Computer Aspects of Solid Freeform Fabrication:

Geometry, Process Control, and Design

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Abstract

Solid Freeform Fabrication (SFF) is a class of manufacturing technologies aimed at the production of mechanical components without part-specific tooling or process planning. Originally used for creating models for visualization, many industrial users of SFF technologies are realizing the greater potential of SFF as legitimate manufacturing processes for producing patterns and, in some cases, functional parts. Thus, SFF is becoming an important aspect of the product realization process in these industries.

Solid Freeform Fabrication arose from the dream of "push-button" prototyping, in which solid reproductions of three-dimensional geometric models are created automatically under computer control. Perhaps more than any other class of manufacturing technologies, computer software development has been an integral part of the emergence of SFF. As SFF technologies evolve toward the ability to create functional parts, computer issues gain more importance.

This paper discusses three aspects of software design for SFF: processing of geometric data, global and local control of SFF processes, and computer-based analysis and design for SFF manufacturing. The discussion of geometric processing issues focuses on accuracy and completeness of input models, and the algorithms required to process such models. The interplay between the physics of SFF processing and the desired output geometry is discussed in terms of the development of model-based control algorithms for SFF. These two areas, geometric processing and control, are necessary for the practical implementation of any SFF technology. However, for SFF to realize its potential as an alternative for manufacturing functional parts, engineers must be provided with analysis and design tools for predicting mechanical properties, ensuring dimensional accuracy, choosing appropriate materials, selecting process parameter values, etc. For each of these three different but related areas of software design, the state-of-the-art is assessed, contemporary research is summarized, and future needs are outlined.

Introduction

Solid Freeform Fabrication (SFF) is a group of emerging technologies for fabricating physical objects directly from computer-based descriptions (such as solid models) of the geometry of the parts. All SFF technologies are enabled by computer hardware and software, from the input geometric descriptions to control of the fabrication machinery. Clearly, the success of SFF depends on the existence of sophisticated and cost-effective computing equipment and software. As the applications of SFF move beyond visualization models and design verification prototypes into fabrication of functional components, SFF will change from rapid prototyping techniques into legitimate manufacturing technologies. One key to this progress is improvement of the software systems that enable advances in the capabilities of SFF. This paper describes potential opportunities for improvement in SFF software in the areas of geometry processing, process modeling and control, and design tools for SFF.

Geometry Processing

Most Solid Freeform Fabrication processes produce parts on a layer-by-layer basis. The process proceeds by first slicing the geometric description of the part into layers. The slicing operation generates the contours of the part for each layer. The contours are then processed in a manner dependent upon the particular SFF technology. For instance, for Selective Laser Sintering (SLS), the contours are discretized into "toggle points" at which the laser beam must be modulated to produce the desired solid.

Faceted Geometry. The form of the geometric description of mechanical parts to be produced by SLS significantly affects the accuracy of the final part. The current state-of-the-art for most SFF technologies consists of tessellating the surfaces of the geometric model into a mesh of non-overlapping triangular facets. The resulting geometry is transmitted in a standard file format, the so-called "STL" file format, established by 3D Systems, Inc. [1] This format has been adopted by many CAD vendors, is readily available, and is considered adequate for most visualization applications. However, for producing accurate patterns and functional parts, the adequacy of the STL format is unclear. There is a trade-off between the accuracy and the size of the geometric description. Highly non-linear surfaces, such as those that comprise turbine blades, manifolds, etc., must be tessellated into a large number of small facets, resulting in very large data files, and the accuracy of such descriptions is still suspect.

In many cases, the tessellation operation itself introduces errors in the model. Tessellation of surfaces with large curvature can result in errors at the intersections between such surfaces (see Figure 1), leaving gaps or "holes" along edges of the part model [4]. Tessellation of fine features is susceptible to round-off error, which leads to non-manifold models of parts, where more than two facets are adjacent to a single edge, or facets with opposing outer normals meet at a single vertex (see Figure 2). These problems are difficult for slicing algorithms to handle and cause fabrication problems for SFF processes, which require valid solids as input.

Algorithms to overcome these problems with faceted geometric descriptions depend on developing richer data structures that explicitly represent the facet and edge adjacencies that are implicit in the STL format. This information enables the development of efficient slicing algorithms that take advantage of the explicit adjacency information when constructing slice contours [5, 11, 12]. Rock and Wozny [10] have also proposed an alternative to the STL file format that captures the adjacency information in the exchange file. Bøhn and Wozny [4] have developed a method to repair faceted geometric descriptions with problems such as that depicted in Figure 1. Their technique uses the adjacency information to locate gaps between facets. They then use a "shell-closure" algorithm to add missing facets to the close gaps.

