Design of lattice structure for additive manufacturing in CAD environment

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Abstract
Additive manufacturing is an advanced manufacturing technology that allows building any complex 3D geometry of product by adding layer by layer of material. One of the most important effectiveness of additive manufacturing is able to manufacture lattice structure inside product space in order to reduce the usage of material and the weight of the product but still ensure its mechanical properties. The lattice structure is a network of bars linked each other in a space of product and it can be quickly manufactured due to the development of additive manufacturing technologies. However, the design of a model of the lattice structure in the computer-aided design environment has many difficulties. The current modeling technologies do not support product designer to automatically create a model of the lattice structure with the different type of configurations. Therefore, the paper will present new approaches to automatically generate a 3D model of the lattice structure in the design space of the product. These approaches allow creating different configurations of the periodic or non-periodic lattice structure.

Keywords: Additive manufacturing, 3D printing, Lightweight material, Computer-aided-design (CAD), Lattice structure

1. Introduction
Additive Manufacturing (AM) is a scientific term to describe manufacturing processes that allow building 3D objects by stacking layers of material over each other (Tateno et al., 2016). This is a reason why AM is called layer manufacturing processes. It was developed from the Rapid Prototyping technologies in the 1980s. AM includes different fabrication technologies in which a three-dimensional (3D) part is produced by adding very thin layers of two-dimensional cross-sectional slices of materials from the 3D model of a product on computer-aided design (CAD) software. These AM technologies are able to quickly manufacture a numerical model of the product before the final release or commercialization (Alkahari et al., 2014; Gibson et al., 2015). The advantage of additive manufacturing is making the preparation for the planning process, tooling and human intervention no longer needed. In addition, AM technologies have an ability to fabricate any complex geometric shapes of product that conventional manufacturing technologies as machining, cutting, forging, etc. cannot perform. That is one of the most important advantages of AM technologies. As a result, a lattice structure can be easily manufactured by AM technologies that the previous manufacturing technologies were impossible.

A lattice structure consists of a pattern repeating systematically or randomly in all directions in the design space. This pattern is called a unit cell of the lattice structure. The lattice structure is a good solution in order to reduce the usage of the material of manufactured parts but still have high strength mechanical properties. When additive manufacturing technologies are invented, lattice structures are able to be manufactured. Therefore, lattice structures are used in many different industrial fields such as improvement of material properties (Challis et al., 2014; Yan et al., 2019), thermal engineering (Pelancioni et al., 2019) and biomedical application (Alabort et al., 2019) due to many outstanding advantages as lightweight, high strength mechanical properties.
2. Methodology

Typically, lattice structures are divided into two different topologies, periodic or non-periodic structure. Periodic lattice structures are created by a set of unit cell structure repeating in all directions and unit cell structure is truss structure including struts interconnected each other. An example of a periodic lattice structure is shown in Fig. 1. The periodic lattice structure has many applications in different industrial engineering due to strength and high specific stiffness. It can be also used to save the usage of material and reduce the weight of the manufactured product. However, a volume of the periodic lattice structure needs to be trimmed off the part outside of design space in order to integrate it into the product. This can break the connection between the bars in the unit cell structure and make the unit cell not to be conformal to the boundary surfaces of the design space. Furthermore, the connection between the lattice structure and the product can be weaker and it can make the designed product with lattice structure at risk not to guarantee durability and mechanical properties. Therefore, the paper presents a new approach to create automatically the lattice structure conformal to the design space based on finite element mesh. This lattice structure can be called a non-periodic one. The non-periodic lattice structure is those such that bars and its shapes are randomly distributed in the design space of product. Each bar can have a different radius and length. As a result, the non-periodic lattice structure can overcome the disadvantages of the period one and it can improve the durability and mechanical properties of the lattice structure by increasing radius and density distribution of the bars.

There are studies to create a model of the lattice structure on commercial CAD software (Azmana et al., 2018; Kara, 2018; Nguyen et al., 2018; Alabort et al., 2019; Chougrani et al., 2019). However, these researches only focus on creating a model of periodic lattice structure manually. Therefore, it needs to have a new method to create both periodic and non-periodic lattice structure automatically on any CAD environment. As a result, the paper will present two approaches to generate two different types of the lattice structure (periodic and non-periodic) on CAD environment.

