Geometric Modeling for Rapid Prototyping and Tool Fabrication

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Abstract

This paper describes the application of a non-manifold geometric modeling environment, NOODLES, to a Rapid Tool Fabrication System. This system integrates stereolithography and thermal spray deposition into a CAD/CAM environment which includes design evaluation tools, robotic spraying, and computer-aided process planning. The level of integration and the number of different models in this system requires geometric representations that can be abstracted at several levels and that can be manipulated over several dimensions. The models in our framework for design, analysis, and fabrication share a single common *unifying* geometric representation implemented in NOODLES.

1 Introduction

The capability to manufacture a wide variety of quality products in a timely and cost-effective response to market requirements is a key to global competitiveness. The opportunities for improving manufacturing technology range across the entire spectrum of industries, materials, and manufacturing techniques. There is no single technological innovation which, by itself, will significantly improve productivity; rather it is a systems issue which involves rethinking many manufacturing activities. One such activity is the manufacture of tooling (i.e., design, prototype, and fabrication) such as dies and molds required for the high-volume production methods that generate most of our manufactured products. Tooling manufacture is typically an expensive and time-consuming process. The reasons lie not only in the fabrication costs and time constraints imposed by conventional machining methods, but also in the organizational framework. In most organizations, different groups employ different processes to design and manufacture tools and products. And the expertise in tool design and product design reside in different groups, impeding communications between them. The representational and physical models used in design, prototyping, and manufacturing, are often incompatible with one another, so transitions between the stages are time-consuming and error-prone. Products often make several complete cycles through design, prototyping, and fabrication before reaching production. Thus, new product development or product modification implies a series of iterative changes for both product manufacturers and toolmakers. For all these reasons, a rapid and smooth transition from product concept to production remains a challenge.

This paper describes the geometric modeling aspects of a CAD/CAM tool manufacturing system to address this challenge for an injection molding paradigm. In this system, both prototyping and tooling fabrication are based upon compatible solid free-form fabrication processes, while the underlying geometric and process models share a common representational scheme.

2 Background

Solid free form fabrication (SFF) processes [1] such as stereolithography, selective laser sintering, three-dimensional printing, and laminated object manufacturing quickly produce prototype parts. In these processes arbitrarily complex shapes are built up incrementally in layers. The requirement to decompose complex three-dimensional geometries into $2\frac{1}{2}$ dimensional layers make it difficult if not impossible to be driven by direct human operation. Furthermore, these processes usually require additional planning where human interaction would not be possible or appropriate. For instance, generation of scan vectors from the cross sections in stereolithography is one such operation. High-level control of free-form fabrication techniques thus require appropriate computer geometric representations for task description as well as for process planning.

The Rapid Tool Manufacturing System [2] uses SFF prototyped parts in a sprayed metal tooling process to quickly build injection molds for manufacturing these parts in quantity. The system currently uses patterns produced with stereolithography apparatus (SLA). Thermal spraying is used to deposit metal onto the SLA patterns. By incrementally depositing multiple fused layers, a free-standing metal structure is formed by separating the metal shell from the plastic substrate. This shell can be used in the fabrication of a broad range of custom tooling including injection molds, forming dies, and EDM electrodes, by filling it's cavity with appropriate backing materials.

To realize the maximum benefits of SLA and sprayed tooling, these processes must be effectively integrated into the overall manufacturing system. Conventional net-shape manufacturing systems (i.e. those which produce the individual parts used to assemble the finished products) are composed of separate organizations , each with their own expertise, equipment, and CAD environments. The transfer of information between organizations is error-prone and inefficient since computer models must be transformed between each environment by additional translators. Independent CAD systems make the software difficult to manage. Further, the lack of downstream process knowledge (i.e. understanding how parts are manufactured) in the design stage leads to time-consuming and costly iterations. Our approach seeks to integrate design, prototyping, and tool fabrication into a common organizational framework. The keys to integration are to incorporate "design-for-manufacturability" into the design stage, to automate robotic spraying, and to use a unifying geometric data structure for part representations and process planning.