Higher Order Geometric Descriptions. The problems with the STL geometry exchange format arise because tessellation is a first-order approximation of more complex geometric entities. An obvious solution to these problems is to exchange higher order geometric entities, preferably the source geometry with which a part is designed. This approach has been adopted at The University of Texas, where an interface based on Constructive Solid Geometry (CSG) has been developed to provide input to SFF processes [7]. With CSG the geometry of a part is modeled as a binary tree whose leaf nodes are scaled and oriented instances of primitive shapes (*e.g.*, spheres, cylinders, parallelepipeds, etc.) and whose non-terminal nodes are the regularized Boolean set operations union ($\cup$), intersection ($\cap$), and difference ($-$). Evaluating the CSG tree with a geometric modeler results in an explicit boundary representation of the part's surfaces.

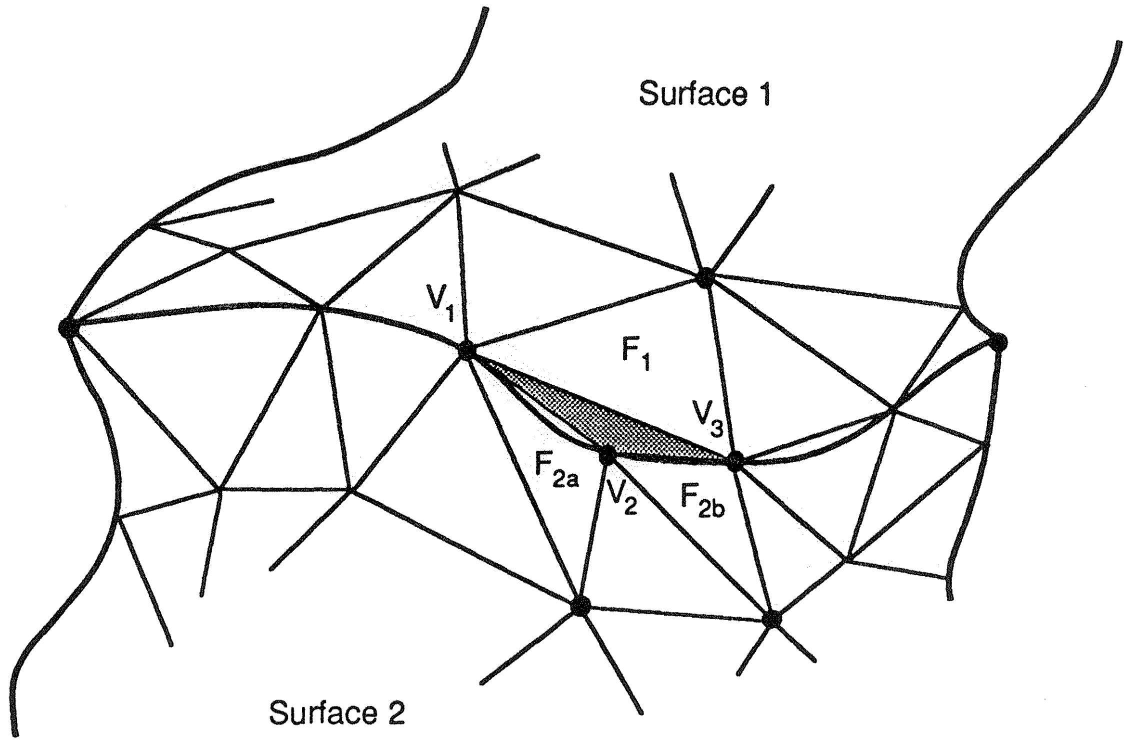

Figure 1. A gap in the seam at the intersection of two surfaces [4].

