3D Texture Mapping for Rapid Manufacturing

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ABSTRACT

Inspired by the developments of biomimetic design and layer manufacturing, we present a microstructure design method which uses complex internal structures to achieve an optimal design. Similar to 2D texture mapping, our approach is based on mapping a 3D microstructure into a design space to generate internal structures. We develop a texture mapping design system which enables a designer to select a microstructure from a library. Accordingly the system automatically generates a CAD model of internal structures based on given design requirements. The system then combines internal structures with a given CAD model. The combined CAD model can be fabricated using a layer manufacturing system. The ability to design microstructures within a part creates tremendous potential for lightweight and high performance components and devices.

Keywords: Cellular structure, geometric modeling, design for Rapid Manufacturing.

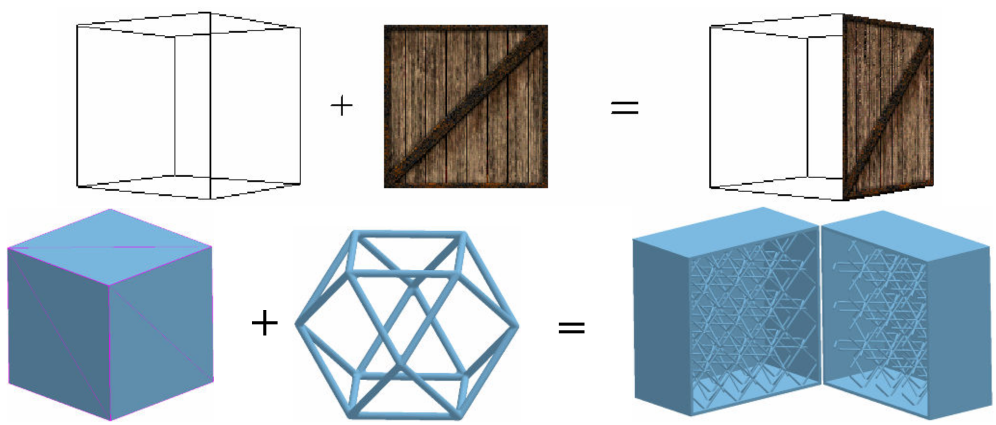


Fig. 1: Illustration of 2D texture mapping for rendering surfaces in Computer Graphics (top) and 3D texture mapping presented in this paper for Rapid Manufacturing (bottom).

1. INTRODUCTION

Texture mapping is a widely used method in rendering 3-dimensional models for adding details (e.g. surface texture or bumps). It has been extensively studied in Computer Graphics and currently supported by most graphics cards. During the rendering process, a source image (*texture*) is mapped onto a surface in 3D object space and then mapped to the destination image (*screen*) by the viewing projection (refer to Figure 1). Many variations are proposed such as normal mapping, displacement mapping, bump mapping, and shell mapping [1-2]. Internal textures are also studied for rendering 3D models such as fruits and marbles [3-4]. In this paper, we propose a 3D texture mapping which uses microstructures to model internal structures for the purpose of product design and manufacturing. The basic idea of the proposed 3D texture mapping is illustrated in Figure 1.

Our research is motivated by the recent developments of two technologies, biomimetic design and layer manufacturing.

- ***Boimimetic design***: The design of living organisms such as bones, cartilages, and honeycombs are amazingly efficient. For example, the skull bones in human skeleton are sandwiched cellular structures (refer to Figure 2 left) consisting of a layer of spongy bone and two thin sandwiching layers of compact bone [5]. The compact bone is dense while the spongy bone has cellular structures which can sustain large impacts and absorb energy efficiently. Therefore the skull bones are light yet strong and stiff. The structure of biological load carrier is optimally adapted to its natural load due to the natural selection process over millions of years. In recent years, biomimicry is being investigated as an emerging field, which creates breakthroughs in material, device, and product design [6].

- ***Layer manufacturing***: Layer-based additive manufacturing processes, such as Stereolithography (*SLA*) and Selective Laser Sintering (*SLS*), have been used for prototyping for nearly twenty years (*Rapid Prototyping*). A main benefit of a *Rapid Prototyping* process is its ability to build arbitrary geometries without tooling. Parts with internal structures can be manufactured by these processes. In fact, it is desirable to build such internal structures. Since less material is added, the part will have less shrinkage and warpage. A test part built by *SLA* is shown in Figure 2 (right) [7]. *Rapid Prototyping* parts can also be used as investment-casting patterns for making structures in other materials such as titanium (*Rapid Tooling*). In recent year, layer manufacturing processes begin to be used as direct manufacturing approaches in applications such as aerospace and hearing aids. *Rapid Manufacturing* is expected to have a big impact to the future product design and manufacturing [8].

Fig. 2: Skull bones in human skeleton [5] (left) and a test part built by SLA [7] (right).

