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AN INTERACTIVE CAD ENVIRONMENT FOR HETEROGENEOUS OBJECT DESIGN

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ABSTRACT

Traditional computer aided design (CAD) systems assume that the solids under design are homogeneous in material compositions. Recent studies have shown that solids made of heterogeneous materials (multiple materials, functionally graded materials etc.) prevail in some aspects in terms of mechanical, thermal or electrical performances. Most of the traditional CAD systems fail to represent, maintain and visualize such heterogeneous components, and there have been no commercial heterogeneous CAD modelers in the market. This paper proposes a new interactive CAD environment for heterogeneous object design, in which the geometry, topology and material information of a CAD model can be simultaneously manipulated. The functionalities of a heterogeneous CAD modeler are identified first, and a framework for heterogeneous object design is proposed. The issues of data representation, data maintenance (edition and update) and 3D visualizations are discussed. An interactive software package based on this framework—*CAD4D* is presented and detail examples are illustrated.

KEYWORDS: Heterogeneous object modeling, Visualization, Functionally graded material, Interactive CAD

1. INTRODUCTION

Contemporary CAD packages focus mainly on the geometry and topology information and assume the objects under design are homogeneous in material compositions. With the latest developments in material science, computer aided design (CAD) and computer aided manufacturing (CAM), this assumption has been frequently challenged in high-performance component design. It has been seen that some objects with multiple material compositions, functionally graded material (FGM) distributions or other heterogeneous structures may have better mechanical, thermal or electrical performances compared with traditional homogeneous objects [1-3]. In other areas, the critical functional requirements can be hardly fulfilled with a homogeneous object, because the function requirements are usually multi-folded.

The wide application of heterogeneous objects calls for a systematic approach in heterogeneous object modeling, analysis and fabrication. As the fundamental process, CAD modeling systems need enhancements to fit into these new requirements. In the past decade, numerous schemes on representations and modeling methodologies for heterogeneous component design have been proposed; however, no commercial interactive heterogeneous CAD system has emerged yet. Most of the researchers try to accomplish this within the frameworks of existing homogeneous CAD software packages [4-6], however, due to the unique characteristics of the heterogeneous CAD modeling, the modeling operations and flexibilities are constrained. This paper presents a new CAD environment which fits naturally for interactive heterogeneous object design. The subsequent sections are logically structured as follows: Section 2 analyzes the functionalities of a typical interactive heterogeneous CAD system and a new framework for heterogeneous object design is outlined; the issues of data representation, data modifications and visualization schemes are discussed. In Section 3, a prototype software package based on the proposed framework—*CAD4D* is presented. Examples designed with *CAD4D* are provided in Section 4. Finally Section 5 concludes this paper.

2. AN INTERACTIVE CAD ENVIRONMENT FOR HETEROGENEOUS OBJECT DESIGN

2.1 FUNCTIONALITIES OF A TYPICAL INTERACTIVE HETEROGENEOUS CAD SYSTEM

Heterogeneous CAD models contain geometry, topology and material information. In a typical heterogeneous CAD system, the following fundamental functional modules are required:

•Heterogeneous data representation scheme: A heterogeneous data representation is used to describe the underling geometry, topology and material distribution, and their inherent relationships, with convenient information retrieval and storage capacity. In homogeneous object modeling, there have been mature data representations such as the B-Rep and CSG representations. In heterogeneous object modeling, the material composition/distribution should also be well described, with proper definitions over the 3D domain. In recent years, heterogeneous representations and modeling methods have been extensively studied and detail schemes can be found in [5-14]. A hierarchical representation is used in this paper, which will be detailed in Section 2.2.

•Visualization for heterogeneous features: The visualization module retrieves information from the CAD models, and generates rendering data for heterogeneous components. Real time interactivity and rendering accuracy (geometry precision and material distribution) are two factors to be balanced [14].

•Interactive model modifications and update: Model modifications are important to interactive heterogeneous object design. Modifications in geometry, topology and material distributions should be properly represented in corresponding data structures, and updated visualization results should be generated at interactive rate.

Traditional CAD software packages contain geometry and topology representations but lack the modeling ability for material definition. Although this can be extended within the existing CAD packages, it is quite difficult to visualize heterogeneous material distributions (such as material gradient) in these packages because their visualization modules are inherently based on the assumptions of homogeneous materials or multiple materials (for assemblies). In this paper, we propose a new interactive heterogeneous design environment which integrates a new representation and visualization scheme together, as illustrated in Fig.1. Issues of data representations, visualizations and dynamic modifications are detailed in the following sections.

