HAPTIC POTTERY MODELING SYSTEM USING IMPROVED CIRCULAR SECTOR ELEMENT METHOD

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Abstract: This paper presents an efficient modeling system of virtual pottery using a haptic interface. Previously, we proposed a Circular Sector Element Method (CSEM) for virtual pottery modeling, which allows the 1 kHz haptic update rate even for very dense models. The CSEM, however, often rendered unrealistic artifacts since it did not consider interactions between adjacent elements. We have improved the CSEM by incorporating the local propagation of response forces in pottery deformation. In addition, a GPU-based synchronization between the visual and haptic models is included in the modeling system, and it greatly reduces the computation time. Compared to the original CSEM, the improved CSEM renders more realistic pottery with much better computational performance.

Keywords: virtual clay, pottery, haptic rendering, deformable object rendering, GPU-based rendering.

I. INTRODUCTION

Making pottery from clay rotating on a potter's wheel is a common worldwide cultural heritage. Pottery making in a virtual environment using a haptic interface allows intuitive interaction with the sense of touch, and provides vivid cultural experiences, especially to children. This research aims at developing a haptic rendering system that can create high-fidelity virtual pottery with an inexpensive haptic device and computationally efficient modeling and rendering algorithms.

In general, pottery modeling belongs to deformable object modeling. To render a deformable object, two major approaches have been used: geometry-based methods such as Free-Form Deformation (FFD) and physics-based methods such as Finite Element Method (FEM). FFD is fast, but considers no physical meanings involved in the interactions. Objects are deformed based on purely geometric constraints in response to external inputs [1]. In contrast, the FEM pursues physically accurate solutions simulating the interaction dynamics in high fidelity [2]. However, the FEM is computationally intensive, and requires simplifications to satisfy the real-time requirement for haptic rendering [3][4][5]. This largely restricts the number of elements of an object model, sacrificing the realism of simulation.

Recently, we proposed a haptic pottery modeling system using a Circular Sector Element Method (CSEM) [6]. In the CSEM, pottery is modeled as a set of circular sector elements based on its cylindrical symmetry. The CSEM leads to excellent modeling resolution and fast computation. However, the CSEM may render unrealistic artifacts, since it does not consider interactions between adjacent elements.

In this study, we have improved the CSEM to make much more realistic pottery while preserving the fast update rate. We now consider local interactions; all deformed elements propagate response forces to the adjacent elements. Furthermore, we implemented a transformation between the visual and haptic models on a GPU, which greatly accelerates the rendering speed of the modeling system. Performance comparisons between the original and improved CSEMs are also presented.

II. MODELING AND RENDERING METHODS

In this section, we introduce briefly the improved algorithms in the CSEM. Detailed information on the earlier version of the CSEM can be found in [6].

A. *Pottery Model Using Circular Sector Elements*

Most pottery is cylindrically symmetrical, and deformed along the radial direction. Therefore, we can express a pottery model using a number of circular sector elements (Fig. 1). A circular sector element is denoted by $\mathbf{S}^i = (S_r^i, S_\theta^i, S_h^i)$ using the cylindrical coordinates of the end-point of the element. An index will be omitted if appropriate. A Haptic Interface Point (HIP) is represented as a sphere centered at point $\mathbf{H}$. The CSEM models only the boundary of the pottery model.

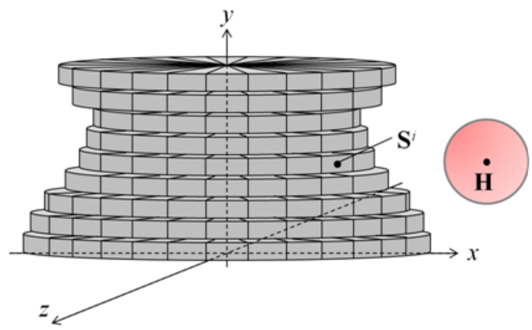

Fig. 1. A Pottery model composed of circular sector elements ($\mathbf{S}$) and HIP ($\mathbf{H}$).

