Virtual Pottery Modeling with Force Feedback Using Cylindrical Element Method

Gabjong Han, Joongchul Kim, and Seungmoon Choi
Haptics and Virtual Reality Laboratory
Department of Computer Science and Engineering
POSTECH, Republic of Korea
{hkj84, kjc8384, choism}@postech.ac.kr

***Abstract*— This paper presents a fast and intuitive modeling technique of virtual pottery using force feedback based on a cylindrical element method. Previous models for simulating deformations such as the finite element method (FEM) and its variants often suffer from expensive computational costs in haptic rendering. In our method, a FEM model is simplified to increase computational speed by utilizing the unique characteristics of the pottery modeling such as its hollow body and cylindrical symmetry. Forces rendered with a force-feedback haptic interface consider the stiffness, friction, and viscosity of virtual clay. The developed pottery modeling system provides realistic force feedback in a computationally efficient manner.**

I. Introduction

Pottery making is one of important cultural heritages in the most of the world. Traditional pottery making process using a rotating stand provides a very intuitive interface for deforming a pottery directly with the hands. In order to recreate such valuable cultural experiences, there have been many attempts to simulate the pottery making process in a virtual environment. However, the most salient feature of the pottery making process, that is, *feeling of touching the pottery*, has been rather lacking in most of the pottery design systems. This paper presents a simple and intuitive pottery design system using a force-feedback haptic interface. Our pottery making system enables a user to touch and deform a virtual pottery rotating on a stand as s/he can with a real pottery.

In haptic rendering, pottery making can belongs to the category of deformable object rendering. The traditional finite element method (FEM) [1], [2] is not very appropriate for haptic rendering due to its heavy computational cost and the hard real-time requirement of haptic rendering [3]. Due to this problem, many simplified methods such as the long element method (LEM) [4], [5] and the boundary element method (BEM) [6], [7] have been adopted for haptic rendering of deformable objects. In the LEM, an array of cubic elements (a base element in the FEM) is represented by one long rectangular hexahedron assuming deformation occurs along the length direction of the hexahedrons. Another popular approach is the BEM where the internal structure of an object is ignored and only the deformation of the object boundary is computed. Despite the simplifications, most of them still require very expensive computations for deformation rendering and may not satisfy the fast update requirement of haptic rendering.

In our pottery design system, we propose a cylindrical element method (CEM) that can compute the deformation of an object with cylindrical symmetry in extremely efficient manner. In the CEM, an object is represented with a 1D array of cylindrical elements, which is adequate to model objects with cylindrical symmetry and homogeneous material property such as the pottery. The CEM greatly decreases the computational cost compared to the LEM or BEM.

For haptic interaction, our system renders three types of interaction forces. First, a resistance force (normal to the pottery surface) that blocks the penetration of a haptic tool held by the user's hand is computed based on the penalty-based haptic rendering method [8], [9]. Second, a viscosity effect is added in the normal resistance force to provide the sense of "sticky" virtual pottery. Finally, lateral friction is calculated also considering the rotating velocity of the stand. The three terms are combined into a final rendering force command to be sent to a haptic interface. This algorithm is simple but delivers realistic sensations of touching the virtual pottery.

This paper is organized as follows. In Section II, related work for modeling and rendering of the virtual pottery is discussed. Section III provides an overview of our pottery modeling system, followed by detailed descriptions on the CEM in Section IV and force computation methods in Section V. Some virtual pottery examples modeled using our system are provided in Section VI. We conclude this paper in Section VII.

II. Related Work

There have been numerous studies on how to model 3D objects in computer graphics, virtual reality, and haptics. Due to the limited space, we focus on methods for modeling virtual clay and pottery with an emphasis on force feedback capability. Galyean developed an early 3D object modeling system in 1991 which provided force feedback with a volumetric model [10]. The system developed by Kameyama in 1997 [11] uses a tactile feedback device to provide a feeling of touching virtual clay via vibrations. A pottery modeling system that uses the cyberglove for gesture-based interaction was proposed by Korida in 1997 [12] although no haptic feedback was included.

After 1997, most of 3D modeling systems began to adopt a haptic device for force feedback. Massie used a 3 DoF haptic device with voxel-based rendering to model 3D objects from clay [13]. The system proposed by Chai uses a variant of the free-form deformation techniques and an exoskeleton haptic device for virtual clay modeling [14]. McDonnel proposed a system based on the FEM for a 3 degrees-of-freedom (DoF) haptic device [15], [16]. Bremer released another system to simulate virtual clay using a volume rendering technique based on the adaptive distance fields [17].

