A method for metal AM support structure design to facilitate removal

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1. Abstract

For powder bed metal additive manufacturing (AM), additional post-processing for support structure removal is required. However, this removal process is not formally considered during the design of support structures. Therefore, when either manual or CNC milling is required, some support structures may not be easily removed due to tool accessibility. In this research, with STL model as input, tool accessibility is calculated and used to map onto the facets to grow supports that are more amenable to machined removal. It provides a way to combine previous analysis on support layout with additional information to guide suitable setups; ones that consider not only critical angles requiring support but also removability. This work could enable better support designs that will lead to higher throughput of metal AM by reducing effort and expense in post-process machining.

2. Literature Review

Support structures are needed in different Additive Manufacturing(AM) processes for a variety of different purposes. In all AM processes, support structures are required for keeping the features in position during fabrication (Gibson et al. 2010). Support structures are required when the critical inclination angle is reached for overhanging geometries (Allen 1994). In powder bed fusion processes, Selective Laser Melting(SLM) for example, support structures are needed for fixing the features to prevent potential warping caused by residual stresses from the rapid solidification of molten metal (Mumtaz et al. 2011). As for Electron Beam Melting(EBM), the support structures also improve thermal and electrical conductivity (Gibson et al. 2010; Harryson & Cormier 2003; Dinwiddie et al. 2013). Since support structures are not part of the final geometry to be created, they need to be removed; a process that requires significant extra time and effort. Even when removal is easy, the surface quality of the part at support attachments can be diminished.

Researchers have developed many methods to alleviate this support structure issue, and some of the methods are widely used in commercial AM systems. One approach is using a secondary dissolvable material for building the support structure. After the part is fully printed, the part is removed from the building tray and moved to a bath and sometimes mechanical vibration and heating to accelerate the dissolving process. A representative example would be the *WaterWorks*™ solutions developed by *Stratasys*. A similar dissolving approach has been proposed for directed energy deposition systems (Lefky et al. 2016). Another very common approach is to optimize the build orientation and design of the support structure to minimize the volume of supports (Strano et al. 2013; Cloots et al. 2013; Vanek et al. 2014).

In full melt metal powder bed fusion processes, support structures cannot be readily built with a secondary material so they cannot be simply dissolved. Moreover, with stronger materials like metals, the support removal effort increases dramatically over polymer. In this research, a geometric analysis method is proposed in order to optimize the build orientation for AM processes to facilitate support structure removal.

3. Methods

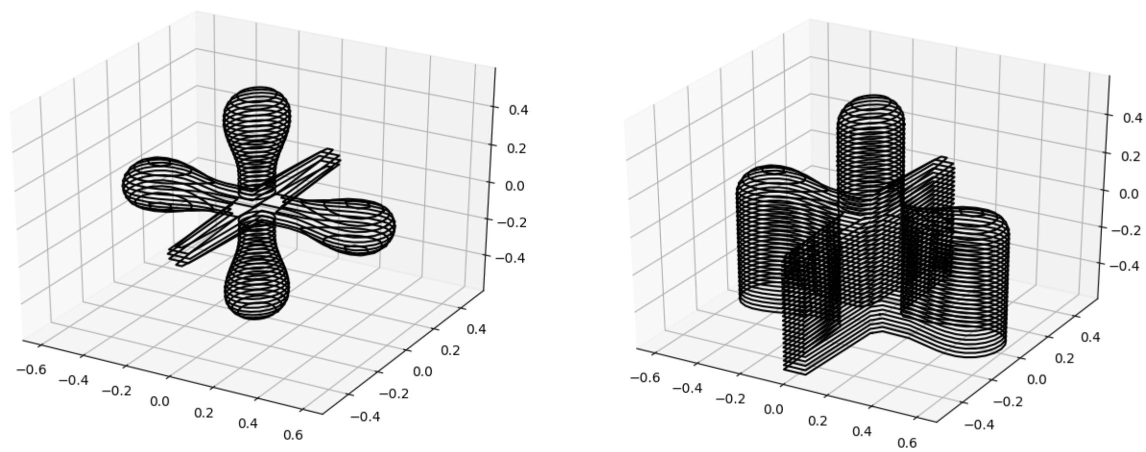
For an AM process, the building orientation determines which surfaces the support structures need to be grown on. In this work, considering the removability of the support structure geometry is essentially considering tool accessibility of the surface that the support structure is grown on. For example, a surface that has low tool accessibility will need a small diameter tool to access the surface, making it less desirable to have supports attached. Tool accessibility is calculated for each facet, and the optimal AM building orientation for support structure removal is calculated based on the tool accessibility. In this research, a STereoLithography(STL) file is used as input data to represent the part geometry, the AM processes considered are SLM and EBM, and 0post processing is assumed to be via CNC milling.