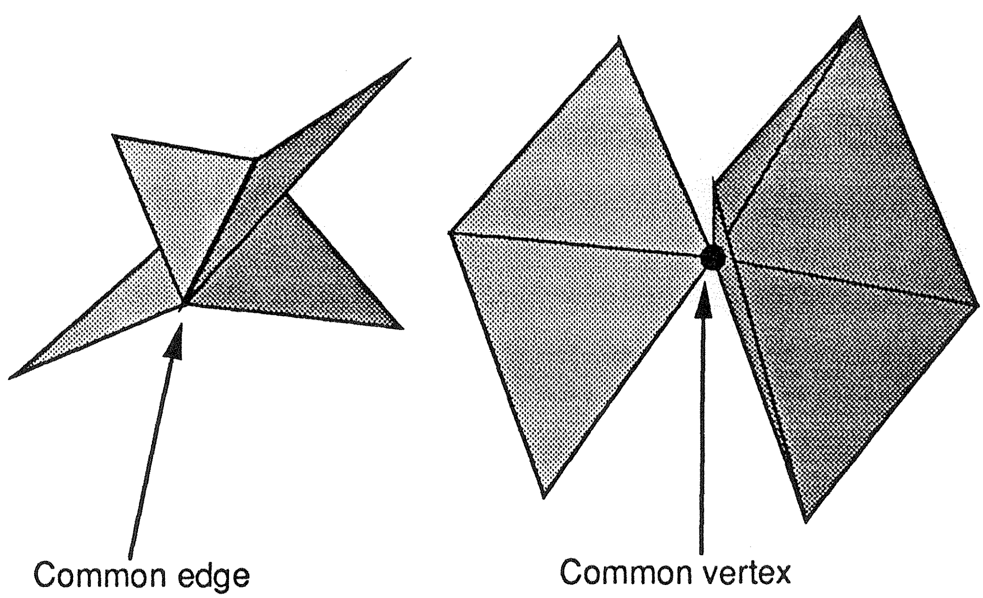

Figure 2. Other examples of non-manifold topology in a faceted SFF model.

Normal evaluation of a CSG tree involves computing the intersection between pairs of primitive or intermediate surfaces and performing set classification in three dimensions. The UT process is based on evaluation of *sliced* primitives rather than 3-D primitives. In this process the primitives in the CSG tree are sliced individually, generating a slice for each primitive. The part contour in the slice plane is then produced by combining the primitive slices based on the Boolean operations at the non-terminal nodes (see Figure 3). The contour of the part in a given slice plane is a collection of piecewise continuous curves. These curves are then scan-converted to produce toggle points.

The net result of this work is a boundary evaluator developed specifically for SFF applications. The approach provides a more accurate, compact part description. Also, all surface-surface intersections are performed in the 2D slice plane, resulting in considerably simpler and more robust algorithms. For the common quadric surfaces (spheres, cones, cylinders, and ellipsoids), the surface-surface intersection calculations are exact (subject to round-off errors). For higher order surfaces, such as the torus, the method requires an approximation of the slice contour of the primitive. Such an approximation is still more accurate and efficient that the linear approximations obtained from a faceted model. In fact, the method provides a rational basis for approximating the geometry, since it is based on error measures in the slice plane. Details of the algorithm are included in [7].

Processing higher order geometry for SFF processes offers several advantages over exchange of faceted geometric descriptions. Generally speaking, files containing higher order information will be smaller and more accurate than comparable faceted geometry files. Also, many of the problems that result in non-manifold geometric information in faceted descriptions can be avoided. For example, because the CSG slicer described above performs the geometric modeling operations, no explicit boundary information is needed in the input file. Instead, it is incumbent upon the SFF geometry processor to ensure that the results are realizable for the particular SFF technology that is used to fabricate the part. Potential problems in the slicing operation can be solved because more information is available about the intended geometry of the part; thus, higher order descriptions are easier to troubleshoot when necessary. Finally, when approximations are necessary for the given input geometry, the approximation process is driven by the particular SFF technology rather than by generic criteria meant to satisfy the requirements of many SFF technologies. This provides a rational basis for approximating the geometry when necessary.

There are disadvantages to higher order geometric data exchange as well. First, there is no single geometry form that is satisfactory for all applications. There are many different geometric descriptions that are used in product design, each with different requirements for a slicing algorithm. Designers of commercial SFF processing software will have to make compromise decisions about which geometric forms to support or risk losing potential customers from lack of geometric coverage. Also, because the geometric input is more complex, algorithms for processing the geometry are more complex as well. Finally, interchange standards must be developed for higher order geometric descriptions. While these standards are under development, they are still subject to change until agreed upon.

Sources of Layered Geometry. Many potential applications of SFF naturally provide data in layer-based formats. For example, Rogers *et al.* [13] report the use of a laser digitizer to provide data for the fabrication of prosthetic devices using Selective Laser Sintering. Levy *et al.* [8] used Computed Tomography (CT) data to produce models of human temporal bones using SLS. Bartels *et al.* [2] used imaging data from a confocal microscope as input to an SLS machine to create models of pollen grains. These are just three examples of the potential applications for SFF in areas other than product engineering. In each of these cases the data was presented to the SFF machine as layers.

