Hybrid Elastic Model for Volumetric Deformation in Multi-modal Virtual Reality Simulation

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Abstract—**As the field of the computer simulation technique has advanced, the computer simulation extends its domain, enlarges its scale, and improves its quality. Nowadays the haptic sense is as important as visual one to recognize a virtual object. While the mechanisms of two senses are highly different, only one model simulates for the visual sense, processing shape deformation, and for the haptic sense, computing the force feedback. Even if the separate models coexist for simulating those two senses, the connections among those separate models are not clearly defined. In this paper, we propose a new computer simulation scheme as a hybrid model for real-time haptic rendering and volumetric deformation. We define the embedded mass-spring model and its mapping functions to haptic s-chain model as well as to graphic mesh model. The experimental results demonstrate the potential for virtual reality simulation in medical education and training.**

Keywords—**volumetric deformable model, haptic rendering.**

I. Introduction

Many researchers have developed a computer simulation model, as the demand for computer simulation has increased. The characteristics of a simulation model are different depending on what the main targets in simulation are. In the case of surgical simulation, one of the important properties of the model is the elasticity of soft body such as human organ. In our proposed model, the realistic volumetric deformation and the volumetric haptic feedback are considered to simulate the behavior of elasticity.

The volumetric deformation is a challenge to real-time computer simulation because of the huge number of high-resolution volumetric data to be computed within a reasonable time. Cotin et al [1][2] propose a deformable model that uses a linear Finite Element Method (FEM), a reduced version of a pure FEM, to compute elastic energy of a human body. Chen et al [3] suggest a spring-mass model for calculating each voxel of volume data. Jailet et al [4] use particles to represent volume data. As the capability of recent GPUs (graphics processing unit) has rapidly increased, Luciano et al [5] accelerate computation by using general-purpose GPUs. The models mentioned above usually use the FEM or the spring-mass algorithm for computing deformations. Since the traditional FEM and the spring-mass algorithm have a large computing overhead, they are difficult to deal with the high resolution volume data. In this paper, we propose an adaptive spring-mass algorithm to reduce such large computational overhead.

Haptic rendering is as important as volumetric deformation in computer simulation. Park et al [6][7] propose the S-Chain (shape retaining chain) model to calculate force feedback of the volumetric deformable model. The real-time haptic rendering requires higher refresh frequency rate (1,000 Hz) than one of visual rendering (30 Hz). The S-Chain model satisfies high refresh frequency because its computing overhead is very low. However, its visual appearance is not good since it employs a linear solver to compute the deformation.

Previously, we developed a dual model as one kind of simulation solution for soft body [8]. The dual model had two separate models – one is a volumetric model and the other is a surface model – to handle haptic rendering and visual rendering, respectively, efficiently and effectively. However, since there was no concrete relationship between the two models, the visual model could not reflect the deformation of the volumetric data. In this paper, we suggest an adaptive mass-spring model as the interface between the haptic model and the visual model to improve the behavior of our dual model. Our proposed model computes the force feedback and computes the realistic deformations at the same time.

II. Method

A. Model Description

There are three different models in our system: haptic model, behavior model, and visual model. Each model has its own role: The haptic model is the S-Chain model that computes the force feedback, the behavior model is a mass-spring model that computes the elastic energy to deform the

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object, and the visual model is what we see in display devices.

Haptic Model: The S-Chain model [6] is suited for the haptic model because it employs a simple algorithm to solve linear system. A basic element of the S-Chain is a chain which has a possible range of its own boundaries where it can move around without disturbing the neighbor chain element. That is, those boundaries indicate the stiffness of each chain element. The smaller the range, more rigid the chain is. The algorithm is simple that it takes the violated chain to the neighbor chains and propagates its residual energy until there is no more energy for deformation. The S-Chain algorithm, unlike the original 3D Chainmail algorithm, guarantees that the model has no residual elastic energy after several deformations. Therefore, the S-Chain provides a way to compute force feedback. Equation (1) shows that F (force) is proportion to the number of moved chains (n) where K_i is the spring coefficient of i^{th} chain.

