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Rapid Planning for CNC Milling—A New Approach for Rapid Prototyping

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Abstract

This paper presents a description of how CNC milling can be used to rapidly machine a variety of parts with minimal human intervention for process planning. The methodology presented uses a layer-based approach (like traditional rapid prototyping) for the rapid, semi-automatic machining of common manufactured part geometries in a variety of materials. Parts are machined using a plurality of 2½-D toolpaths from orientations about a rotary axis. Process parameters such as the number of orientations, tool containment boundaries, and tool geometry are derived from CAD slice data. In addition, automated fixturing is accomplished through the use of *sacrificial support* structures added to the CAD geometry. The paper begins by describing the machining methodology and then presents a number of critical issues needed to make the process automatic and efficient. Example parts machined using this methodology are then presented and discussed.

Keywords: *CNC Machining, Rapid Manufacturing, Rapid Prototyping, Process Planning, Computer-Aided Manufacturing*

Introduction

The cost of producing small numbers of parts has been driven by the cost required to process-engineer the part(s). Traditional computer-aided process planning (CAPP) systems have reduced the time required to plan machined parts, but the cost for one or two-of-a-kind machined parts is still dominated by the cost of planning the part. The current use of CNC machining for these small quantities of parts is further limited by special tooling costs and machine setup.

The typical approach to planning parts for CNC machining has been to define the "features" of the part and match these features and tolerances to a set of processes that can create the required geometry to the specified accuracy. This approach has worked reasonably well for medium to high-volume parts, but it has had marginal success for the production of very small quantities of parts. In most cases, the time required to plan the part, kit the required tooling, and set up the machine (both fixture and tooling) has limited the use of CNC for these applications. The result is that rapid deployment of CNC machining has been relegated to a simple set of part geometries. The promise of minimal process engineering is a major factor that has driven the use of free-form rapid prototyping (RP) techniques. Unfortunately, many of these processes have been restricted to a small variety of materials with limited geometric accuracy.

In the literature, process planning is often approached with a set of goals driven by high production levels of parts—that is, a set of plans that strives for cost effectiveness through maximizing feeds and speeds and creating repeatable setups that can be paid for through economies of scale. Process planning for CNC machining includes tasks such as fixture planning, toolpath planning, and tool selection. There is a considerable amount of work in the literature pertaining to these three areas (Maropoulos 1995; Chen, Lee, and Fang 1998; Joneja and Chang 1999). The concept of *flexible fixturing* has been the topic of much research, though a completely autonomous fixture design system has yet to be developed (Bi and Zhang 2001).

Some exploration into the use of CNC machines for rapid prototyping has been published. Chen and Song (2001) describe layer-based robot machining for rapid prototyping using machined layers that are laminated during the process. The process is demonstrated using laminated slabs of plastic, machined as individual layers upon gluing to previous layers.

A hybrid approach using both deposition and machining called *shape deposition manufacturing* (SDM) continues to be developed (Merz et al. 1994). For each layer, both support and build material is deposited and machined in a combined additive and subtractive process. Sarma and Wright (1997) presented Reference Free Part Encapsulation (RFPE) as a new approach to using phase-change fixturing for machining. The approach was discussed recently in conjunction with high-speed machining (HisRP) (Shin et al. 2002). RFPE, in combination with feature-based CAD/CAM was proposed as an RP system (Choi et al. 2001).

Another approach is to use CNC machining for prototyping dies, an area called *rapid tooling* (Radstok 1999). One approach to rapid tooling uses machined metal laminates stacked to form dies (Vouzelaud, Bagchi, and Sferro 1992; Walczyk and Hardt 1998).

Many of these methods utilize CNC machining but do not address the fundamental problems of automating a fully subtractive rapid machining approach. This paper presents a method for "feature-free" CNC machining that requires little or no human-provided process engineering. The methodology described in this paper is a purely *subtractive* process that can be applied to any material that can be machined. The method described herein was developed in response to the challenge of automating as much of the process engineering as possible. The ultimate goal is to generate both the NC code and an automatically executed fixturing system by the touch of a button, using only a CAD model and material data as input. The process is perfectly suited for prototypes as well as parts that are to be produced in small quantities (~1 to 10).

Before beginning a discussion on the methodology, it is necessary to elucidate the set of constraints, both known problems in CNC machining and some self-imposed by the authors. For one, there will be a general assumption about the user—in particular that the human planner has no experience in machining. This is justified in light of the fact that one use of this methodology is for prototyping. During the early stages of design, one cannot assume that an experienced machinist is available. The system may need to be usable by a designer or engineer inexperienced in machining. The existing RP processes allow users to download CAD files and simply push a button to initiate the part building process. The same will need to be true for a rapid machining process. What does this mean in terms of the typical steps for process planning? The implication is that even moderately skilled tasks, including setting fixture and tool offsets, must be eliminated. More importantly, fixture design and implementation must be at least semi-automated. Overall, it is expected that the user will only be responsible for loading a piece of stock in a workholding device that is straightforward to use (e.g., a simple vise, chuck, collet, etc.).

Another assumption is that feature information will not be available as data input. In some cases of simple prismatic parts, feature extraction may not be a problem; however, for the general free-form part shape, it cannot be assumed that accurate and complete feature information is known. An example would be a CAD model generated by laser scanning of biological objects such as bones. This assumption suggests that toolpath plans must be generated without knowing what type of surface geometries are to be machined. This includes choosing the tool diameter and length, depth of cut, feeds, and speeds. Specifically, this assumption implies that the process planning method is not intended for *populating* features on a piece of stock material; rather, the entire surface of the CAD model must be cut *from* the stock material. In other words, process planning does not have to be done for each feature individually and then each feature milled in a sequence of operations. Although the difference may appear subtle, this assumption will be shown to have a significant impact on the framework of this methodology and will be explored in further detail in the proceeding sections of this paper. Lastly, it will be assumed that this process will be executed in a lights-out operation; given that, any catastrophic failure such as crashing the tool, holder, or spindle with any part of the machine tool or fixture must be prevented.

Overview of the Methodology

Methods have been developed to cover all aspects of process planning for rapid machining, including toolpath planning, choosing tool geometries, calculating setup orientations, and a concept for a universal approach to fixturing.

With regard to toolpath planning, the presented method borrows from layer-based RP methods. The general idea is to machine the visible surfaces of the part from each of a plurality of orientations. From each orientation, some but not all of the part surfaces will be visible. Only parts whose entire external surface is visible can be completely machined with this methodology. In some ways, this limits what can be done when comparing the methodology described herein to traditional RP techniques, but in no way reduces the flexibility when compared to traditional CNC machining. The goal is to machine the part from enough orientations such that, after all toolpaths are complete, all surfaces have been fully machined from at least one orientation. For each orientation, there is not a particular plan for a set of *feature* machining operations; rather, each orientation is machined using simple 2½-D layer-based toolpaths. This is very similar to the existing rapid prototyping systems; however, in this case, one is limited to removing only visible layers from each orientation instead of creating and stacking all of the true cross sections of the part from just one orientation.

