Feature Methodologies For Heterogeneous Object Realization

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1.0 Introduction

Heterogeneous objects are composed of different constituent materials. They are sometime known as functionally gradient materials (FGM). They have the ability to exhibit continuously varying composition and/or microstructure, thus producing a gradation in their properties. Such material gradation can be tailored to achieve multiple functionalities and to satisfy conflicting design requirements. These properties in general cannot be achieved by using one single material.

For example, a prosthesis using the graded interface in the orthopedic implant is shown in Figure 1. Conventional methods of fixing an artificial bone and joining the prosthesis to the bone include total close contact of the prosthesis to the bone. However, this causes pain to the patient during weight bearing because there is micromotion of the prosthesis within the bone, and subsequently the prosthesis may even loosen in the bone. A more effective method for adhering a prosthesis to the bone is to coat it with a porous metal because new bone grows into the pores after the implantation. A graded layer of hydroxyapatite (HAp) is coated on the porous metal. It bonds to the bone physicochemically, thereby increasing the adhesion strength and the rate of binding to the bone. Therefore, porous metal with a HAp coating remedies the drawbacks of cementless prosthesis. It prevents pain to the patient caused by micromotion while walking or loosening of a prosthesis fixed without the bone cement.

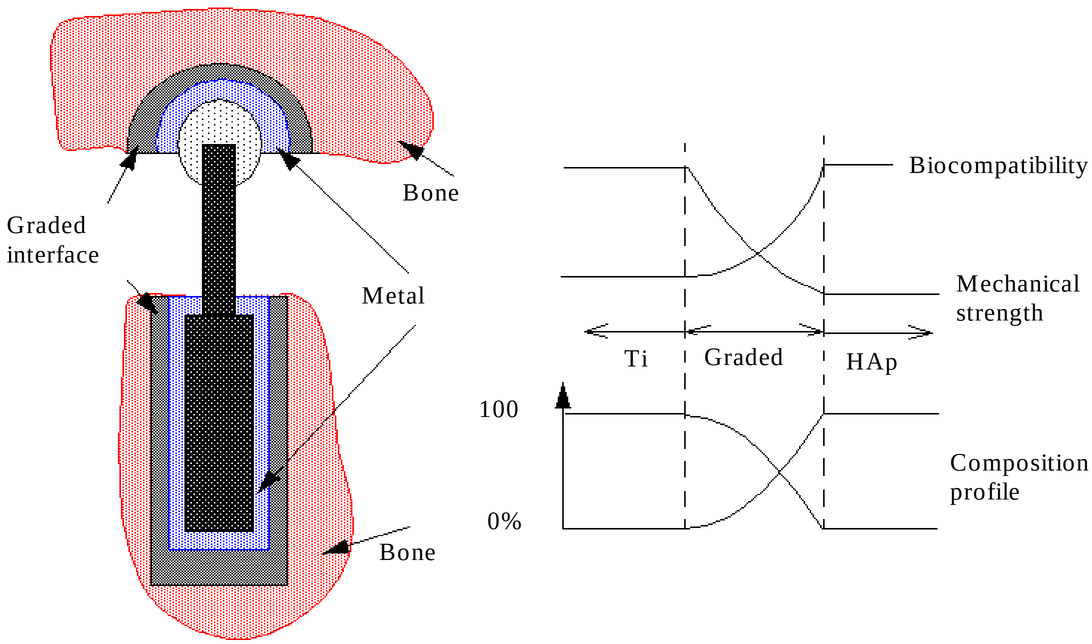


Figure 1 Schematic structure of an FGM interface within a prosthesis

Figure 1 is a schematic structure of such an FGM interface. This FGM region is composed of porous titanium plus hydroxyapatite (HAp). Ti has good mechanical toughness and HAp has good biocompatibility. Simple combination of Ti and HAp would cause bio-incompatibility and weakened strength due to their material property differences. Such material property differences are resolved by using a mixture of Ti and HAp with varying proportions. The sharp interface between the Ti and HAp is eliminated by using a graded zone of Ti/HAp. The bending strength of the resulting material is similar to human bone.

As evidenced in this example, many applications based on the concept of functionally gradient materials can be developed to exploit the multiple desirable material properties. In order to have mass applications of heterogeneous objects, systematic methodologies are needed. Nonetheless, the existing methods for the design and fabrication of heterogeneous objects tend to be experimental and ad hoc.

The state-of-the-art research on heterogeneous object modeling has been primarily focusing on representation schemes for heterogeneous objects. Currently, there is only limited means available to obtain heterogeneous object model. There is not yet any design tools available for designer to design heterogeneous objects. Existing methods are mostly implicit methods, in which designers do not have explicit control over geometry and material composition variation.

In addition to the need for a design methodology, fabrication methodology for heterogeneous objects is also needed for mass applications of heterogeneous objects. The existing fabrication methods are grossly inadequate for the fabrication of heterogeneous objects when objects are of intricate geometry and complex material composition. They are inept for handling the fabrication of heterogeneous objects where material variation are three dimensional through the object space. A recent technique, layered manufacturing, can fabricate objects with 3d material variation. However, there is still a lack of efficient fabrication method for these processes.

Therefore, to enable mass aplications of heterogeneous objects, effective and systematic methodologies are need for heterogeneous object realization. In this research, we propose the use of features to facilitate the design and fabrication processes for heteorgeneous objects.

Features were initially proposed to automate the link between design and NC path generation (1). Since then, feature techniques have been widely and successfully used in CAD/CAM systems. Feature-based design expedites the design process and feature recognition facilitates the fabrication process planning. A feature-based product model also simplifies the assembly, inspection planning, and other downstream applications. (2).

In this chapter, we present feature based design and fabrication methodologies for heterogeneous object realization. Accomplishing these research objectives provides the following set of enabling tools to facilitate the heterogeneous object realization (Figure 2). In heterogeneous object realization, three stages of activities are needed: design, process planning and fabrication. This research provides methodologies for both design and process planning tasks, while the interoperable layered manufacturing data (LMData) (3) address the data exchange issues in layered manufacturing.

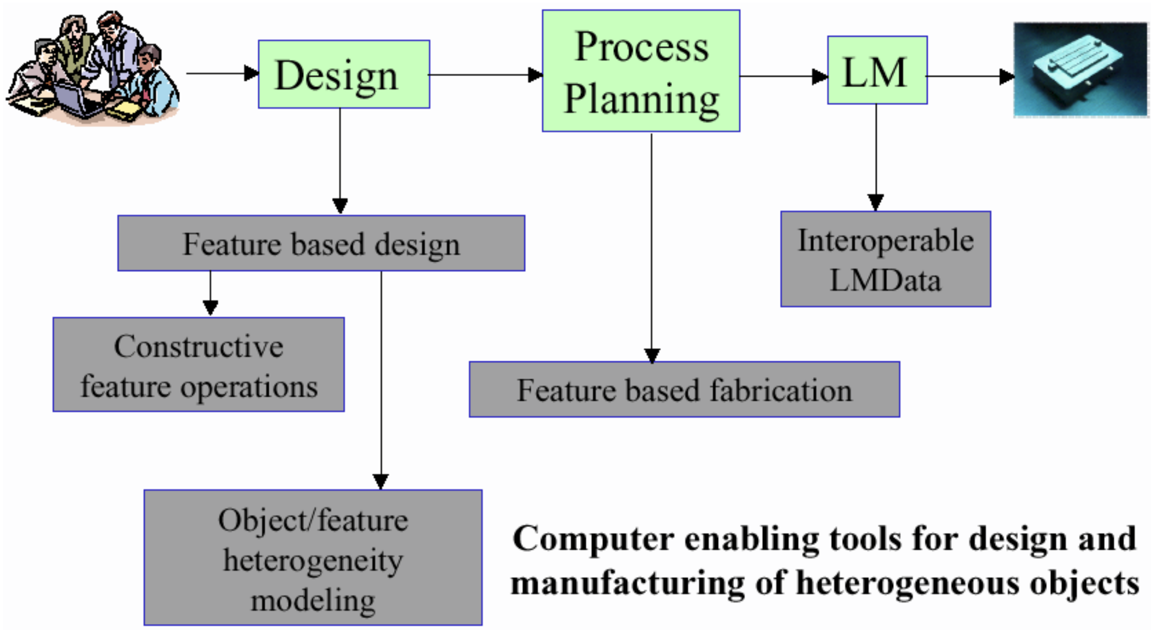


Figure 2 Computer enabling tools for heterogeneous object realization

The remainder of this chapter is organized as follows. In Section 2, we present a review of the existing research relating to the design and fabrication of heterogeneous objects. In Section 3, a general methodology — feature based design for heterogeneous objects — is presented. Section 4 and Section 5, on the other hand, present two enabling component techniques for feature based design, direct face neighborhood alteration for constructive feature operations and physics based modeling for feature/object heterogeneity modeling. Section 6 presents the feature based fabrication methodology for the layered manufacturing of heterogeneous objects. Finally, Section 7 summarizes this paper and identifies future work.

2.0 Literature Review

Many representation schemes have been developed to represent solids. Manifold solids and R-sets were first proposed to represent solid model (4, 5). Radial-edge data structure is another data structure for modeling non-manifold solid (6). For conventional feature modeling, the usage of non-manifold structure was first proposed by Pratt (7). Selected Geometric Complex (SGC) is a non-regularized non-homogeneous point set represented through enumeration as union of mutually disjoint connected open cells (8). Constructive Non-Regularized Geometry (CNRG) was also proposed to support dimensionally non-homogeneous, non-closed point sets with internal structures (9). Middleditch et al present mathematics and formal specification for the mixed dimensional cellular geometric modeling (10). Cellular model provides a geometric basis for heterogeneous object modeling.

Current research on heterogeneous objects has led to many representation schemes for heterogeneous object modeling. Kumar and Dutta proposed R-m sets be used for representing heterogeneous objects (11). Jackson et al proposed another modeling approach based on subdividing the solid model into sub-regions and associating the analytical composition blending function with each region (12,13). Some other modeling and representation schemes, such as utilizing voxel model, implicit functions and texturing, have also been proposed (14-16).

Even though existing representation schemes for heterogeneous objects provide means to represent heterogeneous objects, they do not support the design of heterogeneous objects. The current methods for specifying material composition face a trade-off between the model coverage and operation convenience (17). They only provide a low level description of geometry and material composition within the objects. They do not provide tools for designers to create and edit the heterogeneous object model.

Currently, there are only limited means available to obtain heterogeneous object model. Reverse engineering converts existing objects into computer representation. Such an approach can be utilized to obtain heterogeneous object model. However, these techniques typically represent heterogeneous objects only in the discretized format: 3d voxel (18, 19). Research has also been conducted to convert the 3d images to 3d geometric objects. Nonetheless, the focus has been on recreating the outer geometry. The issues on material composition modeling have not been directly addressed. Capturing material density information inside is a difficult problem, one that has not received sufficient attention thus far.

Homogenization design method is another method to obtain heterogeneous object model based on optimization, in which material composition is varied along with the geometry to achieve the desired functionality (20, 21). These methods consider the effect of material composition variation upon function.