$$F = \sum_{i}^{n} d(i) * K_i \tag{1}$$

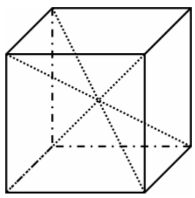

Fig. 1 Element of a Behavior Model

Behavior Model: As an element of the haptic model is a chain element, its corresponding element of the behavior model is a 3D mass-spring box as shown in Fig 1. It consists of a mass, structural springs, and shear springs. The net force is calculated based on Hooke's law. Equation (2) is a spring-mass-damper equation where k is the spring coefficient, b is a damping coefficient, and d is the distance between i and its neighborhood.

$$F_i = \sum_{i}^{n} - k_i d_i + b_i d_i' \tag{2}$$

The spring-mass-damper model has a large computing overhead because the system should compute the net force of every spring at the each simulation time. We propose a way to reduce that overhead for real-time simulation. The elastic energy function is quadratic as shown in (3). We assume that the mass which has low elastic energy can be omitted. In other words, we can ignore some masses which move insignificantly to estimate elastic energy. Therefore, we can compute elastic energy with smaller springs and masses than traditional approaches.

$$E = \frac{1}{2} k d^2 \tag{3}$$

We define the active mass that has enough elastic energy to be deformed. As shown in the right graph of Fig. 2, the simulation time can be reduced when the number of active masses becomes smaller as a result of our adaptive algorithm. Note that, however, the small number of the simulated masses can cause a precision problem. In our approach, our system considers only active mass. Thus, the global deformation would be ignored. That means that our approach takes local minima, rather than global minima. As long as we are in a local range, this limitation does not affect the result, but not for global deformation.

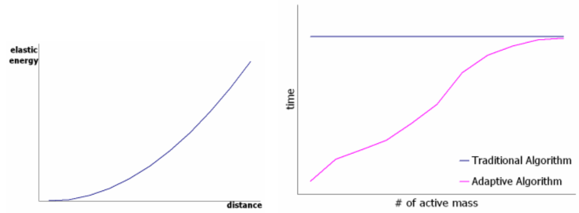

Fig. 2 Elastic energy

Visual Model: The visual model is just a polygonal mesh that will be displayed on the monitor. A surface model is suited for visual model because the user does not see the internal shape of a virtual object. The surface visual model can have bigger resolution (i.e. fine detail) than the volumetric behavior model or haptic model. We employed a mean-value interpolation [9] scheme.

B. *Mapping Functions*

Fig. 3 Three models of the hybrid deformable model

There are three different models as mentioned above [also see Fig 3]. Fig 4 depicts the overview of our system. The white boxes are models or a device. The green labels are data to be transmitted, and the blue labels show the mapping functions.

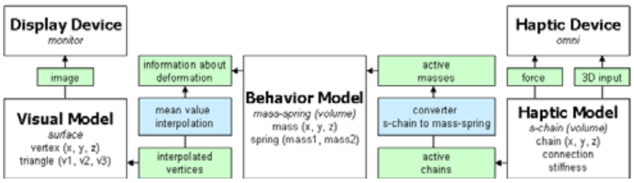

Fig. 4 Our system overview

The haptic model calculates its own deformation to calculate force feedback. Because the S-Chain algorithm is based on linear equation, the linear deformation occurs. The deformation of the S-Chain algorithm is bad for visual model. The behavior model can solve problem. The behavior model simulates the deformation for a visual model. Lastly, we should interpolate that deformation information of the behavior model to the visual model because the resolution of the visual model is denser than that of the behavior model.

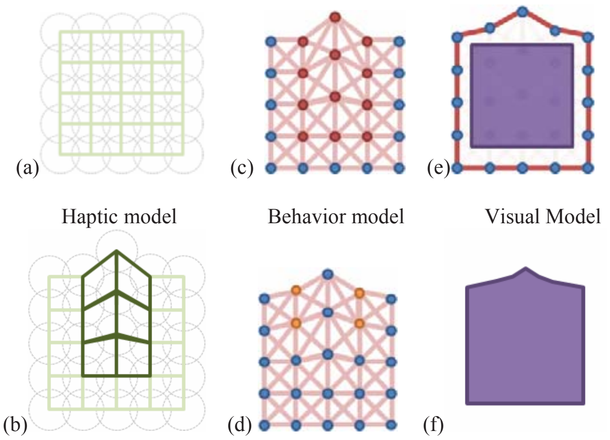

Fig. 5 Illustration

As an illustration, Fig 5(a) depicts undeformed haptic model (S-Chain). (b) shows the configuration where a user pulls the model at the top. (c) shows the adaptive mass-spring model where red points indicate activated area. (d) is the result of mass-spring model deformation. (e) shows the visual model prior to the interpolation. Finally, (f) shows the visual model deformed by the mapping (interpolating) with the behavior mass-spring model. Fig 6 shows the pseudo algorithms of the system.

