Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Expert survey to understand and optimize part orientation in direct metal laser sintering

Authors: David Hoelzle[1], Hao Peng[2], Morteza Ghasri-Khouzani[3], Shan Gong[3], Ross Attardo[4], Pierre Ostiguy[4], Bernice Aboud Gatrell[4], Joseph Budzinski[4], Charles Tomonto[4], Joel Neidig[5], M. Ravi Shankar[3], Richard Billo[6], David B. Go[2,7]

1. Dept. of Mechanical and Aerospace Engineering, The Ohio State University
2. Dept. of Aerospace and Mechanical Engineering, University of Notre Dame
3. Dept. of Industrial Engineering, University of Pittsburgh
4. Johnson & Johnson Co.
5. ITAMCO
6. Dept. of Computer Science, University of Notre Dame
7. Dept. of Chemical and Biomolecular Engineering, University of Notre Dame

Abstract:
The additive manufacturing (AM) process Direct Metal Laser Sintering (DMLS) uses a layer-by-layer workflow to build complex architecture metal structures in low-volumes. The primary process failure mechanism is a thermal stress driven thermal distortion that yields out-of-tolerance manufacture or complete process failure. However, DMLS design experts have developed heuristic rules to optimize the part orientation and support structure to reduce the likelihood of failure. We believe that experts innately attempt to minimize the design metrics of support volume (V), support-to-part surface area (A), maximal cross-sectional area of the slicing planes (X), parallelism of part faces with the recoater blade (P), and part height (H); however, it is unclear what relative weighting of each metric the expert uses. This manuscript details an interactive expert survey, the statistical analysis of the survey responses, and the synthesis of an automatic algorithm for part orientation based on survey data. We received responses from 18 experts and 151 total part orientation responses. The median survey respondent had greater than four years of DMLS experience. Our analysis shows that the expert attempts to minimize metric V the most, metric X the second most, and metric H the third most; experts put essentially no weight on metrics A and P. The manuscript concludes with two orientation design studies where the expert survey responses are used in a least squares minimization algorithm to automatically orient the part for DMLS manufacture. As a comparison set, novice users were instructed to orient the parts for best DMLS printing success without using the tool and required multiple attempts to successfully print the test parts. The automatically oriented parts failed on our first iteration of the code. The manuscript concludes with our proposed modifications to the code to improve results.

Keywords: additive manufacturing, DMLS, optimization, build orientation, support structure, heuristic learning, expert survey

1. Introduction

Direct metal laser sintering (DMLS) has been one of the primary success stories of the adoption of Additive Manufacturing (AM) tools into production cycles. DMLS uses a layer-by-layer build cycle in which at each layer (Figure 1): 1) a recoater blade spreads a thin layer (20 – 50 μm) of metal powder at the melt plane; 2) radiant energy is applied to the melt plane by a raster laser selectively melting a two-dimensional (2-D) pattern; and 3) the part is indexed downward to accommodate a new layer of material. In this manner, complex three-dimensional (3-D) parts can be made for relatively low cost in a low-volume production setting (1 – 1,000 units) [1]. This manufacturing modality has been used in a variety of high performance aerospace industries including GE aircraft engines [2] and the SpaceX rocket engine chamber. Analogously, the orthopedics industry requires high-performance materials with different performance metrics (material purity, biocompatibility, and wear resistance are paramount), and are carefully considering the transition from traditional manufacturing processes (investment casting) to AM to reduce the per part manufacturing cost associated with the labor intensity, materials validation, and patient specific needs of their manufacturing processes. Further, market pressures are driving orthopedic manufacturers to greater reliance on mass customization and batch production, where the advantages of AM over other processes are greatest.

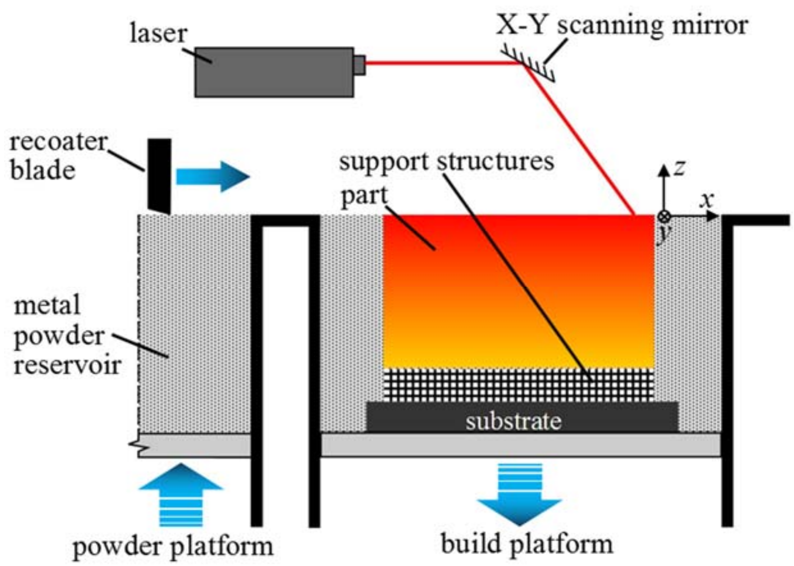


Figure 1. Schematic of the DMLS printing process.

AM manufacturing engineers utilize material supports to mechanically support overhanging features, but also, and perhaps more importantly, create sintered preferred conduction heat transfer paths to more efficiently purge heat from the recently sintered surface, so that cooling is more uniform across the build platform. Although necessary, any support material is inefficient as it requires longer build times, more material waste, and the need to remove the supports via fracture or machining in a post-process step [3]. Furthermore, support design is not a simple, binary (yes or no) decision as there are many competing design objectives that confound the rational decision on a ‘good’ design. For example, part orientation is a critical parameter that influences the amount of support needed [4]. Support structures span a range of design features [3], and some overhanging features have an aspect ratio such that a support structure has a non-appreciable benefit.

Clearly there is an economic design tradeoff between an excess of support material for efficient heat transfer and high-fidelity manufacturing and minimal support to reduce manufacturing costs. However, the design rules for support design are largely *ad hoc* and often require trial and error iteration, increasing development costs and materials and energy waste. Expert DMLS manufacturing engineers have an intuitive knowledge of the appropriate part orientation and shape, structure, and location of supports for heat spreading, but this innate knowledge is not easily disseminable at the rate at which DMLS, and AM in general, is expanding in market share. Furthermore, good design principles are not efficiently transferred to the novice and requires an experiential knowledge: experience is expensive as DMLS instruments cost over 500,000 USD and quality metallic powders cost over 120 USD per kilogram. Existing support design software packages such as Materialise Magics SG+™ (Magics™) have shown promise to automatically design support structures and will even optimize part orientation based on a user-selected levels of z-height, xy-axis projection, support surface, and maximum slice area. However, it is unclear what the correct levels should be.

