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An Effective Geometric Modeling Method for 3D Lattice Structures Using Volumetric Distance Field

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Abstract: An effective method for 3D lattice structure design is proposed using the volumetric distance field (VDF) based on analytic shape functions. By the innovative synthesis of lattice structure and VDF-based Boolean operations, a variety of computational models with intricate exterior shape and arbitrary lattice structure can be constructed. The significant advantage is that this design method can be easily applied to design highly complex lattice structure models. The important parameters such as the cell type and the size of lattice structure are controllable in customized MATLAB program. Design results verify that the presented design method is efficient to generate 3D models with required lattice structure.

1. Introduction

Additive manufacturing (AM) is advanced and promising technology with the geometric freedom that make it possible to create more complex parts containing internal cellular microstructures than ever before [1-2]. Rather than conventional manufacturing, AM creates a new method to fabricate intricate components such as cellular materials in layers largely free of limitations of the use of tooling. Among periodic cellular structures, lattice structures have become a rising concern in research on design and manufacturing due to the attractive and exceptional performance. By building a 3D physical part layer by layer, AM technology enables the manufacturing of parts with highly complex shapes including internal lattice structures that are desirable for engineering applications due to their sufficient strength and stiffness with a lower weight [3-5].

Lattice structure is famous not only for its lightweight but also for the high specific strength and stiffness [6-8]. Besides, it is an excellent multi-functional material more noted for some special properties including energy absorption and heat dissipation [9-14]. Lattice structures have been tested and verified that they usually offer a more homogeneous stress distribution and more stable mechanical properties. The stiffness and strength of a three-dimensional lattice structure fabricated by AM are determined by two aspects: its materials and structure design. Therefore, the research and development of materials and structure design are urgently required to realize the multi-functional performance of lattice structures with tailored mechanical properties.

The volumetric distance field (VDF) is defined as a distance field of a rectangular volumetric region. Every element in a VDF has a specific purpose that is its minimum distance to the boundary of the shape. In order to distinguish inside and outside of the boundary, positive and negative distances are used respectively. In this paper, a new modeling method for construction lattice structures with arbitrarily controlled core structures and complicated external appearance is presented.

The proposed methodology has two advantages: Firstly, it is effective and efficient to design a 3D computational model of lattice structures using VDF. Secondly, multifarious computational models composed of various different types of lattice structures can be produced to study the mechanical and physical properties and to promote the practical applications of lattice structures.

The specific arrangements of the article are structured as follow: Section 2 is devoted to introduce the fundamental concepts of lattice structures and VDF. Section 3 is presented to represent the design procedure for lattice structures using VDF. Section 4 shows a number of test results and several prototypes manufactured by AM technique. Finally, we propose the conclusions and point out future research direction in section 5.

2. Method

2.1 The unit cell of lattice structures

While various examples of unit elements in the lattice structure are presented in the literature, including octet unit cell, pyramidal structure, tetrahedral element, hierarchical cellular material and Kagome lattice structure, this research focuses on several types of lattice structure basing on cubic cells. In this research, there are five unit cells to be created using the volumetric distance field shown in Fig.1: Simple Cubic (SC), Body-centered Cubic (BCC), Face-centered Cubic (FCC), Diamond Cubic (DC) and OCTET Cubic (OC).

We are able to propose a general program based on the characteristics of unit cell for lattice structure. The program firstly designs a unit cube and then marks the vertices of the cube. The unit cell can be realized by connecting the characteristic vertices in a certain order. This is a simple procedure; the vertex is represented by a sphere while the edge is formed by a cylinder, and the key is to determine the position of the sphere and the cylinder. Spheres and cylinders are presented using the volumetric distance field (VDF) that will be introduced in the next section.

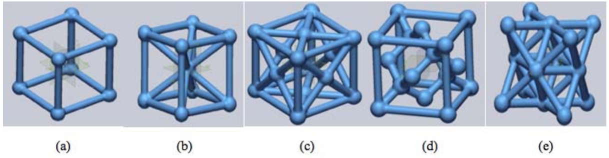


Fig. 1. The unit cells of lattice structures. (a) simple cubic (SC) unit cell, (b) body-centered cubic (BCC) unit cell, (c) face-centered cubic (FCC) unit cell, (d) diamond cubic (DC) unit cell, (e) octet cubic (OC) unit cell.

