Volume Modeling for Rapid Prototyping

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Abstract: The expanding workspace of Rapid Prototyping will draw on the new developments in geometric modeling. Volume modeling has substantial advantages over other modeling schemes to meet the emerging requirements of Rapid Prototyping technology. It provides us with a new approach to design complex geometry and topology. The integration of the volume modeling and Rapid Prototyping technology will help us to fully exploit RP's ability to fabricate objects with complex structures. This paper addresses our research and practice in a volume modeling system toward Rapid Prototyping. Novel techniques in volumetric data manipulation, NURBS volume models and triangular facet generation over solid models are presented. Computer models designed by this system and their corresponding DTM products are also shown at the end of this paper.

1. Introduction

Rapid prototyping (RP), otherwise known as *Solid Freeform Fabrication (SFF)* or *Layer Manufacturing Technology (LMT)*, is among the latest revolutionary technologies in manufacturing which are taking the industry by storm [1]. It represents a range of systems which can fabricate 3D structures from a computer-aided system in a matter of hours. A common feature among these RP systems is that they all apply additive methods in fabrication process, that is, to build a part, prototype, or tool in a gradual, controlled way by laying down material, point by point or layer by layer, until the part is completed. With additive methods the fabrication process is indispensable on the part's complexity. Thus complex objects with arbitrary shapes and microstructures, which, if not impossible, will be very difficult for traditional manufacturing methods, can be fabricated through RP system with the same manner as in fabricating simple geometry objects. The revolutionary development of RP in manufacturing will draw on the new development in geometric modeling.

Applications of computer graphics in the area of CAD/CAM take an important role in the modern manufacturing industry. But existing CAD tools are geared toward the design of parts manufactured by traditional methods, they do not help designers exploit the expanded design space offered by RP technology. In addition, Rapid Prototyping are encountering non-CAD based surface and volume coordinate data increasingly in commercial developing and manufacturing applications [2]. In some areas, such as in medicine, only non-CAD data exists. These data can not be input into current CAD/CAM systems for further modifying and manipulation unless they are converted to geometric representation by fitting or approximating methods.

To overcome these problems, a new modeling scheme – volume modeling is proposed to tackle the emerging requirements of the RP technology. Volume modeling has the ability to

represent arbitrary geometry/topology and supports reverse engineering. The integration of volume modeling and RP will help us to fully exploit RP's ability to fabricate complex structured objects.

2. Volume Modeling

Traditionally, computer graphics studies methods of modeling and rendering geometric objects. Volume graphics [3], as a sub-discipline of computer graphics, focuses on special methods of modeling and rendering complex objects/phenomena with inhomogeneous materials and arbitrary structures in a discrete 3-dimensional space. In volume modeling, objects are stored in a discrete volumetric data set, which is defined by a grid of voxels, figure 1. A voxel is a spatial element which is defined by a unit cube centered at (x, y, z). Each voxel is associated with its properties such as density, color, opacity, physical size and other user-defined parameters.
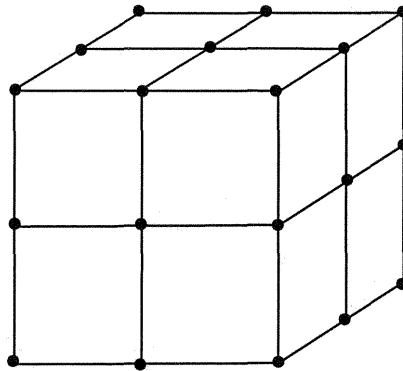
Figure 1: A 3 × 3 × 3 volumetric data set, each solid circle represents a voxel

A volume model is a discrete representation of 3D objects. It has a close correspondence with RP process (layer by layer). The access to a given point in a volume data set is easy. In a linear list, the address of an individual voxel with coordinate (x, y, z) is:

$$Addr = z \times x_{max} \times y_{max} + y \times x_{max} + x$$

where $x_{max} \times y_{max} \times z_{max}$ is the resolution of the 3D data set. This formula can be easily extended to address a layer of voxels. On the other hand, RP process is a "discretized" fabrication process. RP technology decreases the 3-dimensional fabrication process into a 2-dimensional one. In a specific layer, small fabrication primitives, such as drops or layers, are applied over former layer. A volume model is ready to provide corresponding point or layer information with each case.