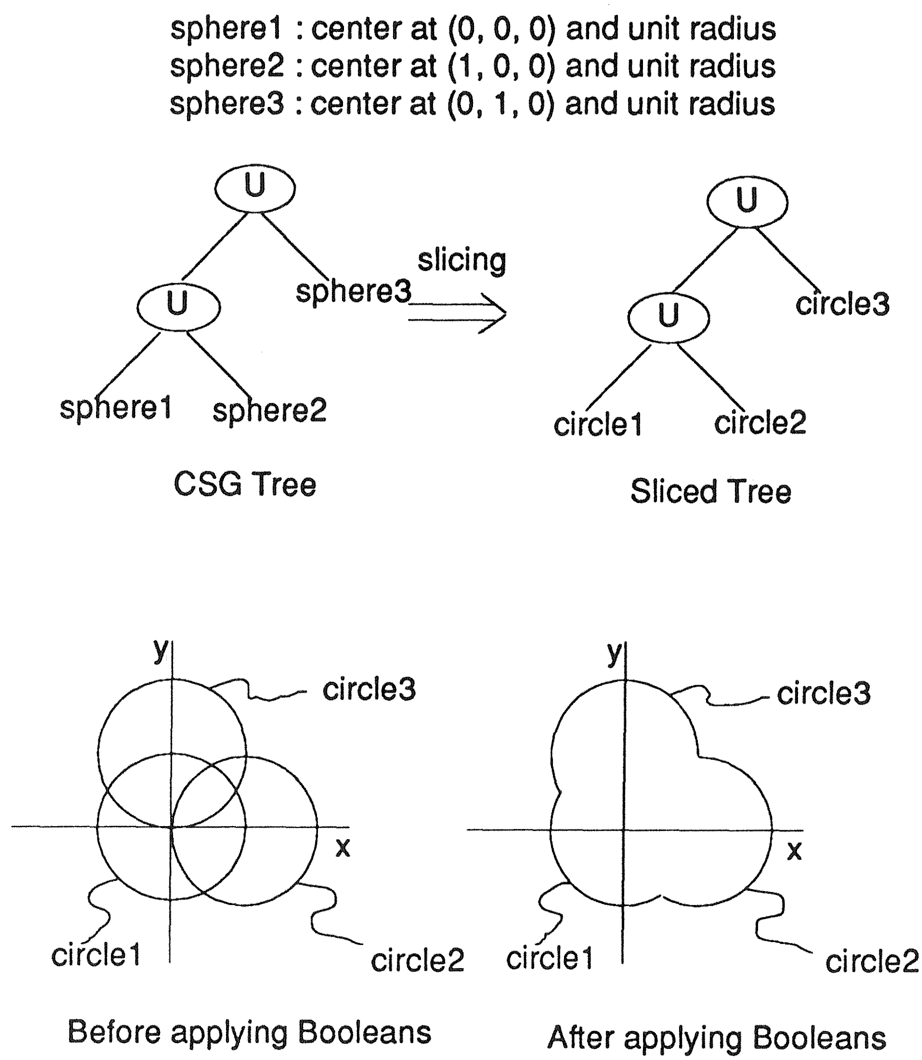

Figure 3. CSG slicing and set operations for SFF [7].

The geometric processing was not particularly sophisticated in any of these cases. For instance, in each of the cases cited above, the thickness of the data slices did not coincide with the thickness required for the SLS process (typically 0.005 to 0.01 in). To compensate for this, the SLS control software either skipped data layers (for thinner layers) or replicated layers (for thicker layers). To achieve higher accuracy, however, more sophisticated strategies must be developed and adopted by the SFF software. The laser digitizer software described in [13] actually interpolates between slices to realize the required resolution for the SLS process. Similar schemes must be developed for processing CT and confocal microscope imaging data.

Both the CT data [8] and the microscope data [2] consist essentially of raster images of the physical objects being imaged. In each case, the data provides a measure of the relative density of the material at each pixel in the imaging plane. However, SFF processes such as SLS require boundary information rather than interior density data. For these studies, then, the raster images were first converted to contour images of the sample slice in each plane by specifying a minimum threshold density below which the data are ignored. For these studies, the threshold value was selected manually and varied from layer to layer. However, to realize the full potential of