2.2 VDF and Boolean operation based on VDF

Volumetric distance field (VDF) has been widely used in constructive solid geometry and surface reconstruction [15-19]. VDF is defined as a 3D scalar field to describe the volumetric model. Each point in that field has a close connection with a sign distance value from the object shape.

VDF is particularly useful in constructive solid geometry because it can make designs simple and fast to form complex shapes using Boolean operations. When given objects are described as VDFs, Boolean operations including intersection, union and subtraction can be achieved utilizing simple max() and min( ) function, represented as follows:

$$\begin{aligned} dist(A\cap B) &= \min(dist(A), dist(B)) \quad \text{(Intersection)} \\ dist(A\cup B) &= \max(dist(A), dist(B)) \quad \text{(Union)} \qquad (1) \\ dist(A-B) &= \min(dist(A), -dist(B)) \quad \text{(Subtraction)} \end{aligned}$$

Where, A and B are defining functions of two models respectively. Computational models based on VDF can be combined using Boolean operations in an intuitive and efficient way that omits the time-consuming computational process.

2.3 VDF-based basic features

As the basic step of the method proposed in this paper, the first step is to define several basic features which are combined to form complex shapes using VDF. Second, lattice structures are arranged in the designed shape taking advantaging of VDF-based Boolean operations. Final step is to generate lattice sandwich model by combing lattice topology and the needed shells. In our research, we define three types of VDF-based basic features such as boxes, cylinders and spheres. So we will discuss these basic features in detail.

2.3.1 VDF of a box

The VDF of a box is defined by

$$\begin{aligned} dist(box) &= dist(box_x) \cap dist(box_y) \cap dist(box_z) \\ &= min\left(dist(box_x), min\left(dist(box_y), dist(box_z)\right)\right). \end{aligned} \qquad (2)$$

Where $dist(box_x)$, $dist(box_y)$, $dist(box_z)$ are determined by the following equations.

$$\begin{aligned} dist(box_x) &= \begin{cases} x - x_c - 0.5WX & x \geq x_c \\ -0.5WX - (x - x_c) & x < x_c \end{cases} \\ dist(box_y) &= \begin{cases} y - y_c - 0.5WY & y \geq y_c \\ -0.5WY - (y - y_c) & y < y_c \end{cases} \qquad (3) \\ dist(box_z) &= \begin{cases} z - z_c - 0.5WXZ & z \geq z_c \\ -0.5WZ - (z - z_c) & z < z_c \end{cases} \end{aligned}$$

Where WX, WY, WZ denote the box size in the x, y and z directions respectively. Parameters x_c, y_c and z_c denote box center coordinates.

2.3.2 VDF of a cylinder

A cylinder in the z direction is represented as follows:

$$\begin{aligned} dist(cylinder_z) &= dist(circle_z) \cap dist(plane_z) \\ &= min\left(dist(circle_z), dist(plane_z)\right) \end{aligned}$$

$$dist(circle_z) = \sqrt{(x - x_c)^2 + (y - y_c)^2} - r \tag{4}$$

$$dist(plane_z) = \begin{cases} z - z_c - 0.5H & z \geq z_c \\ -0.5H - (z - z_c) \end{cases}$$

Where x_c, y_c, z_c, H and r denote center coordinates, height and radius of the cylinder respectively. Similarly, we can get cylinders in the y and z directions by modifying the Eq. (4).

2.3.3 VDF of a sphere

The VDF of a sphere is described as follows:

$$dist(sphere) = \sqrt{(x - x_c)^2 + (y - y_c)^2 + (z - z_c)^2} - radius \tag{5}$$

Where x_c, y_c, z_c and r denote center coordinates and radius of the sphere respectively.