In general, these methods limit the role of the designer in the design process. They can be characterized as implicit design methods where designers do not have explicit control over material composition.

The early methods for the fabrication of heterogeneous objects include powder metallurgy, physical and chemical vapor deposition, plasma spraying, self-propagating high temperature synthesis (SHS) and galvanoforming. Recently, several fabrication methods have been developed that are capable of manufacturing heterogeneous objects in which the material variation are three dimensional. These new fabrication methods can be broadly referred to under the term "layered manufacturing" (LM). They fabricate parts by depositing materials layer-by-layer under computer control. A host of LM technologies are currently available commercially. A non-exhaustive list includes: Stereolithography (SLA) by 3D Systems, Selective Laser Sintering (SLS) by DTM Corp., Fused Deposition Modeling (FDM) by Stratasys Corp., Solid Ground Curing (SGC) by Cubital, and Laminated Object Manufacturing (LOM) by Helisys. In addition, several LM processes are under development at various universities, such as Carnegie Mellon, Stanford, MIT, University of Dayton, University of Michigan, and the University of Texas. Refer to (22) for details of these LM processes.

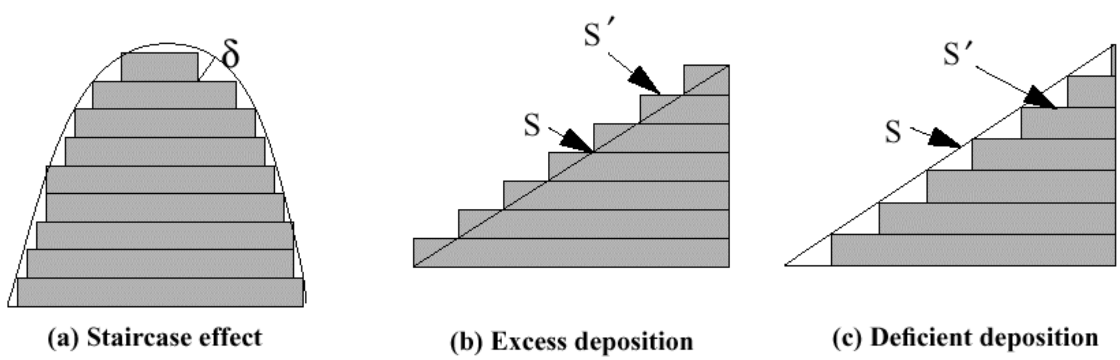


Figure 3 Staircase effect and different deposition situations

Layer-wise fabrication in LM leads to the staircase effect for slant surfaces, as shown in Figure 3.a. (Here δ controls the cusp height, the maximum distance between the nominal part boundary and the boundary of the part produced by LM.) Depending on the intended application of the LM part one would, in general, employ excess deposition or deficient deposition (23). Figure 3.b and Figure 3.c show the two deposition situations, in which S is the part boundary and S' is the boundary of the part produced by LM.

This layer-wise stack in LM has one inherent drawback — staircase effect. To have better surface quality, the thinner layer thickness is desired. On the other hand, the thinner the layers are, the more layers it takes to build the part and the more build time it takes. To overcome the conflicting requirements associated with high surface quality and low building time, adaptive slicing was developed (23-25). The idea was to decrease slice thickness at high curvature (in terms of normal value in slice direction) regions and to increase slice thickness at relatively flat regions. Sabourin proposed a variant whereby adaptive high-precision exterior and high-speed interior can be achieved by layered manufacturing (26).

We term the fabrication inefficiency due to the geometry curvature as *geometry curvature effect*.

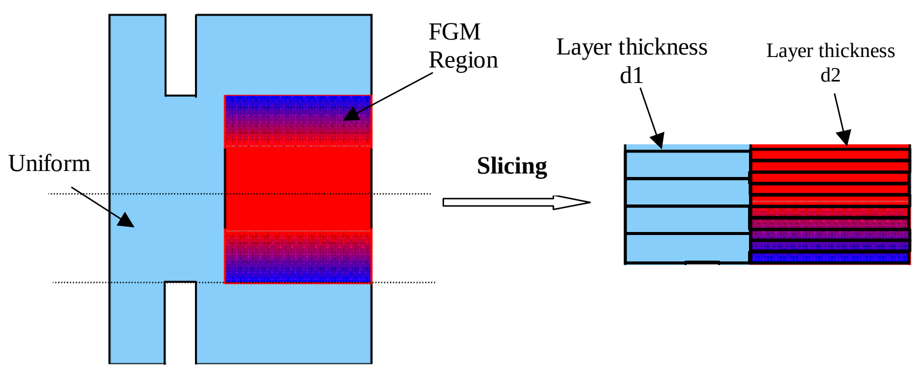


Figure 4 Material variation complicates the layer thickness computation

In the meanwhile, material variation in the objects further complicates the layer thickness computation. Existing methods are inefficient in this since they fabricate heterogeneous objects with the minimum layer thickness of all the building blocks (27). For example, the example part in Figure 4 is composed of two different types of building blocks, one of the uniform material, the second of functionally gradient materials. Even though geometric curvature of the two building blocks are the same and would allow for the same layer thickness, due to material variation in FGM region, it requires thinner layers than the counterpart in the uniform regions, i.e. $d_2 < d_1$. Existing methods would use d_2 as the layer thickness for the entire object, which leads to extra deposition time over the region of uniform material. We term such fabrication inefficiency due to the material gradation in different building blocks as *material gradation effect*.

Both geometric curvature effect and material gradation effect are resolved in this research by localizing the effects within each feature layer.

3.0 Feature Based Design for Heterogeneous Objects

In this section, we examine the relationships between form features and material features in the heterogeneous objects. We synthesize the form features and material features and then propose the constructive feature based design for heterogeneous objects.

3.1 Features

Feature techniques, traditionally, have only been focusing on the geoemtry, i.e. form features. Because of the nature of material variation in heterogeneous objects, we shall examine features not only in terms of the geometry but also in terms of the material composition.

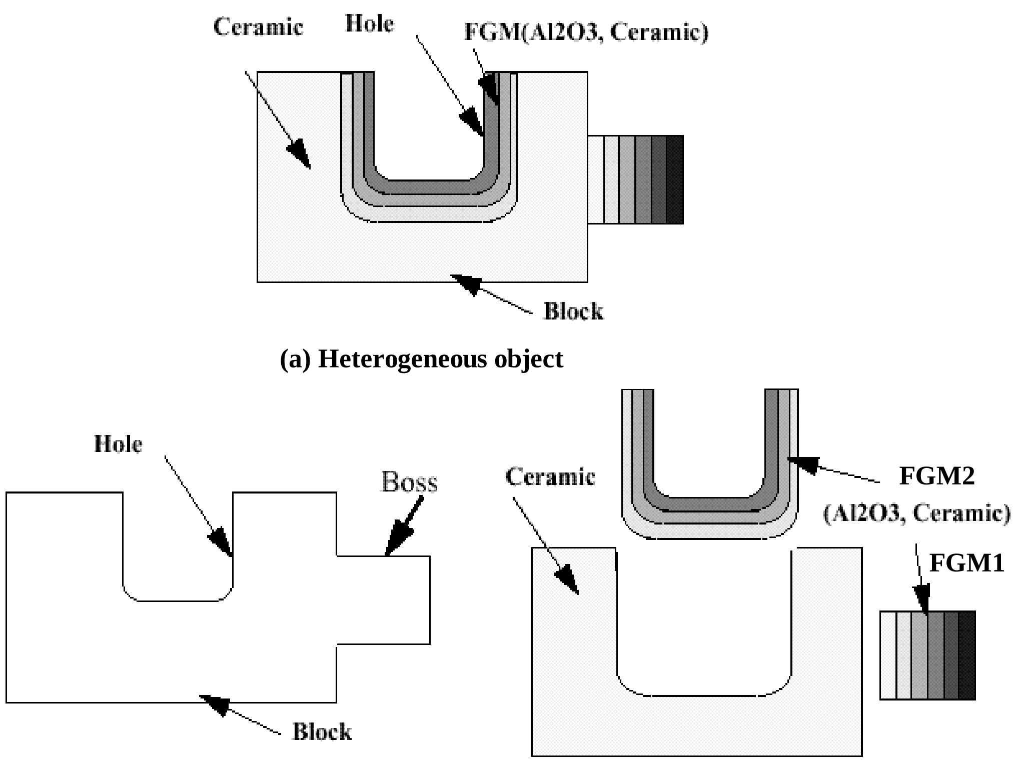
In order to mathematically represent the features, we first define some notations. A part, *P(G,M)*, is defined as a product space , where G is the geometry and M is the material space.

3.1.1 Form Feature

Form feature is a specific geometric shape, which carries engineering significance, such as a hole and a slot. A form feature can be either a volume feature or a surface feature. In this paper, we focus on volume features.

As with homogeneous objects, a form feature in heterogeneous objects is a specific shape within a part regardless of the material composition variation. It should be noted that, in order to distinguish form features from the material features, there are two necessary conditions to the definitions of form features. First, *the shape of the volume must correspond to some specific engineering meaning*. For example, form features such as a hole or a groove, have specific geometric shapes. Second, *such a shape should contribute to the formation of the exterior boundary of the final part geometry*. That is to say, during the part creation process, the evolving part geometries should be different before and after the introduction of the form features. We note the part geometry as G_i before the form feature FF_{i+1} is introduced to the part. We have the necessary condition for form features: $FF_{i+1} - G_i \neq \varnothing$.

For example, in Figure 5, the heterogeneous object has three form features: a block, a hole, and a boss. They each represent a particular geometric shape. If we disregard the material variation in the object, these three form features create the final geometry of the object. In the two FGM regions, FGM1 is a form feature while FGM2 is not. FGM2 does not satisfy the second condition of form feature, i.e. FGM2, as a shape, does not contribute to the final part geometry of the exterior.



(a) Heterogeneous object

(b) Form features

(c) Material features

Figure 5 Features in a heterogeneous object

3.1.2 Material Feature

Before we present the definition of material features, we first examine material variation in heterogeneous objects.

Heterogeneous materials arise in materially optimized structures. They provide a smooth transition between different materials which are otherwise incompatible because of their different mechanical or chemical properties. The material variation usually correspond to some particular functionality and design intent. They can be explicitly captured by a material volume, formally a material feature (28). Such a material volume can be represented in many different ways, e.g. a swept material volume (28) or a B-spline material volume (29).

A material feature is a region with some particular material composition function and this material function is not equal to the neighboring volume's material functions. Such material composition variation is associated with some engineering significance, such as erosion protection, thermal balance, and biocompatibility.

Material feature is an enriched material volume. The relationship between a material feature and the material volume is the same as the relationship between a geometric feature and the geometric volume. The features contain engineering relevance while the volumes do not. Material features can be represented as a pair, MF(g,m), where *m* has certain characteristics in the region *g* and is different from the material function elsewhere.

In this paper, when material functions are equal to each other for two regions(g_1,m_1) and (g_2,m_2), $m_1 \equiv m_2$, it means: (1) there is a C^{∞} function m(x) for $x \in g, g = g_1 \cup g_2$; (2) $m = m_1$ for $x \in g_1$; and (3) $m = m_2$ for $x \in g_2$.

