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Material feature representation and identification with composite surfacelets

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Abstract

Computer-aided materials design requires new modeling approaches to characterize and represent fine-grained geometric structures and material compositions at multiple scales. Recently, a dual-Rep approach was developed to model materials microstructures based on a new basis function, called surfacelet. As a combination of implicit surface and wavelets, surfacelets can efficiently identify and represent planar, cylindrical, and ellipsoidal geometries in material microstructures and describe the distribution of compositions and properties. In this paper, these primitive surfacelets are extended and composite surfacelets are proposed to model more complex geometries. Composite surfacelets are constructed by Boolean operations on the primitives. The surfacelet transform is applied to match geometric features in three-dimensional images. The composition of the material near the identified features can then be modeled. A cubic surfacelet and a v-joint surfacelet are developed to demonstrate the reverse engineering process of retrieving material compositions from material images.

Keywords: Heterogeneous modeling; Implicit surface; Feature identification; Surfacelet transform

1. Introduction

The application of heterogeneous materials has become common in modern product design such as composites and porous media. Computational design tools for such materials, with higher complexity than traditional homogeneous ones, will be a critical component in the realization of modern products with complex functions systematically. It is foreseen that future computer-aided design systems will include the modules for materials design so that the design of functional materials and structures can be integrated for optimal product development.

In the integrated materials-product design, not only a multi-scale modeling method is needed to represent material microstructures in computer, it is also important to allow for integrated reverse engineering so that models reconstructed from material images can be modified and optimized, because imaging techniques have been the major methods to characterize microstructures and properties in materials design. Therefore, it is critical that the geometric features of interest as microstructures can be easily identified and extracted from the images. Those geometric features embody the key characteristics of physical properties in materials design. The modification and optimization of the parameters in those features are the major means to engineer materials to meet the design target. Additionally, the successful identification and representation of the features are important for the abstraction and simplification of the material composition distributions in modeling. Therefore, an integrated and efficient approach for feature identification, modeling, and analysis for materials and microstructures is the goal of this research.

A new dual-Rep modeling approach for materials design was recently proposed to represent property distributions in heterogeneous materials [1]. The core component of this representation is a new basis function, called surfacelet. A surfacelet is a combination of implicit surface and wavelet basis. The surfacelet-based modeling approach enables us to

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capture material distributions at multiple scales. The corresponding reverse engineering method to identify features and reconstruct surfacelet models directly from material images was also developed. This construction process is based on a so-called *surfacelet transform*. The surfacelet formulation will be introduced in Section 2.3 in details.

In our previous work [1–3], three primitive surfacelets (planar, cylindrical, and ellipsoidal) were proposed. It has been demonstrated that with the properly chosen surfacelets, geometric features in images can be identified. For instance, the cylindrical surfacelet can be used to recognize fibers in composite materials. The 3D ridgelet with the planar shape can find orientations of grain boundaries in polycrystalline structures. However, in more general heterogeneous materials, the geometric features in materials can be more complex than some primitive shapes. Identifying the locations and orientations of complex features by primitives becomes inefficient and imprecise. In this paper, the concept of composite surfacelets is proposed, where different combinations of existing surfacelets can be used to construct new surfacelets with more complex geometries. Compared to the primitive shapes in the original surfacelet formulation, composite surfacelets allow for modeling complex geometries with reduced surfacelet parameter dimensions, because the combined primitives are treated with rigid-body transformation during translation and rotation operations. Therefore, there is a need of more complex surfacelets than the primitives. Surfacelets with a better match of complex features can improve the efficiency and accuracy of feature recognition. The extension of the available surfacelets also increases the flexibility of the surfacelet model for different materials.

It is desirable that the surfacelet model can be applied to both design new materials and redesign existing ones. In reverse engineering, the identified geometric features provide the basic structural information of material composition as boundaries and interfaces. Yet, more detailed material composition information such as gradient and distribution should also be modeled in addition to the geometric features. The surfacelet model provides an abstraction of such information in the parametric form so that structure–property relationship can be established. With the parametric model, material property and performance can be optimized by choosing the best composition and distribution with the optimal shape parameters.

In this paper, the concept of composite surfacelet is demonstrated by two specific ones, cubic and v-joint surfacelets. The cubic surfacelet is constructed from six planar ridgelets, whereas the v-joint surfacelet is constructed from two cubic surfacelets. These two composite surfacelets are then used for the identification of complex microstructural features such as in composites with their implicit surface components. The distribution of materials in the interphase region of composites between two adjacent materials is modeled with the wavelet component from the feature identification results, which is also demonstrated. The novelty of the proposed approach is that the new concept of composite surfacelet allows for identifying and modeling of complex microstructures and heterogeneous material distributions with high-level abstraction from images by several parameters, which cannot be done with traditional image-based feature recognition approaches.

In the remainder of the paper, a literature review of the most relevant work is given in Section 2. The details of surfacelet formulation and surfacelet based material feature identification and modeling are also described. In Section 3, the construction and representation of the cubic v-joint surfacelet are described. The methods of applying the cubic and v-joint surfacelets in feature identification are presented in Sections 4 and 5 respectively. In Section 6, examples are given to illustrate how composite surfacelets can be used in modeling distributions of materials.

2. Background

2.1. Heterogeneous materials and multiscale modeling

Various modeling methods for solid heterogeneous materials have been proposed [4], such as volume meshes or voxels [5,6], property interpolation [7–9], local feature compositions [10–13], implicit surface blending [14,15], multiscale porous modeling [16–19], and multi-phase stochastic geometry based on voxels [20], surfaces [21], and Markov random field [22]. Those methods focused on representation of geometries or continuous distributions of volume composition, whereas the feature identification of materials was not considered.

2.2. Image-based feature recognition methods

Edges define the boundaries between regions in an image, which help with feature recognition. The edge detection methods [23,24] can be categorized into two groups: search-based and zero-crossing based. The search-based methods capture the feature edges by first computing edge strength and then searching for the local maxima in a direction to match the edge profile. The edge strength and searching direction can be measured and defined in different forms, such as the magnitude and the direction of the gradient of the image intensity. The gradient is usually represented by the first order derivative. On the other hand, the zero-crossing based methods search for zero crossings based on the second-order derivatives to detect feature edges.

Other methods of identifying geometric features from images have also been developed. For instance, the Radon transform [25] has been applied to identify lines in 2D images [26,27]. Similarly, the Hough transform was applied to recognize spherical features in 3D images [28].

For the purpose of materials design, not only the pixels on the feature edges need to be recognized, it is also important to represent geometric information, such as shapes, dimensions, locations and orientations, of the features at a higher-level abstraction than just pixels. Edge detection methods only extract feature boundaries as pixels. We also need to detect more complex features than simple linear and spherical shapes. The feature identification approach based on composite