Automated Planning for Material Shaping Operations in Additive/Subtractive Solid Freeform Fabrication

Jianpeng Dong, Ju-Hsien Kao, Jose M. Pinilla, Yu-Chi Chang and Fritz B. Prinz

Stanford University
Department of Mechanical Engineering
Stanford, CA 94305-3030

Abstract

Combining the advantages of layered manufacturing and material removal processes, additive/subtractive solid freeform fabrication (A/S SFF) can build parts with complex shapes without compromising precision requirements. However, preparing material removal operations requires special expertise, which has in fact become one of the bottlenecks of the A/S SFF manufacturing process. To achieve automated planning, a shaping process planner is being developed based on 3D solid representation and a surface classification scheme. This planner can generate numeric control (NC) codes for CNC milling in an automatic fashion on non-undercut features of arbitrary 3D input geometry. Planning approaches are also presented in order to shape parts accurately and efficiently. The proposed shaping planner thus delivers on the promise of fully automated process planning in A/S SFF.

Keywords: CAD, CAM, Solid Freeform Fabrication , CNC Machining, Process Planning, Tool Path Generation, Automation

1. Introduction

In most Solid Freeform Fabrication (SFF) systems, CAD models are first decomposed into 2D layers, and then physical parts are built up layer by layer. Decomposing a 3D model and building a physical part in this fashion, however, can result in stair-steps on freeform surfaces; thus sacrificing surface finish and dimensional accuracy of the resulting parts [2].

Additive/subtractive Solid Freeform Fabrication (A/S SFF) combines the advantages of layered manufacturing and material removal processes, such as CNC milling, so it can build parts with complex shapes without compromising precision requirements. However, integration of material removal operations with material addition operations makes process planning for A/S SFF much more challenging than that for purely additive SFF [1]. In particular, preparing for shaping operations and generating numeric control (NC) codes for CNC milling require special expertise and experience, which have in fact become one of the bottlenecks of the A/S SFF manufacturing process. To make A/S SFF more productive, a process planner for shaping operations is indispensable.

In this paper, A/S SFF process will be examined from a process planning perspective. Then how to automate shaping operations will be considered. Based on a proposed surface classification scheme, strategies are presented to improve machining efficiency and maintain part accuracy. Finally, an example part is analyzed to show the capabilities of the proposed planner.

2. Shaping Process Planner

A/S SFF processes [1-3] involve iteration of material deposition and material removal operations, as can be seen from Figure 1. Starting with build direction selection, it then decomposes a CAD model into 3D layers with variable thickness using a 3D model decomposition technique. This technique can identify parting lines of undercut and non-undercut features of a model, and uses these parting lines to split the model [2, 4]. Part and support structures are thus constructed with extrusion operations in the computer. As a result, undercut features of the model will become non-undercut features of one of the decomposed 3D layers; thus no undercut features of the 3D layers need to be shaped during manufacturing. This model decomposition technique enables us to build 3D layers incrementally. Because these decomposed 3D layers can be shaped accurately with CNC milling machines, A/S SFF is capable of building complex parts with higher dimensional accuracy and better surface finish than purely additive SFF.