The sample part in Figure 5 has three material features: two FGM (Al2O3, Ceramic) region and one ceramic region.

3.1.3 Observations on the Form Features and Material Features of Heterogeneous Objects

Next issue to be examined is the relationships between form features and material features.

Since we will define feature operations based on these features, it is important to determine what are the critical chracteristics of these features. In the course of our investigation, we observe a number of significant points regarding to the nature of these features.

Observation 1: Material features MF(g,m) form a partition of the part P. That is,

$$P = \underset{i}{\cup} MF$$

$$\overline{G} = g_1 \mid g_2 \mid \ldots \mid g$$

Note, $\overline{G}$ is defined as a closure in 3d manifold, and '|' is a gluing operation.

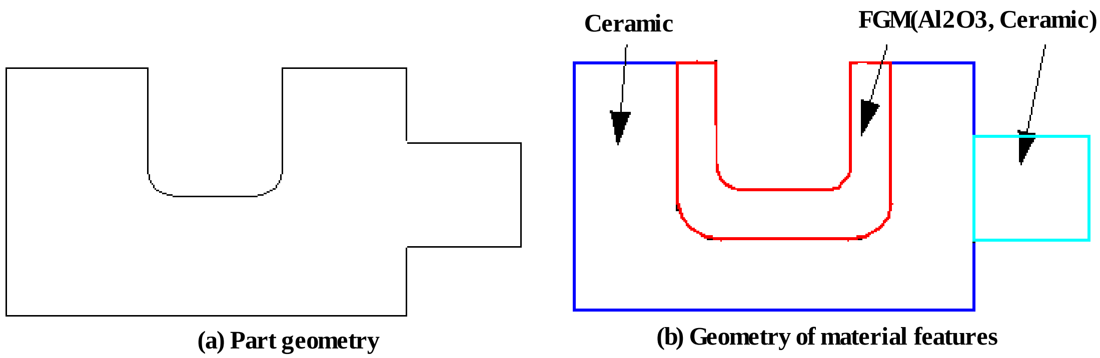


Figure 6 Material features partitions part volume

Figure 6 shows the partition of the part geometry by material features. In the left is a complete geometry of the part shown in Figure 5. In the right is a partition of the part volume. Each sub-volume in the partition corresponds to one material feature in Figure 5.

Observation 2: Form features form the geometry of part volume

$$\overline{G} = \prod_j FF_j$$

$\prod$ refers to the form feature operations, i.e. either an addition or a subtractive operation.

Figure 5**.b** shows how form features form the part volume. Three features are added one by one and lead to the final part geometry.

Observation 3: The geometry volumes in form feature volumes and the material volumes in material features need not to be identical.

In order to examine the relationships between form features and material features, we note the geometric volume of material feature MF_i as $g(MF_i)$, its operation with FF_j as $g(MF_i) \otimes FF_j$. It can be simplified as $MF_i \otimes FF_j$. The geometry of form features and material features have one of the following relationships:

- MF and FF have identical geometric volumes (*identical*)

$$MF_i - FF_j = FF_j - MF_i = \varnothing$$

- MF belongs to FF or FF belongs to MF *(belongin*g)

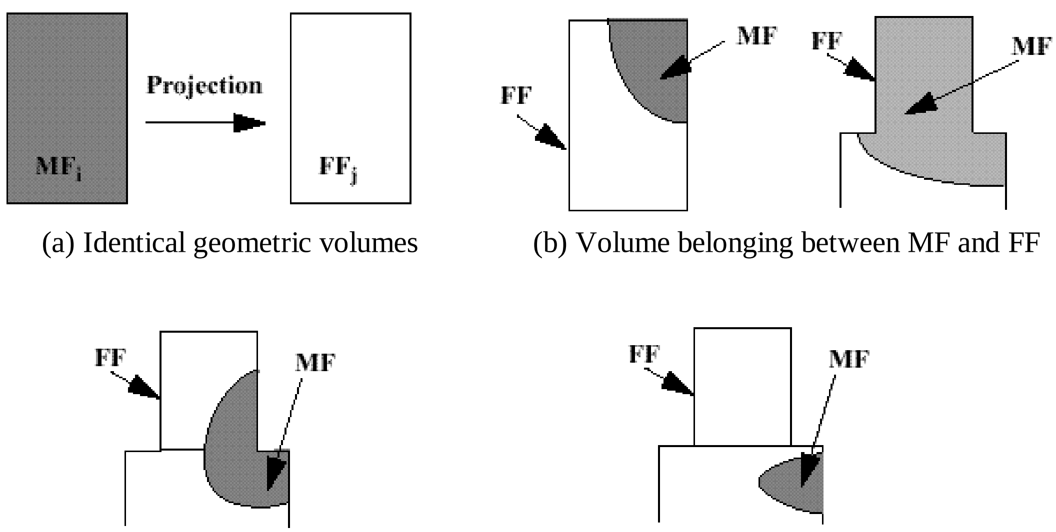
$$MF \subset FF \text{ or } FF \subset MF$$

- MF and FF share some subvolume *(sharin*g)

$$FF_i \bigcap MF_j \neq \varnothing$$

- MF and FF are disjointed *(disjointe*d)

$$FF_i \bigcap MF_j = \varnothing$$



(a) Identical geometric volumes
(b) Volume belonging between MF and FF
(c) Volume sharing between MF and FF
(d) Volume disjointed between MF and FF

Figure 7 Relationships between form features and material features

The above observations reveal that material features describe the part's interior material composition and form features describe the part's exterior geometric shape.

Even though using form features alone or material features alone may be able to construct the design model, using each type of features alone is not sufficient to support the design process. Using form feature alone, no partition of the part volume is obtained.

Using material features alone, the design intent of the geometric features is not captured. Often times both form features and material features are necessary representations of the design intents. Therefore, feature based design for heterogeneous object needs to include both geometric and material features.

3.2 Synthesized Features for Feature Based Constructive Design

3.2.1 Synthesized Features and Semantics Definition

With our understanding of the relationships between the form feature and material features, we can now proceed to the synthesis of form feature and material feature operations.

In STEP, the volume features are classified as additive and subtractive features. In consistency with form feature classification in the STEP and the observed feature properties in heterogeneous objects, we propose the following feature operations in the context of heterogeneous object design: additive material feature, subtractive material feature and partition material feature (Figure 8). In responding to additive and subtractive features in STEP, we propose additive and subtractive material features. In responding to the partition properties of material features in heterogeneous objects, we propose partition material features. This classification is based on the modeling operation's impact on geometry.

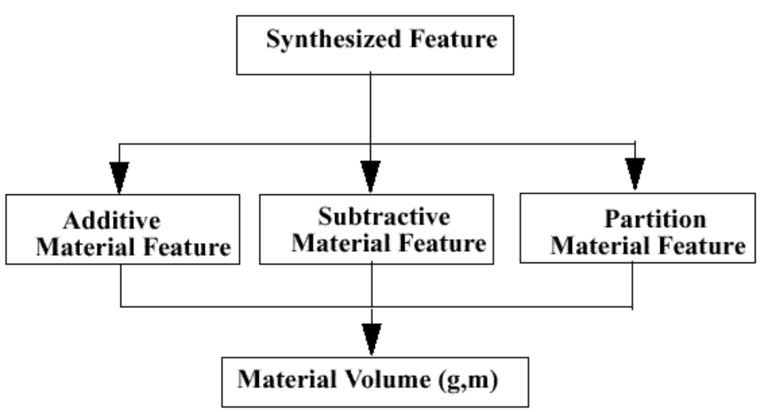


Figure 8 A proposal for feature classification in heterogeneous objects

These synthesized features support both form feature and material feature operations. It associates the each material volume with one geometric/material operator. They preclude redundant definition of the geometry in both form features and material features. The four types of relationships between form features and material features can be supported by the synthesized features using a constructive approach. In this approach, the building blocks are the synthesized features. The designer has two choices: either use the default materials to model form features and then partition the part volume with specific material composition functions, or glue a set of material feature volumes.

Before we present the details of the semantics definition for each feature operation, we define some terms. For an object/region A(g,m), m(A) gives the material information *m*, *p(A)* is the priority of the materials and it is useful when different materials are interacting with each other.

As noted before, "|" is the aggregate/gluing operation. "$|^*$" is the *regularized gluing* operation. For each face, if material functions over the face's two adjacent regions are equal, the face shall be eliminated. That is, $(g_1, m_1)\,|^*\,(g_2, m_2) = (g_1 \cup^* g_2, m_{12})$ when material function equality conditions are satisfied.

The three synthesized feature operations can be defined respectively as:

1. Additive Material Feature

$$(g_1, m_1) + (g_2, m_2) = (g_1 - g_2, m_1)\,|^*\,(g_2 - g_1, m2)\,|^*\,(g_1 \cap g_2, m_1 \otimes m_2)$$

2. Subtractive Material Feature

$$(g_1, m_1) - (g_2, m_2) = (g_1 - g_2, m_1)$$

3. Partition Material Feature

$$(g_1, m_1)/(g_2, m_2) = (g_1 - g_2, m_1)\,|^*\,(g_1 \cap g_2, m_1 \otimes m_2)$$

Figure 9 lists the three types of features and their semantics. Clearly, the part, $C = A \otimes B$, depends on the feature type (operation), and each region's materials and the priority tag.

To resolve the material composition ambiguity over the intersection region, we introduce the material priority tag *p*, to each material volume. That is,

$$m_1 \otimes m_2 = \begin{cases} m_{1,} & \text{if } p_1 > p_2 \\ m_2, & \text{if } p_1 < p_2 \\ m_1 \oplus m_2, & \text{if } p = p_2 \end{cases}$$

Note, here $m_1 \oplus m_2$ is a user defined function. It could be $a_1 \cdot m_1 + (1-a) \cdot m_2$, $a \in (0,1)$, or any other form. The $m_1 \oplus m_2$ has been particularly useful for applications like doping, and implanting, where material volume is “contaminated” by some exotic materials.

The material composition change during the synthesized feature operation is referred to as *material operation semantics*.

The partition feature functions the same as additive features over the intersection region $(g_1 \cap g_2)$, but it is not applicable to the region outside of g_1. This partition feature is used extensively for heterogeneous object modeling when material functions are imposed on a given geometry domain.

