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INTELLIGENT KNOWLEDGE-BASED ENGINEERING

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This report presents a successful approach and implementation for integrating product and process design. The generation of a process plan as an integrated part of a free-form feature-based parametric design system is discussed. The success of the approach, detailed in this report, for an automated process planner integrated with a design system, comes from its capability to reason about and automatically extract a manufacturing representation from the part design geometry. By analyzing the part geometry, and planning around the problems that could be encountered in machining, the automated planner can overcome the difficulties in automating the process plan. No user assistance is required and it does not rely on retrieving and/or modifying the process plans of similar parts stored in a database.

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ABSTRACT

Traditionally, product design and process planning have been disjoint activities. Even with the advent of computer aided design, this juncture has been maintained as CAD systems have been extensively used in the automation of product design, while process design or planning has remained a separate and distinctly manual effort with little or no automation. There have been numerous efforts (e.g. group technology involving variant and generative techniques) and research in the area of product design and process planning integration. Most research has addressed only a part of the problem, i.e., either the product design or process planning. Integration of product design and material characteristics, with the automatic generation of the machining process plan, is a goal which offers many challenges to overcome.

This report presents an approach and implementation for integrating product and process design. The generation of a process plan as an integrated part of a free-form feature-based parametric design system is discussed. The success of the approach, detailed in this report, for an automated process planner integrated with a design system, comes from its capability to reason about and automatically extract a manufacturing representation from the part design geometry. By analyzing the part geometry, and planning around the problems that could be encountered in machining, the automated planner can overcome the difficulties in automating the process plan. No user assistance is required and it does not rely on retrieving and/or modifying the process plans of similar parts stored in a database. This research has been partially funded under a U.S. Air Force Small Business Innovative Research (SBIR) contract number F33615-93-C-5360 and directed by the Materials Process Design Branch, of the Wright Laboratory Materials Directorate. Additional funds were secured through technology partnerships with a number of engineering companies and firms.

IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM

Today's global market requires existing enterprises to compete in an environment that is changing at an ever increasing pace. Such a dynamic market requires making quick decisions appropriately. Customer demands dictate quick response and impose continual changes to the product development cycle. While these demands and numerous changes inevitably result in prolonging the development, process costs and product affordability are clearly the basis for competing in the marketplace. Investigating new materials and processes to lower costs while enhancing product performance is a major goal for the private sector as well as military.

The classic approach to product and process design is to specify-evaluate-revise. This approach is a cycle that often involves time consuming loops. The engineering of a product incorporates numerous stages involving design specification, manufacturing planning, finite element modeling and analysis (FEM/FEA), and inspection planning. Design changes (dimension, tolerance, material, process constraints, etc.) and rework procedures delay time to final production and market deployment. Rework can be very costly especially if revisions are suggested late in the engineering cycle. On the other hand, new ideas or new product technology are often discovered through the development process cycle. It is during this stage that alternative materials and processes are discovered and tested in an attempt to enhance product functionality and to reduce processing costs.

Alternative material and processes will not only benefit new designs, but could also impact the design of retrofit parts for maintaining/refurbishing existing systems. This is the case in the design and production of aircraft components. Such components could be the remanufacture of parts for maintaining existing aircraft or new parts designed to replace existing ones. The opportunity before us is the consideration of past knowledge in new designs to explore alternative materials and processes without today's protracted specify-evaluate-revise cycle.

Developing a system methodology to handle changes dynamically and to minimize the product design cycle could lead to major savings in the product development cycle and therein product affordability. This methodology will enable the investigation of alternative materials and processes to lower the production cost and enhance product performance. The objective is to apply this new methodology across all steps in the production process and begin to consider new material processes and non-destructive inspection methods, while evaluating alternative materials for more affordable products. This methodology will be the basis for the development of an Intelligent Knowledge-Based-Engineering (KBE) system for integrating feature-based, memory-driven design, with material specification, manufacturing/inspection process planning, adaptive meshing, and finite element modeling/analysis. This Intelligent KBE system will support geometrical reasoning for concurrent engineering through the incorporation of inductive/deductive reasoning for design and process optimization across alternative material, processes, and shape.

INTRODUCTION

The benchmark material process for current efforts in integrating product and process design is machining because nearly all products require some machining. Furthermore, machining is the most common form of material removal and is often an alternative to other processes involving small quantities of parts for structural applications.

In addition to functional specifications and geometric shape, process planning of machined parts requires the preparation of an outline that describes all the machining setups, fixtures, detailed machining operations, tooling, machining data and finally the NC part program to cut the part. For small lot sizes (1-25 parts), the design and process planning steps account for a large percentage of the overall production time. Therefore an integrated system for concurrent design and automated process planning generation will significantly increase production efficiency and lower processing costs. The system should enable the user to interactively design and plan the machining process to cut the part. This system will dramatically improve the productivity and shorten the design to fabrication cycle.

The integration of an automated process plan generator by means of a feature-based design environment requires solving a number of problems related to setup generation, feature sequencing, fixturing, tooling, *tool path logic*, and machining parameter computation. Although there are a number of design automation systems for cutting single features, these systems generally are not geometry driven. Many of these systems merely provide a process plan for a limited number of prismatic shapes by generating the machining operation sequence for a single feature, irrespective of any other features whether or not there is feature interaction. The user input is by feature type which limits these systems to a prescribed library of features without any assistance regarding unique setup generation, fixturing, or any other process planning criteria. Some of these systems have been successful in generating setups with related fixtures for machining a part using a part description entered by the user in a text format with a special language and syntax. Such systems are based on the variant approach of comparing, retrieving, and modifying similar prestored process plans. In addition to the limitation of the prestored patterns, these systems do not offer a suitable solution for integrating product design and process planning.

Still other, more encompassing, attempts at automating process planning for machining have been limited to simple geometry. The machining features are extracted from a computer aided design (CAD) system using feature recognition. The feature recognition methodology, often employed in these systems, is limited to a set of machining features with simple orientations and attachments. Such systems do not offer an integrated solution for design and process planning, because the part design and modifications have to be done on a CAD system as an independent application.

The predominant approach employed by Computer Integrated Manufacturing or (CIM) vendors is oriented towards automating tool path generation from the part geometry created by a CAD system. These systems produce a primitive cutting plan by mapping the tool path to follow the contour of a surface. Even though they may handle complex surfaces, these systems offer little or no assistance in the selection of the tooling and machining specifications such as speed, feed and depth of cut. In addition, they tend to rely heavily on user interactions for isolating and sequencing the surfaces to be cut, therefore complicating the process plan generation and tool path logic of even simple parts.

Translating the geometry of a part and extracting the data for automating the process plan and fixturing of customized parts is a challenge. An automated planner for extracting the manufacturing features from the part geometry, generating and ordering the setups, and recommending the fixtures is the optimum solution. This system should also be integrated in a user friendly free-form, feature-based design environment, enabling the user to easily design parts with complex geometry.

The proposed Intelligent Knowledge-Based Engineering (IKBE) architecture, adopted in this research project, supports a concurrent engineering system for interactive design and process planning of machined parts for rapid production. The process plan incorporates the selection of setups, their sequence, fixturing recommendations, tooling, and all the machining data for cutting the part, reflecting the part geometry, the part material characteristics, and the machine selection. In addition, the user can interactively inquire about the production plan to view the effect of the part design and characteristic modifications. The system automatically validates the changes and reconfigures the process plan reflecting the user modifications.

