRI), and we use a spring-mass model to represent the movement of elastic deformation. Haptic sense which is generated from a deformation of the object is given to an operator with haptic device in this system. In this paper, we study a real time rendering and real time deformation which is needed in surgical simulation.

Keywords: Virtual Reality, Surgical Simulation, Haptic Device, Deformation

I. INTRODUCTION

In recent years, there have been various problems in medical treatments, of which human error by the surgeon in an operation is one of the most serious problems. The major cause is considered to be the surgeon's lack of experience. A great deal of experience is necessary in medical operations, and tactile or haptic sensations, such as a manual sensation, become important in order to prevent mistakes. However, it is impossible to use a real human body to practice a medical operation. Therefore, the simulation of a medical operation with a sense of reality, as in a real operation, is required.

We have studied cutting during an operation using the surface model (Koichi [1]), the deformation of the surface model (Ryuichirou [2]), and synchronization between audiovisual and haptic feelings (Yoshihiro [3]) in previous research in our laboratory in order to construct the training system of a medical operation.

In this research, we approach the construction of the training system for a medical operation by creating a virtual human organ model which is deformable, and deforming the model with a haptic device called PHANToM. The data for the human organ were obtained from medical image data such as computed tomography (CT) or magnetic resonance imaging (MRI) to express the patient's organs. Real time rendering and deformation inevitable in surgical simulation are shown in detail.

II. SYSTEM CONFIGURATION

As shown in Fig.1, this system consists of two PCs connected with SCRAMNet+: one PC (PC1) renders a virtual dense elastic object with Open GL and also calculates the deforming process of the object, and the other (PC2) operates PHANToM and calculates the haptic feedback given to the operator through PHANToM. In this way, the process of calculation is able to distribute. A flowchart of the entire process is shown in Fig. 2. Information of PHANToM is shared between PC1 and PC2 through high speed network SCRAMNET to make it possible both for an operator to deform an organ with PHANToM at PC1 and to simulate corresponding deforming process at PC2.

