A Lightweight Design of Tree-shaped Support Structures for SLM Additive Manufacturing

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Abstract. Support structures are used to hold the overhangs of the models and dissipate process heat in the Selective Laser Melting (SLM) processes. However, the support structures are sacrificed afterwards in order to obtain the target 3D models. Therefore, to save both printing time and materials, minimizing the volume of support structures is an effective means. Tree-shaped structure is an effective design for the lightweight design of the support structures. Although existing commercial software such as Autodesk Meshmixer™ have provided the function of generating tree-supports by manually setting the geometric parameters, the problem of designing a stable tree-support of minimum volume to reduce the material and printing time without sacrificing the printing quality for 3D-printed metal models has not been addressed properly. We propose a combination of an experimental method and a volume minimization framework using a strategy of improved Particle Swarm Optimization (PSO). We carried out a set of experiments to compare our method with traditional "point supports" and the tree-supports module of Autodesk Meshmixer™. Simulation and experimental results reveal that our approach is effective in reducing support volume and printing time.

Keywords: Selective Laser Melting, Support Structures, Lightweight, Particle Swarm Optimization.
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1 INTRODUCTION

With the ability of fabricating general freeform 3D models in a layer-by-layer manner with a variety of materials, Additive Manufacturing (AM) such as Selective laser melting (SLM) has been wildly used in producing metal mechanical products [11],[21]. SLM has the capability of producing high-quality, customized, and metallic components [7]. However, the SLM process requires additional support structures beneath the overhangs of the model to avoid the collapsing of these overhangs.

Support structures are sacrificed afterwards in order to obtain the desired shape, thus they represent increased cost in the SLM process, especially when high-value metal materials such as titanium are employed. In addition, the support structures increase the manufacturing time. Therefore, to save both printing time and materials, it is of critical importance to minimize the amount of materials used for fabricating the support structures. For this purpose, there are three manners: the first manner is partitioning the models into support-free parts and then assembling them together; the second is selecting better printing orientation; and the last is designing lightweight support structures.

To reduce material and time consumption, when the precise shape of the model is not of critical concern, partitioning the model into support-free parts and then assembling them together is an effective means of reducing support materials. Along this line, a number of algorithms have been devised for partitioning the models, most of these algorithms also consider the matching error on the interfaces of the parts as a constraint during the partition process [8],[12]. Particularly, for the shell models, a method for decomposing a shell model into the least number of support-free parts based on partitioning the Laplacian skeleton of the model with a randomized algorithm was proposed by Wei et al. [20].

For a given model, the build orientation can be optimized to reduce the printing material and time. If merely the minimum vertical volume beneath the overhangs is considered, this geometric optimization problem has been solved in various ways [6], [14]. Majhi et al. [13] present a theoretical algorithm for optimizing the build orientation to minimize the contact-area and volume of supports for three dimensional convex polyhedra. Zhao et al. [25] proposed a multi-objective function to find the optimal build direction to minimize the volume error, construction time and support volume. Paul et al. [15] proposed an algorithm to calculate the optimal orientation for minimizing the volume of support structures, the cylindricity and flatness errors of the part features. For most metal printing parts, the build orientation is required to be fixed. In the following, we shall focus on the literatures that are closely related to the design and optimization of the support structures with a fixed build orientation.

Using lightweight cellular structures for decreasing the support materials has been studied in the field of additive manufacturing [4],[16],[19]. Hussein et al. [9] explored the potential of using cellular structures for the support of metallic parts based on SLM while distortion of the part occurred. According to their preliminary results, they explored two types of lattice structure (diamond and gyroid) for support structure to reduce the material and build time while fulfilling the structural demands. However, the low volume fraction of cellular structure might be too fragile to be consistently manufactured with an SLM process at the desired resolution [10]. Strano et al. [17] proposed a graded cellular support structure where more robust cells are placed beneath the heavy overhangs and less supports elsewhere using in metallic AM. Cloots et al. [1] studied the building parameters including support interval, scan angle, scan speed, and hatch distance to minimize the volume of crossbar support structures during the SLM processes. Gan et al. [7] explored "Y", "IY" and Pin support structures base on finite element analysis to investigate the design effects on manufacturing thin plates and cuboids for SLM. Dumas et al. [5] proposed a scaffolding structure that was formed by horizontal and vertical bars as the support structure for Fused Deposition Modeling. Zhang et al. [24] investigated the influence of different support parameters on the efficiency and mechanical properties of tree-supports for SLM, but the tree-supports are simple ones with single internal nodes. Vanek et al. [18] proposed a greedy algorithm for generating tree-supports considering stability, but no topology optimization was conducted to minimize the support volume. Particle Swarm Optimization (PSO) algorithm with a novel constraint handling strategy was employed to minimize the contacting area with the consideration of mechanical analysis on the support structures [22]. However, only some simulation work has been conducted on the "point supports" and little has been done on the physical experiments. Autodesk Meshmixer™ has provided the function of generating tree-supports by manually setting the parameters. To summarize, the problem of designing a stable tree-support of minimum volume to reduce the material and printing time without sacrificing the printing quality for 3D printed metal models has not been addressed properly. To tackle this problem, we provide a combination of an experimental method and a simulation algorithm in the remainder of the paper.

