Title:
**Design of Tree-shaped Support Structures for SLM**

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Introduction:
With the ability to fabricate 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 such as high-quality, customized, and metallic components for a variety of applications [3],[7]. However, the SLM process requires additional support structures beneath the overhangs to avoid the collapsing. Support structures are sacrificed afterwards in order to obtain the desired shape, thus they represent increased cost in the process, especially when high-value metal alloys are employed. Therefore, to save both printing time and materials, it is of critical importance to minimize the amount of materials support structures used for fabricating the. For this purpose, there are two ways, one is selecting better printing orientation, and the other is designing smart lightweight support structures. In this paper, we shall focus on the literatures that are closely related to the design and optimization of the support structures.

Using lightweight cellular structures for decreasing the support materials has been studied in the field of AM [2],[6],[9]. Hussein et al. [4] 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 may be too fragile to be consistently manufactured with an SLM process at the desired resolution [5]. Strano et al. [7] 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] study 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. [3] 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. Vanek et al. [8] proposed a greedy algorithm for generating tree support structure considering stability, but no topology optimization was conducted to minimize the support volume. Particle Swarm Optimization (PSO) algorithm with a novel constraint handling strategy is employed to minimize the contacting area with the consideration of mechanical analysis on the support structures [10]. However, only some simulation work has been conducted on the vertical supports and little has been done on the physical experiments. Autodesk Meshmixer™ has provided the function of generating tree-shaped 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 surface 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 PSO with constraints scheme is proposed for generating lightweight tree-support.

Main Idea:

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

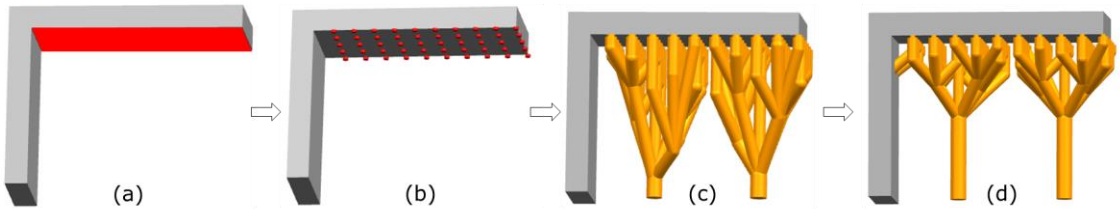


Fig. 1: The pipeline of computing the tree-support structures on a 3D model: (a) Computing the support areas of the model, (b) Generating the support points on the overhangs, (c) Generating the initial tree-support beneath the overhangs, (d) Generating lightweight tree-support using PSO strategy.

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.** Identify the overhang regions of $M$ requiring support (Fig. 1(a).) and generate a uniform sampling of points in the regions of $M$ (Fig. 1(b).), especially the distance between adjacent points are generated based on experiments.

**Step 2.** Construct a random set of $I$ best tree topologies (Fig. 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 (Fig. 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 Particle Swarm Optimization (PSO) (Fig. 1(d).).

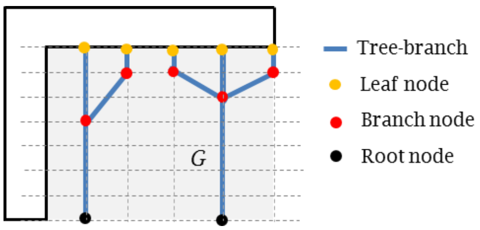


Fig. 2: Illustration of generating a tree topology in G (the dashed grid).

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

**Step 3.1:** Define a tree-support as a particle.

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

*Objective Function*

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

$$F=\min\sum\pi\left(d_i/2\right)^2 l_i \tag{1}$$

*Constraint*

1. To ensure the tree is a stable one, we require that the diameters of the lower branches be larger than those of the higher branches. Let $d_i$ be the diameter of a branch connects to node $i$ from below, nodes $i$ and $j$ are connected and node $i$ is higher than node $j$, then we have the following constraint:

$$d_i<d_j \tag{2}$$

2. To guarantee the printing stability, we need to constraint the tilted angle of a tree-branch with respect to the build platform. Let $\theta$ denote the angle, then we have the following constraint:

$$\theta\geq 45^\circ \tag{3}$$

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

**Step 3.2:** Initialize and process.

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

$$V_i^k=wV_i^{k-1}+c_1r_1\left(pBest_i^k-X_i^{k-1}\right)+c_2r_2\left(gBest^k-X_i^{k-1}\right) \tag{4}$$

$$X_i^k=X_i^{k-1}+V_i^k \tag{5}$$

where $V_i^k$ is the velocity of $P_i$ in the $k^{th}$ iteration, $X_i^k$ is the new state of $P_i$ 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, $c_1$, $c_2$ are set as 2 by convention. $pBest_i^k$ is the best particle of $P_i$ in the previous iterations, and $gBest^k$ is the historically best position of the entire swarm. In the $k^{th}$ iteration, the new state of $P_i$ is updated according to the velocity updating Eqn. (4) and the position updating Eqn. (5), and the newly-updated states are evaluated by the objective function, e.g., Eqn. (1).