3. Design Methodology

There are three main steps for designing a lattice sandwich model with a given external shape and arbitrary core structure. In the first step, five cell types of lattice structures are constructed using VDF. External shell and 3D lattice topology are built in the second step. Finally, a lattice sandwich model is generated though VDF-based Boolean operations.

3.1 Core construction

In this stage, we will construct the external shape from the given basic features as a shell and 3D lattice structures as core structures.

3.1.1 VDF calculation of a basic feature

Let's take a prismatic bar with FCC lattice structures as a simple example. In order to create the VDF of the needed shell, the VDF for the outside boundary of a prismatic bar is calculated though Eq. (2) and (3), it is the exterior shape of the model to be designed (i.e.$dist(box_{outer})$). Then we will calculate the VDF for the inner boundary of a prismatic bar that is the interior shape of the desired model $dist(box_{inner})$. The VDF for the shell is achieved by subtraction Boolean operation as follows:

$$\begin{aligned} dist(shell) &= dist(box_{outer}) - dist(box_{inner}) \\ &= \min\left(dist(box_{outer}), -dist(box_{inner})\right) \end{aligned} \tag{6}$$

3.1.2 VDF calculation of needed core structure

To do this, the VDF for the needed core structure is calculated by unit cell topologies and VDF-based Boolean operations. However, it usually takes a long time to generate a model using traditional CAD design method as a result of the large computational demands and the memory limitations of computers. An efficient method to construct lattice structures is needed. In addition, conventional manual modeling of lattice structures in CAD probably result in failure because of the overwhelming number of trusses in lattice structures. Therefore, an effective geometric modeling method for lattice structures should be developed to save modeling time.

Thus, we propose a new method to create a lattice structure. Cell strategy is used to overcome the difficulties of computational and storage complexities. Cell strategy is described as follows:

$$dist(lattice) = \cup_{k=1}^{nz} \cup_{j=1}^{ny} \cup_{i=1}^{nx} dist(cell_{i,j,k}) \tag{7}$$

Where nx, ny and nz is the lattice number in x, y, z direction respectively.

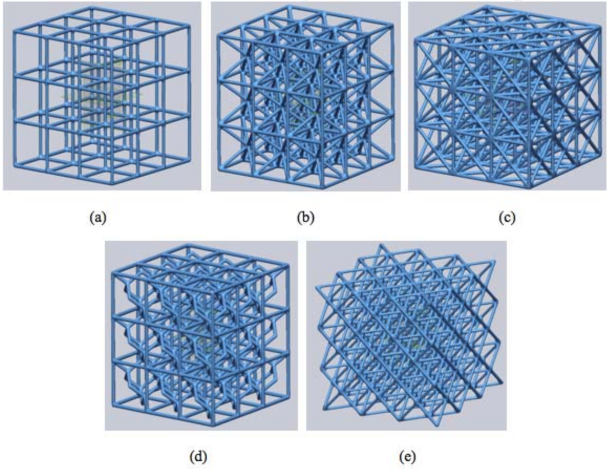


Fig. 2. Various types of lattice structures. (a) SC lattice structure, (b) BCC lattice structure, (c) FCC lattice structure, (d) DC lattice structure, (e) OC lattice structure.

This method greatly reduces the computation time and improves efficiency. In Fig. 2, these are 3D lattice structures with SC, BCC, FCC, DC and OC unit cells. Lattice numbers and strut diameters are controllable in the design method, so we can obtain required lattice structure with various lattice numbers and strut diameters, shown in Fig. 3 and 4.

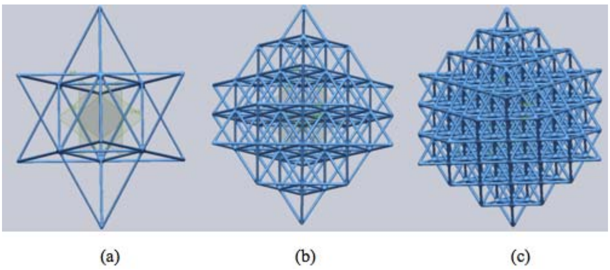


Fig. 3. Computational models of OC lattice structures with various lattice numbers. (a) Lattice numbers in x, y, z direction: $1 \times 1 \times 1$, (b) Lattice numbers in x, y, z direction: $2 \times 2 \times 2$, (c) Lattice numbers in x, y, z direction: $3 \times 3 \times 3$.

