PROCESS PLANNING BASED ON USER PREFERENCES

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ABSTRACT

Typical approaches to adaptive slicing in previous literature have typically used surface finish requirements to control the slicing process. As a result, slice schemes improve the part's surface quality, but do not enable explicit trade-offs between finish and build time. The purpose of this article is to present a process planning method that enables the preferences of the user for surface finish, build time, and accuracy to control how trade-offs are made in a process plan. A multi-objective goal formulation is used by this method to evaluate how well user preferences are met by a process plan. This method consists of three modules, for determining part orientation, for slicing the part, and for determining other parameter values. An example with several scenarios representing different user preferences is provided to illustrate the process planning method.

1 INTRODUCTION

The stereolithography (SLA) technology is inherently a very flexible process, with over 20 process variables. This flexibility allows parts and features on those parts to be built very accurately and efficiently. However, the SLA technology is complex enough that even experienced operators may not be able to select appropriate variable values to achieve desired build objectives. Through the use of empirical data, analytical models, and heuristics, methods of process planning may be developed that enable even novice users of stereolithography to achieve efficient and high quality builds. We believe that the methods, if not the specific data, are applicable to other layer-based manufacturing processes.

Stereolithography creates solid objects using a layer based manufacturing approach [1]. Physical prototypes are manufactured by fabricating cross sectional contours or slices one on top of another. These slices are created by tracing with a laser 2D contours of a CAD model in a vat of photopolymer resin. The prototype to be built rests on a platform that is dipped into the vat of resin. After each slice is created, the platform is lowered and the laser traces the next slice of the CAD model. Thus the prototype is built from the bottom up. The creation of the physical prototype requires a number of key steps: input data, part preparation, layer preparation, and finally laser scanning of the two-dimensional cross-sectional slices. The input data consist of a CAD model, a precise mathematical description of the shape of an object. Part preparation is the phase at which operator controlled parameters and machine parameters are entered to control how the prototype is fabricated. Layer preparation is the phase in which the CAD model is divided into a series of slices, as defined by the part preparation phase, and translated by software algorithms into a machine language.

The key area of interest in this research is the part preparation phase. The set of parameters used to build the prototype, called the process plan, has a significant effect on the quality of the resulting prototype. As such, the purpose of this research is to develop a process planning method for improving the quality of prototypes in stereolithography. This is to be accomplished by assisting the user in setting machine parameters so that characteristics of the fabricated prototype reflect the original intent of the user/designer/customer (we will use the term 'user'). The characteristics under investigation in this paper include build time, geometric tolerances, and surface finish.

2 BACKGROUND

2.1 Process Planning Literature

There has been a good deal of research on process planning of layer based manufacturing technologies such as stereolithography. This literature spans from topics such as build process optimization [2], to inaccuracy prediction and correction [3], and support structure generation [4].

Many researchers have investigated adaptive slicing of parts for layer based fabrication. The objective of adaptive slicing is to develop a slicing scheme, or method of slicing the CAD model, that meets a user-defined tolerance. This tolerance, commonly referred to as a cusp, serves as an indication of the allowable deviation between the true CAD model surface and the physical surface of the prototype. The error associated with this deviation is present in all layer-based manufacturing technologies to one degree or another. Separately, Dolenc and Mäkelä [5] and Tata [6] were some of the first researchers. They adaptively sliced parts that were represented using STL files. Other researchers [7, 8, 9], have presented adaptive slicing methods that slice CAD part models represented by analytical surfaces. All approaches attempt to improve the geometric accuracy of the physical prototype by calculating the appropriate layer thickness based on the local geometry of the CAD model, which will minimize the error associated with the stairstep effect to an acceptable level as defined by the cusp.

Marsan et al. [10] take a broad view of process planning and break it into four steps. The first step involves entering design data into a Solid Builder, used to generate a B-rep solid model. The next step is orienting the solid model in the Orientation Module. Support structures are then automatically generated. Next the oriented solid model is passed on to an Adaptive Slicing Module, where it is adaptively sliced to minimize the error associated with the stairstep effect. The final module is Path Planning which is currently undertaken using commercial software.

