A Process Planning Method and Data Format for Achieving Tolerances in Stereolithography

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ABSTRACT
When building parts in a stereolithography apparatus (SLA), the user is faced with many decisions regarding the setting of process variables. To achieve a set of tolerances as closely as possible, relationships between part geometry, tolerances, and process variables must be understood quantitatively. This paper presents a method for SLA process planning that is based on response surface methodology and multi-objective optimization, where the response surfaces capture these relationships. These response surfaces were generated by extensive design-of-experiment studies for a variety of geometries. An annotated STL data format is also presented that enables the inclusion of tolerance and surface information in facetted representations. Application of the data format and process planning method is illustrated on one part.

1. INTRODUCTION

Build performance is measured by how well the goals set forth by the operator for the build are met. For solid freeform fabrication systems, such as Stereolithography (SLA), the goals are often based on how quickly and accurately the CAD model is reproduced in a solid form. SLAs have dozens of processing variables that can be controlled by experienced operators to meet exacting build requirements of accuracy, surface finish, build time, and others. Experienced operators know qualitatively how process variables are related to build goals and can quantify some of their knowledge. Although SLA machine operation is predictable, the build quality is not always obvious, particularly when trade-offs must be made among goals to achieve specified tolerances.

A process planning method is presented in this paper to aid SLA operators in selecting appropriate values of build process variables in order to achieve a set of tolerances as closely as possible. The tolerances can be specified in order to reflect preferences of the operator or designer. Response surface models were experimentally constructed for evaluating accuracy, which enables the quantitative relationships between desired tolerances and the SLA process variable values that best achieve those tolerances. The process planning method is adapted from multiobjective optimization and utilizes response surface modeling to quantitatively relate variables to goals. Our objective is to render decision support by handling trade-offs among conflicting goals quantitatively. Our method is demonstrated on a part with non-trivial geometries.

2. BACKGROUND

2.1 Related Research
There is already a great deal of research available that is directly or indirectly related to the accuracy of a layer based manufacturing technology such as SLA. This research spans from build process optimization, inaccuracy prediction and correction, to support structure generation, alternative data structures and file formats for communicating between the manufacturing systems and CAD environments. The work presented in this paper relates to the process planning issues that arise when building prototypes. In the following paragraph a brief overview of some of this process planning research is provided.

Tata and Flynn have completed extensive studies in an attempt to quantify and correct down facing z-errors [1]. A down facing z-error is partially caused by the time difference as the laser scans the cross section of the first part and the last part in a multiple part build. This is due to the cure time of the liquid resin after it is exposed to the laser. Down facing z-errors can be reduced by using the correct time between layer scans. Gervasi has investigated the use of statistical process control in the SLA build process[2]. In this investigation statistical process control is applied to the X & Y shrinkage, and line width compensation factors for the SLA over a period of time. If effectively applied this could provide an indication of undesirable system changes during the build process. Onuh and Hon have addressed a research issue that is similar to the issue addressed in this paper[3]. They have applied the Taguchi Method to study and quantify the effects of layer thickness, hatch spacing, hatch overcure depth, and hatch fill cure depth on the quality of SLA prototypes.

Additional research on SLA accuracy is being performed by the Rapid Prototyping and Manufacturing Institute (RPMI) at Georgia Tech. This research is geared toward measuring, predicting, and correcting inaccuracies in parts and injection molding tools made either directly or indirectly from the SLA. One research topic involves measuring the inaccuracies of thin walled SLA parts. Research is also currently underway on an adaptive slicing methodology that takes into consideration build time and accuracy, as well as surface finish. One particular project was the predecessor of the present work. Computer Aided Build Style Selection (CABSS) is a method that renders decision support for building a part on a SLA based on response surface methodology and multi-objective optimization.[4 5] CABSS suggests appropriate values of process variables (limited to only three: part orientation, layer thickness, and hatch spacing) in order to achieve build goals of build time, surface finish, and accuracy as closely as possible. The main objective was to handle trade-off among these conflicting build goal objectives quantitatively. The method of providing the build style decision support described was based on solving a compromise decision support problem. Input to CABSS was an .STL file and user-specified goal weights. Exhaustive search was used to find a solution to the 3-variable, 3-goal problem.

