Controlling-Vertex-Based Approach to Modeling Heterogeneous Objects

Zhenpeng JI, Anping XU, Jingxiong ZHAO, Yi YANG, Yunxia QU
School of Mechanical Engineering,
Hebei University of Technology,
Tianjin 300130, PR CHINA

Abstract: - The paper deals with a novel approach to modeling heterogeneous objects. A controlling-vertex-based algorithm for materials information incorporation is proposed and constructed. In this algorithm, the controlling vertices with material information and geometrical information are selected as the gradient references first, and then the material information at any other points in the model space of the object can be calculated in interpolation manner according to the material information of the controlling vertices. The algorithm has been applied to software implementation. One-, two-, and three-dimensional examples are demonstrated to show the feasibility of the algorithm.

Key-Words: - Computer-aided design, heterogeneous object, modeling, materials distribution algorithm

1 Introduction

Heterogeneous objects are parts or entities which are composed of two or more materials, with the well-regulated distribution in the objects and one or more specific functions. Heterogeneous object model is the extension of homogeneous object but has better properties than it. It has great potential to design and manufacture more realistic artifacts such as artificial bones, artificial teeth, as well as other parts with heterogeneous materials.

Traditional homogeneous material parts are processed and post-processed according to the performance requirements of parts which are the standard of choosing suitable material. The main task is structural design of parts, including establishing the structure of parts shape, size and technical requirements. But with the development of science and technology, more and more performance requirements were not met if using the homogeneous objects in the engineering fields, thus becoming the bottleneck of technological progress. So the more demands, the more functions of the objects in order to meet the functional needs better. And the parts made of heterogeneous material can not only meet the requirement of shape structure, but also can meet the multifunctional the requirements of objects. That is because the material and structure were considered as a whole in the design and manufacture, and the material optimization can give full advantages of the component materials.

Using 3D printing (Z Corp, USA) techniques of rapid prototyping technologies, heterogeneous objects can be fabricated in point-by-point manner. Modeling technology of heterogeneous objects is the crucial step of manufacturing heterogeneous objects, and is very important to heterogeneous objects design, so the in-depth research of modeling techniques and methods has very important practical significance.

2 A Review of the Related Work

Generally, Commercial CAD modeler can only model the homogeneous object (neutral model). So far, there have been many mature modeling methods to model the neutral CAD model, such as Constructive Solid Geometry (CSG), Boundary Representation (B-Rep), etc. Using CSG or B-rep, any complex geometric model of homogeneous objects can be represented. Current researches on heterogeneous objects have led to many representation schemes for heterogeneous objects modeling, but the modeling methods of
heterogeneous objects are not mature. The comparison of several popular modeling methods of heterogeneous objects will be introduced as follows.

Jackson T.R. et al. proposed a modeling method named Local Composition Control (LCC), which is based on subdividing the object model into sub-regions and associating the analytical composition blending function with each region [1, 2].

Zhongke W. et al. proposed a voxel-based model [3]. A gradient function of the object was decomposed into several the cube-modules with uniform size, which can be regarded as homogeneous material block. The geometric and material information of each voxel unit can be separately expressed by the coordinates and material composition value of its geometric center. But the biggest shortcoming of this modeling method is that it requires a large amount of memories.

Dutta and Kumar proposed \( r_m \)-object based method to be used for representing heterogeneous objects [4]. Siu and Tan introduced a concept called “source-based” method and relevant function operations to present the defined modeling space [5, 6]. On the basis of the traditional B-Rep, the whole of geometric CAD model was decomposed for merger of the finite number of sub-regions, and the components of various materials were expressed by the volume fraction of material.

Zhou et al. [7, 8] proposed an approach to modeling and processing functionally graded material objects based on STEP. The material distribution information was added to the surface, shell of the geometric objects by the designated distribution function of material in order to implement the amalgamation of the geometric and material information. The material value of the points within the content of the slice could be calculated by the distance mapping function of the point and the reference feature, and the distribution of material information of the whole slice could be achieved to implement the delamination process of the functionally graded material objects.

