Title:
Novel Lightweight Lattice Structure Generation Methods for Additive Manufacturing

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Introduction:
Additive manufacture is an excellent method for fabricating parts with complex lightweight structures that conventional manufacturing methods is incapable of. Adding lightweight structures into design models can improve their mechanical performance as well as reduce the cost of printing materials effectively. Existing design methods for lightweight structures either generates porous structure on the global scale or design lattice units locally to fit in the original model. Former method treats the whole model directly, leaving shapes and sizes of the structure units independent to controls of design parameters [5],[8],[9]. This method allows designed model to take external loadings from various directions. But the topology of the unit structures is irregular and hard to control, making it lacks flexibility on design and optimization. Later approach is to select variety of lattice structure units to design lightweight structure of a solid model, which has better design flexibility and is also able to achieve ideal mechanical performance [2-4]. For example, shaping of lattice units can be controlled by adjusting node positions and topological connections, as well as modifying unit size to get different porosities. However, the relatively low efficiency for computing lattice units become a major issue of this method. In this paper, we propose a lattice-based 3D printing lightweight structure generation method which can effectively reduce the model material and take the advantages of lattice symmetry and flexibility. The resulting lightweight structure will be used to replace the internal solid space of a given model, which provides an important basis for the optimization of the mechanical properties of the structure.

Conventional lattice structure generation method is implemented by lattice arrays in orthogonal Cartesian coordinate space, which often requires cropping to fit in the surface enclosed space. In that case, some parts of lattice units would lose completeness and desired topological structures due to cropping [6]. Thereupon, the generated internal lattice structures cannot adapt the surface features of the original design model, which significantly affects its mechanical performance. In the matter of this problem, we also propose a conformal lattice structure generation method based on parametric surface, which conducts conformal transformation according to the shape of parametric surface in surface enclosed space to achieve self-adaptability of lattice structure to surface space without cropping.

Periodic Lattice-Based Structure Generation:

Universal description for lattice structures:

Any lattice structures can be considered as spatial net structures consisting nodes and bars. Based on OXYZ coordinate system, the lattice can be regarded as an undirected graph $C = <V, E>$, where $V = \{V_i \mid i = 1, 2, \ldots, m\}$ is a set of all vertices and $E = \{E_k \mid k = 1, 2, \ldots, n\}$ is a set of all edges of a lattice unit. Parameters can be used for describing features of lattices. Namely, for specific cross-sectional shapes such as circles and regular polygons, sizes can be set by one simple parameter D. Thereout, a universal data model can be developed, demonstrated in Fig. 1. To ensure the uniqueness of geometric data in generated lattice arrays and accuracy of computation, the nodal coordinates are digitized to integers to avoid errors during elimination of overlapped vertices or edges. For defining topology of lattices, we built a data library storing presets of common lattice structures using JSON files. Models of typical lattice unit cells are also built and shown in Fig. 2.

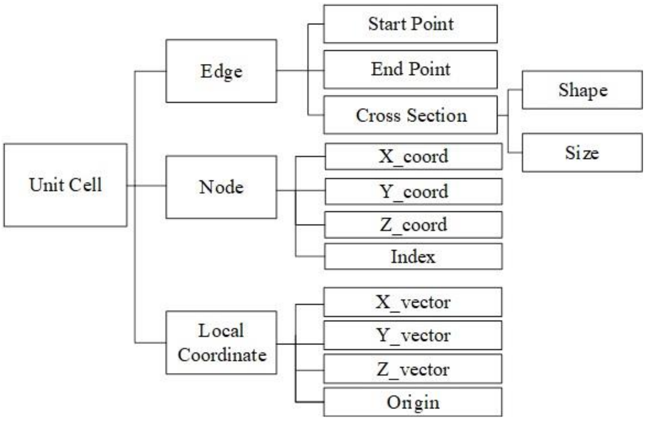

Fig. 1: Universal data structure for describing lattice structures.

