Generative Design of Lattice Structures for 3D Printed Sculptures

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Abstract

First, the Greeks and later the Romans reached a summit of artistic excellence by creating large bronze statues. These sculptures were hollow because the lost-wax technique involved the creation of a non-bronze internal space which was sometimes removed to leave a hol low bronze shell. After making a pos itive model nearly the size of the desired sculpture, artists coated it in wax and refined the details directly on the thin wax surface. The entire model was then covered in clay by using rods passing through the internal part of the statue. The wax was then melted away, and bronze was poured into the negative space left by the melted wax. Nowadays, Additive Manufacturing technologies, especially Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), metal Binder Jetting, and lately Fusion Deposition Modelling (FDM) upgraded to Atomic Diffusion Additive Manufacturing (ADAM), allow the printing in metal of sculptural or mechanical models without

the necessity of a core for the support of the model.

Instead of a hollow space, the model's internal part can be filled with lattice structures for structural and aesthetic reasons.

Using generative design and changing various process parameters, lattice structures can be created with specific electrical, mechanical, thermal, and acoustic properties. For this reason, such structures have been researched mainly for technical, rather than artistic, applications.

In addition to the lattice structures that software can create, Generative Design can be used to realize supports for mechanically sound and aesthetically compelling parts.

Only a few artists specifically explored the aesthetic applications of lattice structures and generative design (for example, Neri Oxman from MIT and a few others).

This paper explores the application of the latest software and specific processes to prepare a variety of sculptures exploring both the aesthetic and mechanical possibilities that these new techniques and processes enable.

1. Introduction

The two authors have collaborated for many years in the study and research of AM technologies and applications for engineering and artistic applications.

Professor Picozzi explains how generative design can be used in connection to design and AM processes. To produce various sculptures, Professor Prete compares different software packages to analyze modelling results for the same initial parameters and different aesthetic aspects of both Generative Design and lattice structures. An initial step-by-step guide helps the understanding of the software and procedures.

2. Generative Design

A solid object is loaded by applying forces somewhere on its surface. Upon being loaded, the solid responds by undergoing deformations throughout its volume, which are in general partly elastic and partly plastic. The former disappear upon removal of the load, while the latter are permanent. The deformations vary with position within the solid with a pattern that depends in a very complicated way on the nature and location of the loads and, critically, on the detailed geometry of the object. As a consequence of such deformations, the loads applied at the surface lead to forces distributed throughout the volume, whose spatial pattern mirrors that of the deformations. If the forces distribute themselves in such a way that their intensity nowhere exceeds the material's threshold for rupture, the object will sustain the loads without suffering any damage. On the other hand, if that threshold is exceeded at some location, the object will rupture at that location, with the initial damage possibly evolving towards catastrophic failure of the entire structure. An exact calculation of the volume force distribution is only possible for very simple geometries; in nearly all practical applications, machine computation is necessary. Lattice structures offer obvious advantages with respect to continuous solid objects in terms of weight saving, and they may possibly exhibit a particular aesthetic appeal as well. The goal is to design the lattice geometry in such a way that the resulting structure will meet the same strength requirements as its fully solid counterpart while being considerably lighter. In general, identifying an "optimal" geometry can be difficult even for an expert designer because even minuscule variations in the lattice geometry may lead to substantial shifts in load-bearing properties. Generative design tackles this challenging optimization problem by "testing" multiple geometries until one is found that is "best" according to criteria established by the designer. The testing consists in generating automatically many different variations upon the initial geometry and in computing, for each of them, the corresponding volumetric force distribution. An appropriate algorithm will score the load-bearing performance of each design so that an optimal solution will emerge corresponding to the highest score. Since the process is entirely computerized, the number of geometries to be tested is limited only by the computing time that the designer is willing to allow. Thousands, possibly millions, of configurations can thus be tested automatically, and the final solution to which the algorithm finally converges can inspire sufficient confidence that said solution is close to the absolute optimum within the specified constraints. In generative design, the designer's input is confined to the specification of the problem's constraints dictated by the nature of the application being considered.