3.1 Tool Accessibility Calculation

The tool diameter in a milling operation affects the machining time and cost. The larger the diameter of the tool used, the shorter the machining time tends to be (Chang & Wysk 1997; Yang & Han 1999). In CNC milling, the tool *accessibility* of a part describes if the surfaces of the part can be machined with the available tools. More specifically, accessibility of a part can be envisioned as a mapping of the maximum diameter tool that can touch each surface of the part. The following sections will present how tool accessibility is calculated.

3.1.1 Tool access volume calculation

Tool accessibility can be calculated based on the selection of a set of tool approach orientations and tool diameters. Existing research used different geometry models for calculating the tool accessibility. Non-Uniform Rational B-Splines(NURBS) surfaces were utilized by Lee and Chang in their research to calculate global tool interference for its control polygon convex hull property (Lee & Chang 1995). Slice models were used in D'Souza's tool sequence selection research for approximating free-form pocket geometries(D'Souza et al. 2004). Voxel model based geometries were employed in Balabokhin and Tarbutton's research to represent part and tools (Balabokhin & Tarbutton 2017). In this research, the STereoLithography(STL) file is used as input for the part geometry for the convenience of calculation and convention in the AM field.



(a) (b)

Figure 1. Tool orientation consideration (a) Slice Model and (b) Effective Slice Model

For a facet on the part model, any other facets that are above the facet have the potential to interfere with its accessibility. The tool accessible bound (TAB) is a set of simple polygons on the same plane that bounds the non-accessible area for a tool; the outside of the TAB is accessible for the tool. In the method developed in this research, the model is first sliced along a given tool approach orientation to obtain the slice model (Figure 1a). Then, we accumulatively union each slice of the part from top to bottom to calculate the effective slice model (Figure 1b). By offsetting the effective slice by the tool radius and then offsetting it inward by the radius of the tool, the tool diameter can be taken into consideration (Yang & Han 1999; Lim & Corney 2000) to calculate the tool accessible bound. The effective tool accessible bound for the calculated tool radius is the area outside the red slice polygon of Figure 2.

