An Approach to Rapid Manufacturing with Custom Fixturing

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Abstract

We present an approach for automatically generating complete process plans, including fixturing and CNC code, from high level shape feature part descriptions. The demonstration system is targeted at a broadly useful class of machined prismatic parts which includes sculpted exterior profiles and features requiring four and five axis indexing for manufacture. The approach introduces a set of process plan templates *which are schemas for a family of process plans embodying a variety of fixturing strategies. The knowledge built into the process plan templates can adapt existing part hole features to be used for fixturing, can modify the workpiece to enable fixturing, and can create custom fixturing components for stages of the process plan.*

The process plan template system automatically transforms a given part design into a complete process plan. The user can provide optional guidance for this transformation and also can edit the resulting process plan to further extend the usefulness of this approach through customization. Domain knowledge in the process plan then automatically generates CNC code for a target machining center.

This research is implemented as an experimental subsystem within our Alpha_1 modeling and manufacturing testbed environment, and has been used to design and manufacture working components for outside client applications.

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1 Introduction

This paper reports recent research on an experimental system for automated manufacturing with custom fixturing. In this approach, high level feature-based shape models are transformed automatically into process plans from which CNC code for target machining centers is then derived automatically. This approach is targeted initially at parts with 2.5 D features including sculpted exterior profiles and features requiring four and five axis indexing for manufacture. This part class has great practical utility and can be used to build very complex assemblies.

Our experimental system uses a method for automated manufacturing based on a new notion called a *process plan template* (PPT). The PPTs are schemas for a family of process plans. A PPT encapsulates knowledge for an approach to manufacturing, including fixturing strategies as an integral part, that is applicable to a class of amenable parts.

The PPTs serve as a repository of manufacturing knowledge that can allow designers with little or no manufacturing experience to produce functional parts from their designs. For the designer knowledgeable of manufacturing, the approach serves to lessen the time required to specify the details of conceptually straightforward manufacturing and fixturing techniques, freeing the designer to spend more time on the higher level aspects of the design. Allowing expert designers to shape the resulting process plans, by providing optional guidance for the PPTs, further extends the usefulness of the approach.

The effectiveness and efficiency of a manufacturing approach depends on many criteria such as lot size, material costs and efficient material use, material handling, tooling and fixturing costs, machine tool run time, number of development cycles, and so on. For very large lot sizes it is worthwhile spending a great deal of time and effort to minimize material waste, number of setups, and machine tool run time. For prototypes and small lots the designer's time, and the total turnaround time from part order to part completion, are likely to be more important than machining time and material costs. The approach described here holds promise for keeping the designer's time to a minimum and has proved to be quite applicable for quick turnarounds on prototypes and small lots. Further, the manufacturing process plans produced by the PPTs are reasonable, if not optimal, with respect to material use and machine tool run time.

2 Background

To automate the manufacturing process it is necessary to analyze the manufacturability of a product and then actually to produce process plans and CNC tool paths. Both of these aspects require extensive geometric computation and reasoning capabilities and research into their automation is ongoing. Approaches have had two distinct thrusts. One is to guarantee that a design is manufacturable as it is created. The other is to create a design and then to evaluate and rate its manufacturability. There is research that exists across the spectrum between these approaches. For a general overview and survey of the state of manufacturability analysis, see [18].

One approach to guaranteeing manufacturability is to design using *manufacturing features*; a parameterized volumetric template that represents the solid volume removed from a workpiece by a single machining operation with a single cutting tool in one tool setup. This clearly has its limits since it embeds a single machine's process within the model. See [9, 10] and more recently [21].

Post design manufacturability analysis usually is performed on feature-based models. Most current CAD systems are either not feature-based or use features that do not contain sufficient information pertinent to this analysis. For this reason there is significant research into feature recognition for manufacturing analysis [20, 16, 24, 23]. Other research decomposes the geometric model into basic removal volumes [17, 26].

