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Heterogeneous object modeling with material convolution surfaces

Vikas Gupta [a,1], Puneet Tandon [b,*]

[a] Ch. Devi Lal Memorial Govt. Engg. College, Sirsa, India

[b] PDPM Indian Institute of Information Technology, Design & Manufacturing Jabalpur, India

HIGHLIGHTS

- A material convolution surface-based approach is presented for modeling complex heterogeneous objects.
- Complex one-dimensional material-distributions are modeled with material primitives and field functions.
- Schema for compound and irregular heterogeneities in two-and three-dimensions is formulated and outlined.
- We report a few examples of complex heterogeneous object modeling for the validation of proposed approach.

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ABSTRACT

The possibility to attain diverse applications from heterogeneous objects calls for a generic and systematic modeling approach for design, analysis and rapid manufacturing of heterogeneous objects. The available heterogeneous object modeling techniques model simple material-distributions only and just a few of them are capable of modeling heterogeneous objects with complex geometries. Even these approaches have also, at time, shown some glitches while modeling complex objects with compound and irregular material variations. This paper unfolds the development of a stand-alone convolution surface-based modeling approach to model complex heterogeneous objects with multi-functional heterogeneities, entailing stratified sub-analytic boundary-representation, convolution material primitives, membership functions and material-potential functions. One-dimensional (associative and non-associative) and compound two-and three-dimensional material-distribution schemas are formulated and outlined to model simple, compound and irregular material-distributions in simple/complex geometry objects. The paper also illustrates a few examples of modeling complex heterogeneous objects by implementing the approach using specialized languages and software tools.

1. Introduction

With the advent of heterogeneous objects (HO), diverse properties may be obtained and advantages of a number of materials can be fully exploited within a single object as per the desired functional requirements. Traditional limitations due to material incompatibility, like stress concentration, non-uniform thermal expansion, etc. can also be avoided with the fabrication of multi-functional components involving multi-fold material variations. Due to excellent performances and unique features of multi-functional objects, HO modeling has become very popular in recent years. Modeling of heterogeneous objects requires a strategy different than that adopted for homogeneous objects. It should be capable of providing varying material composition information along with part geometric information [1,2].

A number of theoretical representations, material function derivations and optimization techniques have been developed for heterogeneous object modeling. Most of the existing HO representations can be broadly classified into two categories: evaluated and unevaluated modeling. Evaluated models are inexact and represent the discrete objects of interest. Unevaluated models generally do not involve intensive spatial decompositions/subdivisions or discretizations, and theoretically, can provide sufficient fidelity in geometries and material-distributions. An approach to model multi-material objects based on R-m sets and R-m classes was proposed [3,4], primarily for application in layered manufacturing. Boolean operators were also defined to facilitate the modeling process. Jackson et al. [5] and Liu et al. [6] defined a local composition

* Corresponding author. Tel.: +91 761 2632 924 (O) +91 94253 24240; fax: +91 761 2632 924.

E-mail addresses: vikasbrcm@rediffmail.com (V. Gupta), ptandon@iiitdmj.ac.in (P. Tandon).

[1] Tel.: +919416434412.

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control (LCC) approach to represent heterogeneous objects, where a mesh model was divided into tetrahedra and different material compositions were evaluated on the nodes of each tetrahedron, by using Bernstein polynomials. Jackson et al. [5] proposed the finite element meshes to represent functionally graded material (FGM) in which volume of the object was decomposed into a collection of linear tetrahedra. Chiu and Tan [7] suggested a method based on material tree structure to store different compositions of an object. The material tree was later added to a data file to construct a modified file format suitable for rapid manufacturing. Huang et al. [8] had modeled FGM objects whose materials follow a distribution characterized by the generic Bezier curves. Qian and Dutta [9,10] proposed a feature-based modeling scheme to represent heterogeneous objects, by defining boundary conditions of a virtual diffusion problem in a solid. The work was further extended by Liu et al. [6], by taking parametric functions, in terms of distance(s) and functions, using Laplace equation, to smoothly blend various boundary conditions, through which designers could edit geometry and composition simultaneously. Marsan and Dutta [11] developed tensor product solids through heterogeneous solid modeling. Zhang et al. [12] optimized the material properties of components made of different materials. Feng et al. [13] developed a computer aided design (CAD) modeling system for the fabrication of functional components with multi-material properties. Kou and Tan [14] proposed a hierarchical representation scheme, for designing and optimizing objects composed of multiple regions, with continuously varying material properties. This approach used boundary-representation (B-rep) method to represent geometry and a heterogeneous feature tree to express the material-distributions. Zhou and Lu [15] used distance as the key parameter to distribute the materials in a heterogeneous object. A level-set based variational scheme was proposed [16], which adapted a variational model as the objective function to locate any point in the material region of a well-defined gradient or on the boundary edges and surfaces of discontinuities; the set of discontinuities was represented implicitly, using a multi-phase level-set model. Tsukanov and Shapiro [17] presented a mesh-free approach based on the generalized Taylor series expansion of a distance field, to model and analyze a heterogeneous object, which satisfied the prescribed material conditions on a finite collection of material features and global constraints. Liu [18] verified the approaches in commercial software packages, such as SolidWorks and Unigraphics. A commercial CAD package independent system was developed by Qian and Dutta [10] to deal with the HO modeling.

