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# Design for additive manufacturing of porous structures using stochastic point-cloud: a pragmatic approach

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#### ABSTRACT

In this article, we address the design for additive manufacturing of porous structures. As a means, we employ Monte Carlo simulation (i.e., stochastic processes) to create a set of layered point-clouds so that the solid models generated from the point-clouds exhibit randomly distributed porous structures. Finally, we build physical models from the solid models using the commercially available additive manufacturing facilities (e.g., 3D Printer). The outcomes of this study will benefit those who need to manufacture the shapes found in nature (fractals) and biological organisms (e.g., artificial tissues) in a more sustainable way.

#### **KEYWORDS**

Design for additive manufacturing; porous structure; point-cloud; scaffolds; stochastic process; monte carlo simulation

#### 1. Introduction

Nowadays, we use additive manufacturing to produce customized engineering parts (aircraft ducts) [10], customized objects having biomedical significance (hearing aid shells, dental braces, artificial tissues, etc.) [10], [14], [28], fractals or self-similar objects [15], [17], [22], [24], and multi-material structures [20]. In general, an additive manufacturing process adds materials layer-by-layer to produce the desired component/product. Although the additive manufacturing can handle the shape, hierarchical, material, and functional complexities in an integrated manner [10], it is still not sustainable compared to other conventional manufacturing processes (turning, milling, drilling, grinding, extrusion, forming, etc.) [16], [21]. Here, sustainability means achieving the material, energy, and components efficiencies [16], [21] in a concurrent manner leading to a low cost, high productivity, high quality, and environmentally benign manufacturing. Sometimes, we can produce complex shapes, e.g., fractals [15], [17], [22], [24], but cannot measure it accurately, e.g., see the work [15]. This means that not only improving additive manufacturing processes itself but also improving other relevant technologies (i.e., measurement technology) must occur simultaneously to utilize the fullest potential of additive manufacturing.

As mentioned before, additive manufacturing can produce complex shapes [10], [14–15], [17], [20], [22], [28] that are difficult to produce by the subtractive manufacturing (e.g., milling), or, even, not at all manufacturable by the traditional means. Nevertheless, while using additive manufacturing, we first need a 3D CAD model of the shape to be manufactured. If such a model creation process is a cumbersome one, then the sustainability of additive manufacturing [21] cannot be achieved, i.e., additive manufacturing cannot compete with the subtractive or formative manufacturing processes, if the 3D CAD model building process of the shape to be manufactured is not a lucid and manageable one. Thus, to tackle the technical issues relevant to the 3D CAD modeling of complex shapes to be manufactured by additive manufacturing in a sustainable manner, a concept called Design for Additive Manufacturing (DfAM) has been introduced [10], [15], [22].

In this article, our goal is to describe a pragmatic approach of DfAM of porous structures. In particular, we use the Monte Carlo simulation [1], [18] as a means to create a set of layered point-clouds. After that, we convert the point-clouds into 3D CAD models that must exhibit randomly distributed porous structures. We also build the physical models from the 3D CAD models using the commercially available additive manufacturing facilities (e.g., 3D Printer) to show the effectiveness of the proposed approach.

Accordingly, the remainder of this article is organized as follows: Section 2 provides a brief description of the work done on the modeling of complex shapes. Section 3 describes both deterministic and Monte Carlo simulation based point-cloud (or stochastic point-cloud) generation processes. This section also shows the general procedures to build both porous and non-porous model building processes using the deterministic and stochastic point-clouds. Section 4 shows some of the useful results obtained using the methodologies described in Section 3. This section also shows the physical models that we build using commercially available 3D printing facilities. Section 5 provides the concluding remarks.

