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Design of Porous Micro-Structures using Curvature Analysis for Additive-Manufacturing

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Abstract

The emerging field of additive manufacturing with bio-compatible materials has led to personalized design of porous micro-structures used in healthcare. Complex micro-structures are characterized by freeform surfaces and spatially varying porosity. Currently, there is no CAD system that can handle the design of micro-structures due to their high complexity. This paper describes a direct expansion of our research on *generating 3D adaptive models of porous micro-structures*. Using this approach, a designer can either manually select a Region of Interest (ROI), or define a curvature based criterion for selecting ROI while defining its level of detail. In the proposed approach, the multi-resolution volumetric model is based on designing a customized model, composed of the following stages (a) Reconstructing a multi-resolution volumetric model of a porous structure; (b) Defining ROIs and their resolution properties; and (c) Constructing an adaptive model. The feasibility of the proposed method is demonstrated on 3D models of porous micro-structures. These models are characterized by a large amount of detail and geometrical complexity. The proposed method has been applied on bone models that were reconstructed from micro-CT images. The proposed approach facilitates the porous characteristic and enables local reduction of the model complexity while optimizing the accuracy. For additive manufacturing application, the approach can be used for designing a porous micro-structure with reduced material volume while eliminating irrelevant geometric features.

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Keywords: multi-resolution modeling; personalized design; porous micro-structures; bone scaffolds; Design for additive manufacturing

1. Introduction

Multi-resolution volumetric modeling is applied in a variety of fields, including additive manufacturing, computer vision, virtual reality, finite element analysis and CAD. In recent years the significance of multi-resolution modeling has increased due to the ability of creating highly detailed models. It increases the effectiveness of computation, transmission, storage and visualization of the geometric model. Visualizing a high resolution model is time consuming and requires high computer resources. In order to cope with this challenge an adaptive method is required. It enables to select Regions of Interest (ROI) with desired resolutions. In this manner an artificial fusion between different resolutions is generated.

Volumetric hierarchical representations allow a bi-directional transition from a macro-resolution model to a micro-resolution model. The most common hierarchical multi-resolution data structures for 2D images and 3D volumes are Quadtree and Octree, respectively. Their main principle is the recursive decomposition of space by a factor of two for each axis [1, 2]. These data structures are also compatible for methods which generate adaptive multi-resolution models. The ROI selection process can be either manual or based on geometric properties.

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In the field of computer graphics and CAD, the geometrical characteristics of surfaces play an important role in many applications such as: feature extraction and suggestive contouring. Curvature is one of the most important surface characteristic. For continuous representation of parameterized surfaces the challenge of deriving shape characteristics can be expressed in a closed form formula of differential geometry. However, for discrete surfaces, represented as volumetric voxel model or by a triangular mesh, an approximation must be made. For volumetric voxel models, to the best of our knowledge, there is no direct method that approximates the voxel curvature. Therefore, in order to approximate the curvature, first the underlying surface must be approximated.

2. Approach

In this research the representation method for Quadtree and Octree proposed by Gargantini [3] has been used. The result of this method is a structure, from which the path to each node along the hierarchy can be extracted. The hierarchical nature of the tree structure is based on an explicit representation of hierarchical levels of detail. The lowest level of detail is the root of the tree. The highest level of detail is the leaves of the tree. An extension of Podshivalov et al approach [4-6] was made, generating the hierarchical structure in a bottom-up approach and storing each level of detail separately. A mask field was introduced for each node and was populated after selecting a region of interest (ROI). The Area of Interest (AOI) was defined in an image, while the Volume of Interest (VOI) was defined in a volume. The mask was populated only for nodes that are inside the ROI. The mask represents the level of detail (LOD) for each node. This mask is the base for an adaptive method and enables the visualization of nodes from multiple levels according to the ROI.

When generating a new upper level there is a need to preserve the mask by finding the nonzero minimum of the mask value from all child nodes and storing it in the ancestor node. This method ensures that if a part of an ancestor is required to be at a certain LOD then each of its children will be accordingly displayed at the maximum allowed LOD. An outline of the adaptive method in the form of a block diagram is depicted Fig. 1

The approach is not limited in the aspect of ROI geometry or the LOD distribution. In previous work [7] four manual, user defined ROIs, were introduced: a) rectangular AOI with a constant LOD; b) circular AOI with a linear change of LOD between center and circumference; c) cuboid VOI with constant LOD; and d) spherical VOI with linear change of LOD between center and bounding surface.

In this work, an ROI selection criteria based on surface curvature is proposed. For volumetric voxel models there is no direct method to approximate the voxel curvature. Therefore, in order to approximate the curvature, first the underlying surface is typically approximated. The "*marching cubes*" algorithm [8] was used for approximating the underlying surface as a triangular mesh. A fairing algorithm [9] was then used to smooth the stair like affect created when approximating the volumetric representation as a triangle mesh. Finally, Rusinkiewicz curvature estimating algorithm [10] was used to retrieve the curvature tensor and principal curvature in each vertex. The curvature based ROI selection criterion is applied on each voxel. Visualization of the principal curvatures is performed using a color coding scheme. For each vertex in the mesh, the principal curvatures k_1 and k_2 were examined.

Each vertex color is determined by a linear interpolation between nine pairs of control values. These control values correspond to all possible combinations, positive, zero and negative, of k_1 and k_2. The result of the interpolation is depicted in Fig. 2. The color coding scheme was chosen this way in an effort to represent both principal curvatures in a single color map.

The calculation of levels of detail requires conversions and manipulations of the data in order to preserve topological information. The 2D and 3D space was defined according to definition 2.1 given by Kong [11], who describes the adjacency for elements which are full and elements which are empty in order to prevent topological paradoxes. The topological preservation process uses the image shrinking algorithm described by Jia et al [12]. The algorithm examines the effect of changing a node's B/W color on the connectivity of its surrounding node neighbours. Fundamentally, this introduces an additional B/W color constraint in images and volume constraint for 3D models when traversing from a higher resolution to a lower one. Finally, the processed model undergoes through a visualization stage where hexahedral faces are drawn on a 2D plane or in a 3D space. The size of the faces is determined by its LOD parameters. This process results in an adaptive model.

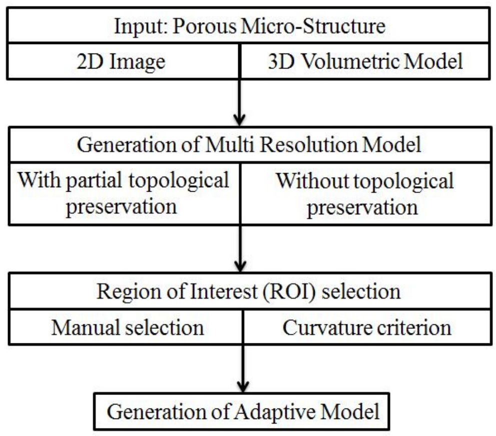

Fig. 1. Block diagram of the adaptation method