As demonstrated by nature's design, optimal design such as maximum strength with less weight can be achieved by various complex internal structures. However, the design and modeling of such complex internal structures are beyond the capability of current commercial CAD software. This research is an effort toward developing a computer-aided design method for designing and modeling internal structures. We propose a novel 3D texture mapping design system as shown in Figure 3. A designer can choose a microstructure based on design requirements from a microstructure library (refer to Section 3). Our system automatically generates a warped design space also based on design requirements. Combined with the selected microstructure, the internal structure is generated and defined in a *XML* file (refer to Section 4). Our system can automatically convert the structure definition file into a CAD model (refer to Section 5). Finally the CAD model of internal structures is combined with an offset CAD model by geometric operations (refer to Section 6). Layer manufacturing systems provide us the capability to fabricate the combined CAD model.

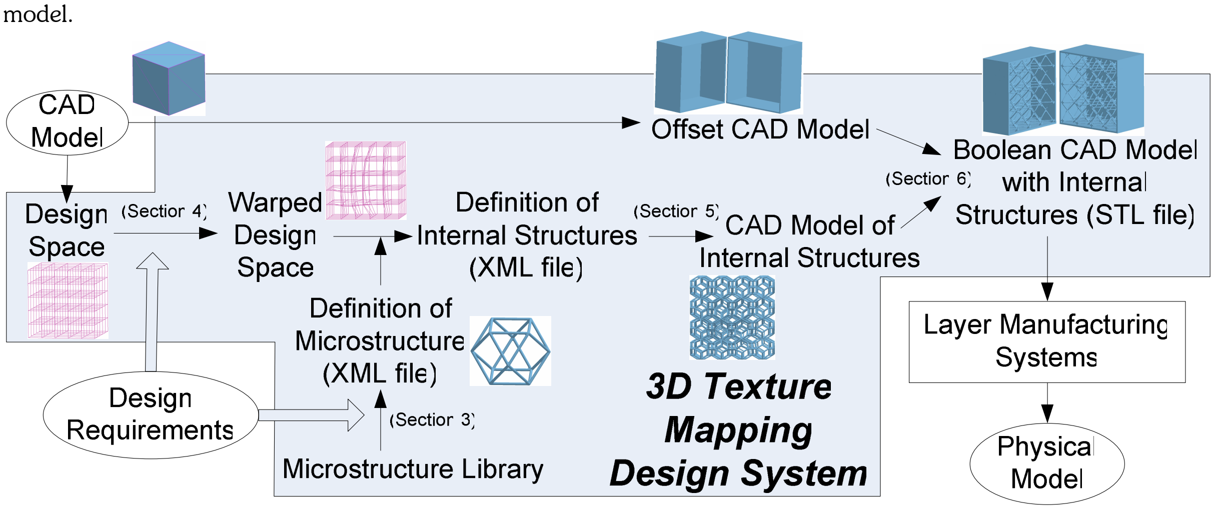


Fig. 3: Data flow of our 3D texture mapping design system and organization of the paper.

The central contributions of this paper are: (1) We present a novel 3D texture mapping approach and related algorithms to automatically generate a CAD model with internal structures; (2) We present a microstructure synthesis approach which enables designer to easily control the density of internal structures based on design requirements; (3) We present a representation scheme for defining microstructure library and synthesized internal structures; (4) We present geometric operation algorithms for generating water-tight STL files for layer manufacturing.

2. RELATED WORK

The benefits of cellular structures have been demonstrated in many structural applications [9]. Ashby et al. [10] studied the properties of metal foams and presented design guidelines on using it for various purposes. However, the cellular structures and metal foams are mainly fabricated by stochastic processes such as metal gas injection. Therefore, accurately defining internal structures in a CAD model is not needed since these processes lack accurate control of the generated structures. The development of *Rapid Prototyping* processes enables the manufacturing of mesoscopic truss structures. *Molecular Geodesic Inc.* had pioneered the manufacturing of periodic cellular structures by using *Rapid Prototyping*. Gervasi and Stahl [11] presented a hybrid fabrication approach by combining layer manufacturing and metal casting to fabricate microstructures in various metals. Wallach and Gibson [12] also utilized a layer manufacturing process, Fused Deposition Modeling, to fabricate sacrificial polymeric patterns for investment casting of metallic cellular structure. They mainly studied a simple type of structures, uniform truss.

Uniform truss is a pattern of unit cells (microstructure) repeated in every direction uniformly. Therefore it is possible to use a simple patterning operation in a commercial geometric modeling package to create the solid model of uniform truss. Mun et al. [13] developed a standard library of unit cells based on Pro/ENGINEER from *Parametric Technology Inc.* (www.ptc.com). Scaffold structures can be created by patterning a unit cell from the library, and the generated models can do boolean operations with other models (e.g. a bone model generated by 3-D reconstruction software from tomographic data) using pro/ENGINEER. However, as pointed out in [7], it takes significant computational resources to generate the CAD models of structures since the generation of each strut requires several boolean operations. Several tests were performed on *ACIS*, a solid modeling kernel from *Spatial Corp.* (*www.spatial.com*) which is also used by many commercial CAD software packages. The maximum strut number can be successfully generated in a personal computer is around 2,400 before the memory limit for a *Windows* application is reached.

