ALPHA_1, REMOTE MANUFACTURING, AND SOLID FREEFORM FABRICATION *

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Abstract

Alpha_1 is a nonuniform rational B-spline (NURBs) based solid modeling system that has been developed at the University of Utah over the past 10 years. In addition to being useful in modeling objects that are described by simple rotation and extrusion operations, the real power of Alpha_1 is demonstrated in the modeling of complex parts with sculptured surfaces. For the past several years, a major research thrust has been to use Alpha_1 to semi-automatically generate process plan information and numerical control code to manufacture mechanical parts directly from the models. A long term goal is to support an on-line remote manufacturing facility for producing prototype parts. Recently, a 3D Systems stereo lithography machine has been added to the advanced manufacturing laboratory. The stereo lithography process and other SFF techniques are of particular interest for supporting a remote manufacturing facility in that these processes are inherently much safer than numerically controlled machining. Special Alpha_1 interfaces including a new slicing algorithm are being developed for the SFF machine use. By generating a SFF part directly from its NURBs description, Alpha_1 should facilitate the manufacture of complex parts while providing smoother surfaces.

1 Introduction

Alpha_1 is a nonuniform rational B-spline (NURBs) based solid modeling system that has been developed at the University of Utah over the past 10 years. While Alpha_1 is quite useful in modeling objects that are described by simple rotation and extrusion operations, the real power of Alpha_1 is in modeling complex parts that include sculptured surfaces.

For the past several years, a major research thrust has been to use Alpha_1 to semi-automatically generate process plan information and numerical control code to manufacture mechanical parts directly from the models. A long term goal is to support an on-line remote manufacturing facility for producing prototype parts. Ultimately, it should be possible to design

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parts or complete assemblies of parts in one location and have them manufactured in one or more remote locations and then shipped to where they are needed. This system would be a mechanical analog to the MOSIS (Metal Oxide on Silicon Implementation Service) that is now available for VLSI designers.

Currently, the University of Utah advanced manufacturing laboratory has several state-of-the-art CNC machines including a 5-axis vertical machining center (milling machine) and a turning center (lathe) with a servo spindle and powered rotary tools. A direct computer controlled coordinate measuring machine is being acquired to both automatically inspect manufactured parts and to input data from existing parts and physical models.

Recently, a 3D Systems stereo lithography machine has been added to the advanced manufacturing laboratory. The stereo lithography process and other solid freeform fabrication (SFF) techniques have several major advantages for initial experiments in supporting a remote manufacturing facility. It is an inherently safe process in that errors can not cause a crash that could damage the machine or even injure the operator. Also, considerably less information is required to manufacture a part using SFF. With conventional machining, it is necessary to have complete process planning information including information on sequence of operations, fixturing, cutting tools, and material properties. Conversely, with SFF there is no material information, no cutting tool information, and almost no fixturing information required.

In many cases, the SFF process should allow prototype parts to be made without machining. This will be especially true if parts can be made from engineering materials either directly or indirectly. Even if more conventional manufactuing techniques are ultimately required, SFF processes can be used to prove out the model before using the conventional techniques.

2 The Alpha_1 Modeling System

Alpha_1 is a spline based, boundary representation solid modeler that is used to model a large class of sculptured and non-sculptured mechanical parts. Objects which fall into this category include turbine blades, airplanes, helicopters, automobiles and automobile parts, sewing machine parts, robots and robot parts, molded plastic parts and the molds to produce them, etc. Even parts that have, at first glance, a simple geometry sometimes cannot be accurately modeled without sculptured surfaces.

Alpha_1 also demonstrates the utility of high quality graphics in the mechanical design process, particularly when dealing with sculptured surfaces. Proper perception of a complex shape is not possible from a line drawing or rough shaded rendering. Much of the perceived information about the shape of a sculptured object comes from the highlights caused by specular reflections from the surface. Without an accurate lighting model and a high resolution image, the highlights, and thus the perceived shape, will be distorted. Surface ripples that might be invisible in a line drawing show up immediately in a shaded raster image.

Alpha_1 also serves as an experimental testbed on which new modeling ideas and techniques can be easily mounted and evaluated.