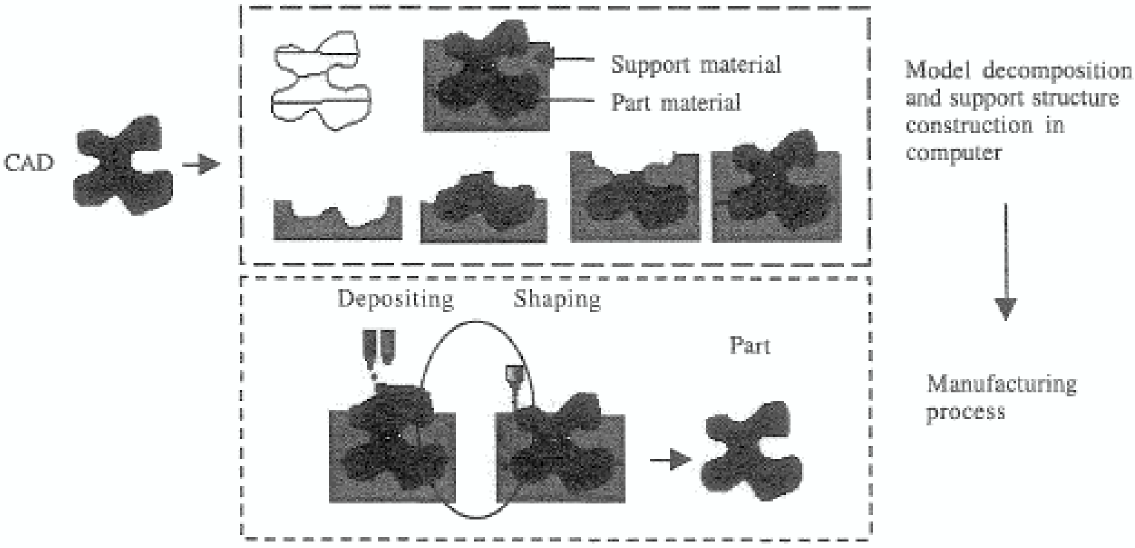


Figure 1. A/S SFF process planning

As discussed above, a distinct characteristic of shaping operations in A/S SFF is that only non-undercut features of the decomposed 3D layers need to be machined during manufacturing. Decomposing CAD models in this way also avoids fixture design for shaping these 3D layers because previously built layers form the natural support structures. In addition, model decomposition takes removal process constraints, such as cutter length, into account; thus making all non-undercut surfaces of each 3D layer accessible by cutters from above. Therefore, shaping process planning becomes easier than conventional CNC machining.

An automated shaping planner has been designed to be capable of generating NC codes for any given 3D layer without human intervention, which is shown in Figure 2. The inputs for this planner are decomposed 3D layers, and the outputs are the NC codes for shaping the layers. It also needs the cutter geometry information before tool paths can be generated and machine information before post-processing can be accomplished. The implementation of this planner lies on top of commercial CAD/CAM packages, Unigraphics, which provides toolkits to access to CAD model database and generate tool paths.

In this paper, the discussion will focus on planning finishing operations on 3-axis CNC milling machines because finishing operations take the majority of the machining time and are crucial to part dimensional accuracy and surface finish.

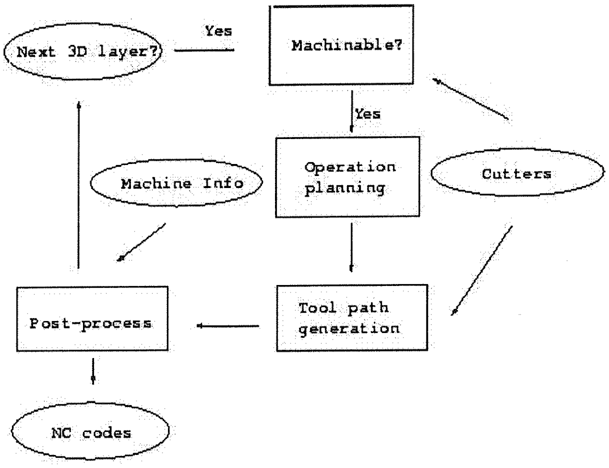


Figure 2. Shaping planner

3. Tool Path Generation

The essential tasks of a shaping process planner are to select and organize different shaping operations and to generate tool cutting paths over the model surfaces to be shaped. These selection and organization decisions are based on what tool path generation methods are available and how tool paths are generated. A variety of tool path generation methods have been developed. Most of recent research work focuses on generating tool paths over freeform surfaces. Usually, a model is a mixture of a variety of surfaces; hence an automated planner should deal with the whole model instead of individual surfaces. But generating tool paths over different types of surfaces is rarely studied. Several non-commercial approaches have been proposed, but they are either impractical or too hard to have a robust implementation [5-7, 10].

In this study, two widely available types of tool paths, layer-based and projection-based, are used. In the case of layer-based methods, a group of parallel planes of constant spacing (which is called the cutting depth) are used to slice the whole model, and intersection curves of these planes with the model are offset with respect to the cutter geometry to form the tool paths. In the case of projection-based methods, a loop of curves are selected as boundary curves. The boundary curves are then recursively offset by a constant distance (which is called the step-over distance). The resulted offset curves are projected onto the up-facing surfaces in order to update the z coordinate of each point of the offset curves. These modified curves are the tool paths.