Wang et al. [7] presented a hybrid geometric modeling method for creating conformal cellular structures. Truss structures are divided into a set of unit truss. Each unit truss has one central joint and semi-struts connected to the central joint. The solid model of each unit truss is created and boolean operations are performed in *ACIS*. After the end faces of all struts are removed, faceted models are generated in STL file format. Meshes of unit trusses can then be stacked together directly to generate the model of the entire structure. Chen [14] extended the work for general structure design and presented a mesh-based geometric modeling method to create tessellated models of various structures. The approach is also adopted in this research.

Interconnected cellular structure can be used as the scaffolds in tissue engineering. It allows cells to penetrate the scaffold and migrate through it due to its high porosity. Sun et al. [15] proposed computer-aided tissue engineering by utilizing layer manufacturing to fabricate tissue scaffold. They also developed an image-based bio-CAD modeling technique [16] and an interior architecture design approach to generate layer fabrication tool path directly without forming a 3D CAD scaffold model [17].

3. MICROSTRUCTURES FOR 3D TEXTURE MAPPING

Microstructure, in this paper, refers to the geometric arrangement of materials within a unit cell on a scale that is insignificant compared to the scale of the component. Different microstructures are suitable for different design requirements. For example, lightweight structures require rigidity under external forces while compliant mechanisms require flexibility in order to transform motion and energy through elastic deformation [18-19]. Microstructures can have various structural topology (geometric configuration of structures, such as the strut connectivity) to generate rigid or flexible structures.

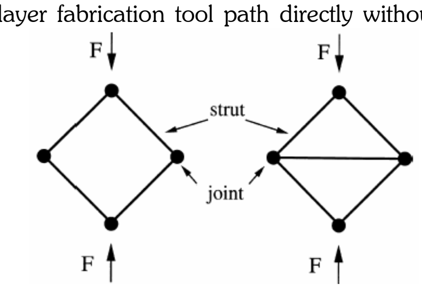
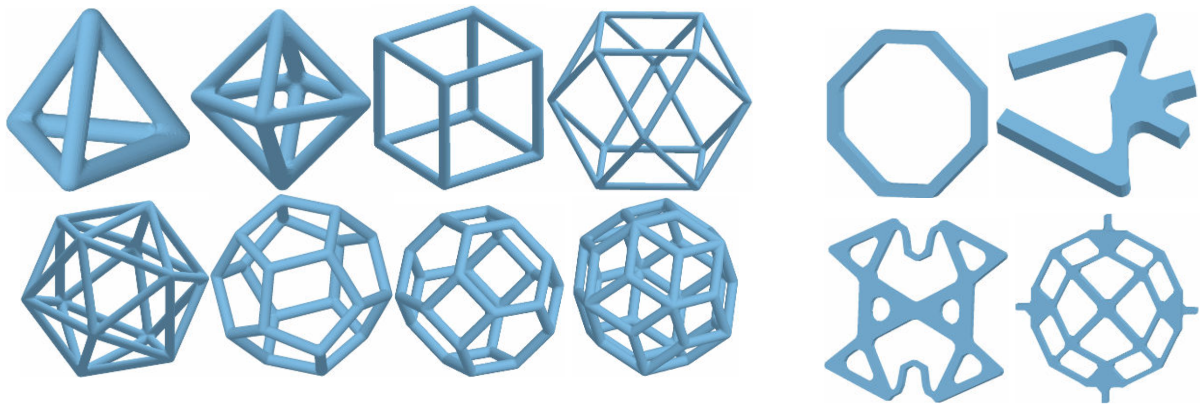


Fig. 4: A bending-dominated four-bar mechanism can be converted to a stretching-dominated triangular truss by adding a strut and vice versa [20].

Deshpande et al. [20] studied structural topology of periodic structures and classified them into stretching-dominated and bending-dominated structures. Stretching-dominated structures are stronger than bending-dominated structures since axial stress is uniformly distributed on cross-section while bending stress is non-uniformly distributed. The two types of structures can



(a) 3D microstructures: Tetrahedron, Octahedron, Cube, Vector (top row, from left to right); Icosahedron, Dodecahedron, Tetrakaidecahedron, Triacontahedron (bottom row, from left to right).

(b) 2.5 D microstructures: Octagon, rubber-band, Iso-material, Bi-stable (from left to right).

Fig. 5: Some microstructures used in 3D texture mapping.

be converted to each other by changing their structural topology. For example, a four-bar mechanism can be converted to a triangular truss by adding an addition strut (refer to Figure 4). Using Maxwell's criterion, they derived that a sufficient condition for the deformation of a periodic structure to be stretch-dominated is that its unit cell consisting of *b* struts and *j* frictionless joints satisfied $b\text{-}2j+3 \geq 0$ for 2D structures and $b\text{-}3j+6 \geq 0$ for 3D structures. Therefore, the structure is generally more rigid with more struts for the same number of joints.

Polyhedra, such as tetrahedron and octahedron, are popular microstructures for analysis. Their properties are studied in [21-22]. Polyhedra are also widely used in tensigrity design to build highly efficient and elegant structures [23]. Some polyhedra we take from tensigrity design are shown in Figure 5.a. We use them as microstructures for 3D texture mapping.