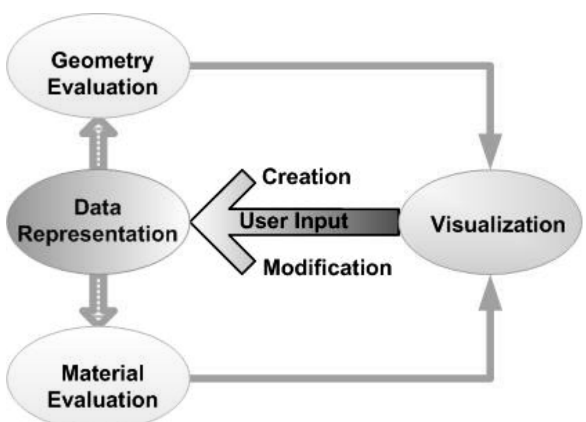

Fig.1 Framework of an interactive heterogeneous object design system

2.2 DATA REPRESENTATIONS

Siu and Tan [6] proposed a source based scheme to model the functionally graded material (FGM) distributions for heterogeneous objects. The geometry features from which the material composition varies are saved in a list structure. For example, to represent a heterogeneous cylinder with a linear material gradation from the top to the bottom face, both the top and bottom faces are saved in a list structure, and these material variation references are termed as 'source' features. By evaluating the distances from these sources, the material composition at a specific location can be determined at runtime.

Let $M(P)$ be point P's material composition, here P is a representative point inside the cylinder. Let M_t and M_b be the top and bottom surface's material composition, say M_t is Aluminum and M_b is Ceramic, then M_t and M_b can be represented as follows:

$$\begin{aligned} M_t &= [1,0] \\ M_b &= [0,1] \end{aligned} \tag{1}$$

The scalar values in the vectors indicate the material compositions of Aluminum and Ceramic, the vector [1, 0] indicates the material composition is 100% Aluminum and no Ceramic.

For an arbitrary point in this cylinder, its material composition can be then formulated as:

$$\begin{aligned} M(P) &= \frac{d_b}{d_t + d_b} M_t + \frac{d_t}{d_t + d_b} M_b \\ d_t &= |PF_t| \\ d_b &= |PF_b| \end{aligned} \tag{2}$$

where F_t and F_b are the top and bottom face of the cylinder, d_t and d_b are the Euclidean distance from point P to F_t and F_b respectively.

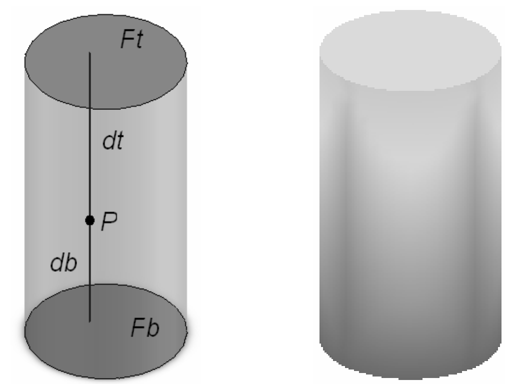

Fig.2 Source-based representation

One of the limitations of source based method is that the reference source features are generally assumed to be homogeneous, as shown in Fig. 2 and so the material distributions that can be modeled are usually 1D dependent only.

To further extend the source based scheme and model 2D and 3D dependent material heterogeneities, a hierarchical representation [7, 14] has been proposed. In this representation, the reference source features can be also heterogeneous. For each reference source feature, if it is heterogeneous, then it can be also represented by its own sources (material variation reference features).