2.2 Compromise DSP Construct

The Compromise DSP deals with only one alternative that is to be improved through modification[6]. This alternative can be improved by solving a CDSP where the values of all the system variables are found simultaneously, the requirements are met, and a set of objectives are achieved as well as possible. The CDSP is used to model decisions that consist of constraints, and linear and non-linear goals. The CDSP incorporates concepts from Goal Programming in that multiple objectives are represented as system goals. When there is more than one system goal, they are often in conflict with one another. In the case of the SLA build, a part is presented in a "default" build style to serve the purpose of the existing alternative to be improved. This build style is then improved by changing the build process variables. The conflicting goals are commonly build speed, accuracy, and surface finish. 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.

Parameters are necessary to complete the modeling of the CDSP, but are not affected by the solution itself. Variables are classified as either of two types: system variables or deviation variables. System variables include design parameters the user can alter. A CDSP must have a minimum of two system variables. A system constraint must be met for the design to be feasible. System constraints are functions of the system variables. System goals model the design aspirations of the designer. For the SLA these goals are: low build time, high accuracy, and smooth surfaces. 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, or build process variables, such that all the system constraints are satisfied while the deviation function is minimized.

3. PROCESS PLANNING METHOD

3.1 Response Surface Methodology

In order to formulate a decision support problem that is based on concrete data, the interactions of the system variables and goals need to be known. Response Surface Methodology comprises mathematical and statistical techniques to enable the construction of approximation models[7]. RSM allows for a better understanding of the relationships between the inputs and the response, in this case between the build process variables and build goals, that can be written in the form of a polynomial function describing a surface, such as the one shown in the equation below. We use second order response surfaces in this work; k = 2.

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=1, i \neq j}^{k} b_i x_i x_j$$

Response surfaces are useful when detailed theoretical knowledge of the model does not exist, and all that is known is that the relationship between the input variables and the output variable is likely to be smooth. This is the case for the SLA. For instance, theoretical equations that give accuracy as a function of layer thickness and hatch spacing do not exist.

In order to create the response surfaces for the system goals, a number of experiments must be run to gather data for an empirical model. When the system goals are dependent on two or more factors (system variables), Design of Experiments (DOE) techniques can be practiced to determine the experiment sequence for the empirical model. Factorial experiment designs involve testing a number of variables, or factors, at different values, or levels. The experiments run in this research will be fractional factorial experiment designs with a face centered central composite design.

In a face centered central composite design, three levels of each factor are considered. The middle level is called the zero level. For example, in the case of the fill overcure variable, 0.009" is the zero level. At equal spacing from the zero level are the α levels at +/- 1 from the zero level. This moves the axial points in a central composite design to the faces of the cube and reduces the required number of levels from five to three levels.

3.2 Variable Selection for Accuracy Models

Two sets of experiments were run in this research, a screening experiment and a model building experiment. Screening experiments identify the most significant variables, reducing the size of the subsequent model building experment. The design chosen for the accuracy screening experiment is the Plackett-Burman design, often utilized for a large number of variables and a small number of physical experiments. This is a 2-level design, using values that are the minimum and maximum range of each variable. The variables selected and their corresponding ranges are shown in Table 1. We used a SLA-250 and Dupont SOMOS 7110 resin for our experiments.

Variables	Layer thickness	Blade gap percentage	Pre-dip delay	Z-level wait time	Hatch overcure	Hatch spacing	Fill overcure	Sweep period
Max	0.008	200	20	20	0.001	0.012	0.012	15
Min	0.004	150	5	5	-0.003	0.006	0.006	5

Table 1 Plackett-Burman Variables and Ranges.

Three different shapes were built in the experiments, cubes, cones, and cylinders. The shapes were built at several orientations, 0, 30, 45, and 90 degrees. The surfaces were measured utilizing a Coordinate Measuring Machine, a Brown and Sharpe MicroVal PFx equipped with a Renishaw TP-IS touch probe (linear accuracy of +/- 0.0002" and repeatable within +/- 0.002").

The conclusion drawn from the Plackett-Burman experiment was that four variables would be carried out in the subsequent model building experiments: z level wait time, hatch overcure, fill overcure, and sweep period. The definitions of these factors are as follows:

1. Z-level wait time: Time between recoating and building the current layer.
2. Hatch overcure: Depth beyond the slice layer thickness to be cured with hatch vectors.
3. Fill overcure: Depth beyond the slice layer thickness to be cured with fill vectors.
4. Sweep period: Time required for one sweep across the length of the vat.

3.3 Response Surface Models

In order to build response surface models, a Face Centered Composite design of experiment was applied. The FCC experiment utilized the same maximum and minimum values as the screening experiment, however added a center value in order to compose the design, see Table 2. Utilizing the same range allowed for 10 of the previous screening runs' data to be utilized in this design. This resulted in 15 new runs to be completed.

