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Keywords

virtual reality, haptic interaction, shape deformation, mass-spring model

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3D Shape Deformation Simulation Algorithm Based on Haptics

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Abstract: Shape deformation is widely used in virtual reality, system simulation, computer animation and other graphics applications. Few people pay attention to introducing haptic interaction into 3D model deformation. *We provide a haptic interactive framework by introducing haptic interaction into shape editing field. Based on the above haptic interactive framework, we propose a 3D model deformation simulation algorithm based on haptics. In order to realize the shape deformation, this algorithm needs to involve three parts: grid hierarchical structure, local mass-spring model and the dynamic shape deformation.* Experimental results show that this algorithm has good stability and strong robustness, and the method can enable operators to perceive and deform the 3D model through haptics interaction. In addition, the entire interactive process is simple, natural, and effective.

Keywords: virtual reality; haptic interaction; shape deformation; mass-spring model

基于触觉交互的三维弹性物体形变仿真算法

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摘要：形变仿真是计算机图形学、系统仿真、虚拟现实等领域的关键技术，但在现有物体形变研究中，将自然交互引入三维弹性物体变形的研究较少。针对该问题，*引入触觉交互至形体编辑领域，在给出视-触觉同步的自然交互框架基础上，提出了一种基于触觉交互的弹性物体变形仿真算法，包含建立栅格层次结构、构建局部“质点-弹簧”系统和数值迭代动态仿真。*实验结果表明，该算法运行稳定，鲁棒性好，能实现视-触觉同步交互感知体验和良好变形效果，且整体交互过程简单、自然和有效。

关键词：虚拟现实；触觉交互；实时形变；质点-弹簧模型

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Introduction

With the emergence of new interactive modalities, nature and intelligence are gradually becoming the main trends of connection between human and information space. Although the means and ways of human-computer interaction are successful, there is still a big gap compared with the means of human-environment interaction. We know that the interaction between human and environment is multi-modal. That is to say, human beings use visual,

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auditory, and tactile ways to perceive the surrounding environment at all times. Therefore, introducing haptics into human-computer interaction is a natural and important technological innovation, and related research has become an active research area.

Model deformation is widely used in virtual reality, system simulation, computer animation and other graphics applications. The mainstream methods can be divided into two categories: the non-physical modeling method and the physical modeling method. Non-physical modeling is common in the early stage, but the lack of physical characteristics can easily lead to deformation distortion, thus it is not enough realistic. With the deepening of research, the shortcomings of traditional method become more and more prominent, and it is gradually replaced by the physical modeling-based method. Common physical modeling methods include the mass-spring-damper model, finite element model and boundary element model.

However in the above research, few people pay attention to introducing tactile sensation into model deformation. In this paper, we propose a 3D shape deformation simulation algorithm based on haptics. At that time, the user can touch, perceive and deform objects in virtual scenes. Meanwhile, the force feedback in the process of operation is acquired so as to obtain better interaction effect and operation experience.

Main Contribution: To this effect, our contributions are as follows:

1) We provide a haptic interactive framework by introducing haptic interaction into shape editing field.

2) We propose a 3D model deformation simulation algorithm based on haptics.

1 Related Work

1.1 Haptic interactions

In recent years, with the emergence of new types of interactive devices, the connection between people and machine has been toward to a more natural, convenient and efficient situation. Similar to voice or visual interaction, haptic interaction is a new type of natural interaction, which plays a very important role in information exchange and communication. By using force/ haptic devices[1-2], people can get rid of the limitation of complex graphical user interface and obtain a good sense of realism and immersion.

After decades of efforts, haptic interaction has great progress in hardware and algorithm. On the hardware level, various types of haptic interactive devices are emerging, ranging from early force feedback mouse for desktop to finger rings or tactile gloves for VR[3-4]. Miniaturization, wearability and flexibility are gradually becoming the main trend of tactile interactive devices. On the algorithm level, the advent of Phantom devices has aroused a upsurge in haptic generation methods. Typical algorithms include God-object[5], Virtual proxy[6], etc. The proposed algorithms make virtual interaction between fingertips and various objects possible, and bring unprecedented accurate and convenient tactile stimulation.