In this manuscript, a method is detailed to codify the workpiece orientation problem in DMLS manufacturing design. Other design considerations, such as support design or operating parameter selection, although critically important, are outside the scope of this work. The orientation design space can be defined by three Euler angles $\mathbf{v} = \begin{bmatrix} \alpha & \beta & \gamma \end{bmatrix}$: $\alpha \in \left[-180^\circ, 180^\circ\right]$, $\beta \in \left[-180^\circ, 180^\circ\right]$, and $\gamma \in \left[-180^\circ, 180^\circ\right]$. There are an infinite number of possible orientations; from a manufacturing perspective, each orientation will have an associated quality (e.g. thermal distortion or surface roughness), requisite designed countermeasures (e.g. support locations and reinforcing members), and manufacturing cost. From discussions with expert DMLS practitioners and a survey of the literature, it was determined that proper orientation design is a weighted minimization of the following metrics:

- Support Volume, $V(\mathbf{v})$: Supports are necessary to improve quality; however, excess support volume wastes material and machine time.
- Part-to-Support Surface Area, $S(\mathbf{v})$: Overhanging part regions in contact with the support will have a more efficient thermal path to purge melt pool heat; however, increasing the surface area increases the support removal cost.
- Maximum Slice Cross-Sectional Area, $X(\mathbf{v})$: Melting induced shrinkage creates a contractile strain in a given layer. The larger the cross-sectional area, the larger the gross deformation; hence, there are advantages to designing orientations such that $X(\mathbf{v})$ is small.
- Parallelism with Recoater, $P(\mathbf{v})$: Experts have defined a heuristic that major faces of the part should not be within 10° of parallel with the recoater blade as the blade incrementally deforms the part during each recoat step if the part-blade contact interface is large.

- Part Height, $H(\mathbf{v})$: An orientation that results in a larger part height requires more layers, hence longer build times and more powder use.

However, depending on the part, the different metrics can be antagonistic; for example, decreasing $V(\mathbf{v})$ may increase $H(\mathbf{v})$. Thus, the definition of the respective weighting vector, $w = [w_1, w_2, w_3, w_4, w_5]$, of a single weighted objective function,

$$J = xw \qquad (1)$$

where $x = [V, S, X, P, H]^T$, is not obvious. In this work, a survey of DMLS experts and corresponding method to interpret survey responses is described. Once an estimate of the weighting vector, $\hat{w}$, is found, the optimization algorithm in Eqn. 1.2 can be applied.

$$\min_{\mathbf{v}} \hat{J} = x\hat{w} \qquad (2)$$

where $\hat{J} = \hat{W}x$ is an estimated cost. This manuscript describes an expert survey to find and then apply the appropriate weightings, $\hat{w}$. The general method uses the workflow diagrammed in Figure 2, the main methods will be detailed in Section 2. The survey results and application to two different test artifacts is given in Section 3. The paper concludes with a discussion on why the first iteration of the optimization based on the survey data failed and how this algorithm could be improved in the future (Section 4).

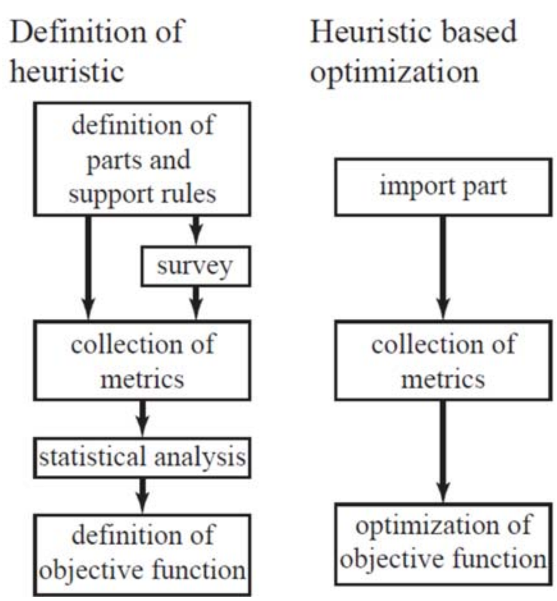


Figure 2. Overview of the heuristic based orientation optimization.

2. Methods

The method for defining a heuristics-based orientation optimization algorithm is divided into two parts (Figure 2): the definition of a heuristic by survey administration and processing and the application of the optimization algorithm using the defined heuristic.

2.1. Preliminaries

In general, the digital file that represents a given part is given by a .stl file, which represents the part as a surface composed of triangular facets. In simplest form, the .stl file is a list of facet parameters; each facet is parameterized by the unit vector normal to the facet and the facet vertices (Figure 3a). For an N facet .stl file, there are two important matrices, $\mathbf{V} \in \mathbb{R}^{3N \times 3}$ and $\mathbf{N} \in \mathbb{R}^{N \times 3}$, which are composed as follows:

$$\mathbf{V} = \begin{bmatrix} v_{i,1_x} & v_{i,1_y} & v_{i,1_z} \\ v_{i,2_x} & v_{i,2_y} & v_{i,2_z} \\ v_{i,3_x} & v_{i,3_y} & v_{i,3_z} \\ \vdots & \vdots & \vdots \end{bmatrix}; \ \mathbf{N} = \begin{bmatrix} n_{i_x} & n_{i_y} & n_{i_z} \\ \vdots & \vdots & \vdots \end{bmatrix}. \tag{3}$$

A given .stl file is rotated via a mathematical mapping operation on the matrices $\mathbf{V}$ and $\mathbf{N}$. Here the convention is used of rotating around intrinsic axes in the sequence x, y', z'', although other equivalent rotation conventions exist (Fig. Figure 3b): matrices $\mathbf{V}$ and $\mathbf{N}$ are post-multiplied by the matrix $R(\alpha,\beta,\gamma) = R_z(\gamma) R_y(\beta) R_x(\alpha)$ where

$$\begin{aligned} R_x(\alpha) &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \\ R_y(\beta) &= \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \\ R_z(\gamma) &= \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{4}$$

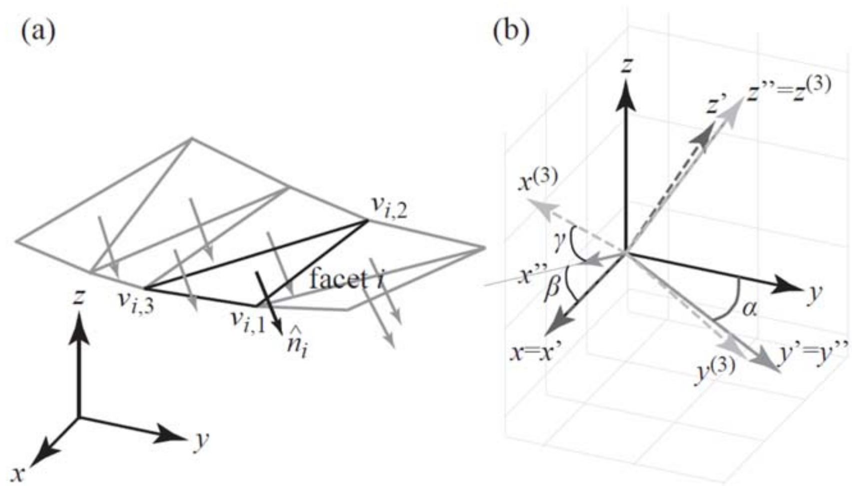


Figure 3. .stl **file conventions and manipulations.** (a) Standard triangular facet part representation by an .stl file. (b) Intrinsic $x - y' - z''$ angle convention for solid body rotation.