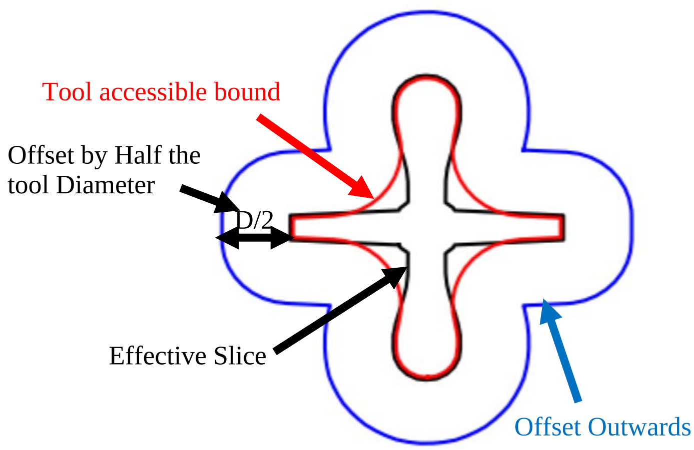
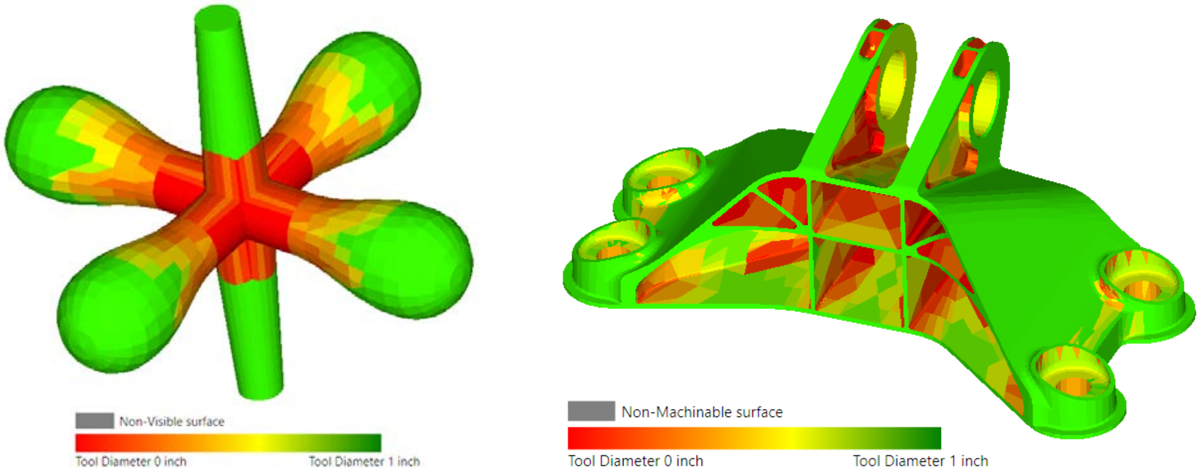


Figure 2. Tool diameter consideration Slice(Black), Offset Outwards(Blue), Tool Accessible Bound(Red)

3.1.2 Mapping tool accessibility to each facet

The tool accessible bound ($TAB_{z,d}$) is calculated for all sampled z-heights(z) and for all tool diameters(d) that are taken into consideration. The tool accessibility for each facet can be calculated by comparing the projection of the facet and the $TAB_{z,d}$. The tool accessibility mapping results for a toy Jack and GE engine bracket example are given in Figures 3a and b, respectively. These maps show a tool diameter range from 0 to 25.4 mm with an interval of 3.175 mm.

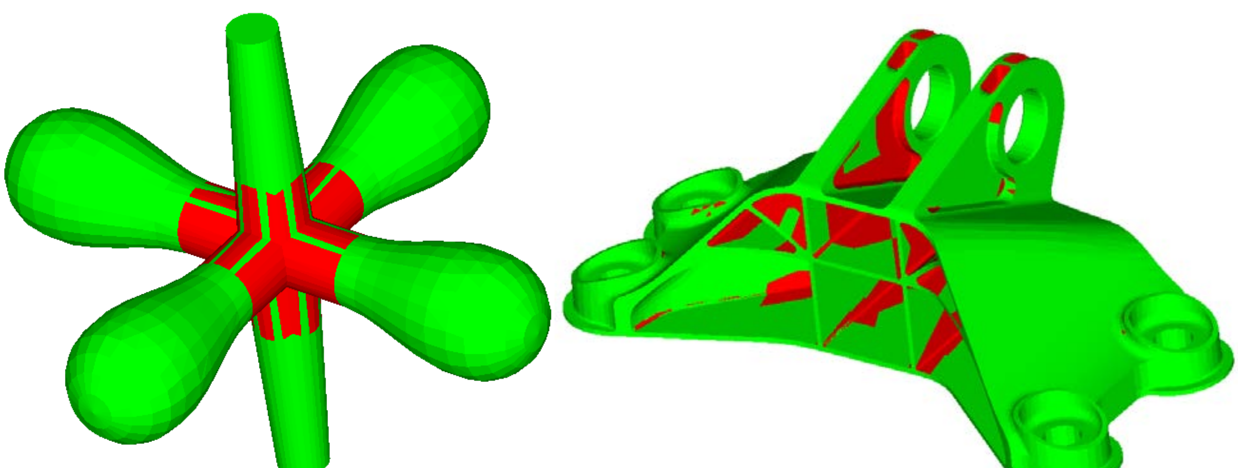


(a) (b)