The behavior of a component depends on both part materials and micro-structures used in the component. In material design, researchers have proposed various micro-structures for different design purposes. Most of them are 2.5D structures, that is, there are no overhanging elements possible. Sigmund [24] presented a micro-structure to get material behavior similar to a rubber band; Kikuchi [25] designed an isotropic material structure to achieve Poisson's ratio as 0.5; Prasad and Diaz [26] designed a bistable structure based on "double curved beam" substructures. Their 2.5D structures are shown in Figure 5.b. We also utilize them as microstructures for 3D texture mapping.

The topology of a microstructure plays a big role in determining its structural properties. A CAD system needs a library of pre-defined microstructures for different design requirements since different microstructures have different topologies. This is similar to a library of 2D textures currently available in most CAD systems. A designer can select a microstructure based on design requirements such as desired strength or flexibility. Microstructures can also be designed to produce unique physical properties. For example, a structure can be designed as non-uniform such that it is stiff in one direction while flexible in other directions.

In current CAD systems, 2D textures are generally defined in common image formats which are interchangeable. In our texture mapping design system, we define a 3D microstructure as a unit cell and save it in an individual file. Therefore, new microstructures can be added to our system easily. We use a general structure configuration model [14] as shown in Figure 6 (left) to define a microstructure. The model can be used to define both 3D and 2.5D structures with different strut shapes, dimensions, and connections. We use the Extensible Markup Language (*XML*), a universal data format (*www.xml.org*), for saving microstructure definition file. For example, the definition of a tetrahedron as shown in Figure 5.a is shown in Figure 6 (right). Our system will automatically use the selected microstructure to generate an internal structure for a given CAD model.

4. SYNTHESIS OF MICROSTRUCTURES

3D microstructures need to be mapped into a design space in order to form an internal structure. Ideally the generated internal structure should be adaptive to the outside part shape. It should also satisfy the given design requirements. For example, a component design should minimize stiffness for some compliance properties, or it should minimize weight to obtain a desirable dynamic performance, etc. Therefore the synthesis of microstructures is the process of determining where to put microstructures in a design space to achieve the given design requirements.

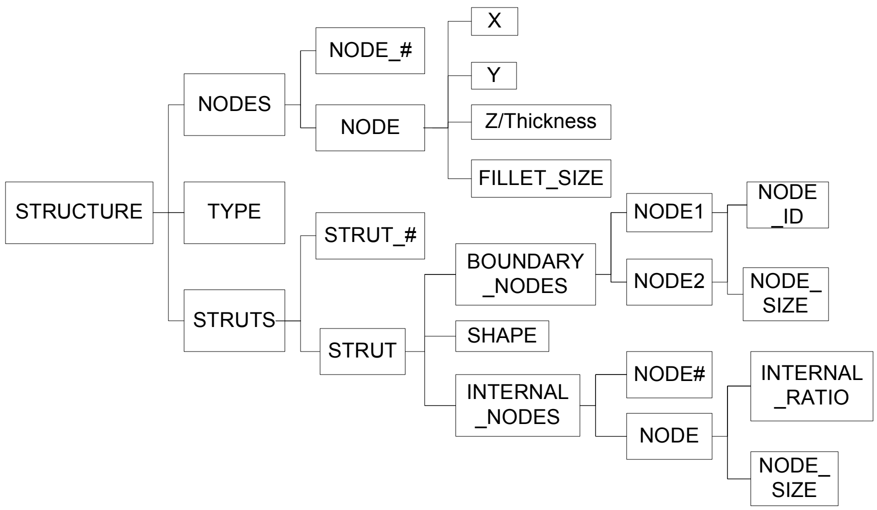



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Fig. 6: A general structure configuration model (left) and related definition of a tetrahedron in *XML* (right).

There are two types of approaches for the synthesis of microstructures. (1) A uniform approach by using a microstructure as a pattern to duplicate in all directions to cover the design space [12-13]. This approach is generally used for uniform cellular structures. (2) Adaptive approaches by using structural optimization to adapt structures based on design requirements. Joo et al. [27] presented a ground structure approach which uses a grid of potential bars connecting any tow nodes in a design space. Nodal locations are fixed and the resulting optimum topology is a subset of the ground truss. Bendsoe and Kikuchi [28] presented a homogenization method employing a composite material as the basis for defining space in terms of material density. Wang [29] presented a unit cell approach for non-uniform structures include lightweight structure and compliant mechanism.

The uniform approach is simple. It is comparably easier to analyze the properties of uniform cellular structures. Many researchers have studied a variety of microstructures and related mechanical properties. However, the structural design based on the uniform approach is usually not optimal since the geometries are not adaptive to neither the outside part shape nor design requirements.

The adaptive approaches generally can get a better structural design. However, since they treat both structural topology and geometry as design variables, a huge number of design variables exist. Some variables such as structural connectivity are discrete. Consequently the optimization problem is quite challenging which requires significant computational resource. Many approaches address it by considering limited design spaces. The generated results may also be irregular and unnatural to designers. More importantly, the adaptive approaches generally provide no control for designers to adjust the generated results.