Our technical contributions: Focusing on metal models with flat overhangs, a strategy of iteratively applying a hybrid of PSO and greedy scheme is proposed for generating lightweight tree-support.

The remainder of the paper is organized as follows: Section 2 presents our methodology, section 3 presents the simulation results, section 4 presents the comparison results, and section 5 concludes the paper with some discussions.

2 LIGHTWEIGFHT DESIGN OF TREETREE-SUPPORTS FOR SLM

In this section, we present our approach for constructing a lightweight tree-support for 3D models. The pipeline of our approach is shown in Figure 1.

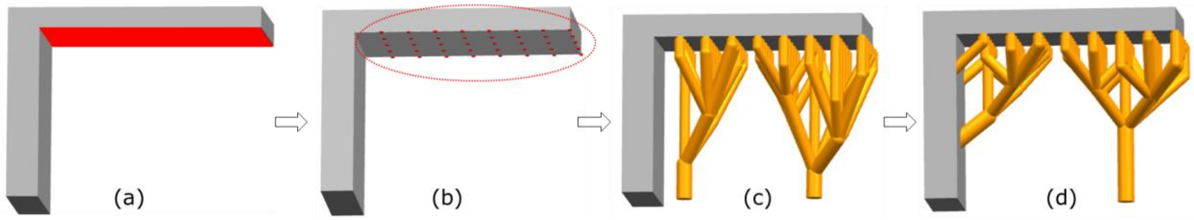

Figure 1: The pipeline of computing the tree-support structures on a 3D model: (a) Computing the support areas of the model, (b) Generating the support points on the overhangs, (c) Generating the initial tree-supports beneath the overhangs, (d) Generating lightweight support structures using the hybrid of PSO and greedy strategy.

Given a triangular mesh model M, the main procedure of generating the lightweight tree-support for the overhangs is specified as follows:

Algorithm : Generate_Lightweight_Tree_Supports(M)

Input: A triangular mesh model M

Output: A lightweight tree-support for the overhangs of M

Step 1. Compute the overhang regions of M requiring support (Figure 1(a)) and generate a uniform sampling of points in the regions (Figure 1(b)).

Step 1.1. Identify the overhangs that requiring a support from below.

Step 1.2. Compute the support points on the overhang region of M that requires support from below. The sampling of the supporting points on the overhang regions, especially the distance between adjacent points are generated based on experiments.

Step 2. Construct a random set of I best tree topologies (Figure 1(c)) from a large set of tree topologies (e.g., $10I$).

Step 2.1. Discretize the space below the remaining support areas by constructing a gird G that is consisted of a set of vertical line segments and horizontal section (Figure 2). The nodes of G are the potential nodes of the tree-support.

Step 2.2. Build the initial tree topologies by connecting proper nodes of G. During the process of generating a tree topology, there is a unique leaf node and a branch node on a vertical line segment of G, which is allowed to connect to at most 6 higher neighboring nodes.

Step 3: For each tree-support obtained in Step 2, minimize the total volume of the tree-supports by using a hybrid of Particle Swarm Optimization (PSO) and a greedy strategy (Figure 1(d)).