Fig. 1 The periodic lattice structure includes unit cells arranged regularly in the design space. Each unit cell has the same configuration. It comprises the bars connecting each other.

Fig. 2 The proposed approach to creating a periodic lattice structure in the design space of a product includes four steps. The first step is to select a configuration of a unit cell in a library. Then a layer of the lattice structure is generated in step 2. Finally, a volume of the lattice structure in design space is created through step 3 and step 4.
2. 1. Creation of periodic lattice structure

The global approach to generate a periodic lattice structure in the design space of the product is shown in Fig. 2. This approach includes four steps as follows:

**Step 1. Creation of unit cell library**

The configuration of each unit cell structure will be created and stored in a library. The configuration of unit cells is mentioned in (Karamoov Ravari et al., 2014; Gorguluarslan et al., 2016). The model of unit cell structure is created in any CAD environment where a product designer needs to design the model of a product. Each unit cell structure includes bars connecting each other. The shape of a bar and the volume of a unit cell will be parameterized by the input parameters in order to easily change the configuration of the unit cell.

The problem of unit cell creation is the connecting intersection point. The intersection among two or many bars is not fully filled as shown in Fig. 3. The section of bars can be a triangle, circle, square or polygon, etc. The input parameters of each unit cell can be the radius of round bar or area, type of section, size of unit cell volume. The values of these input parameters depend on weight ratio, stiffness and material properties of the unit cell that product designer needs to design the model of the lattice structure in the space of product. In order to fix the problem at the intersection point among two or many bars, it is necessary to use a sphere solid to fill the missing space at the intersection points. Its radius can be at least equal or bigger than the radius of bars.

![Intersection point](Image)

**Fig. 3** Each unit cell of the lattice structure includes the bars connecting each other. At the position where the intersecting bars will have an empty space. This space needs to be filled by a sphere solid.

![Missing space and Filling space](Images)

**Fig. 4** (a) An octet-truss unit cell structure is created by the bars connecting each other. (b) The missing space at the intersection point is then filled by the solid spheres with the radius equal to the radius of the bars. (c) The octet-truss unit cell structure is fitted in a cube by trimming off the part outside of the cube. (d) Finally, the octet-truss unit cell is created.
The other issue should be mentioned in unit cell creation that is the overlapping part between two unit cells or among many unit cells when a volume of the periodic lattice structure is created. It is very necessary to design a unit cell structure in a cube space for a 3D model or a square surface for a 2D model. In order to illustrate the design process of a unit cell structure, an example of the design of an octet-truss unit cell structure is presented in Fig. 4.

First of all, the bars of the unit cell structure are created by the input parameters as the radius, the shape of the section of the bar. The length of bars depends on the size of the unit cell structure. The number of bars also depends on the selected configuration of the unit cell structure. Then, the missing space of the connecting bars of the unit cell structure will be filled by the solid sphere with the radius equal to the radius of the bars. In order to solve the overlapping part among unit cells in a volume of the lattice structure, the unit cell structure should be fitted in a cube by trimming off the part outside of the cube. Finally, the creation of the unit cell structure is finished.

As a result, a library of unit cells with different types of configuration is created as shown in Table 1. Each unit cell in the library can be changed by the values of input parameters as presented above.

Table 1 Configurations of Unit cell

| Unit cell configurations     |     |
|------------------------------|-----|
| Cube                         | Octahedron | Octahedron-Cross |
| Octet-truss                  | Dodecahedron | Open-cell |
| Cuboctahedron               | Cross-Cube | Cuboctahedron |
| Square Gyrobicupola          | Great Icosahedron | Icosahedron |

Fig. 5 (a) The octet-truss unit cell structure is selected in the library. (b) A row of octet-truss unit cells is created by assembling the initial unit cell along the direction. (c) A layer of a periodic lattice structure is built by adding each row of the octet-truss unit cell to each other along the direction.

Step 2. Creation of a layer of the lattice structure

Firstly, the configuration of a unit cell structure is selected by the product designer in the library. A row of the selected unit cells is created by placing the selected unit cell side by side in one direction. When the unit cells are assembled together, there are no overlapping parts between them due to the unit cell fitted in a cube. A layer of a periodic lattice...
structure will be then built by adding each row of the selected unit cell to each other in one direction. Similarly, there is no overlapping part between two rows of the unit cell thanks to the row fitted in a box space completely. An example of the creation of a layer of the octet-truss unit cell is shown in Fig. 5.