Unlike existing rapid prototyping methods, CNC machining is a *subtractive* process; therefore, one can only remove the material around the periphery of a part (visible cross section of the part). To simplify the problem from both a process and fixture-planning standpoint, only rotations about one axis for orientations of the stock material during processing are used. This not only reduces the problems associated with process planning, but it will be shown how this supports the collision-free nature of the approach.

The method can be executed on a three-axis CNC milling machine with a fourth-axis indexer. Round stock material is fixed between two opposing chucks and rotated between operations using the indexer. For each orientation, all visible surfaces are machined using simple layer-based toolpath planning. The *feature-free* nature of this method suggests that it is unnecessary to have any surface be completely machined in any particular orientation. The goal is to simply machine ALL surfaces after ALL orientations have been completed. This process is illustrated in *Figure 1.*

In the first operation (*Figure 1a*), much of this surface is visible from the first orientation; however, the dark areas under the overhanging surface are not visible. In the second operation, the originally "shadowed" region of the same surface is now visible (*Figure 1b*). This approach avoids the problem of feature recognition and feature-based process planning. At least two, but more likely numerous, orientations will be required to machine all the surfaces of a part about one axis of rotation. Even a simple part like a sphere will require two orientations.

Because it is assumed that no feature information is available, then a general method for tool selection is required. At each orientation, a tool is required that can reach to the last layer for machining without colliding with any previously machined surface or the stock material. This requires that the shank diameter be less than or equal to the flute diameter. Because simple 2½-D toolpaths are being used, then a flat-end tool is an appropriate choice. One will note that this is similar to *roughing* operations in traditional machining process planning, only in this case the layer depth is set shallow enough (typically, maximum of 0.005 in./125 microns) that one can expect near *finish* machining results. Lastly, the diameter of the tool is simply the smallest diameter available in the given length. Because it is assumed that no feature information is available, then the only general approach is to use a small-diameter tool such that the most general shapes can be accessed. Unfortunately, there can be trade-offs with using the smallest diameter tool. For one, a small-diameter tool does not remove as much material at a given feed rate as a tool of larger diameter. The other problem is that small-diameter long tools can be deflected more easily under cutting forces. Tool deflection and chatter can be a problem. These problems make it necessary to maintain feed rates and depths of cut such that the tool does not bend or break. As such, the method is not very efficient. However, it is not as critically important to find an efficient solution for rapid manufacturing and prototyping, or at least not with respect to the actual material processing. The more important goal is to reduce or eliminate the preprocess engineering. Therefore, it is reasonable to trade off time spent planning the process for actual processing time.

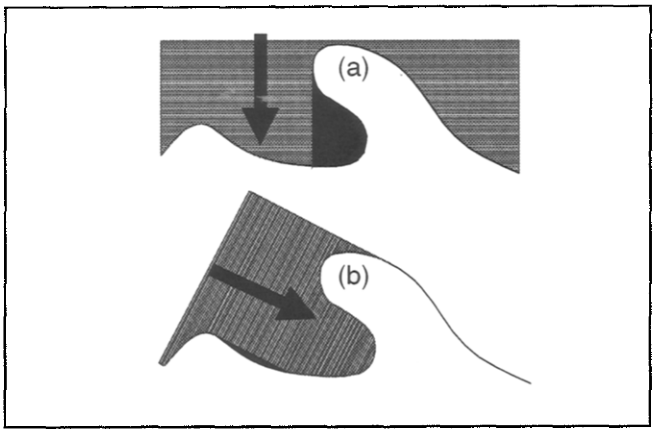
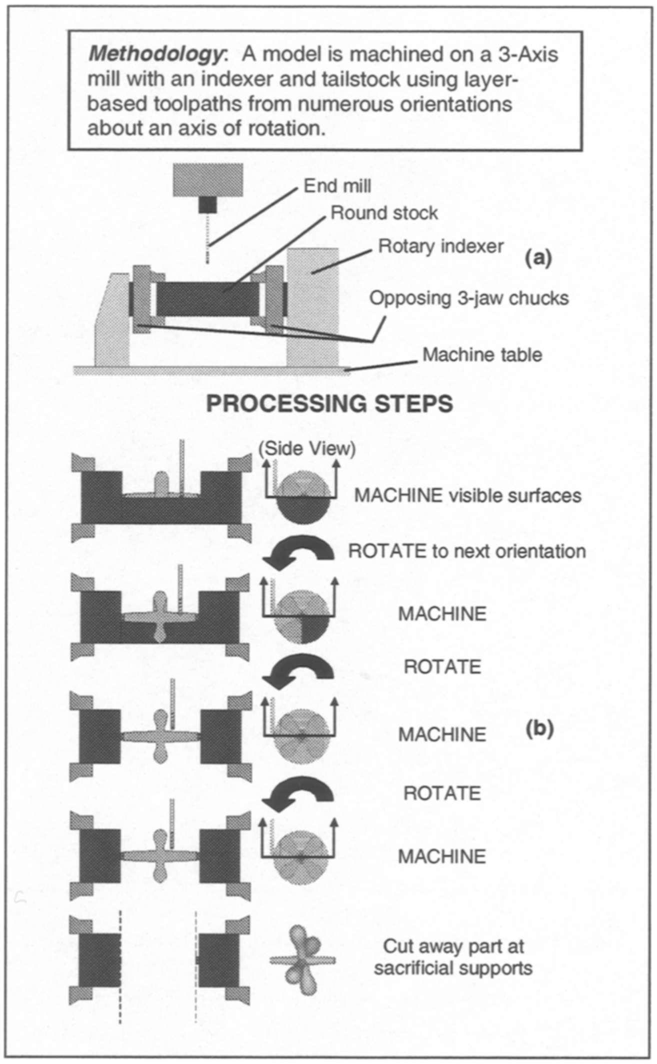


Figure 1
Free-Form Surface Machined with Multiple Layer Based Toolpaths

Using this method, part surface contours are created with the same "staircase" effect seen in other RP methods. However, because machining is able to make very shallow depths of cut, rapid machining can produce very thin layer thicknesses. Although machining time increases with reduction in layer thickness, it does not necessarily do so proportionally because shallower depths of cut enable higher feed rates. Rapid machining can achieve layer thicknesses easily down to 0.001 in. (25 microns) or less.

One would note that if all the visible surfaces of a part from numerous orientations about a single axis of rotation were machined completely, then at some point the part would simply fall from the stock material. However, this method employs a fixturing approach that is similar in concept to the "sacrificial supports" used in many existing additive rapid prototyping processes. In this case, the supports are not added to the physical model; rather, they must be generated as added surfaces prior to toolpath planning. The sacrificial supports are currently implemented as small-diameter cylinders added to the solid model geometry parallel to the axis of rotation. During processing, the supports are created incrementally, along with the rest of the part surfaces. Upon completion, the finished part is left secured to the round stock material by these cylinders. The setup and process steps for creating a part using the current method are shown in *Figure 2*. An example of a toy jack is shown to illustrate the method for a typically complex and challenging part to machine—but straightforward using the current approach.