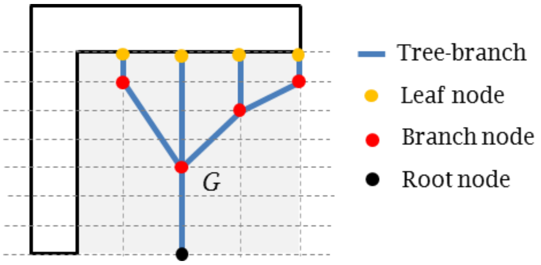

Figure 2: Illustration of generating a tree topology in G (the dashed grid).

The details of Step 3 is given in the following section.

2.1 Optimization of Tree-supports Using PSO

We define a tree-support (one solution) as a particle. Each particle P_i is associated with two vectors, i.e., the velocity vector V_i = [${v_{i1}}^1, {v_{i2}}^1, {v_{i1}}^2, {v_{i2}}^2 ..., {v_{i1}}^D, {v_{i2}}^D$] and the position vector X_i = [$z_i^1, d_i^1, z_i^2, d_i^2, ..., z_i^D, d_i^D$], where D is the number of branch nodes in the tree-support, z_i^k denotes the z-coordinates of branch node i in the k^{th} dimension, which means that each branch node is only allowed to move along a vertical line segment of G (except of the leaf nodes), d_i^k denotes the diameter of the (unique) branch connecting node i downward, ${v_{i1}}^k$, ${v_{i2}}^k$ denote the velocity components of z_i^k and d_i^k .

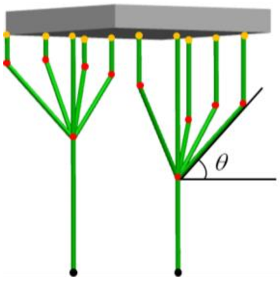

Figure 3: Illustration of P_i : P_i is the tree-support consisting of two trees.

Objective function:

Let d_i be the diameter of the branch connecting node i downward, and let l_i be the length of the branch, we can express the objective function for minimizing the support volume as follows:

$$F = \min \sum \pi \left({d_i}/{2} \right)^2 l_i \tag{2.1}$$

Constraints:

1. To ensure the tree-shaped topology structure it requires that a node of the tree is linked to a unique node below it, i.e., if D_i is the degree of a node that consists of the lower neighbors, then we have the constraint as follows:

$$D_i = 1 \tag{2.2}$$

2. Furthermore, to ensure the tree is a stable one, we require that the diameters of the lower branches be no smaller than those of the higher branches. More precisely, let d_i be the diameter of a branch connects to node i from below, then we have the following constraint:

$$d_i < d_j \tag{2.3}$$

Where nodes i and j are connected and node i is higher than node j.

3. In addition, to guarantee the printing stability, we need to constraint the tilted angle of a tree-branch with respect to the build platform. Let θ denote the angle (Figure 3), then we have the following constraint:

$$\theta \geq 45° \tag{2.4}$$

With the objective and the constraints, we then present our improved PSO for solving the system as follows.

2.1.1 Initialization and process

The initial positions of the particles are given by N tree-supports, and the initial velocity is given as [0, 0,…, 0, 0]. As the evolution goes on, the velocity and position of particle i in the k^{th} iteration can be updated as follows:

$$V_i^k = wV_i^{k-1} + c_1 r_1 \left(pBest_i^k - X_i^{k-1}\right) + c_2 r_2 \left(gBest^k - X_i^{k-1}\right) \tag{2.5}$$

$$X_i^k = X_i^{k-1} + V_i^k \tag{2.6}$$

where V_i^k is the velocity of particle i in the k-th iteration, X_i^k is the new state of particle i in the k^{th} iteration, w is the inertial weight used to control the influence of the previous velocity and we set it linearly decreasing from 0.9 to 0.4 in our program according to works in [23], c_1 is the cognitive parameter and c_2 is the social parameter, they are used to weight the velocity toward the best previous position of the particle in the k^{th} iteration, these two are usually the same and are set as 2 by convention. r_1, r_2 are two independent random variables in the range of (0, 1], $pBest_i^k$ is the best particle of particle i in the previous iterations, and $gBest^k$ is the historically best position of the entire swarm, which be selected from $pBest_i^k$ $(i = 1,2, \dots N)$. In the k^{th} iteration, the new state of P_i is updated according to the velocity updating Equation (2.5) and the position updating Equation (2.6), and the newly-updated states are evaluated by the objective function, e.g., Equation (2.1).