#### 2. Literature review

When we talk about a porous structure, we recall a honeycomb [2], [23]. A conformal shape (i.e., an outer loop or boundary) bounds the cross-sectional area of such a porous structure. Inside the conformal shape, the voids or cells are organized to form a lattice (i.e., a mesh or grid). The channels called struts connect the cells. See [2], [23] for an illustration of conformal shape, lattice, cells, and struts that result a structure referred to as porous lattice structure. When we compile a set of porous lattice structures layer-by-layer, we get a honeycomb like structure. These structures are sometimes referred to as scaffolds. As such, the building blocks of a scaffold are as follows: outer boundaries, lattices, cells, struts, and orientation of the layers. If we randomize the positions of the building blacks of a scaffold, then we get a randomized porous structure or a complex shape. To study the randomized porous structures, a branch of computational geometry called stochastic geometry has been developed [3], [6]. Accordingly, this geometry has earned a great deal of attention among researchers in mathematics, physics, material science, biology, and ecological sciences. Those who design and manufacture the shapes having biomedical significance (e.g., the shapes of tissue and bones) have adopted this concept of randomized porous structure. For better understanding, some of the applied researches on randomized porous structure are briefly described, as follows:

Chen [5] described how to apply Boolean operations to various lattice structures and conforming shapes to create 3D CAD models having porous structures for the sake of additive manufacturing. The commercial systems have been using the similar kind of CAD modeling for creating porous structures [27]. However, numerous authors have worked on further refinement of the geometric modeling of complex shapes having porous structures. Some of the selected papers are briefly described, as follows. Sogutlu and Koc [19] developed a methodology to create scaffolds where the pores were created by overlapping the randomly distributed small spheres in a spherical or square boundary. They also showed a way to control the porosity at different layers of a scaffold. Chow et al. [7] used the methodology called Voronoi diagram to

produce layered models of porous structure. In this work, the main idea is to use the concentric clusters for designing small 2D regions, and, then, expanding these regions in time-dimension to create 3D structures. Chu et al. [8] used a material science based model called structureproperty-behavior model and produced scaffolds using additive manufacturing. Yang et al. [26] introduced a numerical function based methodology to randomize a lattice structure so that the outcome becomes a randomized porous structure. They have also showed how to control the porosity and produced the physical models using 3D printing. Yaman et al. [25] created porous structure using 3D Voronoi diagram. They also developed a slicing algorithm to minimize the 3D printer head movements. Ozbolat and Koc [13] developed a methodology to create medical grade porous structures. They introduced a geometric modeling where the initial input is a medical image of a wound. The steps to create the porous structures have also been described. Kou and Tan [12] developed a flexible methodology to create the irregular porous structures using quadtree (octree) structures. The methodology subdivides an object into small subregions, refines them using T-mesh, and creates polygonized surfaces using the non-uniform rational B-splines (NURBS). Khoda and Koc [11] developed a methodology to build porous structure transforming the medical imaging information of the internal structure of a bone. They introduced a concept called iso-porosity. Based on the similarities in porosity of a region (i.e., an iso-porous region), they have created the conformal shapes and lattices, making the construction of the internal structures of porous bones possible. Fang et al. [9] developed a multi-scale voxel modeling approach to create the internal structures of bone structure for direct fabrication. The data from the medical imaging (i.e., microscopic random trabecular networks of bone rendered from medical imaging systems) was used to create the voxel model of the bone porosity and the outer boundaries. This methodology of direct fabrication does not need the slicing process, as it is an essential process for the traditional rapid prototype technology.

Apart from the methodologies described above, surface generation from point-clouds and creating textures on the surface have been studied by numerous authors, e.g., see the work in [4]. This study takes this path and provides some insights into creating porous structures directly from the point-clouds.

## 3. Concepts of deterministic and stochastic point-clouds

In this section, we describe the concepts of deterministic and stochastic point-clouds.

Let  $A(t) = \{(x_i(t), y_i(t), z_i(t)) \in \mathfrak{R}^3 \mid i = 1, ..., n\}$  be a set of points or a point-cloud created at a point of time *t* by a process *P*. If for a given point of time *t*,  $z_i(t) = h(t)$  (a constant value),  $\forall i \in \{1, ..., n\}$ , then the corresponding point-cloud A(t) is called a planar pointcloud, i.e., a point-cloud on the height h(t). We denote a planar point-cloud by A(t,h(t)). Let  $h_1(t), ..., h_p(t)$  be *p* number of heights at a point of time *t* organized in an ascending order,  $h_j(t) < h_{j+1}, \forall j \in \{1, ..., p-1\}$ . We then get a set of layered point-clouds denoted as  $LPC(t) = \{A(t,h_j(t)) \mid j = 1, ..., p\}$ . We can impose conditions on the process *P* while creating LPC(t). Based on the condition, we get either deterministic LPC(t) or stochastic LPC(t). We describe some of the straightforward formulations of LPC(t), as follows.