Automating process planning is a separate research topic. It is closely related to manufacturability analysis since most analysis approaches require process planning information. This information is either assumed by the analysis package or is generated as a set of alternatives by the package [19].

Process planning involves process selection, determining precedence constraints, including accessibility [29, 13], fixturability and setup planning, determination of machining operations, tool selection, CNC code generation, feeds and speeds specification, and plan evaluation. There are other considerations for avoiding cutting tool and tool holder interference with the workpiece and fixturing. For example, in [19] *removal* and *accessibility volumes* are used to formalize interference conditions for both the tool and tool holder with the workpiece, while [2] uses a similar approach to determine interference-free access directions for features. Solving problems in each of these topics are major research issues. The interdependencies in these issues makes automating process planning an extremely difficult problem for arbitrary parts.

The two most common approaches to computer-aided process planning are variant and generative process planning [6, 28]. Variant process planning techniques are used to retrieve and modify existing process plans based on classification schemes for families of parts. Generative process planning uses part features to generate process plans directly.

Integral to the process plan is a strategy for securely holding the workpiece in each setup as it is being machined. Fixturing design can be divided into planning and configuration tasks. Fixture planning determines sites on the workpiece that can be used to constrain and support it during machining. Systems use a variety of techniques to accomplish this including consideration of geometry, kinematics, deformation, and positional sensitivity [4, 8, 12, 3]. Fixture configuration involves the selection and location of fixturing elements to constrain the workpiece. Much of the research in fixture planning and configuration has assumed the use of modular fixturing systems, in combination with common elements such as vises and clamps, in lieu of custom fixturing. See [22, 12] for recent work in this area.

Automatic toolpath generation, for both roughing and finishing passes, is an important issue in the creation of process plans. This is an area of significant ongoing research in the field.

3 Approach

3.1 Overview

The system we present in this paper currently can take feature-based part designs from two different sources as input. The user can create designs with another experimental research system using a unique gestural interface which exploits familiar pencil and paper sketching paradigms [30, 5]. That system produces three-dimensional geometry which it automatically and continuously transforms into a parallel mechanical feature-based model of the design. Since the user interface abstracts away many of the details of manufacture, this approach is especially appropriate for users with little or no manufacturing experience. Users also can create feature-based models directly with an interpreted modeling command language which allows the use of the full set of features and constructions available in the underlying Alpha_1 CAD/CAM modeling system [1].

Regardless of the route used to produce the model, input to the PPT system is an unordered set of features representing the part we desire to manufacture. One feature in this set is assumed to define the positive volume for the overall shape of the part. This feature can be specified either as a block stock or profile side object (see below), or as a surface of extrusion. The other features in the set are currently restricted to negative volume (subtractive) features which are each, ultimately, decomposable into a series of subtractive machining operations.

The input part design is assumed to belong to the target class of parts. This class consists of piecewise three-axis prismatic parts which include sculpted exterior profiles and features requiring four and five axis indexing operations for their manufacture. It is assumed that part designs conform to the design rules for the given PPT. Such design rules include tool accessibility constraints, tool and fixturing interference checks, part dimension restrictions, length-to-diameter ratios for milling cutters and drills, etc. [5]. Checks for conformity are performed in a preprocessing step.

The system can analyze the model and choose the most appropriate PPT based on overall part shape and features present, or the user can specify the PPT to be used. Guided by the PPT, a process plan is then generated automatically from the features. The process plan specifies a sequence of *stages*, each of which corresponds to a machining setup and includes an ordered set of features to be manufactured, an orientation for the workpiece, and the fixturing specification for that stage. The features present in the complete process plan represent either a) unaltered features from the original design that have been sorted into specific stages, b) features from the original design that have been modified to support fixturing or other operations integral to the process plan, or c) new features created by the PPT to support fixturing.