The connection between Generative Design and Additive Manufacturing is that the lattice geometries emerging from the optimization process are often too complex to be built by conventional (subtractive or formative) manufacturing techniques, while the particular capabilities of 3D printing processes may enable the realization of even the most intricate geometries. Moreover, it is possible that the design chosen by the algorithm, while exhibiting superior mechanical properties, may be deemed aesthetically unappealing. In that case, human judgment may override the algorithm's choice and select instead a suboptimal geometry that still meets minimum strength criteria while also being easy on the eyes in a way that an algorithm cannot easily capture.

3. Lattice Structures

Our investigation presents a practical guide in using lattice structure on artistic models by using generative design and software such as nTopology, Autodesk NetFabb, Autodesk Fusion 360 and providing the right dimensioning for the shell and the internal lattice structure to a digital sculpture. Best settings/performances based on shape/scale/dimensions / AM technology used for fabrication will be presented based on our tests.

We can consider a lattice structure a model or a three-dimensional pattern that is repeated to fill a volume.

We can find natural examples of lattice structures in our bones, in the honeycomb of beehives, fungi mushrooms, and bubbles (as Voronoi structure). All these examples are nature's way to provides lightweight structures.

Figure 1: Mushroom hymenium tissue presenting natural lattice structure.

Our analysis considers only lattice structures that can fill a volume (a mesh or a CAD model) or be applied to surfaces. Lattices can be periodic, non-periodic, or stochastic and can be modeled through beams, plates, or Triply Periodic Minimal Surfaces (TPMS).

A cube of 100x100x100 mm is used first to explain the process and procedures. The second example of the actual application of Adam's hand sculpture provides a practical example and consideration of best practices.

Autodesk NetFabb can be easily used to create a lattice structure and provides a good understanding of the steps used to create a simple internal lattice structure.

After creating or importing a basic cube 100 mm x 100 mm x 100 mm (mesh), we can easily drag the model under the "Lattice Assistant" command to select a series of pre-set lattice structures.

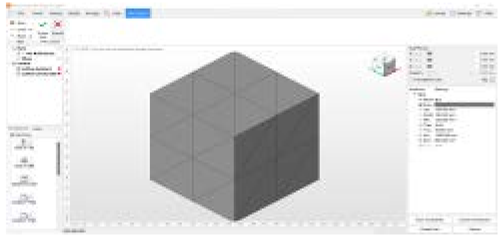


Figure 2: Creation of mesh cube on Netfabb.

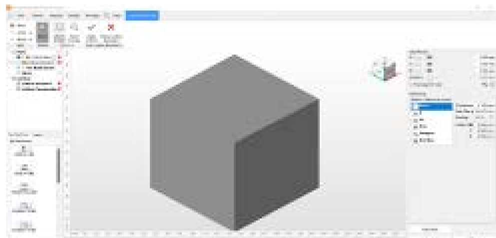


Figure 3: Selection of Lattice Structure on Netfabb.

A window gives the option to select the lattice structure, the thickness of the wall, and the cell size.

The thickness of the lattice structure is proportioned to the size of the cell. A minimum thickness needs to be established based on the technology used for the fabrication and scale of the model.

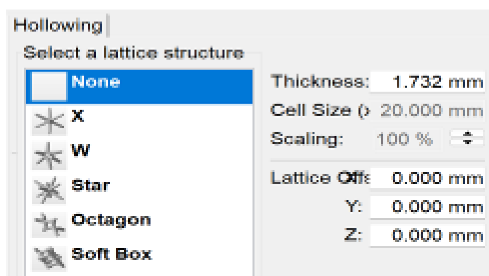


Figure 4: Selection of Lattice Structure type on Netfabb.

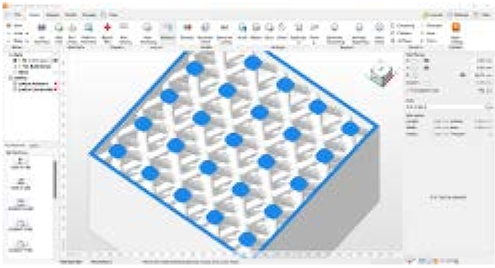


Figure 5: Creation of Lattice Structure type on Netfabb.

With a 20 mm cell and 1.732 mm thickness, we obtain a robust structure with 1/2 of the weight.