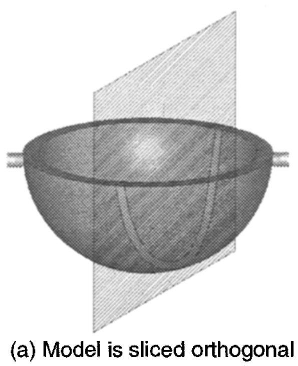
Methodology: A model is machined on a 3-Axis mill with an indexer and tailstock using layer-based toolpaths from numerous orientations about an axis of rotation.

Figure 2
Rapid Machining, (a) setup and (b) process steps

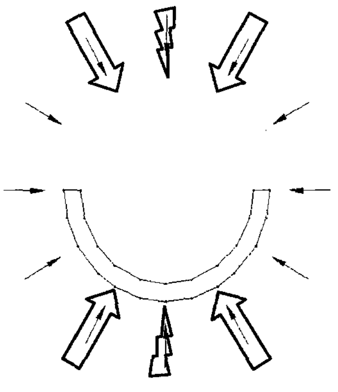
Toolpath Planning Method

The challenges in creating *layer-based* toolpaths is not in the actual cutter location data generation. A commercial CAM software package can easily generate 2½-D roughing toolpaths. It is as simple as setting the *maximum step down* parameter to the desired layer depth. The critical steps in the toolpath planning method are to determine: (1) How many orientations about the axis are needed to machine the part? and (2) Where are they? The problem is two-fold: (1) determine whether all surfaces of the model are machinable with rotations about the selected axis, and if so, (2) calculate the minimum number of orientations (index rotations) required to machine the entire surface. A *necessary* condition for a surface to be machinable is that it must at least be visible. Other *sufficiency* conditions exist, including tool reach and proper cutter contact for complex surfaces. For example, a ball-end mill will need to have sufficient length to reach a surface and be able to contact the surface with some point on the hemispherical end of the tool.

This research has addressed the necessary condition of *visibility* using a simplified approach that does not require feature recognition. Because tool access is restricted to directions orthogonal to the rotation axis, 2-D visibility *maps* for a set of cross sections of the surface of the model are used for finding the set of orientations for machining. This procedure approximates visibility to the entire surface of the model. For example, consider the part illustrated in *Figure 3a*.



(a) Model is sliced orthogonal to the rotation axis

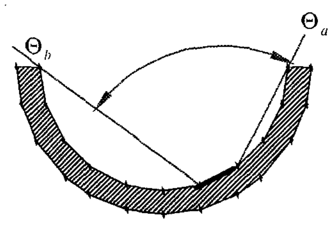


(b) Tool access directions are restricted to the slice plane

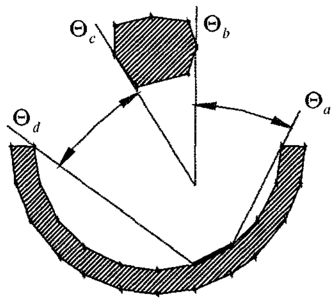
Figure 3
Model with Sample Cross Section used for Visibility Mapping

Cross-sectional slices of the geometry from an STL model provide polygonal chains that are used for 2-D visibility mapping. A simultaneous visibility solution for all cross sections of the model will approximate visibility of the entire surface. For this simple model and the slice shown in *Figure 3a*, the chain of edges in the polygon can be "seen" from many different views. If the views in *Figure 3b* illustrated by the block arrows (⟹) are chosen, four rotations *could* be used to machine the part. This implies that four orientations (index rotations) are used and all visible material from each view is removed. If the two orientations noted by the lightning arrows (↯) are used, then only two rotations are needed. In this case, two rotations is the fewest number required.

The entire presentation of the visibility algorithms will not be covered in this paper; however, a descriptive summary of the approach to visibility is provided in this section. A complete description of the visibility algorithms has been previously described in (Frank 2003) and is the subject of a future publication. For the method developed in this research, visibility for each polygonal chain is determined by calculating the polar angle range where each segment of the chain can be seen (*Figure 4a*). Because there can be multiple chains on each slice, one must consider the visibility blocked by all other chains. Therefore, the visibility data for each segment can be a set of ranges (*Figure 4b*).



(a) Visibility for the segment = $[\Theta_a, \Theta_b]$



(b) Visibility for the segment = $[\Theta_a, \Theta_b], [\Theta_c, \Theta_d]$

Figure 4
Visible Ranges of a Segment of a Polygonal Chain

If a visible range exists for every segment on each chain, for all slices in the set, then the remaining problem is to determine the minimum set of polar directions such that every segment is visible in at least one direction.

The problem of finding the minimum set of rotations sufficient to see every surface of the model can be formulated as a *minimum set cover* problem. The reader will note that the minimum set cover problem is NP-hard. Because large instances of NP-hard problems do not have known solutions that can be solved consistently or efficiently (Tovey 2002), an approximate solution is found using a *greedy* approach (Chvátal 1979), employed after the visibility mapping is complete.

The solution of the set cover provides the minimum set of angles from the set [0°, 360°] such that, for every segment, at least one angle is contained in

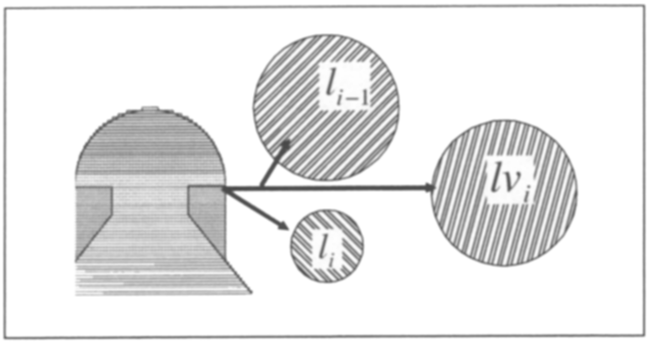


Figure 5
Illustration of Visible Cross Section, l_{vi}, Just Below an Overhanging Feature

one of its visibility ranges. However, other criteria will need to be considered to determine a minimum, yet sufficient, number of 2½-D toolpaths necessary to machine all surfaces of the part. Tool diameter and length, and the processing sequence for the indexing operations, need to be considered. Furthermore, one needs to determine the axis or axes of rotations necessary to machine all the surfaces.

In the current approach, it is only important that all surfaces of the part geometry are visible in some direction. Because this methodology uses segments of polygons, this implies that each segment must be visible from some polar direction, regardless of any other segments around the one being investigated.

Given each orientation, there remains a set of parameters that will need to be given to the CAM system to generate the layer-based toolpaths. Layer-based machining has been illustrated as a feature-free approach to *rough* machining (Balasubramaniam 1999). Balasubramaniam describes the method of "clipping" layers to the vertical shadows cast by all layers *above* it (higher in the *z*-direction). He describes the *visible* cross section at a given *z*-layer as the union of its cross section with the cross section of the layer immediately *above* it (*Figure 5*). In the current approach, *finish* machining is accomplished in a similar manner, using significantly thin layers.