Apart from modeling; design, analysis, and fabrication of heterogeneous objects also depend upon geometric as well as material-distribution information in the object domain. The issues related to design, optimization, analysis and selection of additive manufacturing (AM) process for HO were discussed in [19]. Jonathan and Hod [20,21] had discussed about design and analysis of heterogeneous objects with multi-material topological optimization. A few rapid prototyping (RP) techniques have the capability to fabricate heterogeneous objects but they also require heterogeneous CAD models for part fabrication. Issues related to slice generation had been discussed for rapid manufacturing of heterogeneous objects along with the data retrieval algorithm [22]. To the best of our understanding, most of the existing computer aided models are insufficient to provide generic and uniform representation of heterogeneous objects and there is hardly any effective HO model available that can be integrated with visualization, analysis and rapid prototyping set-ups.

Most of the existing representations can model simple one-dimensional (1D) material-distributions in objects having simple geometry, which generally exhibit limited functional performances, while a few approaches claim that complex heterogeneous objects could be constructed for geometric complexities only. Complex heterogeneous objects with compound material variations, i.e., two-and three-dimensional material-distributions offer great flexibility for multi-fold applications. For example, objects subjected to multiple loading, i.e., tensile, bending and shear require multi-functional properties to counter these loads and get optimal results in all aspects. These multi-functional properties can only be achieved with two-or three-dimensional material-distributions. In nature also, objects with compound material-distributions exist, e.g., wood, human bone, rock. Multi-functional heterogeneous objects call for a systematic approach in modeling compound material variations. A few approaches demonstrate the possibility of modeling compound material-distributions, however most of these methods are rather ad hoc or case specific. Thus, modeling compound material-distributions still remains to be an open problem. Irregular material heterogeneity is another issue which seems to gain increasing importance in recent studies. However, this problem has not been so thoroughly addressed in the past and thus, deserves attention and research efforts. In its current state, modeling complex heterogeneous objects with compound and irregular heterogeneities is still a non-trivial task. Thus, development of a smooth and flexible HO model for compound and irregular material-distributions and its downward applications in design, analysis and manufacturing are a few residual issues that require more focus to realize complex multi-functional components.

These challenges motivate us to seek better solutions for representing and modeling complex heterogeneous objects to offer compound and irregular material variations. Specifically, we hope to provide a uniform and generic methodology to represent complex geometry objects with compound material-distributions, so that two-dimensional (2D) or three-dimensional (3D) heterogeneities can be modeled. Employing our previous work [23–25], gradient reference approach has been reformed and described using the concept of convolution surfaces (see Section 2). The equivalent material convolution surfaces are introduced using membership and material-potential functions. Section 3 focuses on modeling 1D associative and non-associative material-distribution in the object domain. Sections 4 and 5 illustrate the methodology of modeling compound material-distribution in two-and three-dimensions respectively. Section 6 discusses the system implementation of the proposed approach and presents a few examples of complex material-distribution for the validation of the work. Various problems and limitations of the proposed approach are discussed in Section 7. Finally, the paper is concluded in Section 8.

2. Heterogeneous object modeling with material convolution surfaces

The proposed approach is general and uniform if used to model heterogeneous objects and is more flexible to create a variety of heterogeneous objects in contrast to already presented methods [7,13,26,20,14,4]. For modeling any HO, this approach simply requires addressing the following aspects: heterogeneous enclosure, grading enclosure and material convolution surfaces.

2.1. Heterogeneous enclosure and grading enclosure

A number of representation schemes are available for defining the geometry of heterogeneous region in an object. Boundary-representation (B-Rep) has emerged as one of the most powerful and flexible representation schemes for geometric modeling of manifold models. With B-Rep, all objects can be represented by their boundaries. In this approach, surface, edges, vertices of solid objects are represented explicitly, and the topological information for geometrical relationship between these fundamental