We use an integrated approach in our research. (1) Similar to the uniform approach, we assume designers know which type of microstructure is appropriate for the design requirements. Accordingly we will use the same topological connections for all unit cells. (2) Similar to the adaptive approaches, we warp the design space based on design requirements. Accordingly we design an internal structure based on the warped design space.

Space warping has been used in Computer Graphics for reducing image size in texture mapping [30]. The basic idea of our approach is to distribute materials based on design requirements. For example, if a component is designed for loading, the design requirement is to maximize strength. Intuitively we want to put more materials in higher stress areas and less material in lower stress areas. We can achieve this by stretching unit cells from low stress to high stress regions; so smaller sizes of microstructures are used in higher stress regions, and vice versa. This principle is similar to space-optimized texture mapping [30] and adaptive mesh generation [31]. The difference is we warp space based on design requirements such as stress distribution while they warp space based on image curvature and local curvedness of a surface respectively.

Let $Q = [0,1]^3$ be a 3-dimensional unit cube related to a given design space. A scale warping function f is defined by a rectangular grid. We use trilinear interpolation within the quadrilateral faces of the grid. We initialize the algorithm with a regular grid G. We can choose the number of samples along each axis independently. We warp the grid by minimizing an energy function $E(V)$ which is defined as:

$$E(V) = \frac{1}{2}\sum_{i}\sum_{j \in N_i} f(v_j)\left\|v_i - v_j\right\|^2, \quad (4.1)$$

where N_i is the neighboring grids of v_i (e.g. face neighboring). The goal is to move the vertices to new locations so that the distance between two grid vertices v_i and v_j of a grid edge is approximately inversely proportional to the value of f at the mid point. If function f is constant, it is a classical least-squares problem. For the general case of arbitrary function, the existence and uniqueness of solutions are analyzed in [30].

To solve the minimizing problem, we use a successive approximation algorithm. Suppose $f(v_i) > 0$ reflects the design requirements on structure's material distribution. Our algorithm starts from a set of vertices v_i^0 which cover the regular grid G. In each iteration, we calculate the new position of vertices v_i^{n+1} by adding a displacement to the current position v_i^n. That is,

$$v_i^{n+1} = \sum_{j \in N_i} f(v_j^{(n)}) v_j^{(n)} / \sum_{j \in N_i} f(v_j^{(n)}), \forall i. \quad (4.2)$$

We specially handle the positions of boundary points based on some imposed boundary conditions (e.g. fixed borders). The iteration continues until the criterion for convergence $||V^{n+1} - V^n|| < \varepsilon$ is met.

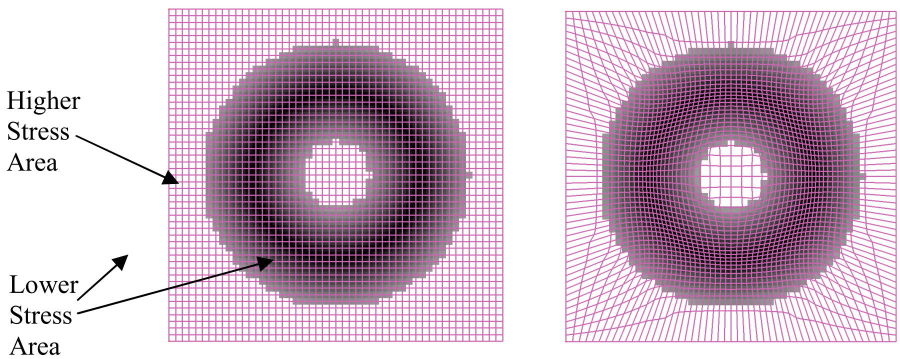


Fig. 7: A space warping example: grids of a design space before and after space warping.

The warping function f can be defined by one or several design requirements. A space warping example is shown in Figure 7. The values of analytically defined stress are represented in shading levels, where the stress is higher if it is darker. For more complicated geometries, the warping function f can also be defined as discrete values imported from finite element analysis result. This function guides the space warping process to achieve: (1) grids are smaller in higher stress regions; (2) grids are aligned to maximum stress orientations and therefore the generated structures are more conformed to external forces. For the warped design space, we can simply map a selected microstructure into each grid. As shown in Figure 5, a 3D and 2.5D microstructures are defined within a cube and a rectangle respectively. Based on the corresponding corner points, we use trilinear interpolation to calculate the positions of structure's joints. The generated structure is guaranteed to be continuous since the same corner points and trilinear interpolation function are used in neighboring cells.

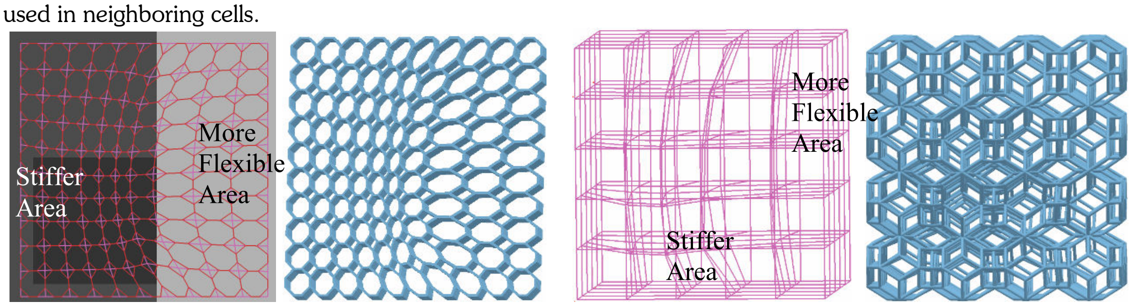


Fig. 8: Designers can modify structures by changing warping function. An octagon is used in 2.5D structure (left) and a vector microstructure is used in 3D structure (right).