For all

$$l\left[l \in L \,\middle|\, \text{set of all cross sections}\right] lv_i = l_i \cup l_{i-1}$$

where lv_i = visible cross section at layer i

Because this is a feature-free approach, the selection of surfaces for each machining operation is straightforward; **all** surfaces of the part are used for toolpath planning for **every** orientation of the solution set. For each orientation, the containment boundary for creating layer-based toolpaths must be defined. Assuming the tool is oriented in the *z*-direction, the containment boundary above the part is specified by a rectangle (*x*-*y*). The other information required is the depth of the maximum and minimum *z*-level layers (see *Figure 6*).

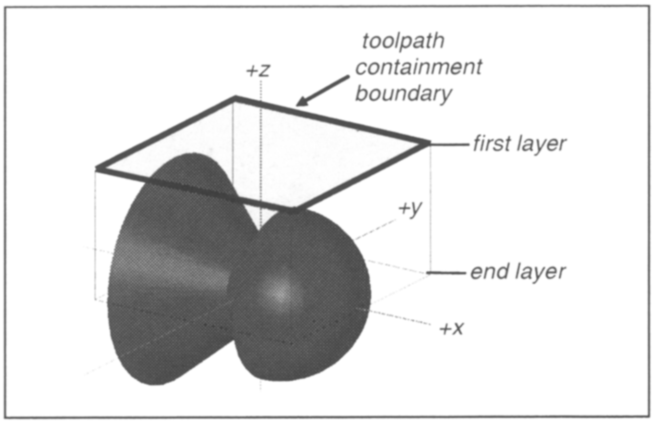


Figure 6
Layer-Based Toolpath Boundaries

The length of the boundary (*x*) must be greater than the part length along the axis of rotation, while the width of the boundary (*y*) must be greater than the maximum part diameter. Specifically, the containment boundary must be greater in both length and width of the part by at least the diameter of the tool (on all four sides). This is necessary because the tool requires a path around the part equal to its diameter in order to machine around the visible boundaries of the part. Given this boundary, layer-based toolpaths can be generated with layer thickness set by the *maximum stepdown* parameter in 2½-D machining. The toolpath layers must begin at or just above the stock surface and proceed through the distance (*z*) to the furthest visible surface from the current orientation.

Recall that the information from the visibility map provides the set of segments visible from a given orientation. From this, one can calculate the maximum distance to all segment endpoints visible from each orientation in the solution set. This distance is the maximum *z*-depth for layer-based toolpaths in an orientation of the solution set (see *Figure 7*).

The data from the visibility method provide the set of segments visible from each orientation in the solution set. Each segment is defined by its endpoints (P_i, P_{i+1}) where each endpoint has coordinates in the

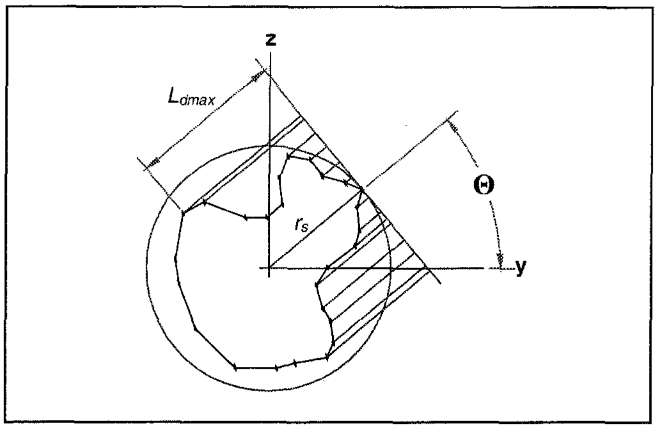


Figure 7
Distance to Deepest Visible Segment at One Orientation

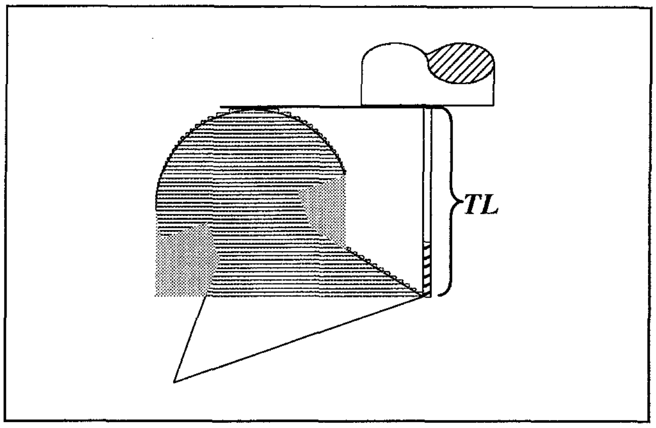


Figure 8
Tool Length Requirement

y-z plane (y_i, z_i). The perpendicular distance from each point to the tangent line at the solution orientation is calculated. The maximum distance to all points visible from each orientation is used as the location of the *maximum layer depth* for that orientation.

Although the STL representation is used for visibility mapping, if a solid model exists then it can be used for toolpath planning in CAM. The model is simply rotated in the CAM environment to each of the orientations from the visibility algorithm, and the toolpaths are created using the other setup parameters from the slice file information.

Tool Selection

Proper tool selection must ensure collision-free machining for any model complexity. One condition to ensure collision-free toolpaths is that the tool length must be greater than or equal to the distance to the furthest visible surface with respect to current orientation. In this manner, one is assured that even on the deepest layer, the toolholder will not collide with the stock (see *Figure 8*).

To ensure that no portion of the tool will collide with any previously machined layers, the tool shank diameter must be less than or equal to the flute diameter. This criterion unfortunately makes a tool more susceptible to deflection and breakage. Typically, long tools are designed with large shank diameters and only have the length of the cutting surface (flutes) at the prescribed diameter. *Figure 9* illustrates a tool with the proposed characteristics reaching to a z-depth without tool collision.

A desired goal is to choose tools that will be capable of machining a variety of complex surfaces at the required accuracy. The current approach is to select the smallest tool diameter available in the necessary length that is specified.

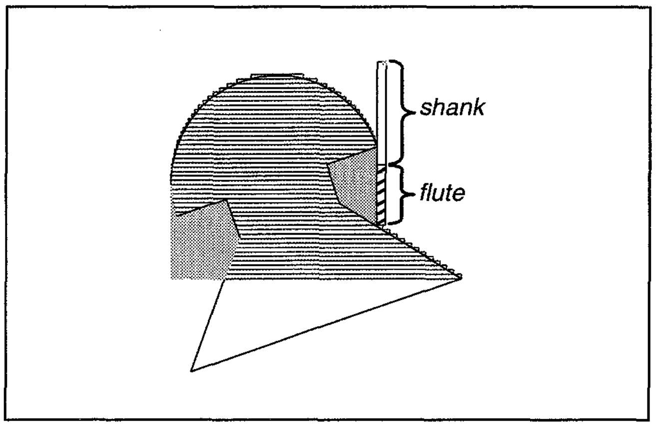


Figure 9
Tool Diameter Requirement

Because only 2½-D layers are to be machined, a flat-end tool is most appropriate. Whereas a ball-end (spherical) tool is able to machine smaller radii surfaces in some cases, the diminishing diameter of the cutter contact patch is a problem because very shallow depths of cut are used each layer (see *Figure 10*).