#### 3.1. Deterministic LPC(t)

To get a deterministic LPC(t), we use a deterministic process *P*, out of many possibilities. As a result, the constituent of a deterministic LPC(t) are all equal irrespective of the points of time used to generate those elements, i.e.,  $A(t_1,h_j(t_1)) = \ldots = A(t_m,h_j(t_m))$ . One of the straightforward possibilities is to use a process *P* for creating a loop-like layered point-cloud, as defined in Equation (1).

$$\begin{aligned} \text{Define } r, n, p, (h_1 \cdots h_p), (x_c, y_c), t \\ \text{For } j &= 1 \cdots p \\ z(t) &= h_j(t) \\ \text{For } i &= 0 \cdots n - 1 \\ P &:: \\ \theta_i &= \frac{2\pi}{n} i, r_i(t) = r \\ x_i(t) &= x_c + r_i(t) \cos \theta_i(t) \\ y_i(t) &= y_c + r_i(t) \sin \theta_i(t) \\ \text{End For} \\ A(t, h_j(t)) \\ \text{End For} \\ LPC(t) \end{aligned}$$
(1)

As defined in Equation (1), the process *P* creates points  $(x_i(t), y_i(t))$  on the circumference of a circle with a radius equal to *r* and the center at  $(x_c, y_c)$  on each plane  $h_j(t)$ , j = 1, ..., p. The number of points at each plane is equal to *n*. If we set n = 50, r = 25,  $(x_c, y_c) = (100, 100)$ , and  $h_j(t) = 5 \times j$ , for j = 1, ..., 10, we get a set of ten layered deterministic point-clouds as shown in Fig. 1(a). If we create the convex hull of the point-clouds using a commercially available package, we get a 3D CAD model as shown in Fig. 1(b). If we prefer, we can augment a set of deterministic point-clouds. For example, consider the case shown in Fig. 1(c). It shows two sets of deterministic point-clouds. One of the sets is taken from Fig. 1(a)

and other corresponds to r = 40,  $(x_c, y_c) = (100, 100)$ , and  $h_j(t) = 2.5 \times j$ , for j = 1, ..., 10. The convex hull of these two sets of deterministic point-clouds is shown in Fig. 1(d), which is a conically shaped object. Nevertheless, we do not observe any porous structures on the surface or even inside the surfaces of the models shown in Fig. 1. It is worth mentioning that concave hull cannot be applied to the point-clouds.

However, we can use other formulations to create deterministic *LPC*(*t*), if preferred. For example, we can use a set of triangular point-clouds using the following formulation:  $x_i(t) = x1(1 - u_i) + x2(u_i)$ or  $x2(1 - u_i) + x3(u_i)$  or  $x3(1 - u_i) + x1(u_i)$ ,  $y_i(t) =$  $y1(1 - u_i) + y2(u_i)$  or  $y2(1 - u_i) + y3(u_i)$  or  $y3(1 - u_i) +$  $y1(u_i)$ ,  $u_i = i(\Delta u)$ ,  $n(\Delta u) = 1$ . Here, (x1,y1), (x2,y2), and (x3,y3) are the vertices of the triangle. This formulation will produce a non-porous structure, too. To create porous structures, we need to create stochastic point-clouds instead.

#### 3.2. Stochastic LPC(t)

To produce a stochastic LPC(t), we need a stochastic process. This means that the process denoted as Pis now a stochastic process hereinafter referred to as SP. As a result, the points at each layer are not the same even though the process SP remains the same, i.e.,  $A(t_1,h_j(t_1)) \neq \ldots \neq A(t_m,h_j(t_m))$ . A straightforward formulation for creating a stochastic LPC(t) is shown in Equation (2). Compared to its deterministic counterpart (Equation (1)), in the case of stochastic LPC(t), SP is introduced to randomly create the radius  $r_i(t)$  for the trials  $i = 0, \ldots, n$ -1.