Some of the steps in the tool manufacturing process and the computer modeling requirements for each are summarized below:

- **Design** - The user designing a part should be allowed to select the appropriate modeling description paradigm depending upon the immediate need. For example, designs, at times, can best be synthesized using constructive solid geometry, or building solids up from sets of surfaces, while at others, sweeping lower dimensional elements, such as curves and surfaces, into solid representations produce more satisfactory results.

- **Pattern generation** - Spray patterns are generated from design models by automatically deriving parting lines and establishing parting surfaces. Surfaces are added to solid model representations to create shapes which represent the complements of the mold halves.

- **SLA** - Building patterns with SFF require valid solid representations. Thus, if the design originates in the surfaced forms, it is vital to have a capability which transforms enclosing surfaces into solid representations. The SLA process planner must convert solid models into an ordered set of $2\frac{1}{2}$ dimensional cross sections (i.e., cross sections with an associated depth or thickness) and span these cross sections with appropriate drawing vectors. This operation inherently involves working simultaneously in several dimensions since one generates planes from solid models, and then vectors, or line segments, from the planes.

- **Thermal spraying** - Robotic spraying, driven by an off-line trajectory planner, automates thermal spraying and facilitates process control by its consistent and tireless performance. Off-line trajectory planning based on design models does not require tedious teach-by-showing operations, and the incorporation of expert rules to formulate spray strategies produces better quality shells. Trajectories for spraying can be generated by projecting grids onto the object models. Interference of the spray stream with the object is assessed by intersecting lines representing the spray cone with the solid corresponding to the pattern.

3 NOODLES Modeling

Geometric modeling can be performed at various levels, such as wireframe, surface, or solid modeling. Topological information is required for feature extraction. The previous examples suggest that all levels of modeling and complete topological relationships are required in the system. Although solid modeling approaches have the richest information, the representation of lower level elements such as lines and surfaces is not explicit. Furthermore, operations provided within solid modeling approaches do not apply when non-solid elements are used. The ideal geometric modeling system should uniformly represent and operate on non-homogeneous (i.e., mixed dimensions) elements such as vertices, lines, surfaces, and solids. NOODLES offers an environment where non-homogeneous elements are uniformly represented and permits Boolean operations between elements of any dimensionality [3]. In addition, the NOODLES representation is rich in topological information which relates adjacencies between all geometric modeling elements.

NOODLES employs a *non-manifold* boundary representation scheme to model geometric objects. Along with the geometry of the elements that make up the objects, the topology is also captured explicitly. Conventional boundary representation schemes model solid objects by their enclosing shells. One significant constraint in such schemes is that the topology of the enclosing shells are assumed to be two-manifold. This assumption implies homeomorphism to an open disc in the neighborhood of every point on the shell. Data structures based on the two-manifold assumption cannot gracefully accommodate elements of lower dimensionality which do not contribute to the construction of shells. Since NOODLES is based on non-manifold (or non two-manifold) topology, objects such as points, wire-frames and stand alone surfaces which are in violation of disc homeomorphism can be gracefully represented along with solids. Furthermore, these non-homogeneous objects can interact with each other in set-theoretical operations.

The capability to unite, intersect, or subtract models and elements of models is an essential component of any geometric modeling system, and is typically implemented as Boolean set operations. In NOODLES, the notion of Boolean operation is applied literally to point set topology. The legal operands of any binary operators (union, intersection, and difference) can be of the form of any point set element, namely, *Vertex*, *Edge*, *Face*, *Solid*. As a matter of convenience, a *Model* represents the union of all fundamental elements, and a *Pset* represents any arbitrary collection of those elements.