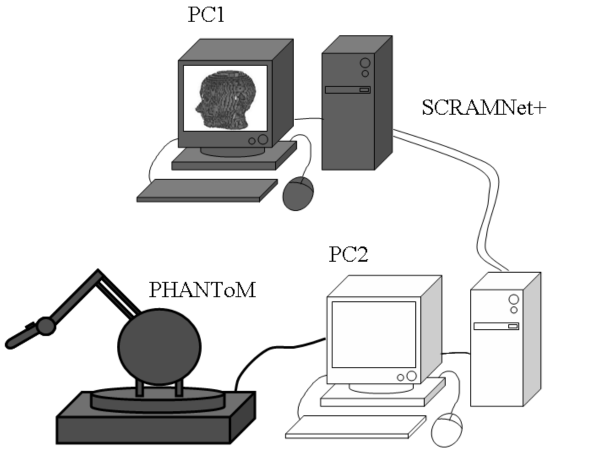


Fig.1 System configuration

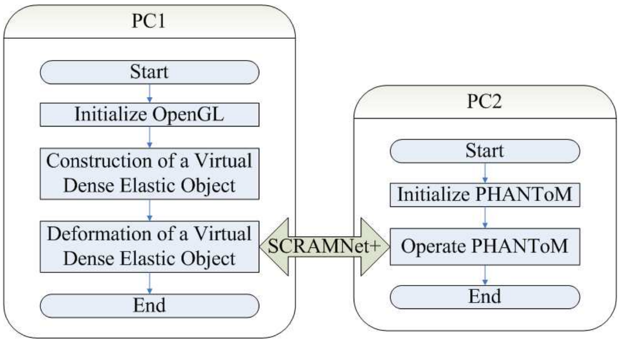


Fig.2 Flowchart of entire process

III CONSTRUCTION OF A VIRTUAL DENSE ELASTIC OBJECT

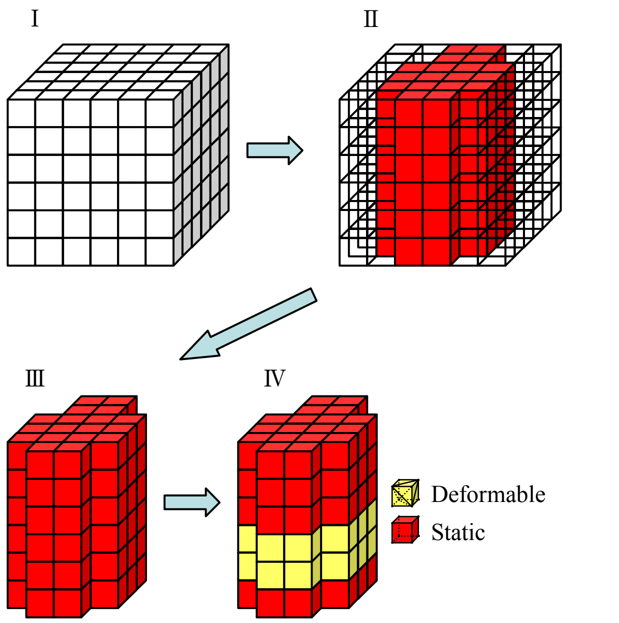
In the surgical simulation which needs the cutting or deforming operation, not only surface information of the object but also the inner one of the tissue must be considered. Therefore, a virtual dense elastic object is constructed in order to create a virtual human organ model reflecting deformable inner tissue of the organ.

1. Creation of the loading data

We use medical image data such as CT or MRI to express any human organs. In order to create the CT or MRI data in a new format, which can be loaded into our system, we used the OpenGL Volumizer. The new format data include size of partition number of voxel of the original medical image data and the RGBA value of each voxel.

2. Creation of a virtual dense elastic object

As shown in Fig.3, at first, rigid voxels are obtained by dividing the area where the model is to be created. The data loaded in our system consist of both voxels corresponding to the substance and those corresponding to the vacancy. Not to waste the memory and for saving the rendering time, only the former remain as real data but the latter are deleted. Position and the connection of the each voxel are stored in the memory to keep the shape of the object. Then, voxels are divided into tetrahedrons to make them deformable. Finally, we set RGBA value as color information to each tetrahedron from the data which we create.



Ⅰ. Divide creating area into voxel
Ⅱ. Load the data
Ⅲ. Delete not necessary voxel
Ⅳ. Divide deformable area into tetrahedron

Fig.3 Construction of a virtual dense elastic object

3. Spring-mass model

A spring–mass model is a model which is a set of mass-less springs with a point mass. As shown in Fig.4, a spring-mass model is given to each tetrahedron in order to realize deformation based on mechanics (Koichi [4]). We replace each side of a tetrahedron by a spring and damper, and each vertex of a tetrahedron by a point mass. When vertex moves, a spring force is generated from the displacement between connected vertices and the object deform elastically. Here by using a damper, we apply a damping which is proportional to the velocity of the vertex to the force.

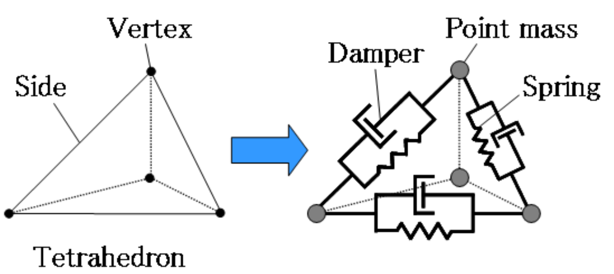


Fig.4 Spring-mass model

4. High performance of rendering process

We set an RGBA value for each tetrahedron as color information to render a virtual dense elastic object.

