# Data Structure and Algorithms for Virtual Prototyping of Heterogeneous Objects

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## ABSTRACT

In contrast to traditional rapid prototyping of homogeneous objects, fabrication of heterogeneous objects (using layered manufacturing technologies) requires additional material information to be incorporated along with the object's geometries. The paper presents relevant data structures and algorithms for virtual prototyping of heterogeneous objects. Heterogeneous CAD models, which represent the ideal digital heterogeneous objects, are first described. Interrogation of the material compositions from the CAD models is then carried out at runtime. Voxels (with location-specific material properties) are subsequently created and maintained in a dynamic scan-line structure, layered-section structure and the virtual-object structure. The proposed data structures and the associate algorithms have been successfully applied in virtually prototyping of heterogeneous objects. Virtually fabricated heterogeneous object examples are provided.

**Keywords:** Rapid prototyping, virtual prototyping, heterogeneous material, heterogeneous objects, functionally graded material.

## 1. INTRODUCTION

The majority of the traditional engineering parts are made of the same uniform materials, e.g. copper cylinders or ceramic pistons, and these objects are generally termed as "homogeneous objects". Different from traditional engineering parts, heterogeneous objects refer to those objects made of multiple materials, with embedded sensors/actuators, with functionally graded material (FGM) distributions or other local compositional/structural variations.

Recent studies have shown that in some aspects heterogeneous objects prevail over homogeneous ones in terms of mechanical, thermal, electrical or combinations of these properties. For example, in aerospace applications, modern aerospace shuttle crafts are subjected to super high temperatures and enormous mechanical loads. In order to get better thermal properties, ceramic materials are preferred due to their high heat capacity and excellent corrosion resistance. However, ceramics are brittle and apt to break when too much force is applied. Conversely, metal materials have excellent strength, toughness and ductility but they are not good heat-resistant materials (for instance, the melting point of Aluminium is 660°C, whereas the exterior temperature of the space shuttle shell may exceed 1400°C [1]). In order to fulfil the critical requirements in both thermal and mechanical properties, metal substrates can be utilized as the skeletons and ceramic materials as coatings, so that both advantages can be achieved. In addition, sharp material changes around the coating interface can be further replaced with functionally graded material (FGM) distributions from pure metals to pure ceramics by continuously controlling the coating compositions. With such FGM based heterogeneous shells, abrupt stress concentrations can be eliminated and the adhesion strengths at the metal-ceramic interface can be increased.

The wide application of heterogeneous objects calls for systematic approaches in heterogeneous object design. Heterogeneous object modelling (CAD) [2-17], object property analysis/design evaluations (CAE) [18-28] and heterogeneous object fabrications (CAM) [29] have caught considerable research interest in the past.

This paper presents data structures and algorithms for virtual prototyping of objects with heterogeneous material distributions, which can be generally used for demonstrations/idea communications, CAD model validations and physical fabrication process simulations. The following sections of this paper are structured as follows: Section 2 presents the detailed data structures and associate algorithms for virtual prototyping of heterogeneous objects. A virtual heterogeneous prototype is represented with series of heterogeneous layers, which in turn are decomposed into heterogeneous scan lines and heterogeneous voxels. Algorithms for virtual prototype construction are expatiated with an example heterogeneous object. Section 3 presents some examples using the proposed algorithms and finally this paper is concluded in Section 4.

## 2. DATA STRUCTURES AND ALGORITHMS FOR VIRTUAL PROTOTYPING OF HETEROGENEOUS OBJECTS

### 2.1 Heterogeneous CAD Models

Different heterogeneous CAD models may require diverse data structures and algorithms in virtual fabrications.

Voxel based models, are possibly the most intuitive approach to represent heterogeneous objects. A heterogeneous object is explicitly represented with a collection of voxels. Each voxel represents a small cube in space, with a specific (usually homogeneous) material distribution. Medical data acquired from CT (Computerized Tomography) machine and MRI (Magnetic Resonance Imaging) devices are such typical examples. Voxel based models are suitable to represent highly heterogeneous objects whose material distributions are extremely irregular. However, one of the pitfalls of the voxel models is that the accuracy of the model is directly related to the data sampling resolutions. To get an accurate heterogeneous model, huge storage spaces are usually needed. In addition, the accuracy of a voxel model is fixed, and when a highly precise facility is used in fabrication, the model can not provided accurate data (both geometric and material) to take advantage of such high resolutions.

