WORKING WITH MULTI-SCALE MATERIAL DISTRIBUTIONS

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ABSTRACT
At present, computer aided design (CAD) software has proven ill equipped to manage the spatial variations in material properties. Most digital design packages employ a surface modeling paradigm where a solid object is that which is enclosed by a set of boundaries (known as boundary representations or “B-rep” for short). In surface models, material representations are often treated as homogenous and discrete. Yet, natural materials are capable of structures where the variability of material within a volume is defined at a multiplicity of scales and according to various functional criteria. With the advent of new 3D printing techniques, a new possibility emerges—allowing new multi-material composite objects to be fabricated in a single build volume with a high degree of dimensional accuracy and repeatability. However, a big limitation facing complex high resolution digital fabrication comes from the software’s inability to represent or handle material variability. This paper proposes a new digital interface for working with multi-material distributions at a variety of scales using a rasterization process. Beyond the immediate benefit of precise graduated control over the material distribution within a 3D printed volume, our interface opens new creative opportunities by enabling the use of existing image processing techniques (such as filtering, mapping, etc.) which can be applied to three-dimensional voxel fields. Examples are provided which explore the potential of multi-scale material distributions.
1 INTRODUCTION

Working with multi-scalar materials in a digital environment requires us to reconsider the ways in which humans have historically represented and manufactured real objects. Vilbrandt et al. describe a general taxonomy of representational categories for physical objects including: simple, complex, and heterogeneous classifications (Vilbrandt et al., 2008).

Simple representations are that which define an object’s surface or shape through simple boundaries that create explicit separations between different materials. Complex representations, on the other hand, represent real-world objects through the organization of three-dimensional blocks (or voxels), which define not just the surface of an object but also its volume. A unit or voxel based system is more detailed than a simple representation and has the advantage of defining the structure and composition of a material in three dimensions. Lastly, a heterogeneous representation of the physical world displays gradual, diffused and continuous transitions between materials throughout its form.

It is no surprise then that the field of computer modeling has also chosen three methods of representation which can be roughly mapped according to the aforementioned categories. In the same order, from simple to heterogeneous, “they can be formally referred to as boundary representation (B-rep) [Baumgart 1972], discrete volume representations or voxels and function representation (F-rep) [Pasko 1995]” (Vilbrandt et al., 2009: p.168).

Most, if not all, current digital modeling packages rely on boundary representations as their underlying framework. This fits with traditional manufacturing and design processes, which assume that any given object will be fabricated from a single, homogeneous material. Yet, this homogenization results in objects that feel man-made and clearly stand apart from naturally occurring materials which are heterogeneous and display “functional adaptations of their structure at all levels of hierarchy” (Fratzl and Weinkamer, 2007:p.1263).

Many biological materials are structured in such a way that “their multifunctionality often occurs at scales that are nano through macro and are typically achieved by mapping performance requirements to strategies of material structuring and allocation” (Oxman, 2010: p.80). Using traditional manufacturing techniques, fabricating designs which called for heterogeneous or hierarchically organized materials were simply impossible. Yet, recent advancements in rapid prototyping, specifically additive layered manufacturing such as multi-material 3D printing, have enabled the possibility of fabricating objects whose properties can be varied spatially throughout its volume and at different scales. The ability to engineer and fabricate multi-scalar and multifunctional materials offers an unprecedented ability to increase a product’s structural and environmental performance and optimize material distribution. Now our CAD tools need to move beyond mere simple representations to more complex multi-scalar representations of graduated material properties within solid objects.

2 HIERARCHICAL MATERIALS

Hierarchical materials abound in nature. It is believed that many of nature’s exceptional mechanical properties such as stiffness, strength, and durability, etc. come from the optimized interactions between hierarchical assemblies that span from the macromolecular level up to the whole organism (Jeronimidis, 2000: p.4). In order to facilitate a productive discourse, the following section examines the femoral bone and how its varied arrangement of hierarchical material structures offer a more appropriate representational model for digital materials when compared to traditionally homogenous material compositions (Figure 1).