Conventionally, a facet has support material beneath it is determined by the angle between the normal vectors of the facet and a unit vector normal to the build plane, $\{0,0,1\}$.

2.2. Definition of Heuristic

Survey Design

To best understand how expert DMLS designers orient a workpiece, an interactive survey was administered. Input was solicited from July 15 2016 through January 3 2017, from individuals with expertise in AM, in general, by contacting members of the America Makes membership, colleagues with AM expertise, and using the professional surveying service Maven. The survey participants provided answers via a web portal written in Java that was divided into two parts: participant information collection and interactive part orientation.

Participant information collection. Participants provided key information on their background and expertise through a set of questions (Table 1). The questions are designed to help us understand the distribution in expertise level of the participant and what are the differences in orientation design between an expert DMLS engineer and a novice DMLS engineer, defined by greater than three years and less than three years of experience, respectively.

Table 1. Survey questions for self-identification of expertise.

Question Number	Question	Response Options
Q1	Name	Free Response
Q2	Position Title	Free Response
Q3	Company / Institution Name	Free Response

Q4	Type of Company / Institution	Choose One: A) Industry: Engineering Design or R&D; B) Industry: Manufacturing; C) Industry: Consulting; D) National Laboratory; E) National Agency;F) Academia; G) Other (if selected, open box for free response)
Q5	Years of experience with 3D Printing / Additive Manufacturing	Choose One: A) 0 years; B) 1 – 3 years; C) 4 – 6 years; D) >6 years
Q6	Which processes do you have experience with?	Choose all that apply: A) Powder Bed Fusion (Direct Metal Laser Sintering, Selective Laser Melting, Electron Beam Melting, Selective Laser Sintering); B) Directed Energy Deposition (Laser Metal Deposition, Wire Welding); C) Material Extrusion (Fused Deposition Modeling, Room Temperature Microextrusion); D) Vat Photopolymerization (Stereolithography, Digital Light Processing); Binder Jetting; Material Jetting (Polyjet); Sheet Lamination (Laminated Object Manufacturing, Ultrasonic Consolidation); Other (open free response box if selected)
Q7	How many years of experience do you have with Direct Metal Laser Sintering (DMLS)	Choose One : A) 0 years, B) 1 – 3 years, C) 4 – 6 year, D) >6 year
Q8	What percentage of your job responsibilities include setting up DMLS builds, part design for manufacturability with DMLS, DMLS post-processing, and DMLS post-process metrology?	Choose One: A) 0 – 10%, B) 11 – 20%, C) 21 – 50%, D) >51%
Q9	What material do you use most regularly with DMLS?	Choose One: A) Titanium alloys, B) Stainless Steel alloys, C) Aluminum alloys, D) Tool Steels, E) Super alloys (e.g. Inconel), F) Refractory alloys (e.g. CoCr alloys), G) Other (open free answer box if checked)

Part orientation survey. The part orientation interface of the survey was designed to resemble a standard computer aided design (CAD) software package. The user can see a 3D rendering of the part, a visualization of the support structure, the build plane, and the recoater blade direction (Figure 4). Users are prompted to "orient the part for best manufacturability by the DMLS process," and provided details on the interface; additionally, users are asked to consider that the material is the material specified in Q8 if they were able to answer Q8 and aluminum if they were unable to answer Q8. The support structure is automatically generated using a standard heuristic that a facet should be supported if the angle of the facet is < 35° and if the facet lies in the bottom 5% of the part.

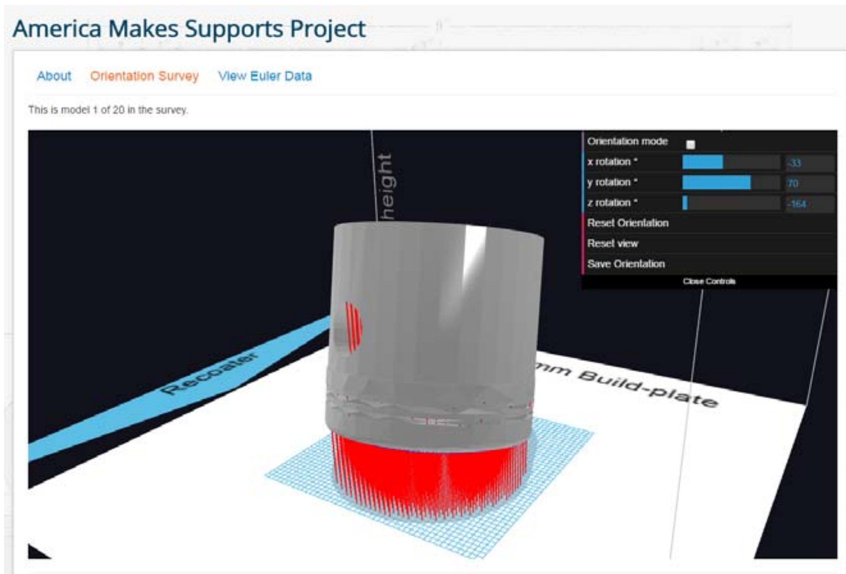


Figure 4. Screen shot of the interactive survey demonstrating a case part (gray), support structure (red lines), build plate size (white plane), and recoater blade direction (blue triangle).

The survey has a catalog of 20 parts, which were compiled from sample parts from the aerospace, automotive, orthopedic industries, and a few miscellaneous parts. In composite, the set includes a variety of features: both flat and contoured surfaces, large and small parts, and small and large holes.

<u>Data Collection and Extraction of Metrics.</u>

All data is logged by the survey software. Each survey respondent has provided an orientation set $\mathbf{v}$, each will have a corresponding set of metrics (e.g. $V(\mathbf{v})$) which are calculated by using the .stl. processor detailed in our previous manuscripts [5]. Each metric then has to be normalized to account for the large difference in part size and form factor of all possible parts. The normalization is computed by the following

$$\hat{V}(\mathbf{v}) = \frac{V(\mathbf{v}) - V_{\min}}{V_{\max} - V_{\min}}$$
$$\hat{A}(\mathbf{v}) = \frac{A(\mathbf{v}) - A_{\min}}{A_{\max} - A_{\min}}$$
$$\hat{X}(\mathbf{v}) = \frac{X(\mathbf{v}) - X_{\min}}{X_{\max} - X_{\min}} \quad (5)$$
$$\hat{P}(\mathbf{v}) = \frac{P(\mathbf{v}) - P_{\min}}{P_{\max} - P_{\min}}$$
$$\hat{H}(\mathbf{v}) = \frac{H(\mathbf{v}) - H_{\min}}{H_{\max} - H_{\min}}$$

where each minimum and maximum metric is computed via an optimization algorithm that searches for the maximum and minimum metrics by searching through the set of all possible angles $\mathbf{v}$ and computes the metrics at each angle. The optimization uses the dividing rectangles (DIRECT) algorithm to sample the design space and then converge to the optimal solution, which is defined as the minimal or maximal metric. Thus, the DIRECT method has to be run ten times for each part in the library of survey parts to generate all ten maximums and minimums of the metrics.