III. Results

The simulation environment is a desktop computer which has Intel Processor 2.4 GHz, 2 GB Main memory, and Nvidia Quadro 3450FX. Fig 7 shows the result of simulation with 1000 chains of S-Chain; 1000 masses and 5400 springs of spring-mass; and 5402 vertices and 10800 triangles.

Haptic Model

1. A user inputs 3-D input by using haptic device.
2. The haptic model finds an appropriate chain to be contacted by user.
3. A user move the contacted chain
4. The S-Chain algorithm computes the force feedback and def ormation of own model. (1000 Hz)

Behavior Model

5. The deformed chains (moved chains) activate the masses as active masses.
6. The spring-mass algorithm computes the deformation.

Visual Model

7. The visual model is interpolated by deformed behavior mode l. (30 Hz)

Fig. 6 Pseudo algorithm

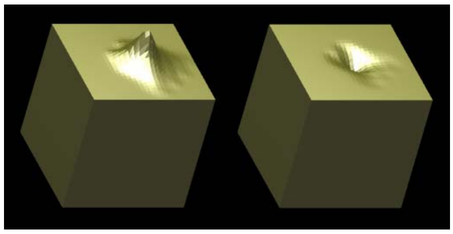

Fig. 7 Experiment with a cubed object

Fig 8 illustrates the result of the non-homogenous volume model. The resolution of each model is the same as those in Fig 7. There are three models: the haptic model (left), the behavior model (middle), and the visual model (right). The left portion of the contacting point is more rigid than the right portion. In the haptic model, the left cyan portion is deformed more than others, thus it generates stronger force feedback. The behavior model and the visual model show more realistic deformation in comparison with the haptic model.

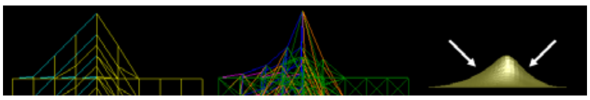

Fig. 8 Non-homogenous data

We also apply our system to a general mesh, a liver, as shown in Fig 9. The mesh has about 7600 triangles. The deformed result is illustrated in each side of Fig 9. The left deformed object is the result when the user pulls the top of the object while the right one is the result of push. Since the behavior model is based on volume data, the energy for recovery is more stable than the surface data.

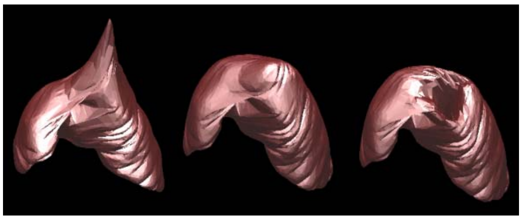

Fig. 9 Liver data

To summarize, the mass-spring behavior model is embedded onto the S-Chain model, and which springs to be activated are adaptively selected by the activated S-Chain elements. Haptic rendering is solely computed by S-Chain model, which provides real-time and realistic force feedback. The visual deformation is then controlled by the behavior model which provides the base deformation for the detailed visual mesh model. Mean-value interpolation is used for robust mapping between behavior model and visual model. Since the behavior model is mass-spring, we also observe the natural restoration of the shape after deformation is released.

IV. Conclusions

In this paper, we propose a hybrid model which supports both haptic rendering and volume deformation in real time. The hybrid model enables us to deform the virtual soft objects with haptic feedback in real time by separating haptic rendering from graphic rendering. We employed the S-chain model to calculate the feedback force and an adaptive mass-spring model to deform the virtual object for a simulation. The mapping function links the S-Chain model and the mass-spring model. Through the experiments, we verified that the hybrid model can handle the virtual soft objects composed of about 20,000 elements in real time. Moreover, we confirmed that the hybrid model provides the realistic visual feedback and conveys the object's internal information with volume data. We are currently working on real-time collision detection for deformable models and on more objective evaluation method for the system.

The proposed hybrid model is a suitable for computer simulation which requires the realistic deformation and the feedback force of high resolution volumetric objects in real time. We plan to apply our model to medical simulation applications and extend the hybrid model to handle topology changes within the simulation framework.

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