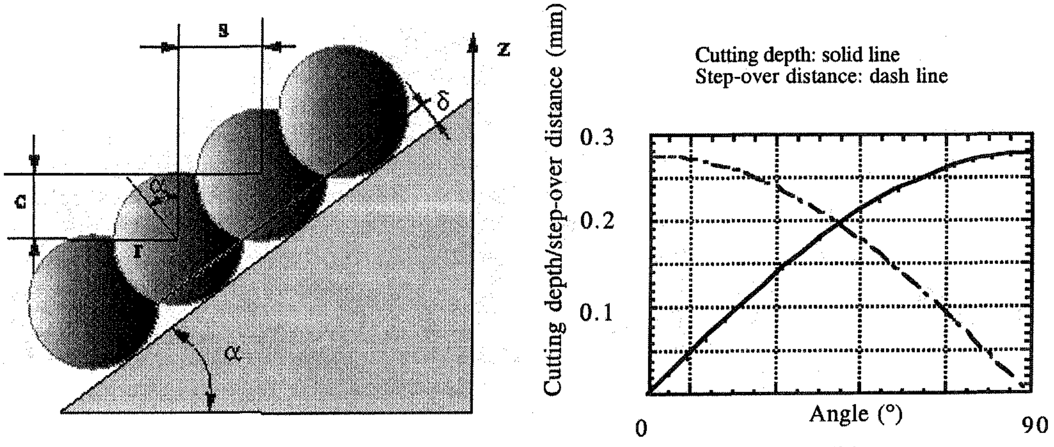
The most important parameters controlling the machining tolerance are cutting depth (in the case of layer-based tool paths) and step-over distance (in the case of projection-based tool paths). Both of them are required by the CAM packages to be **constant** during tool path generation. Some variations do exist [8,9]. For instance, the whole model can be divided into several blocks. Within each block, the constant constraint is required, but the values chosen in different blocks may be different. In addition, the number of such blocks are limited. Owing to these constraints, each method may produce longer tool paths than necessary to meet the machining tolerance. If the cusp height of material left over after the model is machined is used as a measurement of the machining tolerance, how the ideal cutting depth or step-over distance changes as the normal of a to-be-shaped surface changes can be shown in Figure 3.

Figure 3 (a) shows an inclined face being shaped with a ball endmill. The relationship between machining tolerance δ, cutter radius r, face inclining angle α, step-over distance s and cutting depth c is given in the follows expressions:

$$c = \sqrt{r^2 - (r - \delta)^2}\,\sin\alpha \quad (1)$$

$$s = \sqrt{r^2 - (r - \delta)^2}\,\cos\alpha \quad (2)$$

As can be seen from Figure 3 (b), the ideal cutting depth of layer-based tool paths will have the minimum value when the inclining angle α is equal to 0°, and it will have the maximum value when α = 90°; On the other hand, the ideal step-over distance of projection-based tool paths will have the minimum value when α = 90°, and the maximum value when α = 0°. It can also be seen that when α = 45°, the ideal cutting depth and step-over distance have the same value. Owing to the restriction that both cutting depth and step-over distance should be kept constant during tool path generation, the smallest cutting depth or step-over distance value has to be chosen when a freeform surface is to be shaped; otherwise, the machining tolerance can not be guaranteed where the corresponding ideal values are smaller than the specified values. However, this smallest value will lead to longer machining time where the ideal value is greater than the specified one; thus sacrificing machining efficiency in this case. Ways of improving the machining efficiency have to be found.



(a) (b)

Figure 3. Normal direction effect on cutting depth and step-over distance. Cutter radius is 12.7 mm, and cusp height is 0.003 mm.

4. Surface Classification

Considering the effect of surface steepness, non-undercut surfaces (because in A/S SFF only non-undercut surfaces of a compact are to be shaped) are classified into three categories: (1) vertical walls which have normal perpendicular to the z direction; (2) horizontal faces which have normal parallel to the z direction; (3) freeform surfaces or inclined faces. Furthermore, freeform surfaces and inclined surfaces are identified as flat and steep surfaces. The criterion for distinguishing a flat surface from a steep one is to use a 45° angle between the surface normal and the build direction. If the surface normal forms an angle less than or equal to 45° with the z direction, this surface will be identified as steep surface; otherwise, it is flat. If necessary, a freeform surface will be split into flat and steep portions based on the same criterion.

Different types of surfaces should be shaped differently. For instance, to machine vertical walls or horizontal planar surfaces, flat end-mills are usually used; while ball end-mills are usually used to machine curved freeform surfaces or inclined faces on 3-axis CNC machines. To enhance machining efficiency, freeform surfaces or inclined faces are further categorized based on their surface normal values. The details will be illustrated in Section 5.