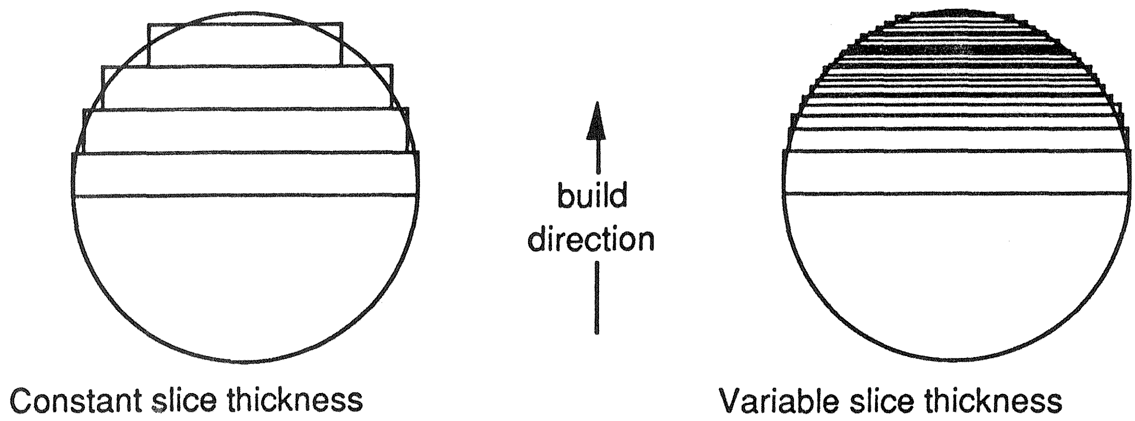

Figure 4. Effect of variable slice thickness on part accuracy.

fabricating such models with SFF, threshold values must be determined automatically. Algorithms for determining optimal threshold values are needed for preprocessing layer-based SFF input.

Before the use of layered data can expand, data interchange standards must be established. Currently there are no standards to specify the form of layer-based geometry for exchange among programs, a necessity for accommodating such data in SFF processing. In the examples cited above, Rogers presented the data to the SLS machine in the form of contours [5]. The other two sources, as described above, present their data as raster bit maps. These examples suggest that two exchange standards should be developed: one for contour data and one for raster data. In any case, the details for processing the input geometry, *i.e.*, interpolation or thresholding as described above, should be left to the particular SFF technology to ensure that maximum part quality can be realized.

Process Modeling and Control

Solid Freeform Fabrication has the potential for producing accurate, structurally sound three-dimensional solid versions of objects. To develop accurate patterns and functional parts with adequate strength, however, requires in-depth basic research to understand the correlation between the mechanical properties and geometric accuracy of the final part with respect to the SFF process parameters [3]. These relationships must be captured in computer models that can be used to control SFF processing. To enable real time control, these models must represent a compromise between accurately modeling the physics of the SFF process and intelligent use of geometric information to approximate optimal processing patterns.

While process planning for SFF is considerably reduced compared to conventional fabrication technologies, there are several considerations which will require reasoning about the geometry of the final part. Scaling and orientation of the part within the work space of the SFF machine have a significant impact on the efficiency of the process. Aside from other factors, the part should be oriented in a manner which minimizes the number of layers. Other factors, however, may override this consideration. For instance, tolerances tend to be directionally dependent. Likewise, the mechanical properties of the final part will depend upon its orientation during the process. These issues require geometric reasoning on both global and local scales. Global reasoning will indicate the best part orientation within the workspace of the SFF machine. Local reasoning refers to considerations of the geometry of each layer to determine scanning and build patterns that maximize geometric accuracy and mechanical properties of the part.

Scanning patterns. Many SFF processes build each layer of a part by raster scanning the powder bed along a single axis, as indicated in Figure 5. For geometries such as this, a unidirectional scanning pattern will result in a large number of very short scanning vectors. A mutidirectional scanning pattern, such as that indicated on the right in Figure 5, will result in a smaller number of longer scanning vectors. Longer vectors reduce the errors associated with laser toggling transients and repositioning of the laser beam, resulting in higher part accuracy. The figure implies that preferred scanning patterns are the result of geometry alone; however, other factors may outweigh geometry. For instance, mechanical properties within a layer may be dependent upon the scanning direction; heat transfer considerations and the creation of thermal gradients may indicate preferred scanning patterns; contour scanning of the layer boundaries may reduce aliasing artifacts and result in better surface quality. These considerations must be incorporated into algorithms for determining arbitrary scanning patterns for SFF processes.

Contour Scanning. Recent research at UT Austin has focused on developing an optimal laser control system for scanning along curves [15]. The scanning algorithm and associated hardware maintain constant laser power density by simultaneously controlling laser speed and laser power. The goal is to produce parts with better surface resolution than can be obtained from vector scanning the part contour (see Figure 6). This research emphasizes the need for higher level geometric descriptions for SFF process. The algorithm uses information about the the curvature of the contour to determine appropriate laser parameters to achieve the desired power density. A polygonal approximation of the contour, such as that obtained from slicing a faceted part model, is not accurate enough to support this control scheme.