In this paper, we employ a type of unvalued heterogeneous CAD model in virtual fabrication, which theoretically, can provide appropriate geometric and material information at any resolutions. A heterogeneous object is represented by its geometries (rigorously this includes both the geometrical and topological information, for simplicity, we use "geometry" to denote both unless otherwise distinguished) and material distributions. Boundary representation (B-Rep) is used to describe the geometry information, and the material information is represented by a Heterogeneous Feature Tree (HFT) structure [8, 30]. A Heterogeneous Feature Tree is an organized structure composed of a collection of nodes, in which each node may have a collection of (or zero) child node(s). The HFT maintains the material variation dependencies among all the constructive heterogeneous features at different hierarchies. The material composition of a feature in a higher level is dependent on (or determined by) its child features, and the material compositions evaluated from each child tree are then blended at their parent level in the material evaluation process.

For example, the material distribution of the object shown in Fig. 1 (c) can be described with a HFT structure shown in Fig. 2. The object has an overall linear material gradation from the top to the bottom plane. The material distributions of the top and bottom planes are also defined with linear material gradations, with their bounding contours as material variation references.

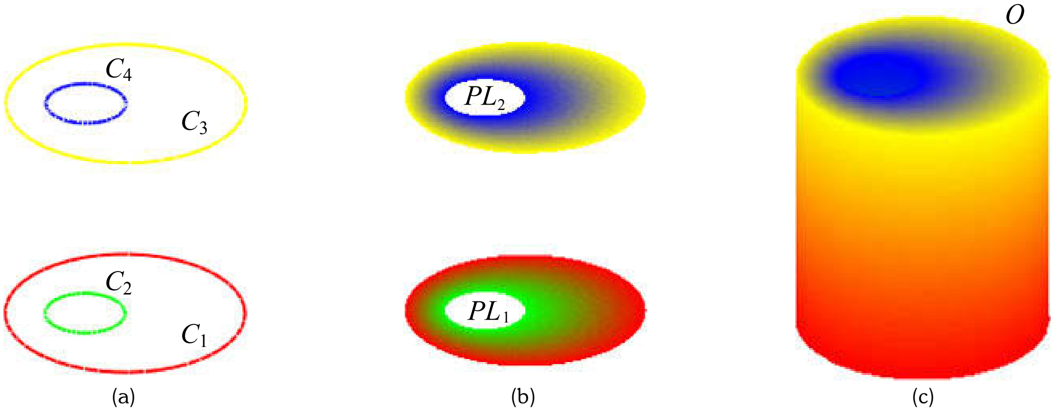


Fig. 1 Construction of a 3D heterogeneous cylinder with lofting operation. (a) Constructive heterogeneous features; (b) Output heterogeneous object; (c) Lofted cylinder.

Fig. 2 utilizes such hierarchical data structures to represent the material distributions, and with the aid of a recursive material evaluation algorithm (REMA)[8], the material composition of an arbitrary point P inside the object geometries can be evaluated at runtime. More detailed discussions on the details are beyond the scope of this paper and interested readers can find such technical details in [8].

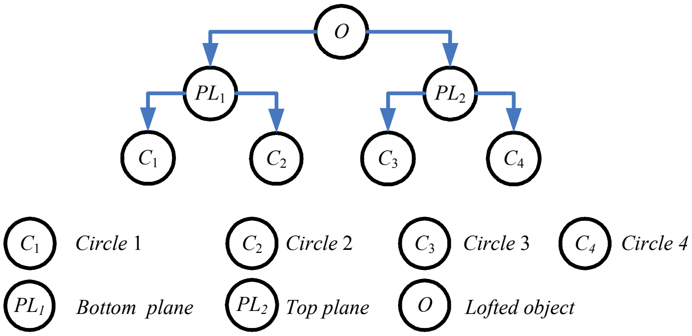


Fig. 2. Modeling a lofted cylinder with a HFT structure.