Variables	Z-level wait time	Hatch overcure	Fill overcure	Sweep period
Max	20	0.001	0.012	15
Center	15	-0.001	0.009	10
Min	5	-0.003	0.006	5

Table 2 Model Building Experimental Variables and Points

After completing the builds and measuring the parts, response surfaces were constructed by computing an analysis of variations on the surface measurements. In this manner a set of response surface models were developed that relate the four build process variables with a specific type of geometric tolerance and surface type. As an example, a primitive cube could be used to measure parallelism for planar surfaces. The resulting response surface equation could then be used to predict how well two parallel planar surfaces could meet a specified parallelism tolerance with a given set of build process variables. Six types of geometrical tolerances were considered: positional, flatness, parallelism, perpendicularity, concentricity, and circularity. Only parallelism, concentricity, and circularity will be applied in the example used in this paper.

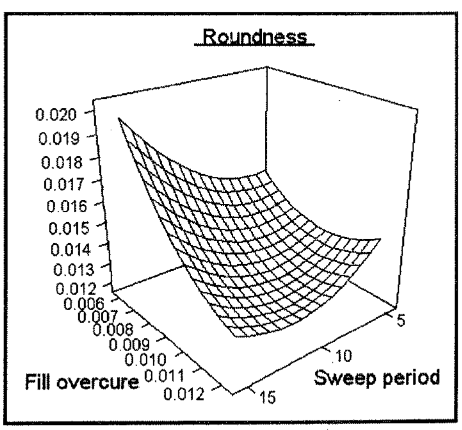

Figure 1 Example Response Surface.

A total of twenty-five different response surfaces were developed based on the type of geometric surface, the orientation of that surface, and the geometric tolerance annotation. Figure 1 provides a graph of roundness (circularity) response surface for a conical surface built vertically. This graph shows that the two concentric circles that make up the tolerance zone, which bounds the conical surface, obtain a more accurate part when the sweep period is long and the fill overcure vector is being drawn deeply.

Utilization of these accuracy models requires a mapping of the response surface equations to the actual CAD model that is to be built. Therefore, each of these accuracy models is associated with a specific type of geometric tolerance annotation that may be placed on the .STA file format. Figure 2 provides an overview of the different types of geometrical tolerances and their mapping to the response surfaces.

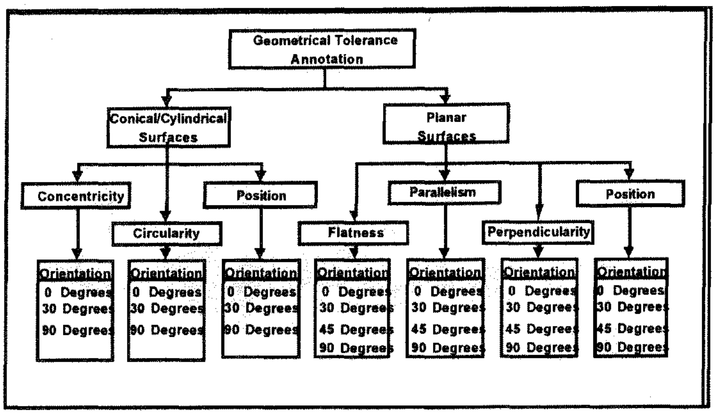

Figure 2 Accuracy Model Mapping.

3.4 The Compromise DSP Formulation

Often, the goals for the build will lead to conflicting methods of selecting the build process parameters. However, by quantifying attributes such as the accuracy or surface finish, these build process variables can be selected quantitatively based on the relative importance of these goals. The word formulation of the Compromise DSP (see Section 2.2) for the selection of the build process variables is provided in Figure 3. The goals consist of surface finish, accuracy, and build time. The accuracy models discussed in the previous section constitute the primary method of measuring the achievable accuracy of a build. Similar models for the surface finish and build time have been developed in related research and are used in this problem formulation[8].

Given
- part geometry in .STA file
- set of operator defined geometric tolerances
- set of operator specified surface finishes

Find

System Variables
- layer thickness
- hatch spacing
- part orientation (build height)
- z-level wait time
- hatch overcure
- fill overcure
- sweep period

Deviation Variables
- deviation from desired surface finish
- deviation from desired accuracy
- deviation from desired build time

Satisfy

Goals
- obtain the specified surface finishes for each surface
- obtain the specified geometric tolerances for each surface
- minimize the build time

Bounds
- set of discrete layer thicknesses
- set of discrete orientations
- upper and lower bounds on the other system variables

Minimize

Deviation Function

aggregate of surface finish, accuracy, and build time deviations

Figure 3 Compromise DSP Word Formulation.