The material distribution of a heterogeneous object can be generally represented by a Heterogeneous Feature Tree (HFT) structure, which describes the material variation dependency relationships, as illustrated in Fig.3. A Heterogeneous Feature Tree structure is composed of a collection of nodes, within each node, a geometry pointer (based on Boundary Representation)

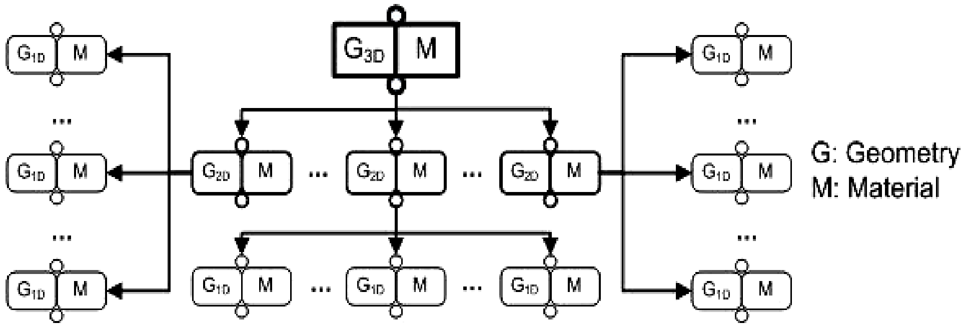

Fig.3 A hierarchical representation for heterogeneous CAD models

and a material descriptor are stored. The material descriptor may further points to a series of (or zero) child nodes/node, indicating that the material distribution inside the object geometry (which is accessible through the geometry pointer) is determined by (or dependent on) its child node features, and these child features can be regarded as the source features of the current node.

Suppose the material distribution for a heterogeneous feature O (G_0, T_0) is represented by a HFT T_0, (here G denotes geometry and T denotes the HFT, and the subscript indicates the level of hierarchies), which has p child trees, $T_{1,0}$, $T_{1,1}$ … $T_{1,p\text{-}1}$. Then for an arbitrary point P inside G_0, its material composition M (P, T_0) can be evaluated from the following equation:

$$M(P,T_0) = \sum_{i=0}^{p} W_i M(P,T_{1,i}) \qquad (3)$$

where W_i is material gradation weights for child feature O_i ($G_{1,i}$,$T_{1,i}$) and can be determined by any user defined linear or non-linear functions (material gradation functions), and M(P, $T_{1,i}$) is the material composition evaluated from the child tree $T_{1,i}$, at a lower hierarchy:

$$M(P,T_{1,i}) = \sum_{j=0}^{q} W_j M(P,T_{2,j}) \qquad (4)$$

where q is the total child node counts of $T_{1,i}$.

In this hierarchical representation, the parent-child relationship in the HFT structure is used to describe the material variation dependency relationships: the material composition of a feature in a higher level is dependent on the material compositions of its child features, and can be recursively evaluated from the HFT structure. For a leaf node feature, its material composition does not depend on any other features, and a NULL pointer is assigned to this terminal node and its material composition, by definition, is homogeneous.

Comparisons of source-based representation and a HFT-based representation are illustrated in Fig.4 and Fig.5. In Fig.4 (a), there is a 1D material gradation in the heterogeneous cylinder and it can be represented by source based method with a list structure. This representation can be considered as a special HFT structure (with only one level of hierarchy), as illustrated in Fig.4 (c).

In Fig.5, a cylinder with 2D material gradation is modeled. The cylinder has an overall radial material gradation from the inner cylindrical surface to the outer cylindrical surface. The inner surface is homogeneous and the outer surface has a linear gradation from the top to bottom. The cylinder in Fig.5 can be hierarchically constructed and represented as follows:

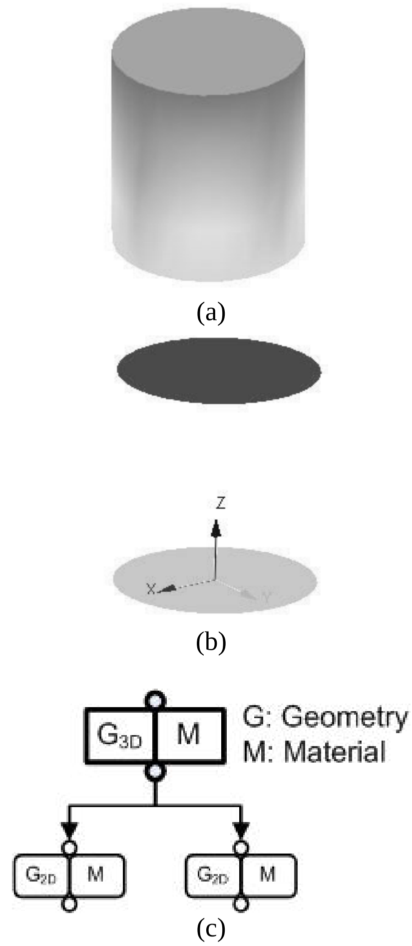

Fig.4 A heterogeneous cylinder example (I)