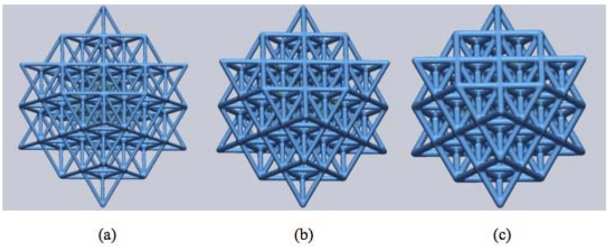


Fig. 4. Computational models of OC lattice structures with various strut diameters. (a) Strut diameter: 1.5mm, (b) Strut diameter: 2mm, (c) Strut diameter: 2.5mm.

3.2 Solid lattice model construction from the VDF

In this step, solid lattice computational model will be constructed by combining the preexisting shell and lattice core structure using VDF-based union Boolean operations, defined by

$$dist(model) = dist(shell) \cup dist(lattice)$$
$$= max\ (dist(shell), dist(lattice)) \quad (8)$$

Where $dist(shell)$ and $dist(lattice)$ is calculated by Eq. (6) and (7). Constructed by Eq. (8), Fig. 5 is a 3D computational model of a prismatic bar with FCC core structure. As mentioned, firstly, we define several basic features such as boxes, cylinders and spheres using VDF. And then we construct the shell of the computational model combining these basic features by Boolean operations and generate a 3D lattice structure utilizing the cell strategy. Each cell of lattice structures is described by constructing cylinders and spheres based on VDF in their inherent order decided by the cell type of lattice structures. Finally, we combine the VDFs between the shell and the 3D lattice structures to form the complete model. Although we take a relatively simple example to introduce our method for computational models with lattice structures using VDF, all the algorithms can be used to construct highly complex models without defect.

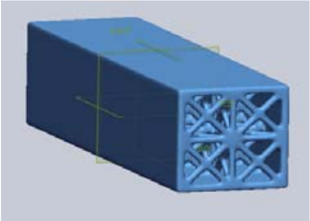


Fig. 5. A computational model of prismatic bar with FCC lattice structure.

Our design method is simple and universal, it can efficiently construct computational models with complex exterior shape and needed lattice core structure. Note that a variety of computational models consisted of various types of lattice structure can be produced in a similar way.

4. Application Results and Discussion

In the previous section, a simple computational model of a prismatic bar with FCC structure was easily and robustly constructed using our design method. This design idea is further developed to obtain more practical and complex solid lattice structure models such as sandwich panel, disk-shaped, cylinder-shaped, I-shaped, L-shaped and ring-shaped models with various types of lattice structures. Using presented modeling method, we can design models with needed lattice structure and arbitrary external shape from modified VDFs for many valuable applications.

A sandwich panel is composed of two plates and a topological lattice structure, shown in Fig.6 (a). Here, we construct upper and lower plate using the VDF of a box defined by Eq. (2) and take BCC topology as core structure. Another example is a disk with OC structure, shown in Fig. 6 (b). This model is composed of a ring-shaped shell and OC topology. The ring-shaped shell is computed by VDFs of two cylinders using subtraction Boolean operation and OC topology is chosen as core structure. In similar way, a computational model of cylindrical part with DC structure is generated by combining two cylinder-shaped shell and DC topology using VDF-based Boolean operations, represented in Fig 6 (c).

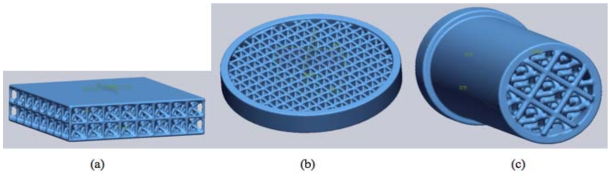


Fig. 6. A set of computational models. (a) a sandwich panel with BCC lattice structure, (b) a disk with OC lattice structure, (c) cylindrical part with DC lattice structure.