Compared with the other modeling schemes, volume modeling has the following distinct properties:

- *model complex geometry / topology object*

As there is no constraints put on the voxel description, complex structures can be achieved just by defining voxels either within or outside the modeled object. In addition, Boolean operations can be easily applied on the volume models. CAD tools built using volume models allow arbitrary shape manipulation and sculpting.

- *design inhomogeneous object*
  By defining the property of each voxel within it, a volume model can represent inhomogeneous objects (composites), flexible objects and objects that are made of solid, liquid and amorphous materials. Conventional design tools are not oriented to the design of composite objects.

- *easy 3D data acquisition*
  3D medical image data obtained from CT/MRI scanners are natural volume models. It is easy to obtain the volume models from these 3D image data set. This is of great value in reverse engineering.

3. Modeling Technology

Due to its discrete property, the control and manipulation over the volume models are not easy. To overcome the drawback of the lack of structural information within a volume model, NURBS-based volume modeling is proposed [4]. NURBS has become the *de facto* standard for the representation, design and data exchange of geometric information processed by computers [5]. An NURBS-based volume modeler will have advantages from both NURBS modeling and volume modeling.

NURBS volume is proposed to represent 3D solid objects. Its Cartesian coordinate form is as follows:

$$v(u,v,t) = \frac{\sum_{i=0}^{m} \sum_{j=0}^{n} \sum_{k=0}^{l} N_{i,p}(u)N_{j,q}(v)N_{k,r}(t)w_{i,j,k}\hat{P}_{i,j,k}}{\sum_{i=0}^{m} \sum_{j=0}^{n} \sum_{k=0}^{l} N_{i,p}(u)N_{j,q}(v)N_{k,r}(t)w_{i,j,k}}$$

where $\hat{P}_{i,j,k} = (x_{i,j,k}, y_{i,j,k}, z_{i,j,k})$ are the Cartesian coordinates of the volume control points. $w_{i,j,k}$ is the weight on the control point $\hat{P}_{i,j,k}$. p,q,r are the order of the volume in the parametric u-direction, v-direction and t-direction respectively. $U = \{u_0, u_1, \ldots, u_f\}$, $V = \{v_0, v_1, \ldots, v_g\}$ and $T = \{t_0, t_1, \ldots, t_h\}$ are knot vectors in the respective directions, $f = m + p$, $g = n + q$, $h = l + r$. $N_{i,p}(u)$, $N_{j,q}(v)$, $N_{k,r}(t)$ are *pth-order, qth-order, rth-order* B-spline basis functions defined on the knot vectors U, V, T respectively.

A NURBS volume is a continuous model while a volume model is a discrete representation. A NURBS volume can be turned into its corresponding volume model through the process of voxelization [6]. As Boolean operations are difficult to be applied on high order NURBS volumes, the key idea of NURBS based volume modeling is to exploit the flexibility of NURBS modeling and use the voxelized objects as components to construct complex objects.

4. Interfacing Volume Modeling with Rapid Prototyping

The general method to interface 3D discrete data set with Rapid Prototyping is to use contour information as input [7]. It requires the extraction of the contour information from a 3D discrete data set. This step is straightforward. But the major drawback in this approach is the need for interpolation when processing contour data sets [2].

As STL is the *de facto* standard input format for RP, it is logical to generate STL files directly from a volume model. Generation of STL files through volume modeling and iso-surface extraction is proposed. A modified Marching Cubes algorithm is used to generate triangle facets and get the gradient information of each vertex from a volume model. Marching Cubes algorithm is a classic iso-surface extraction algorithm [8]. It is performed on a volumetric data set and generates triangle facets within each unit cube using a divide-and-conquer approach. It retains inter-slice connectivity from the original 3D data. After verifying the consistence of facet normals, then write them into a STL format file. Figure 2 shows an ear STL model.
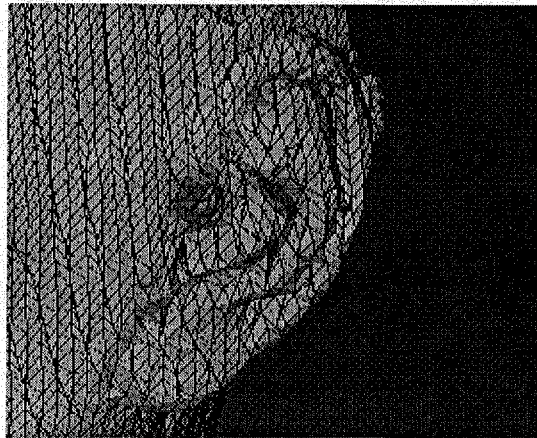

Figure 2: An ear STL model

Volume modelers have advantages over surface and solid modelers in the goal of achieving validity of STL file generation. The seamless representation of a volume model avoids the problems caused by internal walls and structures. The process of Marching Cubes algorithm to produce triangle facet guarantees the final model's shell-closure property. The coherence mechanism makes the final STL free of leaks and overlapping facet. Correct facet-orientation can be obtained by normal verification.