In the past decade, there are many specific fields combined with haptic interactions. Wang et al.[7] proposed a method for calculating the energy of protein molecular field based on the force field of CHARMM. Tactile perception of intermolecular forces can help designers to better grasp intermolecular interactions, in order to facilitate molecular docking and drug design. Borenstein et al.[8] developed a navigation system called GuideCane for

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the visually impaired people, which can provide navigation information through the vibration feedback based on the distance between the obstacles and users. For the accessibility of resources and services in museums, Park et al.[9] constructed a remote museum access system based on tactile interface by using haptic interaction, depth camera and remote robots, enabling the visually impaired to explore museum scenes and remotely realize haptic perception of 3D exhibits. Haptics is also introduced into the learning process of scientific concepts and abstract geometric information to help people better understand the basic knowledge and make the process of learning interesting and interactive. The main research includes: H. N. Kim and I. Han[10-11] present physical concepts such as heat, temperature and force for students through haptic channel.

1.2 Model Deformation

Currently, physical deformation models mainly include Finite Element Models (FEM) and Mass-Spring Models (MSM). The disadvantages of FEM are that the process of modeling is complicated, the amount of calculation is large, and a large amount of pre-processing work is required. MSM does not require continuous parameterization, and is easy to implement. It also has a fast calculation speed, which ensures the real-time performance of the simulation. Therefore, the research based on the enhanced algorithm of the mass-spring model is very important for realizing the deformation shape editing.

The study of MSM model began around 1988. Terzopoulos et al. pioneered a physics-based elastic deformation model in the literature[12-13]. Breen et al.[14] proposed the concept of particle system based on the analysis of the mechanical characteristics of many different material objects. Provotf[15] proposed a landmark mass-spring model. Thereafter, in order to further improve the validity of numerical calculations and ensure the simulation system stability, Baraff[16] shifted the focus of research work to the solution of differential equations. In 2001, Webster et al.[12] proposed a surface mass-spring model when implementing flexible object simulation. San-Vicente et al.[17] proposed a mass-spring model method based on tensile deformation and nonlinear materials. Etheredge et al.[18] gave a parallel processing algorithm for the mass-spring model, which effectively improved the efficiency of the algorithm. In order to better simulate the deformation of objects of different materials, it is an important challenge to solve how to determine the stiffness coefficient of each spring in the particle-spring model. Gelder et al.[19] believed that it is impossible to simulate the precise membrane structure with the mass-spring model, thus giving an approximate spring parameter calculation formula. Lloyd et al.[20] pointed out that the mass-spring model and the finite element model can be accurately implemented when it is in the equilateral triangles and the Poisson's ratio is 1/3.

2 Overview

We provide a haptic interactive framework by introducing haptic interaction into shape editing field. It involves four parts: digital repositories, haptic module, visual module and the operator. Among them, haptic module is the core part of our algorithm framework, which is mainly intended for the interaction, perception and recognition of haptic object. In the processing of the core module, digital objects of repositories are translated into haptic object models. Meanwhile, through the comparison or abstraction of certain mechanisms existing in the real world, the behaviors and states of users' operation can be mapped to a proxy in a virtual environment. Through the operation proxy, the operator can actually touch and perceive the main features about surface of the object in the virtual environment (VE) to realize the haptic interaction and information exchange. Visual module is mainly to present the digital objects of repositories through graphic rendering. The part of operator is also called the human-machine interaction module, and mainly involves two parts. Haptic interactive devices acquire the motion state from the operator. Meanwhile, haptic interactive device renders the haptic signal computed by the haptic module and transmits it to the operator in the sense of force or touch. Fig. 1 is haptic interactive framework of our algorithm.