### 2.2 Virtual Prototyping of Heterogeneous Objects

Once the heterogeneous CAD models (B-Rep and the HFT structures) are available, virtual prototyping of heterogeneous object can be conducted with the following algorithm shown in Fig. 3. In this paper, we assume that the build orientation is determined either through user interactions or by optimizations obtained otherwise.

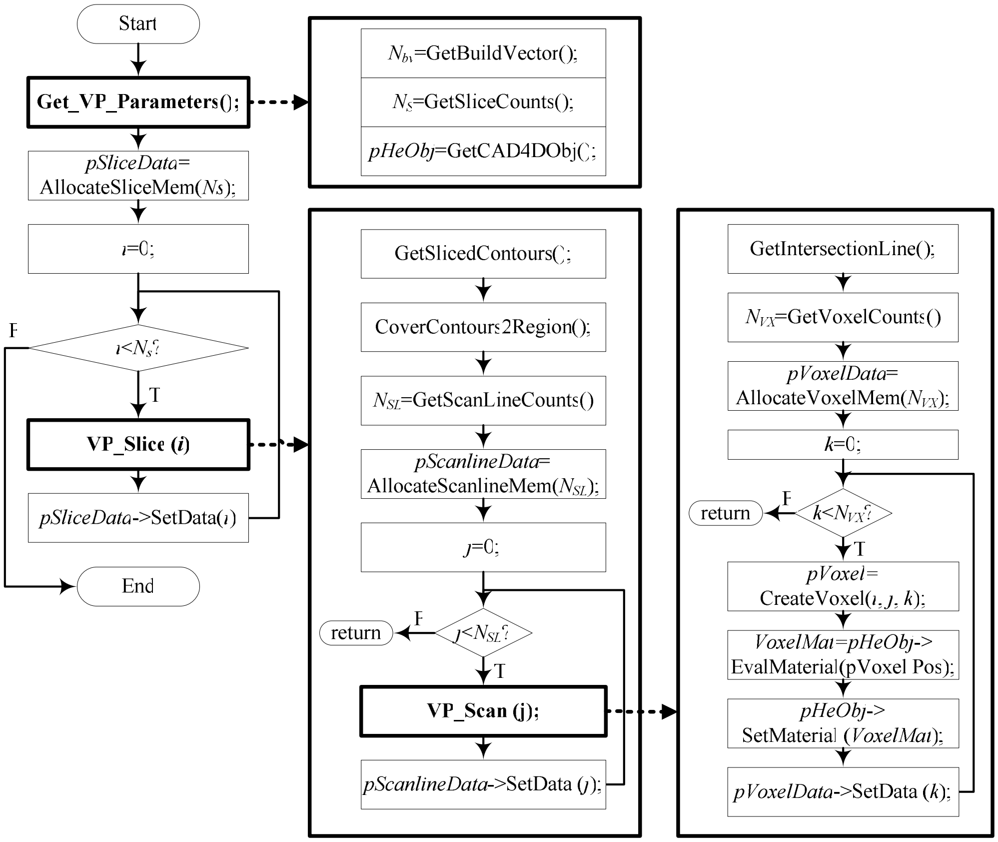


Fig. 3. Flow chart of the virtual prototyping algorithm.

