Title:

gpLattice: from generation to optimization, an efficient and flexible lattice generation software kernal

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Introduction:

Lattice generation software has been a widely researched topic in the field of computational physics and engineering. Over the past few decades, significant advancements have been made in the development of lattice software, leading to more efficient and accurate simulations and predictions in various fields [1]. The development of lattice generation software has enabled researchers to study and model complex systems, ranging from material science to bio-inspired studies [2, 3].

In this work, we proposed a lattice generation software kernel (LGSK) written in c++ –gpLattice, which includes a complete set of lattice model generation schemes. The overall architecture diagram of gpLattice is illustrated in Fig.2. This LGSK is capable of producing three types of three-dimensional lattice: periodic lattice, conformal lattice, and optimized lattice. The periodic lattice consists of regularly arranged substructures, while the conformal lattice conforms to the boundary of the original model . The optimized lattice is based on specific mechanical loading conditions and has an optimized relative density distribution. The examples of these three types of lattice is illustrated in Fig.1.

All three types of lattices are generated based on the wireframe, which serves as the skeleton of the lattice. The wireframe is generated using two key technologies, such as Integer-rep and Polyline-rep. Integer-rep converts floating-point coordinates to integer coordinates to improve data processing speed, while Polyline-rep discretizes the wireframe into multiple segments, enhancing the flexibility of the wireframe structure. Optimization, density mapping, and geometric modeling are key techniques that bridge the gap between the wireframe and the lattice. Optimization and density mapping are used to optimize the generation of the lattice structure, with the former aiming to obtain the optimal density distribution effect and the latter linking the density distribution to the geometric parameters of the final lattice structure. Geometric modeling combines the wireframe and geometric parameters obtained from user settings or optimization calculations to generate the final lattice. By integrating these techniques, gpLattice ultimately generates three types of lattice structures in a efficient and flexible way.

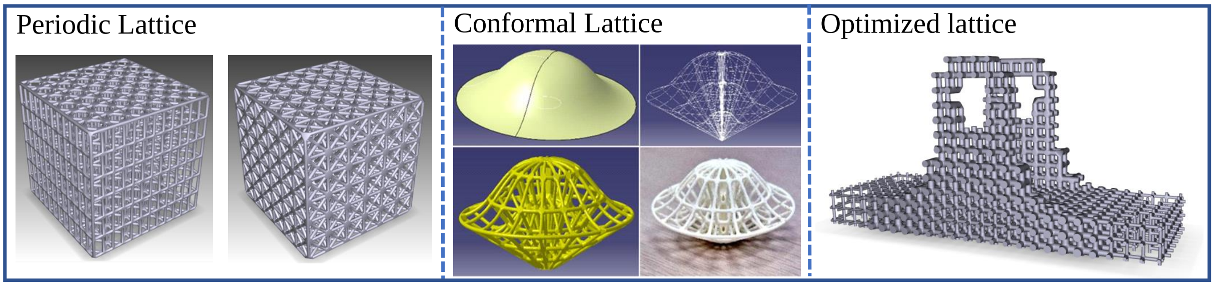

Fig. 1: Examples of three types of lattcie generated by gpLattice.

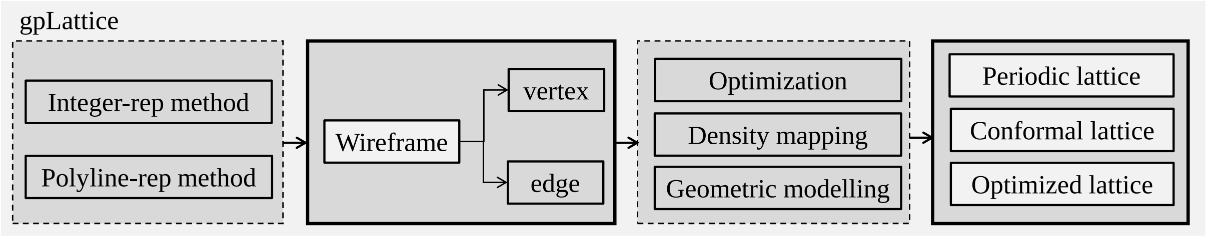

Fig. 2: Overall Architecture Diagram of gpLattice.