2.1.2 A hybrid of PSO and a greedy strategy to achieve lightweight design

For each swarm, it should be noted that when we get the P_i in k^{th} iteration, a greedy strategy of linking a branch node of a tree-support to the model surface is adopted if the linking results in a smaller volume (Figure 4). In this process, the algorithm is greedy in the sense that it greedily links a node to the nearest model surface with a branch whenever the volume of support is reduced. Depending on the sequence of processing the tree-branches, this local optimal strategy may not be stable in generating the optimal result for a particular particle (a tree-support). However, for a large swarm of particles and a large number of iterations, this strategy has a great chance of achieving a nice result. Conventionally, the number of particles and the number of iterations are chosen to be 100 and 2000 are large enough for most applications [2-3].

Finally, we obtain I_{gBest} and select the result with the smallest volume as the optimal support structure.

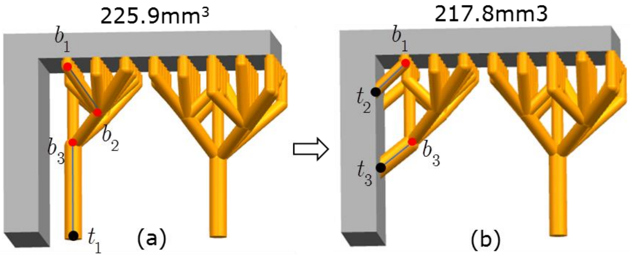

Figure 4: Illustration of the greedy algorithm: (a) Tree-node b_1 is connected to tree-node b_2, and tree-node b_3 is linked to t_1 in the print platform, (b) Linking tree-node b_1 to point t_2 on model surface and linking tree-node b_3 to point t_3 on model surface result in smaller volume.

3 SIMULATION

We implemented the algorithm with Matlab on a PC with Intel i7-4790 and 8 GB RAM. We set I=100 as the initial set of swarms. For each initial tree on a CPU, we perturbed it into N = 100 distinct tree-supports (particles for the adaptive PSO) while maintaining the same topology; further, we set the maximum number of iterations as 2500. Note that I = N =100 is sufficient for the evolution of the PSO process by convention [2-3].

Based on the history data of the SLM machine used for the experiments, we set the interval for the adjacent supporting points as r = 2mm and the diameter of the tip branch as d = 1mm, the diameter of tree root is set as 1.5mm in order to guarantee the feasibility of 3D printing. In addition, to easily detach the tree-support from the desired model, a circular truncated cone (tip) is added at its end as shown in Figure 5. The diameter and height of the tips can be determined by experiments, and we used the diameter of 0.75 mm and the height of 0.25mm.

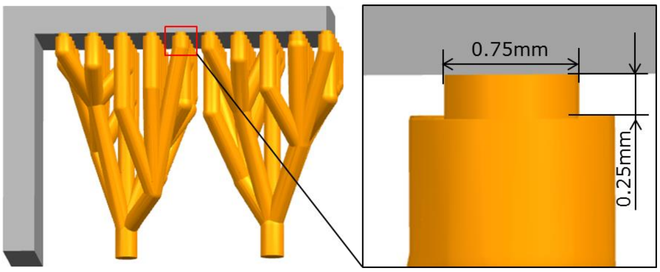

Figure 5: Illustration of the tips of a tree-support.

In order to better evaluate the impact of the tree-supports generated by our approach on SLM, we design the L-shaped model for the simulation. See Figure 6 for an illustration. In a PSO evolution process as the z-coordinates of the nodes vary, the connection topology of a tree is not changed; for each connection structure obtained, a greedy algorithm is conducted (Figure 6(b)).

The curve of support volume of corresponding model is provided in Figure 7. We can see that the volume of support is almost a constant after running the simulation for more than 2000 times, which means that our hybrid of PSO and the greedy strategy leads to a fairly small support volume.

