TWMS J. App. Eng. Math. V.3, N.2, 2013, pp. 223-230.

A REAL-TIME VIRTUAL SCULPTING APPLICATION WITH A HAPTIC DEVICE

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Abstract. In this paper, a 3D virtual sculpting application is developed for 3D virtual models with removing or adding materials by using Boolean operations. Virtual sculpting simulation reads 3D virtual models in a variety of file formats such as raw and stl consisting of a triangle poligon mesh and voxelizes its outer surface and interiror volume to generate its volumetric dataset. We used octree and hashing techniques to reduce the memory requirement needed for volumetric dataset. The surface is locally reconstructed using Marching Cubes algorithm known as the most popular isosurface extraction algorithm after removing or adding material to the 3D virtual model. The user interacts with the model by using a haptic device to give the force-feedback like real-life sculpting.

Keywords: Virtual sculpting, voxelization, octree, hashing, haptics.

AMS Subject Classification: 83-02, 99A00

1. Introduction

Engineers and designers use digital computers for many years to make 3D modeling. In '90s computers were increasing in speed and capacity but also were becaming cheaper. This allowed artists to design and create their work in 3D modeling software. But available 3D modeling software did not have the perception of reality and interaction like virtual reality environments had. Because of this, virtual environments have been developed that allows 3D modeling by using virtual reality tools. This field of virtual reality is called virtual sculpture.

Zhang defines virtual sculpting as the process of creating interacitvely three-dimensionel (3D) models by carving a workpiece on the user's computer screen like a real sculptor can do on a piece of clay, wax, or wood [1].

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§ Manuscript received August 09, 2013.

The purpose of a virtual sculpting system is to allow designers to create and reshape three-dimensional free-form objects via an interactive environment equipped with virtual reality hardware and software.

The aim of our study is to develop a real-time virtual sculpting application for 3D virtual models with removing or adding materials by using Boolean operations. Virtual sculpting simulation reads input triangle poligon mesh and voxelizes its outer surface and interiror to generate its volumetric dataset. We used octree and hashing techniques to reduce the memory requirement and computation time needed for 3D volumetric dataset. The surface is locally reconstructed using Marching Cubes algorithm [2] known as the most popular isosurface extraction algorithm after removing or adding material to the 3D virtual model. The user interacts with the model by using a haptic device to give the force-feedback like real-life sculpting.

The remainder of the paper is organized as follows: in section 2, we mention about the literature review of voxel-based virtual sculpting. We present our steps of virtual sculpting application (voxelization, hashed octree, collision detection and response) in section 3. Last, we conclude and expose some future works in section 4.

2. Literature Review

Virtual sculpting applications are available in many areas especially for training purposes such as virtual medicine[3], dental surgery[4] ,design and modelling [5, 6]. In our virtual sculpting study, voxel-based volumetric approach was used. Because of this relevant literature is discussed below.

The first application of volumetric sculpture in the literature was proposed by Galyean and Hughes in 1991[7]. Initial model defined in uniform dicrete voxel grid is edited interactively to create 3D freeform shapes. Basic operations like addition or subtraction, and several tool definitions (heat gun, sand paper or colour modifier) are proposed. Kaufman and Wang have created another sculpting system where the tools are based on carving and sawing [8].

In these studies mentioned above, uniform voxel representation in which voxels are represented in a 3D discrete array is used. 3D space is divided into equal-sized units voxels and these voxels labeled according to whether they were inside the object or not. In this notation, when resolution was increased ,memory cost also increased because of the number of voxels needed to display the object was increased. For example, in 1024x1024x1024 resolution, billion voxels are needed to represent a 3D object. Because of this, researchers were started to use hierarchical data structures for holding 3 models volumetric data.

In order to work on higher resolution and lower memory cost , Barentzen was used octree data structure which recursively splits voxel-based volume data into eight equally parts[9]. The only tool shape is a sphere, and the only operations are addition and subtraction. Ferley et al. also worked on a hierarchical organization of voxel: a cell can be divided in 27 ones [10]. It permits to reach a high level of detail. The tool is defined by an ellipsoid.