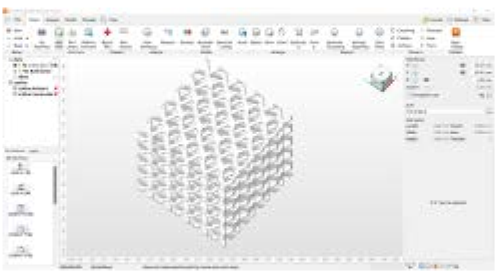


Figure 6: Internal visualization of Lattice Structure created on Netfabb.

After removing the shell, we can see the internal structure with a volume of 165.8 cm3 in contrast to the previous 279.3 cm3.

With a simple beam X structure, we can maintain part of the mechanical qualities important for artistic and s culptural applications with half of the weight. The weight reduction is essential as load reduction for calculating the structure itself and as a saving in material and costs during fabrication. Most AM technologies used for 3D fabrication (SLA, FDM, Binding Jetting, etc.) provide good printing without support with overhangs less than or equal to 40° / 45°.

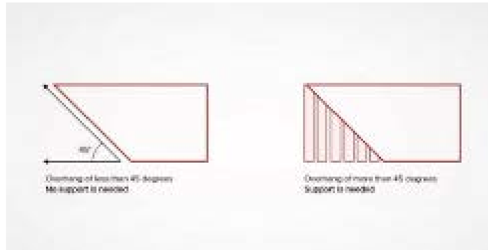


Figure 6: Explanation of overhang less than 45° that is typically safely printable (Source: Mohit via GrabCAD)

If the distance between parts is small enough (horizontally 5 m m) or if the overhang is gradually reached (increasingly proportionate overhang), the angle can be reduced, and additional internal support can be avoided if the orientation is calculated based on t he direction of printing.

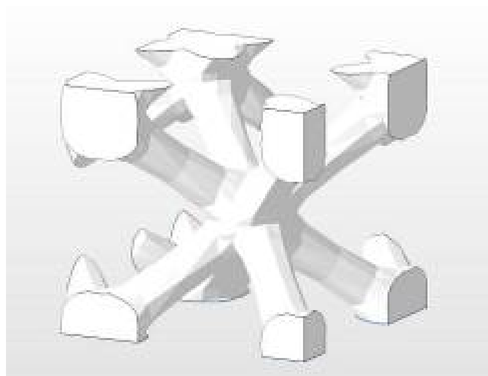


Figure 7: Visualization of the single 20x20x20 mm X unit that presents a max distance of 17.32 mm, 3.6 mm minimum thickness, and angle of 35.26 for each leg.

We also made some considerations based on t he AM technologies used for fabrication.

FDM (Fusion Deposition Modeling) in ABS, ASA, PLA, or other thermoplastic can be eas ily used to print lattice structures. Most of the time, even desktop printers use proprietary slicer software that can provide a s imple internal system regulated by the selected density.

Figure 8: Examples of internal structure 20% density, 50% density and 100% density with FDM printing.

There is no need for additional openings when FDM is used. On the other hand, if technologies such as SLA or Binding Jetting are used, openings for removing the unbonded or uncured materials must be provided in areas that can be eas ily repaired or filled during the postprocessing of the artwork.

In these last cases, stochastic and beam-based lattices are probably easier to clean than TPMS (where unbonded powder or uncured resin can remain inside.

In addition to the simple use of lattice structures for structural/mechanical reasons with improved lightweight characteristics, we also looked at the relationship between aesthetic and mechanical qualities.

Software such as Autodesk Netfabb or Fusion 360, can easily create a lattice structure based on specific characteristics, but always with a predetermined standard dimension and orientation. Other software, such as nTopology can generate a gradient of lattice structure resulting in an anisotropic design where the conformal gradient lattice structures are optimized. This kind of lattice structure mimics the natural organization we find in animal bones. Parts under more stress or thinner are filled with dense structure and parts under less stress or thicker with less structure.