4 Examples

Several examples are presented which demonstrate the power of such non-manifold modeling capability. First, if a design is represented by a set of surfaces, then it must be transformed into a solid representation in order to build it with SLA. When surfaces are introduced, NOODLES identifies and keeps track of enclosed volumes which thus define solids (Figure 1). Another example which uses non-homogeneous representations is the planning of the layering process. The first step is to obtain the cross sections of the object. These sections are obtained from the Boolean intersection between the object and a stack of planar faces that are appropriately spaced. The result of this non-regular operation (i.e., operations between entities of different dimensions) is a collection of cross sections (Figure 2). The vectors to be scanned by the laser are obtained by intersecting appropriate grids with the portions of the cross section. For example, the interior area of a cross section is is intersected with a cross hatch grid (Figure 3). The object boundaries for the laser are quickly found from the perimeters of the cross sections. Similarly, the grids for robotic path planning are defined by the perimeters of the intersection of the surface boundary of the object with mutually perpendicular sets of stacks of planar faces (Figure 4). The robot trajectory is defined by these contours and by specifying the stand-off distance of the spray gun. The spray gun orientation is optimally oriented normal to the surface. Interference is assessed by intersecting lines which represent the planned trajectories of the particle spray with solid models of the pattern. When interference is detected, the spray gun is incrementally reoriented until a direct line-of-sight is achieved (Figure 5).

5 Conclusion

Since most SFF processes build solid objects by creating successive layers on top of each other, the most fundamental geometric operation is to obtain cross-sections from the solid models of the objects. It is very desirable to employ a uniform geometric modeling environment that can represent the solid objects and the cross-sections under the same representational formalism. This is important from the viewpoint of system integration and information flow. Under such an environment, the design process which results in a creation of a solid model of the artifact and the SFF process planning operations can be carried out using the same geometric modeling system. This eliminates the need to use several geometric modeling schemes and the task to translate the representation between different schemes. Futhermore, the representational instances of the solid object and the representational instances of the cross-sections can be informationally linked. Such linking would smoothly propagate the attributes of the solid object to the level of cross-sections. For example, The surface finish requirements specified for the selected surfaces on the solid object can easily be made available as an inherited attribute at the contours of the corressponding cross-sections. This information can then be used to adapt the process to maintain the specified surface finish.

In addition to the uniformity in the geometric representation between the design and the plannining phases, uniformity in geometric modeling operations across these phases is also desirable. The same geometric modeling operations that are used in the design phase can be applied in the process planning phase. The creation of the solid model in the design phase typically involve modeling operations such as booloans, sweeps and extrusions. In the planning phase, cross-sections can be conceived as boolean intersections between appropiately elevated planes and the solid objects.

In this paper, benefits of a non-homogenous geometric modeling environment in the context of a rapid tool fabrication system were discussed. The system integrates streolithograpy and thermal spraying processes to manufacture injection molding tools. The geometric modeling environment, NOODLES, is employed at various stages of the fabrication process to represent and operate on the different geometric abstractions appropriate for each stage.

6 Bibliography

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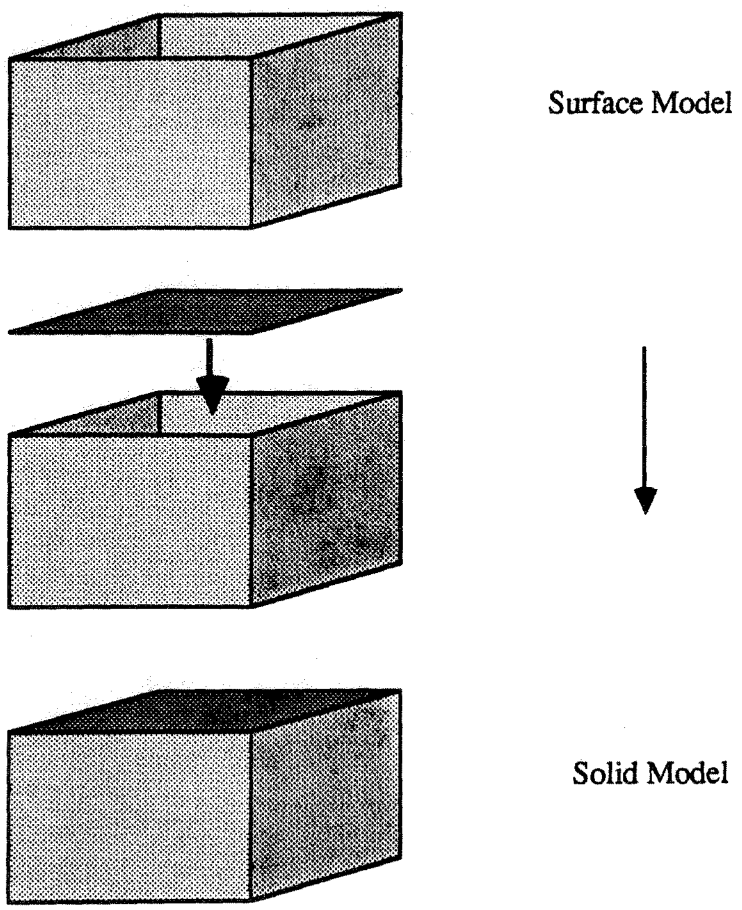