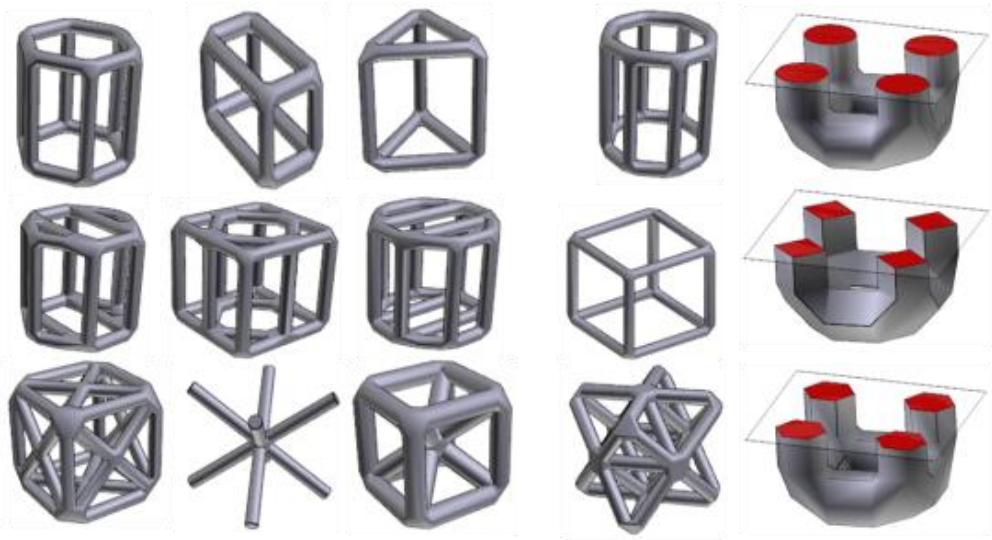

Fig. 2: 3D models of 12 typical lattice unit cells. The right-most column shows three typical cross-section shapes of lattice bars.

Spatial Frame Topological Structure Generation:
We further generated an internal structure where lattices are internally continuous and homogeneously distributed based on a selected lattice, shown in Fig. 3. Such generating algorithm consists two main stages: 1. Digitizing lattice unit, which is a process that transfers float-point type node coordinates to integers, as the input for stage 2. Digitization of lattices is significant for avoiding errors when evaluating overlapped nodes and edges, as they tend to have minor gaps in between when represented by float-point numbers even though they should be regarded as overlapping elements. This process can also simplify the computation, which improves efficiency; 2. Multiplying unit cells in XYZ directions to form a frame model in macroscale. The stage 2 requires elimination of overlapped vertices and edges to eventually attain a spatial frame model represented by undirected graph.

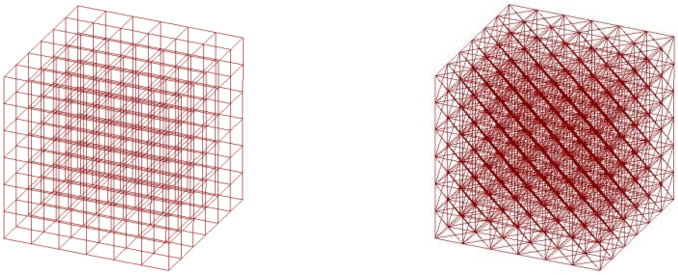

Fig. 3: Generated frame models using unit lattices with different topological structures.

Lattice Structure Entity Modeling:
In previous sections, the spatial frames are only skeletons of design space and are needed to be transformed to entity models. Conventional method uses CAD softwares or geometric modeling kernel to create complete entity model of these complex truss structures and then generates STL models, which often results in high processing complexity and requires tremendous amount of boolean operations [7]. Thus, we used a geometric modeling method that directly constructs spatial truss STL models, which is based on point-set triangulation. Circular profiles are first calculated around every node of truss frames by the principle that no overlapping between bars. Then the trianguar mesh is generated for each node and the mesh at the outer side of circular profile is cut to leave a "notch" for adjacent lattice bars. Finally, mesh at node and connecting bars all blend at the "notch" to form a watertight and overlap-free mesh model. No boolean operation is needed through this process. Fig. 4 shows a rabbit model filled by lattice structure frame.

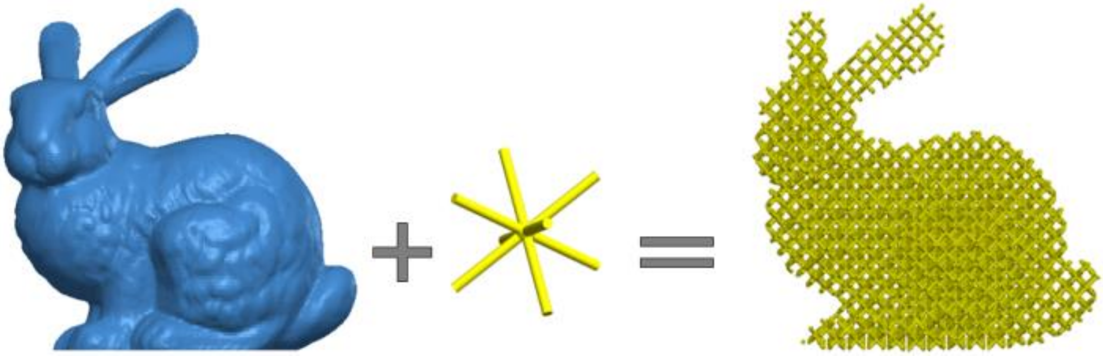

Fig. 4: A model of rabbit filled by lattice structure frame.