Define SP, n, p, 
$$(h_1 \cdots h_p)$$
,  $(x_c, y_c)$ , t  
For  $j = 1 \cdots p$   
 $z(t) = h_j(t)$   
For  $i = 0 \cdots n - 1$   
 $P ::$   
 $\theta_i = \frac{2\pi}{n}i$   
 $r_i(t) \leftarrow SP$  (2)  
 $x_i(t) = x_c + r_i(t)\cos\theta_i(t)$   
 $y_i(t) = y_c + r_i(t)\sin\theta_i(t)$   
End For  
 $A(t, h_j(t))$   
End For  
 $LPC(t)$ 

This means that this time all  $r_i(t)$  are not a constant value equal to r; it various randomly depending on the underlying *SP*. For example, consider that *SP* is either a random number in the interval [a,b] (a > 0) or a normally distributed variable with mean  $\mu$  and standard deviation $\sigma$ , denoted as  $N(\mu,\sigma)$ . To determine  $r_i(t)$ , the



(c) two sets of deterministic LPC(t)

Figure 1. Modeling based on deterministic LPC(t).

procedure defined for Monte Carlo simulation [1], [18] can be used. We describe the fundamental idea behind Monte Carlo simulation in Fig. 2. As seen in Fig. 2, we need the cumulative function *F*(.) [1], [18] of the respective distribution to simulate the values of a variable (in this case the values denoted as  $r_i(t)$ ). We then generate a random number [1]  $rnd_i \in [0,1]$  and equate it to F(.). The corresponding value of the variable is taken as the simulated value, as schematically illustrated in Fig. 2. We repeat the procedure as many times as needed. Fig. 2(a) shows the  $F(r_i(t))$  and the simulated values of  $r_i(t)$  for  $i = 0, \ldots, 49$  (n = 50) when the SP is a uniform distribution in the interval [a = 20, b = 40]. On the other hand, Fig. 2(b) shows the  $F(r_i(t))$  and the simulated values of  $r_i(t)$  for i = 0, ..., 49 (n = 50) when the SP is a normally distributed variable having the form of  $N(\mu = 30, \sigma = 5)$ . Figure 3 shows two cases, one corresponds to uniform distribution and the other



corresponds to normal distribution, as shown in Figs. 2(a)-(b), respectively. We show the orthogonal and top views of the point-clouds in the upper segments of Fig. 3. In the bottom of Fig. 3, we show the 3D CAD models generated by applying the concave hull operations on the respective point-clouds. This time the 3D CAD models exhibit randomly distributed porous structures. It is worth mentioning that the convex hull does not produce any porous structure (not shown this time) similar to the case of deterministic LPC(t) (Fig. 1). In the case of deterministic LPC(t), the concave hull does not work, as mentioned before. In the case of stochastic LPC(t), it is not the case, i.e., concave hull operation works. We observe that both uniform and normal distributions produce similar results, i.e., the 3D CAD models are quite similar. However, the model produced from the normal distributions exhibits more variability than those of the other distribution. To understand this, consider the models show in







(a) Uniform distribution based



(b) Normal distribution based



Fig. 4. In Fig. 4, the shapes obtained for different points of time are shown for both uniform and normal distributions. The models corresponding to uniform distribution

are likely to create more porosity (Fig. 4(a)). This means that one can vary the stochastic process or the associated parameters to create a desired porous structure.



**Figure 4.** Porous structures produced different points of time using stochastic  $LPC(t_k)$ , k = 1, 2, ...

The models corresponding to uniform distribution are likely to create more porosity (Fig. 4(a)). This means that one can vary the stochastic process or the associated parameters to create a desired porous structure. Nevertheless, until a physical model is being created using an ordinary additive manufacturing facility, it would be difficult to judge its (the point-cloud's) effectiveness.

However, the experience of porous structure building process described above can be utilized to create Randomly Disturbed Porous Structures (RDPS).