In order to increase the resolution of the object, we have to divide the object into a lot of tetrahedrons. If partition number of voxels increases, the number of tetrahedrons also increases and the process of rendering all tetrahedrons results in a bad performance. Therefore, we render only the visible part of the object from the user's viewpoint in order to improve the performance. The inner object is invisible to the user, so it is not necessary for it to be rendered. We make a rendering list of visible tetrahedrons, and we obtain a high performance in the rendering process by using that list. In order to judge whether a voxel is visible or not, we check the surrounding of the voxel. As shown in Fig.5, if a voxel is covered with voxels which has color information, the voxel is inner object and it will be invisible. If there is at least one voxel which do not have the color information around the voxel, the voxel is surface of the object and it will be visible.

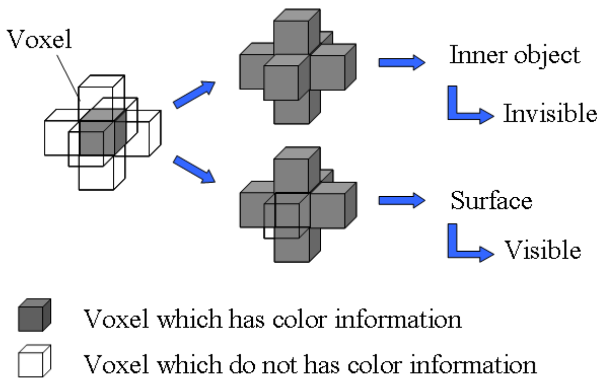


Fig.5 Judging visible or not

IV. DEFORMATION OF A VIRTUAL DENSE ELASTIC OBJECT

Tetrahedrons share their vertices, and if the vertices move, the tetrahedrons deform. Therefore, we can represent the deformation process of a virtual dense elastic object as the movement of the vertices. A medical tool which deforms the object is represented as a rigid stick, and it is controlled with PHANToM. Information such as position, acceleration, and force are stored on each vertex. Each force acting on a vertex can be obtained from the velocity and the displacement between vertices connected with the springs and the dampers, and it can express as an equation (1).

$$F_i = \sum\left(\frac{l_{ij}}{|l_{ij}|}k_{ij}\left(|l_{ij}|-|l_{0ij}|\right)+c_{ij}v_{ij}\right) \qquad (1)$$

$$l_{ij} = x_i - x_j$$

F_i is force of point mass *i*, x_i is position of point mass *i*, x_j is position of point mass *j*, k_{ij} is constant of a spring between point mass *i* and *j*, v_{ij} is relative velocity of point mass *i* and *j*, c_{ij} is coefficient of viscosity of a damper between point mass *i* and *j*. Then compute the motion equation to obtain each position of the vertex using the force. The Euler method is used to solve the dynamic characteristics of the spring–mass model using Hook's law and a motion equation. Then the information stored on each vertex adjacent to the vertex that moved is recomputed and the entire object will deform. The deformation effect passes to the operator through the PHANToM.

1. Multipoint collision detection

Collision between the medical tool and the object is detected at vertices of tetrahedrons, so multipoint collision detection is needed to implement the collision with a rigid stick used as the medical tool. As shown in Fig.6, the medical tool and the vertex are express as a vector to detect collision. Collision is detected by calculating the cross-product and length of the vector. We label the edge of the medical tool *AB*, and the vertex C. Then we can express the vector *AB*, *AC*, and *BC* as $\vec{D}$, $\vec{E}$ and $\vec{F}$ respectively. A collision is detected when *C* is on the segment *AB*. It is possible to judge whether *C* is on the line *AB* or not by checking whether or not $\vec{D}$ and $\vec{E}$ are parallel using a cross product of the vector. A normal vector can be obtained from a cross product. If the result of the normal vector is zero, then $\vec{D}$ and $\vec{E}$ are parallel, that is to say *C* is on the line *AB*. Next, if *C* is on the line *AB*, we check the length of $\vec{E}$ and $\vec{F}$, and if they are less than or equal to length of medical tool, *C* is on the segment *AB*. The length of the medical tool is the length of $\vec{D}$. Multipoint collision detection is implemented by adding the vertex which collides with the medical tool to the list of collided vertex.