(1) A heterogeneous 2D face is created (Fig.5 (a)), the inner circle and the outer circle are saved as the sources (children) for this 2D face feature, as shown in Fig.5 (b);

(2) Two lines are defined to regulate the material variations of the two circles in the process of extrusion. The linear graded line is saved as the sole source feature of the outer circle, indicating the outer circle’s material will change from ‘green’ to ‘cyan’; the homogeneous line is saved as the source feature of the inner circle, indicating the material composition

of the inner circle remains homogeneous (uniformly red) during extrusion, as shown in Fig.5 (c) and (d);

(3) The 2D face is extruded along the height direction, with the two lines defined in (2) as the extrusion vectors, and the 2D face is then saved as the only source feature for the extruded cylinder, indicating the material composition for the cylinder can be traced/evaluated from the 2D face. Combining the HFTs constructed in Fig. (5) (b) and (d), the final cylinder can be represented with a HFT in Fig.5 (f), its 3D visualizations from two different perspectives are shown in Fig. 5 (e).

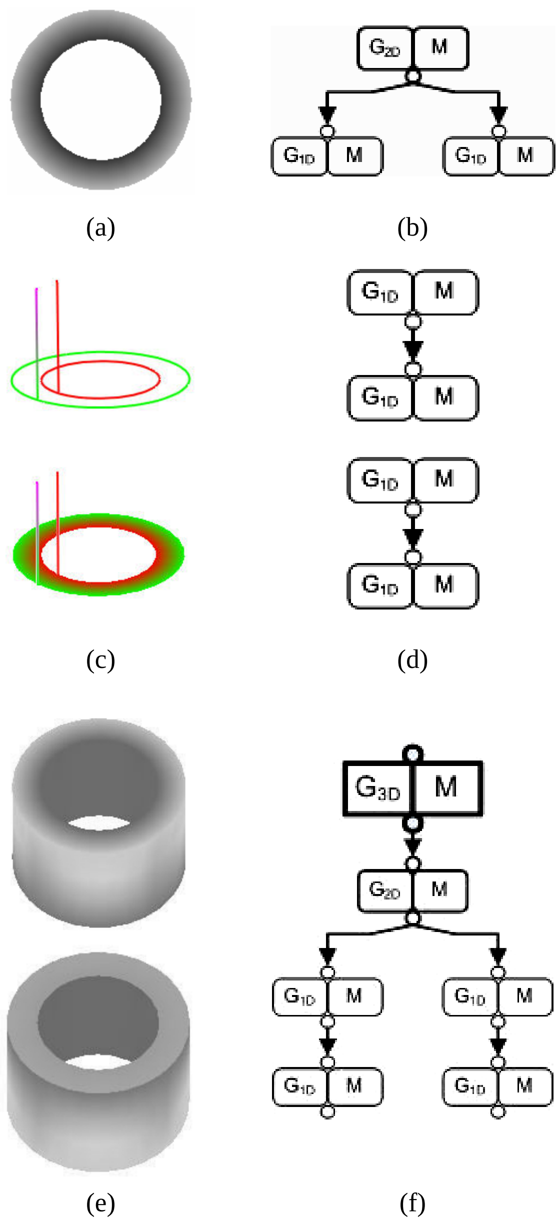

Fig.5 A heterogeneous cylinder example (II)

Note that we only described the HFT construction process here to illustrate the concept and application of this hierarchical representation. To evaluate the material composition of an arbitrary point in the heterogeneous object from this representation, a recursive material evaluation algorithm is needed, for detail please refer to [7].

With this hierarchical representation, objects with heterogeneous material gradations can be effectively represented, especially for those with compound or multi-dimensional variations. The modeling tasks can be accomplished by properly constructing the geometry (B-rep) and corresponding HFT structures for material distributions.

2.3 VISUALIZATIONS

With the hierarchical representation presented in Section 2.2, the material composition of any point inside the feature's geometries can be dynamically evaluated according to the material variation dependencies depicted in the HFT structure. According to the framework presented in Fig.1, two sets of information are retrieved from the data representations: the geometry information and the corresponding material compositions defined over the geometries. The geometry evaluation process is used to tessellate the boundary surface into rendering facets, and the material evaluation process is used to determine the material compositions defined at the tessellated positions. Finally faceted graphical output is generated.

