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A NEW METHOD FOR DESIGNING POROUS IMPLANT

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Abstract

Porous interconnected structure has been widely used in designing bone implant as it provides a three-dimensional space for cell ingrowth and nutrients transportation. Current modeling techniques either uses medical Images reconstruction to form randomized lattice or repeats unit cell spatially to periodical lattice structure. However, none of them is able to achieve sufficient control of mechanical properties. In this paper, a novel method is proposed using the implicit surface modelling and Voronoi diagram to generate randomized porous structure. Implicit surface modelling utilizes 3D scalar mathematical equation to represent complex geometries where several key parameters such as strut thickness and density can be easily determined thus the mechanical properties of the structure can also be determined. The proposed data acquisition method simplifies the CT image to point cloud. The distribution of point cloud is the presence of natural tissue distribution in image data which is inherited the generated artificial porous structure.

Keywords: Bio-inspired design / biomimetics, Design for Additive Manufacturing (DfAM), Complexity, Computer Aided Design (CAD)

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1 INTRODUCTION

1.1 Motivation

As the increasing in life expectancy, patients who suffers from the bone deficit such as osteoporosis has increased significantly over the past few decades. Generally, Osteoporosis is due to the loss of bone mass and demineralization of bone structure which increases the risk of bone fracture, decreases personal independent and causes disability. Two most common techniques have been developed and currently been used in osteoporosis treatment, Autograft and Allograft. Autograft is used to be an optimal solution which takes a section of bone from patient's own body to repair the bone defects (Laurencin et al., 1999). Allograft uses bone tissue from a donor that has been registered in the tissue bank. However, such bone grafting strategies usually leads to complications includes pain, infection, immune rejection(Fleming et al., 2000). Additionally, culturing sufficient bone tissue is a time-consuming process which is unable to satisfy the significant growth of the demand. Therefore, using artificial structure, which is commonly referred to the implants, is considered as an alternative to replace the fractured bone structure and restore its mechanical, biological functionalities. An inherent structural problem, known as the "stress shielding phenomenon", is caused by the mismatch of biomechanics of implant and the surround bone tissue. The mismatch leads to an unfavorable stress distribution at the bone-implant interface and further leads to retarded bone healing(Murr et al., 2010). This indicates that implant mechanical property and its distribution are important aspects in determining the performance of implants.

1.2 Characteristics of bone implants and existing modelling approaches

Bone implants are design to provide a environment for bone tissue generation as well as withstand loading bearing environment. Interconnected porous structure is one of the most popular candidates in biological researches as the porous structure favours the mass transportation and bone cells ingrowth at implant-tissue interface. The interconnected network can provide a solid space for the tissue generation. In general, Three characteristics of highly porous structure has been proposed: (1) porosity (2) pore size; (3) pore interconnectivity (Wang et al., 2016). These characteristics dominant the mechanical properties and biological performance of the designed structure. At present, modelling porous implant can be categorized into two types: (1) Computer Aided Design (CAD) based unit-cell design; (2) image-based design; Current CAD approach maps unit cell periodically in 3D space to construct large periodical lattice structure. This approach provides a easy way to model the porous implant with periodical lattice structure. One drawback is that it is hardly to achieve heterogeneous properties distribution as the entire porous structure is determined on one unit cell. Change of unit cell results in the change of overall lattice structure. Moreover, periodical lattice model does not have all characteristics of natural lattice structure which often has a non-periodic structure, randomized interconnected network. On the other hand, Image based design involves in using High Resolution Computed Tomography (HRCT) and Magnetic Resonance Image (MRI) to develop lattice with randomized structure. Despite the fact that model constructed from image data has the best accuracy of representing the natural bone structure, there are still some technical issues needed to be solved. Since the model is composed from meshes, due to the complexity of mesh structure, manually editing meshes is a time-consuming process which limits its own application. For example, directly manufacturing the reconstructed trabecular bone structure from image data without any modification will dramatically increase its strength and stiffness and eventually leads to the "stress shield phenomena". This is because the material of bone has a lower elastic modulus and stiffness than the most common biocompatible metal such as Titanium and stainless steel. Therefore, a simplification process to reduce the stiffness of structure is necessary. Furthermore, the presence of noise from the medical image will lead to cracks, holes and independent mesh randomly distributed in the space during the image processing but the postprocess involves in model cleaning and repairing is time-consuming. Another main challenge for the reconstruction of bone structure by whatever imaging modalities usually generate large volume of data which is beyond the capability of current computational technology(Parkinson and Fazzalari, 2013). Only a small portion of data can be reconstructed. This makes the large model reconstruction almost impossible thus limits its own use in practice.

