R.K. Arni and S.K. Gupta. Manufacturability analysis of flatness tolerances in solid freeform fabrication. *ASME Journal of Mechanical Design*, 123(1):148-156, 2001.

Manufacturability Analysis of Flatness Tolerances in Solid Freeform Fabrication

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ABSTRACT

Increasingly Solid Freeform Fabrication (SFF) processes are being considered for creating functional parts. In such applications, SFF can either be used for creating tooling (i.e., patterns for casting, low volume molds, etc.) or directly creating the functional part itself. In order to create defect free functional parts, it is extremely important to fabricate the parts within allowable dimensional and geometric tolerances. This paper describes a systematic approach to analyzing manufacturability of parts produced using SFF processes with flatness tolerance requirements on the planar faces of the part. Our research is expected to help SFF designers and process providers in the following ways. By evaluating design tolerances against a given process capability, it will help designers in eliminating manufacturing problems and selecting the right SFF process for the given design. It will help process providers in selecting a build direction that can meet all design tolerance requirements.

1. INTRODUCTION

Solid Freeform Fabrication refers to the class of processes that build parts using a layered manufacturing paradigm. A three-dimensional CAD model of the part is sliced into layers and the numerical data on the geometry of the layers is then fed into the fabrication unit, which builds each layer sequentially until the entire part is fabricated. Some of the commercially available SFF processes are Stereolithography (SLA), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC), Layered Object Manufacturing (LOM), etc. Figure 1 shows how a given part is decomposed into layers for SFF. The main advantages of SFF processes are that they do not require any part specific tooling and are completely automated.

Due to the inherent nature of the process and the high level of automation, SFF processes are conducive to the concept of distributed design and manufacturing [9]. Increasingly, SFF processes are being accessed by designers over the network in a distributed environment. Process providers can publish their process constraints at their web sites. Designers will be able to download these constraints to their CAD system and perform manufacturability analysis to make sure that the design is manufacturable. This will help in drastically reducing the number of iterations of modifying the design when the manufacturing constraints are violated.

Until recently SFF processes were primarily used for creating prototype parts. Increasingly SFF processes are being considered for creating functional parts. In such applications, SFF can either be used for creating tooling (i.e., patterns for casting, low volume molds, etc.) or directly creating the functional part itself. In order to create defect free functional parts, it is extremely important to fabricate the parts within allowable dimensional and geometric tolerances. In order to determine whether a process can produce the part within required tolerances, we need to analyze manufacturability of design tolerances with respect to process constraints. In this paper we primarily focus on manufacturability of flatness tolerances assigned on the planar faces of the part.

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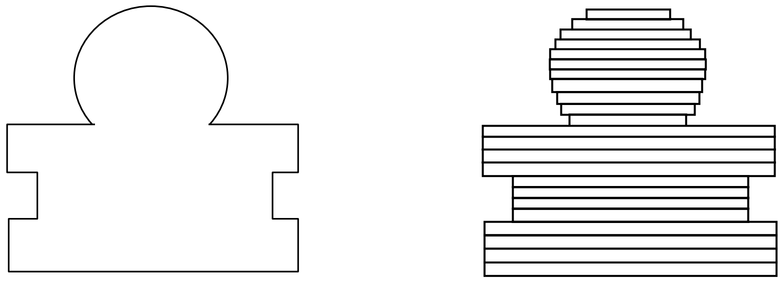


Figure 1. Staircase effect

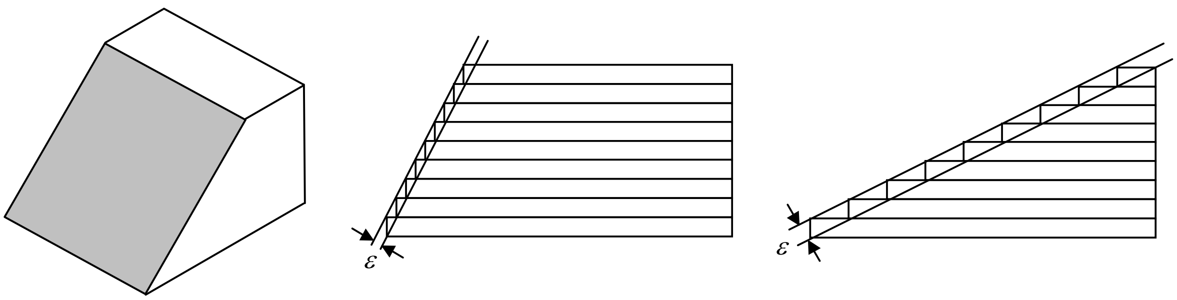


Figure 2. Effect of orientation on accuracy

SFF processes approximate objects using layers, therefore the part being produced may exhibit staircase effect. The extent of this staircase effect depends on the layer thickness and the relative orientation of the build direction and the face normal. The minimum layer thickness for a given process is known. Therefore for a given process, the primary factor that determines the extent of staircase effect is the angle between the build orientation and the face normal. As shown in Figure 2, for two different orientations of the shaded face with respect to the build orientation, the extent of staircase effect on the built part is different. Thus, the achievable accuracies in SFF processes are highly anisotropic in nature. Different faces whose direction normal is oriented differently with respect to the build direction may exhibit different values of inaccuracies. Whether a part face or a part feature can be produced within the required accuracy depends on the build orientation. If a part has many different types of tolerance requirements, it may be possible to find build orientations that can meet individual requirements. But it might be impossible to find a build orientation that simultaneously satisfies all of the tolerance requirements.

This paper discusses our approach to performing automatic manufacturing feasibility analysis for SFF processes. Given the CAD model of a part to be manufactured and the requirements on the accuracies of the planar faces on the part, this paper presents a novel approach to finding out whether the part is manufacturable. We use a two step approach. We first analyze each specified tolerance on the part and identify the set of feasible build directions that can be used to satisfy that tolerance. As a second step, we take the intersection of all sets of feasible build directions to identify the set of build directions that can simultaneously satisfy all specified tolerance requirements. If there is at least one build direction that can satisfy all tolerance requirements, then the part is considered manufacturable. Otherwise, the part is considered non-manufacturable.