The IKBE system supports a sophisticated feature-based design environment, enabling the user to interactively design parts with complex geometry. Form features are basically an macro level descriptions of fundamental shape features (hole and profile) with position and dimensional constraints that enable the transfer of a part model without transferring the geometric instance. This IKBE model incorporates geometric relations and constraints together with non-geometric attributes for reasoning about the selection of material, part shape and least expensive process plan. A Feature Based Design Environment

(FBDE) complements the capabilities of most CAD systems with advanced tools for interactive feature dimensioning, positioning, and orientation specifications. A free-form feature-based capability allows the user to create and customize a suitable design feature library independent of manufacturing features. Finally, the system supports a geometric reasoning algorithm to assist in feature interpretation and instantiation.

In lieu of, yet another, feature-by-feature product and process design system, a more comprehensive approach for an integrated system, optimizing shape, material and process planning, has been researched and prototyped. Whereas previous systems have tended to rely heavily on user specifications to guide the tool selection, machining parameters computation, and the generation of the tool path, the proposed IKBE architecture is based on the capability to compete alternative part geometry with optimal material selection and process design.

The IKBE system incorporates a unique underling object-oriented part model for capturing part geometry and material together with process plans and finite element model. This single integrated part model expedites the interaction among design team participants relative to material specification and manufacturing/inspection planning. For the first time, a KBE system which uses one part model to tightly couple the part design, manufacturing/inspection plans and material properties with a finite element model to ensure a truly integrated conformance of shape and material with low cost processing.

The results and payoff of this research include:

- A parametric, feature-based, interactive design environment to integrate the design-through-manufacture cycle. Products and their manufacturing plans can be team developed concurrently with lower cost and better quality.

- A part model which utilizes a non-manifold geometry engine with the capability and flexibility for modeling all aspects of a part or process. The model supports mixed dimensional representations for integrating solid, surface, and wireframe representations and their respective operations. This unique object-oriented part model integrates material and process knowledge with function and shape requirements.

- Automated generation of detailed machining and inspection plans. These plans are based on geometric shape, stock and tool material properties, and processing resource capabilities. In addition, the system is capable of generating NC (Numerical Control) part programs for five (5) axis machining and scan plans for EC (Eddy Current) inspection of structural components.

- A capability to monitor and improve product designs/reduce process costs through the simulation of the manufacturing plans. As detailed process plans (incorporating tooling, process resource data, machine/tool movement) are automatically generated, production costs are computed based on the tool cost, machining time and setups. In addition, the system will track selected variables from the design through manufacturing process.

- A capability to investigate the impact of alternative materials and processes on the part shape, part performance, and material integrity. Part production cost can be reduced through investigating alternative design parameters to optimize processing cost and time. Part design specifications and manufacturing/inspection plans are concurrently generated and represented in a single part model.

In summary, the overall research objective is to develop a design methodology to facilitate the coupling and competition of shape, material, and process constraints for cost and manufacturing time reduction and performance enhancement.

During Phase I of this program several milestones in the integration of the design and manufacturing process were reached:

- An adaptive object oriented modeling language for parametric modeling and geometric reasoning has been *demonstrated , and installed at the Wright* Patterson Air Force Base (WPAFB) Wright Laboratory, Materials Directorate (WL/ML).

- A parametric, free form, feature-based design environment supporting a limited set of features has been successfully completed, ahead of schedule. This module has been installed at WL/ML and also at the Developmental Modification and Manufacturing Facility (ASC/DMMF) of WPAFB.

- An automated process planner incorporating a 2 1/2 axis NC part program generator integrated within the feature-based design environment has also been successfully completed and installed at the WL/ML and ASC/DMMF.

- An automated setup generator with feature sequencing and part fixturing for prismatic part has been successfully completed and demonstrated.

- A module for feature reduction and simplification supporting features translation, sequencing and re-dimensioning has also been successfully demonstrated.

- An integrated module for automatic mesh generation has been also integrated within the system and successfully implemented.

LITERATURE REVIEW

Two basic approaches for automated process planning exist. The variant approach and the generative approach. Variant process planning is based on the retrieval and modification of a similar part's prestored process plan. The parts are grouped into classes and standard plans are stored for each class. This approach is useful only when all parts being designed can be classified in a number of categories depending on certain attributes. The process plan of a particular part will be generated by identifying the part class, retrieving the plan, and modifying it to fit the new part's attributes. Some systems using this approach are CAPP™, MILTURN™, and MULTIPLAN™.

Generative process planning systems compose a new plan for each part. A generative process plan is synthesized based on information about the part, the machines, tooling fixturing, and certain process planning rules. There are no process plans prestored in a data base. The generative approach tends to be more flexible but also more complex. While the flexibility makes it a better candidate for automating the job shop, existing generative systems are limited to part features which can be processed within one setup. These systems are also not fully automated as they tend to rely on human interaction to provide applicable process and material constraints. Several generative process planning systems have been developed such as APPS™, CPPP™, XPS™, AUTOPLAN™, SURFCAM™ Adlard™, GENPLAN™ and AUTAP™.

As early as 1965, automated process planning had been investigated for turned parts, but the majority of systems are not fully automated. More recently non-symmetric part geometries have been added to the scope of these early efforts but the user is required to make many of the high-level decisions. There are also strict limitations on the type and complexity of the process designs such as generating plans for irregular surfaces and surface blending. The integrated process planner presented in this report focuses on more comprehensive process design, i.e., planning at a higher level of set-up organization compared to other systems which are typically limited to one set-up or non-interacting feature-by-feature process plans.

Of the various but more recent process planning systems for machining, SIPS™, a feature-by-feature process design system is being integrated with the National Institute of Science and Technology's Automated Manufacturing Research Facility (AMRF) for selection of the least cost set of machining operations for creating an individual feature by using a 'best-first' search strategy. CUTTECH™, another feature-by-feature system, orders machining operations and chooses tools together with cutting depths, speeds, and feeds on the basis of feature geometry and material machinability data. XCUT™, a research system similar to SIPS™, extends beyond feature-by-feature process designs to accommodate collective process plans for parts that have a one sided geometry while decomposeing features into separate cuts which use geometry and tolerance information to choose tools. XCUT™ then groups together cuts using the same tool so that they may all be cut consecutively, saving tool changes. Lastly, XCUT™ chooses cutting depths and tool feeds and speeds.

Various artificial intelligence techniques (e.g., rule-based inferencing, constraint-based reasoning, and case-based reasoning) are being employed in a number of automated process planning systems. Effectively all of these AI techniques are used for pattern matching and automated reasoning about constituent part geometry to extract the machining features and their relationships (e.g., constraints such as order of operations, which setup to be included in, best tool material and machining speeds, feeds, and depth of cut).

PROBLEM OVERVIEW AND OBJECTIVES

As stated earlier, process design involves several activities that are typically done manually with little or no automation, while CAD and other feature-based design systems enable the user to interactively design and edit part geometry. The research presented herein focuses on the development and implementation of an integrated feature-based Adaptive Modeling Language (AML™) to automate the manufacturing, inspection, and analysis of custom parts using Knowledge-Based Engineering methods. Critical functionalities of AML include a parametric, feature-based design environment, a mixed dimensional solid/surface modeler supporting non-manifold topology, and a geometrical reasoning kernel for multi-axis machining and inspection (metrological via CMM and material degraduation via Eddy Current) process planning automation. Through joint development with the Wright Laboratory Materials Directorate and other companies, additional integrated technologies include an automated adaptive mesh generation coupled to a multi-physics FEA solver incorporating material characteristics for machining, forging, and extrusion simulation.

The research objective is oriented toward enabling significant reductions in the machining cost and time to produce small quantities of structural components, i.e., automating the breadth and diversity of components typically associated with a small (less than 50 employees) job shop. A job shop specializes in customized single parts or small batches of parts rather than continuous or large quantity 'mass' production. Flexibility is critical for a job shop to accommodate a wide range of customized parts.