Research at Georgia Tech focused on developing methods to facilitate trade-offs among build time, accuracy, and surface finish goals. McClurkin and Rosen [11] developed a computer aided build style selection (CABSS) tool that aids users in making trade-offs among these goals. Only three variables were considered: part orientation (3 choices), layer thickness, and hatch spacing. Lynn [12] extended this work by conducting a detailed study of SLA accuracy, where response surfaces [13] are used to quantify the achievable accuracy for a set of geometric tolerances applied to a variety of surface types. The four build-style variables investigated in that research were fill-overcure, hatch-overcure, sweep period, and z-level wait period. Initial work on integrating the accuracy response surfaces into CABSS was reported in [14].

2.2 Compromise Decision Support Problems

A compromise Decision Support Problem (cDSP) is a hybrid multiobjective problem formulation, incorporating concepts from both traditional mathematical programming and goal programming. The objective is to explore the design space and improve a selected concept based on a set of goals, constraints, and bounds [15]. The cDSP is often used to model decisions consisting of multiple goals that are often in conflict with one another. A satisfactory solution is one that meets both the constraints and bounds and balances the performance of the conflicting goals. In the case of process planning for stereolithography, a part is presented in a "default" build style to serve the purpose of the existing alternative to be improved. This build style is improved by changing the build process variables. The structure of the cDSP is shown below.

Given:	A feasible alternative, assumptions, parameter values, and goals.
Find:	Values of design and deviation variables.
Satisfy:	System constraints, system goals, and bounds on variables.
Minimize:	Deviation function that measures distance between goal targets and design point.

System constraints must be met for the design to be feasible and are functions of the system variables. System goals model the design aspirations of the designer. The deviation variables measure how far away the actual achievement levels are from the target levels and are often weighted when used to formulate the deviation functions. The alternative (in this case a build process style) is improved by finding a combination of system variables such that all the system constraints are satisfied while the deviation function is minimized.

The mathematical form of a goal is given in Equation 1 for the ith goal. Each goal, A_i, has two associated deviation variables d_i^+ and d_i^- which indicate the extent of the deviation from the target (G_i). The deviation variables, d_i^+ and d_i^-, are always non-negative, and the product constraint, $d_i^+ \langle\, d_i^- = 0$, ensures that at least one of the deviation variables for a particular goal is always zero. In a cDSP, the objective that is minimized is called the deviation function. In this work, the deviation function is a weighted sum of the deviation variables (Equation 2).

$$A_i(X) + d_i^- - d_i^+ = G_i \qquad (1) \qquad\qquad Z = \Sigma\, W_i\, (d_i^- + d_i^+) \qquad (2)$$

2.3 Adaptive Slicing Method

Layer thickness has a large impact on both the resulting surface finish of the prototype and the time required to build the prototype. The method of selecting the layer thickness depends upon the type of CAD model (analytical or tessellated) and the method of slicing (adaptive or uniform). In this research an analytical CAD model is used with elements of both adaptive and uniform slicing.

There are two primary methods of calculating the layer thickness of analytical surfaces. Surfaces such as planes and cones/cylinders with a vertical feature axis may be treated as uniformly sliced surfaces. Curved surfaces such as spheres, B-splines, and cones/cylinders that do not have a vertical feature axis must be adaptively sliced. In adaptive slicing, the layer thickness is allowed to vary across the extents of the surface and conform to the local geometry. A more complete discussion of the adaptive slicing methodology may be found in references [8, 9].

The adaptive slicing method utilized in this research is in principle very similar to the method proposed in [8]. The key difference however lies in the calculation of layer thickness. In stereolithography, the layer thickness is often a discrete value. While in theory the layer thickness could be considered continuous, in practice this would be quite difficult since each layer thickness value has associated with it a set of preferred build parameters. An acceptable layer thickness in this method would be one in which the calculated cusp is equal to or less than the user-specified cusp. In this manner a slice scheme may be developed using the adaptive slicing method with a set of discrete layer thicknesses.