5. Software System Development

An experimental system has been developed for volume modeling and STL generation. Figure 3 gives an overview of the architecture of this geometric modeling system. The system consists three layers: input layer, internal layer and output layer, each layer includes both data and operations.

Research has been started with the fundamental issues such as 3D data acquisition, volumetric data segmentation, voxelization of parametric surface and volume, volume rendering, surface boundary reconstruction, and interface with CAD/CAM systems.
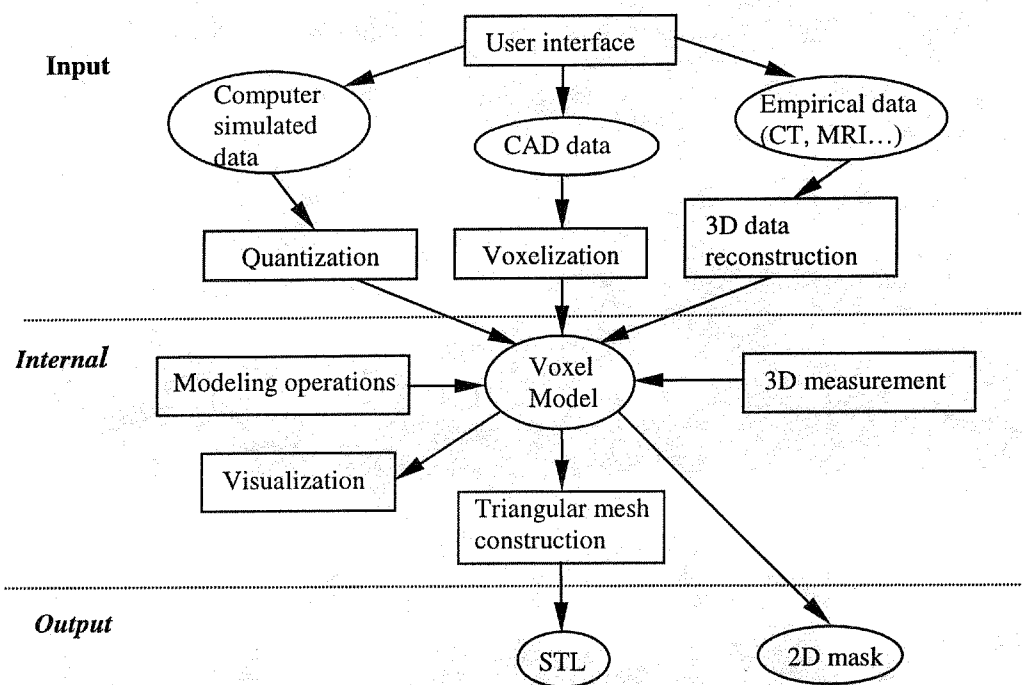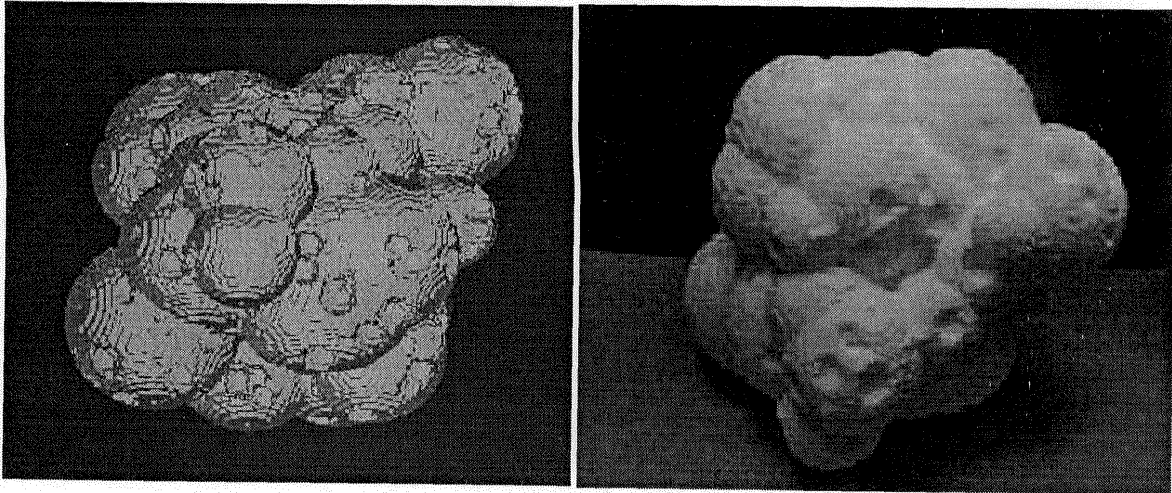
Figure 3: System Architecture