> **Note**: In batch or single part production, machining accounts for a small percentage (10%-15%) of the total time to complete a job, while design and

> process planning accounts for the remainder. Therefore, it is more important to reduce the design/process planning by quickly generating a feasible process plan rather than the lengthy generation of an optimized plan. The emphasis is on short turnaround time for immediate prototyping. This is not usually the case for mass production where it is important to optimize the process plan to cut down the machining time.

The AML™ process planner prototyped and demonstrated during Phase 1 is a generative planner and is oriented toward addressing the above described needs of a typical job shop to enable rapid prototyping and production. AML™ not only enables automated process planning but allows the designer to change or create new parts through the evaluation of alternative process plans. AML™ is based on a single underlying object-oriented architecture incorporating two patented techniques for competing alternative design/material/process constraints. While an engineer(s) is designing the part, AML™ generates the process plan interacting with the system to inquire about alternative materials, processes, and design specifications. Complex part designs with detailed process plans and analysis models will be concurrently developed in hours or days instead of weeks or months.

RESEARCH SYSTEM CHARACTERISTICS

The discussion will highlight the process and materials associated with machining of structural metal parts while the *intended scope* will be all materials and process with more immediate interests in wire-EDM, sand/investment casting, welding, forging, extrusions, coordinate measurement and eddy current inspection, etc.

Part Design and Geometry

The FBDE is a parametric, free-form, constraint driven, feature-based design environment with an icon-based graphic window interface that enables the user to easily create, edit, and modify the part geometry. The limited capabilities prototyped in Phase I will be extended to support 3D mixed dimensional modeling (wireframe/solid/surface mixed modeling). An extended set of features supporting the design of machined parts will be developed. In addition to the standard design feature library, such as pocket, slot, hole, etc., the system enables the user to create a free-form feature and parametrically associate its dimensions and orientation with other features. The user can interactively add attributes to the features together with constraints and relations associating geometric and non-geometric properties. AML™ can reason about complex 3D geometry including multiple intersecting features such as a pocket involving edge profiles blended with a number of bosses. Unlike existing systems, AML™ is not limited to features from a library. AML™ enables the user to create and customize a feature library suitable to his/her needs. A user can generate a free-form design feature that can be edited, copied, or deleted. In general, AML™ provides the user with both a common set of capabilities available with most CAD systems, and tools not supported by standard CADs. A unique characteristic of the AML™ is the capability to validate part geometry by checking the consistency of the constituent features and their interactions (fig. 3). AML™ will analyze the features and the part intersections to suggest to the user the possibilities of the different interpretations of the input parameter specifications. When a number of alternative interpretations exist, the user is prompted to choose one.

Feature Instantiation

To create a feature, such as a generic 'wall-profiled' pocket, the user begins by creating a 2D profile feature which defines the pocket base, and selects a feature base-point (Fig. 1.a). AML™ provides a number of alternative methods to assist in the creation of the profile. For example, once the pocket base is created by the 2D profile feature, the user selects two points, PT1 and PT2 for 3D orientation of pocket walls (Fig. 1.b). The pocket base is translated from the base-point to PT1 . While points PT1 and PT2 form the feature's primary axis for feature orientation, the user will select a point in the plane of the profile to create the local orientation vector (Fig. 1.b). Another 3D point (PT3) is selected in 3D space to form the global orientation vector (Fig 1.c). The system automatically computes the transformation matrix to orient the feature. The feature is projected along the primary axis to set the local orientation vector and the global orientation vector coplanar. AML™ offers a number of tools to assist the user in the interactive selection of the points and vectors.

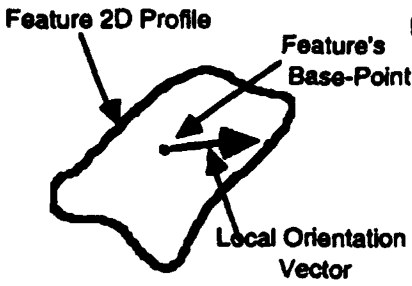


Fig. 1.a

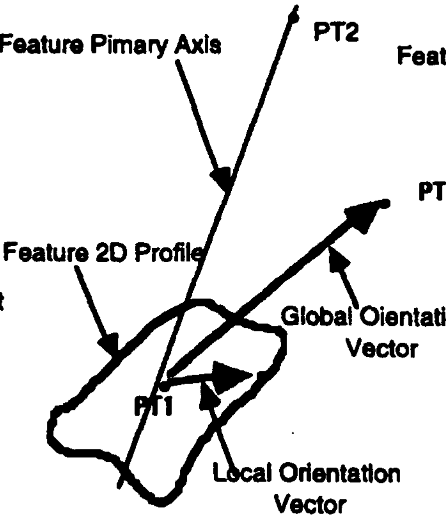


Fig. 1.b

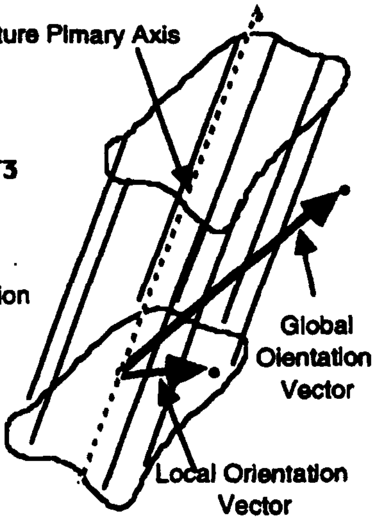


Fig 1.c

AML™ automatically configures bounding surfaces of a feature depending on the intersections of the feature surfaces with the base part geometry and the attribute "blind-feature" (Fig. 1.d) or "through-feature" (Fig. 1.e).

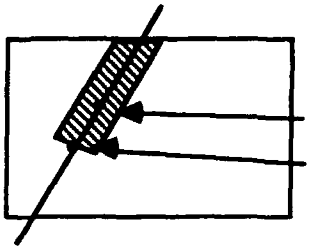


Fig. 1.d

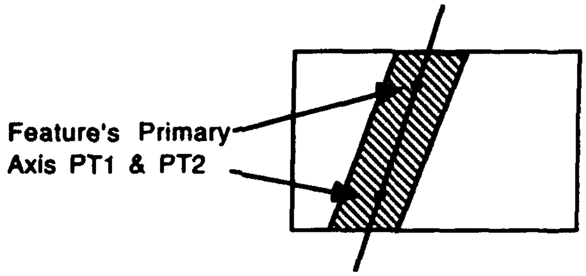


Fig. 1.e

Fig. 1.e and Fig. 1.e illustrates the front view of the instantiation of the blind-feature vs through-feature.

Features Interpretation

When using a feature-based part model to describe part geometry, feature interactions could result in a number of different interpretations or valid aggregate feature geometries. The figure below illustrates the different possible interpretations of a through-hole feature when positioned in a block with two slots.

Fig 2.b illustrates the intended interpretation of a blind-hole with PT1 and PT2 as shown. Figures 2.d, 2.e, 2.f, illustrate the additional interpretations.