In visualization of heterogeneous objects, tradeoffs have to be balanced between the rendering quality and the computation/memory consumptions. In an interactive modeling environment the graphical outputs are required to be generated at interactive rate to offer visual feedbacks to the users.

In some applications boundary surface visualization might suffice while in other circumstances, both the boundary surface and the volume visualizations are needed (e.g. the sliced visualizations in virtual rapid prototyping, visualizations for 3D dependent gradations and other compound isotropic distributions).

In surface boundary tessellation, two major factors constrain the implementations: the geometry rendering accuracy and the material distribution rendering accuracy. In homogeneous CAD visualizations, the material inside the model are assumed to be homogeneous, so the boundary surface tessellation only relies on the curvature measurements of the approximated facets. If the boundary geometry can be well approximated within the given tolerance limits, then the geometry evaluation process terminates. However, in rendering heterogeneous features, the material compositions of the points in the same facet may still be different. In this case, even the geometry accuracy requirement has been met, the actual material distribution might not be properly visualized. The faceted model usually needs a further sub-tessellation/facet refinement in visualizing the material distributions, which satisfies the prescribed rendering quality. Fig.6 (a) and (b) illustrate the graphical output for a 3D heterogeneous object without sub-tessellation and Fig. 6 (c) and (d) show the results with sub-tessellated facets in which more accurate material gradation effect can be generated.

It should be noted that the sliced visualization and the volume visualization can be also easily implemented based on the proposed representation, as long as the sliced planar geometries are properly faceted and the solid volume meshes (e.g. tetrahedron subdivisions) can be provided. The material evaluation from the HFT can be applied to both the boundary visualizations and volume visualizations. Fig. 7 (b)-(f) illustrate some sliced results of a heterogeneous object at different sectioning positions along the height direction. These sliced visualizations help to better understand the internal material distributions inside the object.

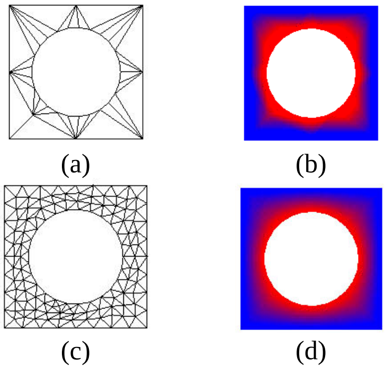

Fig.6 Visualization for a revolved heterogeneous object

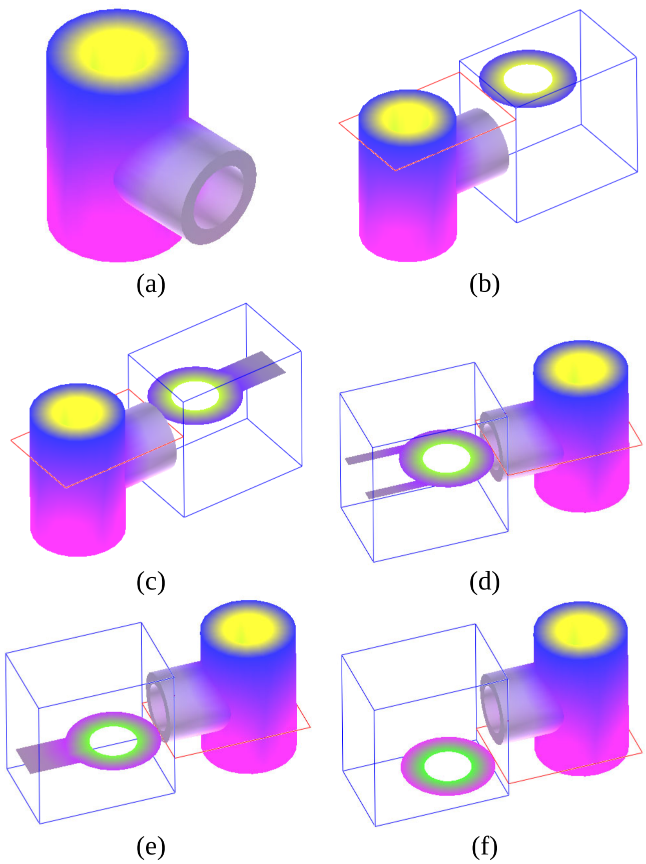

Fig.7 3D and sliced visualization for a heterogeneous object. (a) 3D visualization (b) Slice position at a distance of 0.1*h* from the top surface, where *h* is the height of this object; (c) Slice position: 0.3*h* from top; (d) Slice position: 0.5*h* from top; (e) Slice position: 0.7*h* from top; (f) Slice position: 0.9*h* from top.