Cost Function Design.

Ultimately, all this data should be used to get a sense of what a DMLS designer weights when designing an orientation. The goal was to determine the objective function that is in the head of the designer. To do this, a constrained least squares estimator was used to extract objective function metrics from the data.

$$\min_{\hat{w}} \left\| \hat{X}\hat{w} \right\|_2$$
$$\text{subject to} \quad (6)$$
$$\left\| \hat{w} \right\|_1 = 1 \text{ and } \hat{w} > 0$$

Where $\hat{X}$ is the matrix of orientation data from the N responses organized by metric type

$$\hat{X} = \begin{bmatrix} \hat{V}_1 & \hat{A}_1 & \hat{X}_1 & \hat{P}_1 & \hat{H}_1 \\ \hat{V}_2 & \hat{A}_2 & \hat{X}_2 & \hat{P}_2 & \hat{H}_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \hat{V}_N & \hat{A}_N & \hat{X}_N & \hat{P}_N & \hat{H}_N \end{bmatrix}. \quad (7)$$

$\hat{w}$ is a column vector of the unknown weightings on each metric type. In words, Eqn. (6) states "find the set of unknown weights $\hat{w}$ that minimizes the product of the data and the weights, but subject two constraints: the weights must be positive and they must sum up to 1." The requirement that the weights must sum up to 1 prevents the answer from being $\hat{w} = 0$. This constrained least squares estimator was implemented using the Matlab function fmincon.

2.3. Heuristic Based Optimization.

Optimization.

$\hat{w}$ can now be used to optimally orient any new part. First, a part is imported. Second, minimal and maximal values are found for metrics $\hat{V}, \hat{A}, \hat{X}, \hat{P}, \hat{H}$. Third, the objective function is minimized.

$$\min_{\alpha,\beta,\gamma} \hat{x}(\alpha,\beta,\gamma)\hat{w} \qquad (8)$$

where $\hat{x}(\alpha,\beta,\gamma)$ is a vector for the normalized metrics $\hat{V}, \hat{A}, \hat{X}, \hat{P}, \hat{H}$ for Euler angles α,β,γ. This yields angles α,β,γ for printing. This algorithm was applied to two parts: the rectangular bar and the handle. Optimization of (8) was done by making use of the Direct Method heuristic optimization algorithm. DIRECT optimization algorithm is one type of derivative-free algorithm first introduced in [6], which is capable of solving difficult global optimization problems with bound constraints and real-valued objective function. The history and development of DIRECT method is discussed in [7]. The name DIRECT is short for "DIviding RECTangles" because the DIRECT algorithm keeps dividing the current domain into new hyper-rectangles and identifying potentially optimal hyper-rectangles from the new hyper-rectangles. Figure 5 shows the first three iterations of the DIRECT algorithm [8]. At the beginning of the first iteration, or initialization of the algorithm the search domain is divided along all dimensions. Note that the division starts with the dimension with the best function value so that the best function value is left in the largest space. Then the potentially optimal hyper-rectangles are found by applying the lemmas developed from the Lipschitzian optimization [8]. Next, the potentially optimal hyper-rectangles are divided along the longest dimension. If the lengths along all dimension are the same, the optimal hyper-rectangles are divided along all dimensions, starting with the dimension with the best function value, as what was done in the initialization. The optimization algorithm keeps finding new potentially optimal hyper-rectangles and dividing those hyper-rectangles until the maximum number of divisions is reached.

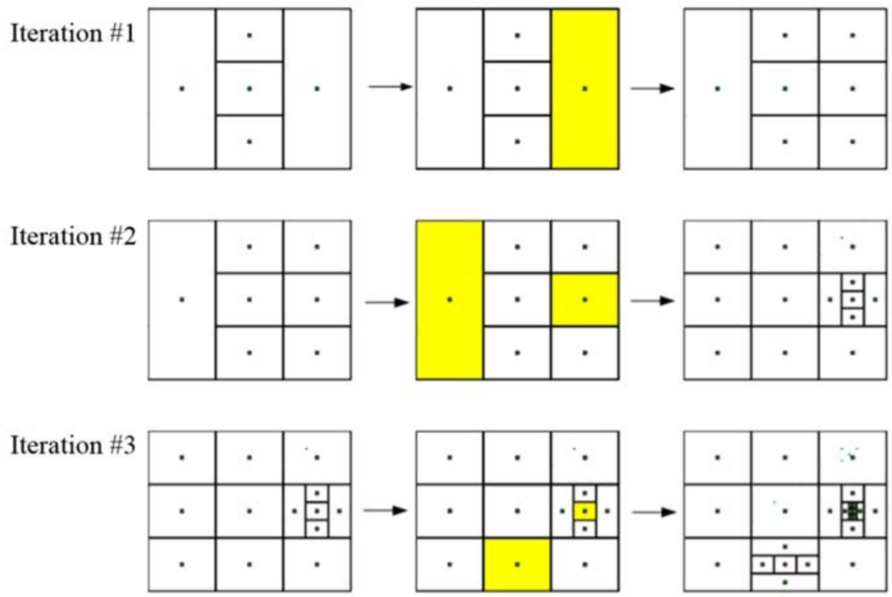


Figure 5. The schematic of the initial three iterations of the DIRECT optimization algorithm (Image has been copied from [8]**).**

Case Study Evaluation

A Case Study was done to validate the effectiveness of the optimization based on an expert survey. The study was comprised of two parts, a 10 x 10 x 150 mm rectangular bar (Figure 6a) and a contoured handle (Figure 6b) with a bounding box of 59 x 16 x 162 mm. The bar was selected because it was a simple structure with linear features, while the contoured handle represented a complex structure with contoured features.

The intent of the case study was to compare the build setup as performed by two novice operators (a baseline condition) to that of the expert survey based orientation optimization. Parts were printed with 316L at 20 µm layer thickness on an EOS M290™ machine using the EOS provided parameter set. The success metrics are 1) Number of Attempts and 2) Maximum Distortion. Distortion measurements were made with a coordinate measuring machine (CMM) both on- and off- the build plate. Removal of parts from the build plate was done through wire electrical discharge machining.

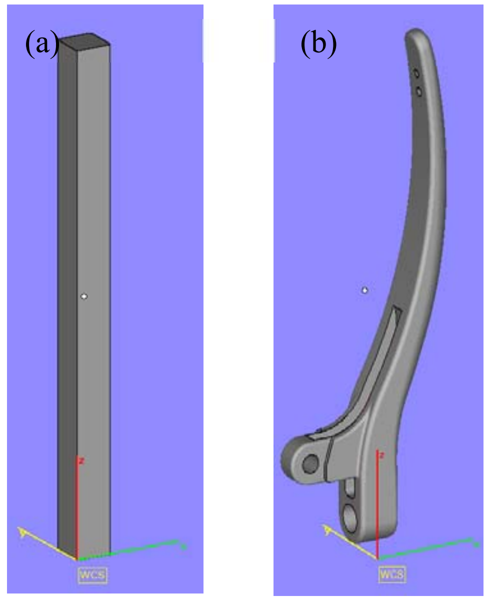


Figure 6. Case Study parts. a) rectangular bar; b) contoured handle.