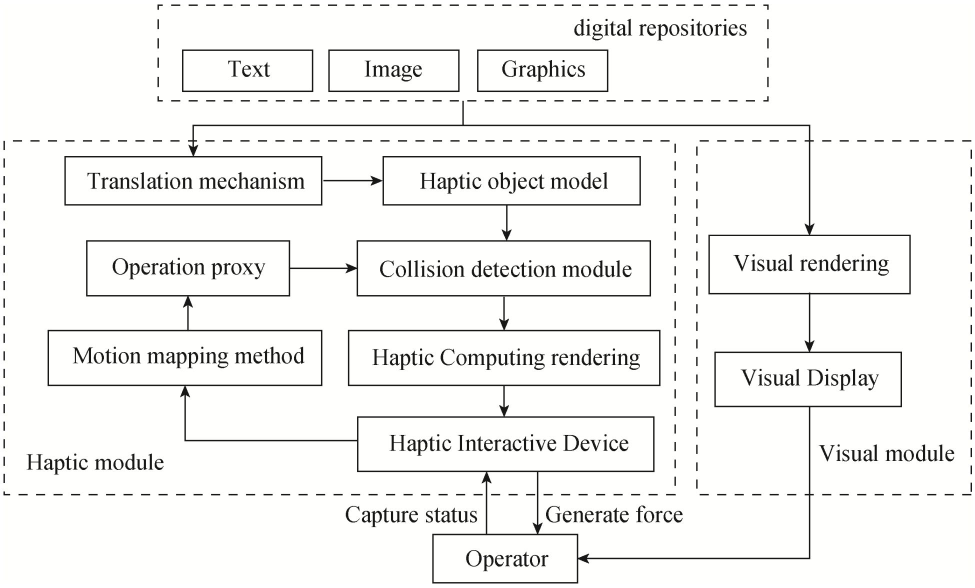

Fig. 1　Haptic interactive framework of our algorithm

3　Our Approach

Based on the above haptic interactive framework, we propose a 3D model deformation simulation algorithm based on haptics. The basic idea of our method is that the input object is firstly fetched and its data is composed of the point sets and topological relations. Then the coordinate-axis bounding box of the object is calculated. By splitting the bounding box, we can build the grid hierarchical tree. Moreover, the relationship between the bottom layer of grid tree structure and point sets of the object is determined. When the operation proxy touches the object surface, we should set the possible affected area and construct local mass-spring system. According to the force by the operation proxy and the basic law of motion, the force of each particle in the local mass-spring system is analyzed and the positions of each affected point are updated in each frame. When these positions of the point sets change, we can obtain a reconstruction model after point sets data being grid processed. After repeated iterations, we finally achieve the model deformation. Our algorithm consists of 7 steps.

step 1: The pre-process of point clouds: Select the maximum and minimum values of vertex coordinates of point sets in each axis, and construct an AABB according to these values. Scale the point set and AABB to form a normalized point set model and bounding box. Finally, the normalized model and

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its AABB are moved to the easy-to-handle position in the coordinate space.

step 2: Construct grid hierarchical structure: Each edge which is parallel to the coordinate axis of the normalized bounding box is divided into 2^{n-1} parts (n=1,2,…,k, k represents level), and forms a grid structure. It divides the bounding box into a series of small grid elements. The minimum coordinate of 8 vertices of bounding box is labeled by p. The number of grid elements, which is also called the index number, deviated from p by other grid endpoints, is calculated, and the coordinates of each grid endpoints are obtained. Finally, the index relationship between adjacent levels is constructed to form the grid hierarchical structure.

step 3: Link model points and grid hierarchies: For each point v, the index number of located grid and the local relative position of model point v in the corresponding grid should be determined. One of 8 vertices of the grid, where point v is located, is selected as base-point b, and the relative relationship between point v and base-point b is established.

step 4: Build local mass-spring system: When the operation proxy touches the object surface, the possible affected area can be set at any level of the grid hierarchy. A particle with mass M is placed at the endpoint of grid in the affected area, and a spring with stiffness coefficient K is used to connect each particle with its adjacent or spaced adjacent particles to obtain a local mass-spring system. Then, the initial motion state of each particle, such as initial velocity $\boldsymbol{v}$, is set.

step 5: Compute the force based on motion trajectory: We construct a spring model to correlate the initial position P_s with target position P_t. Then the feedback force between P_s and P_t is calculated. Here, P_s is the point of contact where the operation proxy touches the object surface, and P_t is the real-time location of operation proxy. When the feedback force is calculated, it is transmitted to the user through the haptic device. Meanwhile, it acts on the local mass-spring system to realize the object deformation.

step 6: Update the coordinates of the affected point: According to the force by the operation proxy and the basic law of motion, the force of each particle in the local mass-spring system is analyzed according to the relationships between the spring. The resultant force of each particle is consisted of spring internal force, damping and gravity which are calculated. Finally, according to Newton's law, the acceleration, velocity and displacement of each particle and its position at the next moment are calculated.

step 7: Draw deformed mesh model: According to the new updated point sets and topological relations, a new triangular mesh model is re-generated. After repeated iterations, we finally realize the model deformation.