Figure 1: Surface patching

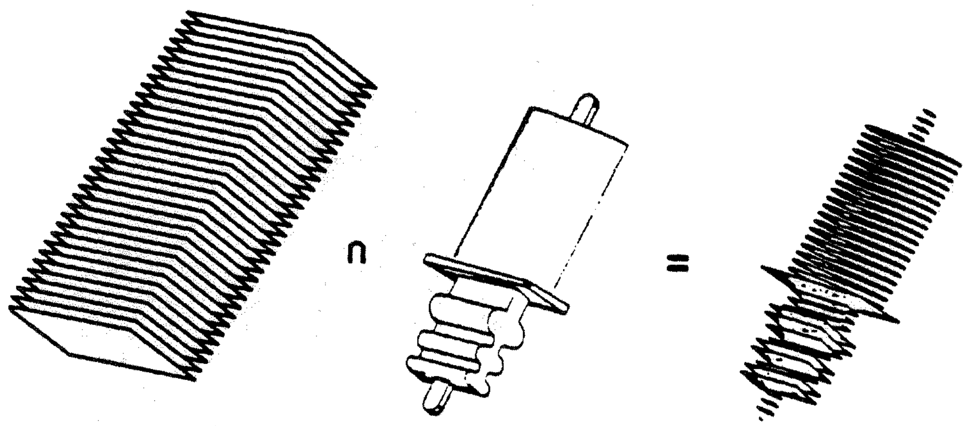

Figure 2: Slicing with NOODLES.

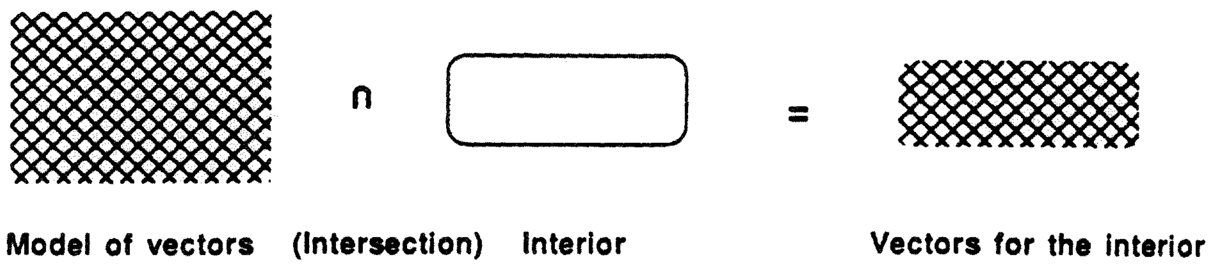

Figure 3: Vector generation with NOODLES.

