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Support grain architecture design for additive manufacturing

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ABSTRACT

Supporting the overhang section, restraining the model deformation or warping, minimizing the residual stress and controlling the cooling rate are some common functions of support structure in multiple additive manufacturing (AM) process. Since it needs to be removed at the post processing stage of fabrication, it is a considerable waste in terms of material, energy and time employed for their construction. Hence, it is advantageous to minimize the amount of support which eventually can improve the overall efficiency of the AM process. In this paper, a novel support architecture design methodology is proposed considering the amount of support volume, maximum contact interface, lower fabrication time, and ease of fabrication. First, the support needed points on the object surface are identified considering their normal direction. The points are clustered considering their uniform curvature and location. Afterward, each cluster of points is segmented iteratively into closed-convex regions i.e. grain boundary, considering the geometric factors such as aspect ratio, fill factor, and contour area to ensure the ease of fabrication and supportability. These convex grains are the model-support interface segments where a partial contact based support removal technique is implemented. Finally, self-supported slanting and pillar support structures are generated that minimizes support material consumption and consequently saving build time. The proposed research is implemented on free-form objects and the results are evaluated with the available support generator software. The result shows the improvement is build time, reduction in support volume and ease of support removal.

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1. Introduction

In Additive Manufacturing (AM), commonly known as layer manufacturing or 3D printing, a 3D model is used to fabricate the object. The digital model is designed by CAD software or obtained by reverse engineering techniques. The fabrication process starts from the bottom of the build platform and continues successively layer after layer to the top. Materials are accumulated/cured in thin layers and stacked along the build direction successively to generate the 3D part. During fabrication the material in each layer must be connected and supported fully or partially by previous layer to ensure the surface continuity and structural integrity. To ensure this, some surface segments or stacks may need support to hold the floating part in mid-air. These areas are called overhangs and it needs support from below by additional sacrificial material. Furthermore, support structure is often used to constrain the model deformation or warping, minimize the residual stress and control the cooling rate for multiple AM processes e.g. powder bed fusion, sheet lamination, and vat polymerization. Depending upon the process, support can be natural or synthetic. Support structures are typically sacrificed at the end of the object fabrication. The fabrication of these support structure requires resources like material, time, computation, machine time and energy. Often time, it is difficult to remove support structure from complex object and may need significant amount of post processing. Thus, minimal supports contribute to the faster fabrication, limiting non-value added activities (e.g. post processing, cleaning) in the finished object. Hence, it is advantageous to minimize the amount of support material and that can improve the overall efficiency of the AM process.

Current common practice for support structure construction starts with identifying the facet in need for support. As STL being the de facto file format, the orientation of each facet is compared with the build vector. By extruding those facets downward, support volume and geometry is computed. A number of approaches have been considered to optimize the support volume that minimizes the amount of support material. Most common pro-active approach for reducing the support volume is to detect the right build vector on the build platform [1–7]. Another common method is hollowing or shelling technique with controlled infill pattern. In this technique, the projected support boundary remains the same, but the internal...
architecture is constructed with porous in fill ray pattern. Traditionally, machine manufacturer uses ‘proprietary’ filling pattern to construct the hollowed support section often time defined as scaffolding. Periodic pattern including Perpendicular raster (0°–90°) and honey comb structure are most commonly used in different AM processes. Hollowing technique provides better solution for saving material and fabrication time, while could create shape retention issue in both support and model object. Also, removing the uncured material from the internal space can be tedious and time consuming and may often-time require minor design modification to avoid trapped volume.

Slanted-wall support structure construction algorithm [8] is proposed to decrease the support volume and facilitating its removability. The STL based algorithm first identifies the facet inclination to determine the support required region. Then, three types of support entities (i.e. upper, middle, and bottom flank) are used to design the support model for each region. However, accommodation of three support entities in free-form complex surface could be difficult. Meshmixer™ from Autodesk generates tree-like support structures to minimize the usage of support material [9]. Similar tree-like support generation algorithm named clever support has been proposed by Vanek et al. [10]. They generate removable smaller contact segment but oftentimes requires user interactions to achieve minimal support volume. Such structure is complex to print due to their discrete contours, concavity, and low slenderness ration; and may require more time during printing [11]. Besides, printing the slanted-structure, like the branches of tree, induces a smaller bonding area between consecutive layers causing uneven warping during their cooling phase. Bridge and pillar based support structure scaffolding algorithm [12] reduces the quantity of material usage while preserving the mechanical integrity. However, since the material in the bridge section is supported on top of two pillars, there may be a significant amount of sagging at the bottom.

