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Slice coherence in a query-based architecture for 3D heterogeneous printing

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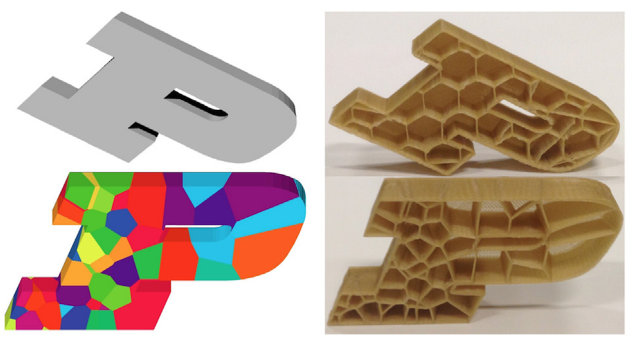
GRAPHICAL ABSTRACT



Homogeneous

vs.

Heterogeneous

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ABSTRACT

We report on 3D printing of artifacts with a structured, inhomogeneous interior. The interior is decomposed into cells defined by a 3D Voronoi diagram and their sites. When printing such objects, most slices the printer deposits are topologically the same and change only locally in the interior. The slicing algorithm capitalizes on this coherence and minimizes print head moves that do not deposit material. This approach has been implemented on a client/server architecture that computes the slices on the geometry side. The slices are printed by fused deposition, and are communicated upon demand.

1. Introduction

Object properties and performance characteristics depend, to a large extent, on the structure of the object's interior. For instance, the strength of polycrystalline material cannot be determined without information about the shape and orientation of the interior cells, and their material composition. The outer boundary of the object normally determines the geometry of the object and reflects intended functionality, but the functionality must be supported by appropriate interior structure. In particular, the structure of the interior determines properties such as density, elasticity, stiffness, fatigue, current flow, sound absorption, thermal conductivity, and other salient properties of the material.

In order to analyze and study these properties in detail, many researchers model the interior structures of the objects as an aggregation of cells. A cell structure based on Voronoi tessellation is one of the most popular approaches in these studies, since it can generate realistic homogeneous and heterogeneous structures in both 2D and 3D. In fact, Voronoi tessellations can be considered to subsume many types of cell decomposition where the Voronoi

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sites are arranged in a special way. For instance, when the sites lie on the vertices of a regular grid we obtain a regular subdivision into blocks. In the following we assume a general position site arrangement unless otherwise noted.

We consider representations in which the volume is partitioned into cells where each cell has an interior with specific geometric and/or material specifications. For example, a particular cell might be stipulated to have

- a particular strength in a given direction,
- or a particular regular geometric structure of a certain characteristic,
- or be a specific, homogeneous material, and so on.

We investigate a manufacturing approach in which cells are separated by a membrane structure, and the interior is fabricated using filament deposition equipment or other fabrication techniques that proceed in the usual layer-by-layer methodology. We restrict to manufacturing the membrane separating the cells of the object partition. Specifically, we assume a cell geometry defined by a 3D Voronoi partition of the interior. The Voronoi partition is defined by a set of interior points, the *sites* of the partition. The sites may be specified explicitly as part of the design. Each such point has attributes that are a description of the cell interior. The attributes are sufficient to unambiguously specify cell interior. Examples include stipulated material, homogeneously filling the cell; variable density material where the density at a point x in the cell might be a function of the distance of the point from the cells site; empty cells; and so on. Cells are therefore convex polyhedra, except for cells that share part of the exterior boundary of the object. The representation is *implicit* in the sense that the cell specification is given by the sites along with the outer geometry of the object.

We will describe how to manufacture the cell membrane throughout the interior. Our algorithm is *incremental*, exploiting the fact that many successive slices are topologically the same, and that slices that differ topologically often differ only locally. Those differences are characterized by only a few cases. More than that, the algorithm seeks to deposit each membrane layer such that, at no time, the head requires repositioning without depositing material, unless the external boundary requires it.

The remainder of the paper is structured as follows. After a review of the literature is presented in the next section, the algorithm for our proposed manufacturing paradigm is given in Section 3. The paradigm is evaluated with various experiments and the results are summarized in Section 4. The paper concludes with some remarks in Section 5.