Figure 3. Tool accessibility maps (a) Jack and (b) GE Engine Bracket

3.2 AM orientation optimization for support removal

For facets that require a tool diameter deemed too small, that diameter threshold can be set for a given part map. For example, when the threshold is set to be 6.35mm tool diameter, the tool accessibility map can be converted to a binary color map as shown in Figure 4 .



(a) (b)

Figure 4. Non-accessible map (6.35 mm tool diameter) (a) Jack and (b) GE Engine Bracket

an

The surface of a part can be categorized into three types; 1) surfaces that require support structures, 2) surfaces that act as the base for a support structure to grow on, and 3) surfaces that have no support structure contact. In this work, both type 1 and type 2 surfaces are considered equally. The criterion for determining which facets require support structures is the critical inclination angle. For a facet, if the angle between the surface normal and gravity direction is smaller than a presumed critical angle, then it is considered needing support (Allen 1994).

The surfaces that will have support structures grown on change when the build orientation changes. In this work, the objective of optimizing the AM build orientation is to minimize the surface area of those regions that both need support AND are deemed non-accessible.

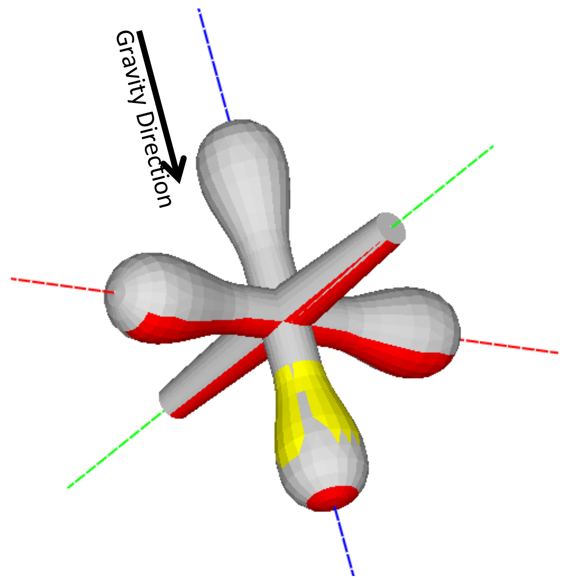


Figure 5. Type 1 surface (red), Type 2 surface (yellow), Type 3 surface (grey)

$$Minimize: OverlapArea(\theta) = \sum_{i=1}^{n} Area(facet_i) \cdot \alpha_i \cdot \beta_i$$

Where:

$\boldsymbol{\theta}$: *AM build orientation*
$\boldsymbol{i}$: *facet index*
$\boldsymbol{\alpha_i}$: *A binary indicator for tool accessibility, set to* 1 *if the facet is not accessible,* 0 *if it is accessible*
$\boldsymbol{\beta_i}$: *A binary indicator for support structure, set to* 1 *if the facet has support structure,* 0 *if the facet has no support structure*

4. Results and Discussion

Two example parts are used to illustrate the method developed in this work. The bounding box of the Jack is $30.480 \times 30.480 \times 25.400\ mm$ and the GE Engine Bracket is $178.000 \times 62.500 \times 108.000\ mm$; as measured in X-0 orientation. The critical inclination angle used to calculate support-requiring surfaces was 39°, and a total of 18 build orientations were evaluated. The results for the Jack and GE Engine bracket are given in Tables 1 and 2, respectively.

