Optimizing Part Quality with Orientation

David C. Thompson   Richard H. Crawford
Research Assistant   Assistant Professor
Department of Mechanical Engineering
The University of Texas at Austin
Austin, TX 78712

Abstract

The orientation of SFF-manufactured parts can have a significant effect on the quality of the parts, in both surface effects and strength. Currently, orientation is either ignored or set on the basis of experience. This paper takes some simple experiments and creates quantitative measures relating different aspects of part quality to orientation. This leads to several computational tools for optimizing the orientation of a part for manufacture with SLS or SALD on the basis of part strength, surface "aliasing" error, volumetric supports, and build time as an alternative to human experts.

Introduction

The implicit orientation (a part is designed in) can be a poor choice for manufacturing in a rapid prototyping system, since part quality varies significantly with the orientation of the part. In Selective Laser Sintering (SLS), where no supports are necessary, changes in quality are primarily due to build time, part strength, and rough surfaces due to the rasterization of faces at angles to the build direction. In Selective Area Laser Deposition (SALD), the main criterion is build time, which is significantly affected by the amount of volumetric support required. These measures of part quality should be used to find a suitable orientation. Tools have been created for processes that require area supports, e.g., [1].

The first step in optimizing each of the quality measures mentioned above is to find a way of computing the quality. The measures should be easy to calculate, so that the expense of computation time does not rival the expense of building the part. The amount of acceptable computation time will increase as layered manufacturing techniques are used in situations other than one-off prototyping.

Build Time without Supports

Because most layered manufacturing processes add material in one direction slower than others (i.e., the build direction), the build time can be minimized by finding the coordinate system where one bounding box dimension is a minimum. To find this coordinate system, the convex hull of the body must be constructed and searched for a set of parallel planes that completely enclose the hull with a minimum distance between the two.

It can be shown that, given a closed, convex surface composed of planar, polygonal faces, the set of planes which bound the object with a minimal distance between them must be coincident with either:

- a face and vertex from the convex hull of the body, or
- two parallel faces from the convex hull of the body, or
- two edges from the hull.

A simple way to visualize this is shown in Figure 1. The three situations listed above fully constrain or overconstrain the parallel planes so that rotating the object about any axis save the bounding plane normal increases the distance between the bounding planes. On the right is a situation when the planes are underconstrained and a rotation exists that allows the bounding planes to "move" closer together.

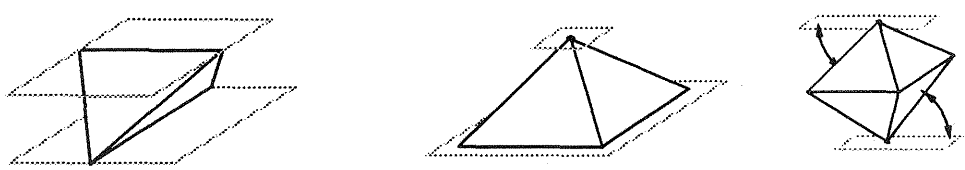


Figure 1: Visualization of minimum build time.

By stepping first through each face in the solid and then through each edge and comparing them to every vertex and edge, respectively, the minimum may be found. In fact, a list of the shortest distances and their corresponding principal axes is kept by the program that implements this search. These directions can be used to find trade-offs with other quality measures.

Strength

Most engineering materials are assumed to be isotropic, and this is usually a good assumption. However, parts made with solid freeform manufacturing techniques are often layered and thus orthotropic. Thus, given the intended loading condition and a stress analysis, a part can be oriented for manufacture to maximize the factor of safety. To do this, a model of material strength must be developed.

According to the maximum stress theory, a layered part will fail when any one of the maximum stresses (shear or normal) is exceeded. Thus, a part can fail from the normal strength of a layer being exceeded, from shear between layers, and from tranverse normal failure. However, this model does not allow for interactions between stresses and is difficult to code. A more accurate model is the Tsai-Wu interactive tensor polynomial model [2].