CNC code for a target machining center is then created automatically from the process plan using a commercially available system [14, 15]. The CNC code includes tool selection, feeds and speeds, and tool paths. The machining center operator need only prepare and load the stock and cutting tools.

3.2 Mechanical Features

The term *features* has been used in a variety of ways by various authors. Often it is used to denote a geometric model of the volume of material to be removed by a single cutting tool during a machining process. Our mechanical feature objects are higher level, and more like those described in [25, 27] in that they contain multiple levels of abstraction. These objects represent designs for functional shapes in the language of mechanical engineering, including slots, holes, bores, pockets, grooves, bolt hole circles, and many others [11, 7, 1]. Besides serving as high level design elements for shape models, these objects also encapsulate domain knowledge. They contain rules for decomposition into low level single tool machining features which, in the context of a process plan, are then further transformed into CNC code fragments with cutting tools selected, and spindle speeds and feed rates calculated.

In the context of the PPTs, mechanical feature objects include positioning and orientation information that can be used for geometric sorting, as well as other detailed shape information like, for example, chamfers, threading, manufacturing tolerances, draft angles, and pocket bottom radii.

The outer shape of a part design, as provided to the PPTs, is specified by a surface of extrusion, or one of the following two features:

block stock feature: Parts will be machined from rectangular blocks of metal or other machinable materials such as plastic. A block stock feature represents the position and dimensions of this block.

profile side feature: The outer profile shape for an extruded part and the depth of the extrusion are given by this feature.

4 Process Plan Templates

The PPTs are schemas for a family of stereotyped process plans that encapsulate manufacturing domain knowledge including several different fixturing strategies. Using the feature set that describes the design as input, the templates guide the creation of complete process plans for manufacturing the finished part. This approach is a hybrid between generative and variant process planning methodologies, the two most common approaches to computer-aided process planning.

The process plan template strategy combines geometric sorting, modifying input features, and creating new features or components. The user in turn can provide additional guidance for the templates (see section 5 below).

Four and five axis indexing operations are supported to simplify fixturing and reduce the number of stage setups. Each of these indexing operations is, conceptually, a three-axis part **subprogram**, executed at an arbitrary orientation. Four-axis indexing operations require, at a minimum, a three-axis machining center with a numerically controlled rotary table.

Three templates, A, B, and C, are detailed to give concrete examples characterizing our approach. Template A is used for parts that have rectangular footprints, or outlines. Templates B and C represent alternative approaches for fixturing parts that have non-rectangular outlines. The choice of template is based on overall part shape and the presence or absence of hole features that can be used for fixturing.

4.1 Template A

This process plan is for parts with rectangular outlines. Features may appear on any of the six faces of the part block with all fixturing done in a machinist's vise that is attached to the bed of the machining center. The individual stages of the process plan for this template correspond to the faces of the part block.

Stage 1: Part block preparation. The part block is rough cut and then planed to the correct dimensions.

Stage 2 - Stage 7: Part top, bottom, front, left, back, and right. These stages correspond to the part block faces in the above order. The part block is clamped in the vise, with each face upward in turn.

The process plan for this template is created from the input feature set by geometric sorting based on feature orientation.

4.2 Template B

This template provides one alternative for manufacturing parts that have non-rectangular outlines, where a vise alone is inadequate for fixturing. Template B involves the manufacture of a custom fixturing plate to hold the workpiece while the exterior profile of the part is machined. This template is appropriate for designs with through holes in the part top that can be used to hold the workpiece against the fixture plate during this stage. The full set of stages for this template follows. Note that stages 2 and 3 of this template represent the recursive application of template A for the fixture plate.

Stage 1: Part and fixture block preparation. The dimensions for these blocks are determined automatically from the input features. The X and Y dimensions are extended to allow for continuous cutting of the part's outer profile.

Stage 2: Fixture plate bottom. If four or five-axis indexing features are present in the part design, then special fixturing is required on the bottom of the fixture plate for use during stage 7.