The remainder of the paper has been organized in the following manner. Section 2 describes the previous work in the related areas. Section 3 describes how SFF can be modeled as a process of layer building and layer assembly. It identifies the various sources of error and presents a mathematical model of flatness accuracy of planar faces. Section 4 describes how a systematic assessment of manufacturability of the part can be performed. It describes an algorithm that can be used to perform such an analysis. Section 5 describes our implementation. It describes how the geometry, tolerance and process information is represented and provides an example. Section 6 describes our conclusions and the current limitations of our work.

2. RELATED WORK

The part accuracy produced by SFF processes is greatly affected by the relative orientation of the build and the face normal directions. The accuracy is also affected by machine and process related errors. In order to produce functional parts, we should be able to satisfy all the tolerance specifications. A systematic method is needed so that the manufacturability of a particular design can be automatically evaluated so that the number of design-manufacturing iterations can be reduced. The following subsections discuss the work done in the areas of process modeling and the effect of build orientation on the part quality.

2.1 Process Modeling: Relating Process Parameters to Part Accuracy

Tumer *et al* [14] have considered surfaces of polycarbonate Selective Laser Sintering parts to determine the characteristics affecting the part quality. Mathematical measures are computed for the surfaces to determine surface precision quantitatively. An analysis-of-variance study is performed to reveal the trends in the surface accuracy as a function of the process parameters.

Gervasi [5] has investigated the use of statistical process control in the SLA build process. He has studied the effect of *xy*-shrinkage factor and the line width compensation factor on the SLA process over a period of time by applying statistical process control techniques.

Rosen *et al* [10] have presented an empirical model for stereolithography machine accuracy, as specified by geometric tolerances. Response surface models were experimentally constructed for evaluating accuracy, which help in establishing the quantitative relationships between desired tolerances and the SLA process variables that best achieve those tolerances.

Onuh and Hon [7] 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.

Tata and Flynn [12] have done extensive studies in an attempt to quantify and correct down facing *z*-errors. 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 has been exposed to the laser. Using the correct time between successive laser scans, the downfacing *z*-error can be reduced.

2.2 Finding Optimal Build Orientation

Frank and Fadel [4] developed a system that takes input from the user on two features of a part and also on their relative importance and suggests an optimal orientation. Their work does not estimate numerically the staircase effect and depends on the user to input the priority of the two features selected. It works only for primitive shapes.

Cheng *et al* [3] describe a method in which each face of the part is considered as the base for fabrication if the part is stable in that configuration. For each of such configurations, the surface area of the face is multiplied by a weight factor that is obtained by considering the effects of staircase effect, support structures, etc. The sum of these quantities over all the faces of the part is used to suggest the best configuration. The configuration with the maximum sum is the best orientation. If more than one of these sums are similar, then the orientation with the smallest build time is selected.

Pududhai and Dutta [8] have considered two different criteria; number of slices and ratio of the staircase area to the total surface area, and suggested an algorithm to find out the optimum build orientation. The primary criterion was the number of slices and the secondary criterion was the ratio of the staircase area to the total surface area of the part. The errors that result from the manufacturing process itself are not considered in their work.

Bablani and Bagchi [2] developed an algorithm to calculate the process planning error, process error and the number of layers. Input is sought from the user on the axis of rotation and the interval of rotation and for each of the orientations the error is quantified and the preferred orientation is suggested. The characterization of process errors was applied only to those processes that use laser beam and photosensitive polymers to build parts.

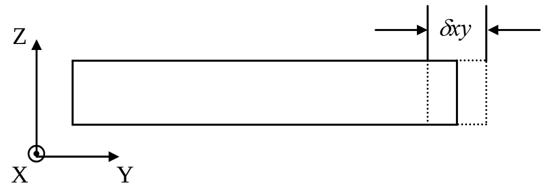


Figure 3. *xy*-error in a layer

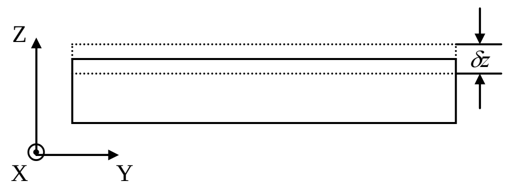


Figure 4. *z*-error in a layer

Thompson and Crawford [13] proposed a method that suggests the optimal orientation using four main objectives, viz. minimizing the build height and the number of supports and maximizing the surface accuracy and the strength of the part. The problem is formulated by choosing one of the four of these objectives as the final objective function and the remaining three as constraints. The problem is then solved optimally to get the best orientation.

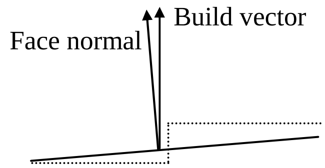
Suh and Wozny [11] developed a method based on feature recognition principles to obtain the optimal part orientation. An objective function is defined with criteria like the height of the trapped liquid, area of the part requiring supports, part strength, surface finish, etc. For each of these criteria, different features are extracted from the model to evaluate the criterion. The objective function is then evaluated using non-linear optimization techniques to find out the best build orientation.

Gupta *et al* [6] have developed an algorithm for finding near-optimal build orientation for Shape Deposition Manufacturing (SDM) process. SDM is a solid freeform fabrication process that allows the creation of complex shaped parts by the iterative application of numerically controlled material deposition and milling operations. The idea behind their algorithm to find a near-optimal build orientation is as follows. They consider a unit sphere that represents all possible orientations and form the set of spherical polygons by taking the intersection of all great circles corresponding to various direction normals in the part. They find the best build orientation within each spherical polygon. Finally, the global best build orientation is selected by comparing best orientations from individual spherical polygons.

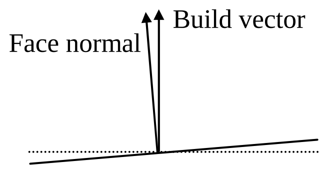
3. MATHEMATICAL MODEL OF ACHIEVABLE ACCURACY IN SFF PROCESSES

We have developed a process model by making an abstraction of the SFF process as a layer manufacturing and layer assembly process. The process model takes into account the dimensional errors, both in the direction of the build vector and in the plane of the layer being built. We identified the following three primary sources of part inaccuracies:

- *Staircase errors*: Solid Freeform Fabrication processes are based on the layered manufacturing paradigm. Layers of finite thickness are used to build the part. As a result, there will be a staircase effect on the part. The effect of staircase error can be seen in the Figure 2. Every layered manufacturing technique has a *build direction* associated with it. Build direction is the direction, normal to which, the part to be manufactured is sliced into layers. The extent of this staircase effect depends on the layer thickness and the relative orientation of the build direction and the face normal. The minimum layer thickness for a given process is known. Therefore, for a given process, the primary factor that determines the extent of staircase effect is the angle between the build orientation and the face normal. Various parameters like the surface flatness, dimensional accuracy, and other geometric tolerances, are affected by staircase errors.

