An Integrated Software System for Process Planning for Layered Manufacturing

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Abstract

An integrated process planning system for layered manufacturing (LM) reduces the time between design and part fabrication and improves the quality of the final part. Process planning for most LM processes includes part orientation, support structure generation, slicing, and path planning. In this paper we describe an integrated process planning system we are developing. Our software accommodates both novel and traditional design models as input, and supports a variety of LM processes. The modules described in this paper include Solid Builder Module, which generates a solid model from design data such as medical images, surface functions, or digital elevation models; Orientation Module, which determines the optimal build orientation of a part and automatically generates the support structures required; and Adaptive Slicing Module, which adaptively slices the part.

Introduction

Process planning for layered manufacturing (LM) is performed to generate the tool paths and process parameters for an object that is to be built by a particular LM process. The steps required are: part orientation, support structure generation, slicing, and path planning. The orientation of a part as it is built will affect the time to build the part, mechanical properties, surface quality and the need for support structures. Thus the first task is to determine an optimal orientation based on those criteria which are most important to the designer. With certain LM processes, layers which form overhangs or enclose voids must have a sacrificial support structure beneath them to support build material as it is added. Supports are built along with the part, possibly by a different material. Once an orientation for the part has been selected, support structures are designed. Then the part and its supports are sliced into manufacturing layers and finally tool paths are generated.

A process planning system is under development by the CAD/CAM Group at the University of Michigan Department of Mechanical Engineering and Applied Mechanics which is the synthesis of several software modules. The software accommodates both novel and traditional design models as input, and supports a variety of LM processes. The system currently has three component modules. The first, Solid Builder Module (SBM), receives design data in the form of planar images and assembles from them a B-rep solid model of an object. This solid model then becomes input to the other two modules in the system. The Orientation Module (ORM) finds the optimal build orientation for an object and generates support structures for it. The Adaptive Slicing Module (ASM) slices the solid model of the object and generates the necessary command files for driving a particular LM process. The final process planning step, path planning, is not treated in this paper because we currently use commercial software for this step. A schematic of the software system is shown in Figure 1. Each highlighted module is described in greater detail in the following sections.

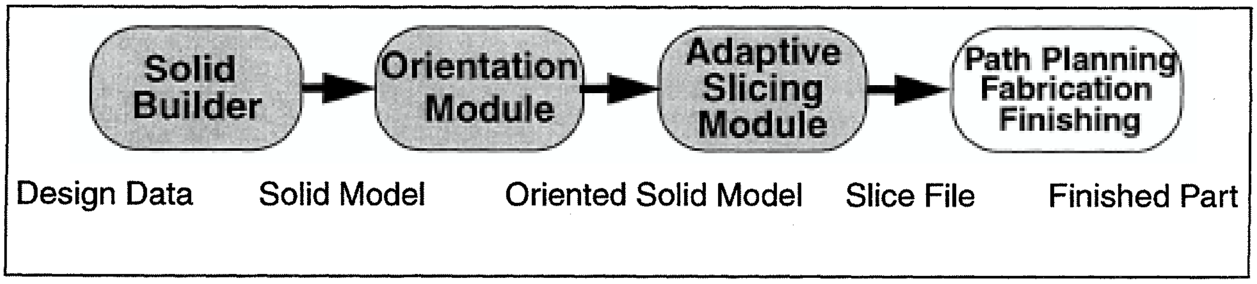


Figure 1. The structure of our software system

Our process planning system has the advantage that it accommodates both traditional and novel design inputs. The engineer can begin process planning with either a solid model of an object (in which case the SBM is bypassed) or image data. A second advantage is that the design model does not need to be converted into an .STL file in order to be read into the system. This increases the potential accuracy of the fabricated part and eliminates the need for .STL correction and repair. Finally, our system automates the process planning tasks resulting in high quality parts in lesser time.

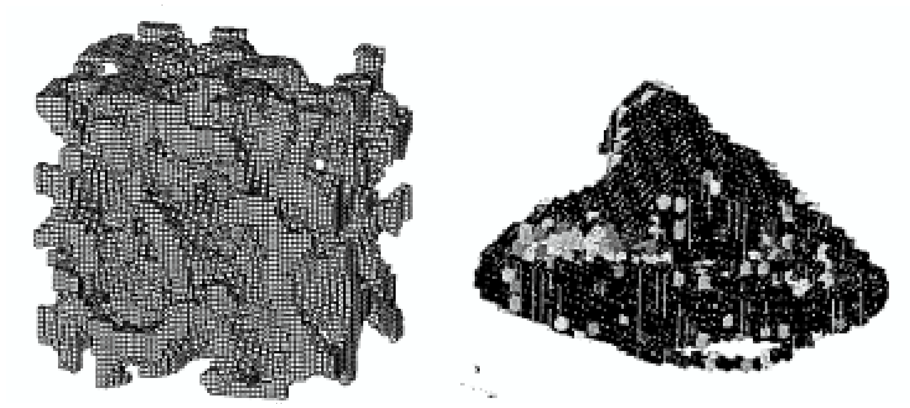
Solid Builder Module

Inputs

The Solid Builder Module takes as input design data and generates a solid model which is then used to prepare for part manufacture. Currently this module accepts implicit (algebraic) surfaces and stacks of planar images (derived from or representing an object). Images can come from a variety of sources including CT and MRI scans (medical images), DEMs (Digital Elevation Models - images representing the elevation of the earth in a certain location), and finite element models from topology design software.

While the sources that produce CT, MRI, and DEM images are not traditionally considered design tools, they can be used as a first step in the design or redesign of, for example, a prosthetic device or physical model of a particular geographic terrain. Finite element models can be treated as a stack of images as long as the structure is modeled with regular brick elements. Each layer of brick elements can be treated as a planar image, each brick translating into a single pixel. Novel structural design software, such as OptiStruct, which is based on a homogenization method developed by Bendsøe and Kikuchi [1], takes a design envelope which has been discretized into brick finite elements and determines the density of material that should be present in each of the elements to form the stiffest structure possible. Thus we can treat the output of this software as a stack of planar images representing a structure and use it as input to the SBM. An example of image data is shown in Figure 2.

Algebraic surfaces that are input to the SBM are converted to a stack of planar, binary images. A z-value is associated with each image, and the pixels within each image represent an x, y cartesian coordinate. A 1-pixel represents a point on or below the surface and a 0-pixel indicates a point above the surface.



(a) (b)

Figure 2. Examples of image data that can be input to the Solid Builder module (a) segmented CT data of bone microstructure (b) finite element model of a suspension arm

Images representing an object composed of a single material will be binary. In other words, the pixels in the images will have a value of 1 if the pixel represents material and 0 if it represents void. However, in the engineering world objects are often composed of more than one material, or material properties can vary throughout an object. In this case, the object will be represented by gray scale images, where a particular gray value is assigned to each individual material or it indicates some material property such as density. This material information that is present in the image model of the object should be passed along to the solid model which is generated. Work is being done to develop enhanced solid models which can represent material in addition to geometry/topology. See for example [2] and [3].

Model creation

Given a stack of planar images, the SBM begins constructing a solid model of the object by extracting points from the boundary of each material region in each image. These become control points for contours which are formed by B-spline curves. Often objects are multi-branched and require several surfaces to completely describe them. For this reason, the contours are then grouped into individual branches of the object and separate B-spline skinning surfaces are fit to each contour group. The surfaces are modified at their ends so that where they touch adjacent surfaces, they join smoothly. In addition, if the contours in a group are non-convex, care is taken in choosing knot values for the surface so that it is continuous and non-twisted. Planar surfaces are fit to the end contours in each group and stitched to the skinning surfaces to form a B-rep solid model of each branch of the object. The union of all branch solids forms the complete solid model of the structure. We use the ACIS geometric modeling functions and data structures for storing and working with our solid models. For complete details on the algorithms used in this module, see [4].

Often a design represented by a stack of planar images can be built in the orientation indicated by the stack direction. In this case, generating a solid model for input into the ORM and the ASM is not necessary. If the images are spaced close together, simply extracting the boundaries of each material region within each image and storing them in a slice file is sufficient. For images spaced farther apart than the maximum resolution of the desired LM process, two approaches can be taken. First, we can interpolate intermediate images between two given images and then extract the boundaries of each material region in this augmented stack of images. This can be expensive if the images are large and quadratic, cubic or higher order interpolation is used. The other approach is to extract the boundaries of each material region from the given images, form contours from the boundaries, group the contours, and interpolate between contours. All of these slicing techniques have been implemented in the SBM module and yield uniformly spaced slices. If support structures are required for fabrication, they must be generated by a separate software module.

Implementation

The SBM has been implemented in the C programming language on the Sun, HP, and SGI platforms and is currently being used by the CADCAM Group to prepare objects represented by images for LM. The user supplies the image data (DICOM version 3.0 Implicit VR Little Endian format, United States Geological Survey 1 degree Digital Elevation Model format, or OptiStruct .fem and .sh files) which is read in and displayed on the screen. The images must be segmented (several image processing operations are provided) and thresholded if they are not already binary. To generate the solid model, the user must indicate the maximum degree of surfaces desired in the u and v directions, the number of filtering passes desired for the control points (to reduce wiggle in the skinning surfaces), and the minimum area of overlap for two contours to be placed in the same group. The software then groups the contours, modifies the end contours of each group, fits skinning surfaces, caps the ends of each group, and performs a Boolean intersection of each group to get the final B-rep solid model of the object. It is saved in an ACIS .SAT file.

The purpose of the Solid Builder module is to take non-traditional design information for an object and build a B-rep solid model. However, quite often a part is designed using a CAD package such as Unigraphics or AutoCAD, so a solid model of the object is available upon completion of the design process. In this case the Solid Builder module is not required and the engineer can directly employ the ORM and/or the ASM.

Orientation Module

Orientation Determination

The Orientation Module determines the optimal build orientation based on one of the following criteria: minimum build height, minimum support contact area, maximum area of base, minimum volume of supports, or minimum average surface roughness. Minimum build height corresponds to less build time. Minimum support contact area and minimum average surface roughness improve the surface accuracy of the final part. Maximum area of base improves the stability of the part as it is being built and often corresponds to less build time. Minimum volume of supports decreases the amount of wasted material.

Orientations are determined by first faceting the solid model, which results in a list of points lying on the part's surface. The convex hull of these surface points is then found. Each face of the convex hull becomes a potential base for the object, thus indicating a possible part orientation. For each possible orientation, the objective function is evaluated and the orientation which minimizes (or maximizes) it is selected.

The build height of the object is measured by finding the bounding box of the object in the candidate orientation and measuring the height of the box in the z-direction. The base area of the object is found by projecting the part onto the x-y plane and measuring the resulting area. For each facet in the object, the surface normal indicates the angle the facet makes with the build direction. Facets whose normal is not perpendicular to the build direction will suffer from the stairstep effect. The distance from the manufactured surface to the desired surface is called the cusp height (see Figure 3). This can be computed for each facet based on the angle its normal makes with the build direction. The average surface roughness R for a particular orientation is

$$R = \frac{\sum_{i=1}^{nfacets} d_i A_i}{\sum_{i=1}^{nfacets} A_i} \tag{1}$$

where A is the area of a facet and d is its cusp height.

Measuring the support contact area and volume of supports requires that the support structures for the object in the candidate orientation first be found. First the surface normal is computed at each point sampled in the orientation step. If the surface normal at a point has a negative z component, the point is Type-s and may require supports. For each Type-s point, we determine if adding support structure at it will prevent the part from toppling over, support a floating component, or support an overhang. If this is the case, the point is tagged as requiring support structure. Now the object is projected onto the x-y plane to form an extended base. The base is divided into a dense, regular grid. If the projection of a Type-s point requiring supports falls into a grid rectangle, a ray is fired from the center of that rectangle up in the build direction. Thin, columnar support structures are constructed up from the base to where the ray intersects the part. Once those facets requiring supports have been determined, their area is summed to determine the support contact area. Volume of supports is found by measuring the area of the facets requiring supports and the height of each facet.

After the optimal orientation has been found, the original solid model of the part is transformed to this orientation and written out to a file. This transformed object becomes input to the ASM. See [5] for more details on the ORM.

Implementation

The ORM has been implemented in C++ and makes use of the ACIS geometric modeling kernel. It runs on the Sun and HP platforms. This module accepts both ASCII .STL and ACIS .SAT files (representing either a surface or solid model of a part) as input, and produces .STL or .SAT output depending on the type of input. The user indicates how many possible orientations should be displayed (these correspond to the largest faces of the convex hull in descending order) and the maximum angle a surface can make with the build direction without requiring supports. The module saves a file of the object in its optimal orientation as output.