Table1. Overlap areas for Jack model (red colored rows are redundant)

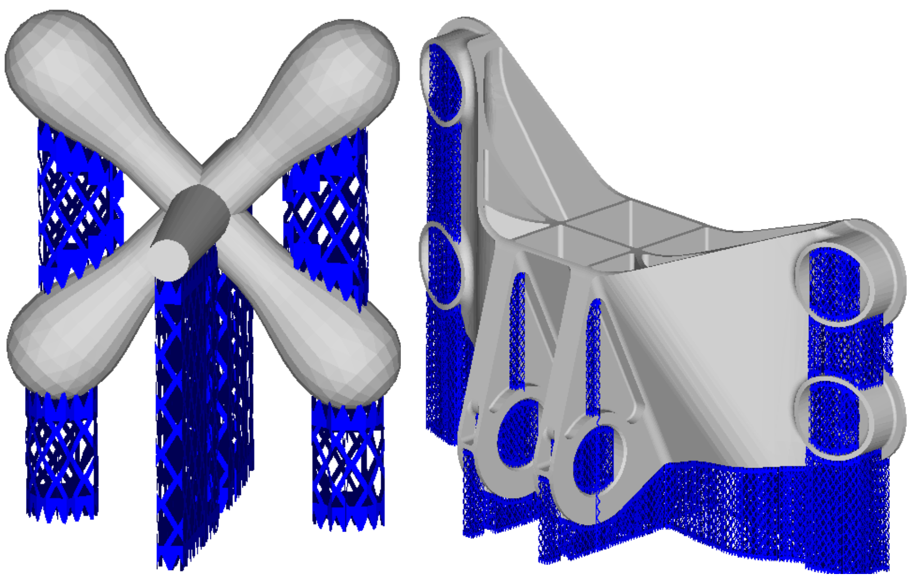
ORIENTATIONS	AREA(MM^2)	ORIENTATIONS	AREA(MM^2)
X-0	8.115	**y-180**	11.454
X-45	9.504	**y-225**	9.488
X-90	20.746	**y-270**	20.736
X-135	10.383	**y-315**	9.503
X-180	11.454	**z-0**	20.746
X-225	9.963	**z-45**	4.578

X-270	21.082	**z-90**	20.794
X-315	9.504	**z-135**	5.592
Y-0	8.115	**z-180**	21.082
Y-45	9.507	**z-225**	4.874
Y-90	20.794	**z-270**	20.736
Y-135	9.316	**z-315**	5.596

Table2. Overlap areas for GE Engine Bracket model (red colored rows are redundant)

ORIENTATIONS	AREA(MM^2)	ORIENTATIONS	AREA(MM^2)
X-0	1229.069	**y-180**	2215.912
X-45	2861.059	**y-225**	3608.825
X-90	8047.597	**y-270**	8624.499
X-135	5422.118	**y-315**	2504.137
X-180	2215.912	**z-0**	8047.597
X-225	2344.834	**z-45**	6552.568
X-270	8648.692	**z-90**	7625.146
X-315	1402.075	**z-135**	4887.713
Y-0	1229.069	**z-180**	8648.692
Y-45	2208.854	**z-225**	4996.274
Y-90	7625.146	**z-270**	8624.499
Y-135	4082.334	**z-315**	6735.083

Across the 18 tested build orientations, the optimal orientation to facilitate support removal for the Jack is a rotation about the Z axis of 45° (with a minimum overlap area of 4.578 mm^2) and for the GE bracket, a rotation about the X axis of 0° (with a minimum overlap area of 1291.268 mm^2). The two parts in the suggested building orientations are shown in Figures 6.



(a) (b)

Figure 6. Optimized build orientation (a) Jack and (b) GE Engine Bracket

Finally, an additional v-block part example is tested to demonstrate how the proposed tool accessibility criterion can be considered as compared to other build criterion, namely, for minimizing build height OR for minimizing overall support structure volume. For this example, the best case (Case 1) for minimizing overall support volume is shown in Figure 7. However, if minimizing z-height has the highest priority, the part could be given either of the two orientations in Figure 8. Data for all 3 cases are given in Table 3. In all cases, minimum inclination angle was 39 degrees and the part bottom was set to 3mm above the build plate for calculating the support volume.