- Prior to the VP data generations, some parameters are retrieved (e.g. the objects to be virtually fabricated (e.g. Fig. 4 (a))) or dynamically calculated (e.g. the number of slices to be fabricated NS). Memories are then allocated to store the slice data collections used during the virtual fabrication process.
- For each slice, the intersection contours of the section plane with the object geometries are first computed and then covered into a 2D region [31] (Fig. 4 (c)).
- The number of scan lines needed to cover the current region (NSL) is then calculated and memories are allocated to hold the scan line data collections for the 2D region. The region is then virtually fabricated through line-by-line scanning.
- Similarly, for each scan line, the number of voxels (NVX) needed to cover the scan line segments is computed and memories are allocated to store the voxel data collections.
- The spatial location of each voxel is then determined (from the object geometric information, the slice index i, the scan line index j and the voxel index k) and its material compositions are interrogated (from the CAD model using the material composition evaluation algorithms briefly described earlier, for more details, refer to [8] and [30]). Fig. 4 (b) shows the exact geometry and material information of the heterogeneous object in the current active slice, and Fig. 4 (d) shows the evaluated result (voxel collections) at a given resolution.
- All the voxels along a scan line are then sequentially saved into a linear voxel array. Similarly all the scan lines of a region and all the 2D slices are saved into scan line collections and slice collections for downstream visualizations and animations, as conceptually shown in Fig. 5.

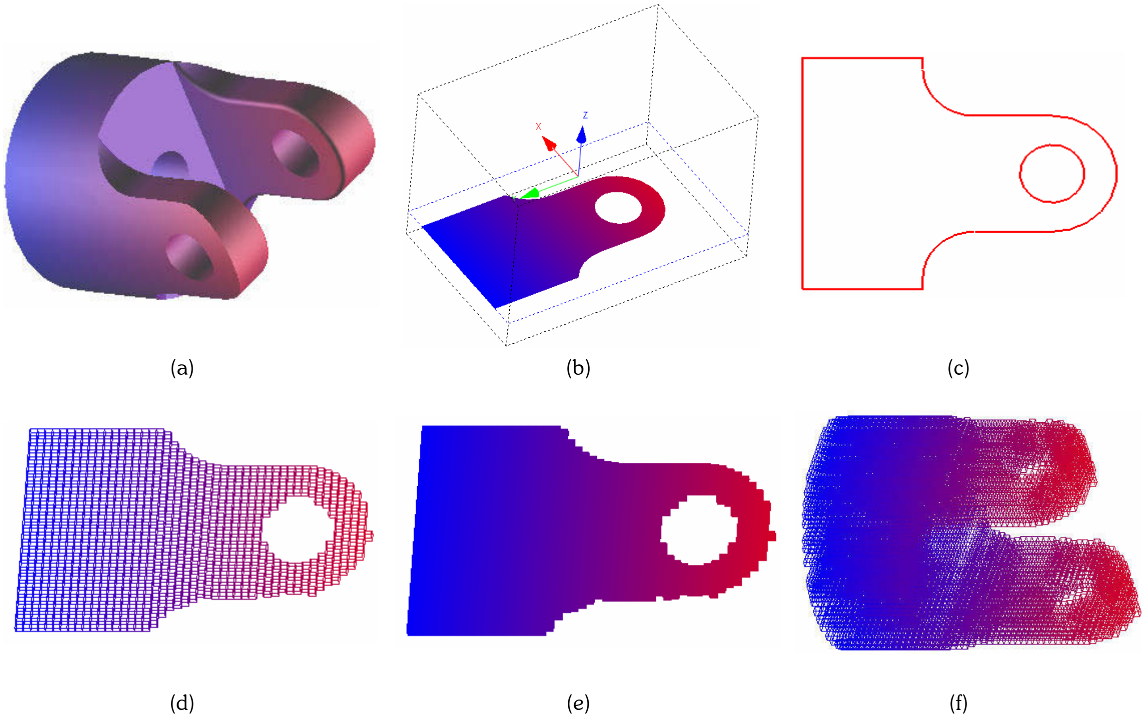


Fig. 4. Virtual prototyping of an example heterogeneous object. (a) An example object to be fabricated. (b) Exact geometry and material distributions of a demonstrative slice. (c) Section curves; (d) Covered 2D region and virtually fabricated slice. (e) Shaded view of (d). (f) the virtual digital prototype.

