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Design of Adaptive Porous Micro-structures for Additive Manufacturing

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Abstract

The emerging field of additive manufacturing with biocompatible materials has led to customized design of porous micro-structures. Complex micro-structures are characterized by freeform surfaces and spatially varying porosity. Today, there is no CAD system that can handle the design of these microstructures due to their high complexity. In this paper we propose a novel approach for generating a 3D adaptive model of a porous micro-structure based on predefined design. Using our approach a designer can manually select a region of interest (ROI) and define its porosity. In the core of our approach, the multi-resolution volumetric model is used. The generation of an adaptive model may contain topological changes that should be considered. In our approach, the process of designing a customized model is composed of the following stages (a) constructing a multi-resolution volumetric model of a porous structure (b) defining regions of interest (ROI) and their resolution properties (c) constructing the adaptive model. In this research, the approach was initially tested on 2D models and then extended to 3D models. The resulted adapted model can be used for design, mechanical analysis and manufacturing. The feasibility of the method has been applied on bone models that were reconstructed from micro-CT images.

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Keywords: multi-resolution modeling; custom design; porous micro-structures; bone scaffolds;

1. Introduction

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

Volumetric 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 four for Quadtrees and of eight for Octrees [1,2]. These data structures are also compatible for the implementation of an adaptive method and therefore allow the generation of an adaptive multi-resolution model.

2. Approach

In this research we have used the representation scheme for Quadtrees and Octrees proposed by Gargantini [3], which was also implemented by Podshivalov et al [4] for the representation of 2D images and 3D volumes. The result

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of this scheme is a structure, defining the path to each node along the hierarchy. We have applied this structure for each node. The hierarchical nature of the tree structure allows a distinction between different 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. We extended Podshivalov et al approach [4-6], generating the hierarchical structure in a bottom-up approach and having each level of detail separately. A mask field is introduced for each node and is populated after selecting a region of interest (ROI). The Area of Interest (AOI) is defined in an image, while the Volume of Interest (VOI) is defined in a volume. The mask is populated only for nodes that are inside the ROI. The mask is essentially a field of levels of detail (LOD) for each node. This mask field is the base for our adaptive method and allows 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 store it in the ancestor node (gradually descending according to the tree structure). 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. Fig. 1 shows an example of the mask preservation in the matrix form (a-d) and in tree data structure form (e) on a 2D image: Fig. 1 (a) represents the initial 8x8 image i.e. the highest LOD and an AOI selection in the shape of a square of size 2x2 in the bottom center (marked in red). The LOD inside the square is defined to be 1. Fig. 1 (b-d) represents the masks of LODs 2, 3, 4, respectively. Fig. 1 (e) demonstrates the tree data structure equivalent of the AOI selection marked in red and the mask field across the different levels.

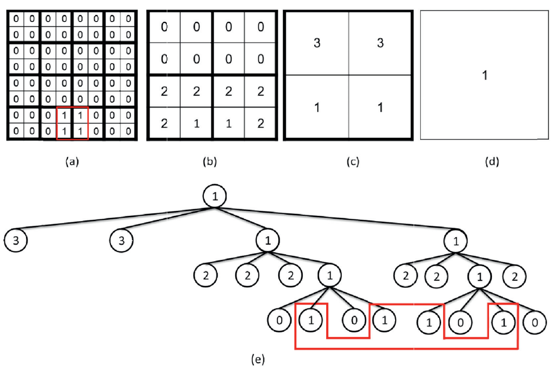

Fig. 1. Mask values in matrix and Quadtree form. (a) mask field of Level 1 – highest level - and AOI marked in red (b-d) mask field of matrix levels 2-4 respectively (e) mask field values in Quadtree structure form with AOI marked in red

The approach is not limited in the aspect of ROI geometry or the LOD distribution in it. We have chosen to implement four definitions of ROI selection (a) A rectangular AOI with a constant LOD, (b) A circular AOI with a linear change of LOD between center and circumference, (c) A cuboid VOI with constant LOD and (d) a spherical VOI with linear change of LOD between center and bounding surface.

The calculation of the levels of detail requires conversions and manipulations of the data in order to preserve topological information. We defined our 2D and 3D space according to definition 2.1 given by Kong [7] 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 [8]. The algorithm examines the effect of changing a nodes color on the connectivity of its surrounding node neighbors. Fundamentally, this introduces an additional color constraint in images and volume constraint for 3D models when traversing from a higher resolution to a lower one.

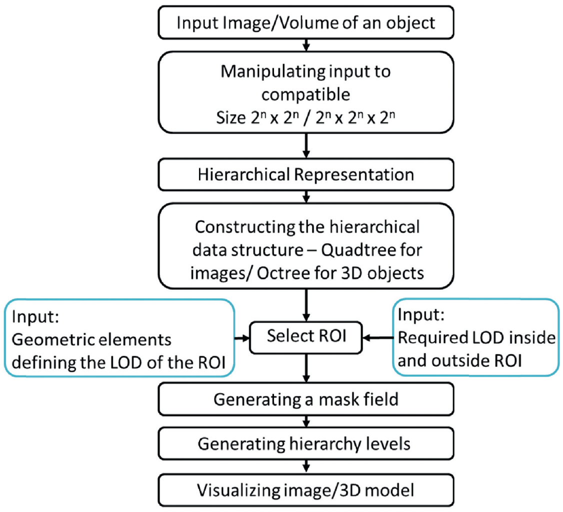

Fig. 2. Block diagram of the adaptation method

Finally, the processed model undergoes through a visualization stage. In this stage 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. An outline of the adaptive method in the form of a block diagram is depicted Fig. 2

3. Examples and discussion

3.1. 2D Examples

In Fig. 3 and Fig. 4 the 2D result models of our method are presented. Fig. 3 (a-e) depicts a synthetic 2D equivalent for a porous microstructure in the form of uniformly distributed circular holes in a 128x128 image. The AOI is marked by a circle of 64 pixels radius placed in the center of the image. The AOI properties are defined to be the maximum resolution in the center of the circle and change