#### 4. Results and discussions

This section describes some of the useful results that we have obtained by applying the methodology described in Section 3.

First, we report the results obtained when we build a thin-walled RDPS using a stochastic LPC(t), as shown in Fig. 5. The underlying point-cloud is a stochastic LPC(t)created by varying the radius  $(r_i(t))$  using a uniform distribution (Fig. 3(a)). The heights  $(h_1 \cdots h_p)$  are small compared to the radii, i.e.,  $h_p - h_1$  is relatively small compared to  $r_i(t)$ . We allow a small variability in the radius  $r_i(t) \in [a,b]$ , i.e.,  $a \cong b$ , too. A typical 3D CAD model created from such a LPC(t) by applying the concave hull is shown in Fig. 5(a). The corresponding physical model built by using a commercially available 3D printing facility is shown in Fig. 5(b). To avoid commerciality, the details of the packages and equipments are not mentioned here. A visual inspection reveals that the physical model resembles the 3D CAD model. This means that we can easily manufacture RDPS using the concept of stochastic LPC(t). As such, the concept of stochastic



(b) physical model of (a)

Figure 5. Producing thin-walled RDPS.

LPC(t) may enrich the field of DfMA, which is the goal of this study, however.

We can extend the abovementioned idea of thinwalled RDPS. One of the noteworthy extensions is called cascaded thin-walled RDPS. We show the results of a relevant case study regarding cascaded thin-walled RDPS in Figs. 6-7.

As seen from Fig. 6, first we create a set of stochastic LPC(t). The radii of two consecutive LPC(t)s do not overlap. The point-clouds shown in Fig. 6 correspond to the uniformly distributed radii in the intervals [24, 20], (20, 18], and (18, 16]. The vector of heights is (10, 11, 12, 13, 14, 15). Since all these point-clouds follow the conditions of thin-walled RDPS, as mentioned above (i.e.,  $||h_p - h_1||$ is relatively small compared to  $r_i(t) \in [a,b], a \cong b$ , we expect highly porous 3D CAD model. We obtain the results as expected, as shown in Fig. 6. We have created three physical models based on the respective 3D CAD models, as shown in Fig. 6. A visual inspection reveals



Figure 6. Producing RDPS using cascaded stochastic point-cloud.



Figure 7. Cascaded RDPS.

that all three physical models resemble the respective 3D CAD models. We assemble the three physical models shown in Fig. 6 to form a cascaded RDPS. We show the assembly in Fig. 7. As seen from Fig. 7, the constituents of cascaded RDPS, i.e., the physical models shown in Fig. 6 fit each other. It is worth mentioning that the upper and lower faces of the physical models are flat without having any pores. If we build the physical models (Fig. 6) halfway, instead, we get pores on the upper or lower face. This means that we may cut some segments of the CAD data to obtain an all through porous structure. This issue can be investigated further.

Nevertheless, in this study we allow a degree of stochasticity in the radius. We consider stochasticity in the layer heights  $(h_1 \cdots h_p)$ . We may consider a degree of stochasticity in the number of points (n) for each layer. We may augment deterministic and stochastic point-clouds. This means that one can explore many different extensions of the concepts of deterministic and stochastic point-clouds while creating complex shapes like the ones the ones shown here. Therefore, we consider that the work presented here is still its infancy, demanding a great deal of future work.

### 5. Conclusions

In this study, we have described a pragmatic approach for design for additive manufacturing of randomly distributed porous structures. The main idea is to use a carefully created stochastic point-cloud. We introduce the algorithms for creating stochastic point-clouds. We report two case studies showing the effectiveness of the proposed stochastic point-cloud based approach of porous structure manufacturing. The first case study deals with a thin-walled porous structure modeling and the other deals with a cascaded thin-walled porous structure modeling. In both cases, the physical models are also created using the data of the 3D CAD models using the ordinary additive manufacturing facilities. The physical models resemble the respective 3D CAD models. The outcomes of this study enrich the field of design for additive manufacturing of complex shapes, in general, and shapes having randomly distributed porous structure, in particular.

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