Kou and Tan [9-11] proposed a hierarchical representation for heterogeneous objects modeling. To model a heterogeneous object, the boundary representation was used for geometry information representation, and a Heterogeneous Feature Tree (HFT) structure was proposed to represent the material distributions information.

To sum up, there are many methods to model heterogeneous objects in the community, but all of the methods dealt with heterogeneous objects either with complex geometries but simple material distributions or with compound materials distribution but simple geometries. They do not completely meet the requirements of heterogeneous objects with both complex geometries and materials distribution. So far in the market, there are no commercial software systems that can model heterogeneous objects.

Liu [12] designed a prototype software system which was written in C++ and integrated with SolidWorks system via its API modules, thus implementing a unified solid modeler for heterogeneous objects. But this software package was strictly dependent on SolidWorks environment. Kou et al. [10] developed a prototype software system named CAD4D, which employed the commercial ACIS modeler (Spatial Corp., USA) as the geometric modeling kernel, and used OpenGL as the rendering engine. But the problem with the CAD4D is lack of interactivity and flexibility for user’s operations.

In this paper, a controlling-vertex-based approach to modeling the heterogeneous objects is proposed and constructed. Examples are demonstrated for showing the feasibility of the algorithm.

3 Controlling-Vertex-Based Algorithm for Heterogeneous Objects Modeling

Combining the advantages of ‘source-based’ representation and hierarchical representation, a controlling-vertex-based algorithm for modeling heterogeneous objects is proposed and constructed, and the algorithm is applied to realize the heterogeneous object modeling procedures.
The algorithm to represent material composition can be described as follows: first, the controlling vertices with material information and geometrical information are selected as the gradient sources, and then the material information at any other points within the object can be calculated in interpolation manner by the material information of the controlling vertices. The storage of materials can be implemented by using the Heterogeneous Feature Tree (HFT) proposed in the hierarchical representation, which could meet the requirement of interactive input for material composition values of vertices, while avoiding taking up too much data storage. The algorithm of the material distribution for one-dimensional line segment, two-dimensional triangular facet and three-dimensional prism will be introduced in the following sections.

3.1 Representation of Heterogeneous Line Segment

The material distribution on the entire line segment is restrained by the material composition values at the two endpoints. The material composition value can be calculated linearly by

$$C(P) = (1 - t)C(S) + tC(E)$$

$$t = \frac{|PP_s|}{|P_SP_E|} \quad (1)$$

where $C(P)$ is material composition value at any point on the line segment. $C(S)$ and $C(E)$ are the material composition value at the start point and the end point, respectively. $|PP_s|$ is the distance from point $P$ to start point, $|P_SP_E|$ is the distance from the start point to the end point. Figure 1 shows a heterogeneous line segment with linearly changed material composition from start point to end point.

Lines can be regarded as special curves, so the representation of the material distribution for curve can easily be derived according to the representation of line segment. Figure 2 shows a heterogeneous B-spline with four controlling vertices.

3.2 Representation of Heterogeneous Triangle Facet

Triangular facet is one of the simplest planes, the representation of material distribution for the triangular facet is very necessary.

The material composition value at any point in the two-dimensional region is determined by the various controlling vertices and their corresponding weight. The material value at any point in the plane will be calculated using Equation (2).

$$C(P) = \sum_{i=0}^{n-1} W_i C(P_i) \quad (n \geq 1) \quad (2)$$

where $C(P)$ is the material value of any point in the plane, $C(P_i)$ is the material value of $i$th controlling vertex, $W_i$ is corresponding weight of
the $i$th controlling vertex, $n$ is the number of controlling vertices.