Process Modeling. Advances in control of SFF processes will depend on developing a better understanding of the physics of each process. For example, the process control program for SLS administers three areas: laser control, control of powder delivery and leveling, and control of the environment within the machine. Input to the module consists of a suitable geometric description of the part layers (at this time, scan lines and laser toggle points) and settings for process parameters, including material properties, bed temperature, gas flow rate, scanning speed, laser power, beam diameter, and scan spacing. The current SLS process control software is built under the assumption that these parameters will be constant for an entire part. However, initial investigations indicate that fabrication of metal parts will require local control of laser beam parameters, allowing these parameters to change from layer to layer or even within different areas in a given layer. Such physically-based scanning is depicted conceptually in Figure 7, where a part layer has been divided into several regions based on part quality predictions from a physical model of the process. A scanning pattern is then generated for each of the simple regions, again based on predictions from a process model. Such a scanning scheme could be precomputed off-line before the part is fabricated, or it may updated on a layer-by-layer basis, with input about the status of previous layers from sensors. The key to solving this problem is development of physical models of the process. While initial models of the SLS process have been developed [9, 14], they are not structured to support real-time process control of this kind. The solution to this problem will likely require a combination of hardware and software development.

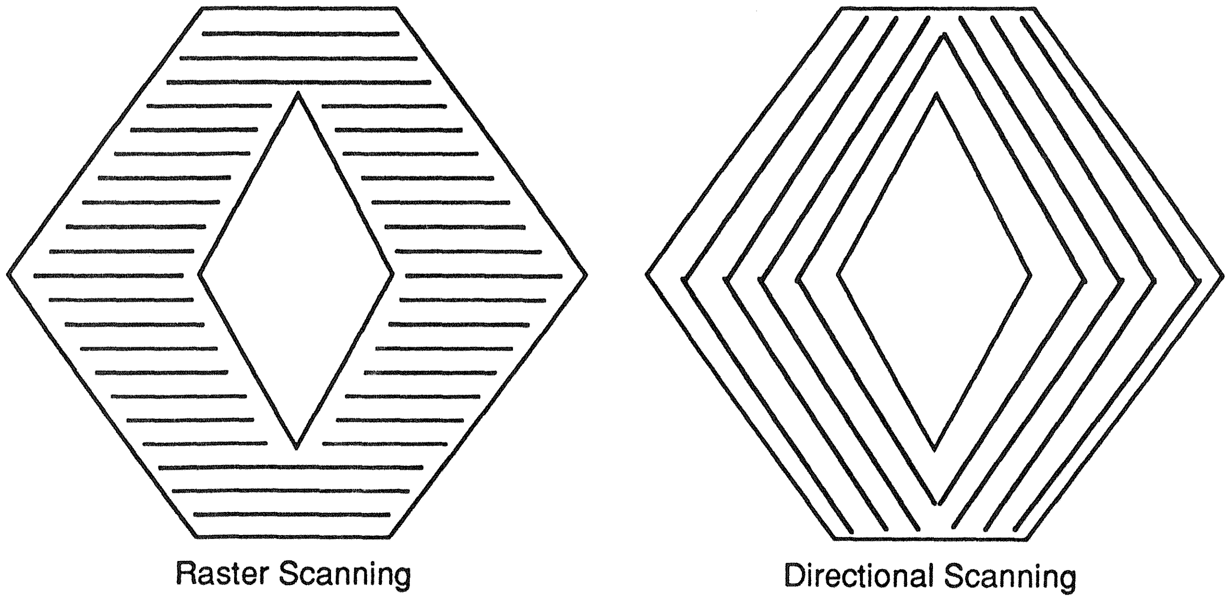

Figure 5. Directional scanning versus raster scanning.