Raffin et.al proposed a combination of a volumetric coding and B-rep in their virtual sculpting application [11]. Volumetric coding is well adapted to express sculpture operation and on the other hand, a B-rep extracted from the volumetic coding enables a fast display of the shape and the interactive modification of the viewpoint. They proposed a multiresolution approach based on octree to lower memory cost and both sculpture and tools have been coded as octrees. Interactions are controlled via spaceball, keyboard and mouse.

Heurtebise ve Thon, proposed a multi- resolution model which is combining octree and 3D wavelet transformation for storing voxel volume data [12].

Williams and others performed volume extraction on a set of discrete voxels to carve a 3D object in real time[13]. In this study input model can be a set of binary voxel taken from CT/MRI image or it can be a triangle mesh. If input model is a triangle mesh , it has be converted into a voxel volume model. The traditional BPA (Ball Pivoting Algorithm) [14] which converts point clouds generated from voxel set to trangular meshes is extended to generate meshes on the carved local area and is called DBPA (Dynamic Ball Pivoting Algorithm). Furthermore, to provide realism and visual appeal the objects being carved display texture. And it allows the specification of a 2D external texture and 3D internal texture for the object being carved.

Later, O'Neill et al. added a realistic force-feedback by using a pen-based haptic device which acts as a 3D Mouse to achive carving in real-time and to interact with the virtual object surface. [15].

3. Virtual Sculpting Application

The application steps of our proposed virtual sculpting system are mentioned below in detail. Figure 1 shows the design of our virtual sculpting system and interaction between graphics and haptic threads.

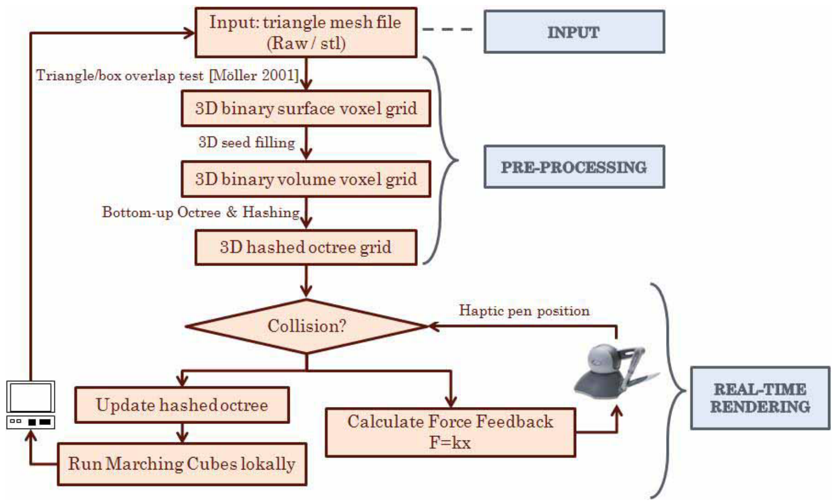
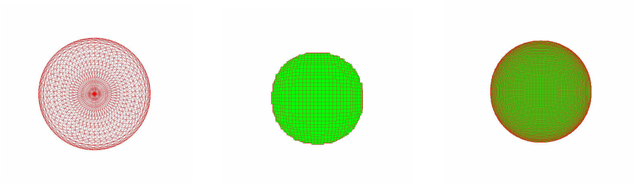


Figure 1. Design of our Virtual Sculpting system and interaction between graphics and haptic rendering.

3.1. Pre-Processing.

3.1.1. *Voxelization.* Voxelization is concerned with converting geometric objects from their continuous geometric representation into a set of voxels that best approximates the continuous object. As this process mimics the scan-conversion process that pixelizes (rasterizes) 2D geometric objects [16], it is also referred to as 3D scan-conversion [17]. This conversion process can be defined to represent the object as the set of voxels in a 3D discrete mesh.

The basic idea of voxelization algorithms is to determine each voxel whether or not covered by the object. Accordingly, if the voxel is covered by the object then the value of the relevant voxel is asssigned to "1", if not, its value is assigned to "0". This kind of voxelization approach which uses a boolean value to represent only the existence of the object is referred to as binary voxelization. Figure 2 shows an initial B-rep and resulting binary voxel representations (32x32x32 and 128x128x128) of a 3D object.