Considering the case of linear distribution of materials, if the material composition values of three vertices are given, the material composition value at any other point in the triangular facet can be expressed as

$$C(P) = \sum_{i=0}^{2} W_i C(P_i)$$

$$W_i = \frac{\prod_{j=0}^{2} d_j}{\sum_{k=0}^{2} \left( \prod_{j=0}^{2} d_j \right)}$$

(3)

If a reverse distance weighting function is applied to calculate the weight, the Equation (3) can be changed as

$$C(P) = \sum_{i=0}^{2} W_i C(P_i')$$

$$W_i = \frac{\prod_{j=0}^{2} d_j}{\sum_{k=0}^{2} \left( \prod_{j=0}^{2} d_j \right)} \quad d_i = |PP_i'|$$

(4)

where $C(P)$ is the material value of the point $P$, $C(P_i')$ is the material value at the orthogonal projection point of $P$ on the $i$th edge, which can be calculated using Equation (1), $d_i$ is the distance of $P$ to its orthogonal projection point on the $i$th edge.

The calculation method of $C(P_i')$ and $d_i$ are shown in Figure 3.

Fig.3 Schematic of calculation method of $C(P_i')$ and $d_i$

Using Equation (4), the material value at any point in the triangular facet can be calculated through the given material composition values of the three vertices. This method can be used to achieve uniform changes of material in the whole plane, and any adjacent material value does not change drastically. Figure 3 illustrates a heterogeneous triangular facet with three controlling vertices. Figure 4 illustrates a heterogeneous sphere surface with three controlling vertices.

Fig.3 A heterogeneous triangular facet

Fig.4 A heterogeneous sphere surface

Triangular facet is a special case of planes, so the representation of the material distribution for other types of planes such as round surface, ellipse surface, torus surface, and so on, can easily be derived according to the representation of triangular facet.

3.3 Representation of Heterogeneous Prism

The representation of the three-dimensional heterogeneous characteristics is based on the representation of the one-dimensional and
two-dimensional heterogeneous characteristics. The material distribution of the entire object can be calculated by using the given controlling vertices and the methods similar to that for the one-dimensional or two-dimensional objects. Figure 5 shows a heterogeneous prism to explain the representation of the three-dimensional heterogeneous objects.

For a prism, the controlling vertices are selected first. Here the eight vertices of A, B, C, D, E, F, G and H are chosen as the material controlling vertices, and the material composition values will be assigned to the corresponding vertices. Next, the material distribution of the surface ABCD, CGHD, GFEH, ABFE, BCGF, and ADHE can be calculated according to the representation of triangular facets in front, and thus the material distribution of the whole surface changes smoothly.

The material distribution within the heterogeneous objects can be derived by the distribution of the point within the plane. As shown in Figure 5, for example, if you want to calculate the material at any point P, in the object, you can choose a plane that the point is in, such as plane KLMN. The material controlling vertices of the plane KLMN is the vertices K, L, M and N, and the material composition values can be calculated using Equation (1), Because the vertex K is on the line AE, L is on the line BF, M is on the line CG, and N is on the line DH, the material distribution of the whole object can be calculated, whether the point is within the object or on the surface. The material distribution changes smoothly. Figure 6 shows a heterogeneous cube with eight controlling vertices. Figure 7 shows a heterogeneous cube with a chamfer at a vertex in order to check the inner material distribution.

4 Conclusions

On the basis of source-based representation and hierarchical representation, a controlling-vertex-based algorithm for modeling heterogeneous objects is developed. It has been applied to software implementation. One-, two-, and three-dimensional modeling examples were demonstrated to show the validity and feasibility of the algorithm. The work in this paper is significant to the development of modeling theory of heterogeneous objects and helpful to promoting the commercialization of software system for heterogeneous objects modeling.
and boosting the digital fabrication level of heterogeneous objects. It is believed that the software system would find good applications in fabrication engineering.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Natural Science Foundation of Hebei Province under Grant Nos: E2004000052 and E2006000039, Natural Science Foundation of Tianjin Municipality under Grant No: 023605411 as well as the Educational Bureau of Hebei Province under Grant No. 2006331. Special thanks are also given to the “211” Project of Hebei University of Technology for the financial support.

References:


