A SLICING PROCEDURE FOR 5-AXIS LAYERED MANUFACTURING

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Abstract

The 5-axis layered manufacturing technology facilitates fabrication of a part with overhanging features without the use of supports, thereby making a direct-to-use part from the layered manufacturing technology a reality. In this paper we describe a direct slicing procedure for a CAD model, a crucial process planning task for the 5-axis layered manufacturing. The neutral exchange format IGES is used as the slice format. The G and M codes for a CNC 5-axis laser deposition machine are generated from the slice format and the deposition process is simulated. Implemented examples are included to explain the slicing procedure. Exciting possibilities for the future work on the slicing procedure are discussed.

Introduction

Layered manufacturing refers to the fabrication of physical parts layer-by-layer. It involves successively adding raw material, in layers, to create a solid of some predefined shape. The use of layered manufacturing typically results in a significant reduction in the component manufacturing times from the conventional metal forming/cutting technologies. When creating a part layer-by-layer, the geometric complexity of the part has significantly less impact on the fabrication process. Furthermore, manufacturing a component of Functionally Graded Material is very much possible with layered manufacturing technologies. Layered manufacturing includes the processes Solid Freeform Fabrication and Desktop Prototyping.

The use of layered manufacturing technology is currently restricted to prototyping, i.e. creating a physical part for the purposes of analyzing its form, fit or function. The use of layered manufacturing typically results in a significant reduction in the component manufacturing times from the conventional metal forming/cutting technologies. With advances in process planning tasks of layered manufacturing and layered manufacturing technologies such as Directed Light Fabrication (DLF) [1], Laser Engineered Net Shaping (LENS) [2] and Direct Metal Deposition (DMD) [3], manufacturing of a functional metal component that can directly be put to use is not far. In the last few years, enterprises such as Precision Optical Manufacturing in Michigan, Aeromet Corporation near Minnesota and Optomec in New Mexico have began to commercialize these technologies [4]. Advances in the process planning tasks include the increasing use of CAD models instead of faceted STL models, the representation of heterogeneous and functionally graded material objects, the more efficient part orientation algorithms and the more efficient adaptive slicing algorithms to increase the surface quality. However, one impediment to the manufacturing of functional components is the issue of overhanging features and the hollow sections in a component. Present layered manufacturing techniques use sacrificial support structures, of a different material, to support the overhanging and hollow features, which necessitate subsequent post-processing operations apart from poor surface quality and increased build time. In this paper, we describe a procedure to manufacture a solid functional component without the use of support structures.

5-axis slicing procedure

To motivate the need for this 5-axis slicing procedure, we briefly describe the overhanging features and the use of support structures. The most common need for support structures occurs when material on one layer overhangs the previous layer by more than a specified amount [5]. Figure 1 shows a part with such overhanging features. Regions O_1 and O_2 cannot be deposited without the support structures in the build direction shown.

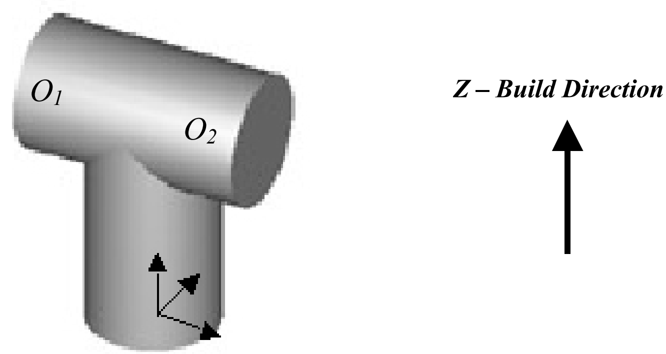


Figure 1. An example part with overhanging features

Since the use of support structures decreases the surface quality and increases the build time a new procedure is required. The 5-axis slicing procedure attempts to build such parts without the use of support structures.

A new generation of layered manufacturing machines has started to emerge in the research domains. A schematic sketch of one such layered manufacturing machine is shown in Figure 2. The machine shown in Figure 2 has 2 additional axes namely, *C*-axis and *B*-axis. *C*-axis allows rotation of the part in the *X*-*Y* plane around the Z-axis in both the directions. *B*-Axis allows the rotation of the part in the *Y*-*Z* plane around the *Y*-axis. These machines eliminate some of the inherent limitations of the existing layered manufacturing such as the overhang issue. The various tasks associated with the 5-axis slicing procedure are:

(1) Model decomposition.
(2) Sequencing the decomposed parts.
(3) Adaptive Slicing and
(4) Tool Path Generation.

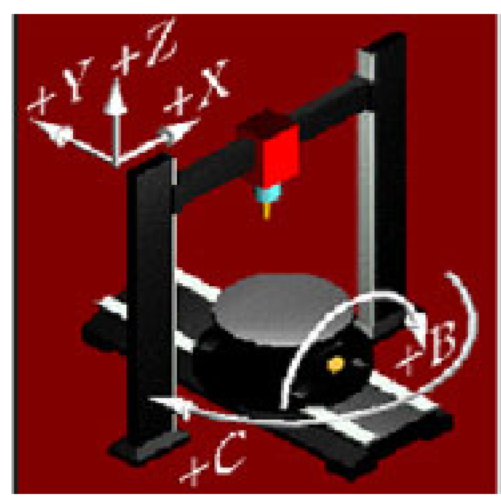


Figure 2. Schematic sketch of a 5-axis layered manufacturing machine

Model decomposition

The build direction is constant and it is assumed to be *Z*. The solid model with the overhanging features is decomposed into sub-volumes. Each of the sub-volume can be built along the given build direction *Z*.

The first task in model decomposition is to identify the overhanging features. Surface interrogation [6] is used as a tool to identify the overhanging features. This is accomplished by analyzing the angle θ that the surface normal, at any point on the model surface, makes with the build direction *Z*. The angle θ is called the overhang angle. At any point p if the overhang angle exceeds the permissible value θ_{max} then we can conclude that point p is a part of the overhanging feature.

Consider a C^1 continuous regular parametric surface $S(u,v)$ and let

$$n(u,v) = \frac{\partial S}{\partial u} \times \frac{\partial S}{dv} \tag{1}$$

be its normal vector field. θ, the angle between the build direction $\vec{Z}$ and the surface normal $n(u,v)$ can then be expressed as:

$$\cos\theta = \frac{\left\langle \vec{Z}, n(u,v) \right\rangle}{\left\| n(u,v) \right\|} \tag{2}$$

θ_{max} is the user specified maximum permitted overhang angle. From equation (2), it is possible to determine the point at which the overhang angle exceeds the maximum permitted value. All the points on the surface at which $\theta > \theta_{max}$ are determined by traversing through the surface. The lowest of all such points p_{min}, in the build direction, is then determined. An intersection section graph is obtained by intersecting the solid model with a horizontal plane at p_{min}. The intersection graph is swept in the build direction to obtain an infinitesimally thin tool body which is open on both the ends. The tool body is then subtracted from the solid model to separate the overhanging features from the solid model as shown in Figure 3. The total number of decomposed parts after the decomposition would be $n+1$, where n is the number of overhanging features. A similar technique with isoclines can also be used to identify the overhanging features [8].

(a) Model to be built (b) Decomposed model

Figure 3. Model decomposition

Sequencing the decomposed parts

The decomposed parts are to be built one-by-one in a sequence. Sequencing includes rotating each of the decomposed parts first around the Z-axis by an angle θ_Z and then around Y-axis by an angle θ_y at the machine origin. θ_Z is the angle between the central-axis of each of the decomposed parts and the ± X-axis in the X-Y plane at the height of the central-axis of that decomposed part. θ_y is always ± 90° such that the overhanging parts are built in the positive build direction Z. The decomposed part to which none of the rotation is applied and which can be built in the build direction is always the first in the sequence. This ensures the physical existence of a base surface on which to deposit. The rest of the sequence is determined based on the height of each of the decomposed part exists. The lowest overhanging decomposed part is second in the sequence and so on till the rest of the decomposed parts are built. Sequencing based on the height at which each of the decomposed part exists minimizes the chances of collision with the layers already deposited.

Adaptive slicing

Each of the decomposed parts is then sliced using the adaptive slicing algorithm [7]. Adaptive slicing involves slicing of the CAD model with varying layer thickness. The user can specify a maximum allowable cusp height for the object and also a deposition requirement (excess or deficient). In order to achieve the user specifications, surfaces of high curvature are sliced with thinner layer thickness and surfaces of low curvature are sliced with thicker layer thickness. Adaptive slicing yields better surface quality, as the staircase effect decreases and the variations in the cusp height across the layers are minimized. Adaptive slicing gives the user explicit control over the surface quality. The other advantage of adaptive slicing is a reduction in the build time. The slice is then reverse transformed to get them to their original location. The Figure 4 shows the model after adaptive slicing and reverse transformation of the slices.

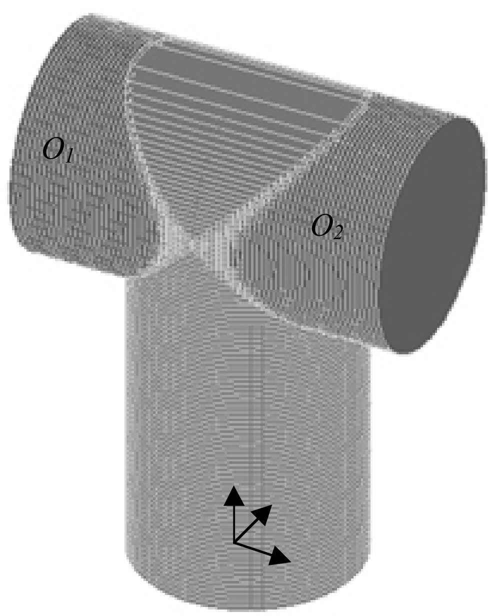


Figure 4. Adaptively sliced model for 5-axis layered manufacturing

Tool path generation

The slice data is obtained from the adaptive slicing procedure in the IGES data format as set of surfaces. Each slice is represented by a planar surface as shown in the Figure 4. These surfaces can be used in any commercially available CAM software with a 5-Axis capability to generate the CNC tool paths. In our case we used SURFCAM®‡. We treated each slice, in a bottom-up approach, as a surface that can be milled and used the 5-axis surface milling option to generate the tool paths that can be used for the 5-axis layered manufacturing machine. This procedure allows us to change the material deposition pattern layer wise giving us the capability to control the physical properties such as residual stresses. Figure 5 shows the steps involved in manufacturing our example.

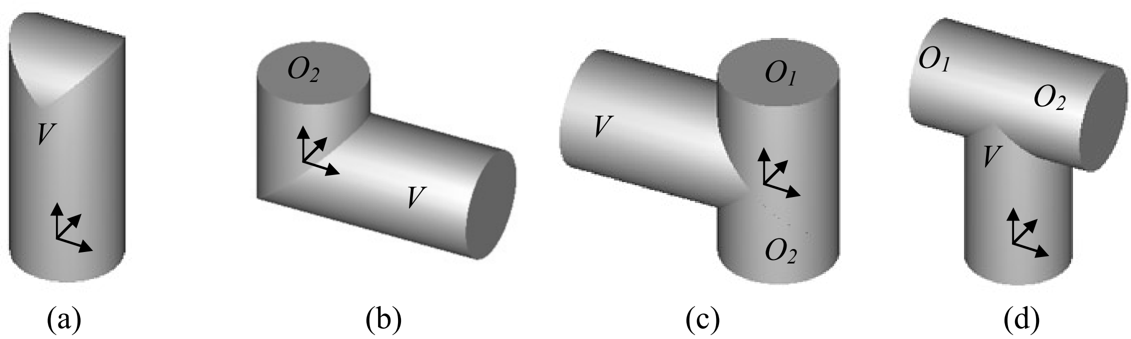


Figure 5. Steps involved in 5-axis layered manufacturing: (a) Vertical build-up of V, (b) Rotation of V and build-up of O_2, (c) Rotation of V & O_2 and build-up of O_1, (d) Model recreated

Algorithm

All the bounding surfaces of the model are first extracted along with their defining geometry. These surfaces are then converted into parametric spline surfaces. These surfaces are then analyzed to identify the overhanging features as explained in the earlier section. Once the lowest overhanging location is found then the model is chopped into buildable vertical regions and unbuildable overhanging regions. Each of these regions are then rotated first around the *Z*-axis and then around the *Y*-axis to make them buildable. Each region is adaptively sliced [7] and reverse transformed. The slices are then exported for path generation in IGES format. The algorithm, including the adaptive slicing, is summarized below.

‡ SURFCAM® is a registered CAD/CAM software from Surfware Inc.

Algorithm 5-axis Slicing

Input: 1. Parametric representation of the object *O*.
2. 3-axis or 5-axis
3. Cusp height, δ
4. Slice thicknesses L_{min} & L_{max}
5. Containment requirements: +ve or –ve.