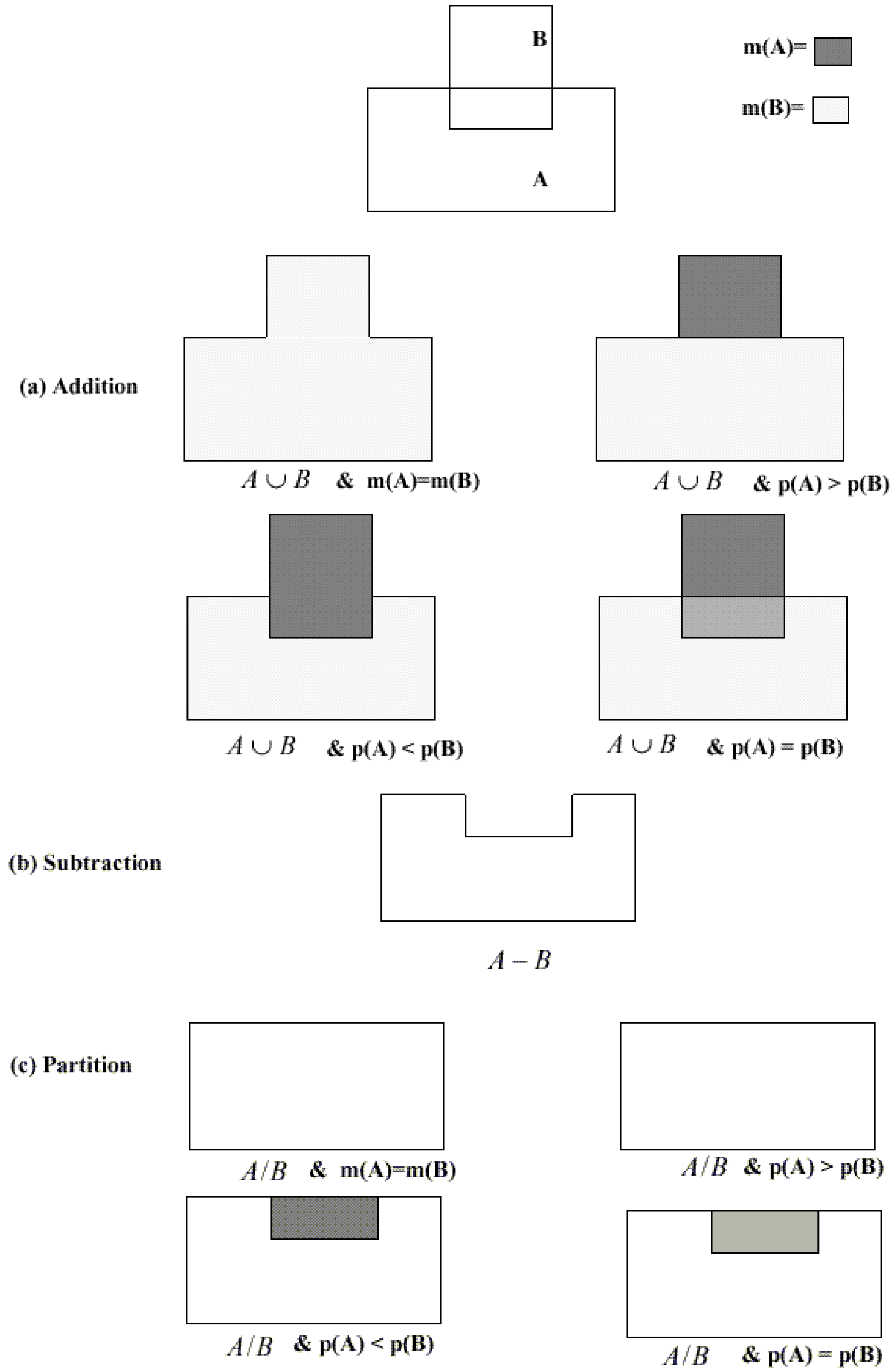


Figure 9 Generic feature operations for heterogeneous objects

These synthesized features operation can be adopted to model heterogeneous objects or manufacturing process. The three features provide a generic tool for heterogeneous object modeling. Many existing design/fabrication automation tools for heterogeneous objects processing are dedicated tools and they can be directly derived from the three synthesized features. For example, the feature operation semantics used in design by composition for layered manufacturing (30) and MEMS simulation (31) can all be derived from the synthesized features (17).

Based on these synthesized feature operations, a feature based design methodology can be developed for heterogeneous object design. Such a methodology needs two enabling component techniques: how to combine material volumes and how to define material composition within each material volume. These two enabling techniques are presented in Section 4 and Section 5 respectively.

4.0 Constructive feature operations and Material heterogeneity modeling

4.1 Constructive feature operations through direct face neighborhood alteration

Constructive feature operations need an effective modeling algorithm for combining the feature volumes. Given heterogeneous objects $A = \{A_1 | A_2 | ... | A_m\}$ and $B = \{B_1 | B_2 | ... | B_m\}$ and the feature operator , the resultant solid needs to be formed. It essentially includes two tasks:

- determine the boundary of A and B that appears in the resultant solid C (*Geometric Boundary Evaluation*) , and
- organize the resultant faces into regions and associate material function m_i to each region g_i (*Material Region Forming)*

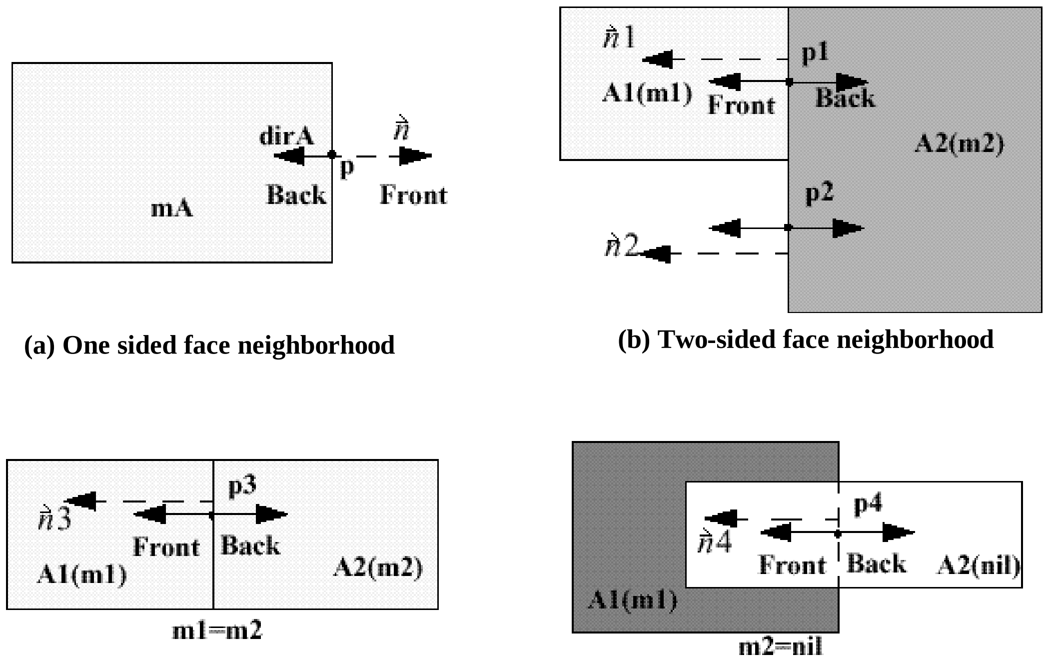
In this research, both the geometric boundary evaluation and material region forming are conducted based on a novel method, direct face neighborhood alteration(32).

Neighborhood is a well known concept from topology (33). Direct face neighborhood alteration is the core part of the constructive operations for heterogeneous objects. In heterogeneous objects, each face has two neighboring regions. We perceive the 3d face's neighborhood as a *two-sided face neighborhood* and represent it as a combination of two one-sided face neighborhood from each adjacent region.

4.1.1 One-Sided Face Neighborhood Representation

The face neighborhood in each region is represented as a combination of normal direction of the face and material function of the region. Suppose point *p* lies on a face of region A, its neighborhood is represented as:

$$nF_A = (dirA, mA) \quad (1)$$



(a) One sided face neighborhood

(b) Two-sided face neighborhood

(c) Full

(d) Empty

Figure 10 3D face neighborhood Representation for heterogeneous solid

Here the *dirA* is the region A's inward normal direction at point *p*, *mA* is the material composition function in region A.

For example, in Figure 10.a, the point *p* in region A's neighborhood is nF(p) = (-n, mA).

Denote the face's preserved reference normal direction at point p as *n(RefNormal)*. The front side refers to the side of a face, which is in front of p along the normal direction *n*. The opposite side is called the back side. So each face has two one-sided neighborhood respectively in two adjacent regions, i.e. nF_{front} = (RefNormal, m_{front}), and nF_{back} = (-RefNormal, m_{back}).

The 3d face's complete neighborhood representation at point p is a combination of nF_{Front} and nF_{Back}.

$$NF(p) = nF_{Front}|nF_{Back}$$

So the 3d face's neighborhood is a quadruple

$$NF(p,F) = (\text{RefNormal}, m_{front}) \,|\, (-\text{RefNormal}, m_{back}) \qquad (2)$$

When both sides of a face have null material, the neighborhood is *empty* and the face is in the exterior of the object. When both sides of a face have the same material function, the neighborhood is *full* and the face is in the interior of a region. During the regularization process, faces with either *empty* or *full* neighborhood shall be discarded.

For example, in Figure 10.b, the two-sided face neighborhood of the points, p1 and p2, are, NF(p1)=(n1, m1)|(-n1,m2), NF(p2) = (n2, nil)|(-n2, m2). In Figure 10.c, the point p3 has neighborhood NF(p3) = (n3,m)|(-n3,m). Therefore, p3's neighborhood is *full* and is completely interior to the region B. In Figure 10.d, the point p4 lies on the boundary of (A1- A2). So its neighborhood after the operation (A1-A2) is NF(p4) = (n4,nil)|(-n4, nil) and is *empty*.