The fixture plate block is clamped in the vise with its bottom face upward. A set of reamed and tapped holes is machined to accept dowel pins and bolts during stage 7.

These features are created by the PPT to hold and register the fixture plate against the adaptor plate used in stage 7. The positions for the holes created in this stage are determined automatically by the system to allow mating with the adaptor plate and so as not to interfere with the (possibly through) holes to be made in the fixture plate during stage 3.

Stage 3: Fixture plate top. The block for the fixture plate is clamped in the vise and details for the fixture plate top face are machined. These internal details will accept fasteners used to hold and accurately register the part block against the fixture plate during stages 6 and 7. See section 5 for more details.

Features for this stage are generated automatically from the part description.

Stage 4: Part bottom interior details. The part block is clamped in the vise with its bottom face upward. Any features on the bottom of the part are then machined.

Stage 5: Part top interior details. The part block is clamped in the vise with its top face upward. Internal details of the part accessible from the top face are then machined.

Stage 6: Part exterior profile. The fixture plate from stage 3 is clamped in the vise (or mounted to the rotary table for five-axis milling – see next stage). The part workpiece from stage 5 is then attached to the fixture plate using a combination of bolts, dowel pins, and shoulder bolts (see section 5 below). The external profile cuts are then made to the part workpiece. The fixture plate is used in this stage to raise the part block sufficiently to prevent these cuts from interfering with the vise (or rotary table).

Stage 7: Part four and five-axis indexing operations. The part workpiece remains affixed to the fixture plate, which is now mounted to the rotary table using an adaptor plate. The adaptor plate accurately locates the workpiece relative to the rotary table axis. Mounting to the adaptor plate is accomplished using two bolts and two dowel pins inserted into the bottom of the fixture plate. Four and five axis features are then milled in the workpiece. Five-axis features must have orientations within 90 degrees of the plane normal for the part block top face.

Note that for five-axis milling, stages 6 and 7 are combined into a single stage requiring a single setup on the rotary table. The general purpose adaptor plate used during this stage can be manufactured using template A or B.

4.3 Template C

An alternative fixturing approach is provided for parts with non-rectangular outlines when there are no hole features that can be adapted for fixturing in the part design. This approach involves extending automatically the thickness of the part block feature so that the block can be held in the vise by its extended (sacrificial) portion while the part profile is being cut. The part will then be turned over and the extension removed.

The full set of stages for this template is as follows:

Stage 1: Part block preparation. As in template B, the dimensions for the block are determined from the overall part shape. Extensions in the X and Y dimensions are used to allow for continuous cutting of the part's outer profile. The depth of the block is extended for fixturing in stages 3 and 4.

Stage 2: Part bottom rotary stage fixturing. If four or five-axis indexing features are present in the part design, then special fixturing is required on the bottom of the part block for use during stage 4.

The part block is clamped in the vise with its bottom face upward. A set of reamed and tapped holes is machined to accept dowel pins and bolts during stage 4. These features are created by the PPT to hold and register the part block against the adaptor plate used in stage 4.

Stage 3: Part top interior details and exterior profile. The part block is clamped in the vise using only the bottom extended portion of the block (or mounted to the rotary table for five-axis milling – see next stage). Internal details for the part top are cut. Then the external profile cuts are made to the outside of the part. The bottom extension of the block is used to prevent any of these cuts from interfering with the vise (or rotary table).

All through part features, including the exterior profile sides, are extended automatically in depth so that the features remain cleanly cut after the bottom of the block has been planed off in stage 5.

Stage 4: Part four and five-axis indexing operations. The part block is mounted to the rotary table using an adaptor plate. The adaptor plate accurately locates the workpiece relative to the rotary table axis. The block is mounted using two bolts and two dowel pins inserted into the bottom of the part block. Four and five axis features are then milled in the workpiece.