4 Components of Our Method

In order to realize the model deformation, the algorithm needs to involve three parts: supporting data structure, physical deformation model and the dynamic effect of deformation.

4.1 Grid Hierarchical Structure

In this section, we introduce a grid hierarchical structure, which can share data among different levels. Grid hierarchy is a tree-like data structure that describes 3D space. Each node of the tree represents a cubic space region. There are only two types of nodes, namely, intermediate nodes and leaf nodes. Generally, the intermediate nodes include 8 child nodes, which means the cube space, where the node is located, is half-divided into 8 identical sub-cube spaces. The leaf node does not include any child nodes, and the corresponding cube space cannot be further subdivided.

The bounding box is used as the root of the tree hierarchy. For each node of the data structure, it is necessary to store pointer to child node, pointer to parent node, reference point to record the spatial position of each grid, coordinate of center point as well as the edge length. In addition, the leaf node stores the index values of point sets in the bounding box, while the intermediate node does not store the information of point sets. Initially, the root is just the leaf node. According to the given number of layer, the initial bounding box is divided into different layers to form a spatial grid structure whose size is $2^{n-1}\times 2^{n-1}\times 2^{n-1}$ (n=1,2,…,k).

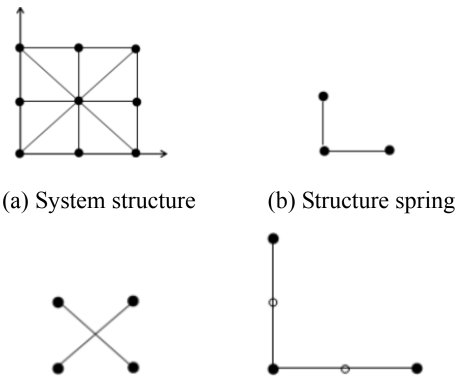
For the bounding box, set the point whose x, y, z-value are less than 0 in 8 vertices as p, then the position of reference point about each grid cell can be obtained. Then the index relation between adjacent levels is constructed. When the grids in all levels are connected, the grid hierarchical structure is formed.

4.2 Local Mass-spring System

Before constructing the local mass-spring system, it is necessary to link the vertex of objects with the above grid hierarchies. There are two steps to establish the relationship: solving the index number of the grid in which the point $\boldsymbol{v}$ is located, as well as the relative position of the point $\boldsymbol{v}$ in the grid. The former is relatively simple, and we will not discuss it in detail. Here, we will mainly introduce the concrete process of the latter. Taking the center of each small grid in the k-layer space grid as coordinate origin, the local space coordinate system is constructed. The base point b (b_x, b_y, b_z) is the vertices where the coordinate values of x, y and z are negative in 8 vertices of the small grid. Calculate the distance between the base point and the three adjacent vertices, and mark them as R_x, R_y, R_z. Then the distance between each point v (v_x, v_y, v_z) and the base point b on three axis components is recorded and the proportions of P_x, P_y, P_z are calculated:

$$P_i = (v_i - b_i) / R_i \quad (i \in [x, y, z]) \tag{1}$$

When the operation proxy touches the surface of object, we should set the possible affected area at any level of the grid hierarchy. After the affected layer and the area are selected, the particles with mass M are placed at these vertices of the grid in the affected area, and each particle is connected with its adjacent particles by various types of springs with stiffness coefficient K. It refers to Fig. 2.



(a) System structure (b) Structure spring

(c) Shear spring (d) Flexible spring

Fig. 2 The mass-spring system in case of 2D

a) Structural spring: A structural spring is a particle connected directly with adjacent particle, referring to Fig. 2(b).

b) Shear spring: A shear spring is a particle connected to its diagonal particle , referring to Fig. 2(c).

c) Flexible spring: A flexible spring crosses a particle and connects other particle, referring to Fig. 2 (d).

For each particle of the cubic grid, there are 6 structural springs, 6 flexible springs and 12 flexible

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springs, which need special consideration at the boundary. After adding springs to all particles in the affected area, a local mass-spring system can be finally obtained.