4.1.2 Neighborhood Operations

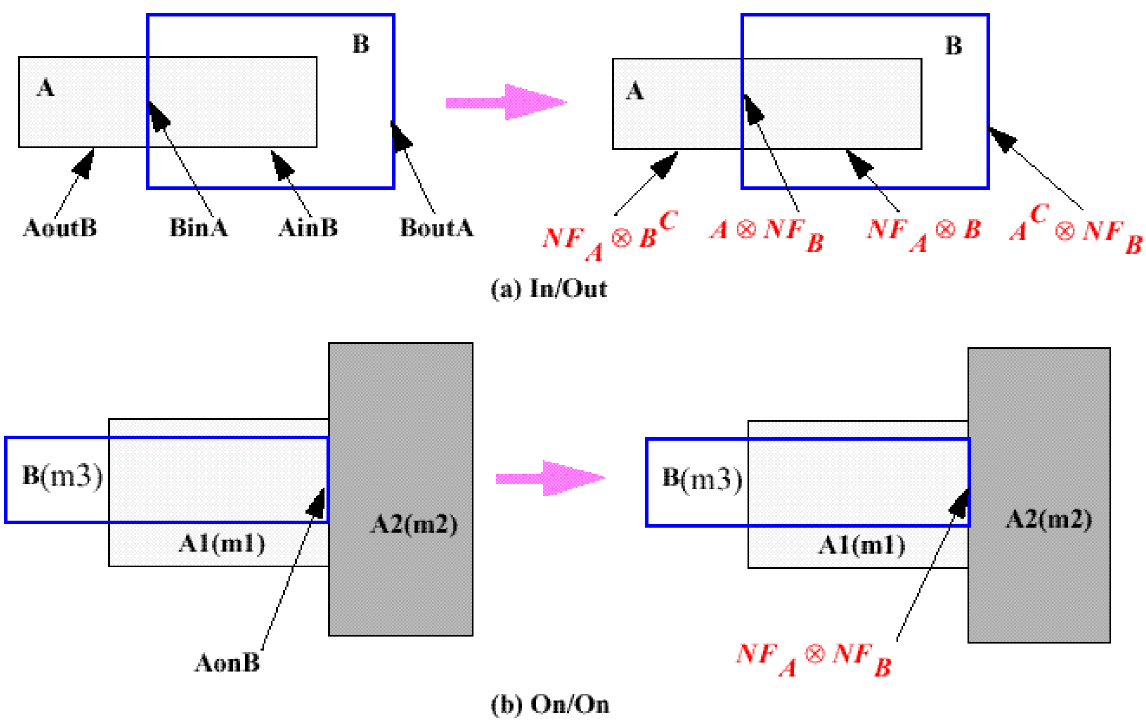


Figure 11 Face membership classification and neighborhood operation

Given the objects A and B, the faces from A and B, noted as F_A and $F_{B,}$ can be classified against each other. There are five types of set membership classification (SMC) values: F_A in B, F_A out B, $F_A$onB/$F_B$onA, F_B in A, F_B out A (Figure 11). Therefore, corresponding to the five SMC values, there are five NF operations for the operation $A \otimes B$: 1) $NF_A \otimes B_j$ for F_A inside region B_j, 2) $A \otimes NF_B$ for F_B inside region A_i, 3) $NF_A \otimes NF_B$ for F_A and F_B that are co-faces, 4) $NF_A \otimes B^C$ for F_A outside the object B, i.e. F_A interacts with region B^C, 5) $A^C \otimes NF_B$ for F_B outside the object A, i.e. F_B interacts with region A^C. Figure 11 shows the five neighborhood operations. Since different regions have different material operation semantics, the NF operations are fulfilled by combining two separate *nF* operations, each of which operates according to the residing region's semantics.

F_A's neighborhood operation with region B_j can be represented as:

$$NF_A \otimes B_j = (nF_{AFront} \otimes B_j) \,|\, (nF_{ABack} \otimes B_j)$$

Here nF_{AFront} and nF_{ABack} refer to the face F_A's front region and back region's neighborhood. For the generality, one-sided face neighborhood in region A_i is referred to as nF_{A_i}. The face neighborhood for the object A's complement set A^c is noted as nF_{A^c}.

An example of F_A interacting with region B is shown in Figure 12(bold line). From the four cases in the union operation, we have the following neighborhood alteration rules:

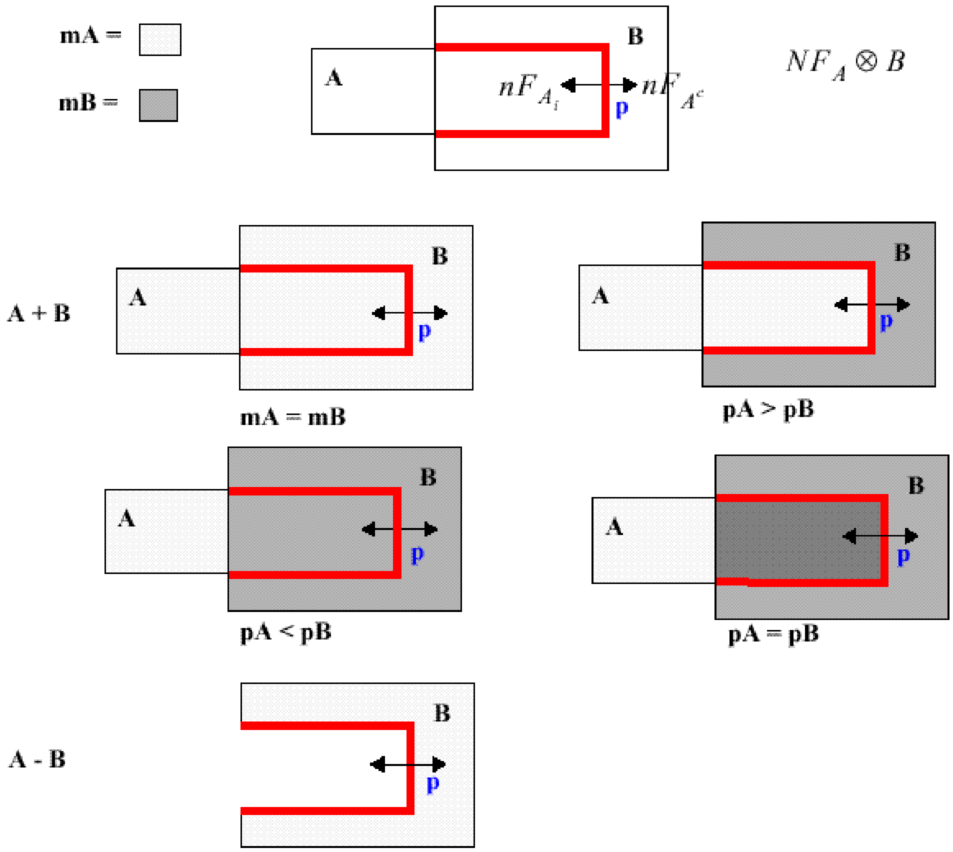


Figure 12 Neighborhood operations for FA in B

$$nF_{A_i} \cup B_j = \begin{cases} nF_{A_i} & mA = mB \\ nF_{A_i} & pA > pB \\ (dirA_i, mB) & pA < pB \\ (dirA_i, mA \oplus mB) & pA = pB \end{cases} \qquad (3)$$

The other types of face neighborhood alteration can be derived similarly.

4.1.3 Implementation of direct face neighborhood alteration

A prototype system for feature based constructive design based on the direct face neighborhood alteration has been implemented using ACIS. Figure 13 shows a sample part, consisting of two feature volumes, A and B. By direct face neighborhood alteration, the system gives different results, depending on the priority of each primitive. The bottom half of the figure is the shaded cross-section of the parts.

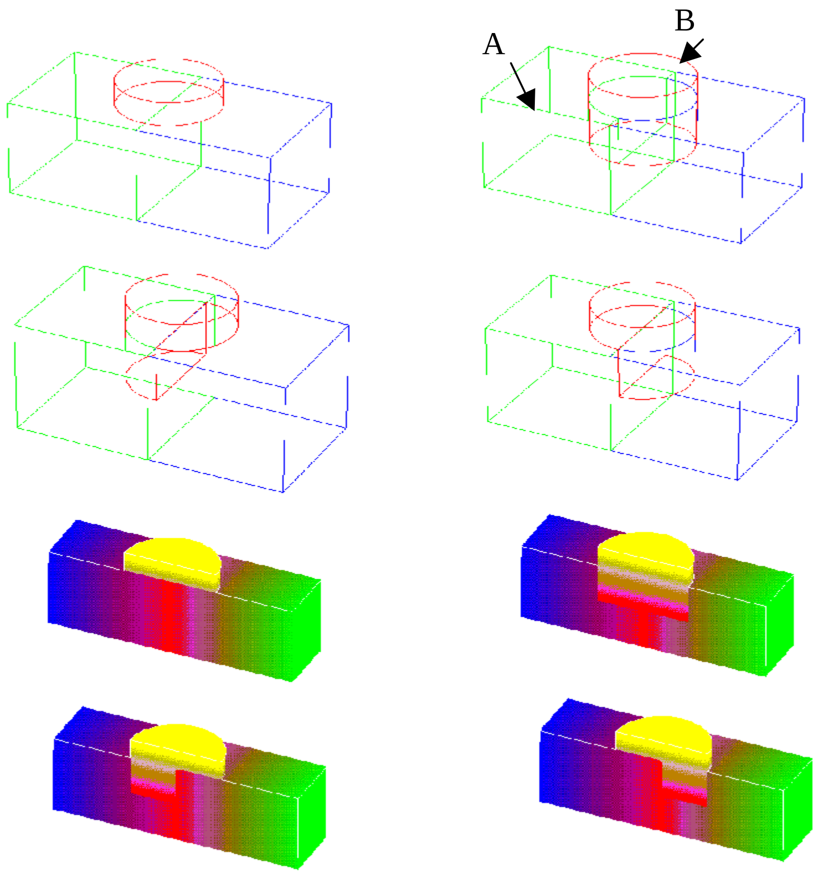


Figure 13 Sample part for face neighborhood alteration

4.2 Material Heterogeneity specification for features/objects

In addition to the geometric modeling, material heterogeneity modeling is another important task in heterogeneous object design. In this section, we present the use of physics (diffusion) based modeling to intuitively control material composition variation within each feature volume (17).

4.2.1 B-Spline Tensor Solid Representation for Heterogeneous Objects

For each point (u,v,w) in the parametric domain of a tensor product B_spline volume V, there is a corresponding point V(u,v,w) at Cartesian coordinates (*x*,*y*,*z*) with material composition *M*, noted as (x,y,z,M). We define such a B-spline volume as:

$$V(u,v,w) = \sum_{i=0}^{n} \sum_{j=0}^{m} \sum_{k=0}^{l} N_{i,p}(u) N_{j,q}(v) N_{k,r}(w) P_{i,j,k} \tag{4}$$

where $P_{i,j,k} = (x_{i,j,k}, y_{i,j,k}, z_{i,j,k}, M_{i,j,k})$ are control points for the heterogeneous solid volume. $N_{i,p}$, $N_{j,q}$ and $N_{k,r}$ are the pth-degree, qth-degree and rth-degree B-spline functions defined in the direction of u, v, w respectively.

We can also have the B-spline representation for material properties:

$$E(u,v,w) = \sum_{i=0}^{n} \sum_{j=0}^{m} \sum_{k=0}^{l} N_{i,p}(u) N_{j,q}(v) N_{k,r}(w) E_{i,j,k} \tag{5}$$

where $E_{i,j,k}$ is material property at each control point. It can be obtained according to the volume fractions at each point.

4.2.2 Diffusion based modeling

In this section, we describe how diffusion process generates different material composition profile. Diffusion is a common physical process for the formation of material heterogeneity: in integrated circuit fabrication, in biological mass transport, in the drug delivery from a polymer, the material composition variation can be described in most cases by diffusion.