The Tsai-Wu model is a quadratic model of the failure surface. Through a series of simplifications, the strength of a laminated object can be represented in its local coordinate system as [5]:

$$\mathbf{F_{ij}} = \begin{bmatrix} \frac{1}{X^2} & -\frac{1}{2}\sqrt{\frac{1}{X^2Y^2}} & -\frac{1}{2}\sqrt{\frac{1}{Z^2X^2}} & 0 & 0 & 0 \\ & \frac{1}{Y^2} & -\frac{1}{2}\sqrt{\frac{1}{Y^2Z^2}} & 0 & 0 & 0 \\ & & \frac{1}{Z^2} & 0 & 0 & 0 \\ & & & \frac{1}{Q^2} & 0 & 0 \\ & & & & \frac{1}{R^2} & 0 \\ & & & & & \frac{1}{S^2} \end{bmatrix} \tag{1}$$

Then, for a given orientation, a change of basis must be applied to the stress tensor to move it into the coordinate system of the material. The test for failure is then a simple inequality:

$$\mathbf{F_i}\sigma_{\mathbf{i}}' + \mathbf{F_{ij}}\sigma_{\mathbf{i}}'\sigma_{\mathbf{j}}' \leq 1 \tag{2}$$

$$\mathbf{F_i T_{ik}}\sigma_{\mathbf{k}} + \mathbf{F_{ij} T_{ik}}\sigma_{\mathbf{k}}\mathbf{T_{jl}}\sigma_{\mathbf{l}} \leq 1, \tag{3}$$

where $\mathbf{T}$ is the transformation between local and global coordinates and σ is the stress tensor. This is incorporated into the optimization routine by checking candidate points for failure. Stresses must be known to the designer from some model analysis, such as a finite element simulation. By including maximum stress points from several loading conditions, a designer can determine whether the part will survive all of the intended loads.

Aliasing

A model has been developed that accurately describes the error generated by approximating a plane with a series of steps (shown in Figure 2), as found in layered manufacturing [6]. This has been shown to be a major contributor to surface roughness, and should be minimized. An equation that gives the error volume for a planar face is required, since the model in Tumer et al. [6] is only for a linear profile. By assuming that the change in width of a triangular facet is not large compared to the height of a layer, a simple approximation can be made:

$$V_a = \frac{A\tan(\theta)\sin(\theta)l_t}{8} \tag{4}$$

where A is the surface area of the face, θ is the angle of the face to the build direction, l_t is the layer thickness, and V_a is the aliased volume.

A routine that sums this error over the entire surface of a part has been written and used in a numerical minimization routine. While the model is fast to evaluate, it is extremely sensitive to the starting point given to the search routine. Perturbing the starting point as little as 2 degrees can lead to a completely different minimum. For this method to work, more research is needed to identify heuristics for generating starting points.

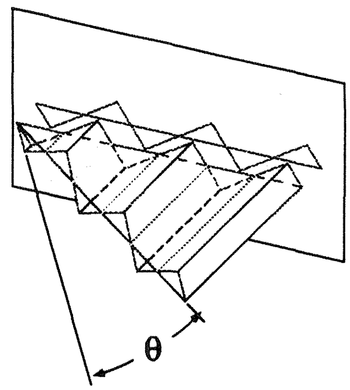


Figure 2: Approximation of a facet at an angle to the build direction

Build Time with Volumetric Supports

In SALD, the speed at which material is deposited is independent of the direction in which the part is built. However, volumetric supports are required. A brute force numerical minimization of support volume on a large part is not feasible, but by retiling the surface the computation time becomes acceptable. Another method that may yield optimum orientations is the visibility map [4].

The visibility map is a mathematical abstraction that approximates the manufacturing process' ability to create surface normals at a given angle. In SALD, the only surfaces whose normals cannot be manufactured (without supports) are those faces pointing "downwards" that are not part of the bottom bounding box of the part. Although it includes some surfaces which might possibly require supports, we can eliminate all faces on the convex hull of the part, and consider the remaining faces as possibly requiring supports, depending on the choice of the build direction. By looking through the remaining faces for a direction orthogonal to every one, we can find build directions that might not require support. Specifically, we are guaranteed to find any direction which does not require supports, but some of the candidate directions may have faces on the convex hull that require supports.

Determining the Optimum Orientation

Once a set of quality measures has been determined, a global optimization must be performed. This entails defining an objective function based on all of the quality measures and employing a method to minimize the function. Combining individual functions into an aggregate is the traditional method of generating an objective. However, there is no subjective way to determine how much each measure should contribute to the objective. Because the importance of each measure varies from part to part, the weighting of these must be determined by the designer.