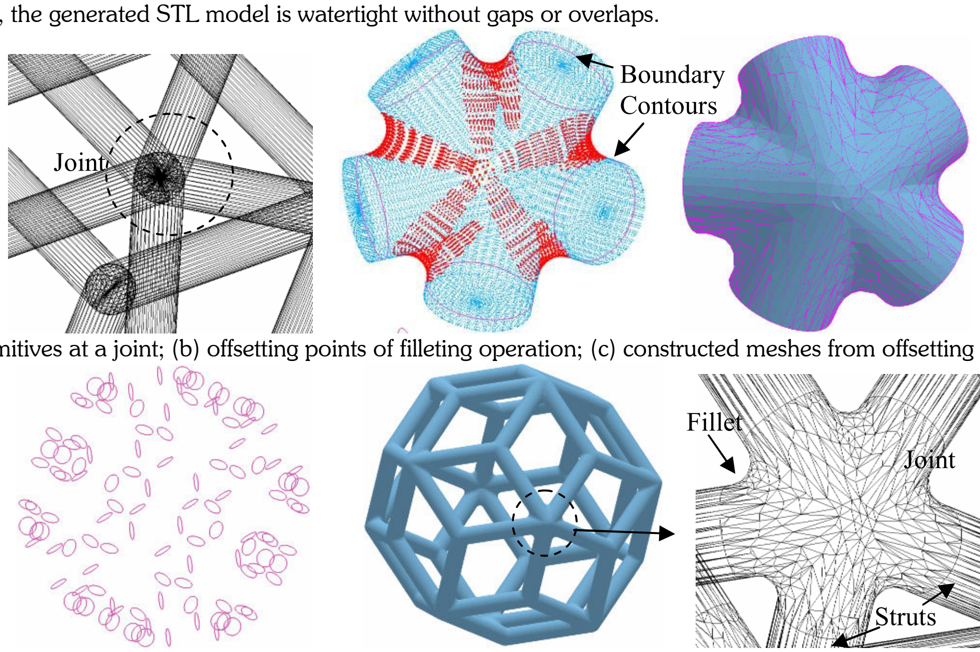
A designer can change the generated structures quiet easily by modifying the warping function *f*(*V*). For example, we can assign different values for various areas. As shown in Figure 8, function *f* in stiffer areas has bigger values (shading is darker). Therefore, designers can interactively specify a stiffer area in the design space and our approach will distribute materials accordingly. The generated 2.5D and 3D structures for the defined warping functions are also shown in the figure.

Our approach is fast since we divide topology synthesis and dimensional synthesis. The structural connectivity is considered in microstructure design. During the microstructure synthesis process, we only change the positions of nodes and therefore structural orientation. Dimensions of each strut can be further optimized based on finite element analysis results. The optimization problem is much easier since all strut connection and orientation are fixed and only dimensional variables are changing. Our approach can also be used to generate an initial structure design for other adaptive approaches. Based on the structure configuration model as shown in Figure 6, we generate a truss definition file in XML format as the output of microstructure synthesis result.

5. GEOMETRIC MODELING OF AN INTERNAL STRUCTURE

A general truss structure defined in *XML* file can have different strut size, shape, and connectivity. Generating a CAD model for such a structure is beyond a simple patterning operation provided in CAD software. A mesh-based geometric modeling method and related algorithms were developed in a universal structure generation system (*USGS*) [14]. We integrate the *USGS* into the 3D texture mapping design system for converting a structure definition file to a CAD model.

The USGS first creates an array of joints and an array of struts based on the input structure configures. It generates meshes for each joint first. In addition, a set of planar contours are recorded as the joint boundaries. Meshes of each strut are then generated from a pair of these boundary contours. Finally all the meshes are combined to get a polygonal model of the entire structure. Since meshes of a joint and all the struts that connect it have the same boundaries, the generated STL model is watertight without gaps or overlaps.



(a) Primitives at a joint; (b) offsetting points of filleting operation; (c) constructed meshes from offsetting points;

(d) Boundary contours; (e) polygonal model of Triacontahedron; (f) a closer look at meshes of a joint.

Fig. 9: Geometric modeling operations for a 3D structure of Triacontahedron.

The above process is illustrated in Figure 9. The major geometric modeling operations used in the *USGS* are:

(1) Using geometric primitives to create joint and strut meshes: A joint corresponds to a sphere for 3D structures and a cylinder for 2.5D structures; a strut can be a cylinder or a cube. For example, a joint of a Triacontahedron is shown in Figure 9.a. Notice the combined model of all the primitives is not valid since there are overlaps between them. Therefore it cannot be fabricated by layer manufacturing systems.