The mathematical modeling of controlled material composition in these processes is based on the Fick's laws of diffusion. Applying Fick's laws and using the divergence theorem, we have

$$\frac{dM}{dt} = Q + \frac{\partial}{\partial x_i}(D_{ij} \cdot \frac{\partial M}{\partial x_j}) \tag{6}$$

By the finite element approximation, it becomes

$$\left[\int_{\Omega} \frac{\partial N_{\alpha}^{m}}{\partial x_i} \cdot D_{ij} \frac{\partial N_{\beta}^{m}}{\partial x_j}\right] M = \int_{\Omega} N_{\alpha}^{m} Q d\Omega - \int_{\Gamma_2} N_{\alpha}^{m} q_n d\Gamma \tag{7}$$

In matrix form, EQ.(7) becomes

$$KM = \vec{B} - \vec{S} \tag{8}$$

where

$$\underset{N\times N}{K_e} = [k \int_{\Omega_e} (\frac{\partial N_i}{\partial x} \cdot \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y} \cdot \frac{\partial N_j}{\partial y} + \frac{\partial N_i}{\partial z} \cdot \frac{\partial N_j}{\partial z}) d\Omega] \tag{9}$$

$$\underset{N\times 1}{\vec{B}_e} = [\int_{V_e} N^m Q dV], \quad \underset{N\times 1}{\vec{S}_e} = [\int_{\Gamma_e} N^m q_n d\Gamma] \quad (10)$$

With function Q and q interpolated in terms of its nodal values, we have $\underset{N\times 1}{\vec{B}_e} = [\int_{\Omega_e} N_i^m N_j^m d\Omega] Q_j$, and $\underset{N\times 1}{\vec{S}_e} = [\int_{\Gamma_e} N_i^m N_j^m d\Gamma] q_j$. K_e is the element stiffness matrix, and $\vec{B}_e$ is the element body force and $\vec{S}_e$ is the element surface force.

4.2.3 Material heterogeneity specification

A prototype system for diffusion process based material heterogeneity modeling is implemented on SUN Sparc workstations. The input of the system is a B-spline solid, consisting of a set of control points. The user interacts with system in two ways. First, the user can change system parameters, such as Q, the material source (material/unit volume) and D, the material diffusion coefficient. Second, the user can impose constraints. The two types of interaction process continues until the user is satisfied with the result. When constraints are changed, the system matrices remain the same. Only when the system properties are changed, should the system stiffness matrix and body force matrix be re-calculated.

4.3 Example: Feature based design of a prosthesis

The following example of prosthesis design demonstrates such a feature based design process.

Figure 14shows a flowchart for the prosthesis design process. Starting from the design functions, users select materials and form the heterogeneous material features, each of which is a B-spline volume. The feature combination algorithm combines these features into a heterogeneous object. After the mechanical and biological properties are obtained from the database for each individual material, these properties at each point in this prosthesis can then be evaluated. If users are not satisfied with the properties, they can select new material for each volume or change volume fractions. These steps of changing material composition of each feature in the constructive process form a feature based design process. After the property evaluation, property in vitro tests and animal tests are conducted before the designed prosthesis is used for medical purposes.

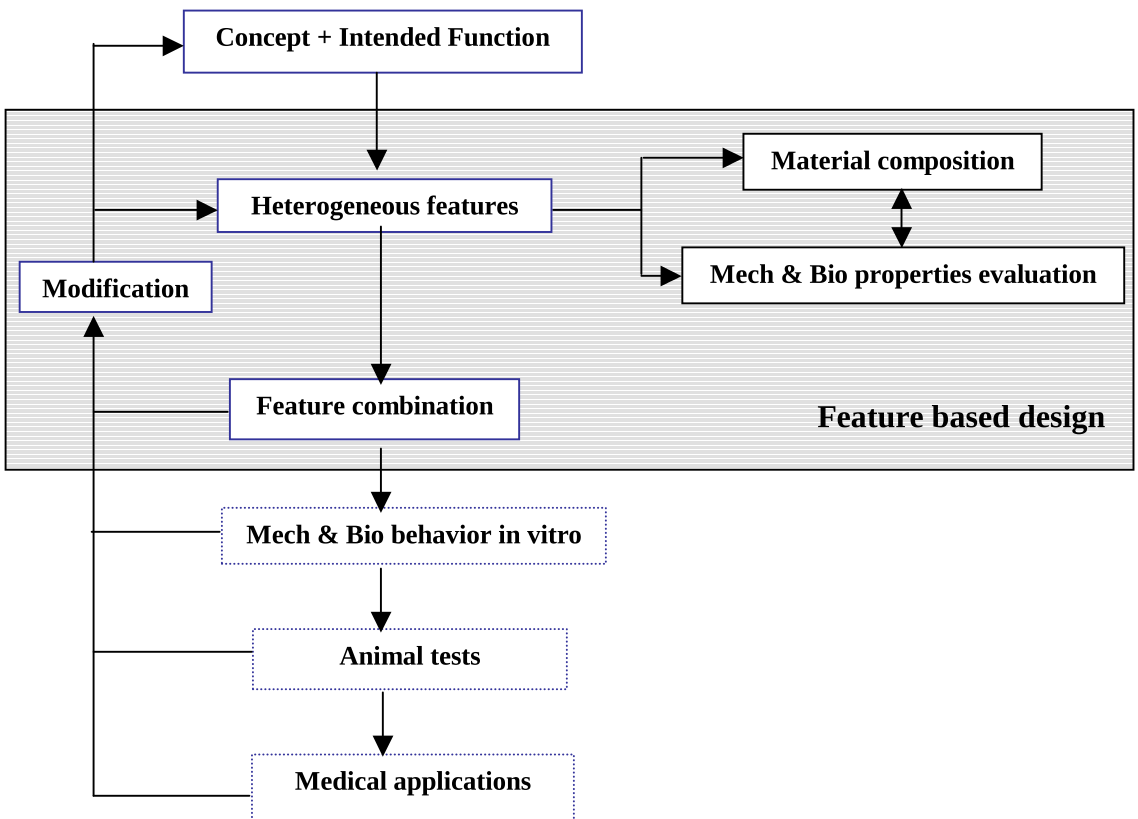


Figure 14 Flowchart of a feature based design process for a new prosthesis

In the example of Figure 15 is a prosthesis designed following the flow chart in Figure 14. The materials are Titanium and graded HAp. Each of these design intents is represented as a separate B-spline volume (heterogeneous feature), such as in Region 2 and Region 7 in Figure 15. In these two regions, pore and HAp are modeled as one material, while the Titanium is the other material. Region 1 and 8 represent the bones. Region 4 and 5 connect the two ends. Once the volume fraction for pore and HAp is known, another fraction is used to separate the pore and HAp. This fraction is constant throughout the region. The Figure 15.a and Figure 15.b show the graded porous structure and graded HAp respectively with the $M_{pore} / M_{HAp} = 0.5$. Figure 15.c shows the construction history. The partition in the construction history is similar to union operation but with the intersection region's material redefined. Modification to the material composition can lead to different Young's modulus and biofunctionality (BF) distribution throughout the region. In Figure 16, we show the properties variation due to the change of Q (material generation source). These values are measured at different distance points from the inner surfaces of the graded regions.

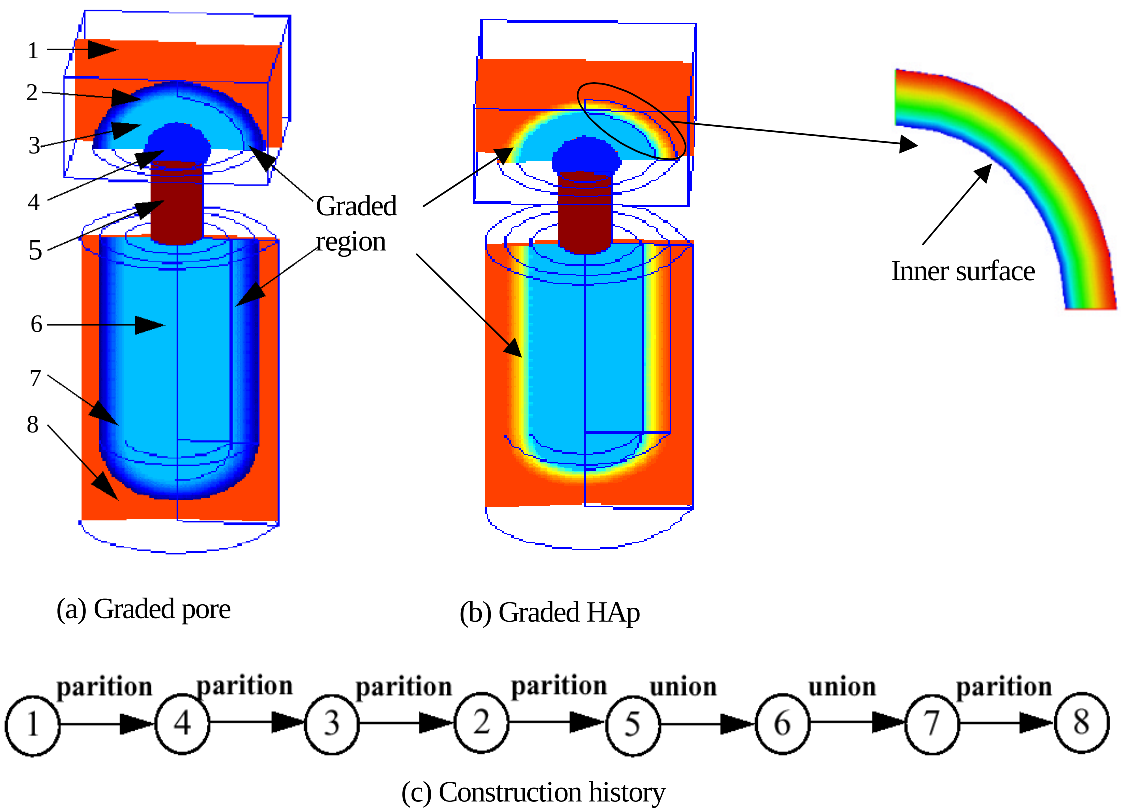


Figure 15 Graded interface with a prosthesis

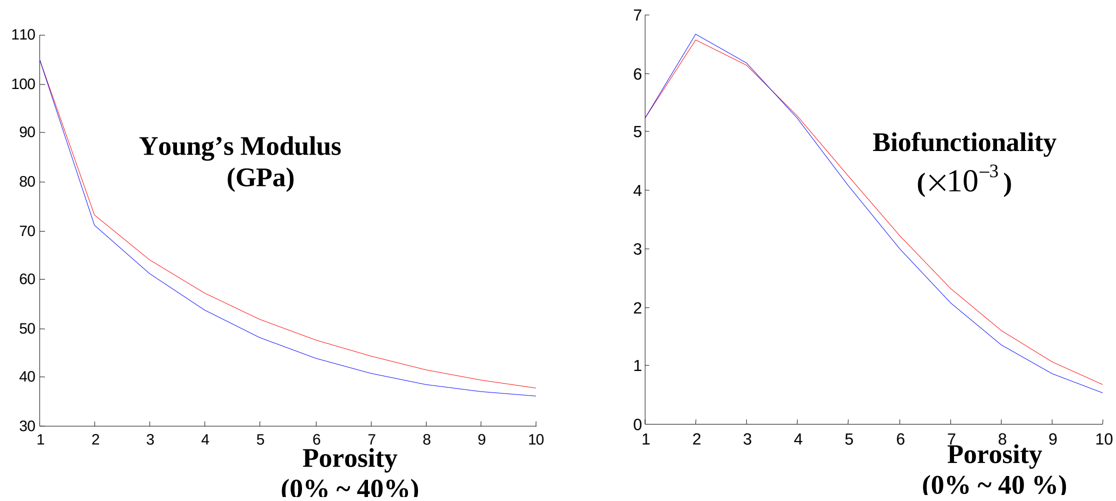


Figure 16 Variation of Young's modulus and biofunctionality due to Q change

This example demonstrates that the feature based design method not only provides an intuitive way to control the material compositions but also provides means to directly control the material properties. This draws a distinction from existing design methods for the prosthesis design, where material composition design and material property evaluation are conducted separately and sequentially.