Adaptive Slicing Module

Slicing procedure

The ASM takes the solid model of the object and adaptively slices it to minimize the error in the final manufactured part due to the stairstep effect. Thus where the curvature of the part is greater, the slices will be thinner. The slice thickness of a part at a particular z-level is determined such that the cusp height - the distance between the 2.5D manufactured slice and the original object surface - is equal to or below a user specified maximum distance. Figure 3 illustrates the cusp height for a layer of a curved surface. By adaptively slicing a part, surface accuracy can be improved without a large increase in the time required to build the part.

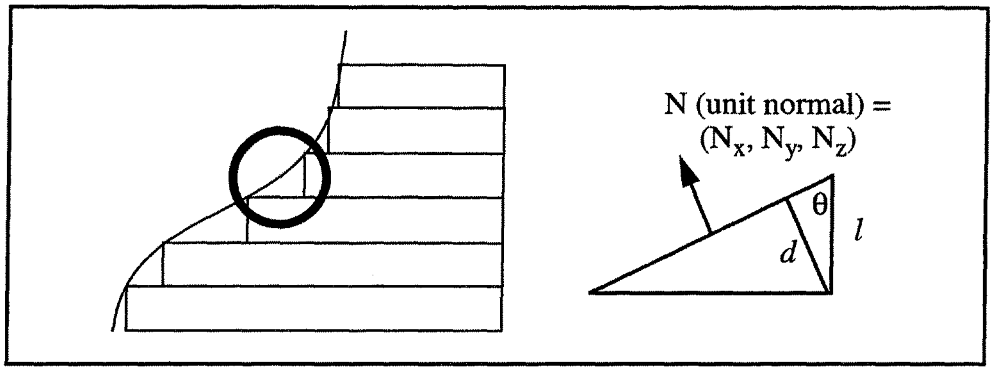


Figure 3. Illustration of cusp height (*d* is cusp height, *l* is layer thickness)

The software begins by determining the base slice for the part. Then given a point on a contour in the current slice, the normal curvature κ_n of the surface in the slicing direction is calculated. We can approximate the normal section of the surface at the considered point with a circle of radius $\rho = 1/\kappa_n$. Depending on whether the manufactured layers should be completely contained within the solid model of the part or vice versa (we refer to this as deposition strategy), the maximum allowable layer thickness l at the considered point on the surface is calculated using the allowable cusp height d, ρ, and the angle the surface normal makes with the build direction θ. As we move around the contour, l varies with ρ and θ. An SQP algorithm is used to find the minimum value for l. See [6] for more details.

Implementation

The ASM has been implemented in C++ using the ACIS geometric modeling kernel. It runs on the Sun platform. The module accepts ACIS solid models as input (.SAT files) and requires the user to supply the maximum allowable cusp height, the deposition strategy (manufactured part contained within the envelope of the solid model of the part or vice versa), and the minimum and maximum allowable slice thicknesses (dictated by the chosen LM process). Slices are generated and are written to a slice file. Currently both the 3D Systems and Stratasys .SLC files are supported.

Example

In Figure 4 we show an example structural part that begins its life as a collection of planar images and results in a model fabricated by a LM technique. The part was designed using a structural topology optimization software and subsequently the SBM was used to generate a B-rep solid model. This solid model then became the input to the ORM module, which determined the optimal orientation of the part and generated the necessary support structure. The part was then sliced using the ASM and finally built by the Stratasys FDM process.