1.3 Manufacturing and design of porous structure

On the manufacturing point of view, conventional implant manufacturing techniques such as direct foaming, powder metallurgy have been used for manufacturing porous metal(Ryan et al., 2006). These techniques have an relatively high unit cost. Practically, medical implant must satisfy patients bio-characteristic such as bone density and shape. Those characteristics vary from patients to patients. Therefore, designing and manufacturing process should be highly customized and bring tremendous difficulties. Solid Freeform Fabrication(SFF) is a novel manufacturing techniques that has the capabilities of producing structure with highly customized external shape and predefined, reproducible internal morphology(Sachlos and Czernuszka, 2003). SFF uses layer-by-layer manufacturing process known as Additive Manufacturing (AM). AM has remarkable advantages of manufacturing highly customized product as it has relatively low unit manufacturing cost and shorten the manufacturing time from design to production(Tang et al., 2015). However, conventional CAD techniques are unable to take full advantage of AM process since it is developed based on the traditional manufacturing process.

Periodical lattice structure is the main stream in scaffold design as it is a relatively easy modelling process but the researches of modelling randomized lattice structure is still limited. Several techniques have been developed in designing randomized porous structure. Schroeder et al. placed random points with Poisson distribution in a solid part then created spheres based on these points and applied Boolean subtraction to remove the volume of sphere to form an internal porous structure(Schroeder et al., 2005). X.Y.Kou et al. uses colloid-aggregation model and B-spline curve to modify the 2D Voronoi Tessellation pattern to form a randomized porous structure in 2D(Kou and Tan, 2010). A Laguerre-Voronoi tessellation model is proposed to generates a 3D Voronoi shape structure to study the mechanical properties of foam(Wejrzanowski et al., 2013). However, the connectivity of the lattice strut based on the aforementioned methods is doubtable. H. N. Chow et al. proposed a method using a stack of 2D Voronoi layer pattern to conform a 3D randomized porous structure(Chow et al., 2007). Many approaches uses Voronoi diagram to form randomized lattice structure. Voronoi diagram is a computational geometry concepts that partition plane into regions based on the location of Voronoi seeds. In every region, there is a Voronoi seed where any point in the region is closer to this seed than any others. These regions are called Voronoi cells. A remarkable feature of Voronoi diagram is that the edge of Voronoi cells are interconnected which can be used to form a interconnected network.

Bearing this in mind, we would like to introduce a novel design method combining implicit surface modelling techniques and Voronoi diagram to improve the ease of designing randomized porous structure.

2 METHODOLOGY: LATTICE GENERATION BASED ON 3D VORONOI DIAGRAM

2.1 Implicit surface modelling

Implicit surface modelling utilizes scalar function instead of polygons or parametric surface to represent geometric surface. Using parametric surface function to model complex geometry which contains multiple surface intersection is problematic since it cannot form smooth transition at intersection area while implicit surface can easily provide a smooth transition with no difficulties. The scalar function is called potential function. For example, in 2D space, a potential function to represent a circle can be expressed as:

$$x^2 + y^2 - r^2 = 0. \tag{1}$$

once the value of r is determined, every point in space satisfies the equation above makeup a circle.

$$\sum_{i=1}^{N} \mathrm{F}_i(\mathrm{x}, \mathrm{y}, \mathrm{z}) - isovalue = 0 \tag{2}$$

In general, Equation 2 describes the superposition of N potential functions in 3D. By changing the value of isovalue, different isosurface is selected and represented. (Opalach and Maddock, 1995). The following pictures are created by blending two circular potential functions with radius 2. Distance of the center of two circles D decreases from 2 to 0.5 and contours represents isosurface with different isovalue.