The proposed method can be directly extended and applied to construct more interesting models. That is the another intrinsic advantage of our work. The design approach is used to produce various lattice structure models with or without surface. The extension is not only applied to design the outside shape of the model but also to create new type of lattice cell as core structure of the model. So we can design large number of models with various outside shape and arbitrary lattice structure. Except boxes, cylinders and spheres, we can construct other basic features such as rings, L-shape and I-shape by modifying the VDFs.

Another significant benefit of the design method is that we can construct computational models with hybrid cells of lattice structures. Similarly, computational models of L-shaped and I-shaped lattice structures composed of FCC and BCC structures are produced without surface, shown in Fig 7.

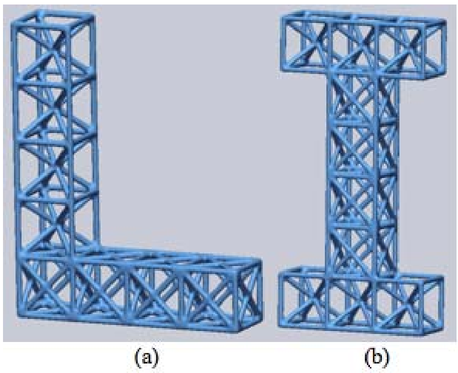
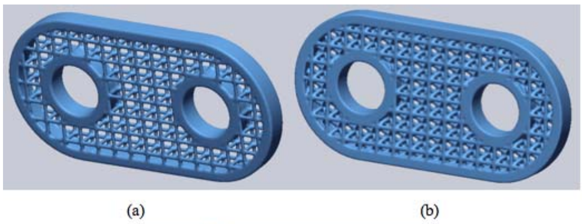


Fig. 7. Computational models of L-shaped and I-shaped part. (a) L-shaped part with BCC and OC lattice structures, (b) I-shaped part with BCC and OC lattice structures.

Then on the base of these, we can also combine more than two basic features to form intricate part models with various lattice structures. Looking at Fig. 8, it shows computational models of a structural plate with SC, BCC and OC structure respectively. The modeling process is automatic and robust, and it is fully proved the effectiveness and simplicity of our design method.

There is another example of the extended idea. Fig. 9 shows computational models of ring-shaped parts with OC lattice structure. We call it as conformal lattice structure. Each unit cell in the conformal structures has complete structure. The stiffness and strength of the conformal lattice structures are higher than incomplete structures. Conformal lattice structures are able to change direction to conform to the part surface by adjusting all vertex coordinates. Here, a ring-shaped part with conformal lattice structure is obtained by polar coordinate transformation. By modifying the locations of all the vertices in the cell, we can make various lattice structures to fit in the ring shape and generate perfect ring-shaped lattice structures. Here we take the strut radius, the numbers of the unit cell in the circle ring distribution and axial distribution as controllable parameters that are denoted as r, θ, z.

The computational results of examples illustrated in this paper are summarized in Table 1. Table 1 demonstrates that the execution time of the proposed design method for parts of lattice structure is only about a few minutes even in the case of big size of STL file. The developed design system automatically generates a STL file for AM without any operator's intervention. Moreover, application results have proved that the design method is very efficient and robust to design various parts of lattice structure which are impossible to achieve by using traditional CAD software. To the best of this paper, the design method is the first realization of automatically generating complete computational models of various lattice structures without the tedious and time-consuming operations.



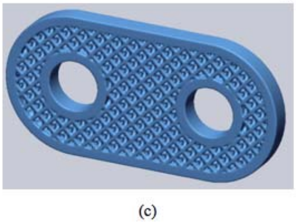


Fig. 8. Computational models of structural plates with various lattice structures. (a) A computational model of a structural plate with SC lattice structure, (b) A computational model of a structural plate with BCC lattice structure, (c) A computational model of a structural plate with OC lattice structure.