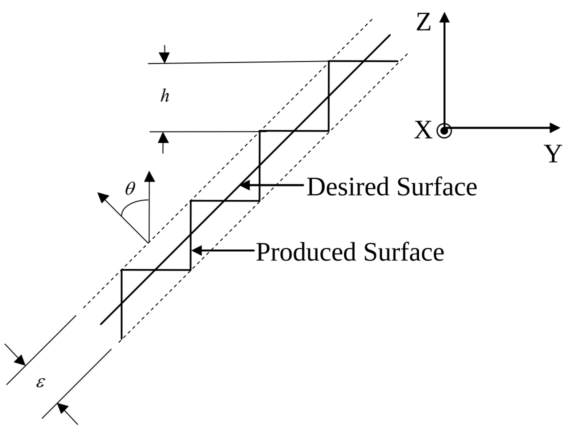


(a) Introducing stair-step may introduce large error

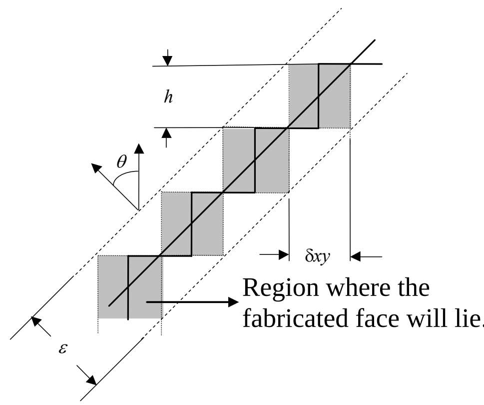


(b) Not introducing stair-step may introduce smaller error

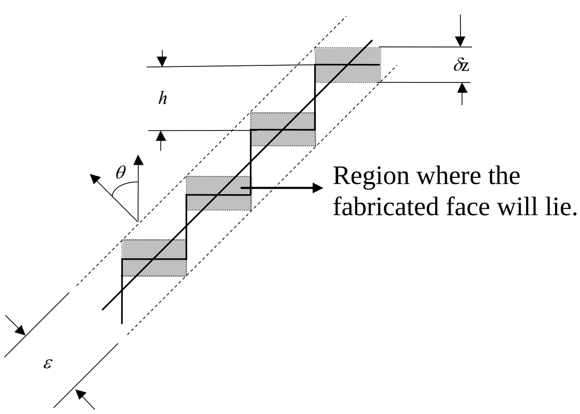
Figure 5: Building faces when the angle between the face normal and build vector is close to zero or π



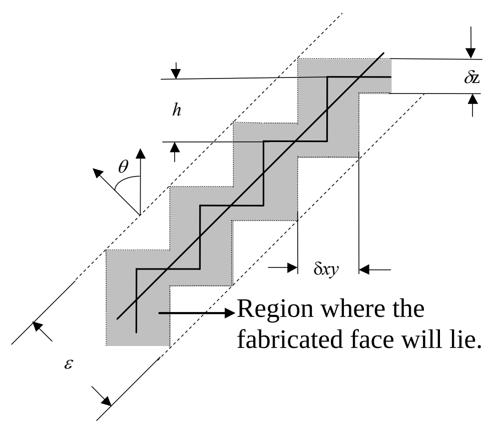
(a) Only staircase error



(b) Staircase error with only *xy*-error



(c) Staircase error with only *z*-error



(d) Staircase error with both *xy* and *z* errors

Figure 6: Effect of *xy* and *z* errors on the flatness error

- *xy-errors*: There could be a variation in the layer, in the plane of the layer, due to machine specific and process specific errors. For instance, as an electro-mechanical system drives the mirrors or the head seating the source of fused material, every time a new layer is built, it may not be exactly located as desired. Depending upon the particular process, there would be other parameters like the width of the laser beam and the post-cure shrinkage in the case of SLA, which will affect dimensional accuracy in the plane of the layer. The *xy*-error denotes this overall inaccuracy in the layer due to the effect of the various parameters mentioned. Figure 3 shows this error.

- *z-errors*: There could be a variation in the layer, normal to the plane of the layer, due to machine specific and process specific errors. For instance, as and when a new layer needs to be formed, the platform which supports the already formed part of the object being manufactured is lowered so as to accommodate the new layer that is to be built. The system that controls the lowering of the platform would have its own limitations and thus would introduce error in the *z*-direction movement and this would in turn affect the thickness of the layer being built. As in the case of the *xy*-error, depending upon the particular manufacturing process, other parameters like the post-cure shrinkage in the case of SLA cause dimensional inaccuracies in the layer normal to its plane. This value of the inaccuracy of the layer thickness in the build direction, due to the combined effect of the various parameters stated, is the *z*-error. Figure 4 shows this error.

We conducted a case study in which we built a test part using Sanders ModelMaker II process. The details of the case study are explained in [1]. The part was then measured on a coordinate measuring machine and using the deviations from the nominal dimensions, representative values of the *xy* and z errors were estimated. The value of *xy* error for the process was estimated to be 0.05mm. The value of *z*-error for the process was estimated to be 0.04mm. These values were used for the *xy* and *z* errors for the purpose of the example in Sections 5.4 of this paper.

In deriving the mathematical model for the flatness error on a planar face, two cases would arise which need to be treated separately. These cases arise depending on whether or not a stair-step is introduced to approximate the face. Whether or not a face is approximated by a stair-step depends upon the value of the layer thickness, the angle between the normal to the face and the build vector and the dimensions of the face. In general, faces are built by stair-step approximation. However, as shown in Figure 5, when the angle between direction normal of the face and the build vector is close zero or π, introducing a stair step may introduce more error than approximating the face by a horizontal face. Figure 5(a) shows the stair-step approximation and Figure 5(b) shows the horizontal layer approximation. The combination of the models in these two cases for a planar face would give the overall model for the flatness error for that face. The following two sections discuss how each of these models are derived to build the composite mathematical model.