5. Machining Strategies

5.1 Hybrid-machining

Machining using either layer-based or projection-based approaches alone is inefficient because the cutting depth or step-over is restricted to be constant. One solution is to apply layer-based and projection-based tool paths one after the other, shaping the whole model. In this case, the smallest ideal step-over distance or cutting depth value does not have to be used. Instead, the corresponding values at a 45° angle are used. The reasons are as follows. If the ideal step-over distance at 45° can achieve the specified machining tolerance, then using the same step-over distance will produce smaller cusp heights over those surfaces with a normal greater than 45°. Similarly, if the cutting depth at 45° can achieve the specified machining tolerance, then using the same cutting depth will produce smaller cusp heights over those surfaces with a normal less than 45°. By applying both tool paths, the whole model is guaranteed to be shaped to the specified machining tolerance.

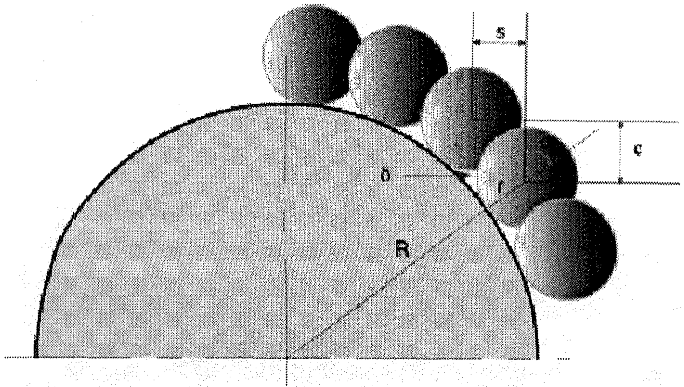


Figure 4. Relationships between different machining approaches

This strategy significantly reduces the machining time even though almost every surface will have to be shaped twice. A simple example is shown in Figure 4. As can be seen, a half-sphere with a radius of 50 mm is being shaped by a ball end cutter with a radius of 12.7 mm. The cutting feed rate is 1000.0 mm/min. No cutter change or tool engage and retract time is considered. If each type of tool paths is applied alone, to shape this model to the specified tolerance, which is assumed to be 0.003 mm, more than 20 hours has to be spent on machining, as can be seen from Table 1. By applying both tool paths, since a greater step-over distance and cutting depth can be used, the machining time is reduced by two orders of magnitude. Obviously, this strategy is still not efficient because almost every surface of the model has been machined twice.

Table 1. Machining efficiency comparison of different tool path generation approaches (Time in minutes).

Approach	Layer-based	Projection-based	Hybrid	Splitting
Machining time	2028	1292	29	20

5.2 Surface-splitting

To avoid machining every surface twice, a surface splitting approach is proposed to distinguish surfaces based on surface normal distribution. First, classify all the surfaces based on the scheme presented above. If necessary, split freeform surfaces and inclined surfaces into flat and steep portions. Generate tool paths on vertical walls or horizontal planar faces using flat end-mills, and generate layer-based tool paths on steep portions and projection-based tool paths on flat portions separately using ball end-mills.

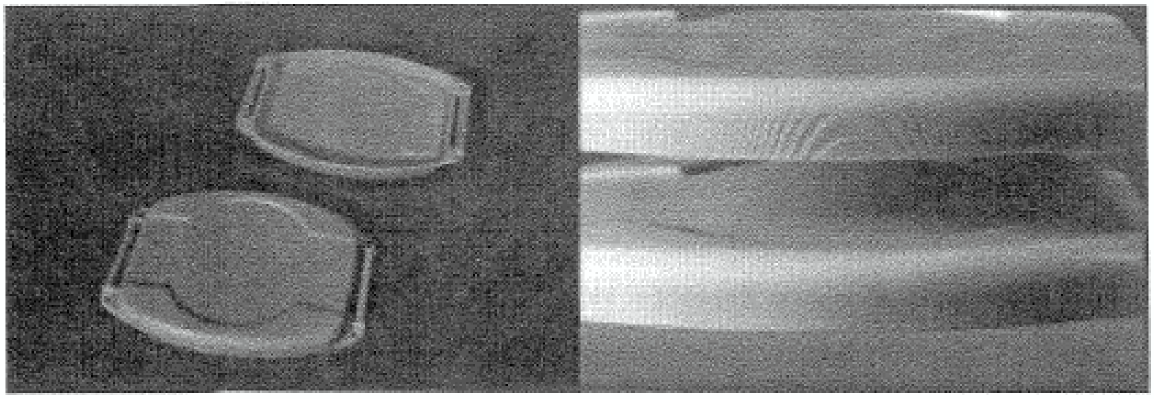
A similar algorithm to model decomposition has been developed in order to find the boundary curves between flat surface portions and steep ones in the model. In this case, instead of finding the parting lines (each point on which has a normal perpendicular to z direction), the splitting curves (each point on which has a normal parallel to a planar face with either a 45° inclination angle) need to be identified. Once the splitting curves are found, they are used to identify which portions of a surface should be machined using layer-based tool paths and which portions should be shaped using projection-based tool paths. Furthermore, same type surfaces can be grouped together; thus reducing the total number of operations.