2. Background

Voronoi based modeling is used in different fields of science and engineering for many applications. Material scientists employ Voronoi tessellations to model and simulate polycrystalline materials under different conditions to analyze their physical properties. In these simulations, each Voronoi cell corresponds to a crystalline cell in the aggregate and the cells form the basis of finite element models used to determine elastic and plastic behaviors of the so modeled materials [1].

Besides analyzing elastic and plastic properties, researchers also analyze sound absorption [2] and thermal insulation [3] properties of materials using Voronoi-based models. Further afield, food scientists [4] model fruits to understand their quality and how to preserve them after harvesting. Here, the intercellular transportation of gases (O_2 and CO_2) and water is the most important aspect for the preservation of fruits [5]. Intercellular passages are modeled by cutting off some corners and edges of the Voronoi cells.

Current CAD/CAM software has been developed to serve conventional machining operations, such as milling and turning of homogeneous materials. Conventional CAD/CAM systems are therefore poor at designing objects with heterogeneous interior. Moreover, the subtractive methodology of milling and turning is unnatural for fabricating heterogeneity. When the design files are converted to the STL format, only the geometric information of the outer profile of the objects is stored. Although computer scientists already criticized the STL pipeline almost two decades ago [6], it remains a dominant format in 3D printing systems. When it is employed, the properties of the objects (material, color, etc.) defined in the corresponding CAD model are not transferred to the standard STL formats. Instead, users seeking to create parts with inhomogeneous interior are forced to edit their models using the software of the 3D printers, and must make do with the capabilities of the machine being used. In the case of FDM printers, such as the Makerbot, the printer software typically restricts the interior structure to a regular pattern, for instance hexagonal tubes, to be instantiated by a preselection of a few diameter choices. In order to overcome this problem in additive manufacturing, new standards for file systems are needed for assigning structural properties to the objects. Unfortunately these emerging standards are not used by the current commercial 3D printers. The STL format is still defacto the dominant format in this field.

There have been various studies to fabricate artifacts where spatially varying colors and properties are defined in advance to perform the required functionality [7–9]. In these works, the interior of the objects are filled with the material that generates the color and functional patterns stipulated for the outer profile. Project Maxwell e.g. [10], is one of the earliest efforts to develop heterogeneous manufacturing paradigms. The project proposed to employ shape optimization techniques on the objects to be printed in order to realize functional properties via geometrical representations. The problem with this approach is that the current commercial 3D printer technologies are not capable of printing the required interior structures.

Heterogeneous objects could be manufactured after sampling the interior using a voxelization as described in the studies [8,9,11]. Since these approaches are not compatible with current CAD software, researchers prefer developing their own application specific software using voxel-based modeling. The proposed 3D editing properties are not as powerful as commercial CAD software. So, the geometry of the objects is modeled in some CAD system and then exported into the research software. Properties are assigned in the research software. In one of these studies, Doubrovski et al. [9] proposed a layered manufacturing paradigm to overcome the limitations of the CAD/CAM tools. They proposed a bitmap-printing method to produce layers of different material composition and demonstrated their approach by printing a customized prosthetic joint socket. The test object incorporated pressure-sensing elements in the interior. Their approach did not compute planar object slices, and instead utilized the default voxel resolution of the 3D printer. They focused on realizing the required material properties through local material composition of the slices.

Another way to fabricate heterogeneous articles is to partition the model so that the generated STL files will represent interior structure. A recent study using this paradigm is done by Prevost et al. [12]. They can shift the center of gravity of the artifacts by designing the interior to consist of cells, some of which are empty, others filled with material. As a result, the fabricated objects can stand in unexpected poses. Depending on the cell configuration and composition, several STL files are sliced and some of the slices printed at the same time. In a different study using separate design files, Lu et al. [13] modeled the interior of the objects with Voronoi cells and hollowed the interior of these cells to increase the strength-to-weight of the objects. It is a common characteristic of these studies [8,9,12,13] that they use resin based 3D printers.

In another remarkable study, Ge et al. [7] introduced the concept of printed active composites, a different type of heterogeneous