Wireframe:

The wireframe is the skeleton of all three type of lattice. The wireframe can be regarded as an undirected graph $C = \langle V, E \rangle$, where $V = \{V_i | i = 1, 2, \ldots, m\}$ is a set of vertices and $E = \{E_k | k = 1, 2, \ldots, n\}$is a set of edges.

Integer-Rep Method:

To ensure the accuracy of wireframe generation and computation of geometric data, the coordinates of vertices are digitized into integers to prevent errors that may arise from the elimination of overlapping vertices or edges. Figure 3 illustrates the specific process. The minimum common factor, which is the smallest factor that can divide all coordinate values of floating-point nodes, is used in this approach. The principle behind this is to determine the minimum common factor of the wireframe, divide the coordinates of each vertex by this value, and obtain integer values. By following this principle, all unit cells of the wireframe can be expressed as a list of integers, ensuring the uniqueness and accuracy of the geometric data.

Polyline-rep method:

The Polyline-rep method is realized by inserting multiple interpolation points into the edge in the wireframe at an equal distance. The edge of the wireframe can be bent, changed section and other operations by controlling the interpolation points. Polyline-rep endows wireframe with great flexibility, so that the whole modeling process can meet more application requirements. As shown in Fig.4 ,the deformed polyline can use multiple small straight line segments to approximate a curve. Polyline-rep is not only the technical foundation of the conformal lattice, but also play an important role in the optimizied lattice.

Periodic Lattice Generation:

To generate a periodic lattice, the Integer-Rep method can be used to easily produce the wireframe. However, the key to transforming the wireframe into a lattice lies in the process of geometric modeling. This step is crucial not only for generating the periodic lattice but also for creating the other two types

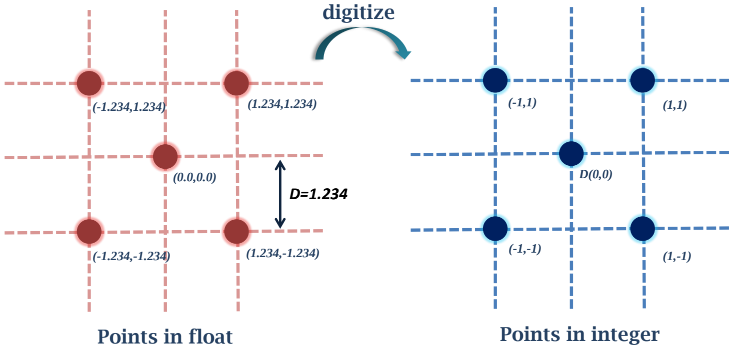

Fig. 3: The digitize process of points.

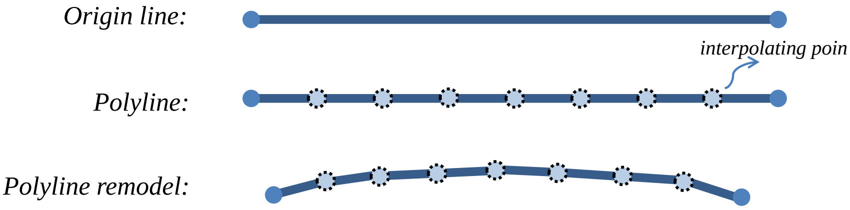

Fig. 4: Ilustration of Polyline-rep method.

of lattices.

Geometric Modeling:

Currently, there exists a wide range of geometric modeling techniques. However, many of them rely on either extensive Boolean operations, sacrificing model accuracy [4], or voxelization methods, which also compromise model precision [5]. Alternatively, some methods use implicit function modeling, but this approach requires a significant number of examples to be effective [6]. This work proposes a geometric modeling method for constructing lattices directly in triangular mesh (STL format model). The method involves calculating circular profiles around each edge of the wireframe, ensuring that the lattice struts do not overlap. The triangular mesh is then generated for each strut, and the outer mesh at the circular profile is cut to create a "notch" for adjacent lattice struts. The resulting lattice model is watertight and free of overlaps, as the triangular mesh at the notch and the struts blend together seamlessly. The QuickHull algorithm is used to generate the triangular mesh at the notch, and there is no need for any high-computation operations like boolean operations.