**Step 3.3:** Obtain lightweight tree-support using PSO strategy.

We set $I$ = 100 as the initial set of swarms. For each initial tree, we perturbed it into $N$ = 100 distinct tree-supports (particles), further, we set the maximum number of iterations as 2500. Finally, we obtain $I$ $gBest$ and select the result with the smallest volume as the optimal support structure.

## Results:

*Simulations*

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 to guarantee the feasibility of 3D printing. We design the model with the optimized parameter for the simulation (Fig. 3(a-c).). The curve of support volume is provided in Fig. 3(d). We can see that the volume of support is almost a constant after running the simulation for more than 1500 times, which means that our approach leads to a fairly small support volume.

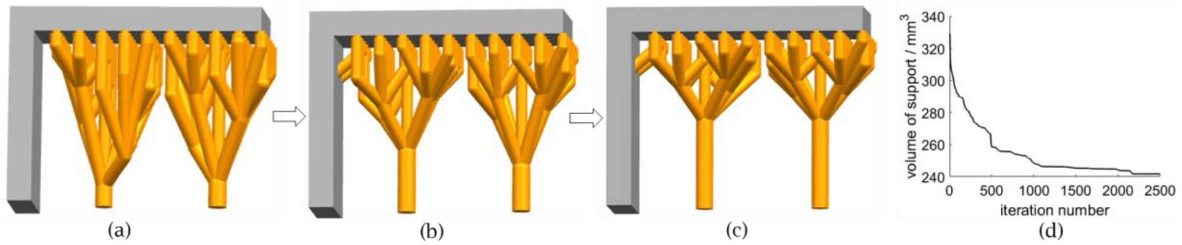


Fig. 3: The effect of the simulation processes for L-shaped model: (a) The initial state, (b) The 100$^{th}$ iteration, (c) The 2500$^{th}$ iteration, (d) The curve of support volume as to the number of iterations.

*Comparison Experiments*
A SLM printer called “Kre-AM280” with stainless steel 1-4404-200 material was used to carry out the experiments to examine the effectiveness of our approach. The process parameters are set at the recommended values of the machine for different materials (see Tab. 1.).

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

Tab. 1: 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. Fig. 4. shows the effects of the 3D printed models. Note that the model designed by Meshmixer™ cannot be successfully 3D printed (Fig. 4(a).). The supported models with “point supports” (Fig. 4(b).) and our approach (Fig. 4(c).) performed well in terms of surface quality.

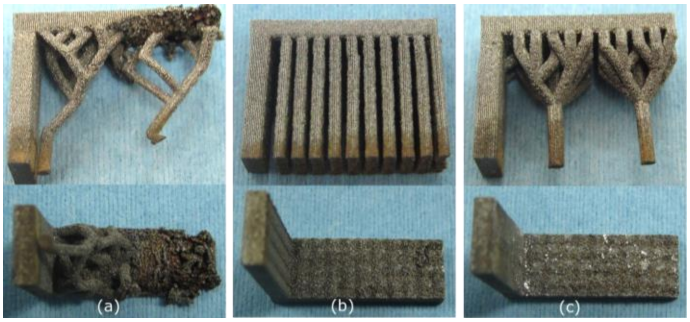


Fig. 4: The comparison of 3D printed model for different design method: (a) The tree-support generated by Autodesk Meshmixer™, (b) The uniform “point supports” generated by traditional method, (c) The tree-support generated by our approach of PSO with constraints.

Tab. 2. summarizes the statistics of the comparison experiment between “point support” and our approach. From the table, it can be seen that the amount of support our method saves reach 57.15%. The percentage of printing material save is smaller than that of support volume save, which means that the tree-supports generated by traditional method and our method are small with respect to the volumes of the naked models. Not that the percentage of save time is very small (3.25%), there is due to the effects of the infill path pattern we used (chessboard path planning strategy).

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

Tab. 2: Statistics of printed models showing the support volume, printing material, time 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.

Conclusions:

We have introduced an optimization framework that attempts to minimize the support structures 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 PSO with constraints. Compared with tree-supports generated by Autodesk Meshmixer™ and “point support” generated by traditional method, the tree-supports proposed by the paper result in faster printing with less material, meanwhile the printing performance also can be guaranteed.

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