3.1 Mathematical model when a stair-step is introduced on the face

Figure 6 shows the effect of *xy* and z errors on the flatness error of a planar face. The coordinate frame of reference is as shown in Figure 6(a). Based on the errors shown in Figure 6, the following mathematical model is used to describe the flatness error of a planar face.

$$\begin{aligned} \varepsilon &= (h+\delta z)\cos\theta + (\delta xy)\sin\theta && \theta_{cr} < \theta <= \pi/2 \\ &= -(h+\delta z)\cos\theta + (\delta xy)\sin\theta && \pi/2 < \theta < \pi - \theta_{cr} \end{aligned}$$

where, ε is the flatness error on a planar face, h is the thickness of the layer used to build the part, θ is the angle between the build and face normal vectors, δxy is the *xy*-error, δz is the *z*-error, and θ_{cr} is a small angle. This angle θ_{cr} arises out of the difference in the mathematical models for the cases when a stair-step is introduced on the face and when it is not. When the angle between the build vector and the face normal is in the range (θ_{cr},π-θ_{cr}), then the projection of the face normal on the build vector is larger than the layer thickness due to which a stair-step has to be introduced on that face. The procedure to find out the value of the θ_{cr} is explained in Section 4.1.3.

When the build direction and the face normal are collinear, flatness is affected only by the *z*-error. When the build direction and the face normal are perpendicular to each other, flatness is affected only by the *xy*-error.

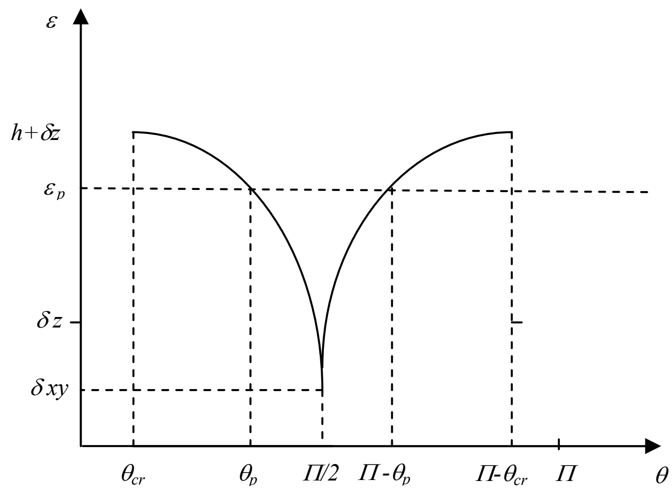


Figure 7. Effect of angle between build and face normal vectors

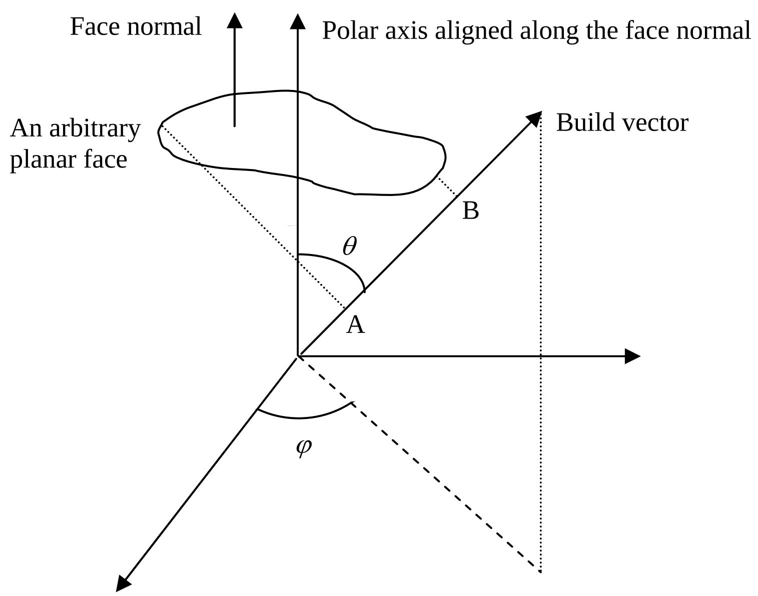


Figure 8. Projection of a planar face on the build vector

In Figure 7, ε_p is the permitted value of the flatness error specified on a particular face, and θ_p is an angle such that the interval $[\theta_p,\pi-\theta_p]$ represents the set of feasible orientations for the specified value of the flatness error ε_p.

3.2 Mathematical model when a stair-step is not introduced on the face

When no step needs to be introduced to build a face, then the flatness inaccuracy solely arises out of the z-error. A step should not be introduced in a planar face when the length of the projection of the face on the build vector is less than the thickness of the layer. The projection of a planar face on the build vector can be shown graphically as in Figure 8. The projection of the face on the build vector depends upon the relative orientation of the face with respect to the build vector. If we align the normal to the face along the polar axis of a spherical coordinate system (as shown

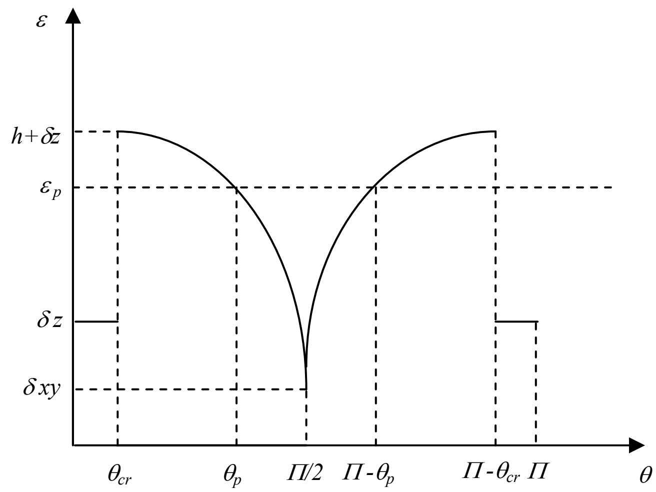


Figure 9. Composite mathematical model

in Figure 8) and the build direction is taken as any arbitrary vector, then for a fixed polar angle θ (angle between the face normal and the build vector), the projection of the face on the build vector, AB, would vary as the azimuth angle φ is varied.