2.4 INTERACTIVE MODEL MODIFICATIONS AND UPDATE

Real time model modification is an inherent feature for interactive CAD systems. With the visual feedback generated, the designer can edit both the geometries and material definitions for heterogeneous CAD models. The geometry and material distribution can be edited by manipulating the heterogeneous feature tree through interactive input. As is seen from Fig.4 and Fig.5, the heterogeneous feature tree has straightforward physical meanings, and the user can modify the geometry as well as the material distributions at any hierarchies in the HFT structure. Fig. 8 illustrates a heterogeneous solid extrusion example, where both the geometry and material definition for the extrusion vector are modified, as shown in (a) and (c). The original and updated extrusion solid are shown in (b) and (d).

Intensive computations are needed in the visualization process [14]. In interactive modification, frequent updates require extensive computation time and memory consumptions to reflect the changes. Even the slightest modifications to the data may require the re-execution of geometry and material evaluations. To reduce the computation work in model modification, we introduce a Modification Flag (*MF*) to eliminate unnecessary computations.

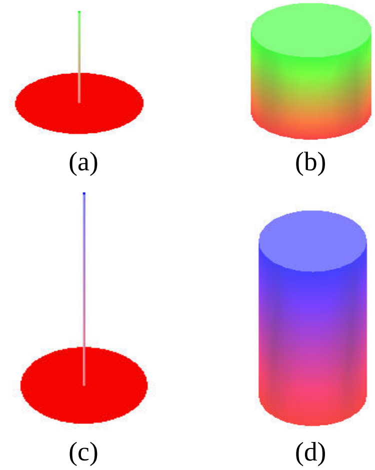

Fig.8 Modification and update for an extrusion object

A Modification Flag is defined for each heterogeneous feature node in a HFT, indicating the types of interactive modifications applied to this node, as shown in Table 1:

***MF* value**	**Definition**
NO_CHANGE=-1	No modification occurs.
M_CHANGE=0	Only modifications of material distribution occur to the current node, the underlying geometry remains the same.
G_CHANGE=1	Modifications of geometry occur to the current node.
ALL_CHANGE=1	Both the geometry and material distribution of the current node are modified.

Tab.1 Modification flags and definitions

The key idea for the avoiding re-computation is that if a child feature's geometry remains the same, any other changes to this node will have no impact on its parental geometries, and only material evaluation needs to be re-executed. Geometry evaluation (Fig.1) can be neglected because of geometry invariance. If the child node's geometry has been changed, its parental geometry must be changed accordingly, and the material definition also needs to be evaluated for the updated geometry, so both the geometry and material evaluation need to be executed.

If all of the child nodes remain unchanged (MF_i = NO_CHANGE), then the parental feature remains unchanged and the MF value for this parental node should also be NO_CHANGE, indicating no update is needed. If any one of the child nodes is changed in its geometry, i.e. MF_i =G_CHANGE, then the parental feature needs to be updated in both the geometry and material compositions, so the MF value for its parental node should be ALL_CHANGE. If one of the child nodes is modified in material distribution, for example, MF_i =M_CHANGE, and if other sibling nodes remain unchanged, then the parental node needs to be updated only in material evaluation, i.e. the MF for its parental node should be M_CHANGE.

To summarize, the following rules can be used to determine the value of MF for a given heterogeneous feature node:

If the node is a leaf node, then the MF value is determined from direct user input type, for example, if the user only modifies the node's geometry, then MF equals G_CHANGE, and if the user only modifies the node's material distributions, then MF equals to M_CHANGE; if both the geometries and material distributions are altered, then MF equals to ALL_CHANGE;

If the node has child nodes, then $MF = max\ (MF_0, MF_1, \ldots, MF_{n\text{-}1})$, Where MF_i is the i-th child node's MF value, and n is the total child node counts, max is the function to get the maximum value from a list of values. Note that this function can be recursively applied to all hierarchies in the HFT structure.

With this improved model update approach, the efficiency of the visualization update after model modification can be improved; and this improvement is significant especially when many heterogeneous bodies are designed in a same workspace.