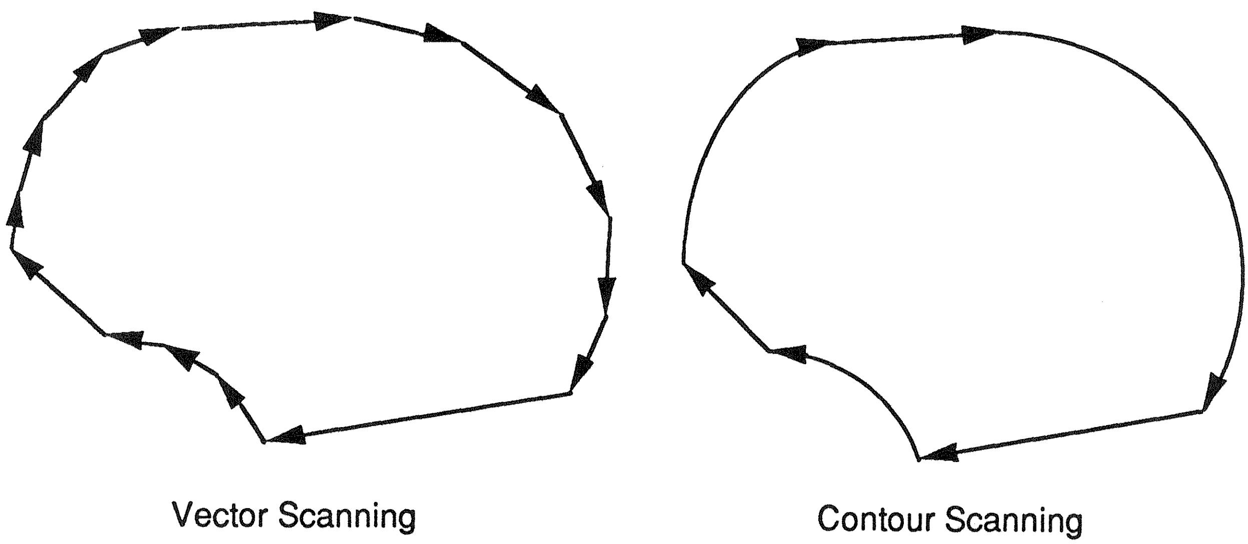

Figure 6. Contour scanning.

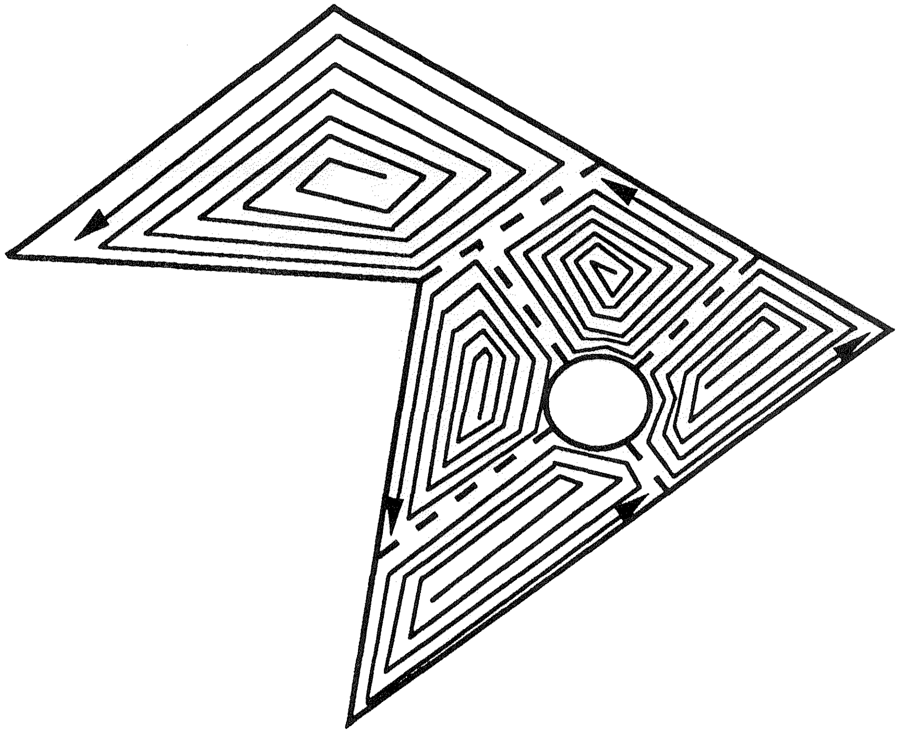

Figure 7. Physically-based scanning.

Design for SFF

Successful design of functional parts produced by SFF will require consideration of the material and mechanical properties in conjunction with their geometry. These properties are directionally dependent due to the layer-by-layer fabrication process. For certain SFF processes, such as SLS, the mechanical behavior of parts is further complicated by the phase change inherent in the process. Therefore, standard techniques for modeling structural behavior of mechanical parts will have to be modified and enhanced to account for these factors. Development of such computer-aided design tools will allow designers to create parts that are optimized for SFF processes.

Physical models of SFF processes provide a starting point for developing these design for SFF tools. However, such models are focused on determining the consequences of choices of process parameters on the properties of the final part. For design, the inverse solution is needed. For desired properties of the final part, the designer must know the appropriate process parameters. Answering such questions will require reformulation of the modeling software.

SFF processes offer the promise of providing manufacturing capabilities that are not realizable by other techniques. One such possibility is selective material property distribution within the part. With conventional material removal processes, the bulk mechanical properties of a part are determined by the stock material chosen, aside from any surface treatment that is applied as a post-process. With SFF technologies the potential exists for the mechanical properties to vary continuously within the part. Again, to realize this possibility, design tools are needed to guide the designer in determining optimal material distribution. Project MAXWELL, a joint effort of the University of Michigan and Carnegie-Mellon University, is developing mathematical techniques for concurrent design of shape and material composition for mechanical components [6]. Tools such as this will become increasingly important as SFF techniques are employed for manufacturing functional parts rather than prototypes.