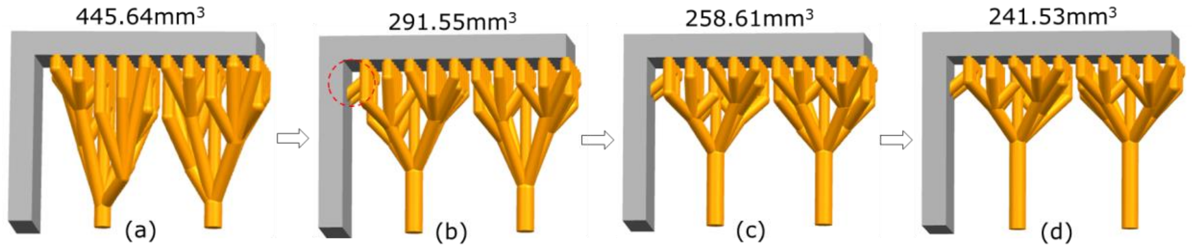

Figure 6: The effect of the simulation processes for L-shaped model: (a) The initial state, (b) The 100th iteration, (c) The 500th iteration, and (d) The 2500th iteration.

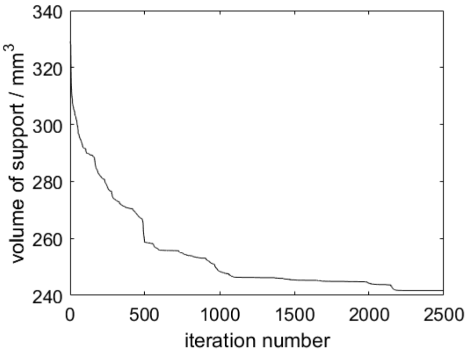

Figure 7: The support volume curve with respect to the number of iterations.

4 COMPARISON EXPERIMENTS

A SLM printer called "Kre-AM280" with stainless steel 1-4404-200 as the printing material was used to carry out the experiments to examine the effectiveness of our approach. The 3D printing experiments is conducted using checkerboard scanning method. To ensure the manufacturability of the model, the process parameters are set at the recommended values of the machine for different materials (see Table 1).

Interval of scan line (μm)	*Beam diameter (μm)*	*Layer thickness (μm)*	*Laser power (W)*		*Scan speed (mm/s)*	
			Contour	Hatch	Contour	Hatch
140	70	30	100	200	800	800

Table 1: Laser parameters for SLM printing.

To further investigate the effects of the supports generated by Autodesk Meshmixer™, traditional method and our approach on printability, we conducted 3D printing experiments using the L-shaped model. To make the comparison a fair one, we used the same r and d as in our experiment. Figure

7 shows the effects of the printed models. In the figure, the different support structure designed for the L-shaped model are shown in the 1st row, the 3D printed model are in the 2nd row, and the target models with support structures detached from the model in the 3rd row. Note that the model designed by Meshmixer™ cannot be successfully 3D printed (Figure 8(a)). The supported models generated by traditional method of adding "point supports" (a set of pillars) and our approach performed well in terms of surface quality (Figure 8(b)-8(c)).