As noted, one of the goals in tool selection for rapid CNC is to minimize the cutter diameter. This is directly opposite of the goals of a typical manufacturing process plan. However, based on the assumption that feature information is not known, one must use the smallest diameter tool available in a given length. From a purely geometric standpoint, this increases the likelihood that the smallest features of the part can be machined. Tool selection is both related to, and impacts, other process planning param-

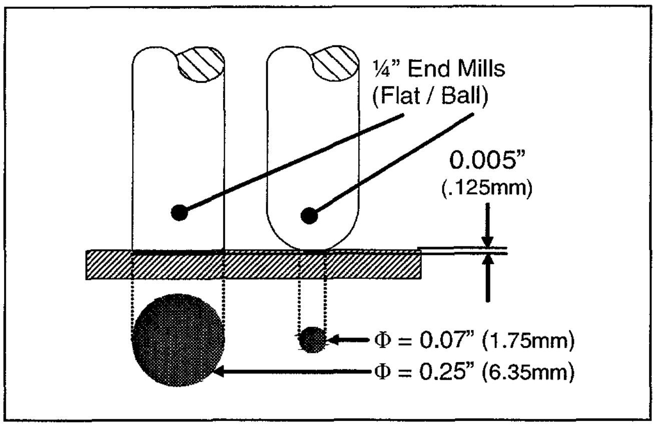


Figure 10
Cutter Contact Area for Flat and Ball-End Mill

eters. For example, the diameter of the tool defines the extent of the toolpaths along the rotation axis direction. This affects the length of the sacrificial support cylinders because they need to protrude from the ends of the part.

Fixturing Challenges for Rapid Machining

Designing a fixture scheme for CNC machining is a difficult task that requires a significant amount of work from a highly skilled technician. In general, fixturing or *workholding* serves three primary functions: location, clamping, and support (Chang, Wysk, and Wang 1998). This section presents these functional requirements in the context of rapid CNC machining.

Just as the approach to developing toolpaths of this research differs from traditional machining, the fixturing requirements for rapid machining are significantly different. Typically, a human operator orients the stock material between setups. Fixtures, in combination with hard stops and/or probes, are used to establish reference locations on the stock material. If a part is to be machined in multiple setups, it is critical that the fixture scheme facilitates repositioning of the stock such that dimensional constraints can be satisfied. Once the stock is located in the fixture, sufficient clamping force is needed to withstand the machining forces. In addition, the fixture must provide support for overhanging or slender features so that the stock material will not deflect too much under the machining forces.

The goals of rapid machining make the fixturing problem both more and less difficult. In rapid machining, accessibility to the surfaces of the part is of paramount importance. When using traditional vises, for example, much of the part surfaces are in contact with either the jaws or the bottom of the vise. This is not always a problem in traditional CNC machining, where a piece of stock (usually prismatic in shape) is *populated* with features. For example, in one setup the process plans for a part may include a pocketing operation, then a slotting operation in the bottom of the pocket. The face of the stock where these features are being created may be cut during the machining operation, or created in a preprocessing step, or it may simply be the result of the original stock production. In the current method, one does not assume that any shaping operations have occurred, nor is the original stock shape considered viable for a finished feature. The current methodology suggests a *feature-free* manufacturing approach whereby all surfaces of the part are candidate "features" to be machined from an orientation. Consider a comparison between a typical machining approach and the current methodology, as illustrated with a simple part, shown in *Figure 11a*. In *Figure 11b*, the pocket and slot are machined on the face of a block, with the sides of the block clamped by the jaws of a vise. Because these are the only two features to be machined in this setup, then the vise fixture is appropriate. This is the case where the stock material is being populated with two features, namely the pocket and slot. In *Figure 11c*, the same part is being machined out of a larger piece of stock material. In this case, the top, front, back, and sides of the block must be machined (to some depth) in addition to the pocket and slot on the top.

Recall that for each setup orientation **all** surfaces are used in process planning. The intent is that all visible surfaces from any orientation *may* be machined in that orientation. The feature-free nature of this method demands that the fixture solution provide as much access to the part as possible.

Each rotation places the stock material in a new *setup* orientation; however, the work offset must be retained for each orientation without having the user re-establish it. Therefore, the fixture solution for rapid machining must allow rotations of the part without the need to relocate reference points. The current fixturing method takes advantage of the fact that reorientation of the stock is only executed about one axis, which makes it easier to develop an automated method.

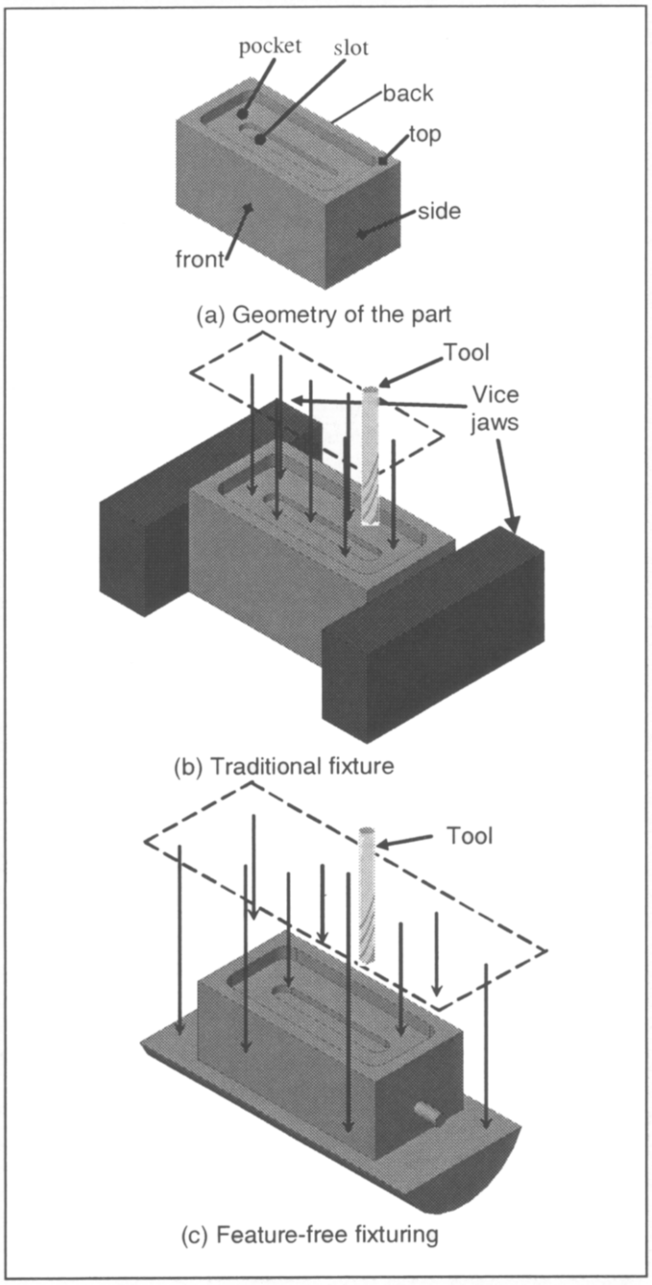


Figure 11
Comparison of Traditional vs. Feature-Free Fixturing

Typical cutting forces during machining can cause the stock material to slide or shift, and some elements of the part can deflect under load. A characteristic of the method of rapid machining is that cutting forces are significantly lower in magnitude and less variable because the depth of cut is very shallow and is the same for all operations. This results in a significant decrease in the amount of clamping and support that the fixture needs to provide. Although cutting depths in traditional machining vary, if one considers the fact that a constant 0.005 in. (125 microns) or less depth of cut is used in this method, the cutting forces will be orders of magnitude less than those of a typical machining process plan.