3 PROCESS PLANNING FORMULATION

3.1 The Overall Approach

Selection of SLA process variable values in many cases depends upon the intended function the user might have in mind for a given prototype. The expectations for a prototype to be used in marketing might be dramatically different than the expectations for functional testing. In such a situation, one would also expect that the process plans to fabricate these prototypes would be different. However, to effectively develop these alternative process plans, there must exist an understanding of the tradeoffs being made when one process plan is compared to the next. By quantifying attributes such as accuracy, surface finish, and build time, process variable values can be selected quantitatively based on the relative importance of these attributes.

In developing the process planning method, a cDSP word formulation is the first step. This provides a means of organizing the important inputs, variables, constraints, and goals to be dealt with in the development of a process planning method. The word formulation for the process planning method consists of three cDSP's, as shown in Figure 1. The system variables include two part parameters: the slice scheme and the orientation, two layer parameters: hatch and fill overcure, and two recoat parameters: sweep period and z-level wait. Part parameters pertain to the build variables directly associated with the part. Layer parameters pertain to the build variables that control how each layer is solidified in the vat of resin. Recoat parameters pertain to the build variables that control how a new layer of resin is deposited over the previously solidified layer. There are two constraints that are taken into consideration as well, the presence of large horizontal planes and the presence of support structures. The goals in the problem formulation consist of surface finish, accuracy, and build time.

Problem Formulation		
Orientation Module	**Slicing Module**	**Parameter Module**
Goals	**Goals**	**Goals**
Build Time	Build Time	Build Time
Accuracy	Accuracy	Accuracy
Surface Finish	Surface Finish	Surface Finish
Variables	**Variables**	**Variables**
Orientation	Layer Thickness	Sweep Period
		Z-Wait
Constraints	**Constraints**	Fill Overcure
Support Structures	Horizontal Plane	Hatch Overcure
Horizontal Planes		**Constraints**

Figure 1 Process Planning Problem Formulations.

Each of the three cDSP's shares the same build goals, however the system variables and constraints differ depending upon the sub-problem of interest. The start of process planning begins with an ACIS based CAD model, and a set of feature tolerances (surface finish and geometric requirements) and goal preferences for the different build goals, which are supplied by the user. These inputs are used to generate and evaluate a set of suitable orientations in the orientation module. Select orientations are sent on to the slicing module where sets of slice schemes are developed for each orientation. Again each of these slice schemes is evaluated. Suitable slice schemes are then sent to the parameter module where build and recoat parameters are evaluated for each of the slice schemes. Next, multiple solutions are presented to the user. At this point in the process planning method it is up to the user to look at the resulting process plans and decide which plan will be the most suitable to fabricate the prototype.

3.2 Constraints

In this work, constraints are issues that must be addressed when developing a process plan, such as the presence of support structures, trapped volumes, large horizontal planes, and small or thin features. In some situations, these issues could result in a crashed build or seriously detract from prototype quality. With this line of thinking, the method of handling constraints in this research is to assess penalties to the build goals if a constraint is present. The constraints taken into consideration in this research are the presence of support structures and large horizontal planes.

Support Structures Support structures help to hold a prototype in position while it is being built, but can have a detrimental effect on the surface quality of the surfaces affected. The presence of support structures usually has the effect of increasing the surface roughness of the affected surface, especially in the localized area of contact. The sum of the areas of the affected facets in a given surface may then be used to assess the degree of support structures present on the surface. The penalty assessed to the surface finish, SF_Penalty, for the affected surface can be calculated by $SF\_Penalty = SLCoef * \left(\frac{SPArea}{TLArea}\right)$. A ratio of the supported area, *SPArea*, and the total surface area, *TLArea*, is used to capture the degree of support structure contact. The surface finish coefficient, *SFCoef*, is developed empirically (see Surface Finish Goal below).

Large Horizontal Planes The presence of large horizontal planes often requires the process plan to be adjusted locally at the vertical location of the horizontal plane. This is done to ensure that the horizontal plane will exhibit a smooth flat surface. To prevent this surface error both the sweep period and the z-level wait are increased for a number of layers above and below the horizontal plane according to this equation:

$BT\_Penalty = \sum_{i=start\_slice}^{end\_slice}(newsweep - sweep[i] + newwait - wait[i])$ where the *start_slice* and *end_slice* are the slices a set distance from the horizontal plane and the quantities (*newsweep* – *sweep*[i]) and (*newwait* – *wait*[i]) represent the increases in sweep period and z-level wait for slice *i*.