**Step 3. Creation of a volume of the lattice structure**

A volume of the selected unit cell structure is built by adding a layer of unit cells upon the layers in one direction. The rest of the bar in the unit cell structure after being trimmed off the part outside of a cube will connect to each other at the overlapping plane to create a complete bar. Due to the design of the unit cell by fitting in a cube space, it is not necessary to eliminate the overlapping part between rows or layers. However, the geometry of the unit cell structure should be symmetric in three directions of the cube space. The volume of the octet-truss unit cell is created as shown in Fig. 6.

![Overlapping plane](image)

**Step 4. Lattice structure in the design space of the product.**

Typically, a volume of lattice structure created in the previous step is bigger than the volume of design space. It is necessary to remove the excess volume of the lattice structure. A new volume is trimmed according to the volume of the design space of the product. Then it will be assembled into the design space on the product model.

### 2. 2. Creation of non-periodic lattice structure

A non-periodic structure is those such that unit cell and its shapes are randomly distributed in the design space of product. Each unit cell can have different sizes and configurations. In addition, most of the current commercial CAD software does not support to create a model of non-periodic lattice structure automatically. Thus, the creation of a non-periodic lattice structure in the CAD environment is done manually and it takes product designer a lot of time.

![New approach](image)

**Step 5. Additive manufacturing process**

A new approach to generate non-periodic lattice structure is based on the meshing model in finite element method. The meshing model contains the data of vertex coordinates and edge indices. The data are used to create the non-periodic lattice structure.
A new approach to automatically generate non-periodic lattice structure will be presented in the paper. This approach allows helping product designer to create a model of the non-periodic lattice structure in any CAD software. The overview of this approach is shown in Fig. 7.

A numerical model of design space where the non-periodic lattice structure will be built needs to be created in the CAD environment. The finite element mesh generation is used to create a meshing model of the design space. The creation of the non-periodic lattice structure is implemented by using the meshing model. The data of the meshing model include nodes and edge connectivity between nodes of elements. The shape of elements can be tetrahedron or hexahedron element. As a result, each element in the meshing model is defined as a unit cell of the non-periodic lattice structure. The configuration of the unit cell is the type of element. Each bar of the lattice structure is built based on each edge connectivity between nodes of the element. The density distribution of the unit cell in the lattice structure can be adjusted by the input parameters as the number of mesh elements and element size. Therefore, the data including vertex coordinates and edge indices of each element from the meshing model will be extracted as input data for the creation of lattice structure. The radius of each bar in the lattice structure will be extracted as input data for the creation of lattice structure. The radius of each bar in the lattice structure will be extracted as input data for the creation of lattice structure.

A volume of non-periodic lattice structure is generated in a design space from the data of vertex and edge from meshing model. The bars on the boundary surfaces of the design space will be overlapped with the product. The overlapping bars between the volume of the lattice structure and the product need to be removed. The algorithm to create a volume of the non-periodic lattice structure is proposed in Fig. 8. The space of the lattice structure will be assembled in the product. Then, a model of product with the lattice structure will be created in the CAD environment. Finally, a real product with the lattice structure can be manufactured by any additive manufacturing technology.

3. Results and discussion

3.1 A case study: Design of periodic lattice structure in SolidWorks®

An example of a periodic lattice structure design for a helical gear will be presented in the paper in order to explain the mentioned approach. Firstly, it is necessary to identify a design space for a lattice structure on helical gear. A cylindrical space in grey color as shown in Fig. 9 is selected in this case in order to simplify the manufacturing process.
A helical gear is used to demonstrate how to create a periodic lattice structure inside the design space. The design space of the periodic lattice structure should be defined before in the CAD environment. It is a cylindrical space in this case.

A macro program developed in SolidWorks has two interfaces. The first one is a library of unit cells to help a product designer selecting the configuration of the unit cell. The second interface is to enter the data of the input parameters of the selected unit cell.

The selected configuration of the unit cell is the octet-truss. The input parameters in the second interface include the diameter of the bar (d), the size of the unit cell (a), the number of the unit cell according to x, y, and z-direction.
It is called the design space of the lattice structure. A volume of periodic lattice structure fully filled in this space will be generated and the design space will then be replaced by a cylindrical volume of the lattice structure.