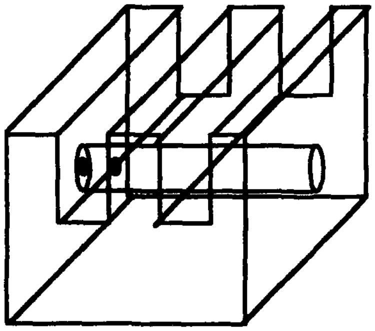


Fig 2.a

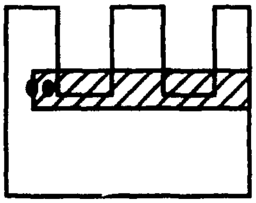


Fig 2.b

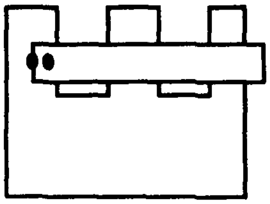


Fig 2.c

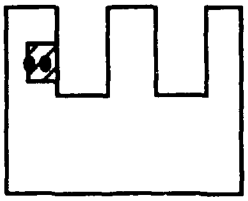


Fig 2.d

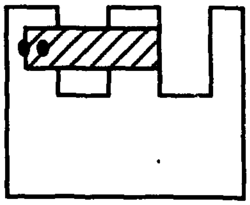


Fig 2.e

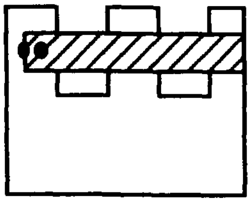


Fig 2.f

The AML™ geometric reasoning engine enables the user to create a surface attachment constraint to limit the feature instance to only one of the interpretations illustrated in the above figures (2.b through 2.f). When several interpretations of the input specification exist, the AML™ will assist the user in the specification of the selection. This methodology enables the user to easily interact with the FBDE without resorting to detailed feature descriptions.

Process planning

The part model (geometry) generated by the FBDE is basically a description of the part geometry in terms of the so-called starting geometry (stock) and "design features" with their associated dimensions, tolerances and orientations. An equivalent manufacturing part model is required to account for the different (manufacturing) interpretations of the same part geometry (design). Extracting the necessary manufacturing information from the part geometric description is required to produce the process plan. Therefore a *manufacturing* part model, depicting the part before and after each setup in terms of the manufacturing features and the associated geometry, is generated. The design features are translated into manufacturing features to extract the attributes and objects needed to automate the machining process plan (see Features Translation). Each design feature is mapped into one or several manufacturing features. Some manufacturing features may be later refined and reclassified depending upon the selected setup and part orientation. A *manufacturing* feature is represented by a number of machining operations which satisfy the part geometric description to include surface finish and tolerances.

A successful automated machining process planner, integrated with a feature-based design environment requires the solution to several fundamental problems related to features translation, intersection and sequencing, setup generation and sequencing, and 'part-stock' fixturing. These fundamental problems require the translation and manipulation of part geometry to produce the specifications needed to generate the overall process plan. The goal of the automated process planner is to generate a machining process plan with the following details and specifications:

- The number of setups required to machine a part
- The sequence of the setups
- The features within each setup and their sequence
- The part geometry before and after each setup
- The intermediate part geometry after removing each feature within a setup

- **The detailed machining operations for machining each feature (including cutting dimension, speeds, feeds, horsepower, material removal rate, etc.)**
- **The tooling for each operation including alternatives**
- **The feasible sequence for the machining operations for the different features within the same setup**
- **The recommended part orientation, and valid surfaces for contact with the fixtures**

The first problem to be addressed in automating the process design is to divide the features into a number of sequenced setups and determine the appropriate fixtures to be used. A setup establishes the number of features which can be machined while the part is held within the same fixture. If the part needs to be repositioned to machine any remaining features, a new setup or alternative fixturing should be considered. Since features may be defined by one or more sides of the part-stock, and may intersect with each other, cutting one group of features (a single setup) will alter the geometry for successive setups. Grouping the features to generate the minimum number of setups while minimizing the number of operations associated with machining one setup before another requires careful visualization and alysis as the number of permutations grow exponentially with the number of features.

A number of different setups may be required to completely machine a part. Prerequisite to generating one or more alternative setup sequences together with the recommended fixtures for a particular part, a study of the part features and their respective intersections with the initial part-stock is required. In addition, certain machining parameters, such as fixturing rigidity, tool clearance, thin wall conditions, etc., must be evaluated, along with the effect of machining one setup on the successive ones. A fixturing method(s) is associated with each setup and grouping the features into a minimum number of setups with the required fixtures is the goal. All features within a setup are machined while the part is held fixed in one particular position, and therein, each fixture restricts the number of features that can be incorporated in any one setup. All machining operations associated with a feature within a particular setup should be accomplished without changing the position or orientation of the part within the fixture(s). Some features may belong to more than one setup, thus the features are initially grouped into potential setups that will be later refined to minimize the overall time required to machine the part.

For each setup, AML™ will generate the available surfaces that are suitable for fixturing, using conventional fixturing methods. In lieu of selecting among alternative fixturing methods, AML™ will identify the possible surfaces that can be used as fixture contact areas. The adequacy of these surfaces, their position, and dimensions will limit fixturing alternatives. If an insufficient number of surfaces are determined adequate for fixturing using conventional methods, the system will interactively assist the user in the selection of commercially available modular fixtures, by specifying the criteria for the fixturing surfaces. Additional fixturing surfaces are selected by AML™ to validate part equilibrium criteria and accessibility of contact surfaces by a particular fixture. AML™ will interactively, with the use of the mouse, assist the user in locating the contact points for the fixtures and validate the user selection.

Manufacturing Features

A manufacturing feature is comprised of a set of machining operations, related to milling and holemaking constrained by part geometry. These constraints, involve conditions before and after successive machining operation, and are related to the tool access, the part geometry (open-pocket vs. closed-pocket), and machining capabilities (coolant available), etc. Depending on the bounding surfaces, part-stock dimensions, and other characteristics, a feature to be machined is translated into one or more manufacturing features, each representing a number of machining operations.

Features Translation

A design feature is translated into one or more manufacturing features because, in addition to the machining attributes, a number of surface and vector objects are created relative to intersections with other features and the part-stock. These objects are associated with feature type, dimensions, tolerances and orientation. These objects constrain the range of tool approach directions relative to non-interference access and orientation of tooling in addition to any required safety or preparatory operations such as drilling highly toleranced corner 'cut-in' surfaces as identified in Fig 3.c below. Note that these additional manufacturing features must also be included in setup generation discussed previously.

Tooling and Machining Data

The manufacturing part model is basically an enhanced object structure representation in terms of the machining features. The machining operation sequence for each manufacturing feature is generated as constrained by both feature dimensions and tolerances and material machining resources. Tool criteria selection is based on the tool material, part-stock material, machining resources, the operation, and tooling standards.