(2) Filleting operation: Rounds and fillets are important design features which can greatly improve the mechanical properties of a structure by reducing its stress concentration. We use a point-based method to automatically add fillets to a joint [32]. Offsetting points for the joint shown in Figure 9.a are shown in Figure 9.b. The constant radius filleting operation is based on a combination of two offsetting operations $F_r(S) = S\uparrow_r\downarrow_r$, where we define two offsetting operations, S grown by r as $S\uparrow_r = S \oplus b_r$, and S shrunk by r as $S\downarrow_r = S \otimes b_r$ for any model *S*. Symbols $\oplus$ and $\otimes$ are the Minkowski sum and difference of two sets respectively. The reconstruct polygonal mesh from the offsetting points is shown in Figure 9.c. Notice the filleting operation also acts as a boolean operation (union) for a joint model.

(3) Planar plane cutting: A cutting operation is used to ensure meshes of a joint and a strut have a common boundary. Therefore the generated triangle meshes will be watertight. All the cutting lines are saved for constructing struts. The boundary contours for Triacontahedron are shown in Figure 9.d.

(4) Constructing a strut from a pair of planar contours: Two neighboring contours form a pair for constructing a strut. Since the two contours are single branching, mutually centered and reasonably similar, we used a "shortest diagonal" algorithm to reconstruct strut meshes.

The generated STL model of a Triacontahedron is shown in Figure 9.e. A close look at the same joint as shown in Figure 9.a is shown in Figure 9.f. Notice the reconstructed model is watertight and manifold.

6. GEOMETRIC MODLEING OF A CAD MODEL WITH AN INTRNAL STRUCTURE

Boolean operations (subtraction, intersection and union) are well-defined set operations. We use them to combine an input CAD model *M* with an internal structure *S* which is generated in Sections 4 and 5. In tissue engineering, there are two types of internal structures, plate based and rod based.

1. To create a part *P* with plate based internal structures, we define $P = M - S$, where – is subtraction;
2. To create a part *P* with rod based internal structures, we define $P = \Delta(M, r) \cup (S \cap M)$, where $\cap$ and $\cup$ are intersection and union respectively, and $\Delta(M, r)$ is the shelling operation of model *M* by distance *r*.

An example for combing *M* and *S* into *P* is shown in Figure 10. We use octahedron as the microstructure for generating internal structures. In Figure 10 (left), we generate an internal shell for a cube by a distance *r* first. We then use the cube to clip the internal structure ($S \cap M$). Finally we perform a union operation on the clipped internal structure and the shelled cube model. A split model is shown in Figure 10 for displaying purpose. In Figure 10 (right), we perform a subtraction operation on the cube and the internal structure. The generated part *P* has a lot of small holes inside the cube model.

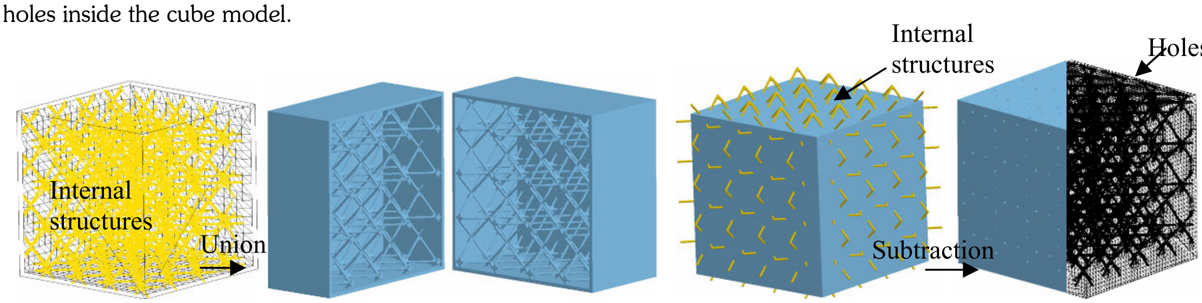


Fig. 10: Geometric modeling operations for a cube example.

We use a sampling-based method for the boolean operations on two arbitrary polygonal models [33]. We first use an initial cell size to construct a uniform volumetric grid for rough sampling of two models. Based on the rough sampling results, we then use an octree to refine the cells with complex shapes inside. We identify those cells based on an adaptive sampling test, in which an error-minimizing point is tested to determine if it captures all the geometric objects inside the cell. After a uniform grid and an octree grid are constructed, we use an isosurface extracting method for reconstructing booleaned polygonal model. We guarantee the reconstructed surfaces have the same topology as the exact surfaces, and the maximum approximation error from the exact surfaces is bounded by a user specified tolerance.

The shelling operation $\Delta(M, r)$ can be performed based on an offset operation. Suppose a ball with radius r is defined as b_r. We can use an offsetting operation $S\downarrow_r = S \otimes b_r$ to generate an internal shell of *S*, which can then be combined with *S* to generate a shelled model. We use a point-based method for offsetting a polygonal model by an arbitrary distance *r* [34]. We use a hybrid data structure which combines point samples, voxels, and polygonal surfaces. Each face, edge, and vertex of the original solid generate a set of offset points. We then judge the offset points to generate a set of boundary points, from which the offset boundary is reconstructed by an isosurface extracting algorithm.