The projection would also vary if the azimuth angle is fixed and the polar angle is varied. For every value of the azimuth angle, there exist two values of the polar angle such that the projection of the face on the build vector is equal to the layer thickness. If we call the smaller of the two angles as the critical polar angle θ_{cr}, then for all the polar angles between [0, θ_{cr}] and [π-θ_{cr},π], the projection of the face on the build vector will be less than the thickness of the layer. When the length of the projection is less than the layer thickness, no step will be introduced when building that face. In such a case, the flatness inaccuracy on that face will only be the z-error.

Using the same notation as in Section 3.1, the mathematical model for the flatness error in this case is the following.

$$\varepsilon = \delta z \quad 0 \le \theta \le \theta_{cr} \ and \ \pi - \theta_{cr} \le \theta \le \pi$$

Figure 9 shows the composite mathematical model for a given value of the azimuth angle.

4. ASSESSING MANUFACTURABILITY OF PART TOLERANCES

Given the initial orientation of the part, we consider a unit sphere. This unit sphere represents all possible build directions. For every possible tolerance T, we can construct a feasibility region on the unit sphere such that if we select the build orientation within this region, T will be achievable. By analyzing the effect of the layer-building process on various tolerances, it is possible to mathematically define feasibility regions for various types of tolerances.

For a given tolerance, the following three possible cases might arise with respect to the feasibility region:

- *There is no feasible build orientation*. The required tolerance is so tight that there is no build orientation that can satisfy this tolerance.

- *The set of feasible build orientations is a subset of the unit sphere*. The required tolerance is such that only a limited number of build orientations will be able to meet the tolerance requirements.

- *All build orientations are feasible.* The required tolerance is so relaxed that all possible build directions can produce this tolerance.

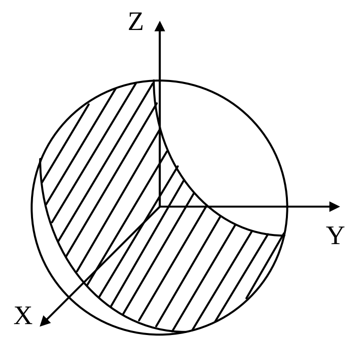


Figure 10. A band on a unit sphere

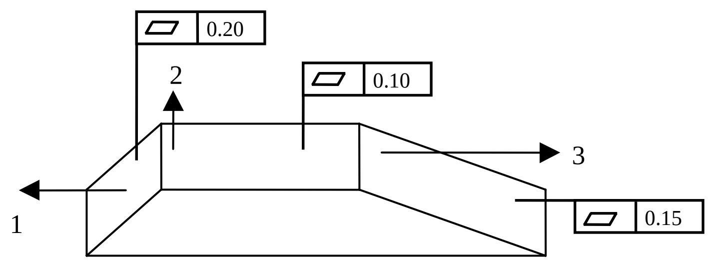


Figure 11. A simple manufacturable part showing the required flatness accuracies

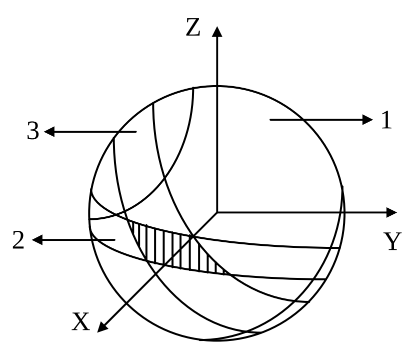


Figure 12. The feasibility regions for the part shown in Figure 11

4.1 Constructing Build Orientation Feasibility Regions for Flatness Tolerances

As the feasibility regions are mapped on to a unit sphere, we shall use the notation of a spherical coordinate system to mathematically represent the feasibility regions. To construct the feasibility region for a face, we align the polar axis of the spherical coordinate system along the face normal. Thus the polar and the azimuth angles could be used to represent the extent of the feasibility region. The discussion presented in this section is applicable to every planar face on which a flatness tolerance has been specified.

The nature of the build orientation feasibility region and the procedure to compute it are different for the cases in which a stair-step is introduced on the face and when it is not.

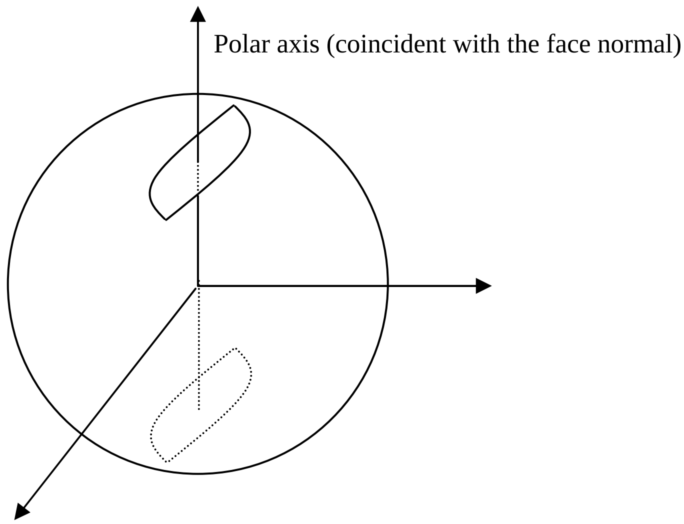


Figure 13. Feasibility region for case 2 in Section 4.1.2

4.1.1 Feasibility region when a stair-step is introduced on the face

If the permitted value of the flatness error on a face is denoted by ε_p, then the mathematical model shown in the Figure 7 presents three distinct cases. These three cases are described below:

1. If $\varepsilon_p > \delta xy$, then the feasibility region S, on a unit sphere, in the usual notation of a spherical coordinate system, will be defined by,

   $$S = \{ (r,\theta,\varphi) \mid r=1;\ \pi/2-\theta_p \leq \theta \leq \pi/2+\theta_p;\ 0 \leq \varphi \leq 2\pi \}$$

   This represents a band on the unit sphere, which is symmetrical about a diametrical plane (as in Figure 10).

2. If $\varepsilon_p = \delta xy$, then the feasibility region is given by,

   $$S = \{ (r,\theta,\varphi) \mid r=1;\ \theta = \pi/2;\ 0 \leq \varphi \leq 2\pi \}$$

   This represents a *great circle* on the unit sphere. A great circle on a sphere is a circle whose radius is equal to the radius of the sphere itself. This can be approximated by a band of very small thickness.