In order to generate a volume of lattice structure automatically, a macro program is developed using API functions in SolidWorks. The program has two main functions as shown in Fig. 10. The first function is to collect the input parameters as the type of unit cell, the diameter of the bar (d), the size of the unit cell (a), the number of the unit cell according to x, y, and z-direction. The input parameters allow us to build a geometric model of the unit cell in SolidWorks. An example of the creation of an octet-truss unit cell with the input parameters is shown in Fig. 11. Each bar of octet-truss is created by the extrusion technique using API function FeatureExtrusion2 in SolidWorks. The cross-section of the bar is defined by a circle with the diameter d. This circle is drawn on the sketch plane perpendicular to the axis of the bar. The axis of the bar is created using API function CreateLine in SketchManager method. The sketch plane where the circle is drawn is defined by API function InsertRefPlane in FeatureManager method. After the octet-truss unit cell structure is created, it will then be fitted in a cube space by trimming off the part outside of the volume.

After creating the geometric model of unit cell structure, a second function of the macro program is to create a layer and then a volume of the lattice structure. A layer of the lattice structure with this unit cell will be generated using the linear-pattern feature technique in SolidWorks. It is done using API function FeatureLinearPattern5 with the input parameters nx, ny that are the number of unit cells in X and Y direction of the coordinate system. The layer of the lattice structure is shown in Fig. 12a. The function FeatureLinearPattern5 is used once again to create a volume of the lattice structure with the number of unit cell nz that is an input parameter. The volume of the lattice structure with the octet-truss unit cell is created automatically by adding layer upon layer of the lattice structure. It is shown in Fig. 12b. The volume
of the lattice structure in the design space of helical gear is then created using the trim technique in SolidWorks. The lattice structure outside the design space is removed. Finally, the volume of a periodic lattice structure with the octet-truss unit cell in the design space of the helical gear is obtained and it is shown in Fig. 12c.

The final volume of the lattice structure in the design space will then be assembled into the space of helical gear. The model of helical gear with a periodic lattice structure is created in SolidWorks. Its numerical model is given in Fig. 13a. This model is then manufactured using electron beam technology on ARCAM machine. The real manufactured helical gear with a periodic lattice structure is shown in Fig. 13b.

### 3.2 A case study: Design of non-periodic lattice structure in Rhinoceros®

A model of helical as shown in Fig. 9 is used once again in order to illustrate how to design a non-periodic lattice structure in a design space by the proposed approach. In this case, the design of the non-periodic lattice structure will be implemented on another commercial CAD software as Rhinoceros®.

Firstly, the numerical model of the design space of helical gear is used to generate a meshing model by using a finite element mesh generator. The Mesh function in Grasshopper can be used to generate the meshing model of the design space. However, this function supports to only create a surface mesh and a volume mesh generation is not supported in Rhinoceros. Thus, the mesh generator in Abaqus software is used to generate a meshing model of the design in this case. The input parameters including element size and type of elements are used to define the meshing model. In this case study, the type of element is an eight-node brick element (c3d8 element in Abaqus) and the element size is chosen as 15mm. The meshing model of the design space of the helical gear created in Abaqus is shown in Fig. 14a. The data of meshing model including coordinates of nodes and element connectivity between nodes in elements will be then imported to Grasshopper to generate the lattice structure.

Secondly, a python script function in Grasshopper is used to develop a program to import the data of the meshing model including coordinates of nodes and node connectivity and then generate the lattice structure. The program is
developed by using the algorithm presented in Fig. 8. The function AddPoint in the RhinoscriptSyntax library is used to define a point in Rhinoceros. A line connecting two points is defined by using the function AddLine. The data of element connectivity are converted totally into lines in Rhinoceros. The meshing model of the design space is imported in Rhinoceros by the program as shown in Fig. 14b.

Finally, the non-periodic lattice structure of the design space is created by using pipe technique in Rhinoceros. A function CreatePipe is used to create the bars of lattice structure based on the radius of the bar. The non-periodic lattice structure of the design space is created in the helical gear with the same value of the radius of bars as shown in Fig. 15a. Fig. 15b shows the model of the non-periodic lattice structure with different values of the radius of bars. As a result, the product designer can change the radius of the bars quickly and especially it is possible to change the radius of any bars in the lattice structure.