<u>Baseline Conditions</u>

In the baseline condition, two novice operators were used at Johnson & Johnson for the build set up utilizing their limited knowledge of the process. Operator 1 was a technician with one year of machine operation experience, but limited build preparation experience. Operator 2 was a high school intern with a month of polymer additive manufacturing experience and no metal additive manufacturing experience. Each operator was given basic instruction on Magics™, similar to that provided by EOS in their machine basic training curriculum.

Each operator was given the .stl files with parts orientated as depicted in Figure 6 and the default Johnson & Johnson Magics™ support structure parameters. Each individual was instructed to orientate the part and modify support structure as needed for successful printing, as defined by no part-support delamination through visual inspection. The operators were blind to the other's attempts.

3. Results

3.1. Expert Survey-based optimization results

There were 18 respondents and a total of 151 different part orientations completed for an average of 8.4 orientations per respondent. The respondents spanned industry, national labs and agencies, and academia. The histograms in Figure 7 demonstrate the experience level corresponding to each orientation response.

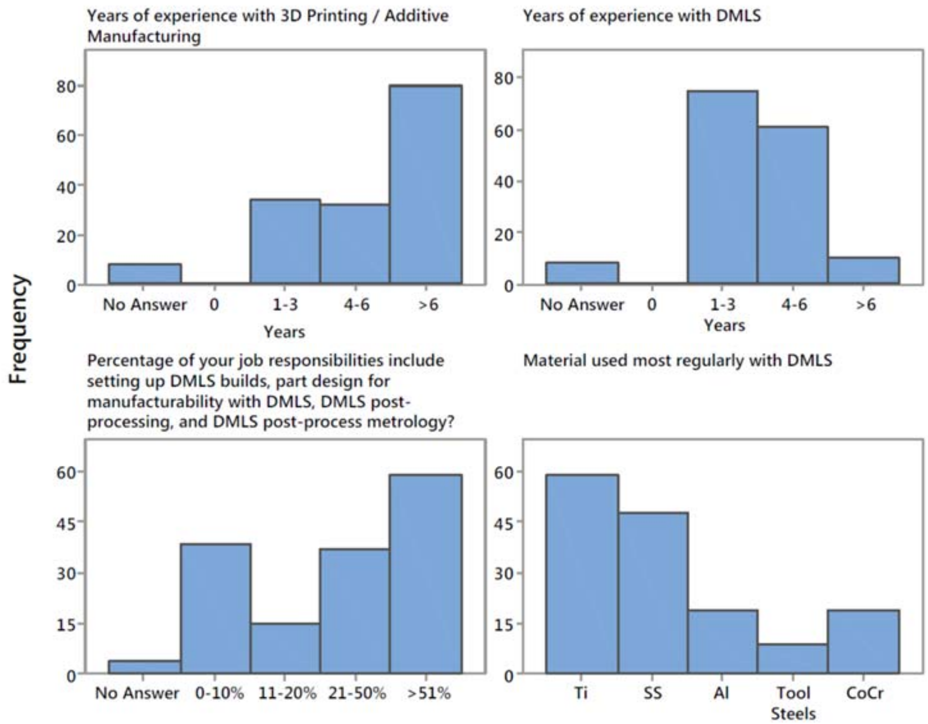


Figure 7. Experience level of the respondents. The frequency is the number of orientations for each experience level. As some respondents provided more orientations than others, I decided to present the experience tied to each orientation.

Figure 8 is a boxplot of the metrics for all responses. In general, respondents ensure that their orientations led to smaller support volumes (V), maximal cross-sectional area of a plane (X), and parallelism of faces with recoater blade. Respondents did not minimize the support-to-part surface area (A) and part height (H).

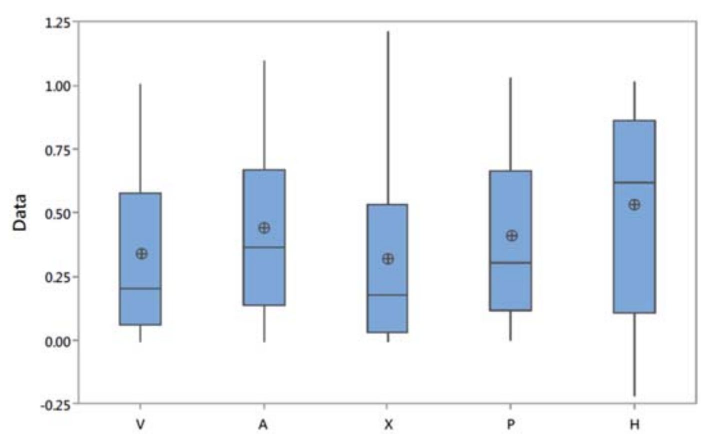


Figure 8. Box plot of the orientation design metrics of all responses (N = 151).

There are some reasonably interesting trends observed by breaking the orientation design metrics down by experience level (Figure 9). However, one should be careful to draw too much insight from the trends as the main effects of the different experience categories do not have a statistically significant effect on the metrics (all $p > 0.05$). In general, the more experiences DMLS practitioner allows a larger support volume and height, but penalizes the maximal cross sectional area of a plane. Trends are even less noticeable for level of DMLS duty cycle in one's job (Figure 10) or primary material used (Figure 11).

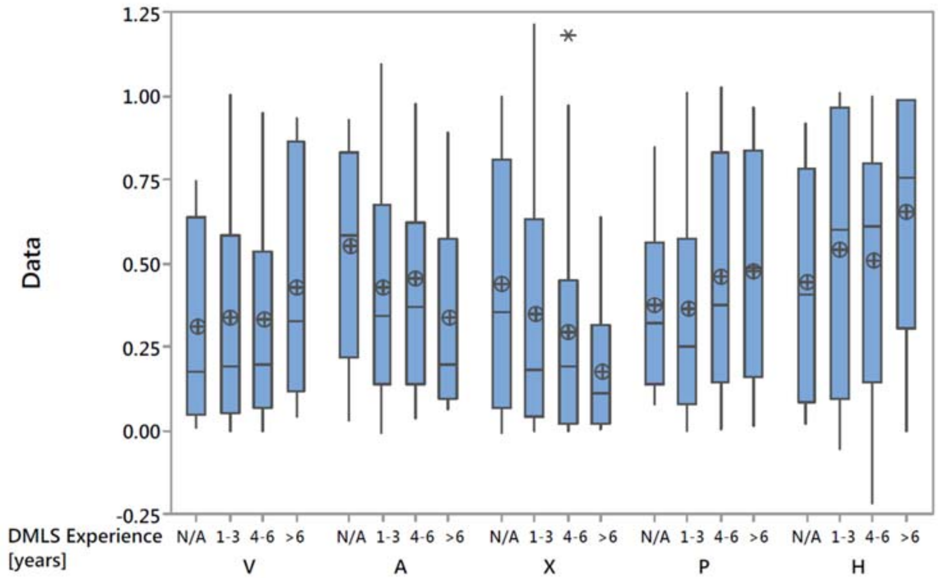


Figure 9. Box plot of metrics separated by DMLS experience level. All differences are not statistically significant.