3.3 Build Goals

The three build goals, surface finish, accuracy, and build time, are used to evaluate the process plan at the three different stages of its development (Orientation, Slicing, and Parameter stages). The objective of both the surface finish and accuracy goals is to minimize the deviation between that which is specified by the user (geometric tolerances and surface finish requirements) and that which is obtainable by the stereolithography process. The objective of the build time goal is to minimize the time necessary to build the prototype.

Surface Finish Goal A composite evaluation of how well each surface finish tolerance may be met serves as the overall evaluation for the surface finish goal. Empirical data are used to develop models that predict the obtainable surface finish for a given layer thickness on a surface at a given orientation. Previous research [16] reported data in which the finish of a planar surface is measured for a series of different orientations. Similar experiments were performed in this work [17], but instead of associating the surface finish with the orientation, the cusp (a function of both layer thickness and orientation) is associated with the surface finish. In this manner the surface finish corresponding to a given cusp and layer thickness can be predicted for all surfaces in a part.

Accuracy Goal As with the surface finish, each geometric tolerance is evaluated separately then combined into an overall composite evaluation of accuracy. The accuracy models used in this work come from the response surface models developed by Lynn et al.[14]. Six types of geometric tolerances were considered in this work: positional, flatness, parallelism, perpendicularity, concentricity, and circularity. A total of thirty-six different response surfaces were developed based on the type of surface, the orientation of that surface, and the type of geometrical tolerance [12]. Given the tolerance type, orientation of the surface to which the tolerance is annotated, and the values of the layer and recoat parameters, predictions of the achievable accuracy for every geometric tolerance can be made.

Composite Evaluation of Goals The concept behind creating a composite evaluation of the surface finish or accuracy goal is to measure how well the overall accuracy or surface finish goal is being met. To develop the composite evaluation, the specified tolerance is divided by the achievable tolerance and then multiplied by a weighting factor for that specific tolerance. This product is summed for each tolerance. The general form for both surface finish and accuracy goals is

$$GOAL = \sum_{n=0}^{n=T} \begin{cases} \dfrac{SpecTol_n}{AchievTol_n + Penalty} \geq 1 \Rightarrow & weight_n * 1 \\ \dfrac{SpecTol_n}{AchievTol_n + Penalty} \leq 1 \Rightarrow & weight_n * \dfrac{SpecTol_n}{AchievTol_n} \end{cases}$$

$$GOAL + d_i^- - d_i^+ = 1$$

In this development T represents the number of surface finish or accuracy tolerances, $SpecTol_n$ represents the user defined requirement for either the finish or accuracy tolerance, $AchievTol_n$ represents the predicted value, and d_i^+ and d_i^- represent the deviation from the desired overall finish or accuracy tolerance. If the specified tolerance is greater than the achievable tolerance, the current feature is surpassing the specified tolerance and is not counted against the goal achievement. If the sum of the weights is equal to 1, d_i^+ will always be 0, and d_i^- will always lie in the interval [0,1]. In this manner a single measure for the overall surface finish or accuracy is obtained, where it is always desirable to minimize d_i^-. The *Penalty* for the surface finish goal would be the *SF_Penalty* described earlier.

Build Time Goal Quantification of the build time goal is based upon empirical data collected from a computer based build time estimator for stereolithography. The build time estimator [11] reads the vector (.v) and range (.r) files created by Maestro, 3D Systems's software, and calculates the build time to within roughly 2 percent. Using empirical data, three build time models (response surfaces) are developed that predict the time necessary to trace out the three vector types (hatch, fill, border) for one slice of the prototype. Summing up the time for all of the slices for a given slicing scheme, and adding the recoat time associated with each slice, yields a prediction of the build time for a given process plan. The general form of the build time goal is $\dfrac{(BuildTime + BT\_Penalty) - BuildTime_{\min}}{BuildTime_{\max} - BuildTime_{\min}} + d_{BT}^- - d_{BT}^+ = 0$ where d^-_{BT} is always 0 and d^+_{BT} will lie on the interval [0,1]. In this manner a measure of build time is obtained where it is always desirable to minimize d^+_{BT}.