Fig. 4 illustrates an example object and the virtual prototyping process described as above. Fig. 4 (a) shows the object to be fabricated and Fig. 4 (b) illustrates a section view of the FGM object, with the exact geometry and material distributions visualized. The boundaries of this section are extracted and organized into a contour array, as shown in Fig. 4 (c). After covering the contours into a 2D solid, a planar section model of the object is obtained, whose material distribution is represented by the same HFT structure as the object to be virtually fabricated. Scan lines are then cast and intersected with the 2D FGM sections, and discrete voxels are generated. For each voxel, its material composition is evaluated by applying the aforementioned recursive material evaluation algorithm. Once the material properties (e.g. volume fractions) of a voxel/scan line are assigned, visualizations of the voxels along the scan line are updated. The same processes are repeated until the 2D section got fully scanned, and the sliced section view of the heterogeneous object is obtained, as shown in Fig. 4 (d) and (e). By carrying out the above operations layer by layer, the complete virtual digital prototype can be derived, as shown in Fig. 4 (f).

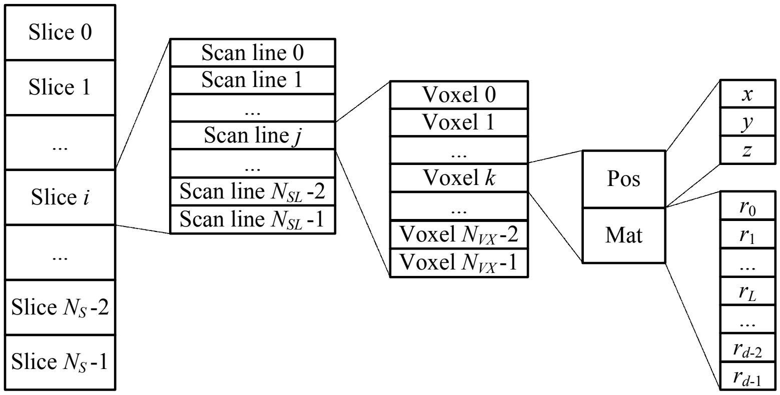
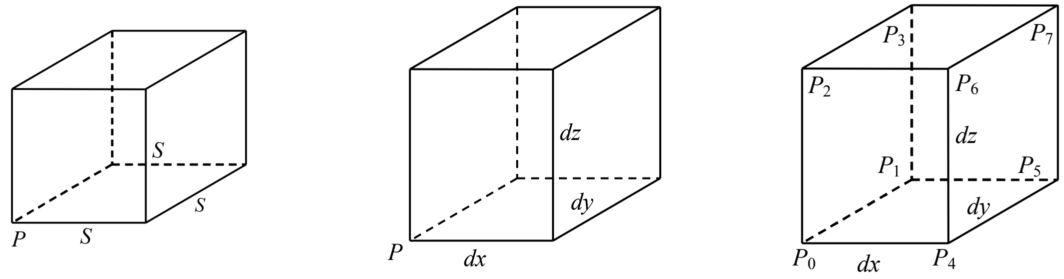


Fig. 5. Data structures used in virtual prototyping of heterogeneous objects.

The most commonly used voxel structure is shown in Fig. 6 (a), which has uniform size S (geometric resolutions) in all the x, y and z directions. The base location (anchor position) P of the voxel is represented by three scalars x, y and z, and the material composition of the voxel is represented by a k-dim vector [r1, r2 , … , rk], where k corresponds to the number of predefined primary materials [8]. Two variant types of voxels are shown in Fig. 6 (b) and (c). Fig. 6 (b) shows a voxel with different sizes along the x, y and z directions. Both the voxels in Fig. 6 (a) and (b) are assumed to be homogeneous in material compositions inside each voxel, whereas the voxel in Fig. 6 (c) uses interpolations (e.g. Bernstein polynomials [32]) of the material compositions defined at the eight vertices (P0 to P7).



(a) (b) (c)

Fig. 6. Voxel structures for VP of heterogeneous objects.