B. *Response Force Propagation*

In the original CSEM, we did not consider interactions between adjacent elements. Thus, it sometimes generates unrealistic artifacts, for example, unnaturally sharp edges. In the improved CSEM, we take into account response force propagation between adjacent elements as follows.

As the pottery model has an empty interior in our system, the effect of global deformation propagation is negligible. Hence, we only consider the local interactions; each deformed element propagates response force to the adjacent elements until the force becomes smaller than a predefined threshold.

First, we find circular sector elements that are touched by the HIP sphere using a collision detection algorithm in [6]. The elements in the boundary of a contacted region can be found during the collision detection without further computational overhead. If the region of collision is not convex, several boundary elements can be omitted, but this occurs rarely in practice due to the use of a spherical HIP.

In real deformation of pottery, force is propagated circularly from each contacted element. In our model, force propagation is simplified to use tetragonal hulls as illustrated in Fig. 2.

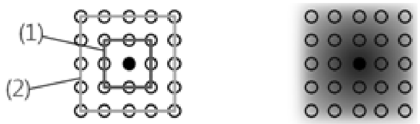

Fig. 2. A colliding element (black circle) propagates deformation along tetragonal hulls (left). The nearer hull (1) goes through larger deformation than the farther hull (2). This also can be illustrated using gradation (right).

Then, the desired change of the radius of an element in a tetragonal hull is computed by

$$l = \frac{\Delta S_r}{(c_i \delta)^2 + 1} = \frac{\Delta S_r}{(c_i u_\theta s_r n)^2 + 1},$$

where ΔS_r is the change of the radius of the colliding element (the center point in Fig. 2), c_i is the coefficient of propagation, and δ is the distance between adjacent elements which can be computed approximately from the angular resolution u_θ, the radius of the element s_r, and the serial number n of the tetragonal hull. Despite of the simplification, rendering results show naturally smooth boundaries since the propagation effects are accumulated for all boundary elements (Fig. 3).

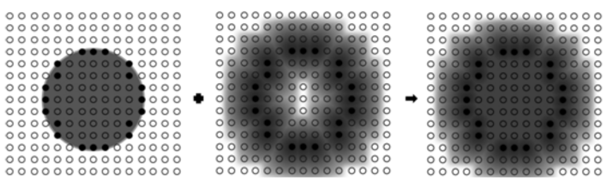

Fig. 3. Deformed radius of each element after force propagation. Darker color indicates longer deformed radius.

C. *GPU-based Visuo-Haptic Synchoronization*

All sub-algorithms of the CSEM are performed in the cylindrical coordinates to utilize the cylindrical symmetry of a pottery. However, to render the pottery visually, all elements must be transformed to the Cartesian coordinates, and the normal vector of each element must be computed. Typically, our pottery model consists of hundreds of thousands of elements, and more than a thousand elements may simultaneously collide with the HIP sphere. Thus, coordinate transformation and normal vector computation are computationally intensive, requiring the largest computation time in the rendering process. We accelerate this synchronization between the visual and haptic models using GPU, similarly to [7][8].

In the CSEM, each element is deformed only along the radical direction; only S_r is changed whereas S_θ and S_h remain constant. All elements are also separated evenly in the θ and h directions. Thus, S_θ and S_h can be rendered as a 2D grid using the OpenGL display list. S_r is mapped to an alpha value, and stored in the 2D alpha texture. The OpenGL vertex shader reads S_θ and S_h from the display list and S_r from the alpha texture, and then transforms the coordinates and computes normal vectors. For example, the transformed end-point of an element can be computed using the following OpenGL vertex shader code:

```
v = vec3(texColor.a * cos(gl_Vertex.x),
    gl_Vertex.y,
    texColor.a * sin(gl_Vertex.x));
```

Since normalized S_r, S_θ, and S_h are used in the OpenGL model, `texColor.a`, `gl_Vertex.x`, and `gl_Vertex.y` are scaled properly in the implementation.