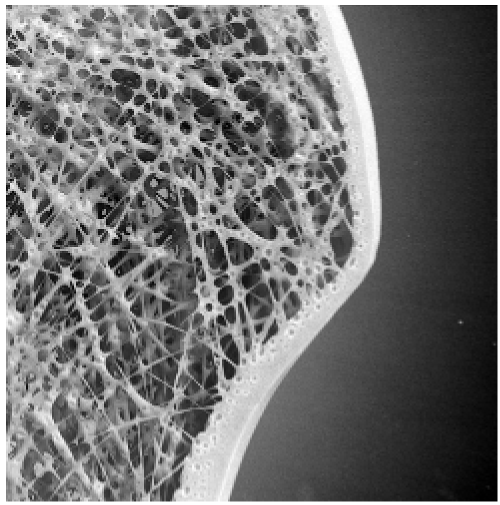


Figure 9: Examples of internal bone structure.

nTopology software provides a easy solution to create conformal lattices showing interesting aesthetic characteristics.

After importing two surfaces that define the top and bottom of our basic cube,

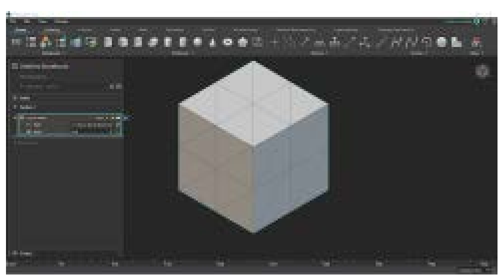


Figure 10: Creation of 100x100x100 mm cube on nTopology.

I used a an eas y tool called "Simple Conformal Lattice between faces" to create my first lattice in nTopology.

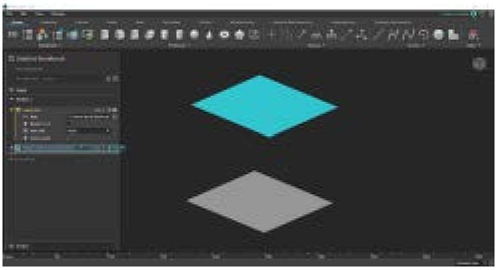


Figure 11: Creation of two faces based on 100x100x100 mm cube on nTopology.

nTopology provides several units that can be us ed for the structure and also allow the personalization of the unit's design.

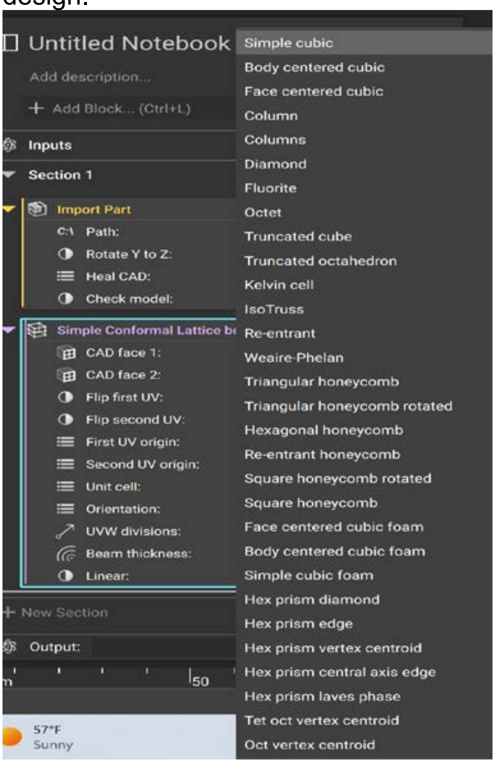
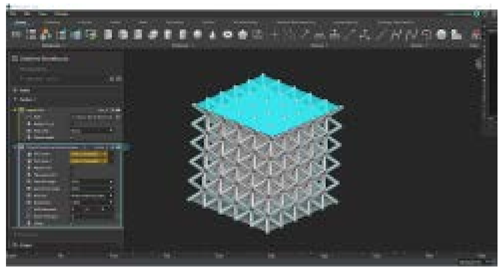


Figure 12: Selection of the unit cell type on nTopology.

A simple cubic design presents similar design of other software.



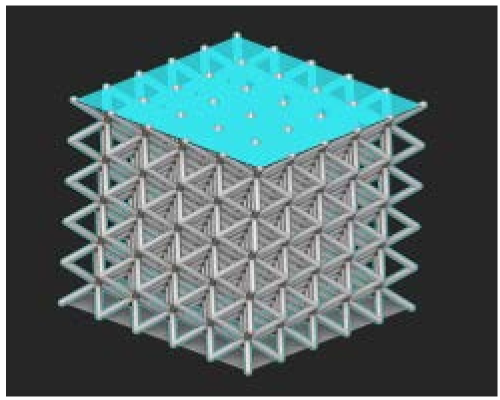


Figure 13/14: Lattice structure created by using "Simple Conformal Lattice between faces" on nTopology.