Bone has an assortment of structural systems working together over many different scales to provide “mechanical, biological, and chemical functions; such as structural support, protection and storage of healing cells, and mineral ion homeostasis” (Rho et al., 1997: p.92). Scale is critical when discussing the architecture of bone, as the structure is hierarchical and complex. Generally speaking, there are five scalar structural organizations: (a) the macrostructure which includes trabecular and cortical bone, (b) the microstructure which ranges from 10 to 500µm, (c) the sub-microstructure from 1 to 10µm, (d) the nanostructure which consists of elements from a few hundred nanometers to 1µm, and finally (e) the sub-nanostructure which is below a few hundred nanometers. While irregular, this hierarchically organized structure is optimized in both arrangement and orientation of the components, making the bone heterogeneous and anisotropic. A digital model of the femoral bone using a boundary or surface model representation (Figure 1a) is simply unable to reproduce the granular characteristics of the bone’s hierarchical composition.
3 DIGITAL MATERIALIZATION

Multi-material 3D printing technologies are based on the rasterization of layers similar to the way colors have been mixed in inkjet and laser printers in the past. This suggests an extension of typographic techniques and two-dimensional image processing concepts which can be applied to three dimensions (Figure 2).

Materials are mixed in a dot pattern that resembles diffusion dithering to give the impression of continuous smooth gradients. Diffusion dithering is isotropic macroscopically but there are situations where we may want to enforce optical or structural anisotropy at the rasterization scale. This opens up the possibility of anisotropic half tone patterns. Any three-dimensional voxelized cell can be used as such a halftone pattern provided its field has a relatively flat histogram. At different mixing ratios of the overall field we can pick up a different threshold of the cell field and this creates a continuously varying halftone pattern with the desired anisotropy and variable mixing ratio between the two materials (Figures 9, 10, & 11).

In addition, we need to develop techniques in order to analyze and optimize the structural behavior of such systems. One such method is topology optimization, which in its simplest formulation suggests a continuous gradient of elasticity in space—something that we can actually materialize now using multi-material 3D printing (Figure 3). For our experiments we used the programs topostruct and millipede, which use the minimum compliance design algorithm by Bendsoe and Siegmund (Bendsoe and Siegmund 2003). This method is interesting because it implies a different way of thinking about the problem of structure. The designer should intuitively approach such a problem not as one of an assembly of distinct components, but rather as a continuous material distribution in space. This characteristic makes such an approach conceptually and practically appropriate for multi-material 3D printing. In one of our experiments (Figure 3) a fuzzy bone-like structure can be created using gradients between a transparent rubbery material and an opaque hard material. In this way the actual outcome of the topology optimization process (top) can be directly materialized (bottom). In this way the hard interface that usually separates reinforcement and bulk material is dissolved avoiding certain stress concentrations along this boundary. Another interesting development that can bind well with multi-material printing is the design of compliant mechanisms where nonlinear elastic effects such as buckling and large deformations are used in order to achieve particular types of controlled movement within the material body.

4 WORKFLOW

We present a workflow and a software prototype for the definition and manipulation of multi-scale fields for multi-material additive manufacturing.

An object in our software is described by a pair of voxel fields plus a voxelized halftone pattern cell. The halftone pattern determines the local anisotropy in the material mixing at the mesoscopic scale.
and can be parameterized so that it varies from point to point. A voxel file format (extension .vol) is used in order to compactly store and transfer information about the dual field representation between programs. Each voxel file also contains data about the object’s resolution, physical dimensions, etc.

The main voxel field contains parameters which describe the density (ratio of void to solid) and material mixing (ratio between the two base materials) of the three-dimensional object respectively. At the moment, because of limitations such as the requirement to provide support material, the first field is only interpreted as a continuous gradient that is cast to a sharp solid void model via an adjustable threshold. That is, there is no microstructure in the solid/void raster. This still has the advantage in that it captures the gradients of the generating field and can reduce pixilation (aliasing) of the final geometry.

