# A Method to Generate Lattice Structure for Additive Manufacturing

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*Abstract* – **Additive Manufacturing (AM), popularly called 3D Printing, is a scientific term indicating the Rapid Prototyping (RP) technologies developed in 1980s. AM technologies can directly fabricate a complex 3D object from three-dimensional Computer Aided Design (3D CAD) model by adding layer-by-layer of material. Advances in AM technologies are capable of manufacturing highly complicated geometries of product without the need for process planning, the reduction of product development time and cost, the removal of tooling compared to conventional manufacturing technologies. The production of lattice structures is quickly performed by AM technologies in order to attain a product with lightweight and stronger and to provide the high specific mechanical properties such as strength and energy absorption. However, the current product modelling technologies have many difficulties for generation of lattice structure model. Thus, the paper proposes a new approach that allows to create different configuration types of conformal and non-conformal lattice structure model.**

*Keywords* – **Additive Manufacturing, Computer-Aided-Design (CAD), cellular structure, lattice structure.**

## I. INTRODUCTION

Additive Manufacturing (AM) is an appropriate word to describe technologies that build a highly complex geometries of 3D object by adding layer-upon-layer of material as plastic, metal and concrete, etc. These technologies are developed from Rapid Prototyping (RP) used in a variety of industries to indicate a manufacturing process for quickly creating a real representation of product before final commercialization or release [1]. There are many advances in AM technologies such as the reduction of product development time and cost, the removal of tooling. However, the most significant advance of AM technologies in comparison to conventional manufacturing ones as machining, cutting, forging, etc., is its ability to fabricate extremely complicated geometries of product. Especially, it is capable of building topology structure and material of product such as cellular structure in order to obtain a product with lightweight and stronger and to provide the high specific mechanical properties.

Cellular structure solid is a network of truss including struts or plates interconnected each other. The struts and plates form the edges and faces of cells [2]. There are different types of cellular structure including foams, honeycombs, lattices and similar constructions [3, 4]. A lattice structure consists of a repeating structure element as called cellular structure element or unit cell structure that is tessellated over a region. Lattice structures have many inherent advantages due to their ability to provide lightweight, high specific strength, stiffness and impact absorption materials. They have been used in many industrial engineering applications such as improvement of material properties [5, 6], thermal engineering [7], and biomedical application [8].

The recent AM technologies such as electron beam melting (EBM), direct metal laser sintering (DMLS), selective laser melting (SLM) and selective laser sintering (SLS) allow to directly fabricate lattice structure with controlled mechanical properties of material and desired external and internal characteristics. However, it needs to have a digital model of lattice structure storing 3D geometric data and additive manufacturing processes use this model to slice it into each layer and translate into the trajectory tooling of AM machine. The numerical model is usually created in computer-aided design systems.

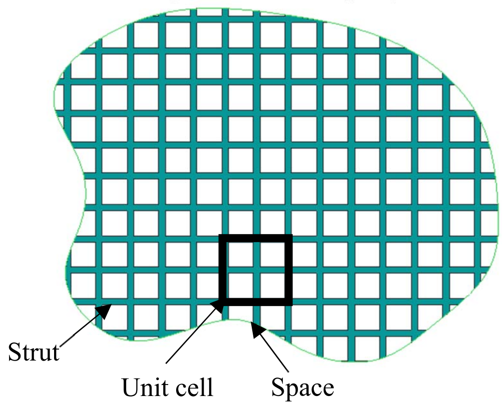



Fig. 1. An example of lattice structure.

There are different methods to generate three-dimensional, virtual geometry of lattice structures for additive manufacturing. Several research groups have attempted to design and develop periodic lattice structures with commercial CAD software [9-12]. However, these studies focus on methods to build a cellular structure element and to generate periodic lattice structures in a simple 3D region. Therefore, the paper focus on presenting a method that allows to automatically generate a numerical model of three-dimensional lattice structure with different configurations of cellular structure element. In addition, this method permits to create periodic and non-period lattice structure in a complex 3D region of product and especially complex skin lattice structure on a surface.