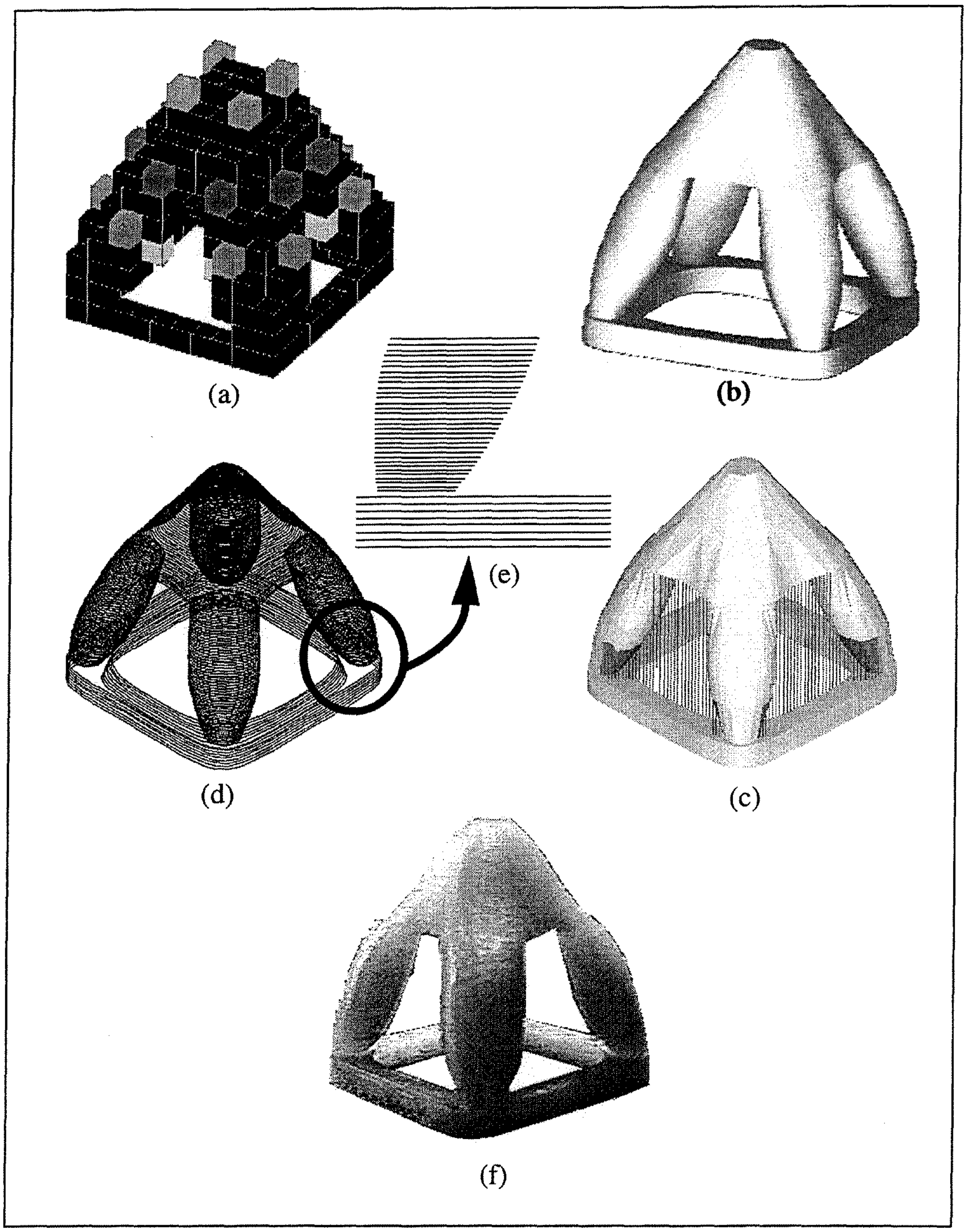


Figure 4. Structural example: (a) Image data (b) Generated B-rep solid (c) Optimal orientation and generated support structures (d) Slices (e) Close-up of slices (e) Fabricated structure

Future Work

The three modules which make up our LM process planning system thus far are currently in the final stages of development. Further enhancements and improvements will allow the engineer more flexibility in using them. In addition, new modules can be added to the software system as changes in the design and manufacturing processes continue. For instance, a technique for selectively thickening the walls of thin-walled objects so that they can be built without supports is being investigated and a module to be added to our system is under development [7]. We have thus far used commercially available software for path planning after contours are generated. However, we are now developing tools to aid the engineer in choosing a deposition strategy to decrease the time to build a part and increase its stiffness and strength [8]. Finally, we are investigating different file formats for the transfer of design data to process planning software, process planning data between different process planning tools, and process planning data to the various LM hardware tools in an effort to develop appropriate neutral file formats [9]. (Readers may check our website given on the title page for software developments and usability status.)

Acknowledgments

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