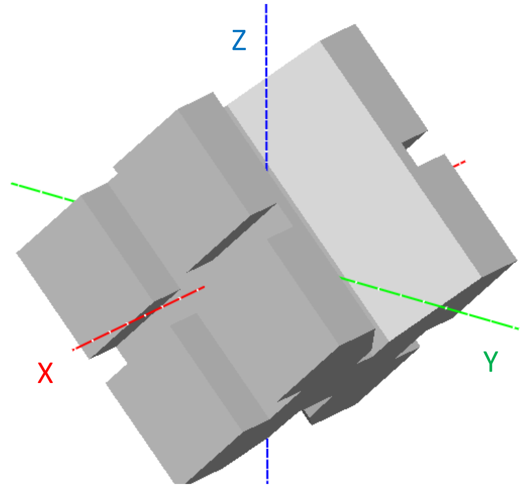


Figure 7. Best case for minimum support volume (Case 1)

For Case 1, since there is no support, it will also be optimum for the tool accessibility for support removal criterion; making the proposed accessibility calculations moot. However, for the latter 2 cases, the proposed tool accessibility metric provides a clear choice of orientation 3 for tool accessibility, even though support structure volume for Case 2 is less (2590 mm^3 versus 4740mm^3). That is, assuming a minimum tool diameter of 6.35 mm, all the support structure in Case 3 can be removed, but Case 2 has a total of 1239.630 mm^2 non-accessible area. Regardless, the selection of build orientation is complex, and there is perhaps not a clear choice across all factors; however, the proposed method provides yet another criterion to factor into the decision.

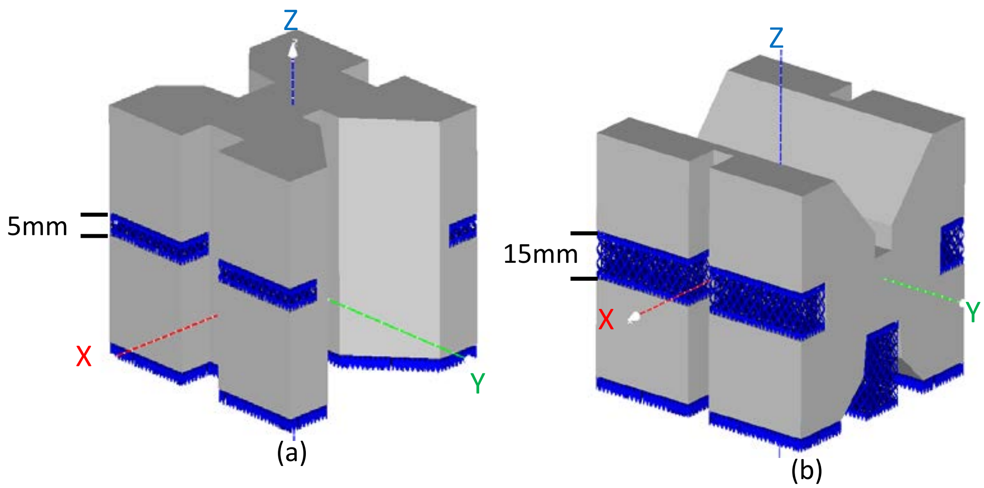


Figure 8. Two possible orientations with Z-height as priority

(a)Case 2 and (b) Case 3

Table3. AM building orientation selection comparison (red colored as optimum case)

DATA OF COMPARISON	CASE1	CASE2	CASE3
Z-HEIGHT(MM)	71.842	50.800	50.800
SUPPORT STRUCTURE VOLUME(MM^3)	0.000	2590.000	4740.000
OVERLAP AREA FOR TOOL ACCESSIBILITY(MM^2)	0.000	1239.630	0.000

In closure, the results calculated using the proposed method provides a new consideration to the idea of an *optimized* choice of build orientation. This method may offer a new perspective of designing for hybrid additive/subtractive manufacturing that allows for considering the challenging post-processing required for most metal AM technologies today. Future work will include improvements in the proposed accessibility calculations, more intelligent support planning, and formal integration of this new metric with existing build orientation criteria.

5. References

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