## II. METHOD DESCRIPTION

A lattice structure can be considered as a hierarchy of different cellular structure elements. At the first level, a structure is consist of a series of struts and a cell structure is a group of struts interconnected each other. The lattice structure is created by arranging these cells in a space periodically (see Fig.1). In order to generate a numerical model of lattice structure on CAD system, the paper proposes a method that allows to automatically create lattice structure of a product. This method has two way to generate lattice structure, the first is to create periodic lattice structure in three-dimensional space of product frontier and the second permits to generate non-periodic lattice structure on surface or 3D space of product.

### *1) Generation of periodic lattice structure*

In order to create periodic lattice structure in a three-dimensional space of product, the paper propose a method including the following steps:

**Step 1. Create library of unit cell structure**

The shape and topology of unit cell structure are designed relating to mechanical properties of material. The method to design and optimize topology of unit cell structure is proposed by several research groups [13-15]. As a result, any unit cell structure can be easily created in CAD system. Each unit cell structure should be created in a cube volume for three-dimensional lattice structure and a square surface for two-dimensional lattice structure space.

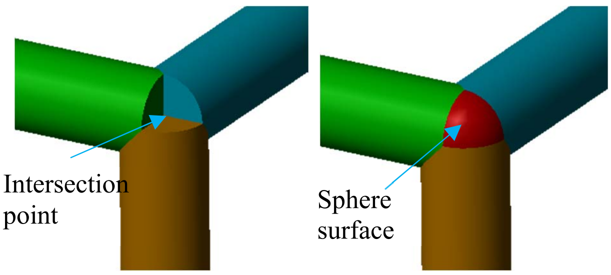
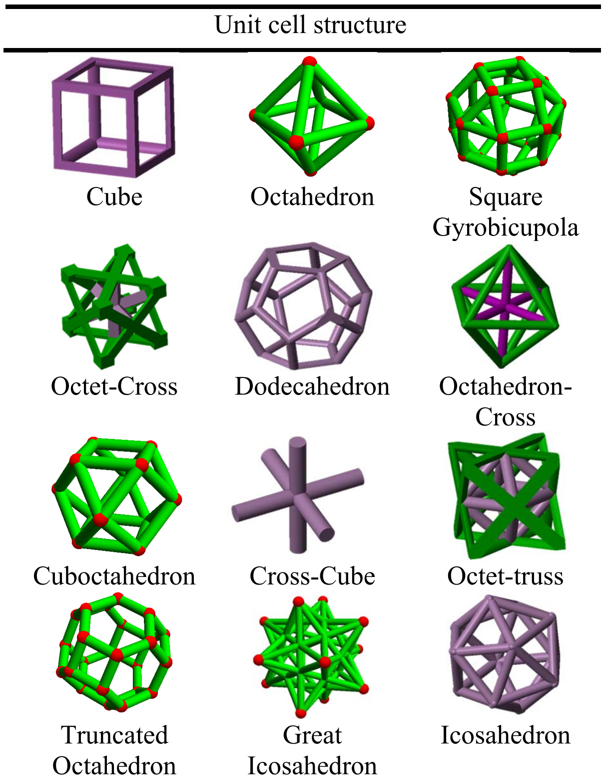



Fig. 2. Connecting intersection point.

The struts of unit cell structure can be round bars or the bars with any geometric section such as square, triangle and polygon, etc. The dimension of struts depends on weight ratio that it needs to be reduced by lattice structure, stiffness and material properties. In the case of round bars, it is necessary to correct the intersection points between the bars (see Fig. 2). A sphere solid needs to be added at the intersection points to fill the missing space. The radius of added sphere surface should be at least equal to the radius of bars.

A library of unit cells should be developed in order to change the configuration of lattice structure quickly. The different type of the topology of unit cell in a library is shown in Table I.

TABLE I
UNIT CELL LIBRARY OF LATTICE STRUCTURE




**Step 2. Create a layer of unit cell structures**

Basing on the unit cell structure created in the library, an array of points as called lattice points is generated according to dimensions of unit cell structure. A layer of unit cell structure is generated by assembling each unit cell structure in each point of lattice points.