III. System Overview

The main goal of the system is to enable a user to easily design a deformable virtual pottery model with realistic force feedback. At present, we use the PHANToM family (Sensable Inc., USA) for a force-reflecting haptic interface.

A. Interaction Design

Prior to developing necessary components for a pottery modeling system, an interaction scenario needs to be determined with appropriate selections of input/output methods. In the beginning of simulation, a large cylinder representing virtual clay on a rotating stand is presented on the computer screen. The user holds the stylus of the PHANToM and controls the position of the stylus tip to touch and deform the virtual clay to make a pottery (see Figure 1). The computer monitor displays the virtual pottery on the rotating stand as well as the haptic interface point (HIP; the end-point of a haptic tool) represented by a sphere. If the user presses a button on the stylus, the stand rotates at a predefined angular velocity. If the user releases the button, the stand stops rotating. The cylinder representing the virtual clay is modeled using a set of cylinders exploiting the cylindrical symmetry of the pottery. The virtual clay is deformed accordingly if touched while the stand is rotating. During deformation, the radius of each cylindrical element is decreased gradually in times. An appropriate rendering force is computed based on the sphere size, the CEM model, and the material property of the pottery. The user can also change the radius of the HIP sphere using a keyboard. This scheme of user interaction allows an easy and intuitive interface for the user to design a virtual pottery.

B. Software Structure

Our pottery modeling system consists of two software modules. The first module is a graphic rendering loop which draws the virtual pottery, the stand, and the HIP. The second module is a haptic rendering loop which updates the HIP, calculates a force, and deforms the pottery structure using the CEM. Figure 2 shows the overall structure of the framework along with update rates for each rendering module. The two modules are implemented in separate threads.

The graphics loop (the left box in Figure 2) displays a sphere, a set of cylindrical elements, and a cube representing

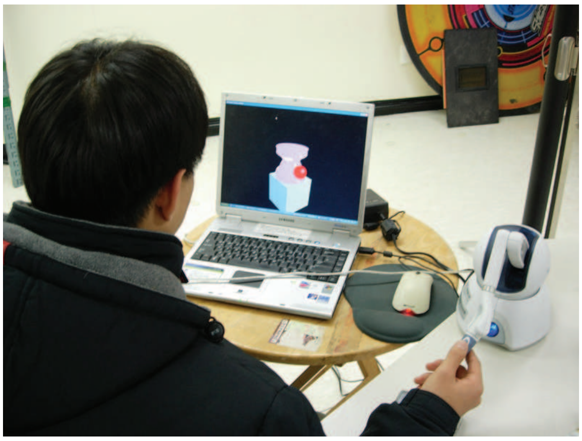

Fig. 1. A user is modeling a virtual pottery by touching the pottery with the force-feedback device. The red sphere on the monitor in the center of the figure represents the haptic interface point (HIP).

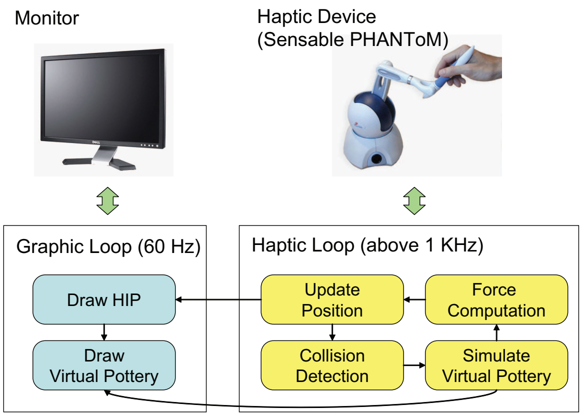

Fig. 2. Software structure of the pottery modeling system.

the HIP, a virtual pottery, and the rotating platform, respectively. Note that the cube is placed underneath the pottery (see Figure 1). This loop runs at 60 Hz and has little effect on the computation cost of the whole system. During the visual rendering process, the radii of cylindrical elements are interpolated to smooth a staircase effect between elements and reduce unnecessary drawing.

The haptics loop (the right box of Figure 2) is the most important part of the system. The first step is retrieving the position information from the haptic device and sending the position of the HIP to the graphics loop. In the second step, the HIP and the CEM model of the virtual pottery are compared to each other to find collisions between them. In the third step, the cylindrical elements contacted by the HIP are deformed appropriately and this updated CEM model is sent to the graphics loop. Finally, we compute a force command based on the HIP, the CEM model and the material parameters of the pottery.

