Generating Topologically Optimized Cellular Structures for Additive Manufacturing

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Overview
We introduce a new method for generating an STL definition of a lattice structure that can be 3D printed using standard Additive Manufacturing technologies. Using a topology optimization code developed at Sandia, an organic shape designed to accommodate specific loads and boundary conditions is first meshed using the Sculpt application. The hex elements produced are used as the basis for generating a lattice structure that is exported as an STL file. Following 3D printing, the result is a reduced-weight component using minimal material to meet structural strength criteria.

Topology Optimization
Based on various load conditions and material properties, an optimized shape is produced.

Sculpt Hex Meshing
From the STL boundary representation produced from the topology optimization, Sandia’s Sculpt code is used to generate an all-hex mesh at a user defined resolution.

Lattice Templates
A template geometry to be used in each hex of the mesh is selected. Templates are defined from Boolean operations on analytic cylinders configured to optimize strength and density characteristics. Templates are required to be super-symmetric, where rotations in u, v, or w directions yield identical results. To reduce memory requirements, analytic surfaces are reduced to a minimal set of triangles for each configuration.

Transfinite interpolation is used to map a given STL triangle vertex on the unit cube with coordinate \( u,v \) to a 3D \( x,y,z \) coordinate. Edge and face coordinates can be computed as follows:

\[
E_0 = N_0 + u(N_1 - N_0) \\
E_1 = N_1 + v(N_2 - N_1) \\
E_2 = N_3 + u(N_2 - N_3) \\
E_3 = N_0 + v(N_3 - N_0)
\]

With the 3D coordinate computed as a linear combination of the three coordinate directions.

\[
P_{u} = \frac{P_{u_{\text{min}}} + u(P_{u_{\text{max}}} - P_{u_{\text{min}}})}{3} \\
P_{v} = \frac{P_{v_{\text{min}}} + v(P_{v_{\text{max}}} - P_{v_{\text{min}}})}{3} \\
P_{w} = \frac{P_{w_{\text{min}}} + w(P_{w_{\text{max}}} - P_{w_{\text{min}}})}{3} \\
P_{3D} = \frac{P_{u} + P_{v} + P_{w}}{3}
\]

Triangles on the faces of the template are only mapped to the 3D hex element if it lies on the exterior boundary of the model. This allows for a single continuous water-tight volume composed of STL facets.

Paper reference:
 Validation Modeling

To computationally validate the strength of lattice structures, two different finite element approximations were used: (1) a continuum model composed of 3D cylinders and conformally meshed with hexahedral elements, and (2) a beam element approximation, where each cylinder is approximated by a single beam element.

(1) 3D Continuum model composed of hexes of two lattice templates of the tetrahedron configuration
(2) 3D beam model composed of beams of the same tetrahedron configuration.

A cantilever beam modeled as a lattice structure was used to validate the characteristics of the lattice structure. Sandia's Sierra/SM code was used for analysis.

Graphs on left illustrate the computational approximation differences between using a continuum vs. a beam model for displacement and stress values. Those on the right utilize the continuum model and modify the lattice cell size to compare values for stress and displacement.

Continuum Vs Beams - Displacement
Max Stress Vs Cell Size

Continuum Vs Beams - Stress
Displacement Vs Cell Size

3D Printing

Image of STL model of a high resolution tetrahedron lattice structure with over 26 million triangles

Image of STL model produced from mapping procedure. Shaded region on inset shows a single hex element where a unit cube tetrahedron template has been mapped.

Topologically optimized geometry with coarse cellular structure printed in 316L stainless steel using a 3D Systems ProX 700. Courtesy of David Saiz and Bradley Jared, Sandia National Laboratories.