Note that in addition to the term “geometric resolution”, in Rapid Prototyping &Manufacturing (RP&M) of heterogeneous objects, the concept of “material resolution” also deserves particular attentions. Given the exact material compositions retrieved from the CAD model, the material resolution denotes the closest material compositions that can be offered/controlled by a specific facility (e.g. in VP context the rendering facility such as display monitors). In his PhD thesis, Siu [33] has discussed this topic and provided detailed solutions (such as truncation based scheme and interpolation based scheme) to address this problem. As Siu’s approach [33] is applicable to the VP of our heterogeneous models as well, therefore his algorithm is directly used in this paper and relevant technical details are omitted here for brevity reasons.

### 2.3 Process Simulation and Animations

Once the virtually fabricated model has been constructed, the complete virtual fabrication process can be simulated with additional trivial programming. Initially all the voxels can be configured to be invisible in the workspace and by "turning on" each voxel in each scan line/each slice with predefined time intervals, animations simulating the whole process can be generated.

An alternative approach to realize the process simulation is to "live show" the voxels right after their creations. After the location and compositions of each voxel are determined, the voxel is dynamically added to the rendering queue buffers, and messages are sent to the virtual workbench to signal the required display updates.

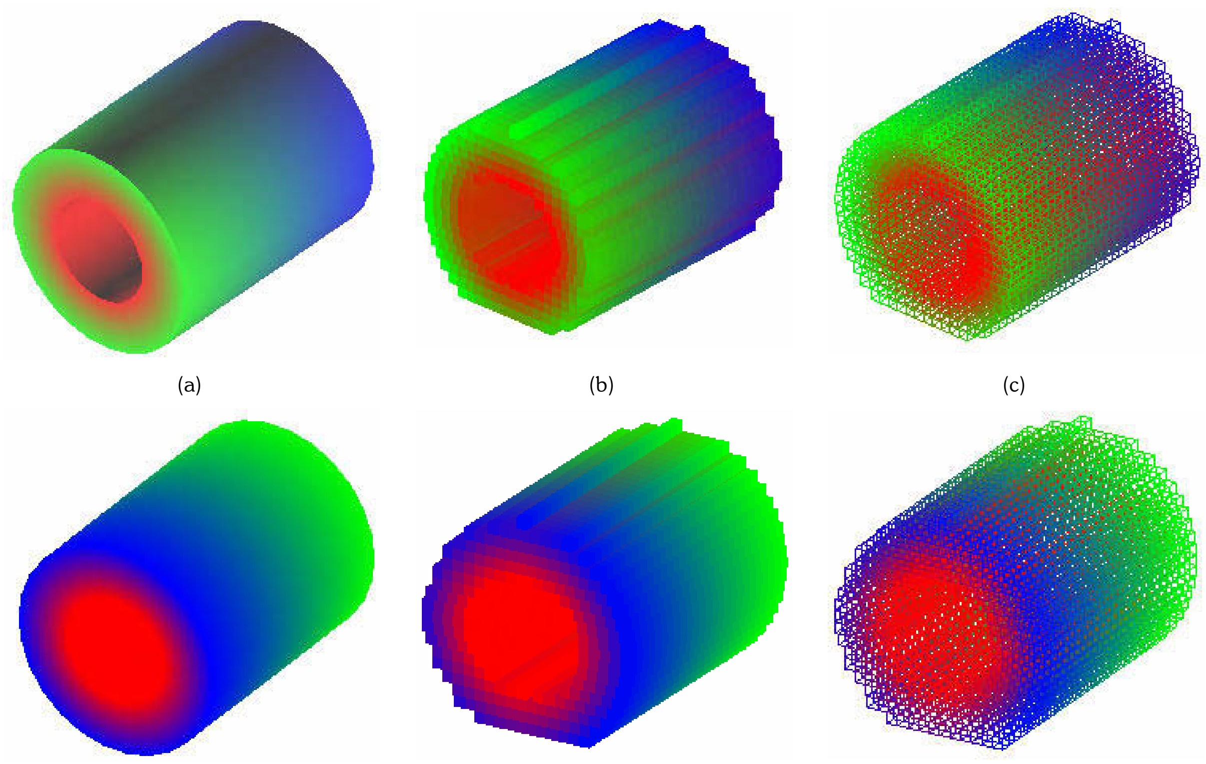
To facilitate other simultaneous modeling and viewing operations (for instance, during the virtual fabrication process, the end users may frequently change the viewing orientations to navigate in the workbench), multi-threaded programming [34, 35] is used to handle more than one operation at the same time.