A significant challenge for developing a fixturing scheme for rapid machining is that the fixtures must be generated automatically. Existing rapid prototyping techniques are usable by unskilled people in a *turnkey* application. One cannot assume that a user will be available to design and create a custom fixture for each part, nor will he/she be available to rotate/flip the stock between each new setup orientation.

Fixturing Approach

The approach to fixturing for CNC RP borrows from the general idea of *sacrificial supports*, which are used in existing RP systems. In this work, the general intention is retained, however, the requirements for the support structures are different. The goal is to have a fixture solution that is created in-process and is customized for each part. Specific to this work, the fixture supports need to allow the part to be rotated about the axis while providing access to as much of the part surface as possible. Conventional fixturing methods for CNC often utilize vises, clamps, vacuum surfaces, and so on. These approaches occlude visibility to a significant amount of the part or make it difficult to reorient the part for multiple setups. The following paragraphs describe an approach to fixturing using sacrificial supports in CNC machining.

In this method, the *sacrificial supports* are added to the ends of the model (in CAD) such that the model remains attached to the round stock material throughout the set of machining operations. In the current implementation of the method, small diameter cylinders are manually added to the CAD model at its ends prior to creating the process plans, so that toolpaths are created to machine the cylinders in the same layer-based fashion that the model is processed.

At least one sacrificial support is necessary, but numerous ones may be required to fixture the part during machining operations. This concept is illustrated in *Figure 12*, where a finished part is fixed within a cylindrical piece of stock material, which in turn is fixed between the jaws of two opposing chucks. For every orientation about the axis, the relative tool ($z = 0$) offset location is constant at the cen-

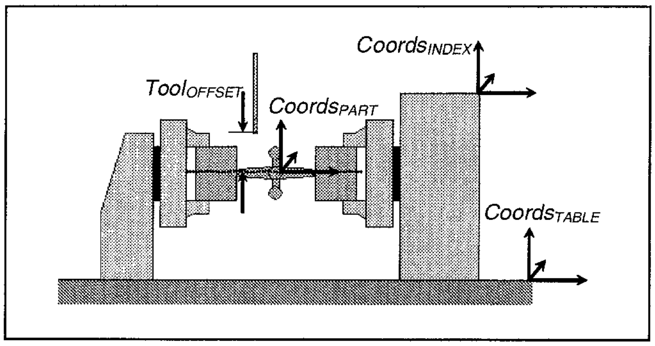


Figure 12
Illustration of Fixture Setup

ter of rotation. Similarly, the part coordinates ($Coords_{PART}$) remain at a consistent location with respect to the stock material clamped in the indexer ($Coords_{INDEX}$) and located on the table ($Coords_{TABLE}$) for every rotated orientation.

A practical advantage of using sacrificial support fixturing is that, for a given setup orientation, the amount of visible surfaces can be increased compared to traditional fixtures. If a traditional vise were used and features needed to be machined on numerous surfaces, the part will need to be unclamped, reoriented, and then reclamped for each orientation. It is difficult to reorient and reclamp a part without introducing error during location. Utilizing sacrificial supports, the stock is reoriented without changing the relative location of the part with respect to the machine table.

When the complete set of rotated toolpaths has been executed, the cylinders are cut by the user, which releases the part from the round stock material. This of course adds a post-processing step, where the surfaces of the model at the contact point of the cylinders must be sanded, ground, and so on. A proposed improvement is to generate a separate set of machining operations that focus on reducing the diameters of the cylinders for easy removal.

Using a sacrificial support, a minimal amount of the surface (the support contact "patch") will be left inaccessible. Another drawback is the rigidity of sacrificial supports, depending on the size and number of supports used. There is a trade-off between minimizing the size of the support for accessibility while maximizing the overall rigidity of the fixture.

In addition to the technical advantages of using sacrificial supports, there are practical advantages with respect to making this rapid machining method straightforward to implement. To set up the workpiece for the current method, the user clamps a piece of round stock between two chucks. The diameter of the stock is simply as large as the diameter of the part about the rotation axis, and its length can be calculated in a straightforward manner (see *Figure 13*).

The *collision offset*, *b*, ensures that a part program can be run with no risk of collision between the toolholder and either of the chucks. It is assumed that the rest of the spindle will not collide, given a proper choice of toolholder length. A significant advantage of this fixturing methodology is that work and tool offsets do not need to be set before running a part program. The collision offset, *b*, can be used to translate the part coordinates such that tool collision cannot occur, given a toolholder and maximum