Conformal Lattice Generation:

Conformal lattice changes according to the shape of the model [7]. The generation method of conformal lattice is the derivative utilization of Polyline-rep method.

A approach of conformal transformation based on parametric surface is utilized in this work. The vertices and edges of wireframe go through conformal transformation together to adapt the form of model surface, where Poly-line method is utilized for transformation. There are three general enclosed surface space for wireframe to conform: point-to-surface, curve-to-surface, and surface-to-surface. The definitions are expressed as Eq.2.1:

$$\begin{cases} \varphi_{\mathrm{p.to.s}} = \{P(x,y,z), S(x,y,z,u,v,w)\} \\ \varphi_{\mathrm{c.to.s}} = \{C(x,y,z,u,v,w), S(x,y,z,u,v,w)\} \\ \varphi_{\mathrm{s.to.s}} = \{S(x,y,z,u,v,w), S(x,y,z,u,v,w)\} \end{cases} \tag{2.1}$$

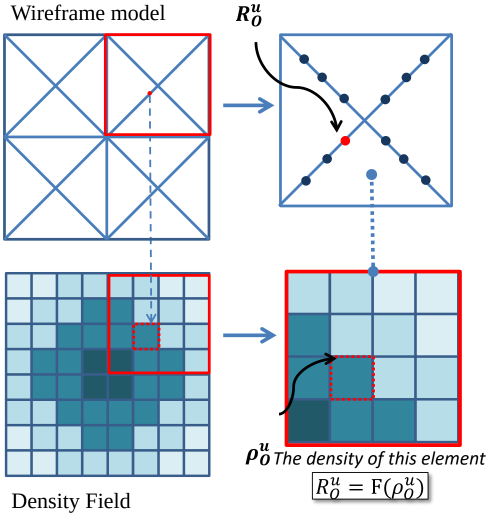

Fig. 5: Density mepping to radius

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

Conformal transformation is like twisting and bending the enclosed space bounded by point-surface, curve-surface, and surface-surface geometries to adapt the shape of the surfaces and curves. Parametric points on the frame inside the enclosed space follows the curvature of the tansformed frame but still remain the same parametric (topological) coordinates.

Optimizied Lattice Generation:

The optimized lattice is generated by combining topology optimization and the Polyline-rep method. By using optimization, the density field is generated. The lattice is able to achieve a more optimal arrangement based on density field, resulting in a highly efficient structure for specific loading conditions. An example of optimizied lattice generated by gpLattice is shown in Fig.5.

The representative voxel element(RVE) method is used to carry out mechanical calculations [8]. The detailed description of the optimization is beyond the scope of this article, for readers who are interested in this topic, the references [9, 10, 2, 11] are prefered. This paper focuses on the density mapping method in the process of optimized lattice generation.

Density mepping:

The whole mapping process can be divided into two steps. The first step is to determine which density element of the density field each vertex of wireframe is located. Here, KDtree is used as the basis of the method for searching adjacent nodes. Through this step, we obtain the density value ρ^u corresponding to any interpolation point in the wireframe model. The second step is to calculate the radius value for model reconstruction at the node according to the relationship between the slenderness ratio and the density value calculated by topological optimization. The relationship between the radius value R^u of any point in the frame model and the density valueρ^u is

$$R^u = \alpha \times \rho^u \tag{2.2}$$

where α is the radius coefficient which was calculated and fitted by RVE method.

As shown in Fig.5, the mapping method in the two-dimensional plane is illustrated, and the three-dimensional method uses the same principle. Wireframe and density Field are generated from the same outline of origin model. The generation of the wireframe model is based on the method mentioned before, which are consists of a number of lattice cell structure. The corresponding radius values at these interpolation points determine the final optimized model shape.

Conclusions:

In conclusion, this article has presented a software kernel called gpLattice that enables the modeling of periodic lattices, conformal lattices, and optimized lattices, and the principles of each method are explained. gpLattice is a useful tool for researchers and engineers in various fields who need to model complex lattice structures.

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