4.3 Model Deformation

The essence and basic works of model deformation are analyzing the force of the local mass-spring system and updating the coordinates of affected points. Then, we generate a new triangular mesh model according to the topological relationship among the updated point sets. After that, the generated mesh model is rendered into the current frame of the animation, and the next frame of the animation is determined by the state of the local mass-spring system based on dynamic equation. Finally, we can realize the model deformation through multiple iterations. The specific processes are as follows:

The internal spring force, damping, gravity of each point are detected by progressive scanning method, and then the position coordinates of each point at the next moment are obtained according to Newton's law and explicit Euler integral method. Therefore, we realize the local update of mass-spring system. Finally, the position of the affected point sets in the corresponding area is updated by spring system. It is mainly divided into the following 3 steps:

step 1: Detect the affected mass of the local mass-spring system, and analyze the force of each mass by progressive scanning. Firstly, each point is subjected to the internal force of the mass-spring system. $\boldsymbol{f_{ij}}$ is used to represent the force of the spring acting on the mass point i between point i and j, where the spring follows Hooke's law, then:

$$\boldsymbol{f_{ij}} = k_{ij}(\|\boldsymbol{x}_j - \boldsymbol{x}_i\| - l_{ij}^0) \times \frac{\boldsymbol{x}_j - \boldsymbol{x}_i}{\|\boldsymbol{x}_j - \boldsymbol{x}_i\|} \tag{2}$$

Here, k_{ij} is the spring elastic coefficient between the mass point i and j, $\boldsymbol{x_i}$ and $\boldsymbol{x_j}$ are the position of the two mass points respectively, $l^0{}_{ij}$ is the initial length of the spring. In this paper, k_{ij} is the stiffness coefficient K mentioned above and $l^0{}_{ij}$ is the initial length L_0 of the spring mentioned above.

Therefore, the total force of mass i can be expressed as:

$$\boldsymbol{f}_i = \sum_{(i,j\in E)} \boldsymbol{f_{ij}} = \sum_{(i,j\in E)} k_{ij}(\|\boldsymbol{x}_j - \boldsymbol{x}_i\| - l_{ij}^0) \times \frac{\boldsymbol{x}_j - \boldsymbol{x}_i}{\|\boldsymbol{x}_j - \boldsymbol{x}_i\|} \tag{3}$$

Secondly, we also use the damping model, as follows:

$$\boldsymbol{f_d} = -C_d(\boldsymbol{v}_i - \boldsymbol{v}_j) \tag{4}$$

Here, $\boldsymbol{f_d}$ is the damping force acting on the mass point i between the point i and j. C_d is the damping coefficient, and $\boldsymbol{v_i}$ and $\boldsymbol{v_j}$ are the velocities of two mass points respectively. The total damping force acting on the mass point i can be expressed as:

$$\boldsymbol{f}_i^d = -C_d \sum_{(i,j\in E)} (\boldsymbol{v}_i - \boldsymbol{v}_j) \tag{5}$$

In addition, each point in the local mass-spring system has the same mass M. Due to the attraction of the earth, the force is also called gravity. The magnitude of the gravity is proportional to the mass of the particle. The gravity $\boldsymbol{f_{gi}}$ of mass point i is:

$$\boldsymbol{f_{gi}} = m_i \boldsymbol{g} \tag{6}$$

Where $\boldsymbol{f_{gi}}$ is the gravity of mass i at time t; m_i is the mass of point i, which is M mentioned above. $\boldsymbol{g}$ is the acceleration of gravity, which is a constant value. According to Newton's second law of motion, the interal resultant force $\boldsymbol{f}_i^r$ of point i is:

$$\boldsymbol{f}_i^r = \boldsymbol{f}_i + \boldsymbol{f}_i^d + \boldsymbol{f_{gi}} \tag{7}$$

step 2: After the force analysis is completed, we use the explicit Euler integral method to compute the velocity and displacement values after the time interval Δt. The specific formula is as follows:

$$\begin{aligned} \boldsymbol{a}_i &= \boldsymbol{f}_i^r / \boldsymbol{m}_i \\ \boldsymbol{v}_i^{n+1} &= \boldsymbol{v}_i^n + \Delta \boldsymbol{t} \times \boldsymbol{a}_i \\ \boldsymbol{x}_i^{n+1} &= \boldsymbol{x}_i^n + \Delta \boldsymbol{t} \times \boldsymbol{v}_i^n \end{aligned} \tag{8}$$