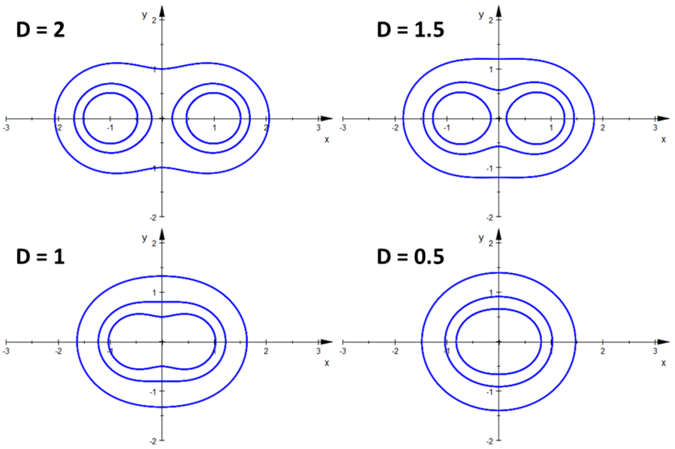

Figure 1. Merging of 2 potential functions. Contours are iso-values equal to 25,16,9 from inside to outside

2.1.1 Metaball potential function

Generally, the potential function used in describing sphere is considered as primitive geometry to represent all other geometries by using principle of superposition. Early generation of potential function is expressed as follow:

$$D(P) = be^{-ar^2} \tag{3}$$

Equation 3 describes a spherical equipotential field using spherical coordinates. One great drawback is the impact of this potential field expands infinitely in space. If a large number of potential functions superimposing together, the isovalue of each point in space is contributed by each potential function. This makes the blending process inefficient and expensive in computing. A modified potential function is designed to overcome the disadvantage which is known as Metaball potential function

$$F(r) = \begin{cases} a\left(1 - \frac{3r^2}{b^2}\right) & 0 \le r \le 3/b \\ \frac{3a}{2}\left(1 - \frac{r}{b}\right)^2 & 3/b \le r \le b \\ 0 & b \le r \end{cases} \tag{4}$$

where b is the effective distance. Once the distance between an arbitrary point and the location of potential function is greater than b, the contribution is reduced to 0. The computation process is simplified by implementing the piecewise functions.

Spherical potential function has its benefit in expressing all other geometries. Superimposing point-based potential function can only approximate this bumpy surface. Additionally,” bulge” occurs where two lines or surfaces intersects due to the inappropriate blending of potential function. Later, this problem can be solved by adjusting the density of potential function at local area. In the proposed design methods, line segment will be heavily used and Metaball algorithm has a better performance.

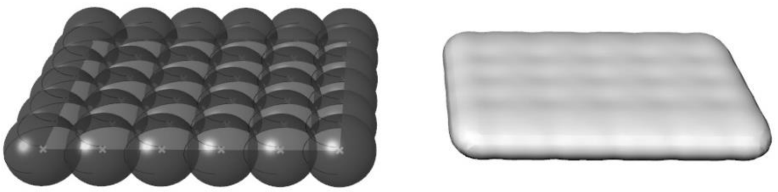

Figure 2. point based potential function visualization(left) and superimposed isosurface(right)