3.4 Deviation Function

Using the deviations of the three build goals, a single aggregate deviation function is created to measure the overall performance of the build goals. The stereolithography user specifies, at the start of process planning, a relative importance or weight for each of the build goals, with the sum of these weights equal to one. The overall deviation is calculated by summing the product of the weight and the deviation for each of the build goals. The general form is presented here:

$Z = SFwt * (d_{SF}^- + d_{SF}^+) + ACwt * (d_{AC}^- + d_{AC}^+) + BTwt * (d_{BT}^- + d_{BT}^+)$, where d_*^+ and d_*^- represent the deviations from the specified goal. The value of the overall deviation Z will always lie in the interval [0,1]. The build process variables that minimize the individual goal deviations, and thus the overall deviation function, represent a solution that satisfies the operator preferences.

4 RESULTS

4.1 A Sample Problem

To demonstrate the process planning method outlined in this research an example problem is presented. This example is used to step through the process of annotating the model, running the process planning software and selecting the process plan that will best meet the requirements set by the user. The selection is made by examining the goal achievement of each of the three goals as indicated by the deviation values as well as the predicted values for accuracy, surface finish, and build time. In this formulation, the process planning software reads an ACIS based CAD model (.SAT file). The user is first queried for goal preferences. The values of the preferences must sum to one with higher values indicating a stronger preference for a given goal. In this example problem, one set of goal preferences is investigated in depth and the results of several different sets of goal preferences are discussed briefly. The purpose of examining several different scenarios is to develop a better understanding of the tradeoffs being made in any given process plan based on the user preferences. The set of layer thicknesses used for this example problem is 2, 4, and 8 mils, which are typical values for a SLA-250. The CAD model shown in Figure 2 is a bracket and provides a variety of geometric surfaces.

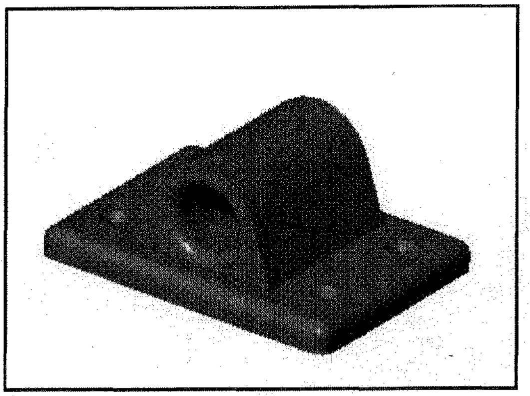

Figure 2 Example Part, Bracket

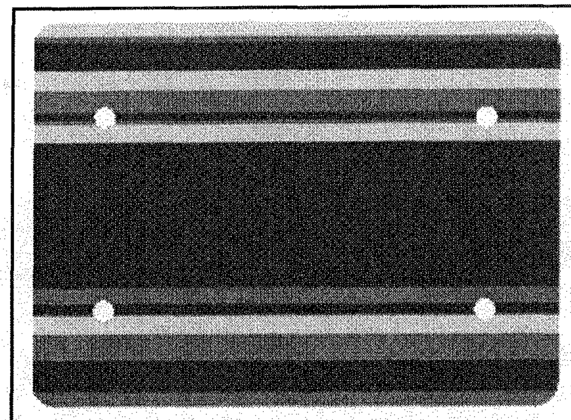

Figure 3 Slice Scheme for Trial 5

4.2 Tolerance and Finish Requirements

After specifying the goal preferences, the user is queried for the surface finish requirements of each surface. Four surfaces of the CAD model in Figure 2 are deemed to be critical. The inner cylindrical surface is to have a 2.5 micron surface finish. The two rounded edges on either side of the cylindrical surface should have a surface finish requirement of 3.8 micron. The down facing planar surface at the base of the bracket is to have a 3.8 micron surface finish. The remaining surfaces are set to a default surface finish of 7.6 micron. Next the user is queried for geometric tolerances. A cylindrical tolerance (0.003 in.) is applied to the inner cylindrical surface. A parallelism tolerance (0.004 in) is applied between the bottom surface and the top up facing planar surface, and a flatness tolerance (0.004 in) is also used on the bottom surface.