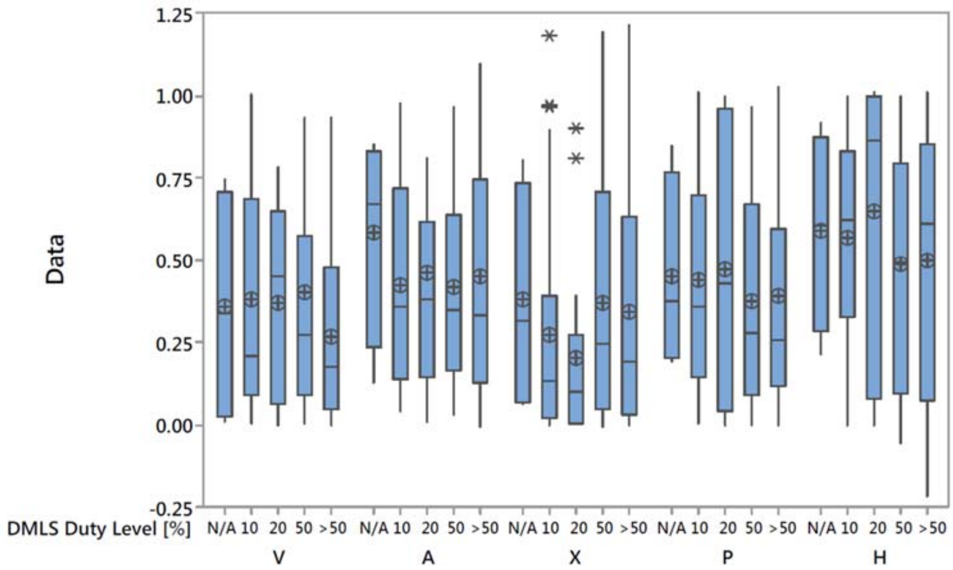


Figure 10. Box plot of metrics separated by DMLS Duty Level. All differences are not statistically significant.

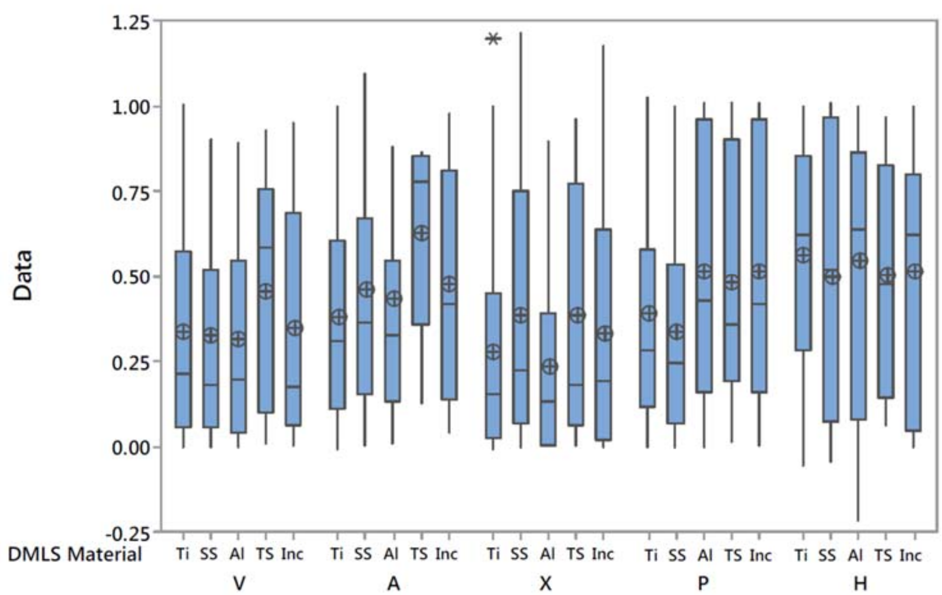


Figure 11. Box plot of metrics separated by DMLS Material used. All differences are not statistically significant.

This constrained least squares estimator from Eqn. (6) was implemented using the matlab function fmincon. The result is the following weights on V, A, X, P, H, respectively.

$$\hat{w} = \begin{bmatrix} 0.5232 & 0 & 0.3571 & 0 & 0.1197 \end{bmatrix}^T \quad (9)$$

What this result ultimately says is that the respondents weighted (penalized) support volume the highest, maximal cross-sectional area the second highest, and part height the 3rd highest. The respondents put essentially no weight on the part-to-support surface area and parallelism with the recoater blade. Comparing weights (9) to Figure 8, you may think there is an error because the respondents did not keep the part height to be small. The team is still investigating this further, but this result should be correct, and may have to do with a correlation between V and A, a random nature of P, and an influence, but lack of correlation with other metrics, for H.

Heuristics based optimization: $\hat{w}$ can now be used to optimally orient any new part. First, a part is imported. Second, minimal and maximal values are found for metrics V, A, X, P, and H. Third, the objective function (8) is evaluated, yielding angles α, β, γ for printing. The algorithm has been computation optimized to be very fast. The bar computes in 3 min and the handle computes in 3 hours, both on a 10 core cluster. Part orientations and support structures are provided in Figure 12.

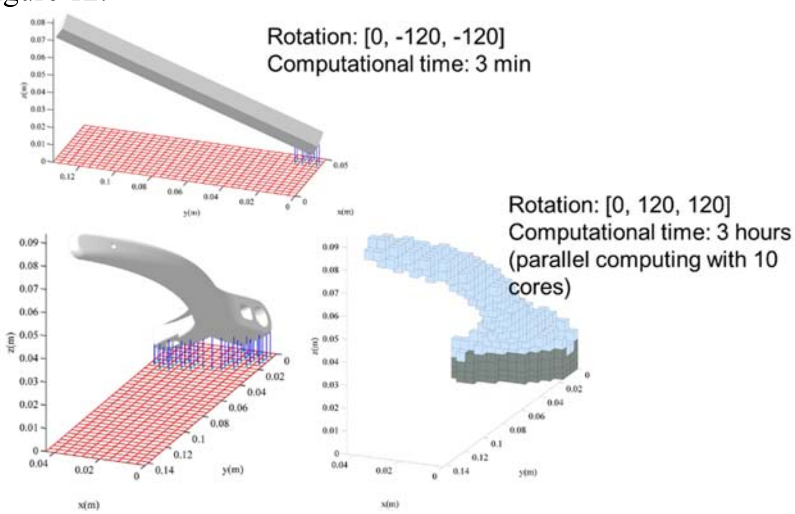


Figure 12. Optimal orientations and support structures using the survey-based heuristic optimization.

3.2. Novice Operators (Baseline Condition)

Table 2 - Table 5 represent each novice operator's attempt at the different parts in the baseline tests, with the highest attempt number being the successful print.