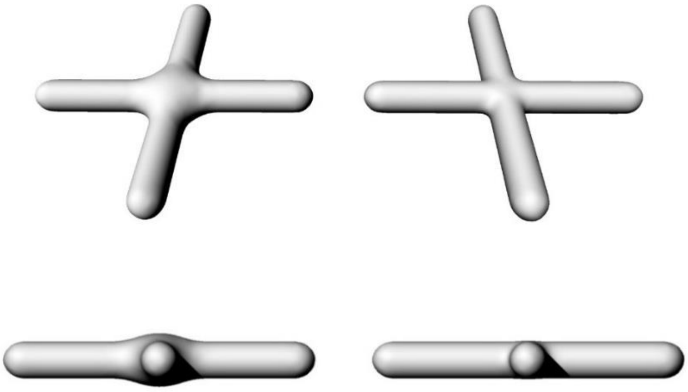

Figure 3. implicit surface model without adjustment (left) and with adjustment (right)

2.2 Overall design workflow

This design workflow starts with data acquisition from CT images. A slack of CT images is first converted to binary image then the information is further translated to points in space which are used to generate 3D Voronoi diagram. Details of data acquisition process will be showed in the next section. Once the Voronoi diagram is generated, edges of each Voronoi cell are extracted to form a set of line segments. Consequently, thousands of spherical potential functions are placed along the line segments to form an overall potential field. By selecting different isovalue, the isosurface is created and covers the line segment.

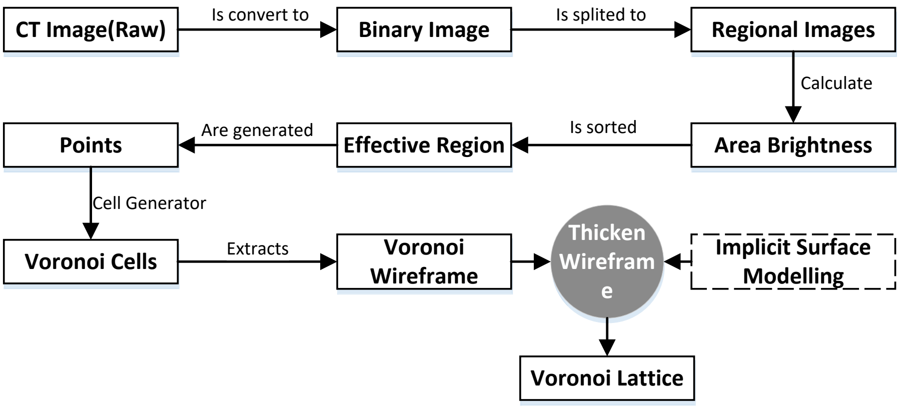

Figure 4. Design workflow

2.2.1 Data acquisition

Point selection plays an important role in determining the structure density distribution. Due to the property of Voronoi diagram, higher point density at a fixed volume gives more Voronoi cells in this which provides more lattice struts. Sine the thickness of struts remains a constant everywhere. It is easy to say that more space is occupied by the struts in the fixed volume space, In consequence, the density at local area increases. Therefore, point distribution and density are important parameters that affects the local mechanical properties. A novel method is developed to serve this idea to map the substances density in CT image to point density. Points are generated based on the brightness of pixel since whiter area means more bone tissue in CT image. To fast demonstrate the feasibility of proposed method, our region of interest(ROI) is defined in a small region which has 256x256 pixels. The image stack contains 50 images acquired form CT scanner *Skyscan1172*. The data acquisition process contains the following steps:

1. Raw image is processed through noise cleaning, reshaping operation and finally converted to binary image to reduce the data capacity.

2. Binary image is divided into 256 image blocks. Each block contains 16x16 pixels. Value stored in each pixel is denoted as brightness of the pixel. The average brightness(AB) is to take the average of the brightness value in each pixel that within one image block. Then blocks are sorted based on its average brightness (AB) from high to low.
3. A small portion of images blocks is selected as effective regions to reduce the data capacity. Only image block in the effective region has a non-zero average brightness. The rests AB will be set to 0. In this example, we only take top 30% blocks as effective region and set the rest 70% blocks to be zero. This criterion can be changed depends on the computational and hard drive capacity.
4. Based on the value of average brightness; 4, 2, or 1 points will be assigned to each image block. Therefore, a connection between the substance density and point density is established because the point density has a positive correlation with the average brightness of the image block. These Points extracted from single image are in two dimensional. To recover its spatial position, z-position information which is recorded in the information of CT image will be manually added to each point. Points are generated and collected layer by layer from the CT image and form the overall points distribution.