### 2.4 Material Statistics

Some materials are expensive and mass stock of such materials increases the expenses of fabrication. Statistics on the required material quantities can be roughly estimated from the virtual prototyping models. This can be accomplished by accumulating the material compositions of all the voxels in the VP model. These data provide useful information necessary to the physical rapid prototyping and manufacturing.

## 3. EXAMPLES

Fig. 7 shows a heterogeneous object virtually fabricated with the presented virtual prototyping algorithm.

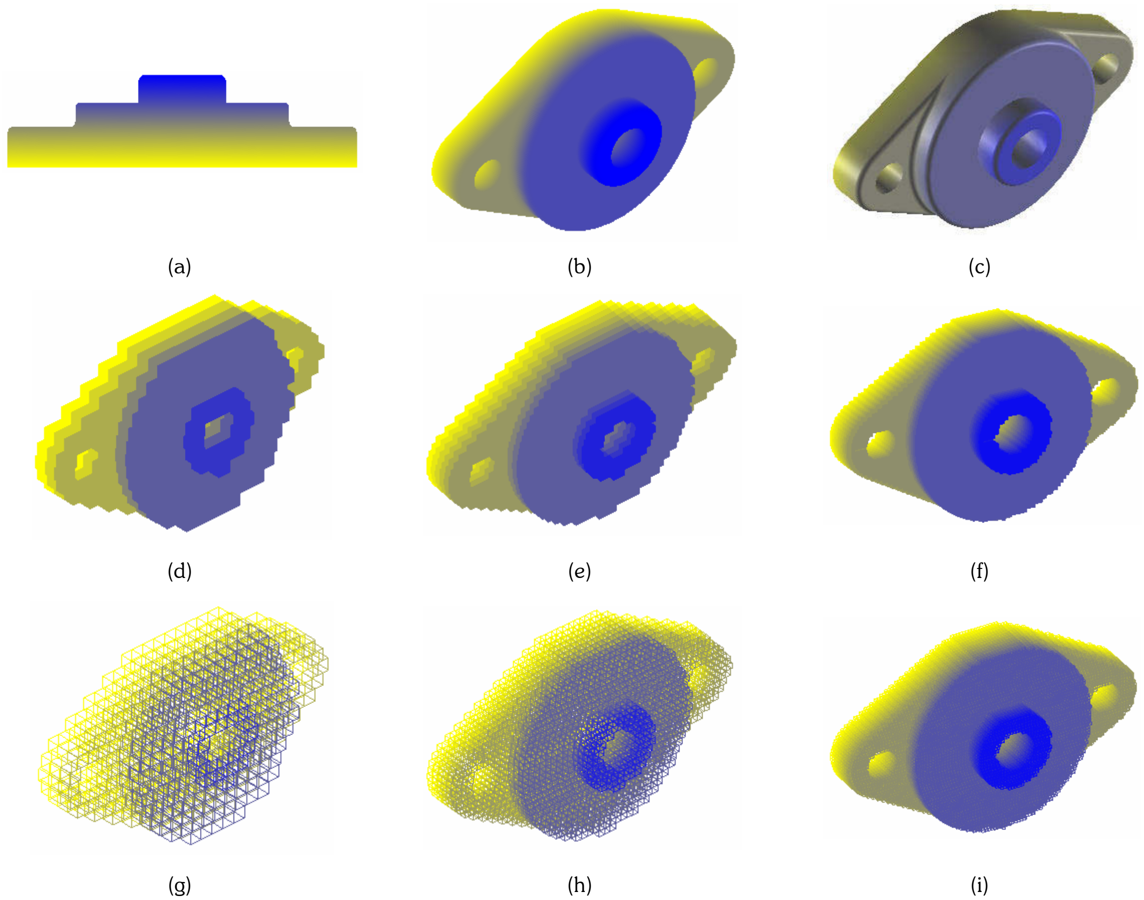


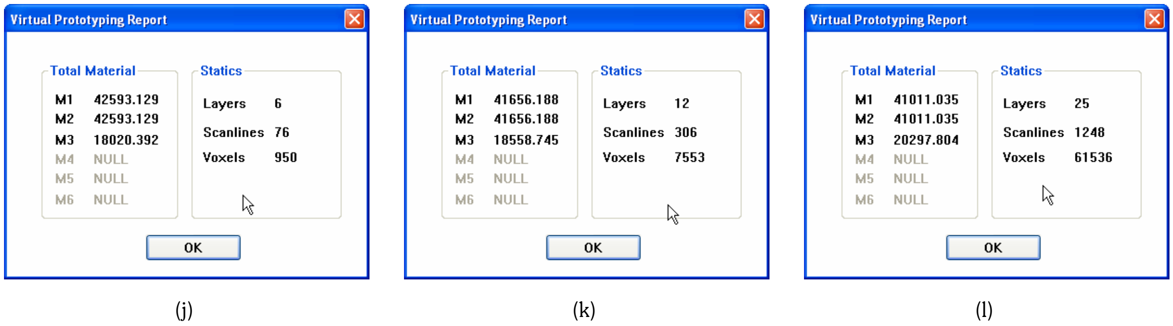
(a) (b) (c)

(d) (e) (f)

Fig. 7 An example heterogeneous object and virtually fabricated prototypes. (a) and (d) Heterogeneous CAD models; (b), (c), (e), (f) Virtually fabricated prototypes, viewed from two perspectives; (b), (e) Shaded views of the virtual prototype (c), (f) Wireframe view of the virtual prototype, viewed from two perspectives.

Fig. 8 shows another heterogeneous object virtually fabricated with different resolution voxels. Fig. 8 (j), (k) and (l) show the estimated quantities of the three primary materials. In this example, M1, M2 and M3 denote three primary materials used for modeling the material gradations (for instance, M1 is a ceramic material, M2 is a metal and M3 is plastic) and they are rendered with red, green and blue colors.





Virtual Prototyping Report

Total Material
M1 42593.129
M2 42593.129
M3 18020.392
M4 NULL
M5 NULL
M6 NULL

Statics
Layers 6
Scanlines 76
Voxels 950

Virtual Prototyping Report

Total Material
M1 41656.188
M2 41656.188
M3 18558.745
M4 NULL
M5 NULL
M6 NULL