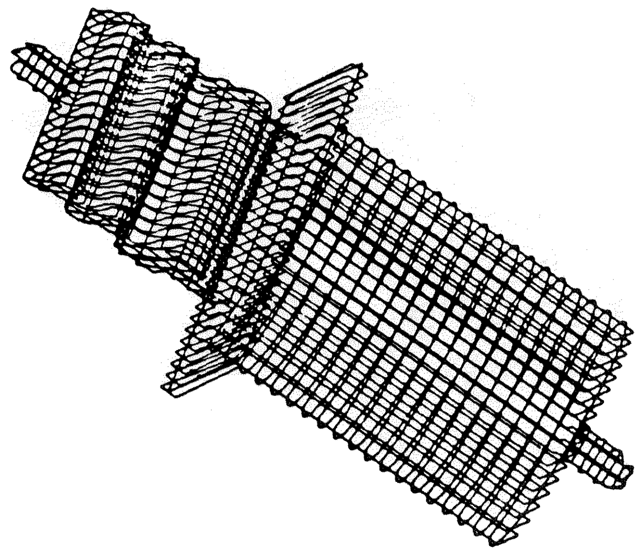

Figure 4: Robotic spray pathes

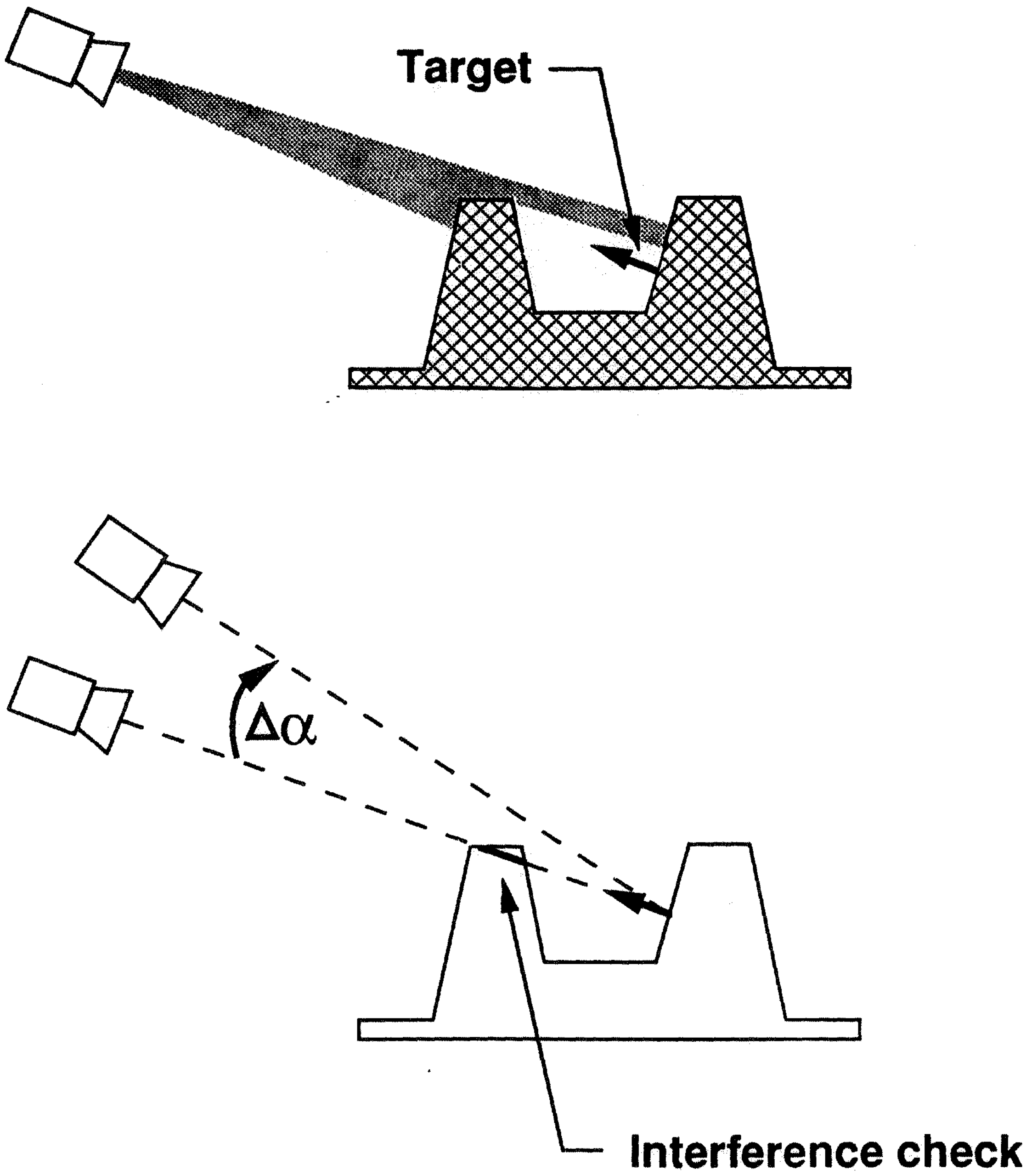

Figure 5: Interference checking