The Surface Finish and Accuracy Goals

The accuracy goal (and surface finish goal) is modeled using a weighted composite measure of the achievement of all specified tolerances, where achievement is the deviation between what is desired and what is achievable. 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. The general form for these goal is presented below. In this development T represents the number of specified surface finish or accuracy tolerances and d_i^+ and d_i^- represent the deviation (overachievement and underachievement) from the desired overall surface finish or accuracy. If the specified tolerance is found to be greater than the achievable tolerance, then the current feature is surpassing the specified tolerance and is not counted against the composite measurement. Otherwise, the current feature is not meeting the specified tolerance and is penalized. In this formulation, 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 and accuracy is obtained, where it is always desirable to minimize d_i^-, the underachievement of the goal.

$$GOAL = \sum_{n=0}^{n=T} \begin{cases} \dfrac{SpecifiedTol_n}{AchievableTol_n} \geq 1 \Rightarrow & weight_n * 1 \\ \dfrac{SpecifiedTol_n}{AchievableTol_n} \leq 1 \Rightarrow & weight_n * \dfrac{SpecifiedTol_n}{AchievableTol_n} \end{cases}$$

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

Based on the tolerance's type, the surface it tolerances, and that surface's orientation, a specific response surface equation is used to predict the achievable tolerance value for that surface. The specified and achievable surface finishes are also handled in a similar manner. Weights for tolerances and surface finish specifications are computed based on the tightness of the tolerance.

The Build Time Goal
The quantification of the build time is also based upon a response surface, very similar to that used to quantify the accuracy. The build time goal is based on the prediction of the build time using the current build process variables and the maximum and minimum build times as dictated by the upper and lower bounds of the build process variables. The build time goal is presented below.

$$\frac{BT(X) - BT_{\min}(X)}{BT_{\max}(X) - BT_{\min}(X)} + d_{BT}^{-} - d_{BT}^{+} = 0$$

In this equation d^{-}_{BT} is always 0 and d^{+}_{BT} will lie on the interval [0,1]. In this manner a single measure of the build time is obtained where it is always desirable to minimize d^{+}_{BT}.

The Deviation Function
Using the three goals outlined above, the deviation function is simply a measure of the deviations of each of the goals. The user specifies the importance of each of these goals and the targets to be met. In the case of surface finish and accuracy, these targets are the tolerances annotated to the .STA file format, while the target for build time is a reasonable minimum time, which can be determined from the STL file. To measure the degree to which these targets are met the deviation function is evaluated for different combinations of the build process variables. The general form is presented below.

$$Z = SFweight * \left(d_{SF}^{-} + d_{SF}^{+}\right) + ACweight * \left(d_{AC}^{-} + d_{AC}^{+}\right) + BTweight * \left(d_{BT}^{-} + d_{BT}^{+}\right)$$

The build process variables that minimize the deviation function represent a solution that satisfies the operator preferences. This solution may be found through a variety of methods that search the feasible design space. Currently since this space is small an exhaustive search is used.

4. ANNOTATED STEREOLITHOGRAPHY FILE

The current *de facto* file format for rapid prototyping technologies is the .STL file format. The .STL file format merely lists the triangular facets of the tessellated part surface. The goal of .STL file *annotation* is to add important information to the .STL file format to create a more useful format, which is called the .STA (for .**ST**L **A**nnotated) format.[9] This important information includes topological information such as triangle connectivity and the presence of different types of surfaces which is derived from the existing .STL file. Additional annotations are supplied by the user, including tolerances and surface finish requirements for the part.

The .STA file format classifies surfaces as *planar*, *cylindrical*, *conical*, *spherical*, or *other*. After classifying surfaces, information pertaining to those surfaces is computed, including orientation, curvature, and surface area. Each of these properties is calculated using computational geometry algorithms implemented in a computer program. The next step is for the user to add information pertinent to the building of the part, such as required surface finish and accuracies. When this information is complete, everything is written to a new annotated .STA file. The information in this file will progress from high level to low level as shown in Figure 4.