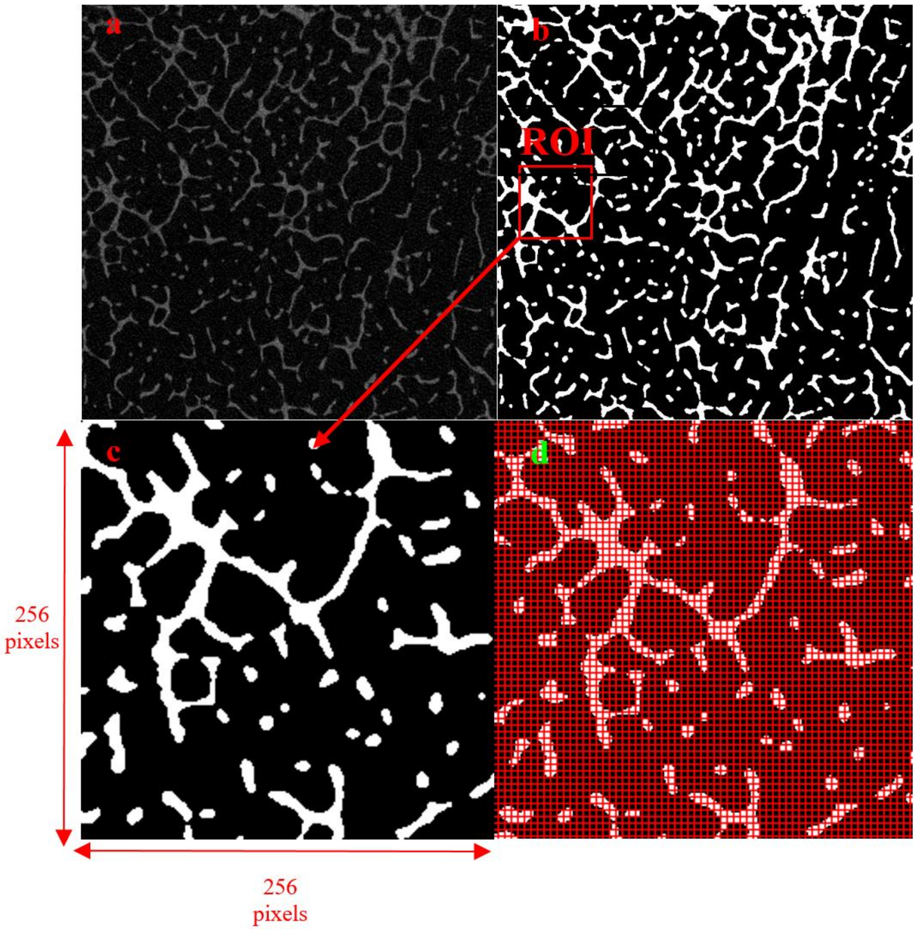

Figure 5. Image processing. a) original CT scan image b) binary image. c) 256x256 pixels image d) image split into image blocks. Each small cube has dimension 16x16 pixels

2.2.2 Building 3D Voronoi diagram and generate lattice structure

The collected points are imported to Voronoi generator to generate 3D Voronoi cells. The edges of Voronoi cell are extracted. Each Voronoi cell shares faces and edges with neighbouring cells thus the extracted edges have overlapping line segments. An extra operation needs to be taken to eliminates duplicated line segments. Thereafter, hundreds of potential functions are placed in line segments and forms an overall potential field. By selecting different isovalue, different isosurface is created and further converted to solid meshes.