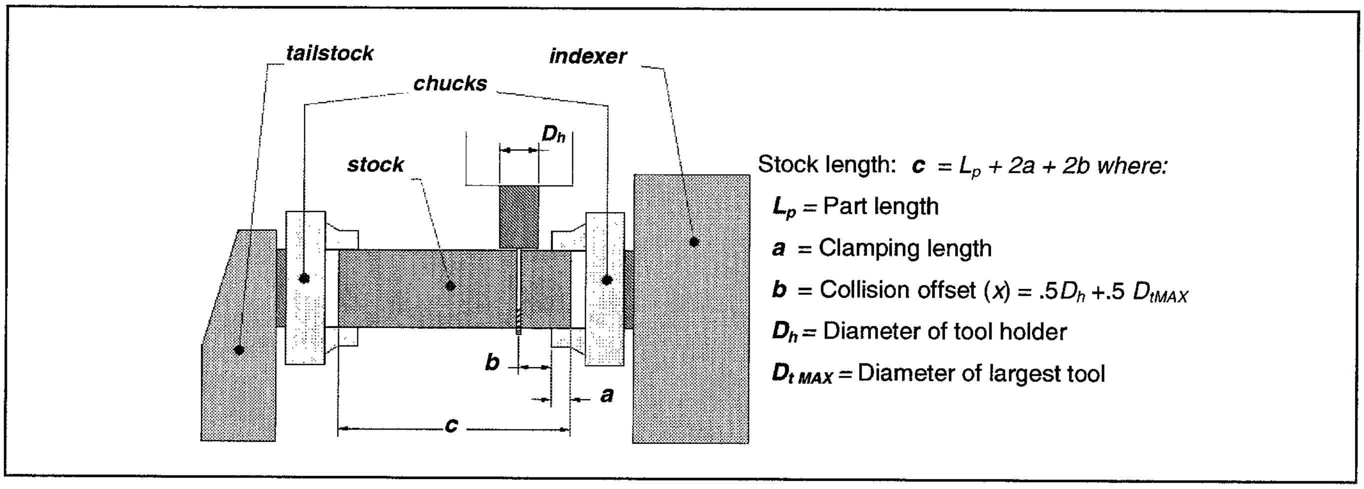


Figure 13
Fixture Setup and Stock Material for Rapid Machining

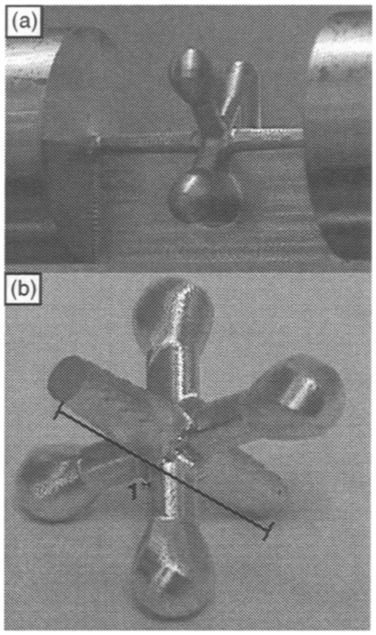


Figure 14
Jack Model, (a) between orientations and (b) finished part

tool diameter. This makes setting the work offsets for each new part unnecessary. The work offset coordinates [$x(0)$, $y(0)$] will always be aligned with the axis and located at the face of the stationary (along x-axis) chuck on the indexer. Similarly, the tool offset is set to the z-height corresponding to the axis of rotation, as mentioned previously. If a proper length and diameter stock is clamped between the chucks, a part program can be executed collision-free with no need for the user to set offsets; a time-consuming and often error-prone task in CNC machining.

Example Parts Using the Rapid Machining Methods

The visibility algorithms were implemented in C and tested on a Pentium 4 2.0 Ghz PC running Windows XP. The software accepts slice files as input and returns several critical process parameters: (1) the minimum number of orientations, (2) the minimum stock diameter, and (3) the distance to the minimum and maximum layer depth for each orientation.

Using the set of orientations, max/min depths of cut, and stock diameter, toolpath plans can be generated using CAM software. Several metal prototypes have been machined in the laboratory. Although the intent is to integrate the visibility software with CAM and automate process planning tasks, at present the steps of toolpath processing are done manually. The steps that were executed are as follows:

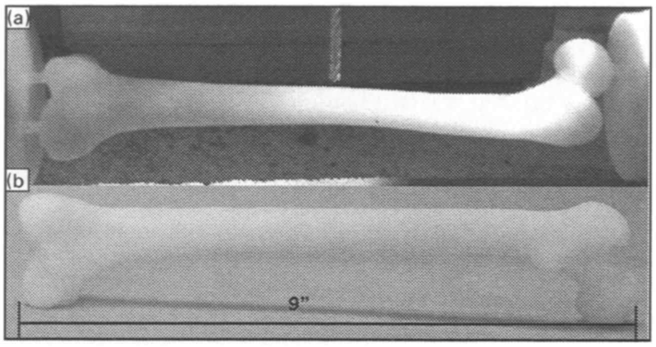


Figure 15
Bone Model, (a) attached via sacrificial supports and (b) finished model

1. Visibility software executed.
2. CAD model rotated through each of the orientations of the visibility solution.
3. Toolpath containment boundary created using stock and tool diameter and length of part.
4. For each orientation, *rough surface pocket* toolpaths (MasterCAM) generated. Minimum depth set at stock radius and max depth set to parameters given by visibility software.
5. NC code for each orientation combined manually into file with fourth-axis rotation commands.

Time required for step 1 is on the order of seconds, and less than half a minute for most parts. Steps 2–5 require 5 to 15 minutes depending on the number of rotations and the processor speed of the computer. The following are example prototypes machined in the laboratory.

The first prototype is the toy jack. The jack was machined on a Haas VF-0 three-axis machining center. The number of orientations provided by the visibility method was five. The part was created in approximately three hours. *Figure 14a* shows the prototype of the jack in between machining operations, while *14b* shows the jack after being cut from the stock at the sacrificial supports once all orientations were machined.

The next model is of a human leg bone, the femur. The model was machined from Delrin plastic. *Figure 15a* presents a view of the femur prototype during processing. As can be seen, the bone model is secured to the remaining stock via three sacrificial supports. The stock material is clamped on both ends

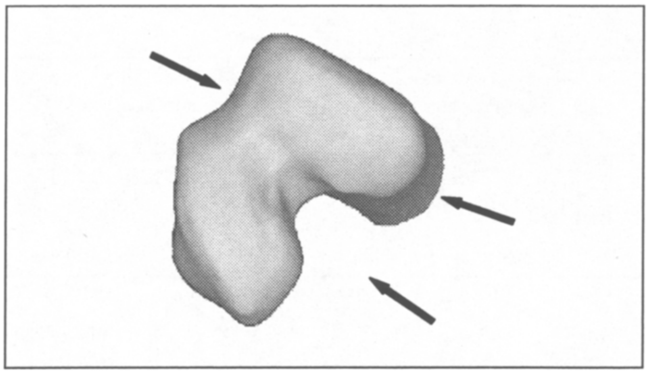


Figure 16
Visibility Orientations for the Femur

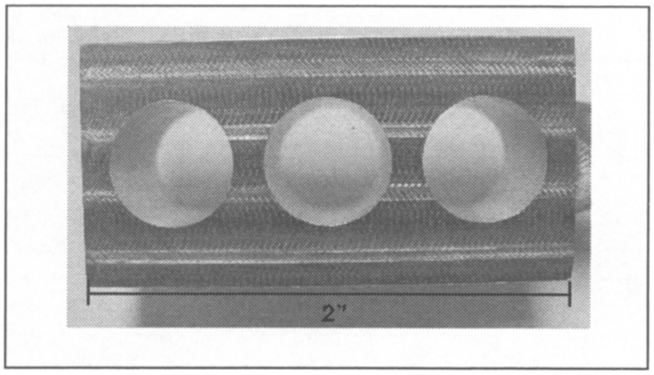


Figure 17
Finished Prismatic Model

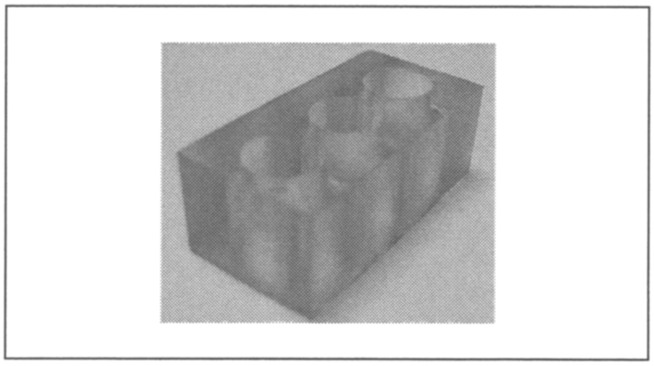


Figure 18
SLA Model

in three-jaw chucks, one on a tailstock and one on the face of a rotary indexer. *Figure 15b* shows the finished prototype after machining from three orientations. The three orientations for machining are illustrated by the arrows in *Figure 16*, as viewed from the distal end of the femur (left end in *Figures 15a* and *15b*). The total machining time was approximately 12 hours.