IV. Cylindrical Element Method

The virtual pottery model in our system uses the CEM, a simple and effective way that we came up with to represent the geometry of a deformable object with cylindrical

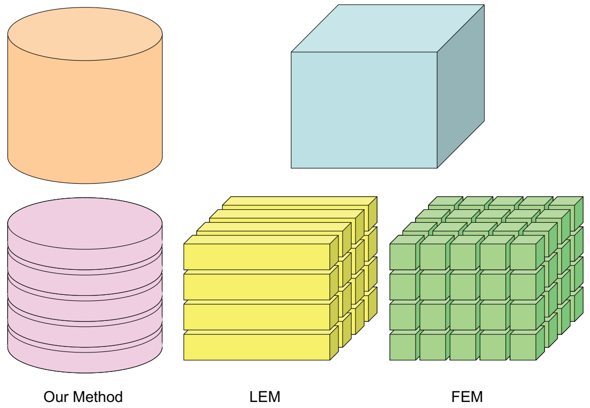

Fig. 3. Different model representation methods.

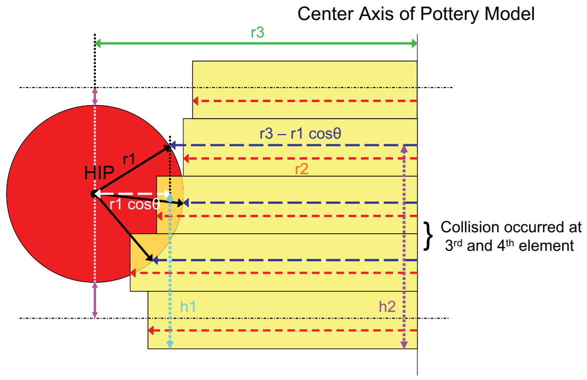

Fig. 4. Illustration of the collision detection algorithm. The first and last elements are excluded by the height comparison. The second element is also out of consideration due to the distance comparison. The third and fourth elements are declared as contacted elements.

symmetry. In the CEM, the entire volume of a deformable object is discretized with a set of thin cylinders for its boundary representation. The CEM allows a significantly smaller number of elements to represent an object than the FEM or LEM. This is the major advantage of the CEM taking advantage of the cylindrical symmetry of the virtual pottery. Figure 3 illustrates the structures of the CEM, LEM, and FEM. As is evident in the figure, the CEM is equivalent to a discretization in the 1D space and thus requires a very small number of elements.

Each cylindrical element can be represented by a few parameters, e.g., the coordinate of its center, radius, height, and normal vector of the top circle. Depending on the configuration of an object, most of the parameters can be constant during simulation. Another advantage of the CEM is that it enables very fine spatial resolution along the height direction of the virtual pottery. In the height direction, the CEM can have a much higher spatial resolution than the FEM or LEM, which is appropriate for modeling artistic object such as the pottery.

A. Collision Detection

Another benefit of the CEM is that collision detection between the HIP and virtual pottery can be performed using a simple closed-form equation. We explain the algorithm using Figure 4. First, the height of each element's centroid, $h2$, is tested whether $h2$ is within the height range spanned by the HIP radius, $h1 \pm r1$. If it is not, the element is labeled with no collision. If it is, a further test is performed. A collision is occurred when the distance between the HIP and the center of the pottery, $r3$, is less than the sum of the element radius, $r2$, and the magnitude of the sphere's radius vector projected onto the horizontal plane, $r1 \cos\theta$. In this case, Equation 1 becomes negative, and this proximity information is used for deformation and force rendering.

$$proximity = -(r1 \cos\theta + r2) + r3 \qquad (1)$$

B. Deformation

After a collision is detected, the pottery's shape is deformed by decreasing the radii of the contacted cylindrical elements gradually in time. The rate of decrease is proportional to the proximity between the HIP and the cylindrical element and inversely proportional to the HIP sphere radius. For each touched element, its radius at rendering time t is computed as below.

$$radius_t = radius_{t-1} - \frac{|proximity|}{c1\ r1}, \qquad (2)$$

where $c1$ is a constant that keeps $c1\ r1$ always higher than 1.