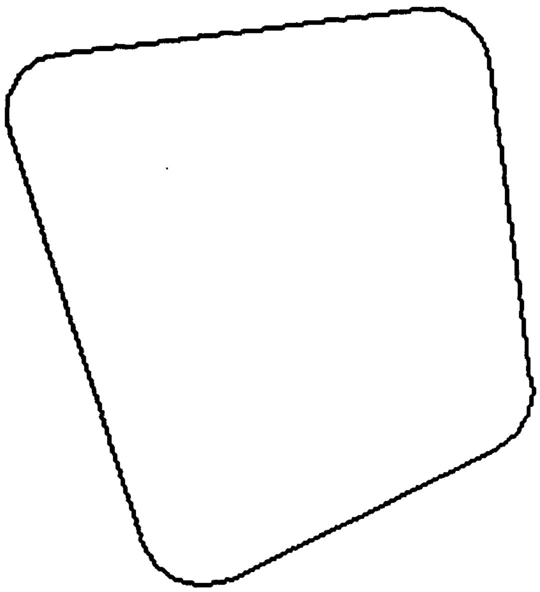


Fig 3.a

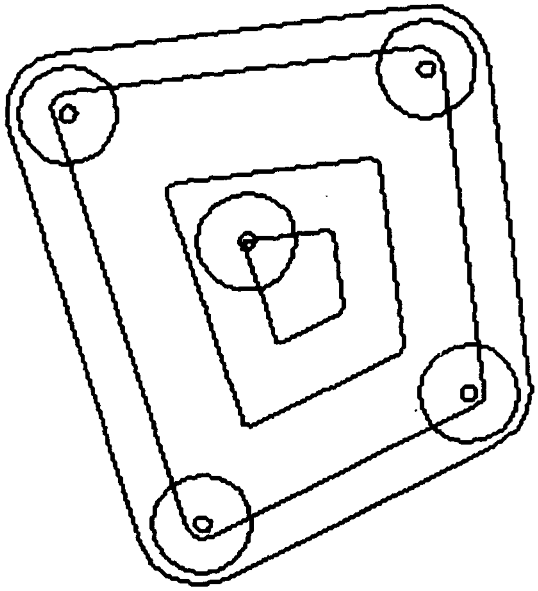


Fig. 3.b

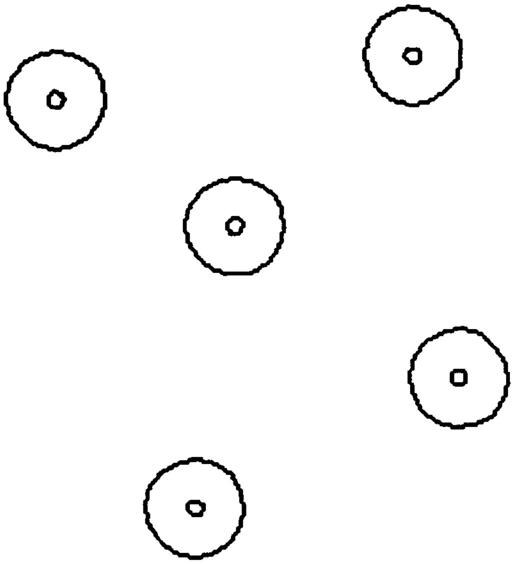


Fig 3.c

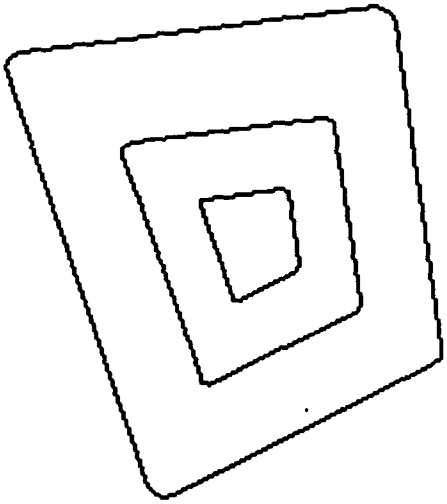


Fig. 3.d

Fig 3.a is the profile of a pocket in Fig. 3.a. Fig 3.b depicts the manufacturing features superimposed to completely cut the pockets. Fig. 3.c identifies the additional manufacturing features: the four relief holes at the center of each corner to maintain the corner tolerance callout, and a clearance hole in the middle of the pocket to allow for the safe entrance (in lieu of plunging) of the rough end mill. Each hole is preceded with a center-drill operation. Fig. 3.d establishes the milling operations for roughing and finishing the pocket.

Process Optimization - Setups

As discussed above, a part typically consists of several features and grouping the features into a minimum number of setups with appropriate fixtures is a difficult task. Listed below are the steps that the system follows to generate a minimum number of setups from the part geometry:

- Features Translation - Generate an enhanced part model in terms of the manufacturing features and all related objects and attributes.
- Potential Setups Generation - A manufacturing feature is associated with a number of machining operations that require a certain part orientation, depending on the feed direction and the tool rotational axis. A number of potential setups are generated, grouping the features with similar tool orientations. Some features, such as open-pocket, may be cut with the part-stock in a number of different orientations. Therefore, a feature may belong to more than one setup. Each setup is characterized by a group of features and part-stock orientation.
- Elimination of the Redundant Setups - A setup is redundant if all its features belong to other setups. All the redundant setups should be eliminated, before determining the final sequence of setups. To minimize production costs, it is desirable to have the least number of setups in a process plan. The first step in minimizing setups is to eliminate redundant setups beginning with the setups comprised of the least number of features.

The algorithm for eliminating the redundant setups is as follow:

```
—> Select one of the setups with the least number of features to
   check it for redundancy.

—> The common features (setup intersections) between the
   selected setup and all the other setups are computed.

—> The union of the setup intersections (common features from
   the previous step) is then computed.

—> Test
        IF  the union of the setup intersections is equal to the
                selected single setup
        THEN the selected setup is redundant and it should be
                deleted
        ELSE keep the setup

—> Repeat steps for all other setups in the order of increasing
   number of features within the setup.
```

At this stage all the redundant setups are deleted, but among those setups remaining, there may exist duplicate features. Those features which are duplicated must be further evaluated to select the best setup for processing.

- Setup Optimization - This step is for the elimination of the feature duplications among the different setups that are left. The algorithm for eliminating the redundant setups is as follow:

  —> Select the setup with least number of features. Eliminate all the features that are common to other setups.

  —> Repeat the above step for all other setups in the order of increasing number of features within the setup.

The setups that now remain have no common features and, as a consequence, the process plan has been globally optimized for the minimum number of setups. Further optimization can be achieved by sequencing features and operations and by eliminating intersection overlap among features.

Process Optimization - Fixturing

The process plan requires the identification of fixturing surfaces, based upon the type of fixture, for holding the part while allowing machine/tool access to cut the features. The inputs to this module are:

- The starting part-stock, i.e., a cut piece of bulk raw stock, casting or forging or the intermediate part geometry from a previous setup.
- The features within the setup.
- The tool orientations and feed directions.

Depending on the selected fixturing method, such as a vice, certain criteria are used to identify the best fixturing surfaces. AML™ uses an algorithm to analyze the part surfaces before and after the setups. In addition, a fixturing frame or envelope representing the part bounding surfaces is generated. This frame depicts the bounding surfaces of the part before and after the cutting operations associated with the features within the setup. Attributes related to the fixturing surfaces' center of mass, orientation, type, boundaries, etc., are also stored in the frame together with all surfaces that the cutting tools will pass through and, therefore, cannot be obstructed or used for fixturing. The computed limits of the frame are used to determine feasible surfaces for a certain fixturing method based on the criteria associated with the selected fixture. The objective of the analysis is to determine a feasible, yet least time consuming fixturing method to reduce overall processing time and costs.

Vise Fixturing

Vise fixtures are flexible and allow for good fixturing rigidity in machining. The vise's ease of use, quick setup and accommodation for a range of part dimensions, makes it a favorable fixture for machining. For holding a part in a vise, a machinist simply places the part between the jaws of the vise, and rotates the vise handle to firmly tighten the part. Even though it may seem a simple matter, the suitability of the vise for fixturing is dictated by the part geometry and the features within the setup.

In order to hold a part between the vise jaws, two parallel sets of external surfaces with normal vectors orthogonal to the tool rotational axis must exist. These surfaces will be referred to as the 'VPsides'. In addition, a resting base is a set of one or more coplanar surfaces with equal normal unity vectors. This set, referred to as the 'Vbase' and is oriented as the bottom of the part when placed in the vise. Note that this set should be normal to the cutting tool rotational axis and orthogonal to the VPsides. If we were to use sine tables, the Vbase would only need to be orthogonal to the VPsides surfaces (see Fig. 5).

Fig. 5 illustrates vise fixturing orientations

Validation of the Selected Surfaces

The selected VPsides and Vbase should be validated to check if they are accessible and if the part is in equilibrium (Fig. 5).