4.1 GEOMETRY DEFINITION

We propose a variety of ways for the generation of three-dimensional volumetric fields and provide prototype tools for some of them.

1. BY DISTANCE FIELDS (SPACE GRADIENTS)

Any geometric object (points, curves, surfaces, or solids) can be used in order to define a gradient field around it. We can simply calculate the distance of each voxel to the closest point on the geometric object and apply some decay function to the calculated value. Exponentially, quadratic or linear decay will give different results when we add the fields of different objects together. As such, the decay functions control the shape of the field around any single object.

When we have more than one object we can calculate the field around each one of them and then simply composite them together using standard composition operations. In our interface, we have implemented additive composition (which in conjunction with an exponential decay gives rise to blob-like blending), multiplicative, and minimum value (which is the closest to a linear wrapping around the objects). In addition, we can generate gradients around parameterized objects such as curves and surfaces using their parameterization information. For example, given a curve we can find the closest point on the curve from each voxel and use the parameter \( t \) along the curve at that point as the field density. This will result in a gradient that sweeps along the curve in space rather than fading as a halo around the curve. In our system two groups of objects are used in order to define the solid/void relationship and the material mixing fields respectively (Figure 4).

2. BY FUNCTIONS

Alternatively, simple scalar functions of the form \( F(x,y,z) \) can be used in order to generate the field density (Figure 5). This method is often less intuitive than using geometric objects but can generate complex gradients and periodic forms that would be difficult to achieve otherwise.

3. BY IMAGE (ADDITIVE/MULTIPLY/EXTRUSION PATTERNS ETC.)

Another intuitive way to construct either the three-dimensional object or its halftone pattern is to use an image file. Of course an image contains only two dimensions of information but it can be useful in defining objects with radial symmetry, or those that are extruded or have cubic symmetry.

We provide an easy interface for converting any image file to a voxel field. The red channel of the image file is translated to the solid/void field and the green channel to the material mixing field. Using images it is fairly trivial to create sheet like objects with complex elasticity patterns like origami and anisotropic plates. This is achieved using the extrusion operator.

We can also project the image through the three faces of a cube and combine the result at each voxel additively or multiplicatively.
in order to generate a three dimensional object. This is useful in creating halftone patterns such as simple dots or crosses, but applied creatively it can yield even more interesting outcomes.

4. BY TRIVARIATE NURBS AND FREPS

These are the natural extensions of familiar spline type interpolation schemes to volumetric data. In the most general case we can have a cage (three-dimensional grid) of control points with five parameters per point (x,y,z,w homogeneous coordinates plus the field density).

4.2 RASTER PROCESSES

There are many advantages to using a voxelized representation of an object. The first is that we can apply all of the methods from image analysis and filtering with little modification. Procedures such as blurring/softening, histogram equalization, convolution and others can be applied directly and offer an easy way to achieve complex geometric manipulations. For example, complex geometric operations such as filleting are trivial through the use of a blurring filter on the density field (Figure 7).

Another benefit is that any voxel field can be used as a localized halftone pattern. In general it is a good idea to use a field with a good distribution of grayscale values so that the mixing becomes more even along gradients. All the procedures we described before for the definition of the actual geometry can also apply to the description of halftone patterns. In particular, the generation of a halftone pattern from an image file or from a periodic three-dimensional function is quite easy and intuitive.

After the user has defined the overall field (macroscopic scale), he/she can pick up a halftone pattern that will be used in order to generate the actual printable bitmaps which determine the exact location of each base material. The voxel field is in general at a...
lower resolution than the printer’s native one so the rasterization process has to interpolate between values. For each printed layer, the algorithm generates two monochromatic bitmaps (Figure 8) — one for each material using the resolution specifications of the 3D printer. Then at each pixel, we use a tri-linear interpolation of the object fields to find the value at the corresponding point as well as a trilinear interpolation of the halftone field. If the interpolated density value is greater than the threshold, then the pixel is a solid, otherwise it is a void. If the pixel is solid, we check to see if the interpolated material mixing value is greater than the interpolated halftone value and the result of this check determines whether the pixel is assigned one material or the other.