5.0 Feature based fabrication in the layered manufacturing

In addition to facilitating the heterogeneous object design processes, the form features and material features in the heterogeneous object can also facilitate downstream applications. For example, material features can facilitate the material deposition process and form features can facilitate the NC machining and part assembly. This section details how features can facilitate the layer decomposition in layered manufacturing.

5.1 Staircase interaction in layered manufacturing

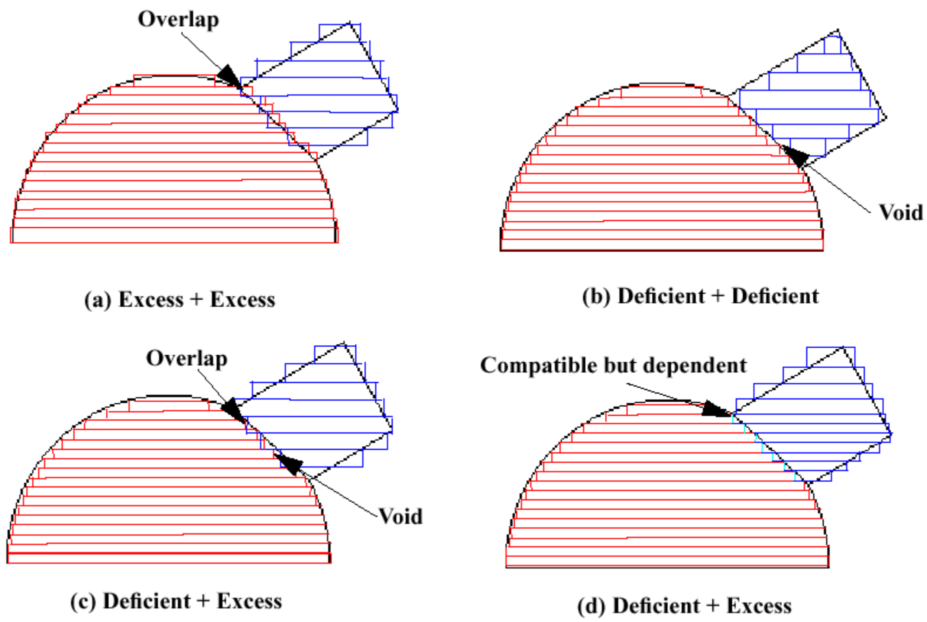


Figure 17 Staircase interaction

In order to increase the fabrication efficiency, feature based fabrication localizes the geometric curvature effect and material gradation effect within each feature layer. However, the layer-wise deposition in layered manufacturing may lead to staircase interaction between neighboring volumes. This staircase interaction results in geometric incompatibility. For example, in Figure 17, a part, made of a hemisphere and a slant cylinder, is fabricated by feature-based slicing to decrease the build time (34). If both feature A and feature B are fabricated by excess deposition, the layers in A and B would interfere with each other (Figure 17.a). If both feature A and feature B are fabricated by deficient deposition, a large void area is created between the neighboring layers in A and B (Figure 17.b). If one is fabricated by excess deposition and the other by deficient deposition, the interaction typically results in both interference and void since the layer thickness of A and B do not match. (Figure 17.c). The layers of A and B can become compatible only when the build direction of A is the same as B and the layer thickness of A and B are exactly the same (Figure 17.d). However, this compatibility is achieved by sacrificing the fabrication independence between neighboring volumes. This kind of fabrication is equivalent to fabrication without volume decomposition.

5.2 Staircase interaction free strategy

To eliminate the staircase interaction for each feature interaction, we propose the following two concepts.

Feature interaction volume (FIV) *is a transition volume formed to eliminate the staircase interaction between adjacent feature volumes.*

Refined feature volume (RFV) *is a feature volume devoid of all of its feature interaction volumes.*

For example, in Figure 18, features are to be fabricated along vertical direction. An FIV is formed with the vertical and horizontal parting surfaces. This FIV eliminates the staircase interaction, and the adjacent RFVs can be fabricated independently and compatibly.

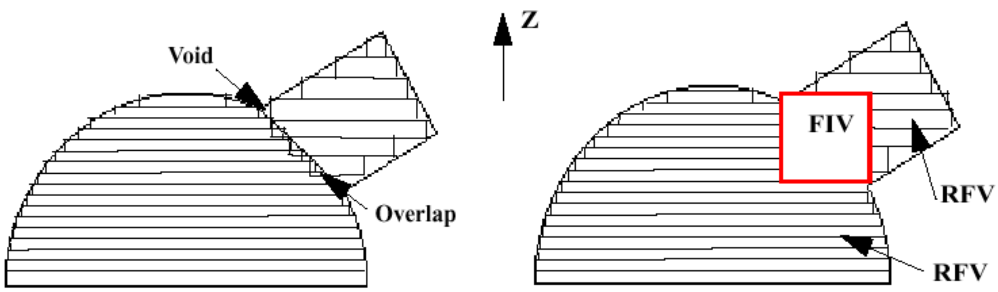


Figure 18 FIL eliminating staircase interaction

In Figure 19, FIV is generated for the features with different build directions. Still the separating surfaces of RFVs is either perpendicular or parallel to the build directions of the features. So there is no staircase interaction.

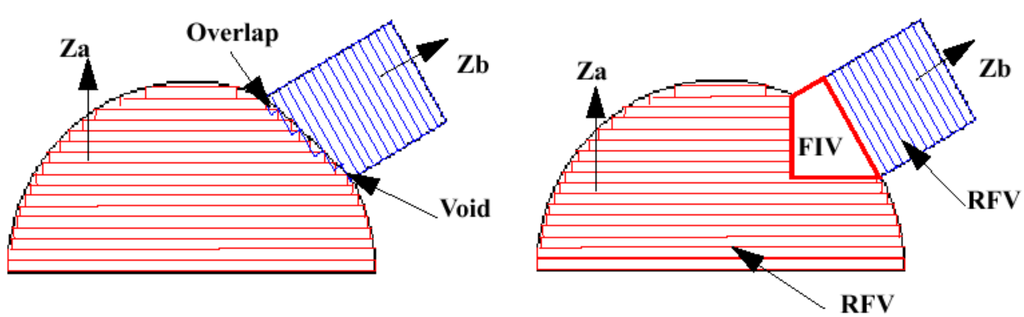


Figure 19 FIV eliminating staircase interaction for features with different build directions

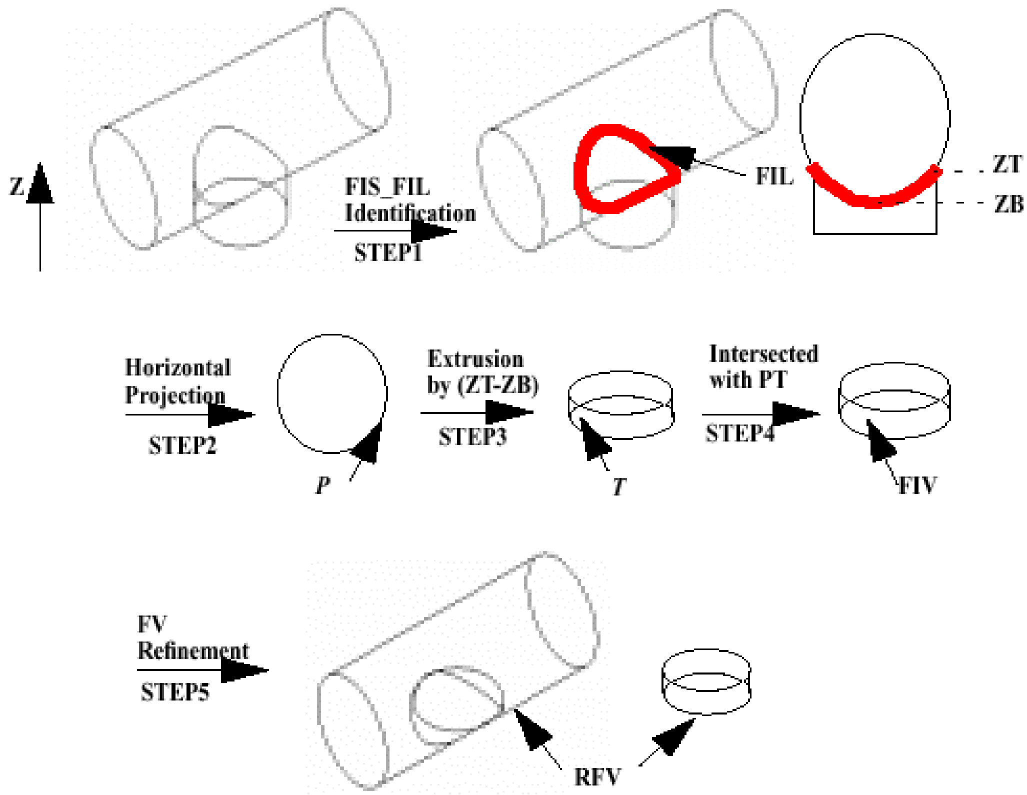


Figure 20 Processing of feature interaction

Figure 20 presents an example of feature volume decomposition for two intersecting cylinders. The processing of the feature interaction includes the following steps: (1) identifying the feature interaction surface and/or feature interaction loop; (2) obtaining the heights of the top point (ZT) and bottom point (ZB) at each feature interaction surface and/or feature interaction loop; projecting the *FIL/FIS* onto a horizontal plane and get the projection *P*; (3) extruding the projection *P* from ZB to ZT; (4) intersecting the extruded volume *T* with the part volume to get the feature interaction volume; (5) generating the refined feature volume.

The details of the algorithm and the properties of FIV are discussed in (34).

5.3 Implementation

5.3.1 Compatible volume decomposition

With the above feature interaction processing, we developed a system that can decompose the parts into a set of volumes, of which compatible deposition can be achieved. That is, there is no staircase interaction between the neighboring volumes and the slicing of the features volumes are independent.