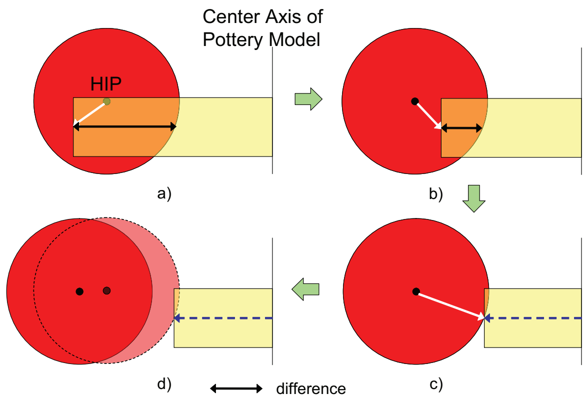

Fig. 5. Deformation process between the HIP and a cylindrical element.

The whole deformation process is illustrated in Figure 5. In the first step, the HIP moves into the pottery by the user and a collision is detected (Figure 5(a)). In the second step, the deformation process is activated and reduces the radius of the contacted element (Figure 5(b)). Note that this step can be repeated as long as the user maintains the contact. In the third step, the contact is eventually off and the deformation process is terminated (Figure 5(c)). Finally, the HIP is in the free space and the element is appropriately deformed by the previous contacts. (Figure 5(d)). In this scenario, the deformation proceeds gradually in order to simulate the continuous deformation of the clay with high viscosity.

The current CEM model and deformation techniques have a few limitations. First, the current CEM model allows only symmetrical deformation. When a real pottery is stationary

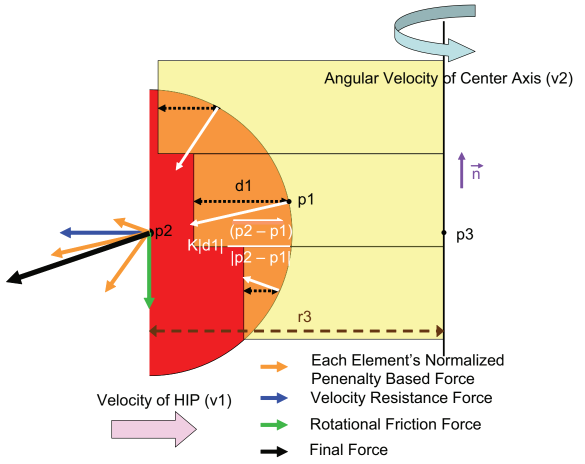

Fig. 6. Force computation. Final force (black) is calculated from stiffness force (orange), viscosity force (blue), and friction force (green).

and touched by a tool, a local deformation on the contact region occurs. However, such effect is not implemented in the current CEM model. Second, a scenario wherein the user touches the top part of the virtual clay to carve inside the clay is not considered. We plan to develop ways for these two limitations by refining the partitioning structure of the CEM in the near future.

V. Force Rendering

As we mentioned earlier, we compute three kinds of forces for force feedback when the sphere centered at the HIP touches the virtual pottery and add them up for a final rendering force. The first component $\mathbf{F_s}$ is to render the stiffness of the virtual pottery and is augmented with viscosity effect $\mathbf{F_v}$. The two components are perpendicular to the surface of virtual pottery. The last component is for lateral friction and denoted by $\mathbf{F_f}$. The net force equation is:

$$\mathbf{F} = \mathbf{F_s} + \mathbf{F_v} + \mathbf{F_f}. \tag{3}$$

A. Stiffness Rendering

In order to render the stiffness of virtual pottery, we utilize the conventional penalty-based haptic rendering method. Since there can be multiple contact points between the deforming tool (sphere including the HIP) and the cylindrical elements, our algorithm finds all cylindrical elements in contact with the sphere, compute a forced component for each cylindrical element, and add all force components for stiffness rendering.

Rendering force calculation for each cylindrical element is illustrated in Figure 6. After deformation processing, the force magnitude is computed based on the proximity between the HIP and each collided element ($d1$). The force direction is from the collision point ($\mathbf{p1}$) to the HIP ($\mathbf{p2}$) (see white vectors from each element in Figure 6). After summation, the net force is normalized with respect to the number of collided cylindrical elements (see orange vectors in the figure). Equations for this procedure are summarized below:

$$\mathbf{F_s}^i = K|d1|\frac{\mathbf{p2} - \mathbf{p1}}{|\mathbf{p2} - \mathbf{p1}|}, \tag{4}$$

$$\mathbf{F_s} = \frac{1}{n}\sum_{i \in I} \mathbf{F_s}^i, \tag{5}$$

where I is a set of all cylindrical elements i that are in contact with the HIP sphere.