3. If $\varepsilon_p < \delta xy$, then the feasibility region, for the case when a stair-step is introduced, will be empty.

Figure 11 shows a simple part with requirements on the flatness accuracy specified on three of its planar faces. The feasibility bands for these faces are shown in Figure 12.

4.1.2 Feasibility region when a stair-step is not introduced on the face

When a stair-step is not introduced on the face, then, depending upon the value of the tolerance specified on that face, there could be two distinct cases. Suppose that the permitted value of the flatness error on the face is denoted by ε_p.

1. If $\varepsilon_p < \delta z$, then it is not possible to build this face since the best accuracy that can be achieved when no step is introduced is only δz. Thus, for this case, there is no region of feasibility on a unit sphere.

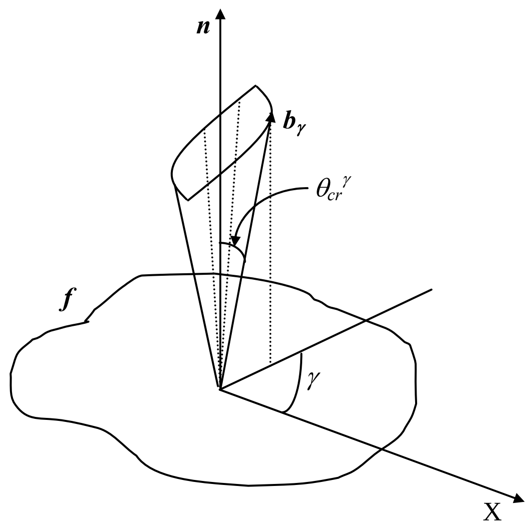


Figure 14. Computing the value of θ_{cr} for a given value of γ

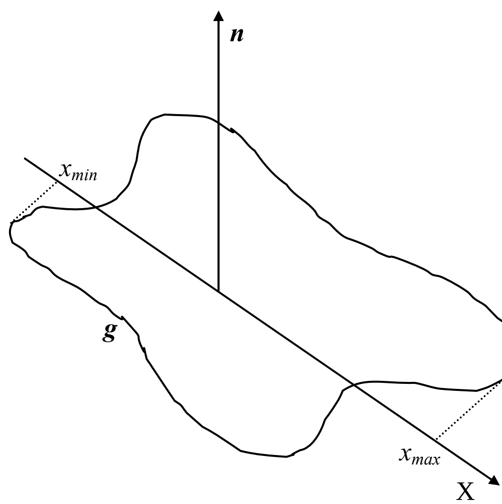


Figure 15. Finding the values of x_{max} and x_{min}

2. If $\varepsilon_p >= \delta z$, then as explained in Section 3.2 and the Figure 8, for a given value of the azimuth angle, the polar angle could be varied, starting from a value of zero, to find out the value of the critical polar angle θ_{cr} such that the projection of the face on the build vector is equal to the layer thickness. Similarly, different values of critical polar angles can be found out for different values of the azimuth angle. The values of the critical polar angle for different values of the azimuth angle can be plotted on a sphere. A closed curve can be obtained by joining all such points. This would denote a region such that if the build vector is inside it, then no step will be introduced on that particular face.

   Figure 13 shows such a region on a sphere. From the considerations of symmetry of the projection of the face on the build vector, it can be seen that the value of θ_{cr} is the same when the azimuth angle is φ and $\pi+\varphi$. Hence, the closed region obtained is symmetrical about the polar axis. Moreover, for the same azimuth angle φ, if the angle between the build vector and the face normal is in the range $[\pi-\theta_{cr},\pi]$, then it can be seen that projection of the face on the build vector is again less than the layer thickness. Hence, there is another exactly similar region diametrically opposite to the first region. These two regions constitute the feasibility region for the case when a stair-step is not introduced on the face.

4.1.3 Procedure for finding the value of θ_{cr}

For every planar face on which a flatness tolerance has been specified, we need to construct a cone, as shown in Figure 14, around the face normal such that if the build vector is inside the cone, then the projection of the face on the build vector is less than the layer thickness. In Figure 14, $\boldsymbol{f}$ denotes the planar face, $\boldsymbol{n}$ is the face normal, $\boldsymbol{b}$ is the build vector, γ is an angle that varies from 0 to 2π and is measured with respect to an axis X that is arbitrarily fixed in the plane of the face, and θ_{cr}^{γ} is θ_{cr} for a given value of γ.

Let $\boldsymbol{f}$ denote the face in its original configuration, $\boldsymbol{g}$ denote the face that is obtained by rotating $\boldsymbol{f}$ by a certain angle about the face normal, h denote the thickness of the layer and $\delta\gamma$ denote the increment in γ. The following is the procedure to find out value of θ_{cr} for different values of γ:

Step 1:

a. Initialize γ to 0.

b. Select the value of $\delta\gamma$ (we choose a value of 1° because it is small enough an increment to be used to vary γ from 0 to 360 degrees and provides an estimate of θ_{cr} with sufficient accuracy)

Step 2:

While $\gamma<2\pi$, do the following.

a. Rotate the face $\boldsymbol{f}$ by $-\gamma$ about $\boldsymbol{n}$ and call the rotated face $\boldsymbol{g}$.

b. Find the values of x_{max} and x_{min} of $\boldsymbol{g}$ (as shown in Figure 15) and set $L= x_{max} - x_{min}$.

c. $\theta_{cr}^{\gamma} = \arcsin(h/L)$

d. Set $\gamma = \gamma + \delta\gamma$

4.2 Algorithm for Manufacturability Analysis

We use the following algorithm to perform the manufacturability analysis:

Step 1: Construct the build orientation *feasibility regions*.

For every part feature that needs control on its accuracy, the feasibility region is constructed on a unit sphere representing all possible build orientations (Section 4.1 describes our approach for computing feasibility regions). The feasibility region for a feature is the set of all points on a unit sphere such that if the build vector lies inside this set, then the specified tolerance is achievable for that feature.

Step 2: Intersect all the feasibility regions.

- If the final common feasible region is not empty, then the part is manufacturable to the specifications.
- Otherwise, the part is not manufacturable.

5. IMPLEMENTATION

We have implemented a system based on the algorithm described in the previous section. The input to our system consists of the following three main components:

- geometry of the part
- tolerance information on the part
- process parameter information

Using this information, our manufacturability analyzer determines whether the part is manufacturable to the specifications or not.