The final prototype example is a simple prismatic part, a block with three through-holes. Although this is a considerably simple part to machine using traditional methods, it can easily be measured on a coordinate measuring machine (CMM) to evaluate the accuracy of the current process (*Figure 17*). Again, the part was made without the use of a tailstock. A grossly oversized sacrificial support was used on one end to ensure stiffness for this test.

The prismatic block was measured on a Zeiss Vista CNC CMM. A runout error of 0.002 in. (50 microns) was detected in the fixtured stock prior to machining and is presumed to be the source of much of the measured error, in particular the undersizing of the width of the part. Overall the largest deviation in dimensions was on the order of 0.005 in. (125 microns), but it is expected that machine accuracy can be achieved with a fully implemented fixture scheme. In particular, runout with respect to the axis of rotation should be eliminated using the proposed fixturing method using opposing three-jaw chucks.

The same prismatic part was also created using a stereolithography (SLA) machine (see *Figure 18*). The processing time on the SLA machine was estimated using a software build time estimator (Georgia Tech-BTE 2002) at 2 hours and 56 minutes; however, the laser on the machine was old (laser power reduced from 35 mW to 19 mW) and the part required additional time (total of 4 hours and 46 minutes).

For the SLA part, the larger deviations in dimensions were the diameter of the holes (0.004–0.005 in./100–125 microns) and the largest was in the height of the part (~ 0.02 in./500 microns). The total time to create the SLA part was ~7 hours. This included 4 hours and 46 minutes to build it on the machine, 15 minutes to clean it and remove the supports, and finally, 2 hours in the post-curing oven.

Although the CNC machined prismatic block was not built with two appropriate sacrificial supports, it is estimated that removal of the supports would have required ~15 minutes, as was true with the jack and the bone. A comparison of the actual, or estimated (Georgia Tech-BTE 2002; Stratasys), build times for creating the three parts using rapid machining (CNC RP), fused deposition modeling (FDM), and SLA are shown in *Table 1*.

For the three examples listed in *Table 1*, rapid prototyping using CNC machining is shown to be the fastest of the three rapid methods in all but one case (SLA of bone). There is also the added benefit

Table 1
Comparison of Build Times

	Estimated Build Time			Actual Build Time			Estimated Post Process Time			Total Processing Time (est. and/or actual)		
Process	block	jack	bone	block	jack	bone	block	jack	bone	block	jack	bone
CNC RP	*	*	*	3h 30m	3h	12h	15m	15m	15m	3h 45m	3h 15m	12h 15m
SLA	2h 56m	3h 56m	9h 34m	4h 46m	*	*	2h 15m	2h 15m	2h 15m	7h 15m	6h 11m	11h 49m
FDM	4h 16m	1h 31m	15h 48m	*	*	*	2h	2h	2h	6h 16m	3h 31m	17h 48m

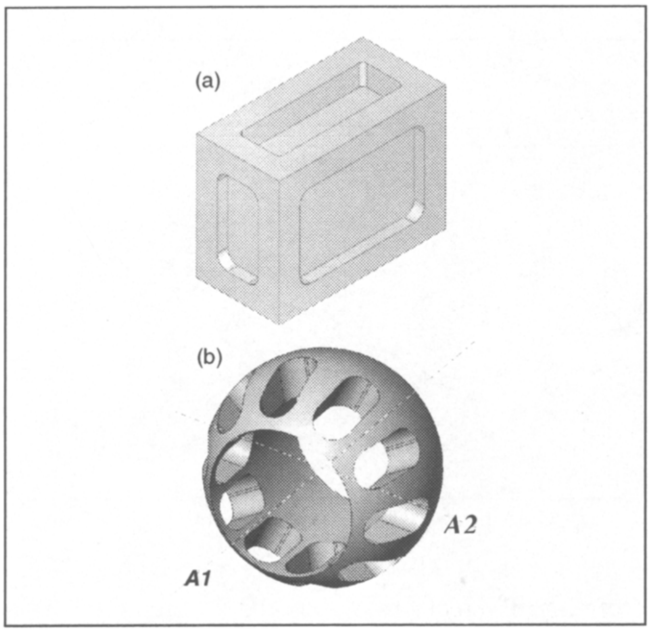


Figure 19
Parts with No Feasible Axis

of having a part made of better materials (aluminum and Delrin plastic) rather than ABS plastic or photosensitive resin.

Conclusions and Future Work

This paper presented a new methodology for rapid planning in CNC milling. The method makes it possible to rapidly plan and create machined parts and prototypes with little or no human intervention. The method presented involves milling parts using a plurality of 2½-D toolpaths oriented about an axis of rotation. Because the method strictly adheres to feature-free solutions, the complexities of most models do not affect system performance. Visibility approaches using 2-D slice geometry have made it simple to extract critical process planning information. The research has also further developed the concept of *sacrificial supports* for use in a subtractive process.

The method can be used for moderately complex part geometries. That is, parts with complex geometries that are accessible by rotations about one axis are possible; however, even simple geometries that are not visible about the axis of rotation are not machinable. Parts with severely undercut features can also be a problem, and hollow parts are, of course, impossible. In addition, small inside-corner radii are difficult or impossible to machine, depending on tool geometry. Not all parts will have a feasible axis of rotation such that all surfaces can be machined using the proposed method. An example of a prismatic part that would not have a feasible axis of rotation is shown in *Figure 19a*. This prismatic block has three pockets located on mutually orthogonal faces. As such, at most two pockets could be machined from one axis of rotation. The next example is a spherical-shaped part with several slots about its surface (*Figure 19b*). If an axis is chosen such that all slots can be machined (A1 in *Figure 19b*), then a significant amount of the interior will not be accessible. If an axis is chosen such that the entire interior can be milled (A2 in the figure), then only as many as two of the slots can be completely machined.

The visibility algorithms answer the question of whether an axis of rotation is feasible, but they currently do not search for a better solution. In its current implementation, the visibility method accepts a model oriented by the user and generates visibility information based on that axis of rotation. The next development will be in a method for evaluating multiple orientations and guiding the user at least semi-automatically to a "better" axis of rotation. A significant research effort is being directed at the automatic generation of sacrificial support fixturing for CNC machining. Sacrificial supports will greatly reduce the cost in both prototyping using CNC machining, and in many cases, in short production runs or batch processing of parts.

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