The stiffness can be set to different values depending on whether the platform for the virtual pottery is rotating. For example, we can set $K = 0.1$ N/mm when the stand rotation is on and $K = 0.5$ N/mm when it is off. With the PHANToM Omni, this stiffness set renders well deformable pottery when it is rotating, and firm and hard-to-deform pottery when it is stationary.

B. Viscosity Rendering

The clay for real pottery is sticky with certain viscosity. Such effect in the virtual pottery is simulated by adding a force component for viscosity to the final rendering force. The viscosity force component is computed as:

$$\mathbf{F_v} = -c2\mathbf{v1}. \tag{6}$$

That is, the viscosity component prohibits the movement of the HIP deforming the virtual pottery and its magnitude is proportional to the viscosity constant $c2$. The effect of $\mathbf{F_v}$ is more evident when the HIP comes into and leaves out of the pottery surface.

C. Friction Rendering

The last component is for rotational friction caused by the self-rotating virtual pottery. Even if the HIP is standing still, the rotating pottery exerts tangential frictional force to the HIP in the direction of rotation. This force component is modeled as:

$$\mathbf{F_f} = c3\ v2\ r3\ \frac{\mathbf{p3} - \mathbf{p2}}{|\mathbf{p3} - \mathbf{p2}|} \times \mathbf{n}, \tag{7}$$

where $c3$ is a friction coefficient, $v2$ is the angular velocity of the rotating stand, $r3$ is the distance between the HIP and the center axis, $\mathbf{n}$ is the unit vector of the rotational axis, and $\mathbf{p3}$ is a projection of the collision point ($\mathbf{p2}$) onto the center axis (see Figure 6 again).

With adequate choices of $c2$ and $c3$, the final rendering force $\mathbf{F}$ in Equation 3 provide realistic force feedback for pottery deformation.

VI. Results

We have implemented the pottery modeling system on an Intel Zeon 3.2GHz computer with 1.00GB RAM and a NVIDIA Quadro FX 3450 Graphics Card (256MB RAM). Our system was also tested in a labtop (Samsung Sens X15) which has Intel Pentium M 1.4GHz CPU with 512MB RAM and Intel Extreme Graphics 2 Graphics Card (64MB RAM), as a representative of low-end machines. For force-feedback, we used a Sensable PHANToM Omni device. Our system

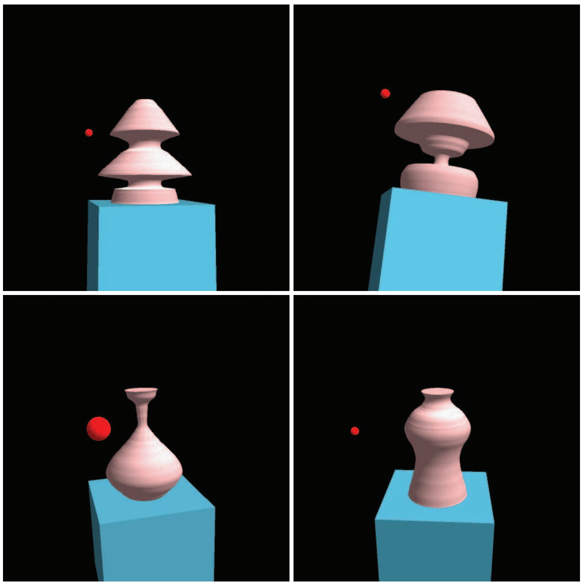

Fig. 7. Pottery example modeled using our system.

achieves the visual update rate of 60Hz and the haptic update rate above 1 kHz in both environments.

With our pottery modeling system, users can easily design virtual pottery in a time-efficient manner. Figure 7 shows examples modeled using our system in just a few minutes. Furthermore, due to the intuitive and natural interface of our system, most users became familiar with the modeling process immediately. This is an important merit for using the system for education or training purpose.

The current implementation of the CEM uses 2000 cylindrical elements. For a 20-cm high virtual pottery, this allows 0.1 mm spatial resolution in the height direction of the virtual pottery. This extremely fine resolution, even approaching the position sensing resolution of the PHANToM ($\simeq 0.03$ mm), is the most apparent advantage of the CEM.

VII. Conclusions

In this paper, we have proposed the virtual pottery modeling system based on the CEM with additional haptic rendering techniques. The CEM uses a 1D array of cylinder elements to achieve high computational speed on simulating a deformable object. Moreover, our system uses additional forces that can give more realistic force feedback such as the viscosity and rotational friction of a deformable object. These methods facilitate fast and intuitive virtual pottery modeling.