There are primarily two kinds of users – process providers and designers. Process providers signup with the service and create individual accounts using which they can register and update their process capability information.

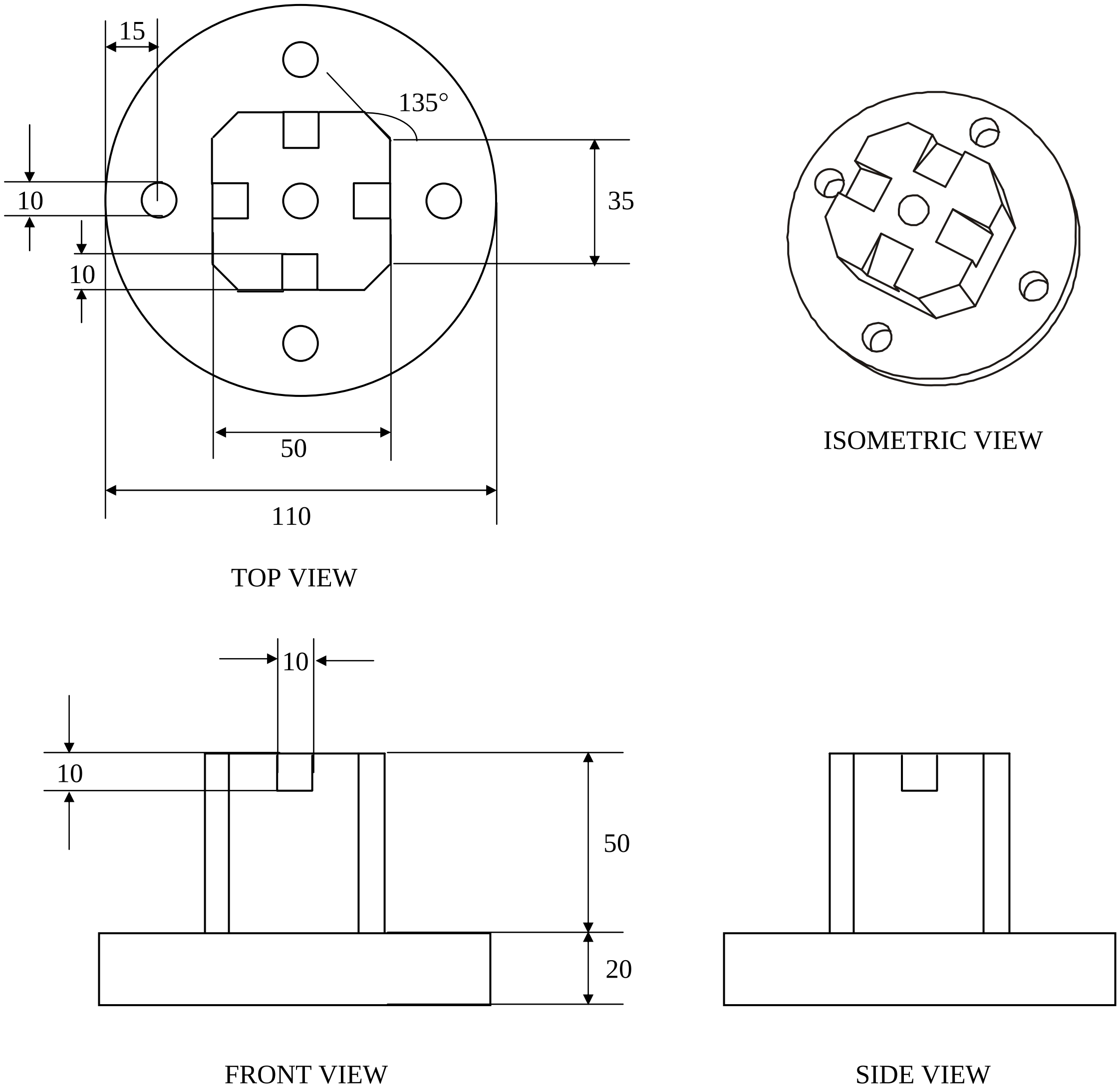


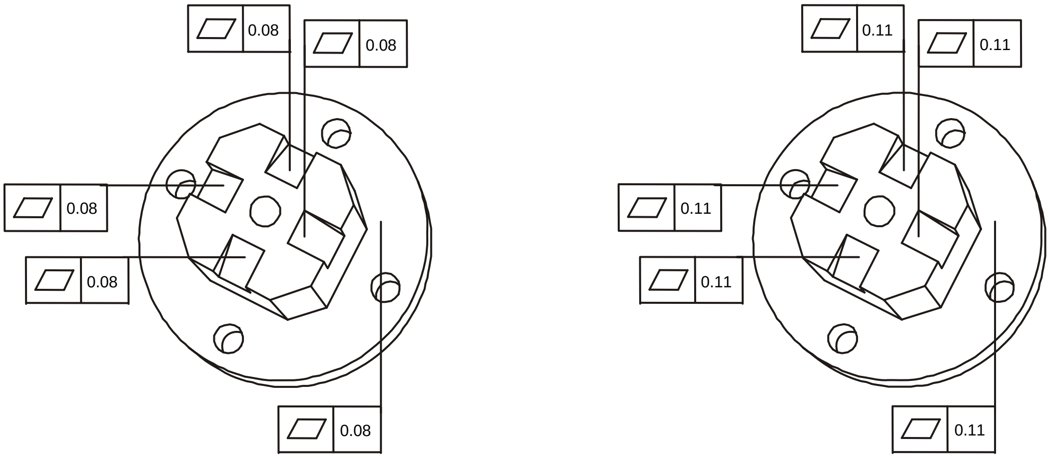
Figure 16. Drawing of the example part (not to scale)

Designers use our service to find out if their design can be manufactured by any of the existing layered manufacturing technology providers. They would upload the necessary geometry and tolerance information to our service and also select a process from the list of registered processes and perform a manufacturing feasibility analysis.

We make use of C++ and ACIS 4.0 to perform geometric computations. We use Java 1.2 and Java 3D to build the graphical user interface. As explained in Section 4.1.1, the region of feasibility contains a band on the unit sphere. Depending upon the specific case, the band could be empty or non-empty. We have developed an algorithm to perform the intersection of such feasibility regions and give the final result. Depending upon the result, a decision can be made on the manufacturability of the part. The following sections describe various inputs in detail and show an example.