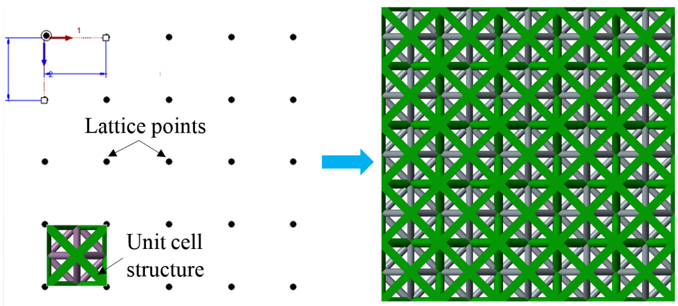



Fig. 3. Generation of a layer of lattice structure.

**Step 3. Create a volume of lattice structure**

After generating a layer of unit cell structure, a three-dimensional lattice structure is created by adding layer upon layer of unit cell structure.

**Step 4. Trim volume lattice structure according to product space.**

A volume of lattice structure created by step 3 is a cube space and bigger than product space. In order to create lattice structure inside product space, it needs to embed product model into the volume lattice structure and remove lattice structure outside of product space.

*2) Generation of non-periodic lattice structure*

Non-periodic lattice structure is very different from periodic one. The unit cell structure is not uniform in the three-dimensional space. Thus, the second method is proposed in this paper in order to create non-periodic lattice structure in a three-dimensional space of product and especially on the surfaces of product. The proposed method is shown in Fig. 4.

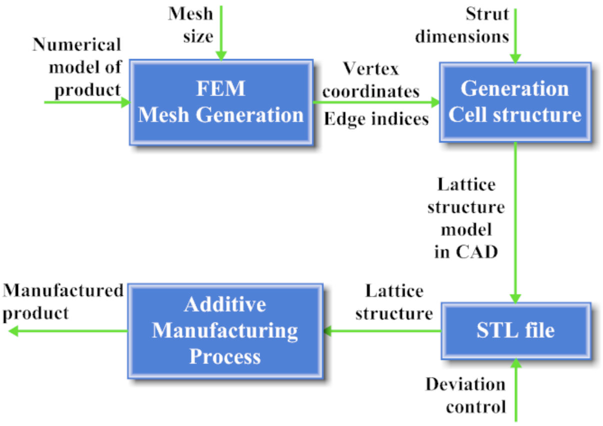



Fig. 4. The overview of proposed method.

The numerical model of product created in CAD system will be used to generate finite element meshing. The size of meshing element is chosen depending on the weight ratio of product that needs to be reduced, the mechanical properties of material and surface regions on product. The data including vertex coordinates and edge indices of each meshing element are used to generate lattice structure. Each strut of structure is the edge connecting between points of each meshing element, it could be a round, square, triangle bar or any geometric section. As the method presented above, it is necessary to add a sphere solid at intersection points between the bars of structure in the case of round bar.

The model of lattice structure is generated by a set of sphere solids and network of struts. The lattice structure is non-periodic because the size and structure configuration of unit cell structure are different from each other. A STL file format is used to store the model. Each slice of the model will be generated by additive manufacturing process to manufacture product with lattice structure.

## III. A CASE STUDY

In order to illustrate the method presented in the paper, a case study will be proposed to create a periodic lattice structure model of product in a commercial CAD software as PTC Creo Parametric® and a non-periodic lattice structure model in three-dimensional space and on surface of product.

***1) Generation of periodic lattice structure on PTC Creo Parametric®***

In this case, a helical gear is used to create periodic lattice structure. The numerical model of helical gear created in PTC Creo Parametric and the space that needs to be generated lattice structure are shown in Fig 5.

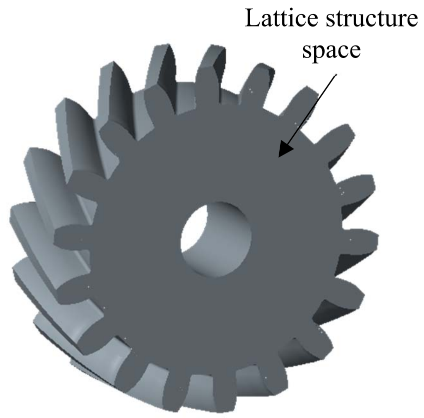



Fig. 5. Generation of lattice structure for helical gear.