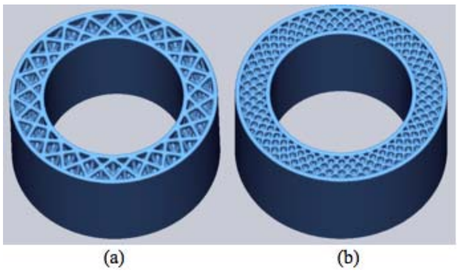


Fig. 9. Computational models of ring-shaped part with conformal lattice structure. (a) Lattice numbers in r,θ,z direction: 1×24×4, (b) Lattice numbers in r,θ,z direction: 2×48×8.

Table 1 Computational results for a set of models with different lattice structures.

Model	Triangles	Computing times (s)
Prismatic bar model (Fig. 5)	416,140	50
Sandwich panel model (Fig. 6(a))	717,180	72
Disk model (Fig. 6(b))	818,416	159
Cylindrical part model (Fig. 6(c))	964,384	213
L-shaped model (Fig. 7(a))	593,796	62
I-shaped model (Fig. 7(b))	470,004	56
A structural plate model (Fig. 8(a))	497,924	58
A structural plate model (Fig. 8(b))	528,724	60
A structural plate model (Fig. 8(c))	676,424	68
Ring-shaped conformal part model (Fig. 9)	3,689,304	368

Another distinct advantage of this study is that we can directly apply the design method to more lightweight structural design areas. Several basic features described in Section 2 are used to construct exterior shape, and various lattice topology structures are generated basing on VDF. Therefore, we can produce a variety of parts with arbitrary exterior shape and required lattice core structure by using VDF-based Boolean operations.

In order to verify the validity of our design method, we have manufactured several prototypes of lattice structures using AM technology, shown in Fig. 10. Using these computational models, all the prototypes are accurately fabricated and shows the feasibility of the design method presented in this paper.

5. Conclusion and Some Ideas for Future Research

It is possible to design and manufacture complex models with arbitrary lattice structure combining computer aided design with AM techniques. By using VDF, we can define several basic features such as boxes, cylinders and spheres to form geometric configuration of the model and the cell topology of lattice structures. We successfully design a variety of computational models with intricate external shape and needed lattice core structure. Through these design results, it is shown that the presented design method is efficient and simply to generate perfect lattice structure models. By rational distribution of the lattice structure, we can optimize the mechanical and physical properties of the parts.

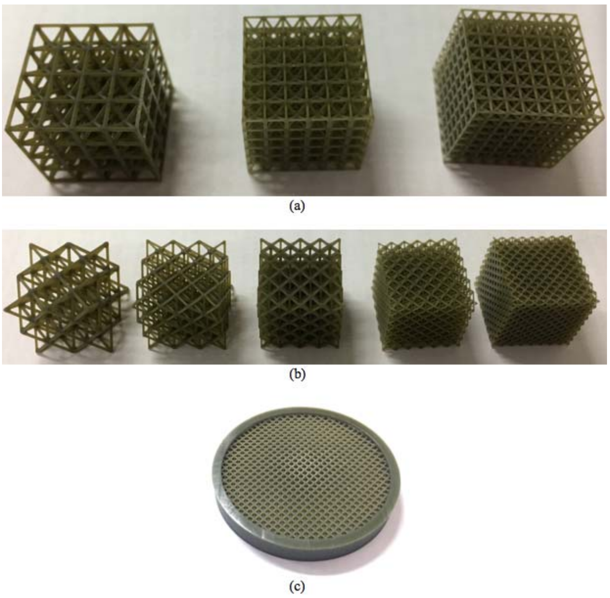


Fig. 10. Prototypes. (a) BCC lattice structures, (b) OC lattice structures, (c) a disk with BCC lattice structure.

The introduced modeling method has two major advantages: (1) the presented method can create needed 3D lattice structure models rapidly and accurately from the defined basic feature, and (2) five types of lattice structure topologies can be automatically arranged in the given shaped as core structure. It promotes our systematic study of lattice structures for their mechanical properties.

Another remarkable advantage of the method is that we can easily extend and apply our method to design more complex models with changeable outside shape and inside core structure. In order to make the design method more perfect, a parametric solid modeling method is under development.

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