Stage 5: Part bottom. The part block is clamped in the vise with its bottom face upwards. The extended portion of the block bottom is planed away. Any features on the bottom face of the part are then machined.

Note that for five-axis milling, stages 3 and 4 are combined into a single stage requiring a single setup on the rotary table.

5 Advanced User Guidance

In some situations the process plans produced by the templates may be correct, but not exactly what the user desires in some details. To extend the usefulness of this system, users can provide guidance for the templates to modify the resulting process plans. This guidance takes the following forms:

Change system parameters: System parameters that influence process plan generation can be changed by the user. These parameters include cutter clearances, block stock X, Y, and depth extensions, four and five-axis fixturing grid dimensions, diameters and thread pitch for fixturing fasteners, through feature extensions, and fixture plate thickness.

Change coordinate systems: The overall part position and orientation can be changed to allow for easier manufacturing. Coordinate systems for individual stages produced by the templates also can be modified.

Specify fastener options for fixturing: Process plan template B recognizes existing part hole features that can be used for fixturing. These features include through holes that have axes aligned with the negative Z direction and that have diameters appropriate for the standard fasteners used. These hole features are machined in the part block during stage 5 of template B. These hole features also can give rise to features in the fixture plate for possible use during stages 6 and 7. Possible fixturing uses for these holes are designated as follows.

> **don't use:** The hole feature will **not** generate any features for the fixture plate and will not be used for fixturing during stages 6 and 7.
>
> **use shoulder bolt:** The hole feature will generate a corresponding counter drilled tapped hole in the fixture plate. The hole in the part block will be used in combination with the generated hole in the fixture plate to accept a shoulder bolt that both holds and registers the part block against the fixture plate during stages 6 and 7. The depth of the counter drilled section is discretized so that standard length shoulder bolts may be used.
>
> **use bolt:** The hole feature will generate a corresponding drilled and tapped hole in the fixture plate. The hole in the part block will be used in combination with the generated hole in the fixture plate to accept a standard bolt that will hold the part block against the fixture plate during stages 6 and 7.
>
> **use dowel pin:** The hole feature will generate a corresponding hole in the fixture plate. Both the hole in the part block and the hole in the fixture plate will be reamed to a very high tolerance and used in combination to accept a dowel pin that will accurately register the part block against the fixture plate during stages 6 and 7.

By default, all hole features that can be used for fixturing will be used to accommodate shoulder bolts as fasteners. The user can change this default to any of the other three options given above. The user also can easily set the fixturing fasteners used on an individual hole by hole basis. Thus the user can specify, for example, a combination of standard bolts and dowel pins for fixturing.

The system will warn the user if the part hole features designated for fixturing are not the correct diameter to accept standard fasteners.

Add features to any stage: The user can provide additional features from the modeler that are appended to any stage of the finished process plan. The system will check the alignment of these features and warn the user if they cannot be machined during the specified stage. Otherwise the system makes no modification of these features.

Specify jaw inserts: Template C requires a final stage where the extended portion of the part block is planed off. The part block is inverted and then clamped in a machinist's vise to accomplish this. Not all part shapes lend themselves to this approach. Some parts may require inserts placed in the jaws of the vise that conform to the part shape on one side and are flat to mate with a vise jaw on the other side. The user can specify a portion of the outer shape of the part to be used to generate automatically a part description for the inserts. The part descriptions can then be used to create process plans for manufacturing the inserts by recursively invoking process plan template C.

6 Results

Figure 1 shows the finished workpiece for a template B part mounted on the fixture plate used to cut the outer profile part shape. The fixture plate was generated automatically from the part description. Figure 2 shows a part design requiring template C for manufacture. The machined workpiece after stage 4 of the template is also shown. The full sequence of stages for this part is depicted in Figure 3.