The loading on helical gear is primarily pure torsion loading. As a result, the unit cell structure in this case has to be designed to resist torsional loading. The model of unit cell structure shown in Fig. 6 is an "octet-cross" structure in 10x10x10mm cube volume space.

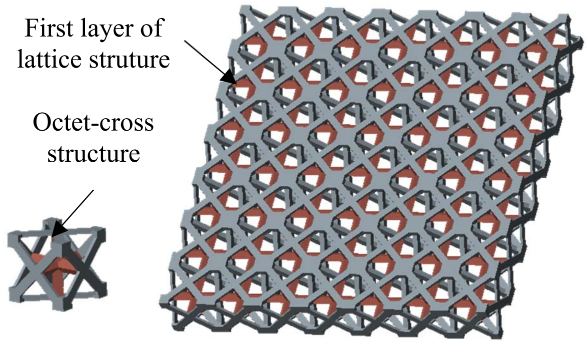



Fig. 6. Unit cell and layer of lattice structure.

A layer of lattice structure is generated using pattern technique in software according to two directions X and Y axis in PTC Creo software. A space of periodic lattice structure is created by adding layer upon layer of lattice structure. In this case, pattern technique is once again used to add each layer of structure upon layer relating to direction Z axis. The design space of lattice structure is created by removing material technique in software (see Fig. 7).

The design space of periodic structure is merged in to model of helical gear. Finally, a model of helical gear with lattice structure is created in a CAD software (see Fig. 8). The STL format file of the helical gear model is easily generated to use in additive manufacturing process.

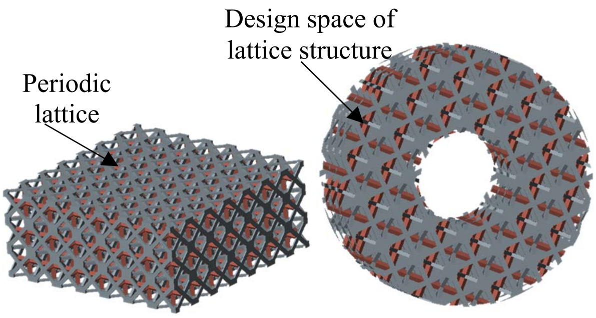



Fig. 7. Periodic lattice structure and its design space.

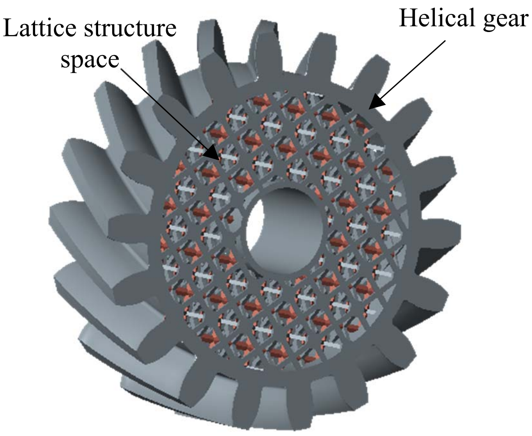



Fig. 8. Helical gear model with lattice structure.

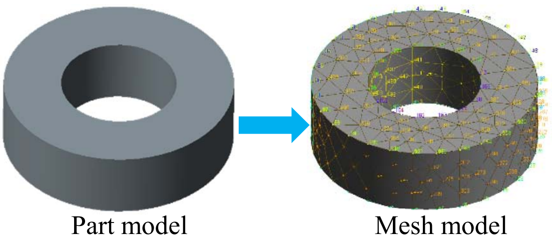



Fig. 9. Product and Meshing element model

***2) Generation of non-periodic lattice structure on Mathematica***

In order to automatically generate non-periodic lattice structure of product model, a program is developed in Mathematica software to generate lattice structure from data of meshing element. Firstly, model of product or lattice space created in any CAD software is used in finite element method (FEM) to create meshing element including vertex coordinates and edge indices of part model. The type and size of meshing element depend on loading forces applied on the part or product and lightweight ratio that it needs to be reduced.