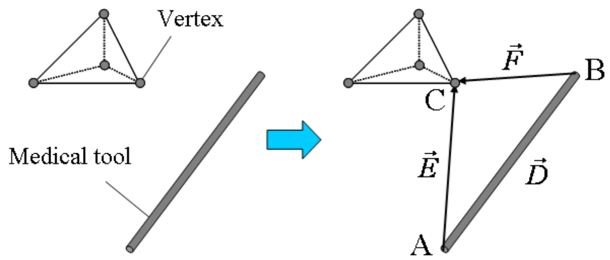


Fig.6 Multipoint collision detection

2. High performance of deforming process

If partition number of tetrahedrons increases to improve the resolution, the number of vertices to calculate also increases. The process of deforming the object requires high computational power when we calculate all part of the object. In a real medical operation, the target tissue is only a portion of the whole organ. This time, in order to reduce the computational load of deforming process, we select a portion of the object as a deformable object. In order to select a portion which deform, we mark the target when we create the loading data. Then change around the area where the target exists into deformable area. Deform not all part of the object, but select deformable area and deform only the area to reduce the computational load.

V. EXECUTION RESULT

A virtual dense elastic object restored from CT is shown in Fig. 7, where the partition number of voxels is (256, 256, 77). The entrails appear as shown in Fig. 7 if the threshold amount is changed. This fact shows that a virtual dense elastic object is successfully implemented.

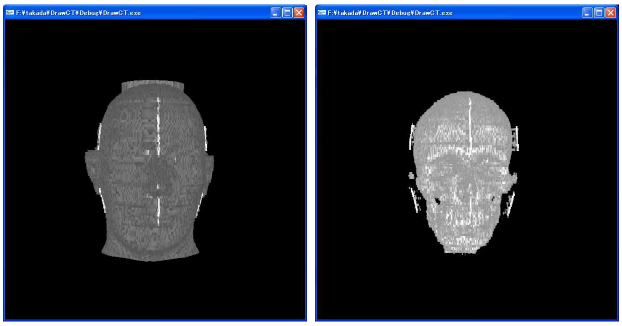


Fig.7 Rendering head data

Fig.8 shows the deformation of the virtual dense elastic object. This time, the MRI data of blood vessel of brain on which aneurysm occurred is used as the virtual human organ object. The partition number of voxels is (336, 336, 140). 10 voxels around the gravity center of the aneurysm are transformed into deformable area and they are deformed by operating PHANToM. In this case, we confirmed that the blood vessel is deformed with a medical tool and the adequate haptic feedback is returned to operator's hand.

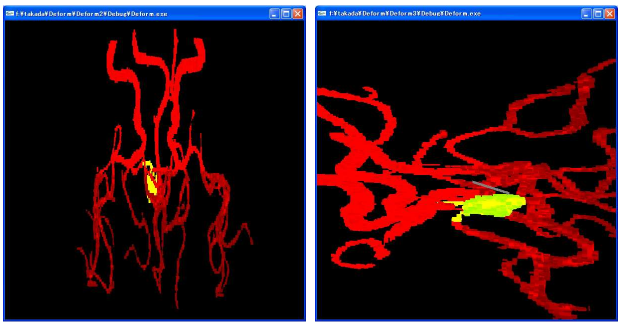


Fig.8 Deforming blood vessel data

VI. CONCLUSION

We have constructed a system of rendering a virtual dense elastic object obtained from medical image data such as CT or MRI data, and expressing deformation of the tissue in order to achieve the development of the training system for a medical operation.

This time, in order to render and deform in a real time, we render only the visible part of a virtual dense elastic object from the user's viewpoint, and deform only the deformable part which is selected by a user. However, there is a limit of partition number of voxels to process in real time and more improvement of performance is demanded. In a real medical operation, deforming part is not only the tissue of the target but also the route to access the target must be deformed. We are now studying how to accelerate the deforming process by using the parallel processing such as OpenMP or GPU to improve the performance of deforming process. In this research, we also confirmed the force obtained from computing the amount of deformation. However, we need the real haptic feeling as in a real operation in the surgical simulation. In the future, we would like to give the operator a real haptic feeling.

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