6. Experimental Result

STL models generated from the experimental system were fabricated by DTM Corporation's Sinterstation 2000 system. The SLS (Selective Laser Sintering) process creates three-dimensional objects, layer by layer, from CAD data files in the industry-standard STL file format using powdered materials with heat generated by CO_2 laser within the Sinterstation 2000 System. The interaction of the laser beam with the powder raises the temperature to the glass transition temperature which is below the point of melting, resulting in particle bonding, fusing the particles to themselves and the previous layer to form a solid [9].

Figure 4, 5 show the STL models and their corresponding DTM's products respectively. STL files are displayed by Materialise's Magics View.

Part Por (Figure 4) is a porosity model created by a computer simulation process. The arbitrary shape and inner microstructure of part Por illustrate the ability of volume modeling in complex topology and geometry design.
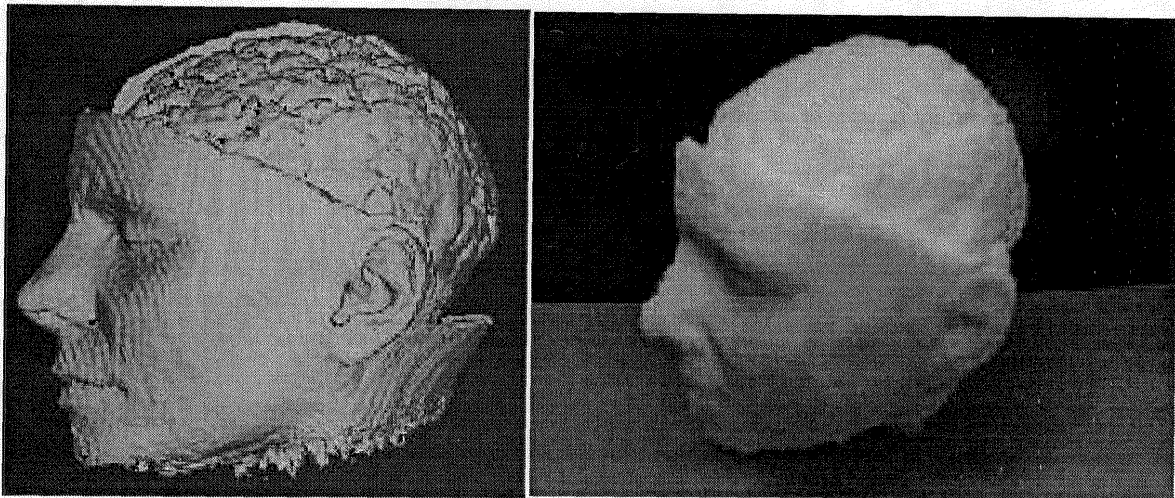
The original image data of part Halfbrain (figure 5) is obtained from a $128 \times 128 \times 84$ resolution version of UNC chapel Hill brain data, an MRI scan of human head. We only use half part of the brain model.

(a) STL model   (b) DTM product

Figure 4: Part Por

(a) STL model   (b) DTM product

Figure 5: Part Halfbrain

7. Conclusion

This paper addressed the research and practice in a volume modeling system toward RP. By its close resemblance with the process of RP and its ability to represent natural objects/scenes, volume modeling is proposed as the modeling scheme to tackle the challenges posed by RP technology. As the lack of structural information in a volume model causes the manipulation and control over a volume model difficult, NURBS-based volume modeling is proposed to handle this problem. NURBS-based volume modeling possesses advantages from both NURBS modeling and volume modeling. The issue of interfacing between volume modeling and RP is also addressed. A novel approach is proposed for generating STL file format through volume modeling and iso-surface extraction. This approach guarantees the validity of the final STL files.

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