In this case, a simple example is used to explain the proposed method in the paper (see Fig. 9). The data including vertex coordinates and edge indices of each element are used to generate lattice structure. The different type of configurations of non-periodic lattice structure are created and a STL file format can be automatically generated to use in additive manufacturing process (see Fig. 10).

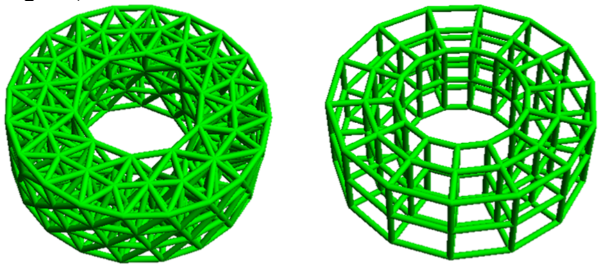


Fig. 10. Different model of non-periodic lattice structure.

## IV. DISCUSSION

Periodic or non-periodic lattice structure can be created in different type of configurations of unit cell structure and its model can be also generated into a STL file format that is used as post-processing in additive manufacturing process to fabricate product with lattice structure in AM machine. Due to the development of AM technologies, lattice structure has been become a very useful and effective tool not only to reduce the weight of product but also to improve mechanical properties of material such as stiffness, Young's module, etc. In the case study, if the material of helical gear is steel, the weight of initial helical gear model is 1.344kg. The new helical gear with designed lattice structure is 0.678kg, its weight is total reduced 49.58%. This is the most important advantage of lattice structure.

However, the current modeling technology as commercial CAD system has many limitations to generate lattice structure, especially non-periodic lattice structure. One of these limitations is time and memory-consuming process. Table II shows time and memory-consuming process to generate a space volume of lattice structure with a 10x10x10mm$^3$ volume space of "octet-truss" unit cell. The calulations were performed on Intel Core i5 M460 2.53GHz with 6 GB of RAM. The memory to store lattice structure is very huge if number of unit cells increase.

TABLE II
TIME AND MEMORY-CONSUMING

| Volume (mm$^3$) | Time (s) | Memory (KB) |
|---|---|---|
| 30x30x30 | 3.52 | 7234 |
| 50x50x50 | 20.53 | 30609 |
| 70x70x70 | 107.76 | 87183 |
| 100x100x100 | 683.47 | 271550 |

In addition, another issue in additive manufacturing process is the use of STL file format to slice layer to layer of manufacturing part. In STL format file, the triangulated surfaces are used to describe surfaces of manufacturing part, it can decrease precision of manufactured part by AM process. The roughness surface of manufactured part by AM technologies is a new challenge in academy research. The roughness surface of part manufactured by additive manufacturing process using STL file format is visibly not fine and smooth comparing to conventional manufacturing technology because of layer-based manufacturing and especially triangulated surfaces in STL model. A part is fabricated by Arcam election beam melting machine (see Fig. 11). The surface of manufactured part have many polygonal waviness on surfaces resulted in triangulated surfaces in STL model. They are easily visible on the manufactured part. It is shown in Fig. 11.

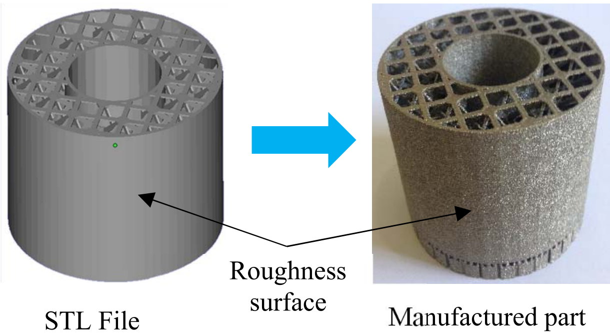



Fig. 11. From CAD file to metal part by AM technology.

In order to deal with these issues, it is necessary to directly use CAD file format replacing STL file for additive manufacturing process to increase quality of manufactured product. Thus, it should have to study requirements for a new CAD file format in order to quickly generate and store data of lattice structure for additive manufacturing in the future.