5 VISUALIZATION

Our interface uses OpenGL and special shaders which take advantage of three-dimensional multi-texture extensions to produce real-time visualizations of the voxel field results. Normals within the volume are estimated in the fragment shader to achieve approximate lighting effects.

Using voxel field visualization techniques, we can achieve a detail view of internal structure and gradients with subsurface lighting effects—something that is impossible to achieve with visualizations based on isosurface meshes. In addition, it is trivial to visualize the halftone pattern in real time in its micro-scale which would be extremely expensive in terms of memory and CPU power to do otherwise. Hence the designer can get a better idea about the optical properties of her design in real time.

The object is rendered as a series of planes from back to front along the viewing directions of the camera. Each layer is rendered as a quad using a special fragment shader. The fragment shader takes the x,y,z coordinates at the fragment location and scales them in order to find the three-dimensional texture coordinates for the overall field and the halftone pattern (which is a repeating three-dimensional texture). The colors of the two materials are passed as uniform variables. Using the gradient of the alpha values of the material as they are mixed by the halftone texture, the shader determines the normal used for lighting calculations. Fragments with small alpha values are discarded in order to speed up rendering times, but also in order to take advantage of the depth buffer when combining the voxel object with other geometry.

6 EXAMPLES

Multi-material printing offers many opportunities; but given the current availability of certain resins, we have begun by exploring prototypes which take advantage of the material’s optical or elastic potential. This section shows some preliminary investigations that we have conducted in these domains.
Optical lenses or filters are just one example of how macro scale and micro scale changes can alter or enhance the transmittance of light. In addition to aesthetic augmentations, we can also address visibility and privacy concerns simply by modifying the orientation of the 3D printed panel, or by differentiating the direction of the two dimensional halftone mapping (Figure 9).

Flexible mechanisms which translate an input force into another point through elastic deformation is often referred to as compliant mechanism design. Through precise graduated control over both soft and hard materials, we can program specific bending parameters into the design of a material. Figure 12 shows two perpendicular grain patterns, each resulting in different anisotropic bending deformations.

7 FUTURE WORK

Our software is in early beta version and a lot of features are under development. There is still ample space for improvement and extension in terms of functionality, internal representation and analysis. In terms of usability, it would be desirable to preserve the different volumetric layers similar to the way image processing packages do in order to improve editing.

As mentioned above our system works with a volumetric FE analysis system in order to provide feedback on the elastic properties of the complex aggregate. However in the future we would like to couple it with a nonlinear analysis module that would make it invaluable as a tool for the definition of compliant mechanisms and other structures that rely on flexure.

The file format must be both extended to maintain more of the multilayer information, including the geometry and formulas for different field generators (similar to multi layered tiff files), and to support compression in order to reduce file size.

In terms of visualization more accurate models are needed to reflect the nonlinear variation of transparency when mixing a transparent material with an opaque material.
8 CONCLUSION

The current representational framework that most, if not all, digital modeling tools employ today is the boundary representation (B-rep). Yet, the explicit nature of this paradigm has proven inadequate when trying to express the granular or hierarchical structure of more complex, natural materials. With the arrival of new additive manufacturing techniques like multi-material 3D printing, we now have the ability to produce highly tuned and highly optimized objects which display gradual material transitions throughout its volume.

This paper suggests that a voxel or raster based process is more suited for complex material representations and we provide a prototype software interface for working with multi-scalar material distributions. The benefits of this workflow include: precise graduated control over the material distribution at multiple scales within a 3D printed volume; the ability to extend existing two dimensional image processing techniques on three dimensional voxel fields; structural feedback (that is topology optimization), which can help analyze and optimize the mechanical behavior of hierarchical systems; and lastly, provide new creative avenues in the design and engineering of objects whose aesthetic qualities and material organization are highly modulated to fit its structural performance.

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WORKS CITED


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