4.3 Analyzing the Alternative Solutions

Table 1 provides an overview of the goal preferences and the resulting deviations for each of the different scenarios. The solutions that are shown in the table represent the process plans with the lowest overall deviations for the given goal preferences.

Table 1 Process Planning Results

Trial	Weighting of Goals (AC, SF, BT)	Overall Dev.	Accuracy Dev.	Surface Finish Dev.	Build Time Dev.
1	(0.90, 0.05, 0.05)	0.30	0.31	0.07	0.21
2	(0.05, 0.90, 0.05)	0.04	0.31	0.01	0.32
3	(0.05, 0.05, 0.90)	0.07	0.68	0.36	0.02
4	(0.60, 0.20, 0.20)	0.24	0.31	0.09	0.19
5	(0.20, 0.60, 0.20)	0.13	0.31	0.01	0.30
6	(0.20, 0.20, 0.60)	0.15	0.31	0.23	0.07

As can be seen from the table, the weightings of the build goals have some affect on the resulting deviations. There are significant tradeoffs being made between the surface finish and build time goals, as one would expect. However, the accuracy goal does not appear to be significantly influenced by either of the other goals. Comparison of trial 6 with trial 3 provides the best example of the tradeoffs being made between the build time and surface finish goal. Both trials have a weighting scheme with the build time goal having the highest goal preference (0.90 for trial 3 and 0.60 for trial 6). The build time deviation is slightly higher for trial 6 yet at the same time the surface finish deviation is also slightly lower. Thus it is evident that there is some degree of tradeoff being made between the build time and surface finish goals.

The accuracy breakdown for solution (1:1) is:

Tol #	Face #	Tol Type	Desired Value (mm)	Actual Value (mm)
0	2	Cylindrical	0.0762	0.0762
1	19	Parallelism	0.1016	0.381
2	33	Flatness	0.1016	0.152

The surface finish breakdown for solution (1:1) is:

Face #	Desired Value (micron)	Actual Value (micron)
0	3.8	5.05
1	7.6	4.34
2	2.5	1.3
3	3.8	2.64
4	7.6	0.13
5	7.6	6.05
...		
32	7.6	1.55
33	3.8	1.24

Figure 4 Results of Trial 5.

The slicing scheme for Trial 5 is shown in Figure 3, where the darkest shading represents areas where the model is to be built with a 0.008 in layer thickness while the lighter shading represents 0.004 and 0.002 in layer thicknesses. As one would expect, the rounded edges on the bracket require the use of a smaller layer thickness to meet the surface finish requirements. Figure 4 shows the output from the process planning software for trial 5. In this printout, all accuracy and surface finish requirements are listed as well as the predicted values. Face 2 represents the inner cylindrical surface, while faces 0 and 3 represent the rounded edges on either side of that cylindrical surface. Thus in this process plan, most of the critical surfaces are meeting the specified surface finish requirements. By looking at the slicing scheme and the surface finish and accuracy predictions a much better understanding of the given process plan may be developed. Armed with this type of information, the user can make much more informed decisions as to which process plan should be ultimately used for the fabrication of the prototype.

5 CONCLUSIONS

A process planning method was developed that allows the use of multiple build goals in setting up a process plan for stereolithography. Surface finish, accuracy, and build time are the three build goals used in this method. The intent of this process planning method is not to develop the optimal process plan for the fabrication of the prototype, but rather, to assist the stereolithography user in the development of a process plan by quantifying the tradeoffs between the three build goals. These tradeoffs have been shown to exist and can be quantified using the methods outlined in this paper. By quantifying these tradeoffs the stereolithography operator is in a much better position to develop the process plan that will be used to achieve the specific goals and characteristics that are desirable in the end prototype.

This process planning method has the potential to significantly aid stereolithography operators in process planning, but it is not without limitations. The dependence upon empirical data for the evaluation of the build goals is a limiting factor. The goal evaluations used in this process planning method have been developed using empirical data for a SLA-250 machine, thus specific predictions for accuracy, build time, and surface finish are limited to prototypes built with a SLA-250 machine. It has also been observed that the use of a large number of blocks (greater than eight or nine) in the slicing module results in long computational times. Continuing efforts are being made to further define the capabilities and limitations of this process planning method.

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