Comparison was made between our generation algorithm and lattice design function in Siemens NX software. The test object was a 100mm radius sphere entity, and same design parameters were set for both trials. The modeling results showed that our algorithm is at least 40 times faster than NX's, and the obtained mesh is much smoother (Fig. 5).

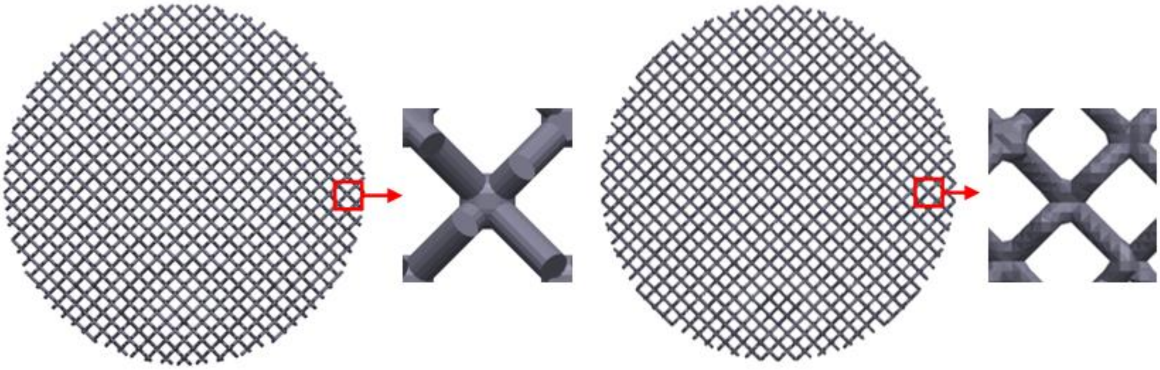

Fig. 5: Modeling result comparison between proposed method (left) and NX software (right).

Parametric Surface-Based Conformal Lattice Structure Generation:

To avoid defects due to cropping while fitting lattice skeletons into design models, we adopt the approach of conformal transformation based on parametric surface. The skeleton nodes and edges go through conformal transformation together to adapt the form of model surface, where interpolation points with same amount and distance are inserted to each edge for transformation. There are three general enclosed surface space for lattice skeleton to conform: point-to-surface, curve-to-surface, and surface-to-surface (Fig. 6). The definitions are expressed as Eqn. 3.1:

$$\begin{cases} \varphi_{p.to.s} = \{P(x,y,z), S(x,y,z,u,v,w)\} \\ \varphi_{c.to.s} = \{C(x,y,z,u,v,w), S(x,y,z,u,v,w)\} \\ \varphi_{s.to.s} = \{S(x,y,z,u,v,w), S(x,y,z,u,v,w)\} \end{cases} \tag{3.1}$$

Where $\varphi_{p.to.s}$, $\varphi_{c.to.s}$, $\varphi_{s.to.s}$ are three eclosed space. P, C, S are point, curve, and surface in three dimensional space. x, y, z are Cartesian coordinates representing positions of parametric points, curves and surfaces. u, v, w are topological space coordinates for establishing mapping between skeletons before and after conformal transformation.

Conformal transformation is like twisting and bending the enclosed space bounded by point-surface, curve-surface, and surface-surface geometries to adapt the shape of the surfaces and curves. Parametric points on the frame inside the enclosed space follows the curvature of the tansformed frame but still remain the same parametric (topological) coordinates. Mathematical process of conformal transformation can be illustrated through curve-to-surface transformation procedure: Set P_0 as a topological point on lattice skeleton, whose topological coordinate is (u_0, v_0, w_0). A point on the parametric curve, P_c (u_c, 0, 1), corresponds to a Cartesian coordinate (x_c, y_c, z_c), which can also be represented as (x_c, y_c, z_c, u_c, 0, 1). A point on the parametric surface P_s has the coordinate (x_s, y_s, z_s, u_s, v_s, 0). The calculation of conformal transformation:

$$\begin{cases} x = x_s + w_0(x_c - x_s) \\ y = y_s + w_0(y_c - y_s) \\ z = z_s + w_0(z_c - z_s) \end{cases} \tag{3.2}$$

Then we generate the entity model by blending convex hull mesh and polygonal mesh using QuickHull algorithm [1]. Through CATIA Geometry Modeler, the parameters of model surface get be extracted and used for constructing surface space for conformal transformation. Examples of lattice models and 3D printed samples implemented by our generation methods are shown in Fig. 7.