If this approach is applied to the same model shown in Figure 4, it reduces machining time by about 1/3 compared with the above hybrid-machining method, as can be seen in Table 1.

6. Case Study

The proposed shaping planner can be used to shape non-undercut features of any 3D layers and output the NC codes with few limited manual inputs, such as cutter information (tool number) and machining tolerance. Currently, it also needs to manually identify narrow deep cavities and select different cutters based on the geometry of such cavities. But an automated cutter selection module will be developed as a part of the planner based on a medial axis transform (MAT) representation of the model [11].

Figure 5 shows two sample parts built with this planner. The right photograph shows two parts shaped with different approaches. The above one was shaped only using projection-based tool paths. The bottom one was shaped using hybrid-machining approach. Both of them use the same step-over distance. As can be seen from this photograph, the hybrid-machining approach exhibits better surface quality. Because a greater step-over distance and cutting depth were adopted, the machining efficiency was also enhanced.



(a) (b)

Figure 5. Sample parts built using different approaches. (a) Sample parts, (b) parts shaped by projection-based tool paths alone (above) and by hybrid-machining approach (bottom)

7. Conclusions

A generic shaping operation planner purely based on model geometry is presented. Using widely available tool path generation methods, its implementation is simple and its performance is robust. Two approaches, hybrid-machining and surface-splitting, are proposed to reduce machining time and enhance efficiency of the material removal operations in A/S SFF. In particular, the proposed surface-splitting approach can reduce machining time by two orders of magnitude. This method splits the surfaces into different portions or distinguish individual surfaces into different types based on surface normal. Tool paths are then generated by alternatively applying layer-based and projection-based methods on different types or portions of surfaces. This planner will not only reduce the planning overhead introduced by the shaping operations in A/S SFF, but it will eventually become part of a fully automated A/S SFF process planner.

Acknowledgments

The authors acknowledge support from the Defense Advanced Research Projects Agency, the Office of Naval Research and Unigraphics Solutions Inc.

References

[1] J. M. Pinilla, J. Kao and F. B. Prinz, 1998, Process Planning and Automation for Additive-Subtractive Solid Freeform Fabrication, SFF Symposium 1998, Austin, TX

[2] L. Weiss, R. Merz, et al, 1997, Shape Deposition Manufacturing of Heterogeneous Structures, Journal of Manufacturing Systems, 16 (4), 239-48

[3] A. G. Cooper, S. Kang, J. W. Kietzman, F. B. Prinz, J. L. Lombardi and L. Weiss, 1998, Automated Fabrication of Complex Molded Parts Using Mold SDM, SFF Symposium 1998, Austin, TX

[4] Krishnan Ramaswami, Process Planning for Shape Deposition Manufacturing, Ph.D. Dissertation, 1997, Stanford, CA.

[5] S. Marshall and J. G. Griffiths, 1994, A Survey of Cutter Path Construction Techniques for Milling Machines, INT.J. PROD. RES., 32 (12), 2861-77

[6] K. Suresh and D. Yang, 1994, Constant Scallop-height Machining of Free-form Surfaces, J. Engineering for Industry, 116 (2), 253-9

[7] R. Lin and Y. Koren, 1996, Efficient Tool-Path Planning for Machining Free-form Surfaces, J. of Engineering for Industry, 118 (2), 20-8

[8] P. Kulkarni and D. Dutta, 1996, An Accurate Slicing Procedure for Layered Manufacturing, Computer-Aided Design, 28 (9), 683-97

[9] A. Dolenc and I. Makela, 1994, Slicing Procedures for Layered Manufacturing Techniques, Computer-Aided Design, 26 (2), 119-26

[10] B. S. Prabhu and S. S. Pande, 1999, Automatic Extraction of Manufacturable Features from CAPP Models Using Syntactic Pattern Recognition Techniques, 37 (6), 1259-81

[11] J. Kao, Ph.D. dissertation, 1999, Process Planning for Additive/Subtractive Solid Freeform Fabrication Using Medial Axis Transform, Stanford, CA.