2.1 B-Splines in Alpha_1

The tensor product parametric NURBs surface representation is the single representation that occurs throughout the Alpha_1 system, and is supported by the entire system. Much of the system has been extended to support the "trimmed" surfaces, which are the results of Boolean operations derived from the CSG design paradigm.

B-splines have a number of desirable properties for use in computer-aided geometric design. A B-spline curve/surface is a piecewise rational function and exhibits specified degrees of continuity along specified isoparametric values, called "knot lines". For example, cubic B-spline curves can be C^3, C^2, C^1, C^0, or discontinuous at such a knot value, as specified. This ensures that a curve which should be smooth is indeed smooth, but by properly manipulating the knot vector, discontinuities of specified derivatives may be inserted in the curve.

B-splines have the *convex hull* property; that is, the curve always lies within the convex hull of the control points. It is therefore easy to bound the curve/surface, simplifying the calculations such as those required for producing an image or calculating errors in NC paths. Another feature of B-splines that is useful in a design system is that they provide "local control". Changing the location of a single control point modifies the shape of only a portion of the surface; the rest of the surface remains unchanged. This allows, for example, a designer to shape one region of a surface without affecting other regions that may be already complete.

The use of rational B-splines allows the exact representation of a large class of shapes, including the common quadric surfaces such as spheres, cylinders and cones. A polynomial B-spline, since it is a piecewise parametric polynomial curve or surface, can only approximate a circular or elliptical shape. By adding a weight or homogeneous component at each control point, it is possible to model these shapes exactly. Since many common mechanical parts have circular cross sections, it is critical that a design system be able to reproduce such shapes exactly.

A B-spline may be evaluated by computing the value at any given point. Often, however, an approximation to the entire curve or surface is desired. This may be found via a "subdivision" or "refinement" process. The Oslo Algorithm provides a method for taking a B-spline and computing a new B-spline, point for point identical to the original, but with more knots, and therefore more control points and more polynomial spans. It can be used to split, or subdivide, a B-spline into two pieces that, together, make up the original. The new control polygon, formed by joining the control points in order, more closely approximates the curve than did the original. Thus, by adding enough new knots, the control polygon itself may be used as an approximation to the curve.

2.2 A Short Description of the Alpha_1 System

The Alpha_1 system provides a number of capabilities. A short listing of the features of Alpha_1 includes:

- an interactive, extensible geometric editor,
- drafting style geometric construction operators,
- high-level shape modification and design operators,

- automatic creation of primitive objects,
- support for parametric design,
- feature based design,
- the ability to perform set operations to combine objects into more complex assemblies,
- high quality graphical renderings of object models,
- computation of simple mass properties of modeled objects,
- direct interface to 3D systems stereo lithography machine, and
- model driven CNC code generation

2.3 Set Operations

The ability to perform set operations, usually union, intersection, and difference, on models is recognized as one of the characteristics of a true solid modeling system. Set operations perform a number of useful functions in the modeling process. They can be used to combine simpler objects into more complex ones. It is not necessary to design an entire object in one piece; it may be broken down into simpler components that can be designed independently. The regions where the different parts meet are not explicitly designed, but arise from the interaction between the independently designed pieces. Using set operations to combine the parts produces the interface region automatically. A good example of this interaction occurs in a turbine blade, where the airfoil portion of the blade must be designed to meet certain aerodynamic or hydrodynamic constraints. The root of the blade is designed to hold the blade into the turbine during operation, and must meet an entirely different set of mechanical constraints. The airfoil must, however, be attached to the root, and a set operation is an ideal way to model the merger of the two.

The Alpha_1 system has the ability to perform set operations on "partially bounded sets". As long as they satisfy certain loose criteria, boundaries of objects to be combined by set operations need not be closed. This is a nice feature for the designer, who is not arbitrarily forced to close object boundaries just so that set operations may be performed. A good example of this is seen in the design of a turbine blade root, where none of the boundaries of the subpieces completely enclose a volume, but the final model does have a closed boundary.