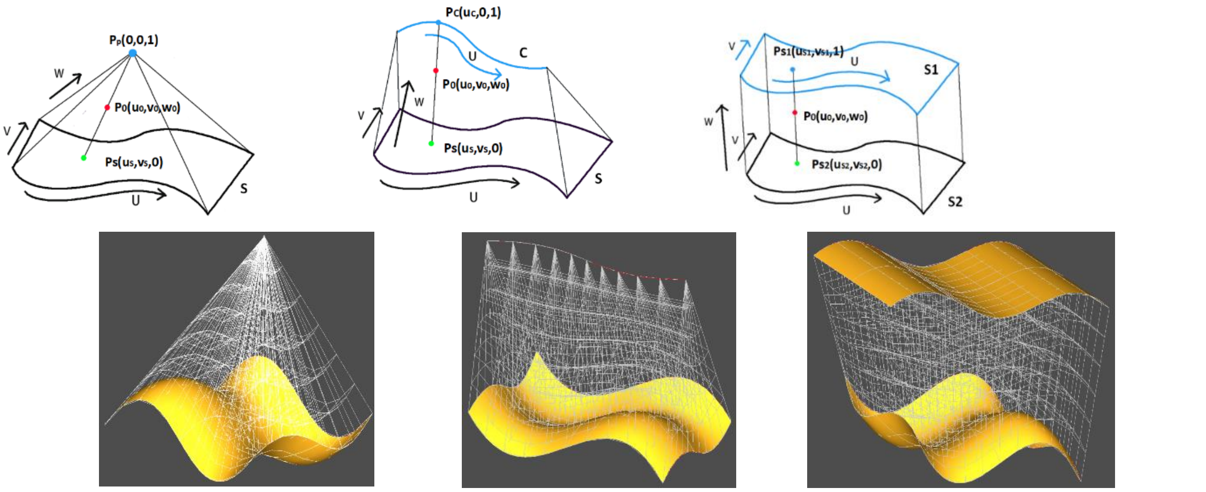

Fig. 6: Enclosed space and corresponding frame models, from left to right: (a) point-to-surface, (b) curve-to-surface, (c) surface-to-surface.

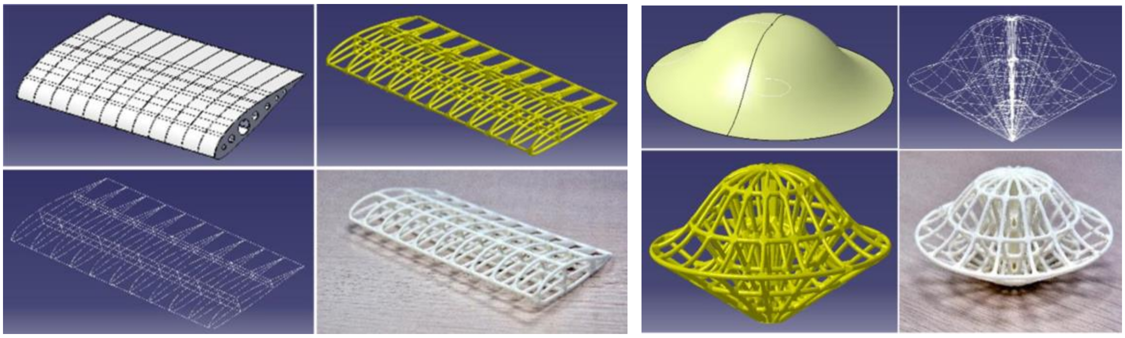

Fig. 7: Example models and 3D printed samples.

Conclusions:

Facing existing issues in conventional lightweight structure generation methods in 3D printing, this paper presented a novel method based on periodic lattice and conformal transformation. We developed a highly efficient entity modeling algorithm which was proven to be faster than a commonly used CAD software. We furtherly adopted conformal transformation method for adapting lattice frames to models with freeform surfaces. Implementation cases are also demonstrated and discussed. Further research will be conducted on mechanical performance and optimization of the generated models as well as the universality of the algorithm.

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