The highest level of information pertains to the entire part. This includes how many surfaces, facets, and unique vertices comprise the part, as well as total part volume and surface area. The next level of information describes the surfaces of the part. Each surface is listed along with its surface area, orientation, and any other annotations. The list of facets that make up the surface along with their connectivity information is also given for each surface. Facets comprise the highest level of information that the current .STL format exhibits. The facet level of the .STA format lists each facet along with the vertices that make up that facet. This alleviates the problem with .STL files of repeated vertices, and corresponding round-off and size problems. Numbers in the facet list then refer to these vertices. The final, lowest level of information is the vertex list. The vertex list lists each unique vertex in the .STL file and describes it using the 3D floating point Cartesian coordinates used in the original .STL file.

Information Location in the file	*Information Level*	*Information Regarding...*	*Information*
Beginning	High	...the entire part	• # of surfaces • # of facets • # of vertices • Volume • Surface Area • Theoretical surface finish • Dimensional extents • The surface list
		... each surface	• Type of surface • # of facets • Area • Orientation • Curvature • Derived surface finish • User annotations • Surface topology (facet list)
		... each facet	• The vertex number of each of the 3 vertices that comprise the facet
End	Low	...each vertex	• The x, y, and z coordinates for each vertex expressed as a floating point number.

Figure 4 General Information Structure of the .STA File.

5. RESULTS

To demonstrate the accuracy models and .STA file format developed in this research the following example problem is presented. This example is used to step through the process of annotating the model and selecting the build process variables that will best meet the preferences of the operator and the specified tolerances. The selection process was accomplished by refining the previous problem formulation of CABSS. In this formulation, the optimization program reads a .STA file directly, including the annotations. Then, the user is prompted for priorities for each of the build goals. The optimization program steps through the CDSP previously described and selects the best values for the variables accordingly. The CAD model shown in Figure 5 is a simple model with a geometry that will require a compromise to be made between the three goals: surface finish, accuracy, and build time. Several different trials (scenarios) are run in which the relative importances of the goals are altered to investigate the behavior of each of the individual goals. In addition, the model is simple enough that the results in most cases should be fairly intuitive.

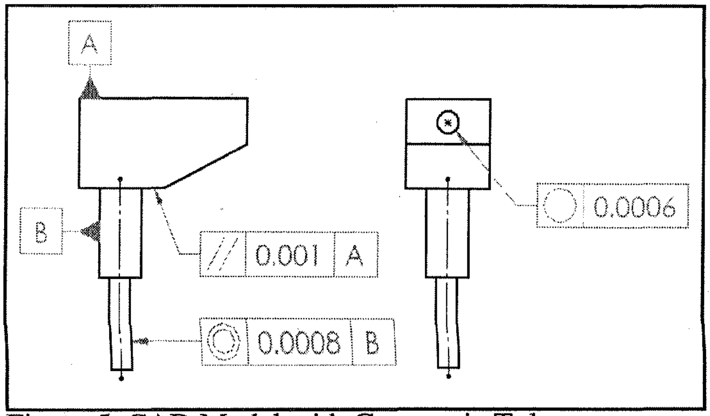

Figure 5 CAD Model with Geometric Tolerances.

5.1 Annotating the Model

The first step involves annotating the .STA file format with the desired geometric tolerances and surface finishes. Figure 5 shows a drawing of the CAD model with three geometric tolerances. The first geometrical tolerance is a parallelism tolerance controlling the planar surface from which the cylindrical shaft extrudes. The second geometric tolerance is a circularity tolerance annotated to the hole in the part, due to this being a mating feature. The final geometric tolerance is a concentricity tolerance, which ensures that the cylindrical shaft and shank lie on the same axis. The desired surface finish of the cylindrical shaft and cylindrical hole are specified as 300μin. All other surfaces are assigned a default surface finish of 400μin. Shown in Figure 6 is a sample of how this type of information is stored in the .STA file format. After listing all the surfaces and their corresponding information, there is a list of the datum and tolerances.

```
solid SFF_example
Surfaces:          13
Facets:            468
Vertices:          236
Z-Height:          2.00
Area:              49.02
Volume:            15.56
Surface Finish:    383.61

Surface_List
Surface  0
        Type:                          planar
        Number of facets:              2
        Surface area:          4.000000
        Orientation:           90.000000 x -180.000000
        Curvature:             0.000000
        Theoretical Finish:    363.000000

 Facet_Connectivity and Angle List-
 Fct  Nbr1 - WVN - Angl  Nbr2 - WVN - Angl  Nbr3 - WVN - Angl
  42   88   0  90.000000   43   2  0.000000   91   0  90.000000
  43   42   0  0.000000    92   2  90.000000  39   0  90.000000
. . .
Surface  7
        Type:                          cylindrical
        Number of facets:              76
        Surface area:          6.275793
        Orientation:           90.000000 x 90.000000
        Curvature:             0.5
        Theoretical Finish:    868.643494

 Facet_Connectivity and Angle List-
 Fct  Nbr1 - WVN - Angl  Nbr2 - WVN - Angl  Nbr3 - WVN - Angl
 169  168   1  9.729700   170   2  0.000000    1   0  90.000000
  95  170   1  9.729801    96   2  0.000000    2   0  90.000000
. . .
Datum_list
 datum primary 2
 datum secondary 6
 datum tertiary 0
end_datums

Tolerance_List
 Parallelism 3 value 0.001 datums 1
 Roundness 5 value 0.0006 datums 2
 Concentricity 7 value 0.0008 datums 3
end_list
```