A polygonal model *P* based on the boolean and shelling operations can be saved as a STL file, a de facto CAD format, and built by most layer manufacturing systems.

7. AN EXAMPLE

We tested our 3D texture mapping design system on different CAD models and microstructures. A Beethoven statue example is shown in Figure 11. The input CAD model is shown in Figure 11.a (Tri#: 5,050). Shelling operation is used to create an internal shell inside the model, which is shown in Figure 11.b ((Tri#: 48,604). An internal structure based on Dodecahedron is designed and saved in a structure definition file. The file is input to the *USGS* which creates the CAD model of the internal structure as shown in Figure 11.c (Tri#: 219,950). We use a boolean operation (intersection) to clip the internal structure by the input Beethoven model. The generated result is shown in Figure 11.d (Tri#: 196,503). Finally we perform a union operation on the clipped internal structure and the shelled Beethoven model. The generated model has 245,107 triangles. We split the model for viewing purpose. The split models are shown in Figure 11.e. We also used a Selective Laser Sintering machine and A6 steel, both from *3D Systems Inc.* (www.3dsystems.com), to fabricate the split models. A picture of the build model is shown in Figure 11.f.

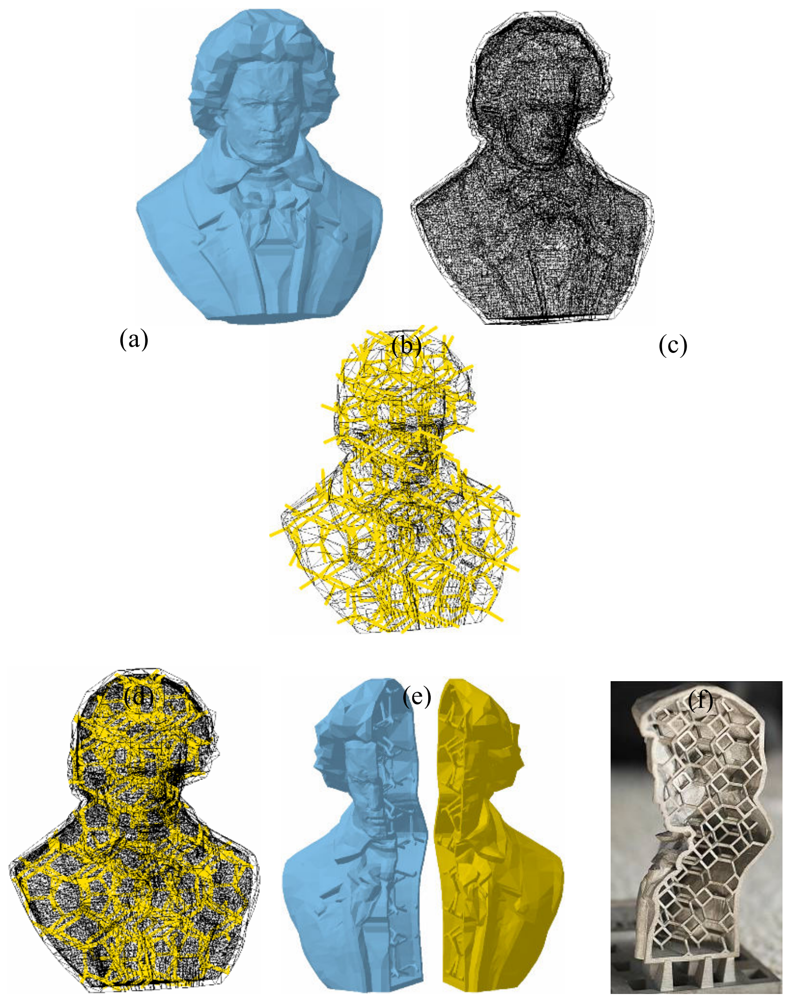


Fig. 11: A Beethoven statue example in which Dodecahedron is used for 3D texture mapping.

8. CONCLUSION AND FUTURE WORK

Layer manufacturing enables us to fabricate a physical model with complicated internal structures. However, designing such a model is beyond the capability of current CAD systems. In this paper, we have presented a design method based on mapping a microstructure into a design space to generate internal structures. We present a representation scheme for defining general structures and use it to build a library of microstructures. It is challenging to synthesize microstructures based on various design requirements. We present an approach based on space warping technique. Our approach is fast since we divide topology synthesis and dimensional synthesis. Our approach also enables designer to easily control the density of internal structures. We use a set of geometric modeling operations to automatically generate a CAD model. The generated model can be saved as a water-tight STL file for layer manufacturing systems. The experimental results have verified the effectiveness of our method.

We envision several avenues for future research. We would like to compare material properties of different microstructures. We would also like to add finite element analysis in the synthesis of microstructures to optimize strut dimensions and compare it with other synthesis approaches. We plan to investigate how to integrate multiple microstructures within a part, which requires extra care to ensure the continuity between different microstructures.

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