2.4 Graphics

A key concept put forth by the Alpha_1 project is that design of mechanical parts and, in particular, of sculptured mechanical parts, is greatly aided by high quality graphic rendering of the model. Towards this end, the Alpha_1 system incorporates both a scanline rendering program and a ray tracing program that can produce images of B-spline surfaces. This process can adaptively subdivide surfaces until the pieces are flat, to a given resolution, produce polyhedral approximations, and either ray trace or scanline render the resulting polygons. The program has many options to control the rendering process, the lighting model, surface characteristics, and output form. It is possible to specify transparent or semi-transparent surfaces, allowing the designer to see interior details as well. Control over lighting is also provided, to allow careful placement of highlights to give maximum shape information. Images created with the ray tracing program may also include shadows, reflections, and texture mapping.

2.5 Geometric Editor

The geometric editors for Alpha_1, *shape_edit* and *model_server*, are implemented in Portable Standard Lisp (PSL). Lisp provides a rich interpretive environment in which arbitrary and extensible data structures may be easily created. The embedding of the editor in a language leads easily to the concept of the program as the model, rather than the output created by the program. It is also easy, therefore, to create a *parametric model*, one that can represent a family of parts by changing a set of parameters. Many tools and operations are provided for shape definition. These include drafting operations, sweep operations, shape modification operations and primitive objects.

The drafting paradigm of design is supported by providing a number of drafting type operations that deal with points, lines, and arcs in the plane. Arcs and line segments may be chained together into a B-spline curve. Curves can be used to construct surfaces in many ways. Alpha_1 also has a particularly rich set of sweep operators that can be used to generate sculpted surfaces in a predictable manner.

To simplify the task of working with B-spline surfaces, high level shape modification and design operators have been created. For example, the *bend* operator takes a previously defined surface and bends it. A thickening operation starts with a single surface, computes a surface that is offset from it by a given amount, and joins the edges of the two to form an object shaped like the original surface.

To accommodate models created by CSG systems, or for those cases when primitive shapes are desired, routines are included for automatically creating some basic objects. These include boxes, spheres and ellipsoids, cylinders and cones, and tori. The surfaces of the primitives are represented as B-splines, so any of the shape modification operators can be applied to them. Real objects often have rounded corners, instead of the sharp corners on the primitive shapes. Therefore, provision has been made to create versions of some of the primitives with rounded corners. In particular, cuboidal shapes with rounded edges and corners are supported. The radii need not be identical on all edges, and the faces need not be at right angles.

Finally, special purpose routines can be written to model any desired family of shapes. An example of this are the manufacturing features which can be optionally loaded into the geometric editor. Features including counterbores, countersinks, slotted holes, and rounded pockets have been defined in terms of built-in objects in the geometric editor. Linear and radial patterns of those features can also be constructed.

3 Using Alpha_1 for Solid Freeform Fabrication

SFF machines will be accessible to a potentially much larger user community than milling and turning machines. Therefore it is important to be able to drive them as automatically and as directly from the model as possible.

Special Alpha_1 interfaces are being developed to drive the 3D SFF directly from the model. To implement this interface, it is necessary to generate a complete solid polyhedron whose facets are *properly triangulated.* This means that the process requires triangles arranged so that an edge of one triangle cannot contain a vertex of an adjacent triangle.

Fortunately, the scanline rendering algorithm produces polygonal approximations for both trimmed and regular NURBs surfaces. Using that form, it is relatively easy to generate properly triangulated surfaces for models that have only a single surface or a collection of surfaces with correctly declared adjacencies. As most real models contain many surfaces, it becomes relative difficult for the designer to design surfaces that exactly meet the other adjacent surfaces and provide the correct adjacency information. For complex parts it is generally easier to design simple overlapping surfaces and trim them using boolean or set operations. It should be noted that it is sometimes possible to generate the effect of combining surfaces by using the 3D Systems " merge" operator.

A more complex algorithm has been developed to properly triangulate models with the trimmed surface boundaries that result from using the boolean or set operators. Several recent parts represent the output from this algorithm. One potential problem with the current method of treating trimmed surfaces is that the current slicing routine used by 3D Systems tends to collapse long thin triangles into degenerate lines.

Anticipating potential future interfaces for SFF machines, we have also investigated the requirements and algorithms that would provide the necessary slice and layer information directly from the NURBs model and have demonstrated the ability to directly generate oriented slice curves from complex Alpha_1 NURBs models. By generating a SFF part directly from its Alpha_1 NURBs description, the manufacture of complex parts would be facilitated while providing more accurate surfaces.

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