Figure 6 Sample of the .STA File Format.

5.2 Developing the Solutions

The results of each run are shown in Table 3. The weighting and deviation for each of the goals are provided in the table as well as the build process variable values. The three goals are accuracy (AC), surface finish (SF) and build time (BT). The seven build process variables are layer thickness (LT), hatch spacing (HS), build height (BH), z-level wait (ZW), hatch overcure (HO), fill overcure (FO), and sweep period (SP). Each of the trial runs is intended to demonstrate different aspects of the problem formulation. The first three trial runs basically represent a search for a single goal. One might expect the deviations for each of the three goals to be quite different across each of the three runs. The fourth trial run, in which all goals are assigned equal weighting, demonstrates the compromises that can be made between the three goals. Trial 5 provides a demonstration of the ability of compromises to be made in a more realistic scenario. The sixth trial was added after the surprising results for trial 2.

Trial 1, 3, and 6 all indicate that the problem behaves in a predictable manner. In each of these trials one of the three goals was given the highest priority and the resulting deviation for that goal was found to be the smallest. The results from trials 2 and 6 provide an excellent demonstration of a compromise in progress. The original intent for these trials was to minimize the surface finish. However, Trial 2 produced a surface deviation that was a little higher than that found in Trial 6, but had a significantly lower build time deviation. This indicates that a slight improvement might be obtained in the overall surface finish if a large build time deviation is acceptable. The results of these trials also indicate that the settings for Trials 2, 3, 4, and 5 are the most robust.

Trial	Weighting of Goals (AC, SF, BT)	AC Dev.	SF Dev.	BT Dev.	Build Process Variables (LT, HS, BH, ZW, HO, FO, SP)
1	(0.90, 0.05, 0.05)	0.181282	0.141986	0.374125	0.007, 0.02, 4, 5, -0.003, 0.008, 5
2	(0.05, 0.90, 0.05)	0.383276	0.129583	0.001495	0.007, 0.02, 2, 5, 0, 0.009, 10
3	(0.05, 0.05, 0.90)	0.383276	0.129583	0.001495	0.007, 0.02, 2, 5, 0, 0.009, 10
4	(0.33, 0.33, 0.33)	0.383276	0.129583	0.001495	0.007, 0.02, 2, 5, 0, 0.009, 10
5	(0.60, 0.05, 0.35)	0.383276	0.129583	0.001495	0.007, 0.02, 2, 5, 0, 0.009, 10
6	(0.01, 0.98, 0.01)	0.181282	0.101584	0.811627	0.007, 0.02, 6, 5, -0.003, 0.008, 5

Table 3 Results of Six Trial Runs with Various Operator Defined Preferences.

6. CONCLUSIONS

This research identified four of the build process variables that have a quantifiable effect on the accuracy of a prototype built on a SLA machine. The responses of these variables for different geometrical tolerances are developed and fitted to a set of response surfaces. The trends that may be drawn from these accuracy models are used as a means of selecting the build process variable values to achieve a specified level of accuracy. The validity of these accuracy models is subject to the accumulated errors of the empirical measurements and approximations necessary to the development of the response surface equations. A file format was also introduced that aids in the selection of these process variables by allowing an operator or designer to indicate the preferences for the prototype in terms of accuracy and surface finish tolerances on specific part features. Finally a method of evaluating conflicting trade-offs between the multiple goals was developed to provide process planning for SLA using the accuracy models developed. Continuing efforts are underway to increase the validity of the accuracy models and expand the types of geometrical tolerances that have been developed in this research.

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