In this paper, a novel support architecture design methodology is proposed that will decrease the support volume, provide maximum contact support at the model interface, bring ease in fabrication and expedite its fabrication time. The proposed algorithm is directly applied on the surface/poly-surface model instead of triangular surface approximation (STL), which will provide higher accuracy in capturing and supporting the actual free-form surface. First, the parametric surface is analyzed to determine the points that require support. Based on their location and curvature, the points are clustered into coherent region to reduce fabrication complexity. Each cluster of points is segmented iteratively into convex boundary regions, which are defined as the grain in this manuscript. The grain boundary is optimized for the ease of fabrication considering their geometric factors such as aspect ratio, fill factor and area. As a result, a collection of discrete and homogeneous support grain is created on the model surface interface. Partial contact support removal technique is proposed for the ease of support removal which is based upon the raster width and sagging. A slanting surface and pillar algorithm is proposed to generate the support volume with each grain constructed that ensures minimum support material and associated fabrication time. The proposed methodology is implemented on free-form surface geometry and results are compared with existing built-in support generator. An overview of the proposed methodology is shown in Fig. 1.

The succeeding part of the paper is organized as follows. Section 2 represents the methodology for optimized support structure generation. This section suggests the optimum segmentation of support needed points and generation of support structure. The implementation and results are discussed in Section 3. Finally, Section 4 concludes the paper.

2. Support generation

The AM process starts with a valid digital model often known as a CAD model. A computer aided forward or reverse engineering technique is used to represent the object or component in a digitized environment. Generally, the forward design validates the ideas through computer modeling and the digitized information is processed from CAD platform. The de facto STL file format is the standard interface between the CAD designs and AM fabrication system which utilizes triangles to approximate the surfaces of a part model. It does not carry all the geometry and topological information from the actual CAD file. Thus, to ensure the higher accuracy, poly-surface model is considered in this proposed methodology.

2.1. Determination of support needed points

The support needed points need to be determined on the object surface to design and generate the support structure. The parametric surface \( S(u, v) \subseteq \mathbb{R}^3 \), of the object can be represented with the parameters \( u \) and \( v \), where \( u, v \in [a, b] \). A set of finite number \( N \) of points \( \mathbf{P} = \{ \mathbf{p}_n = (x_n(u_n, v_n), y_n(u_n, v_n), z_n(u_n, v_n)) \}_{n=1}^{N} \) is sampled on the object surface \( S(u, v) \) as shown in Fig. 2(a). Normal vectors \( \mathbf{n}_n \) are determined at all points sampled on the surface, which can be represented as follows:

\[
\mathbf{n}_n = S_{u_n}(u_n, v_n) \times S_{v_n}(u_n, v_n), \quad n = 1, \ldots, N
\]

where \( S_{u_n}(u_n, v_n) = \frac{\partial S(u_n, v_n)}{\partial u} \) and \( S_{v_n}(u_n, v_n) = \frac{\partial S(u_n, v_n)}{\partial v} \). The direction of normal vectors \( \mathbf{n}_n \) at each point will determine whether the point requires support or not. The angle, \( \phi_n \) is defined as the angle between the build direction, \( \mathbf{b} \) and normal vector, \( \mathbf{n}_n \), which can be measured using the Eq. (2) as shown in Fig. 2(b).

\[
\phi_n = \cos^{-1} \left( \frac{\mathbf{n}_n \cdot \mathbf{b}}{|\mathbf{n}_n| \cdot |\mathbf{b}|} \right)
\]

To identify the location of points that requires support, a threshold angle \( \psi_c \) (generally 30°–45° for extrusion based AM [13,14]) needs to be defined based on the process and material specific requirement. A point on the object surface will require support if
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