One way to avoid having weights for each measure of quality is to minimize just one of the measures and impose constraints on the others. An example is the minimization of

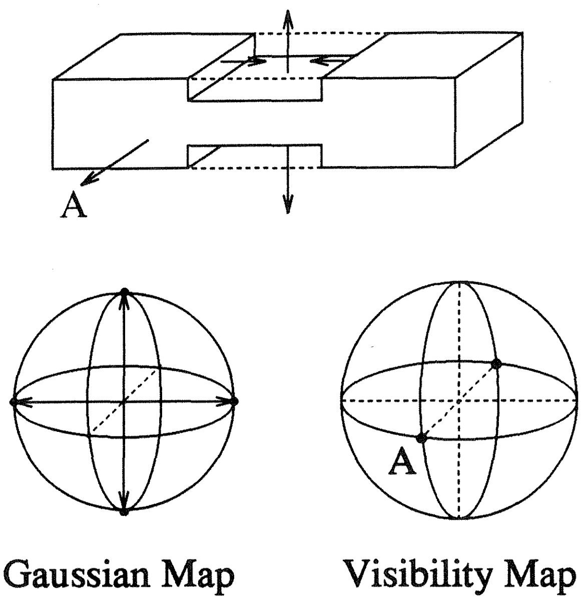


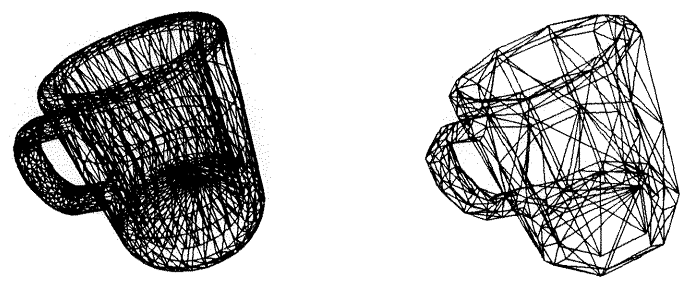
Figure 3: Obtaining a visibility map

	Direction			Build	Alias
	x [in.]	y [in.]	z [in.]	Distance [in.]	Volume [in.^{3}]
1	-3.49	-1.44	0.18	3.78	0.0944
2	0.00	0.00	-5.00	5.00	0.0718
3	0.14	-0.34	5.00	5.01	0.0504
4	1.77	5.09	0.00	5.39	0.0718

Table 1: Optimization results for the mug.

build time of the cup shown in Figure 4. The constraint that the alias volume be below $0.1 in.^3$ was added. Table 1 shows the results of the optimization. The build distance is the distance between the two bounding planes along the given direction, and is proportional to build time. In this case, the direction for a minimum build time also met the alias volume constraint. The minimum alias volume (from the set of directions generated by the build time routine) was produced with a build distance of 1.3 times the minimum.

Besides limiting the search to candidate directions, computation time may also be reduced by decimating the number of facets that describe the surface. The image of the mug in Figure 4(a) has 2426 facets while the mug in Figure 4(b) has only 360. Since some of the techniques described earlier are not linear, an order of magnitude difference in the number of facets can reduce computation time by several orders of magnitude. For instance, to find the minimum build time, the convex hull must be generated. This is an $O(n \log(n))$ process. The search through each face-vertex pair is an $O(n^2)$ process. In both cases, n is the number of vertices, which was reduced from 1213 to 180 during decimation.



(a) Initial model, 1213 vertices (b) Decimated model, 180 vertices

Figure 4: A coffee mug.

Another set of methods for handling multiple part quality measures is multicriteria optimization as presented by Osyczka [3]. The technique used in the example above is similar to Pareto minimization. More information may be given to the designer if algorithms such as the min-max optimum are implemented, since this class of techniques presents some sensitivity information.

Conclusion

In addition to a more sophisticated minimization routine, future work should include the implementation of visibility maps to determine candidate directions for volumetric support minimization and the identification of more heuristics to aid in part orientation. As an example, one might consider minimizing the cross-sectional area of the first layer in an SLS part to avoid curl.

Acknowledgments

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