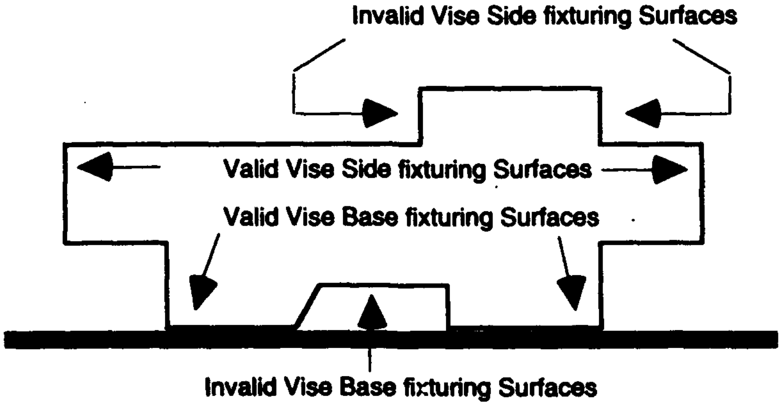


Fig. 6 illustrates the validation of the vise sides and base fixturing surfaces

The VPsides validation criteria are:

- Two sets of parallel surfaces facing opposite directions. Each set of surface members are coplanar and have identical orientation.
- The surfaces are orthogonal to the tool rotational axis.
- The surfaces are not obstructed from the bottom.

The Vbase validation criteria are:

- **The Vbase surfaces are coplanar and facing same side.**
- **The Vbase surfaces are normal to the VPsides.**
- **The Vbase surfaces are facing the opposite side of the tool cut surfaces.**
- **The Vbase plane should be an extreme external plane that is coplanar with the bed of the vise.**

For the part equilibrium validation, three tests are made:

- **Free equilibrium accounting for gravity forces only.**
- **Equilibrium about the Z axis accounting for the forces of the vise's sides.**
- **Equilibrium about the X axis also accounting for the vise's side forces.**

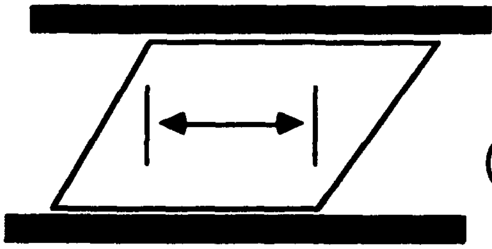
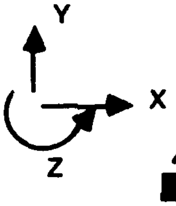


Fig 6.a



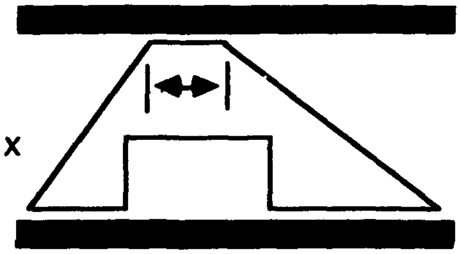


Fig 6.b

Fig 6.a and Fig 6.b are part top views to illustrate the required dimension of fixturing surface and vise contact to be in equilibrium.

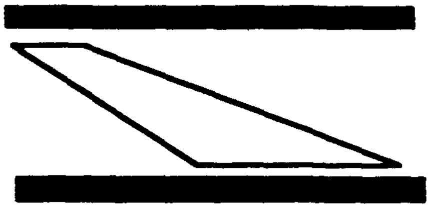
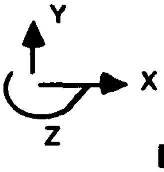


Fig 6.c



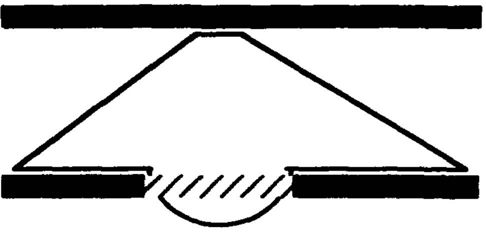


Fig 6.d

Fig 6.c is a part top view not in equilibrium about the Z axis, fixtured in a vice, while in Fig 6.d the part cannot be in equilibrium about the Z axis.

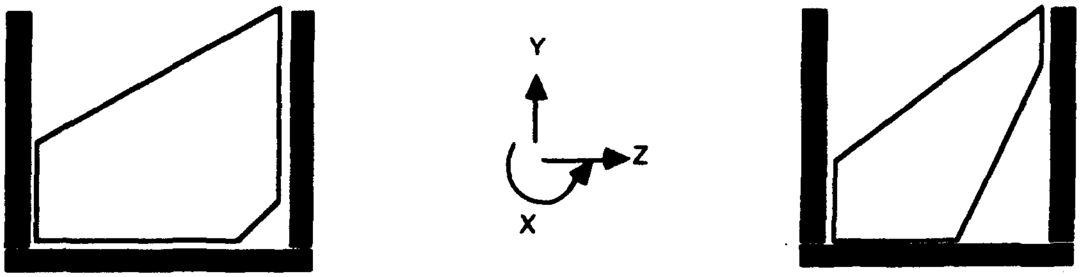


Fig 8.a Fig 8.b

Fig 8.a. shows the top view of a part in equilibrium about the X axis, fixtured in a vice. Fig 8.b. shows the top view of a part that cannot be in equilibrium about the X axis.

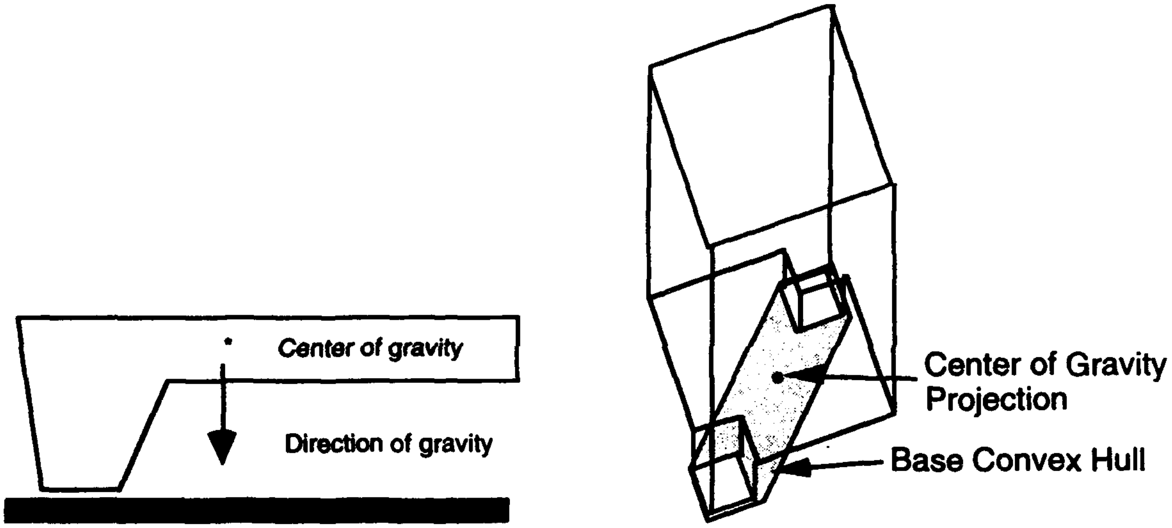


Fig. 9.a Fig. 9.b

Fig. 9.a illustrates an invalid Vbase, part is not in free equilibrium. Fig. 9.b illustrates a valid Vbase, part is in free equilibrium.