Bar	Support Modifications	Print Time	Setup	Result

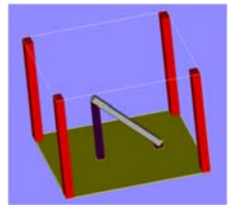
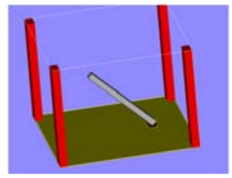
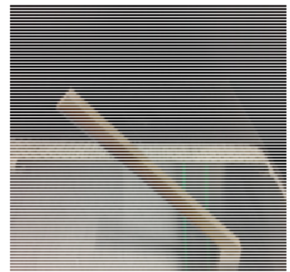
Attempt 1	N/A	23 hours 17 minutes		 Step in part at the location of different colors
Attempt 2	N/A	22 hours 48 minutes		 Successful print

Table 2. Operator 1 rectangular bar result per attempt

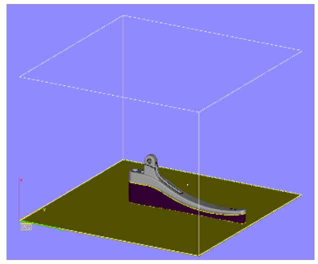
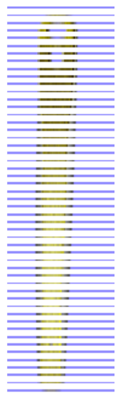
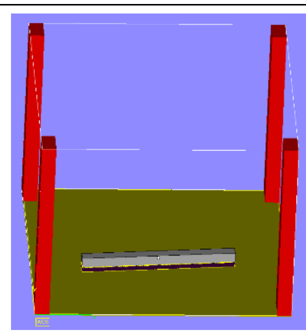
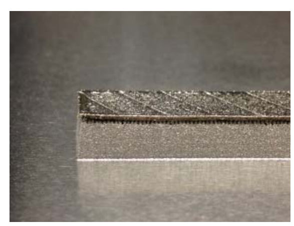
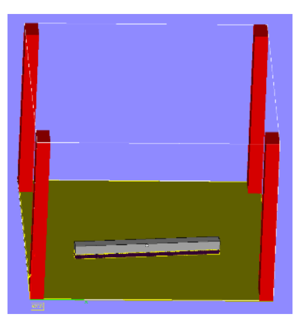
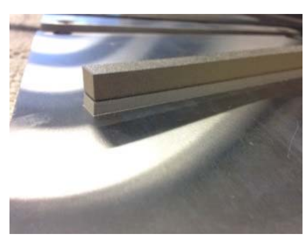
Handle	Support Modifications	Print Time	Setup	Result
Attempt 1	N/A	15 hours 49 minutes		 Edge delamination
Attempt 2	Hatching = 0.4 mm on far left side. Hatching = 0.8 mm on rest of part	16 hours 1 minute		 Successful Print

Table 3. Operator 1 contoured handle result per attempt

Bar	Support Modifications	Print Time	Setup	Result
Attempt 1	Hatching = 1.5 mm	Didn't complete		 Delamination and machine jam
Attempt 2	Hatching = 1.0 mm perforations = on	5 hours 21 minutes		 Edge delamination

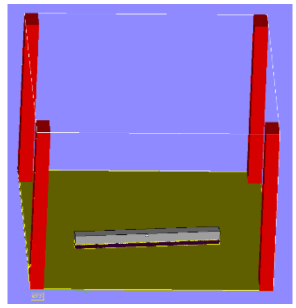
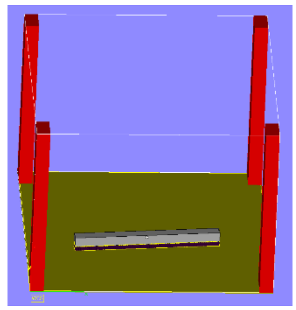
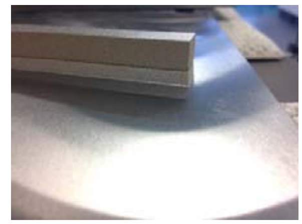
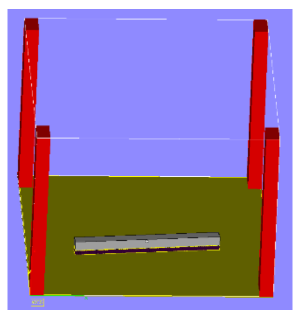
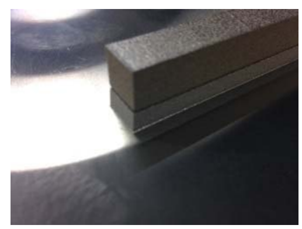
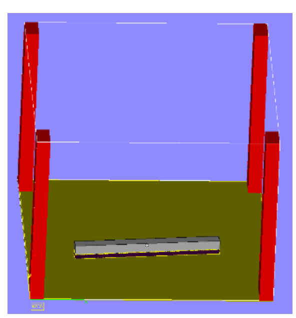
Attempt 3	Hatching = 0.5 mm, perforations = on	5 hours 30 minutes		 edge delamination
Attempt 4	Hatching = 0.5 mm, hatch teeth base length = 0.7 mm, border teeth breakpoint top addition = 0.35 mm	5 hours 30 minutes		 Edge delamination
Attempt 5	Hatching = 0.5 mm, hatch teeth top length = 0.3 mm, hatch teeth base length = 0.7 mm, border teeth breakpoint top addition = 0.35 mm	5 hours 30 minutes		 Edge delamination
Attempt 6	Hatch = 0.2 mm	6 hours 6 minutes		 Successful Print

Table 4. Operator 2 rectangular bar result per attempt

Handle	Support Modifications	Print Time	Setup	Result

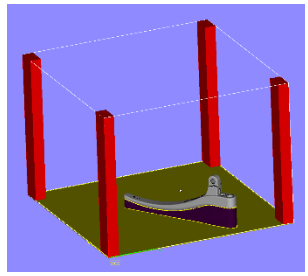
Attempt 1	Border Teeth top length = 0.35 mm Hatching teeth top length = 0.7 mm Hatching = 1.0 mm support angle = 45°	15 hours 40 minutes		Photo not available

Table 5. Operator 2 contoured handle result per attempt

As shown in Table 2 - Table 5, each operator used support structure modifications to get a successful print. Once an orientation was chosen, it was not changed for subsequent attempts. Of the two test parts, the bar was the only one to have a different orientation between the operators. Operator one decided on a 45° print angle while operator two decided on a horizontal print orientation. Operator one believed that the flat part geometry would cause the bar to bow from distortion. The support structure in Attempt 1 was placed at both ends, thinking it would anchor the bar in place. Upon seeing the result and the step in the part corresponding to the z-height of the support and part rejoining, operator one realized that the bowing would have already occurred before it reached this point and it wasn't necessary. Operator one's second attempt was to remove the tall support and leave just the base supported, resulting in a successful print.

Operator two, in an attempt to reduce build time, orientated the part horizontally and increased the support structure hatch distance. This part failed to print as the support structure was not strong enough to withstand the deformation of the bar and jammed the machine. In the subsequent attempts, operator two utilized increasingly stronger support structure by reducing hatch distance and increasing top teeth length. This resulted in more connection points between the part and support, and ultimately, a successful print.