5.1 Part Geometry Representation

We use ACIS *.sat* representation to represent the part. Currently tolerances are only assigned to the faces that are planar in nature. Input geometric models may contain curved surfaces. But these surfaces are not analyzed by our



(a)

Figure 17. Two cases of manufacturability analysis for the example

system. To maintain correspondence between various faces and tolerances, we assign a unique face number to each face in the model. Our current implementation is based on ACIS 4.0.

5.2 Part Tolerance Representation

We developed a graphical user interface in Java using the Java 3D packages that allows the user to interactively assign flatness specifications on various faces of the part to be manufactured. After the specifications have been assigned, a tolerance specification file is created. Tolerances for the part are written in a *.tol* file. A one-to-one correspondence is maintained between the face numbers in the part geometry file and the tolerance specification file.

5.3 Process Accuracy Description

We have developed an analyzer, which takes the part geometry file, the tolerance specification file and the process specification file and performs the manufacturability analysis. The following is a typical process specification file. The data shown in this file are the representative values of the process parameters obtained for Sanders ModelMaker II process.

```
#sanders.pro file
#process specification file (all dimensions in mm)
envelope 250 250 250
minimum_layer_thickness 0.0762
z_error 0.04
xy_error 0.05
```

where, *envelope* represents the dimensions of the largest part that can be manufactured by the process.

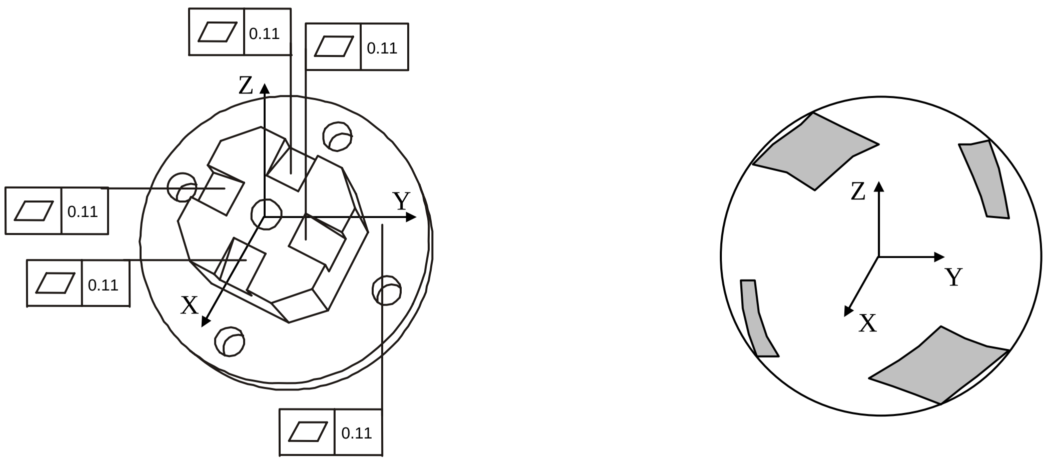
5.4 Example

Figure 16(a) shows an isometric view of the part considered in this section. Figure 16(b) shows the front view and Figure 16(c) shows the top view. Figure 17 shows the part with two different sets of flatness accuracy requirements. The results of manufacturability shown in this example are for the process data shown in Section 5.3.

- The part shown in Figure 17(a) is not manufacturable.

- In Figure 17(b), when the tolerance requirements are relaxed, the part becomes manufacturable.

Figure 18 approximately shows the sets of feasible build orientations as shaded regions on a sphere for the case in Figure 17(b).



(a): A possible set of tolerances (b):Feasible build orientations for part in (a)

Figure 18. Set of feasible build orientations

6. CONCLUSIONS

This paper describes a two step approach to analyzing the manufacturing feasibility of parts produced by SFF with flatness requirements on the planar faces of the part. We first analyze each specified tolerance on the part and identify the set of feasible build directions that can be used to satisfy that tolerance. As a second step, we take the intersection of all sets of feasible build directions to identify the set of build directions that can simultaneously satisfy all specified tolerance requirements. If there is at least one build direction that can satisfy all tolerance requirements, then the part is considered manufacturable. Otherwise, the part is considered non-manufacturable. Our research is expected to help SFF designers and process providers in the following ways. By evaluating design tolerances against a given process capability, it will help designers in eliminating manufacturing problems and selecting the right SFF process for the given design. It will help process providers in selecting a build direction that can meet all design tolerance requirements.

The mathematical model of accuracy presented in this paper is applicable only for flatness tolerances on the planar faces of the part. If tolerances like concentricity, cylindricity, etc. need to be analyzed, then suitable models of accuracy for non-planar faces need to be developed to mathematically express the relationship between the process parameters and the tolerances.

It is assumed in this paper that no secondary operations are performed on the part. In practice, secondary operations are performed to meet the final tolerance requirements. The approach developed in this paper could be extended to find out those tolerances from the given set that can be met so as to minimize the cost of secondary operations on those that are not met. The approach could also be extended to quantitatively estimate the cost of secondary operations on tolerances that are not met.

The manufacturability analysis algorithm only returns the set of feasible build orientations that can be used to fabricate the part. No optimization is performed to find out the best possible build configuration. By choosing a suitable objective function like build time, it is possible to extend the work to also perform an optimization to find out the feasible build configuration that optimizes the objective function.

The prototype service helps the designer to select a suitable process to manufacture the part. No advice is provided on the choice of material. The designer has to select a process every time he/she needs to perform an analysis. The system could be improved to analyze the given design using all the processes in the database. But the designer might have some requirements on the choice of materials. In that case, all the processes that can build the part using the chosen material should first be isolated. An analysis of the design could then be performed with all those processes.

We conducted a case study in which we built a test part using Sanders ModelMaker II process and measured it on a coordinate measuring machine. The data obtained from the measurements was used to estimate the values of *xy* and *z* errors of the process. The above process of experimentation could be formalized to estimate the process parameters for any SFF process.

ACKNOWLEDGMENTS

This research has been supported by a subcontract from Stanford University on the NSF Grant MIP-9617994. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of authors and do not necessarily reflect the views of the sponsors.

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