Clamping

When a part is not suitable for vise fixturing, clamping is a desirable alternative. Side clamps and top clamps are commonly used. A side clamp is usually anchored to the machine bed and positioned normal to the part surface. The fixturing surfaces in this case are perpendicular to the machine bed. A top clamp is also anchored to the machine bed but is positioned normal to a surface parallel to the machine bed. For clamping, a machinist places the part on the machine table and then locates the valid surface for clamping, orients the clamps and tightens them.

For side clamping the clamping surfaces should be normal to the machine bed and thus perpendicular to the bottom base of the part while the part is in equilibrium. A part is in equilibrium when the sum of the clamping forces is equal to zero. These forces should be coplanar and concurrent, or coplanar and parallel with net resultant force equal to zero (Fig10.a, Fig10.b).

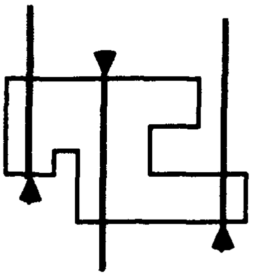


Fig. 10.a

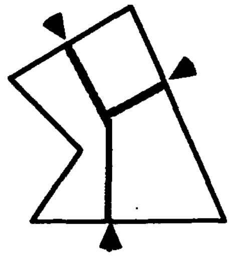


Fig. 10.b

Fig. 10 illustrates the top view of parts fixtured using side clamps.

As for top clamping, the fixturing surfaces should be parallel to the machine bed and therefore also parallel to the bottom base of the part. For equilibrium, the sum of the clamping forces and the reaction of the machine bed should be equal to zero. Also, the sum of the moments about the X and Y axes should be equal to zero (Fig. 11)

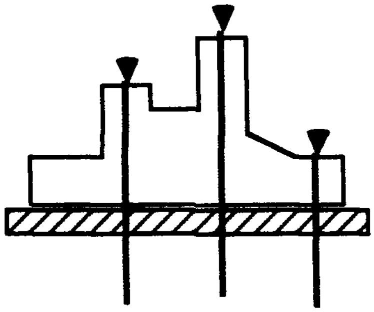


Fig. 11 illustrates a part fixtured using top clamps

Therefore, for clamping, a base surface set referred to as 'Cbase' (clamping part base) should be selected, and a validation test performed. The validation test for the Cbase is identical to the Vbase test from vise fixturing. The clamping surfaces are selected following the criteria mentioned before. These surfaces are valid if the part is in equilibrium.

Process Optimization - Features

Within each fixtured setup a preliminary sequence of machining operations is generated for all intersecting features and subsequently adapted to include sequencing of non-intersecting features for optimization of processing within a setup. Although not immediately apparent, the number and dimensions of the manufacturing features can be different from the associated design features.

AML™ uses a patented technique to optimize the machining process by evaluating dimensions and associated machining parameters for all manufacturing features as they are recomputed based on the selected sequence for processing the design features. These machining parameters include: thin wall conditions, thin floor conditions, and tool clearance (axial and radial). All these parameters are associated with the manufacturing interpretation of the design features to produce an accurate and complete part geometry.

Figures 4.a through 4.f illustrate the various manufacturing interpretations for machining three nested pockets, one inside another, on the same side of the part-stock. It should be noted that each interpretation changes the dimensions of the respective nested pockets and the sequence for machining the indivdual features. The patented AML™ technique referred to as 'inductive/deductive coupling' assists the user in selecting the optimal sequence. When the *manufacturing feature dimensions of the selected sequence* are different from the associated design feature dimensions AML™ will automatically recompute part feature dimensions. This enables the user to easily interact with the FBDE without resorting to part redesign as required by exiting CAD/CAM system.

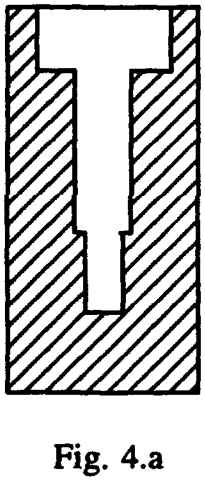


Fig. 4.a

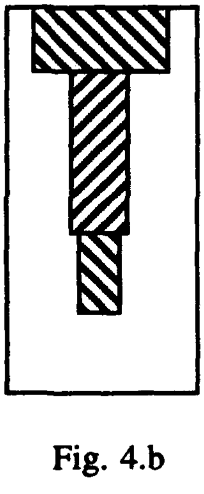


Fig. 4.b

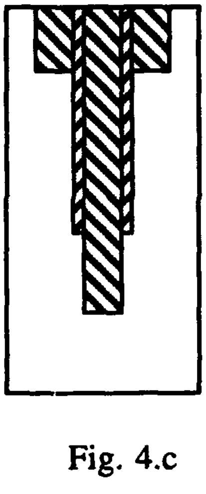


Fig. 4.c

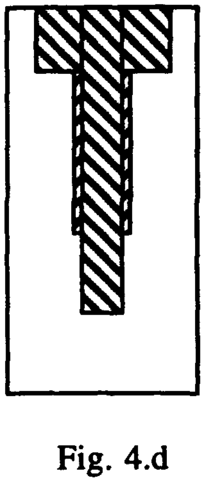


Fig. 4.d

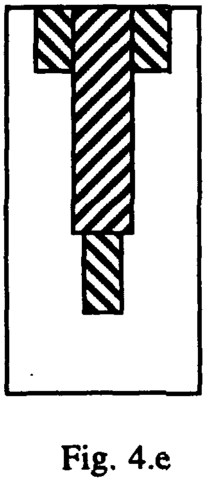


Fig. 4.e

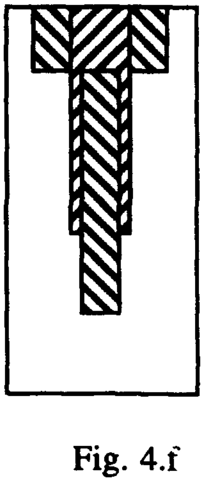


Fig. 4.f

Fig.4.a shows a cross section of a part with three intersecting (nested) pockets as specified in the design representation. Figures 4.b through 4.f, illustrate five (5) different interpretations of the part geometry with associated sequence and dimensional differences.

Machining/Inspection Tool/Probe Path Logic

The architecture of a 'reasoning engine' for tool path planning has been initiated in Phase I. This reasoning engine generates a tool path for cutting part features based on the process plan. After the tool grades, tool geometry, and machining data have been recommended by the process planner the cutting tool path is generated. AML™ cross correlates the tool body shape with the part's initial and final geometry and orientation along with the machine tool capabilities (number of axis, travel capabilities) to produce a feasible path logic.

When generating a tool path, consideration for optimizing the tool travel in addition to surface integrity is being considered. The figure below illustrates a tool path computed by the path generator optimizing tool travel.