The formulas show that each point needs to store two attributes: speed and position. After the time step Δt, the above formula can be used to calculate the new speed and coordinates at the next moment.

step 3: When the above steps are completed, each affected mass point has the new position, and realizes the overall update of the local mass-spring system. And then the position of each affected point $v(v_x, v_y, v_z)$ in 3D model is driven by the mass-spring system. The details are as follows:

$$v_i = P_i \times R_i + b_i \quad (i \in [x, y, z]) \tag{9}$$

Here, (b_x, b_y, b_z) is the coordinates of the base point b in the grid where the point sets of model are located. We need to notice that the base point coordinates of each grid cell are different. P_x, P_y, P_z are the calculated scale factors, R_x, R_y, R_z are the distance between the base point b and the adjacent point in the updated mass-spring system. Finally, the coordinate values of affected points are calculated.

5 Result

By introducing a typical desktop haptic device (Phantom Omni hand controller has 6 degrees of freedom (DoF) for position and posture detection, 3 DoF for force feedback, its detection accuracy is about 0.055, the maximum of force is 3.3 N, workspace>160W×120H×70D mm), we construct a 3D interactive presentation system based on haptic interactive framework. In this paper, we have implemented our 3D shape deformation simulation algorithm with OpenGL and Visual C++ 6.0, and gathered experimental results on a Win7-PC with one CPU of Intel Core4*4 3.60 GHz with 8 GB RAM.

Fig. 4 is a sketch of cutting effect of bunny model in wireframe and entity mode. The haptic device is used to cut the model at different positions. Meanwhile, the entire interactive process is simple, natural, and effective.

Fig. 5 is a sketch of deformation effect during touch bunny model. When the haptic interactive device touches the surface of the body, the surface of the object deforms and the touch sense of the body surface is feedback.

Fig. 6 is a sketch of the deformation effect of bunny model in the pull mode. It mainly simulates the effect of pulling the surface of the body. The experimental results show that the surface of object is pulled out and deformed, and the corresponding elastic effect is brought to the user.

Fig. 3 3D interactive presentation system based on haptics

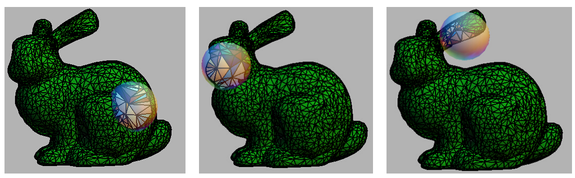

Fig. 4 Diagram of cutting effect (Wireframe + Entity Mode)

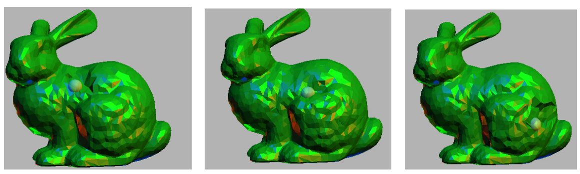

Fig. 5 Diagram of deformation effect in touch mode

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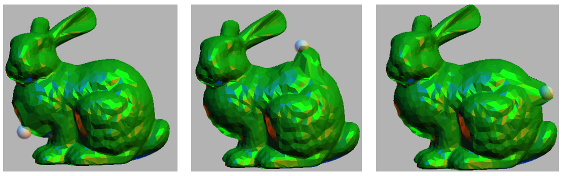

Fig. 6 Diagram of deformation effect in pull mode

6 Conclusion

In this paper, we firstly provide a haptic interactive framework by introducing haptic interaction into shape editing field. Based on the above haptic interactive framework, we propose a 3D shape deformation simulation algorithm based on haptics. In order to realize the shape deformation, our algorithm needs to involve three parts: grid hierarchical structure, local mass-spring model and the dynamic shape deformation. Experimental results show that this algorithm has good stability and strong robustness, and the method can enable human operators to perceive and deform the 3D shape through multiple channels. In addition, the entire interaction is simple, natural, and effective. For future work, the following research will focus on precision of the model and haptic rendering algorithm to further improve the efficiency and robustness of the algorithm.

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