3.3 Discussion

Today, most of the current commercial CAD software has many difficulties and limitations to generate lattice structure. They can only create a model of the periodic lattice structure in STL format. Therefore, the new approaches proposed in the paper can help product designer create a model of the periodic or non-periodic lattice structure in the design space of product on CAD environment quickly. The product with the lattice structure can be manufactured by any additive manufacturing technology using this numerical model.

![Fig. 15](image)

Fig. 15 (a) A model of the non-periodic lattice structure with the same value of the radius of bars is created in Rhinoceros. (b) A model with different values of the radius of bars is created.

The time-consuming to create lattice structures increases rapidly when the number of unit cells is high.

The performance of the creation of a lattice structure with the different configuration of a unit cell will be investigated. It is implemented by a computer Intel Core i5 M460 2.53GHz with 8 GB of RAM. The processing time, memory-consuming and file format to store model of lattice structure are mentioned in this case. The different volume of a periodic lattice structure with a different configuration of a unit cell is generated in SolidWorks by the proposed approach. Table 2 shows the processing time to generate a volume of a lattice structure with different types of a unit cell.

![Fig. 16](image)

Fig. 16 The time-consuming to create lattice structures increases rapidly when the number of unit cells is high.
The processing time to generate a volume of lattice structures depends too much on the type of unit cell and the volume of lattice structures. From the charts shown in Fig. 16, the time-consuming to generate lattice structures will increase exponentially if the number of unit cells goes up.

| Size of lattice structure | Unit cells | Unit cells |
|---------------------------|------------|------------|
|                           | Cube       | Cross-Cube | Octahedron | Octahedron | Octet-truss |
| 3x3x3                     | 8.3        | 5.1        | 7.2        | 9.0        | 15.5        |
| 4x4x4                     | 11.1       | 5.9        | 10.6       | 11.6       | 20.7        |
| 5x5x5                     | 16.5       | 8.0        | 14.7       | 16.8       | 31.8        |
| 7x7x7                     | 36.9       | 15.1       | 31.4       | 36.5       | 75.1        |
| 10x10x10                  | 113.1      | 56.8       | 118.8      | 147.4      | 280.1       |

A different volume of a periodic lattice structure with the input parameters as the diameter (d = 2 mm) and the size of a unit cell (a = 10 mm) is generated in SolidWorks®. The data of memory-consuming of STL and SLDPRT file format in SolidWorks® have been collected in Table 3 and Table 4. The data show that if the SLDPRT file format used to store model of lattice structure is more efficient than STL file format in term of memory size. The storage of a model of the lattice structure in the CAD format file is much better STL for. This is one of the most advantages of the proposed approach compared to the methods of generation of lattice structure by STL file format. Furthermore, the important issue is that product designer can design lattice structure by the change of any parameters of it and the integration of lattice structure into the product model in the CAD environment.

| Size of lattice structure | Unit cells | Unit cells |
|---------------------------|------------|------------|
|                           | Cube       | Cross-Cube | Octahedron | Octahedron | Octet-truss |
| 3x3x3                     | 1.0        | 0.8        | 2.1        | 3.7        | 5.0         |
| 4x4x4                     | 2.1        | 1.8        | 4.9        | 8.7        | 11.3        |
| 5x5x5                     | 3.9        | 3.4        | 9.5        | 17.0       | 21.7        |
| 7x7x7                     | 9.9        | 8.9        | 26.0       | 46.6       | 58.1        |
| 10x10x10                  | 26.9       | 24.8       | 75.9       | 136.0      | 166.0       |

4. Conclusion

The paper presents the new approaches that allow product designer to be able to design a model of the periodic or non-periodic lattice structure in the design space of a product. The model of lattice structure can be generated automatically in any CAD software. They can help product designer change any parameters of the model of the lattice structure and store it in CAD-file format. A case study to design periodic lattice in SolidWorks® is proposed in the paper.
in order to explain the approach. The program using the API functions in SolidWorks® is developed to help product designers to create a 3D model of lattice structure automatically and to change the parameters of the lattice structure as the radius of bars, size, and type of unit cell. Furthermore, an example to design a model of the non-periodic lattice structure in Rhinoceros is also presented. The new approaches mentioned in the paper have been illustrated by two examples.

In the future, it is very necessary to focus on reducing the processing time and memory-consuming to generate the lattice structure as well as the development of the library of unit cells. In addition, CAD file format replacing STL file for the additive manufacturing process to increase the quality of the manufactured product should be overcome.

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