(a) (b) (c)

FIGURE 2. Representation of a 3D object (a) The original B-rep model, (b) Voxelization of 32x32x32, (c) Voxelization of 128x128x128

In our virtual sculpting application, the input triangular mesh model is converted to voxel-based volumetric data. Because, it is easier and faster to achieve Boolean operations (addition, subtraction) needed for sculpting by using voxel-based data. Binary volume voxelization is enough, because this voxel-based data will not be used for rendering. The following process steps are performed respectively to adapt 3D discrete binary voxel data achieved by voxelizing the input triangular mesh model.

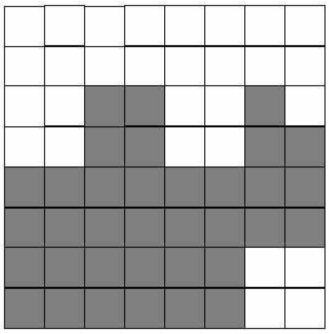
- Calculate the bounding box of 3D input triangular mesh model.
- Create discrete voxel grid in this bounding box in the desired resolution and flag each voxel as "0".
- Surface voxelization: Apply these steps below for all triangles in the model.
  - Calculate bounding box (AABB)
  - Apply Möller's 3D triangle-box overlap test on each voxel wihin this bonding box if its value is "0" [18, 19].
  - If voxel and triangle overlaps, convert this relevant voxel's flag to "1".
- Interior voxelization: Fill the interior volume of the 3D voxel model by using 3D flood filling algorithm [20].
- Resulting 3D binary volume data is converted into hashed octree data format instead pointer octree which each node consists of eight child nodes. This data structure decreases the computation cost needed for sculpting and allows us to get real-time performance by also decreasing the time took in the traversal and search process during interactive collision detection.

3.1.2. *Hashed Octree.* Octree [Samet89], is a hierarchical data structure based on recursive subdivision of a 3D space or region. The whole region is the root node of the octree and each node represents a cube and has eight child octants divided equally by three directions of the 3D space.

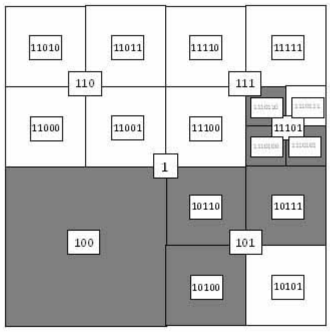
The most common methods used for storing octree data structure in memory is linear and pointer based method[22]. Linear octree only store leaf nodes and place them contiguously in memory and does not use pointers. In pointer octree every parent node keeps their eight child nodes addresses in pointers. These child nodes can represent space as empty, full or partially empty.

In this study, we proposed hashed octree data struture for representing voxel volume to reduce the memory cost and to increase tree traversal speed in the collusion detection stage [23]. Keys were used to accessing tree nodes in memory intead of pointers [24].

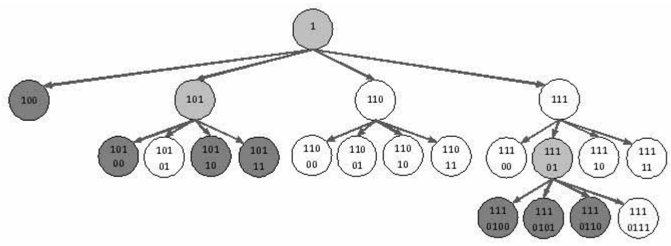
Figure 2 shows an example 2D binary shape, its quadtree represenation and corresponding keys of nodes, its hierarchical (pointer-based) octree representation, and hash-based octree representation, respectively.



