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Equal distance offset approach to representing and process planning for solid freeform fabrication of functionally graded materials

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Abstract

This paper deals with the representation and process planning for solid freeform fabrication (SFF) of 3D functionally graded material (FGM) objects. A novel approach of representation and process planning for SFF of FGM objects, termed as equal distance offset (EDO), is proposed. In EDO, a neutral arbitrary 3D CAD model is adaptively sliced into a series of 2D layers. Within each layer, 2D material gradients are designed and represented via dividing the 2D shape into several sub-regions enclosed by iso-composition contours. If needed, the material composition gradient within each of the sub-regions can be further specified by applying the equal distance offset algorithm to each sub-region. Using this approach, an arbitrary-shaped 3D FGM object with linear or non-linear composition gradients can be represented and fabricated via suitable SFF machines.

Keywords: Equal distance offset; Functionally graded materials; Solid freeform fabrication; Representation; Process planning; Arbitrary-shaped objects

1. Introduction

Solid Freeform Fabrication (SFF) has great potential to fabricate heterogeneous objects. In recent years, SFF has been increasingly used in biomaterial related applications such as dental restorations, orthopedic implants, scaffolds, and drug delivery where complex-shaped objects made of multiple materials or functionally graded materials are typically desired. To model a functionally graded material (FGM) object, a CAD system should first be able to know the material composition of each point of the object. But unfortunately, the traditional geometrical solid modeling has focused on modeling the geometry and topology of the object with no information of the material composition. The most commonly used representation schemes for the traditional models are the Constructive Solid Geometry (CSG), Boundary Representation (B-Rep), Decomposition Representation (D-Rep), or a hybrid of these schemes. All these representation methods are not capable of including the material composition information.

Recently, several FGM modeling and representation methods have been reported [1–13]. These methods have allowed designers to design not only the geometry, but also the material composition of an object. However, all of these methods have mainly focused on simple-shaped FGM objects with simple gradient schemes. It is very difficult (or impossible in some cases) to use these methods to process arbitrary-shaped FGM objects with authentic 3D gradients. Kumar and Dutta [1–3] first proposed an approach for modeling heterogeneous objects by using regular sets (r-sets) extended to include composition r_m-sets with accompanying Boolean operators. A r_m-object is defined as a finite collection of these r_m-sets with each r_m-set being a material domain with an analytical material function. Pegna and Sali [5] proposed a model by representing multi-material models as point set including Cartesian coordinates plus material composition. Jackson et al. [6] exploited an approach to produce functionally graded material objects based on sub-dividing a model into sub-regions (tetrahedrons). For each region, an analytical composition blending function is assigned to define the material composition variation. Patil et al. [7] presented an information model to represent

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heterogeneous objects using the information modeling technology developed for the STandard for the Exchange of Product (STEP) model data. Shin et al. [9,10] presented a hybrid approach named constructive representation, which retains all the information of heterogeneous models involved in the construction tree so that it is possible to detect and solve any material discontinuity problem occurring at the interfaces. Although these approaches can theoretically model the FGM object with complex gradients, they suffer from the disadvantages of requiring an enormous amount of storage space.

Unlike the heterogeneous object representation schemes mentioned above, Park et al. [8] presented a volumetric multi-texturing representation scheme. Siu and Tan [11,12] proposed a 'source-based' heterogeneous solid modeling scheme and defined extended operations (e.g. insertion, merge, and immersion) in addition to the CSG type Boolean operations to model the grading sources. Zhou et al. [13] presented a STEP-based modeling and processing method for FGMs. In these methods [11–13], the material composition is expressed in terms of distance functions with a single entity or multiple entities as the reference(s). Compared to finite cell, *r*-sets, or point set approaches [1–3,5–7,9,10], storing material information in terms of distance functions has greatly saved much memory. In spite of this advantage, the method proposed by Siu and Tan [11,12] can only be used for FGMs with simple geometry and composition gradients because the reference for the distance function is a simple geometrical shape such as a point, a plane, a line, or a regular surface. Similarly, the method by Zhou et al. [13] is also limited to FGMs with relatively simple geometry and composition gradients, because different compositions may be obtained at the same point or the composition may not be the desired one when the multiple references must be used for complex-shaped objects. Thus, it is necessary to develop new representation and processing methods for modeling FGMs so as to meet the requirement of modeling and fabrication of 3D complex-shaped FGM objects.

In this paper, a novel approach of representation and process planning for SFF of FGMs, termed as equal distance offset (EDO), is developed. In EDO, a neutral arbitrary 3D CAD model is adaptively sliced into a series of 2D layers. Within each layer, 2D material gradients are represented via dividing the 2D shape into several sub-regions enclosed by iso-composition boundaries, which is then followed by applying the equal distance offset algorithm to each sub-region. Using this approach, an arbitrary-shaped 3D FGM object with linear or non-linear composition gradients can be represented and fabricated via suitable SFF machines. The framework established in this study will pave the way for further development of the EDO approach to address more complex situations than what has been discussed in this study. The framework of the EDO approach is described in the following several sections.

2. Reconstruction of neutral complex-shaped 3D objects

In most cases, practical complex-shaped 3D modeling will start with medical computed tomography (CT) images, any commercial CAD modelers (such as EDS UGS NX, Pro/E, etc.), or point clouds obtained from a coordinate measuring machine (CMM). For medical applications, the medical CT images that are obtained from patient specific implants can provide detailed information about the regional structure and function of the patient implants. Alternatively, for general purposes, it can start with any commercial CAD modelers or point clouds from CMM. A different modeling approach can be selected for different data sources.

For the medical CT images, commercial software, such as 3D-Doctor (Able Software Corp. Lexington, MA, USA) or Mimics (Materialise, Belgium), can be used to reconstruct the 3D CAD model. In order to accomplish the 3D CAD reconstruction, the 3D model needs to be sliced into a series of 2D layers first. These slices should then be segmented to separate the various tissues according to the optimized gray tone threshold. After this, the connected components analysis needs to be done so that the topological relationship between different tissues can be successfully established. Once all slices have been processed, 3D volumetric models can be easily generated based on the Computer-Aided Geometrical Design (CAGD) theory and data fitting methods. For the point clouds data source, a 3D model can also be built using some commercial software such as Magics RP (Materialise, Belgium). It is noted that there is no material information included in this stage of the 3D CAD model. Thus, the next step is to integrate the material information into the CAD model.

3. The EDO approach to designing and representing 3D graded objects

In order to integrate the material information into the neutral freeform CAD model, the 3D CAD model should be translated into IGES format, which is then discretized into a series of slices along the building direction (set it in the *Z*-direction) using adaptive slicing method [14], and the layer thickness here will be determined by the *Z*-directional local slope and the desired gradient step-width in the *Z*-direction. Then, for each thin slice, only 2D gradients need to be designed and represented. Fig. 1 shows one of the most complicated situations, in which the thin slice consists of one internal boundary C_i and one external boundary C_e, and the material composition is