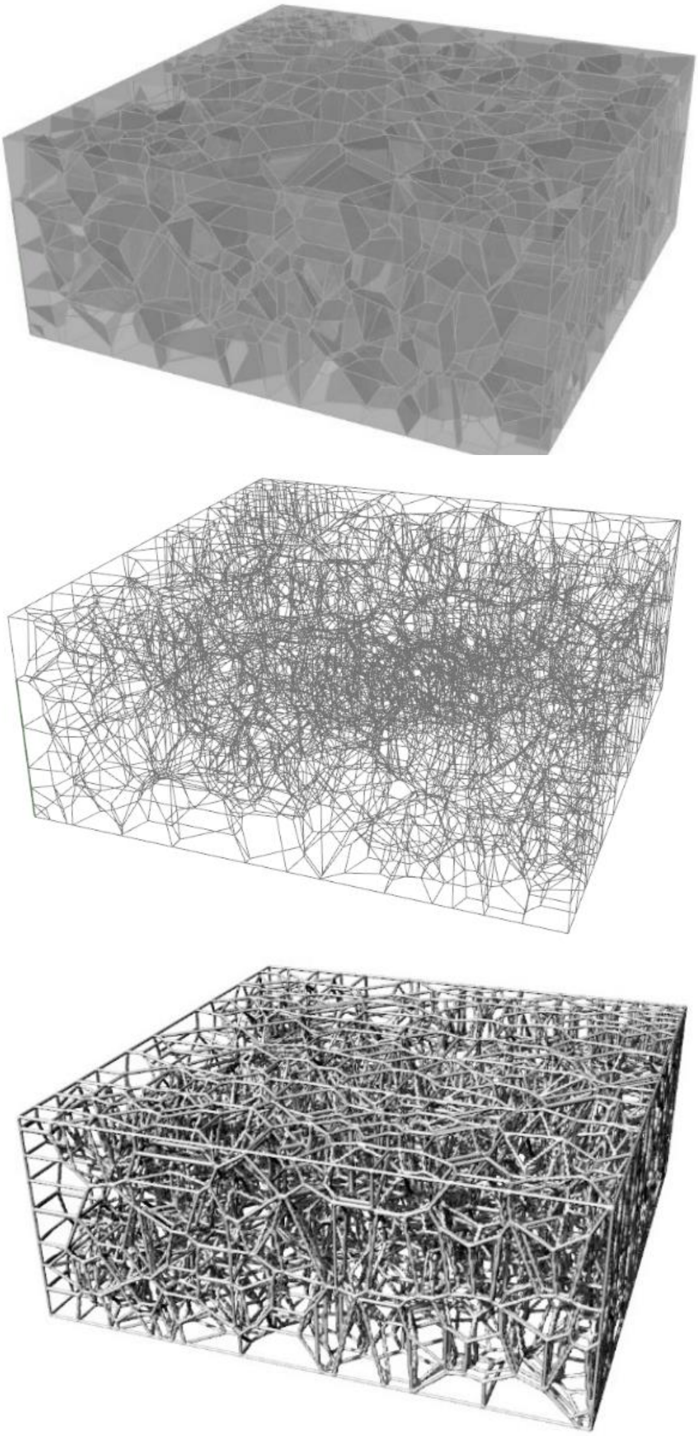

Figure 6. a) 3D Voronoi cells. b) wireframe of Voronoi cells. c) randomized lattice based on Voronoi wireframe

3 CONCLUSION AND FUTURE WORK

This new method demonstrates its remarkable ease to model lattice structure by using implicit surface modelling technique. Metaball formula can be used to perform quantitatively analysis because the potential function determines the lattice struct thickness and it is an analytical mathematics equation. Additionally, the data acquisition process shows a new way of utilising CT data from natural bone structure but the performance needs to be investigated as it only takes a small portion of information from image data.

Our next goal will be focusing on quantitively analysing the relation between struct thickness, potential function, isovalue and the mechanical properties. The performance of our data acquisition process will also be evaluated.

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