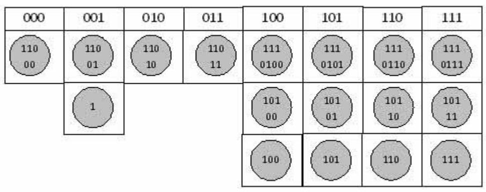
(a)



(b)



(c)



(d)

FIGURE 3. (a) 2D binary shape example, (b) its quadtree represenation and corresponding keys of nodes (traversal direction is bottom left, bottom right, top left, top), (c) hierarchical (pointer-based) representation, and (d) hash-based octree representation

3.1.3. *Collision Detection and Response.* To provide interaction and real sense of touch to the user, collision detection is performed by testing a possible collision between 3D model's voxel-based volumetric data and virtual probe of the haptic device controlled by Phantom Omni Haptics Device. When collision between 3D model's voxel-based volumetric data and virtual device occurs, two rendering is performed. One of the rendering is performed on the haptic device display and the other is performed on graphics display.

Graphcis Rendering. When collision between 3D model's voxel-based volumetric data and virtual device occurs, voxels, subject to collisions are removed from the voxel-based volumetric data and local marching cubes algorithm is applied on the region that the collison takes place to reconstruct the isosurface [2].

Haptics Rendering. The sense of touch is a very important element of the art of sculpture. Today's hardware and software technologies, have the ability to give the user the sense of touch to virtual object. The technology that provides this kind of sense is called haptic technology. By using haptic technology, it is possible to feel properties such as hardness, softness, texture, stickiness, heat or pressure by touching objects in a virtual environment.The sense of reality that virtual reality application gives to the user, is achieved by using Phantom Omni Haptic Device which provides force feedback.When collision between 3D model's voxel-based volumetric data and virtual device occurs, haptic device force feedback is returned to users. Figure 3 shows the Collision Detection & Response of haptic rendering.

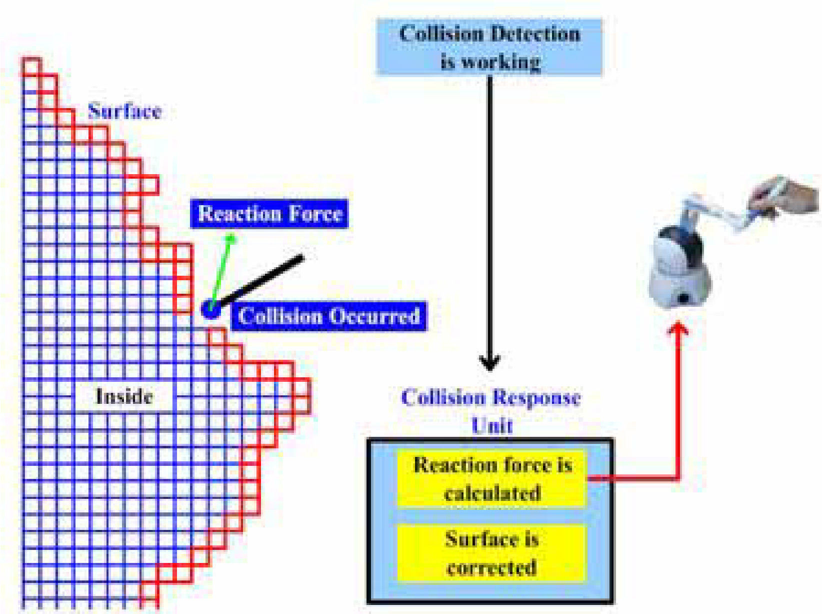


FIGURE 4. Collision Detection & Response of Haptic Rendering

4. RESULTS AND FUTURE WORK

In this paper, a 3D virtual sculpting application is developed for 3D virtual models with removing or adding materials by using Boolean operations. Virtual sculpting simulation reads 3D virtual models in triangle poligon meshes and voxelizes its outer surface and interiror volume to generate its volumetric dataset. We used octree and hashing techniques to reduce the memory requirement needed for volumetric dataset. The surface is locally reconstructed by using Marching Cubes algorithm after removing or adding material to the 3D virtual model. The user interacts with the model by using a haptic device to give the force-feedback like real-life sculpting.

To decrease the compuation time of pre-processing by using GPU and SIMD is our future work and we plan to optimize octree traversal in hashed octree, for example, by using a statistical technique.

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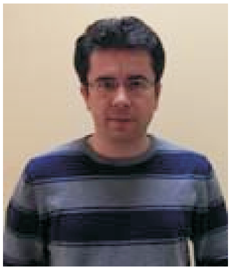

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