3. A PROTOTYPE SOFTWARE PACKAGE FOR INTERACTIVE CAD MODELING

Based on the proposed framework, we have developed a prototype software package—*CAD4D* for interactive heterogeneous object design, as shown in Fig.9. ACIS API is used as the geometry kernel, and OpenGL is utilized as the rendering engine.

We have developed collections of 1D, 2D and 3D heterogeneous features, which are encapsulated in a heterogeneous object library—*Lib4D*, with an open architecture for extension and development. *Lib4D* is an object class library containing over 8000 lines of C++ codes, written in Windows platform, and provides convenient interfaces for heterogeneous model creation, modification and visualization.

4. EXAMPLES

In this section we present some heterogeneous objects designed with *CAD4D*. These examples show that the proposed framework is effective in both data representations and visualizations for heterogeneous solid design. The interactive data modifications from the user input guarantee flexible feature editions and real time update can rapidly reflect such changes. Detail examples are shown in Fig.10.

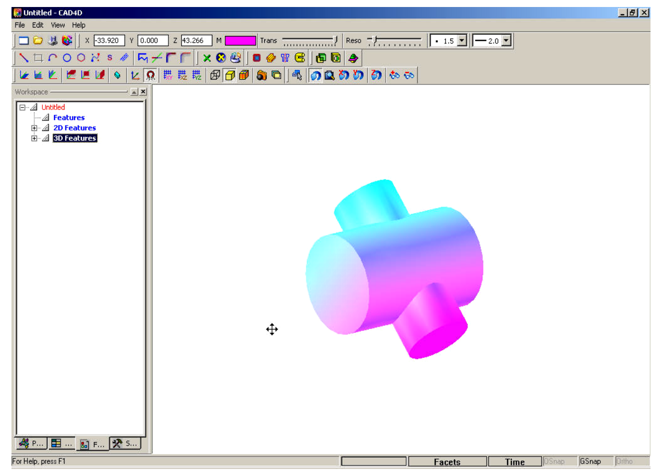

Fig.9 An interactive CAD package for heterogeneous object design

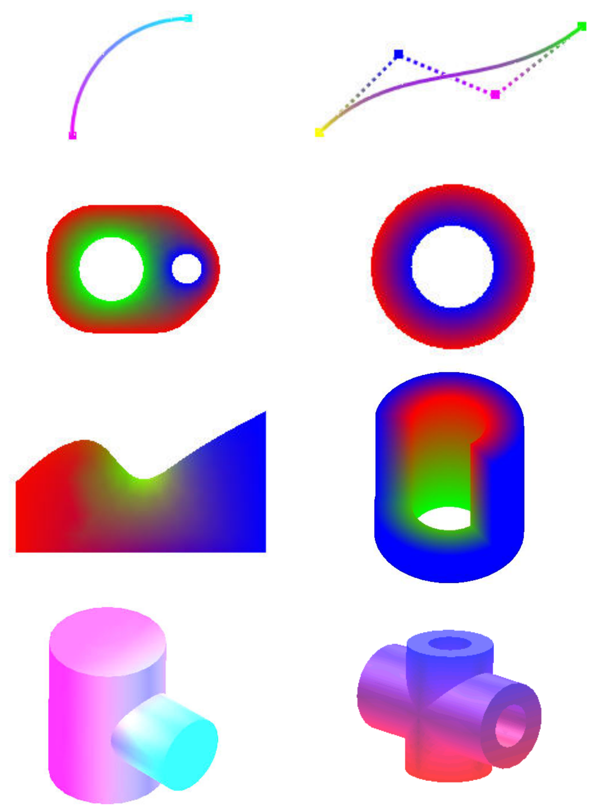

Fig.10 Example 1D, 2D and 3D heterogeneous features designed with CAD4D

5. CONCLUSIONS

In this paper, we present a new environment for interactive heterogeneous object design. Instead of designing these solids within the traditional CAD frameworks, we propose a new framework, in which a hierarchical data representation and a heterogeneous visualization module are utilized. Issues on interactive data modifications and visualization updates are discussed in detail. A prototype software package based on this framework is introduced, and detail examples designed with this software package are demonstrated. These examples show that the proposed framework has key advantages in interactive heterogeneous object modeling compared with existing CAD software packages, including powerful representation in material variations, easier heterogeneous object visualization, more flexible feature modifications and updates.

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