Our system can be extended in various ways. First, we plan to improve the current CEM to extend the class of deformations that the CEM can represent. For example, deforming a local area, the top and bottom surfaces, or the internal structure is not supported in the current CEM. Resolving the limitations will allow interactions more close to the real pottery making process. Second, we are investigating various ways to make the force feedback more realistic. We will also compare our method to previous methods in terms of performance and preference.

Acknowledgments

This work was supported in parts by a grant No. R01-2006-000-10808-0 from the Korea Science and Engineering Foundation (KOSEF) funded by the Korea government (MOST), by the Brain Korea 21 program from the Korea Research Foundation, and a grant from KT.

References

[1] P. G. Ciarlet, *Finite Element Method for Elliptic Problems*. Society for Industrial and Applied Mathematics Philadelphia, PA, USA, 2002.

[2] O. C. Zienkiewics, R. L. Taylor, P. Nithiarasu, and J. Z. Zhu, *The Finite Element Method*. Elsevier/Butterworth-Heinemann, 2005.

[3] N. Swarup, "Haptic interaction with deformable objects using real-time dynamic simulation," Master Thesis, Massachusetts Institute of Technology, 1995.

[4] I. F. Costa and R. Balaniuk, "Lem-an approach for real time physically based soft tissue simulation," in *Proceedings of IEEE International Conference on Robotics and Automation*, vol. 3, 2001, pp. 2337– 2343.

[5] K. Sundaraj, C. Laugier, and I. F. Costa, "An approach to lem modeling: construction, collision detection anddynamic simulation," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 4, 2001, pp. 2196–2201.

[6] C. A. Brebbia, *The boundary element method for engineers*. Pentech Press, 1978.

[7] C. A. Brebbia, J. C. F. Telles, and L. C. Wrobel, *Boundary element techniques: Theory and applications in engineering*. Berlin and New York, Springer-Verlag, 1984.

[8] C. B. Zilles and J. K. Salisbury, "A constraint-based god-object method for haptic display," in *Proceeding of IEE/RSJ International Conference on Intelligent Robots and Systems, Human Robot Interaction, and Cooperative Robots*, vol. 3, 1995, pp. 146–151.

[9] D. C. Ruspini, K. Kolarov, and O. Khatib, "The haptic display of complex graphical environments," in *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, 1997, pp. 345–352.

[10] T. A. Galyean and J. F. Hughes, "Sculpting: an interactive volumetric modeling technique," in *Proceedings of the 18th annual conference on Computer graphics and interactive techniques*. ACM Press, 1991, pp. 267–274.

[11] K. Kameyama, "Virtual clay modeling system," in *Proceedings of the ACM symposium on Virtual reality software and technology*. Lausanne, Switzerland: ACM Press, 1997, pp. 197–200.

[12] K. Korida, H. Nishino, and K. Utsumiya, "An interactive 3d interface for a virtual ceramic art work environment," in *Proceedings of the 1997 International Conference on Virtual Systems and MultiMedia*, 1997, pp. 227–234.

[13] T. Massie, "A tangible goal for 3d modeling," *Computer Graphics and Applications, IEEE*, vol. 18, no. 3, pp. 62–65, 1998.

[14] Y. Chai, G. R. Luecke, and J. C. Edwards, "Virtual clay modeling using the isu exoskeleton," in *Proceedings of IEEE Virtual Reality Annual International Symposium*, 1998, pp. 76–80.

[15] K. T. McDonnell, H. Qin, and R. A. Wlodarczyk, "Virtual clay: a real-time sculpting system with haptic toolkits," in *Proceedings of the symposium on Interactive 3D graphics*. ACM Press New York, NY, USA, 2001, pp. 179–190.

[16] K. T. McDonnell and H. Qin, "Virtual clay: Haptics-based deformable solids of arbitrary topology," *in Proceedings of the Second International Workshop on Articulated Motion Deformable Objects, Lecture Notes in Computer Science*, vol. 2492, pp. 862–866, 2002.

[17] P. T. Bremer, S. Porumbescu, F. Kuester, B. Hamann, K. I. Joy, and K. L. Ma, "Virtual clay modeling using adaptive distance fields," in *Proceedings of the International Conference on Imaging Science, Systems, and Technology*, vol. 8, 2002.