## V. CONCLUSION

The paper proposes a method that allows to automatically generate periodic and non-periodic lattice structure of product for additive manufacturing. This method helps product designer to deal with limitations of the current CAD systems for creation of lattice structure. An example of periodic lattice structure generation for helical gear is presented in the paper using a commonly commercial CAD software as PTC Creo Parametric. After manufacturing a model of lattice structure of a part by Arcam EBM machine, the investigation of method is shown in the paper. Furthermore, some research ideas in additive manufacturing for the future are also proposed.

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## REFERENCES

[1] I. Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*: Springer, 2015.

[2] L. J. Gibson, and M. F. Ashby, *Cellular Solids Structure and Properties*: Cambridge Solid State Science Series, 1999.

[3] C. Chu, G. Graf, and D. W. Rosen, "Design for Additive Manufacturing of Cellular Structures," *Computer-Aided Design and Applications,* vol. 5, no. 5, pp. 686-696, 2008/01/01, 2008.

[4] D. W. Rosen, "Computer-Aided Design for Additive Manufacturing of Cellular Structures," *Computer-Aided Design and Applications,* vol. 4, no. 5, pp. 585-594, 2007/01/01, 2007.

[5] V. J. Challis, X. Xu, L. C. Zhang, A. P. Roberts, J. F. Grotowski, and T. B. Sercombe, "High specific strength and stiffness structures produced using selective laser melting," *Materials & Design,* vol. 63, pp. 783-788, 11//, 2014.

[6] Y. Shen, S. McKown, S. Tsopanos, C. J. Sutcliffe, R. A. W. Mines, and W. J. Cantwell, "The mechanical properties of sandwich structures based on metal lattice architectures," *Journal of Sandwich Structures and Materials*, June 10, 2009, 2009.

[7] M. Wong, I. Owen, C. J. Sutcliffe, and A. Puri, "Convective heat transfer and pressure losses across novel heat sinks fabricated by Selective Laser Melting," *International Journal of Heat and Mass Transfer,* vol. 52, no. 1–2, pp. 281-288, 1/15/, 2009.

[8] J. Parthasarathy, B. Starly, and S. Raman, "A design for the additive manufacture of functionally graded porous structures with tailored mechanical properties for biomedical applications," *Journal of Manufacturing Processes,* vol. 13, no. 2, pp. 160-170, 8//, 2011.

[9] K.-F. L. Shoufeng Yang, Zhaohui Du, and Chee-Kai Chua, "The Design of Scaffolds for Use in Tissue Engineering. Part II. Rapid Prototyping Techniques," *Tissue Engineering,* vol. 8, no. 1, pp. 1-11, 2004.

[10] M. A. Wettergreen, B. S. Bucklen, W. Sun, and M. A. K. Liebschner, "Computer-Aided Tissue Engineering of a Human Vertebral Body," *Annals of Biomedical Engineering,* vol. 33, no. 10, pp. 1333-1343, 2005//, 2005.

[11] D. S. Nguyen, "Towards a Geometric Devation Model of Product in CAD environment," in Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition, San Diego, California, USA, 2013, pp. 1-10.

[12] G. Littlefair, I. Gibson, C. Usma, P. Collins, T. Hilditch, M. Mmillan, M. Jurg, M. Leary, and M. Brandt, "Programmatic Lattice Generation for Additive Manufacture," *Procedia Technology-Proceedings of The 1st International Design Technology Conference, DESTECH2015, Geelong,* vol. 20, pp. 178-184, 2015/01/01, 2015.

[13] A. G. Evans, J. W. Hutchinson, and M. F. Ashby, "Cellular metals," *Current Opinion in Solid State and Materials Science,* vol. 3, no. 3, pp. 288-303, 6//, 1998.

[14] M. R. Karamooz Ravari, M. Kadkhodaei, M. Badrossamay, and R. Rezaei, "Numerical investigation on mechanical properties of cellular lattice structures fabricated by fused deposition modeling," *International Journal of Mechanical Sciences,* vol. 88, pp. 154-161, 11//, 2014.

[15] R. M. Gorguluarslan, U. N. Gandhi, R. Mandapati, and S.-K. Choi, "Design and fabrication of periodic lattice-based cellular structures," *Computer-Aided Design and Applications,* vol. 13, no. 1, pp. 50-62, 2016/01/02, 2016.