By changing parameters on U VW orientation or UVW division we can iterate trough different variations for aesthetic or structural reasons.

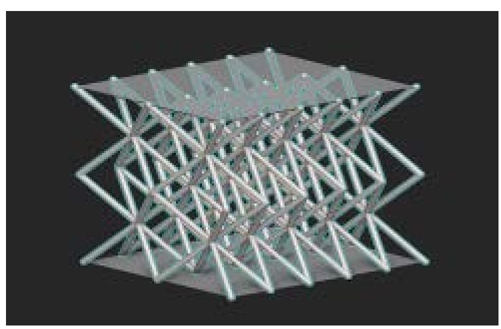
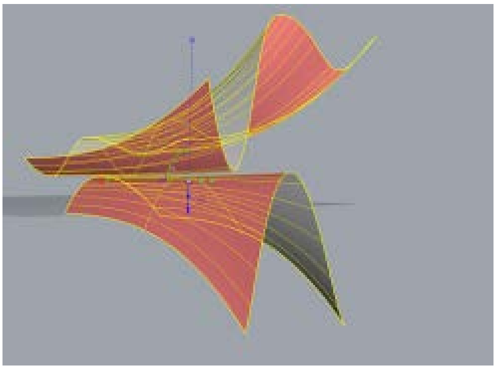


Figure 15: Variatons of lattice structure based on UVW modifications.

In the case of more complex shapes created using other CAD software and imported in nTopology, these parameters can adapt the lattice to the surfaces.



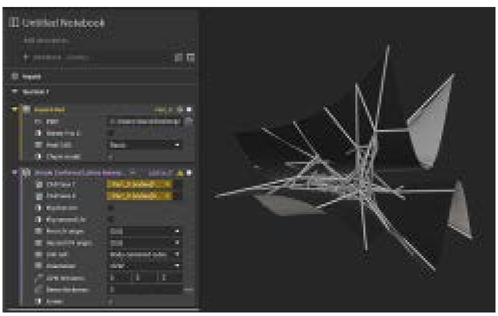


Figure 16/17: Adaptation of lattice structure on more complex surfaces.

Multiple variations can be created by changing basic parameters to achieve different results.

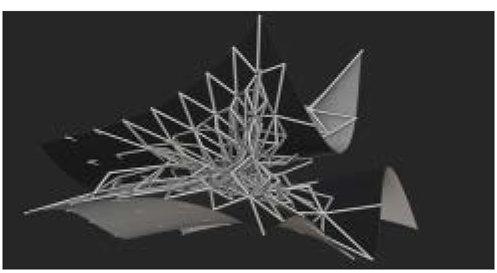


Figure 18: Adaptation of lattice structure on more complex surfaces.

These few examples are far from a detailed description of the tools and capacities of the software and want to be only an inspiration and a starting point for new creative processes.

For a more practical example, Professor Prete worked on a hand sculpture inspired by Adam's Hand to test possible aesthetic values of the lattice structure.

Starting from the mesh and after hollowing the model, a spiral selection of the surface was determined to visualize both internal and external spaces.

The design was just a way to maintain enough understanding of the original mesh and balance the visualization of the internal structure.

The lattice structure was so created only on the internal mesh obtained from the hollowing operation to reach 3 m m thickness for the shell.

A minimum thickness of 2 mm was defined for the lattice structure that covered the internal mesh and mixed it with the original spiral design.

The connection points with the external mesh were left even if outside the surface, creating an interesting connection between the internal "negative space" defined by the lattice and the "positive space" of the spiraled hand. The model was printed in plaster by using binding jetting and infiltrated with epoxy resin.

4. Conclusions:

Software able to create lattice structures, such as nTopology, NetFabb, and Fusion360 are changing how artists and designers adapt supporting structures by analyzing and selecting variations on the same project for aesthetic and mechanical reasons.

Artistic research and creative choices in lattice structures are just beginning and will soon unlock the full potential of generative design, topology optimization, and lattice structures for Additive Manufacturing.

Key words:

Generative design, additive manufacturing, 3D Printing, computational design, lattice structure.