Conclusion

One key enabler of Solid Freeform Fabrication technologies is computer software in geometric modeling and process control, without which most SFF processes would be difficult to implement. However, many opportunities exist for improving the performance of SFF processes by improving the software, thereby broadening the application of SFF from producing models and prototypes to functional part manufacturing. This paper provides an outline of some of the issues in software development in the areas of geometric modeling, process modeling and control, and design for SFF. Progress in any one of these areas, however, is dependent upon improvements in the other two areas. These interdependencies are depicted in Figure 8. To realize the potential of SFF, research must continue simultaneously in all of these areas.

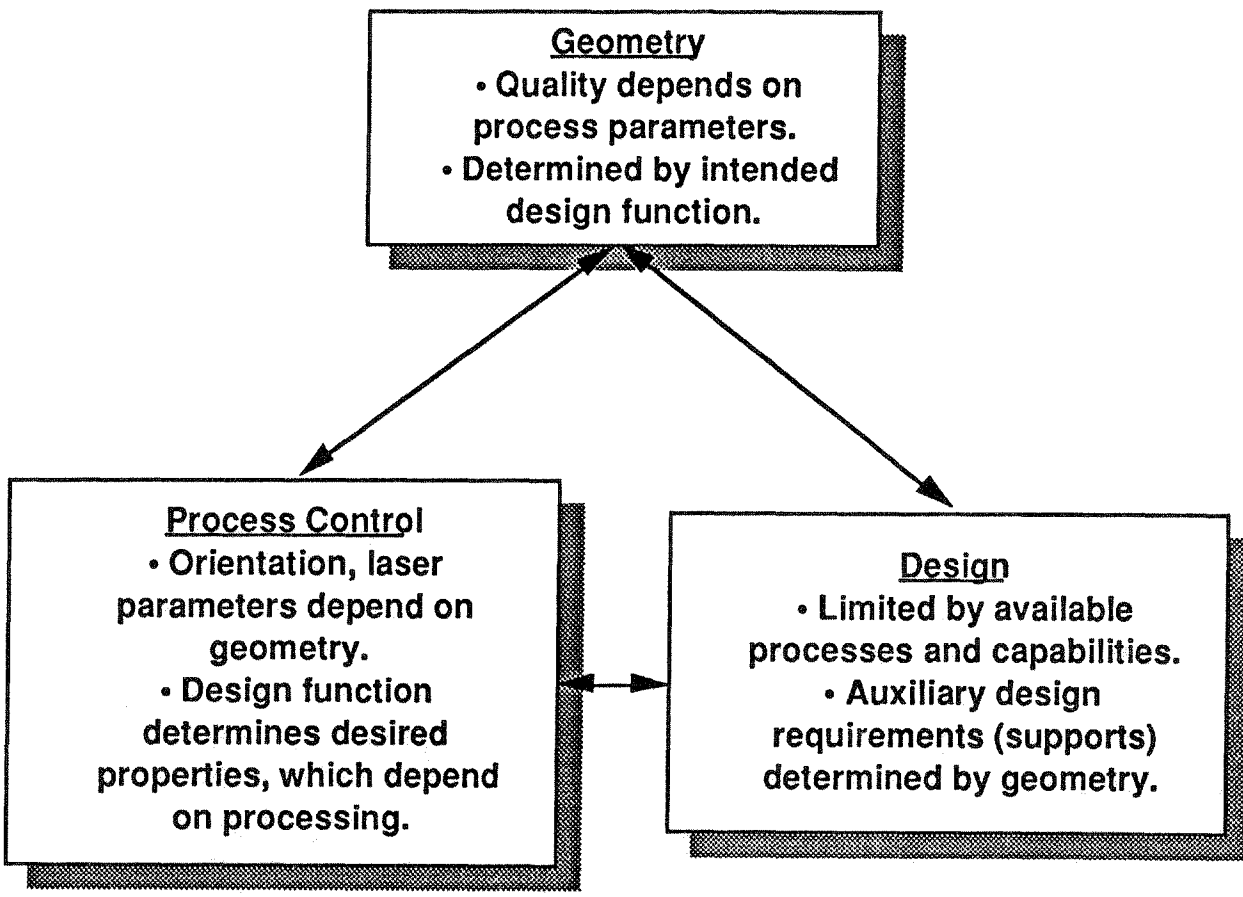

Figure 8. Interdependencies among geometry, process control, and design for SFF.

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