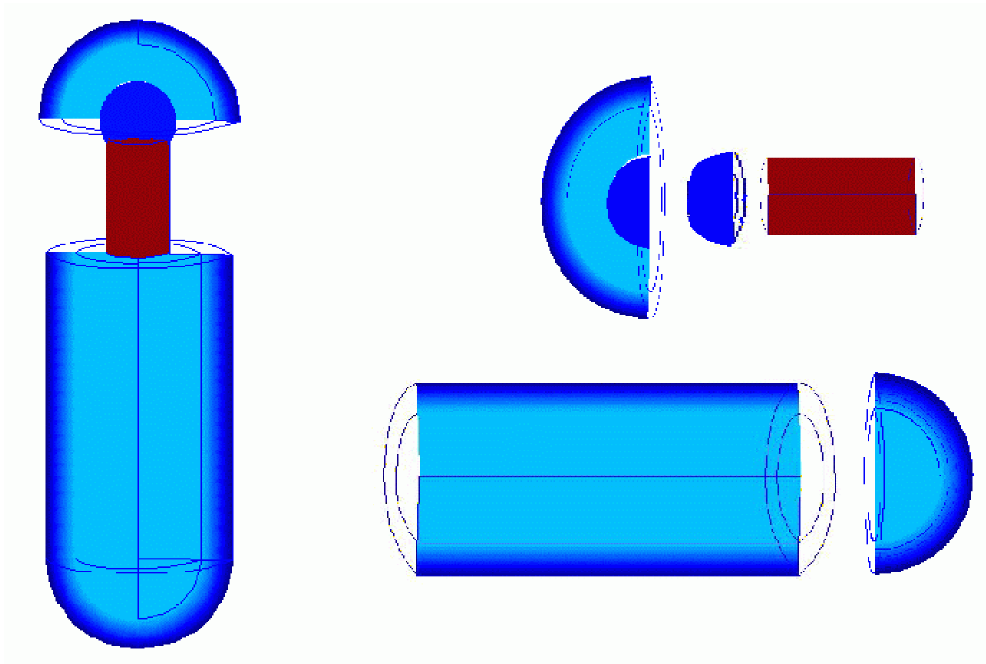


Figure 21 Compatible volume decomposition

Figure 21 shows a volume decomposition of the prosthesis in different build directions. With the orientation as in Figure 21.a, there is no material gradation effect. With the orientation as in Figure 21.b, the volumes are decomposed in a way that the curvature effect and material gradation effect is localized with each feature.

In order to experimentally validate the effectiveness of feature based fabrication in resolving the staircase interaction, we devise our experiments on the Stratays FDM machine. The dimensional and strength test experiments indicate that compatible deposition by the vertical parting surface introduced by FIV gives overall better dimensional accuracy and surface quality, and higher strength.

5.3.2 Build time saving using feature based fabrication

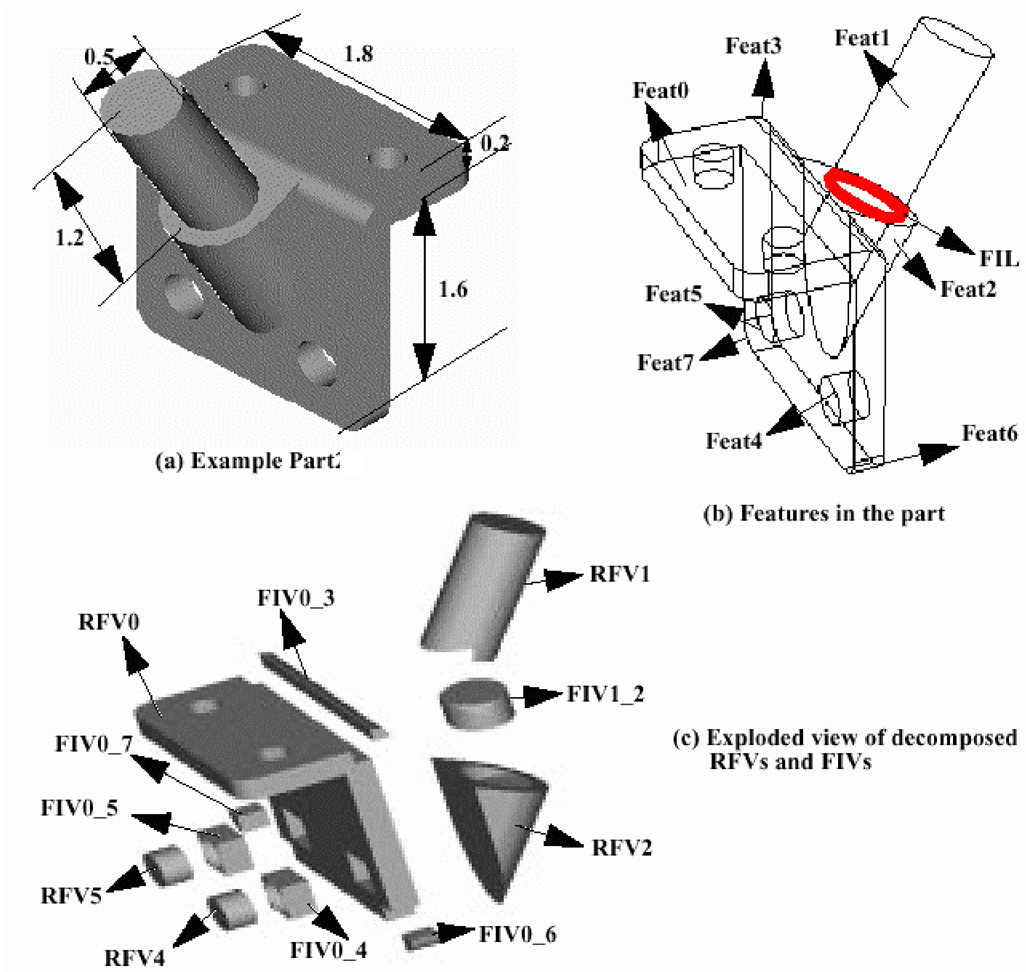


Figure 22 Example (with FIVs)

A build time comparison study is conducted to validate the build time efficiency using feature based fabrication method. In the example part of Figure 22, the sample part (downloaded from NIST repository (35) with a scale 0.02) is also sliced by the adaptive slicing, local adaptive slicing and feature-based slicing method. For this part, there are FIVs generated by the volume decomposition algorithm. Figure 22.b shows a list of those features in the example part that have FIVs. An FIV is generated for each feature interaction and the feature volumes are refined. For instance, the bold dark line in Figure 22.b is an FIL between *Feat1* and *Feat2*. *FIV1_2* is then created for the feature interaction between *Feat1* and *Feat2* as shown in Figure 22.c. After the FIV is generated, the features are refined and *RFV1* and *RFV2* are obtained respectively from *Feat1* and *Feat2*.

The features in Figure 22 fall into three categories: additive features (*Feat0*, *Feat1*, and *Feat2*), subtractive features (*Feat4* and *Feat5*) and surface features (*Feat3*, *Feat6*, and *Feat7*). Correspondingly, the protrusion features have RFVs (*RFV0*, *RFV1* and *RFV2*) made of part material; depression features have RFVs (*RFV4* and *RFV5*) made of sacrificial support material; and surface features have no RFVs. All the FIVs are made of part material (*FIV1_2*, *FIV0_3*, *FIV0_4*, *FIV0_5*, *FIV0_6*, and *FIV0_7*).

After all the volumes are obtained, adaptive slicing is done separately for each volume. In this example, the cusp height for the part is 0.005 *in*. The minimum layer thickness is 0.002 *in* and the maximum layer thickness is 0.015 *in*. The boundary box of this part is 2.8 *in* x 1.8 *in* x 2.7 *in*. The key dimensions of the part are shown in the Figure 22.a. The time comparison is shown in Table 1. Note, the build time for the underneath support structure is approximately 1.6 hours and is not included in the time shown in Table 1. Feature-based slicing yields a savings of 27% build time when compared to adaptive slicing method and local adaptive slicing method (36).

Table 1 Time comparison for various methods

Methods	Time(hr)
Adaptive Slicing	3.8
Local Adaptive Slicing	3.8
Feature-based Slicing	3

6.0 Conclusion and Future Work

6.1 Conclusion

In the context of heterogeneous objects, we propose the use of features to facilitate the high level (explicit) conceptualizing of material composition and gradation and its downstream transforming to the fabrication. Based on our examination of the relationships between the form features and the material features, a feature based design methodology is developed for heterogeneous object design. It is a constructive design process based on a set of user pre-defined heterogeneous features. To speed up the efficiency of such constructive feature operations, a direct face neighborhood alteration method is developed. To model material heterogeneity effectively and efficiently within each feature, a physics based B-spline heterogeneous object modeling method is researched and developed. In this method, B-spline representation is utilized to increase model coverage, and a physics process (diffusion process) is used to generate material composition profile to increase operation convenience.

This paper also presents an effective feature based fabrication methodology for LM. Such a method is developed to resolve the inherent dilemma in layered manufacturing — conflicting requirements in low build time and high surface quality. Feature based fabrication effectively handles this issue. It localizes the curvature effect and material gradation effect within each feature layer. A new concept, *feature interaction volume*, is introduced to eliminate the staircase interaction between the neighboring fabrication volumes. Experimental results and quantitative analysis demonstrate that feature based fabrication saves build time and gives better overall surface quality, dimensional accuracy and material strength.

6.2 Future work

This research has addressed two important issues in heterogeneous object realization — design methodology for heterogeneous objects and the fabrication methodology in layered manufacturing. The contributions resulted from this research shall impact the future research in the field of heterogeneous object realization. This section lists some future research areas based on these contributions. Some of the following topics are direct extensions of the ideas presented in this work, while others are generalizations of the concepts that are applied in this work. These topics include: design feature interaction, development of a feature-base for heterogeneous object design, feature recognition from heterogeneous object model, applications of time dependent heterogeneous objects in bio-medical field, design/analysis integration and process planning for the fabrication of heterogeneous objects.

Design feature interaction: In this work, when features interact with each other during the design process, three operations (additive, subtractive and partition) are used. At the feature interaction regions, users have to explicitly specify material composition. It may be better to have automatic material survival rules at those design feature interaction regions. This study of material feature interaction can be greatly enhanced by a more detailed understanding of how physically different materials can be synthesized together and the resulting material properties.

Feature base for heterogeneous object design: A generic feature based design methodology is presented in this paper. Applications based on this methodology can be developed for many fields, such as prosthesis design, cutting tools design. Each specific application requires a dedicated design feature base. Building such feature-base needs design knowledge and experience in each specific field.

Feature recognition from heterogeneous object model: This paper presents a feature based fabrication methodology for layered manufacturing. Explicit feature information (both geometry and material composition) can facilitate process planning for layered manufacturing. In this work, feature information are assumed to be given. For those heterogeneous object models where explicit features are not give, a feature recognition module is necessary.

Applications of time dependent heterogeneous objects: Based on the physics based B-spline heterogeneous object modeling method, a time dependent heterogeneous object modeling system can be derived. Existing modeling methods only model the geometric deformation. The work in this research opens a new chapter in volume modeling. It models the dynamic material variation. This method can be used in applications where the material composition changes over time, particularly in bio-medical/diagnosis fields, such as bio-degradation.

Design/analysis integration: The physics based B-spline heterogeneous object modeling method uses finite element method to calculate the material composition at each control point of B-spline volume. That is to say, each B-spline volume has already had discretized elements. Therefore, transferring such a model for analysis preclude the need for meshing. In the meanwhile, such B-spline representation has also been extended to represent material properties. Therefore, an integrated design/analysis system can be derived based on this work without meshing process.

Process planning for the fabrication of heterogeneous objects: This paper only presents a methodology in layer decomposition to resolve the conflicting requirements between the surface quality and build time. The other process planning tasks for layered manufacturing, such as orientation selection, support creation and tool path generation, have to be addressed in the context of heterogeneous object fabrication. Existing methods have only addressed the issues in the fabrication of homogeneous objects. The variation in materials in heterogeneous objects creates a new dimension to these problems.

Acknowledgement

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