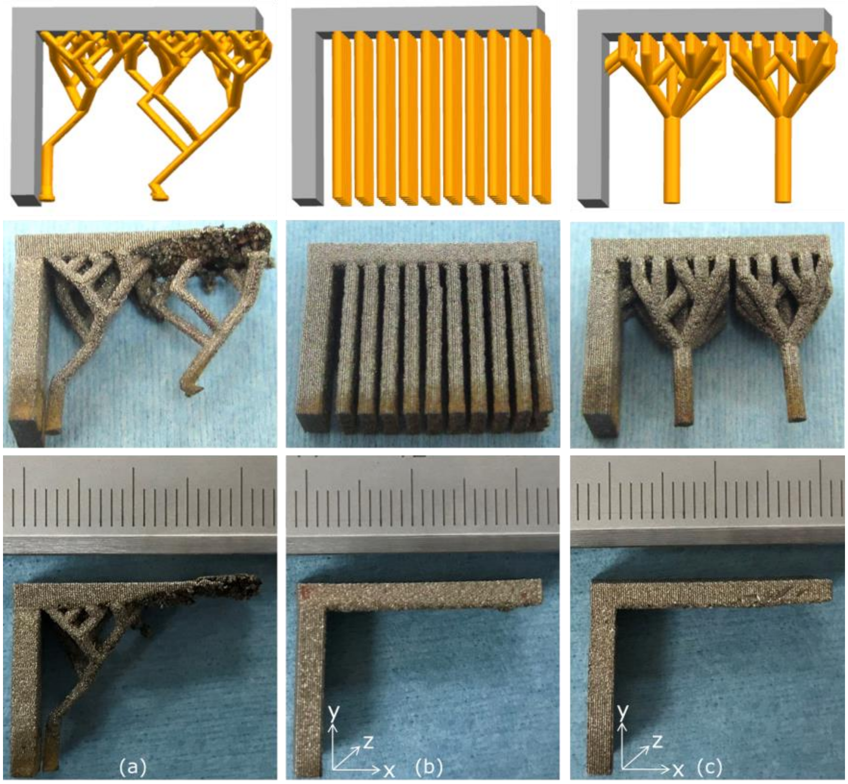

Figure 8: The comparison of 3D printed model for different design method: (a) The tree-support generated by Autodesk Meshmixer™, (b) The uniform "point supports" generated by traditional method, (c) The tree-support generated by our approach of combining PSO with the greedy strategy.

In order to further evaluate the effect of the tree-supports generated by our approach on the surface quality of the 3D printed models, we measured the 3D dimensions of the 3D printed models by our approach and traditional method, and determined the geometric error (deviation) and warpage based on the difference of the 3D printed models and the CAD design models. For brevity, we used the maximum warping deformation in z-axis direction to express the warpage of the flat overhangs. From Table 2, we can see that there is no significant difference between our method and the traditional method in the dimensional deviation of the 3D printed model, and using tree-support generated by our approach can lead to less warpage of flat overhangs compared with the uniform "point supports" generated by traditional method.

Orientation	*Overall dimension (mm)*	*Deviation*	*Warpage (mm)*

	Design model	Traditional method	Our approach	Traditional method	Our approach	Traditional method	Our approach
x	22.15	22.06	22.08	-0.41%	-0.32%	N/A	N/A
y	8	8.07	8.09	0.88%	1.13%	N/A	N/A
z	17.15	16.97	16.95	-1.05%	-1.17%	0.16	0.13

Table 2: Dimensional deviation and warpage of the 3D printed models (with the removal of support structures) by our approach compared to the uniform "point supports" generated by traditional method.

Table 3 summarizes the statistics of the comparison experiments between "point supports" generated by traditional method and our approach. From the table, it can be seen that the amount of support material our method saves is about 57.15%. The amount of material and printing time are calculated based on the simulation of the Materialise Magics™ and the Build Processor module of the Materialise software. The percentage of material save is smaller than that of support volume save, which means that the support structures generated by traditional method and our method are small with respect to the volumes of the naked models (638.58mm^3). Note that the percentage of save time is about 3.25%, there is due to the effects of the infill path pattern we used (chessboard path planning strategy).

Uniform point supports			*Our approach*					
Support volume (mm^3)	Time (min)	Material (g)	Support volume (mm^3)	Time (min)	Material (g)	Save volume	Save time	Save material
563.66	187.1	9.85	241.53	181	7.13	57.15%	3.25%	27.61%

Table 3: Statistics of printed models showing the support volume, printing time, material and savings compared to the uniform "point supports" generated by traditional method.

Note: "save volume" refer to merely support structures, while "save time" and "save material" respect to the printing time and material of model with support structure.

5 CONCLUSION

We have introduced an optimization framework that attempts to minimize the support structures of 3D printed models without sacrificing the printing quality in SLM. By creatively taking a support structure as a particle as the input of the PSO scheme, we addressed the support minimization problem by using the hybrid of PSO with constraints and greedy strategy. Gan et al. [7] explored "Y" and "IY" support structures which are only suitable for supporting the flat plate with regular shapes that are easy for the propagation of the "Y" or "IY" units. Similarly, Zhang et al. [24] provided the tree-support which are simple ones with single internal nodes that is constrained by the shape of the model. However, the technique in this paper can be used to handle other geometrically complicated models without any problem. Meanwhile, we validated the effectiveness of our approach via selecting the appropriate parameters (the interval of adjacent supporting points and the diameter of tree branches).Compared with "point support" generated by traditional methods and tree-supports generated by Autodesk Meshmixer™, the tree-supports proposed by the paper result in faster printing with less material, meanwhile the printing performance also can be guaranteed.

However, our approach can still be improved in the future, and some potential extensions of the work are listed as follows:

1. For the tree-supports, a suitable path planning strategy (other than chessboard path pattern) that leads to less printing time is worthy of future research.

2. More geometrically complicated examples should be tested and the geometric parameters such as curvature and the angle of overhangs should be taken into consideration for an optimization of the support density and topology.

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