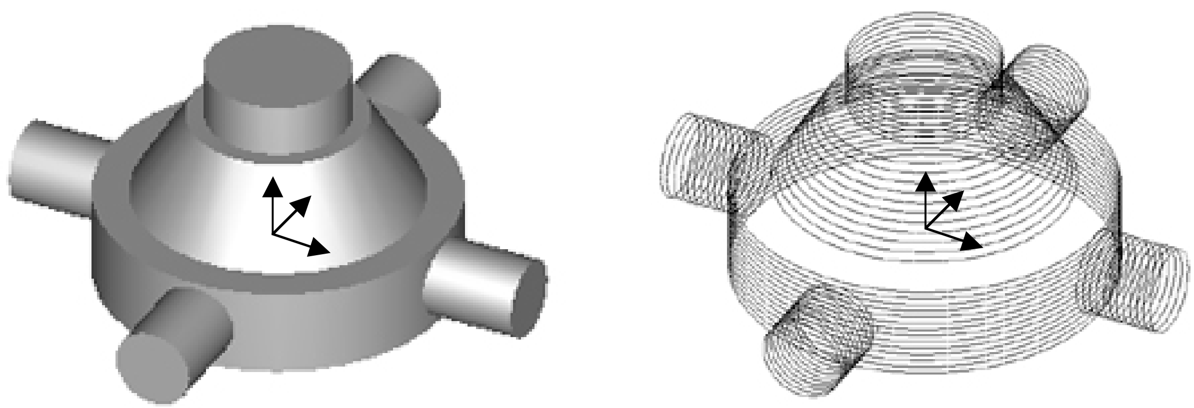
Output: The heights of all the adaptive slices for the layered manufacture of *O* in 3-axis or 5-axis

Set R= decomposed parts of *O*
Set S= all the surfaces that bound each *R*
Set B= blocks obtained by slicing the object through the vertices of each *R*

```
START

Overhang detection by the surface analysis of O
IF (overhang = TRUE)
    Decomposition of the model O into R
    Overhang detection by the surface analysis and decomposition of
    each R recursively.
    5-axis transformation of each R

WHILE  (R ≠0) DO
{5-axis transformation applied to R
     WHILE  (B ≠ 0) DO
     {    z= bottom of block
          WHILE  (z < top of block)
          {    Si = no. of surfaces that intersect with slice z
               I=0
               WHILE (I ≤ Si)
               {    d = layer thickness (Si, z, δ)
                    IF d > L_max THEN   height_i = L_max
                    ELSE IF d < L_min THEN height_i=L_min
                    ELSE height_i = d;
                    I=I+1}
               Slice thickness t= min. height_i;
               IF (sign_normal (z) = TRUE) containment => TRUE;
          }
          increment z = z+ t
     update B}
update R }

END
```

Implementation and examples

A prototype program has been implemented including the algorithms discussed in the previous sections. Based on the ACIS®[†] solid modeling kernel, the software module is built on a Sun Sparc workstation with an user interface based on Tcl/Tk[‡]. Figure 6(a) shows an example model, which is unbuildable with conventional 2.5-D layered manufacturing techniques without the use of support structures. However the same model can be built with the 5-axis layered manufacturing technique. Figure 6(b) shows the same model sliced for 5-axis layered manufacturing. The 5-axis layered manufacturing of this object is then simulated using the 5-axis surface milling features of the commercially available CAM software SURFCAM® demonstrating the feasibility of 5-axis layered manufacturing. The results are shown in Table 1. From Table 1, it is clear that adaptive slicing decreases the deposition time. Deposition times given are for the 5-axis deposition. Support structures and the associated post processing would only add up the deposition times.



(a) Unbuildable Model (b) Buildable in 5-axis layered manufacturing

Figure 6. 5-Axis adaptive slicing of a model

Table 1. Simulated deposition times (*Process Parameters: Nozzle Speed V = 14.82 mm/sec; Nozzle Diameter = 700 μm; Overlap = 10 %*)

Parameters	Example 1 (Figure 1)		Example 2 (Figure 6)	
Bounding Box Dimension	$26 \times 13 \times 36.5$ (mm)		$30 \times 30 \times 13$ (mm)	
Model Volume	6.7017 cm^3		2.7065 cm^3	
	Adaptive Slicing	Uniform Slicing	Adaptive Slicing	Uniform Slicing
Total No. of slices	269	296	123	136
Deposition Time	125 min 3 sec	137min 36 sec	48 min 39 sec	53 min 47 sec

[†] ACIS® is a registered geometric modeling kernel from Spatial Corporation.
[‡] Tcl/Tk is a freely available scripting language with extensions for creating user interfaces.

Conclusions

A procedure was developed for manufacturing an object, with overhanging features, without the use of support structures using 5-axis layered manufacturing process. 5-axis layered manufacturing is a promising new method to manufacture any given part. However, further development of this process is required. In this paper, we have considered only the solid objects with overhanging features. Further work is necessary to manufacture objects with hollow interior. The on-going development of multi-axis deposition machines in the research domains necessitates a more advanced procedure based on the concepts presented in this paper. This paper considered only one of the process planning tasks involved in the process namely the slicing, other process planning tasks such as part-orientation, sequencing and collision avoidance of the deposition nozzle with the object are to be investigated. The algorithm for overhang feature detection can further be optimized using a feature based detection procedure in addition to the surface analysis presented in this paper.

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