Statics
Layers 12
Scanlines 306
Voxels 7553

Virtual Prototyping Report

Total Material
M1 41011.035
M2 41011.035
M3 20297.804
M4 NULL
M5 NULL
M6 NULL

Statics
Layers 25
Scanlines 1248
Voxels 61536

Fig. 8 Example heterogeneous objects fabricated from virtual prototyping. (a) The front view showing the 1D material gradation; (b) Shaded view of the heterogeneous model; (c) Shaded view of the heterogeneous model with lighting effect enabled; (d) to (i) Virtually fabricated object; (d) to (f) Shaded views; (g) to (i) Wire frame views. (j), (k), (l) Detailed report of the fabrication parameters for the case (d)/(g), (e)/(h) and (f)/(i) respectively.

## 4. CONCLUSIONS

Data structures and algorithms for virtual prototyping of heterogeneous objects are presented in this paper. Different from most of the existing RP algorithm, the proposed scheme can simulate the fabrication process of objects with inhomogeneous material distributions. Exact, unevaluated heterogeneous object representation is introduced to construct appropriate virtual prototypes at arbitrary pre-defined resolutions. In this sense, the proposed data representation is resolutions-independent and can help to assure sufficient precisions in terms of geometries as well as material accuracies. Detailed data structures and algorithms for the virtual prototype construction, process simulation, animation and statistics on the required material quantities are presented. Experiments show that the proposed methodologies can be effectively used to heterogeneous CAD model validation and physical fabrication process simulations.

## 5. ACKNOWLEGEMENT

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