III. RESULTS

Our pottery modeling system has been implemented on a desktop PC (Intel Pentium 4 3.2GHz CPU, 1.00GB RAM, NVIDIA Geforce 8800 GTS graphics card) using a PHANToM Omni device (Sensable Technology, Inc.) as a haptic interface. The user deforms the virtual pottery using the Omni stylus. The user can control the rotation speed of the potter's wheel and change the HIP size using a keyboard. The viscosity coefficient of the pottery can also be adjusted. During performance evaluation, the HIP automatically followed a predefined trajectory.

The effect of response force propagation was demonstrated as follows. The computer moved the HIP automatically from the top to the bottom of a virtual pottery while the potter's wheel rotated slowly. The pottery made by the original CSEM has unrealistically clear and sharp edges, but the improved CSEM did not contain such artifacts and rendered much more realistic and smooth pottery (Fig. 4).

We then compared the computational performance of both modeling systems to evaluate the effect of GPU programming. The pottery model consisted of 144,000 circular sector elements was used. Total execution time and the time required to transform the coordinates and compute the normal vectors were measured (Table I). On average, the improved CSEM was 4.7 times faster than the original CSEM. In particular, the model transformation time was greatly decreased in the improved CSEM.

We also compared graphic and haptic rendering frame rates. In the original CSEM, the graphic rendering frame rate was 52 Hz, and the haptic rendering frame rate was 259 Hz on average. In the improved CSEM, the graphic rendering frame rate was 510 Hz, and the haptic rendering frame rate was 879 Hz on average. The slowest haptic frame rate was 136 Hz for the original CSEM, but 567 Hz for the improved CSEM. This improvement in the haptic frame rate significantly contributes to more stable haptic rendering.

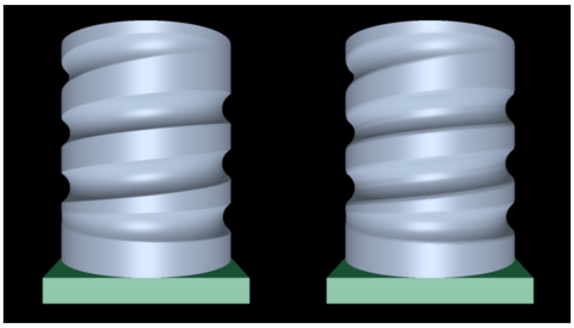

Fig. 4. Pottery modeling example of the original CSEM (left) and the improved CSEM (right).

Table 1. Total execution time and the time required for model transformation.

		Total (ms)	Transformation (ms)
Original CSEM	Max	8.56	5.71
	Min	0.93	0.75
	Average	3.93	2.84
Improved CSEM	Max	1.99	0.28
	Min	0.16	0.02
	Average	0.83	0.07

IV. CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed a virtual pottery modeling system that includes the sense of touch. Using the CSEM that exploits the cylindrical symmetry of pottery, the system provides very efficient modeling and rendering algorithms. We improved our earlier work to make much more realistic pottery while preserving a fast update rate. We considered interactions between the adjacent elements by implementing a simple local deformation propagation model. Transformation from the haptic model to the visual model was implemented using GPU to increase the rendering speed. We showed that the improved CSEM generates much more realistic pottery with dramatically improved computational performance. If an inexpensive haptic device such as Novint Falcon [9] is used, our system may be particularly useful for e-learning in elementary schools owing its efficiency, providing an enjoyable experience of pottery making.

At present, the haptic tool for deformation is modeled as a sphere to simplify the collision detection and response computation. Since this limits the types of decorations that can be made on the pottery surface, we plan to extend the algorithms to support a tool consisting of a general polygonal model.

ACKNOWLEDGEMENTS

This work was supported in parts by an NRL program R0A-2008-000-20087-0 from NRF and by an ITRC program NIPA-2009-C1090-0902-0008 from NIPA, both funded by the Korean government.

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