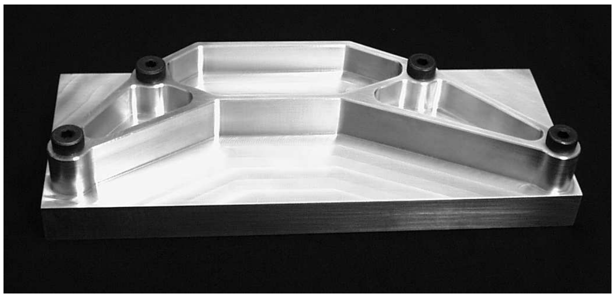

Figure 1: Engine mounting bracket using template B for manufacture. The finished workpiece is shown mounted on the automatically generated fixture plate.

7 Conclusions

This paper has presented encouraging results of ongoing research in automated manufacturing. Process

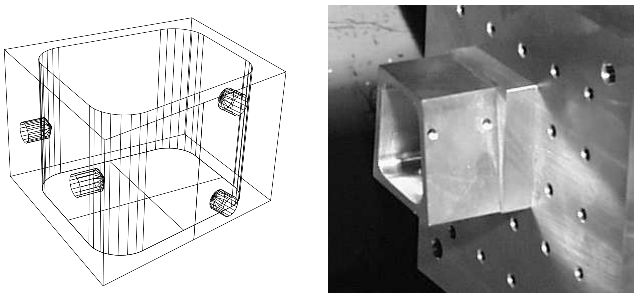

Figure 2: Mounting bracket for a small video camera using template C for manufacture. Left: feature model. Right: workpiece fixtured for four-axis milling.

plan templates guide the automatic generation of process plans from feature-based models. These templates represent schemas for a family of process plans that include fixturing as an integral part. This approach helps designers produce functioning machined parts from their designs without requiring extensive manufacturing experience. For designers knowledgeable of manufacturing, this approach helps minimize the time required to design fixturing details which would otherwise have to be specified in full. Such users can shape the resulting process plans further by providing optional guidance for the templates.

The system currently works with a class of non-trivial prismatic parts that have wide practical use. Further, the templates require fairly standard tooling and embody standard manufacturing practice. This makes the templates widely applicable to the resources of many manufacturing facilities. Although the process plans produced by the templates do not represent strategies which are optimal by certain criteria, such as machine tool run time and material use, we believe this approach is viable for production of prototypes and small lots; cases where optimal use of the designer's time is of crucial importance.

The current set of templates allows the manufacture of a useful class of parts. We also feel that these templates are evocative of an approach that can be further generalized. Recent work has focused on extending the present templates and developing new ones, thus extending the part class that can be manufactured with this approach.

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(a)

(b)

(c)

(d)

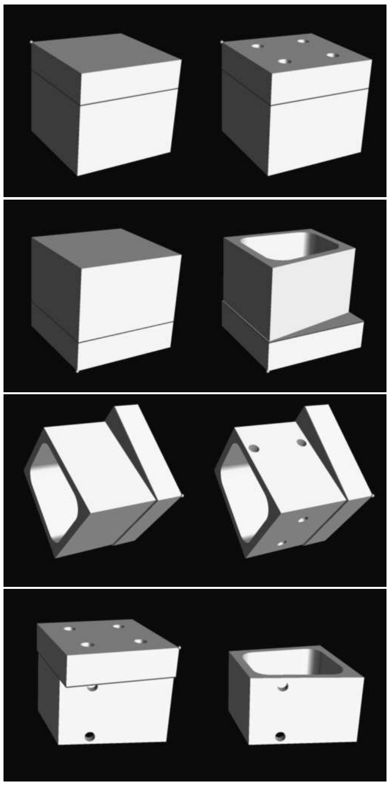

Figure 3: Depiction of full process plan for the part of Figure 2. Dark line around workpiece indicates extended portion of part block. (a) Part bottom fixturing (stage 2). (b) Part top details (stage 3). (c) Part four-axis details (stage 4). (d) Removing block extension (stage 5). Tool approach direction is from the top in these figures.

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