Both operators chose the horizontal orientation for the handle and were able to apply the knowledge learned from the bar. Operator one's first attempt was using the default support structure and resulted in part delamination at the edge. The logic used on operator one's first bar attempt to prevent bowing and distortion was used on the second attempt of the handle and decreased the support hatch distance in the failed region. Again, this was an attempt to increase the connection points between the part and support, resulting in a successful attempt. Operator two utilized the same logic and increased the number of connection points between the part and support through support modification on their first attempt.

3.3. Expert survey based optimization

Table 6 illustrates the orientation recommendation from the expert survey based optimization. In the following sections of this report, these model recommended outputs were compared to the results achieved by the novice operators.

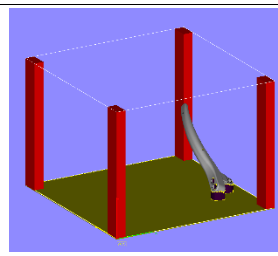
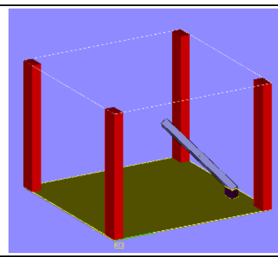
	Expert Survey Optimization		
	Print Time	Setup	Results
Handle	Didn't Complete		
Bar	Didn't Complete		

Table 6. TCN-QTM Optimization model and Survey Optimization model recommended orientation and supports location for contoured handle and rectangular bar.

The Expert Survey Optimization attempts on the handle and bar were both unsuccessful. In the case of the handle, the edge began to curl up causing a recoater arm jam. For the bar, the base support was not strong enough and failed during printing. Upon recoating, the part was pushed further down into the powder, with successive layers printing on a bed of powder instead of the bar. This led to the stair case appearance on the part and poor sintering, as seen in the photo of Table 6, before ultimately causing a recoater jam. The failure of both parts of the Expert Survey Optimization could also be attributed to the low print angles (<35°).

4. Discussion and Conclusions

Existing, commercial-grade support design software packages such as Magics™ have orientation design modules that use a weighting of different metrics (support area, height, etc.) to find an optimal orientation with respect to these weighted metrics. However, it is up to the user to determine the weighting on each metric and the weighting values are not intuitive, nor have proper weightings been reported on. To remedy this lack of knowledge, the team set out to survey experts in the field of DMLS to better understand how they orient parts for DMLS. The survey was very unique compared to a simple multiple choice survey; users interacted with a CAD-like environment to orient parts as they best saw fit for DMLS printing. As DMLS is a nascent field, there are a limited number of people from which meaningful input can be extracted. Despite this complication, the survey had eighteen participants with a total of 151 different part orientations completed and the respondents spanned industry, national labs and agencies, and academia. The analysis of the survey responses demonstrated that the DMLS researchers surveyed find orientations that maintain a small support volume, small maximal cross-sectional area of any given slice, and a small height in the z direction (see the weightings in Eqn. (9)). All three of these design objectives are intuitive. A small support volume leads to a shorter build time, less materials waste, and less support removal time. A small maximal cross-sectional area of a slice leads to less residual stress in the part from a smaller shrinkage in the x-y plane. A smaller height leads to less machine time because there will be fewer recoater blade passes. Interestingly, the survey respondents did not attempt to minimize the support-to-part surface area or the parallelism of slice edges with the recoater blade. Some users did comment that they did not think about the parallelism of the part edges with the recoater blade until they had made multiple submissions.

Although the team now has more information on how experts orient a part, they still failed to yield a favorable printing result with the optimization using a survey data based heuristic (Table 6). The rectangular bar and handle artifact prints failed at about mid build because the orientation algorithm selected an angle of the major axis of the part with in reference to the substrate that was too small. The team sees a single major issue why this may have happened. The .stl processor automatically generates support structures using the simple heuristic .stl. facets that have an angle between the facet normal and the substrate that is less than 35 deg should be supported. This is a common heuristic and used in many commercial software applications. However, this heuristic fails to account for edges in a part. Consider the simple part in Figure 13. The faces of the part are oriented such that the angle with the substrate is greater than 35 deg and hence should be unsupported. However, the line that makes the edge is less than 35 deg and should be supported. The team is currently working to fix this oversight in the code.

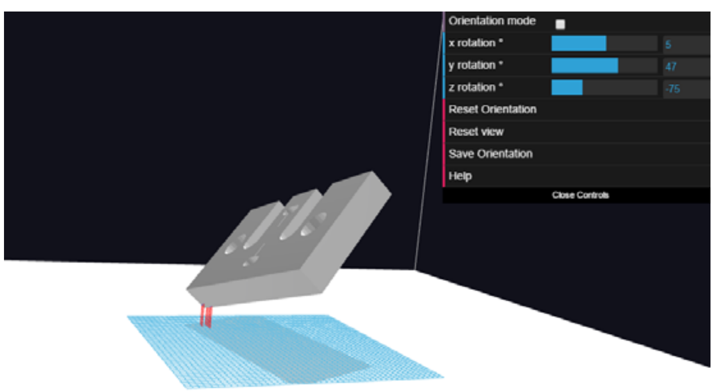


Figure 13. Example of fault in support design heuristic. The bottom edge of the part is less than 35 deg from parallel with the substrate and should be supported. However, the intersecting

faces that form the edge are both greater than 35 deg from parallel with the substrate, so the current heuristic will not support the faces.

5. Acknowledgements and Disclaimer

This material is based on research sponsored by Air Force Research Laboratory under agreement number FA8650-12-2-7230. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of Air Force Research Laboratory or the U.S. Government.

6. References

[1] W. Frazier, "Metal Additive Manufacturing: A Review," *J. of Materi Eng and Perform*, vol. 23, no. 6, pp. 1917–1928, Jun. 2014.

[2] "3D Printing in Aerospace - Revolution or Evolution? Overcoming Challenges for Wider Adoption," Frost & Sullivan, 9831–22, Apr. 2015.

[3] F. Calignano, "Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting," *Materials & Design*, vol. 64, pp. 203–213, Dec. 2014.

[4] S. Allen and D. Dutta, "On the computation of part orientation using support structures in layered manufacturing," in *Solid Freeform Fabrication Symposium*, Austin, TX, 1994.

[5] H. Peng, D. B. Go, R. Billo, S. Gong, M. R. Shankar, B. Aboud Gatrell, J. Budzinski, P. Ostiguy, R. Attardo, C. Tomonto, J. Neidig, and D. J. Hoelzle, "Part-scale model for fast prediction of thermal distortion in DMLS additive manufacturing; Part 1: a thermal circuit network model," in *2016 Annual International Solid Freeform Fabrication Symposium*, Austin, TX, 2016.

[6] D. R. Jones, C. D. Perttunen, and B. E. Stuckman, "Lipschitzian optimization without the Lipschitz constant," *Journal of Optimization Theory and Applications*, vol. 79, no. 1, pp. 157–181, 1993.

[7] R. M. Lewis, V. Torczon, and M. W. Trosset, "Direct search methods: then and now," *Journal of Computational and Applied Mathematics*, vol. 124, no. 1–2, pp. 191–207, January 12.

[8] D. E. Finkel, "DIRECT Optimization Algorithm User Guide," 2003.