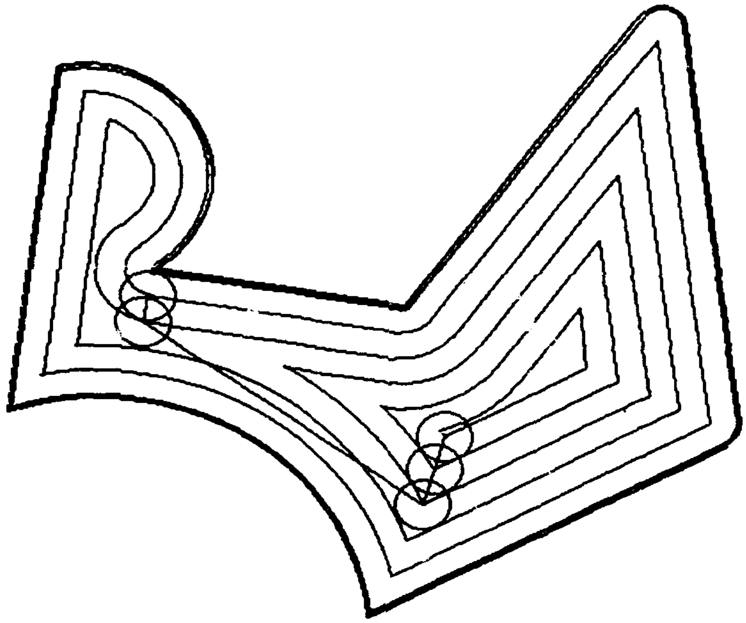


Fig. 12 island profiling

As for machining free form surfaces, tool path planning also presents a number of challenges that will also be addressed in phase II. An accurate tool path will be generated for 5 axis machining that will result in cutting the part without gouging. The figure below illustrates a part that is being cut using a ball nose end mill. It should be noted that the ability to automatically generate accurate tool paths without gouging could elevate and/or further enhance the process of machining as a 'Rapid Prototyping' technology, i.e., thereby competing with more recent processes such photo-polymer stereolithography, laser sintering and 3D printing.

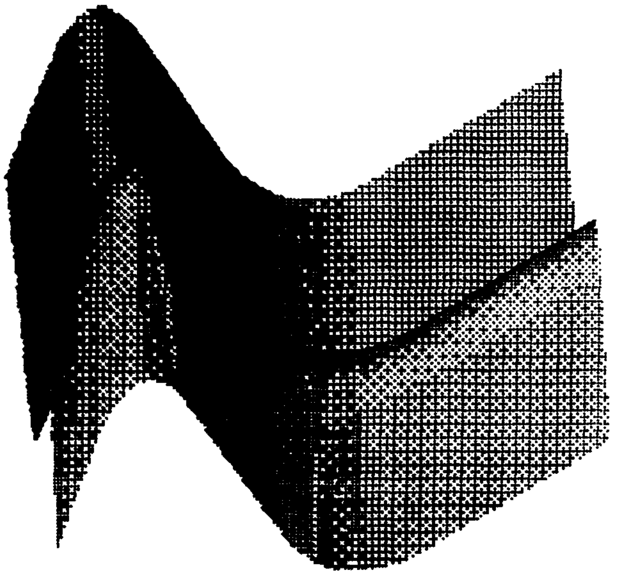


Fig. 13. a

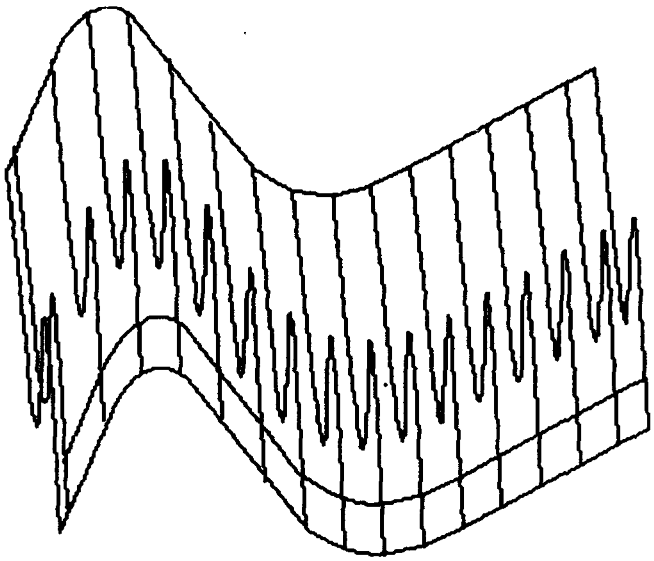


Fig. 13.b

Fig. 13.a illustrates a sculpted surface.
Fig. 13.b shows the actual tool path on that surface.

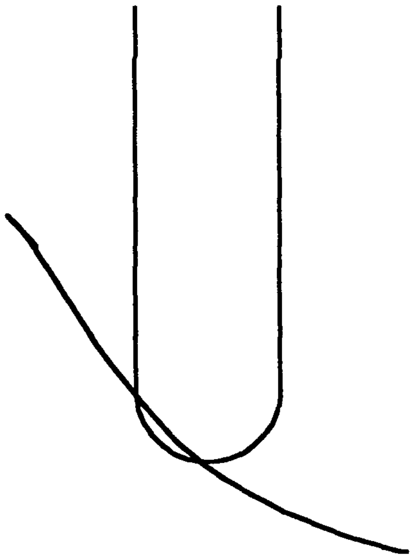


Fig 13.c gouging

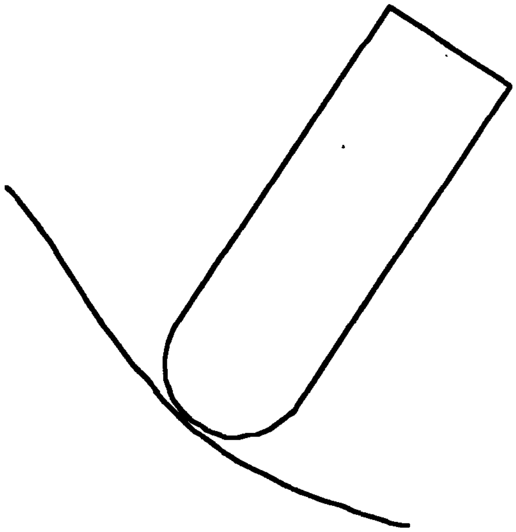


Fig 13.d no gouging

To eliminate gouging and minimize the size of the scallops resulting from the tool nose when using the ball end mill, the tool must be oriented in reference to the normal to the surface at the contact point (Fig. 13.d). Surface machining requires at least three axis, but there is an advantage in using simultaneous four and five-axis NC machines. Simultaneous control of the tool position and part orientation in reference to the contact points on the surface being machined is desirable because more complex parts can be machined in one setup. With five-axis machines, the end mill cutter can be oriented to cut angle surfaces with a better surface finish than three axis machines that may require a larger number of passes for cutting the same surface.

There are three basic approaches for four and five-axis machining of surfaces. The first is the "Normal to the Surface" approach. This approach is used with the tip of the tool doing most of the cutting since the ball nose cutting tool is normal to the surface, This approach requires small 'step-over' tool paths leading to relatively low stock removal rates. The second approach is 'lead/lag' machining with the tool always oriented at an angle in reference to the normal to the part surface. This method allows most of the cutting to be done near or at the tool outside diameter. The third method allows cutting with the tool either parallel or at a specified angle to the surface. This method is used with flat end mills when cutting angled flat or slightly curved surfaces.

CONCLUSIONS

In this report a review of the issues related to the integration of product design with material and process planning has been presented. The research issues have been discussed and a demonstrated solution presented. Previous systems have been designed to take input either from a GT code or from a descriptive file created by a user. In some instances, these previous systems have involved a descriptive language implemented via shape features (holes, pockets, etc.) to interpret the part geometry and convert it into a special format to generate prescribed process planning information.

We have seen a technology leap in the development of CAD systems, leading to a growing gap between design and process planning automation. AML™ is intended to close that gap and provide a process design capability which is completely automated. The process planner generates process specifications based on the part geometry, material, and process constraints. As exemplified by machining, the plan specifications are then passed to the tool path planner that generates and simulates the cutting path. The NC part program is automatically generated accounting for tool geometry, tool changes, machining data, and obstacle avoidance (fixtures). No user interactions are needed, all parameters are automatically extracted or computed. AML™ is capable of validating the recommended vise fixturing surfaces. The geometric reasoning capabilities for five-axis machine tool path planning are similar to the probe path planning for Coordinate Measurement and Eddy Current inspection. These capabilities will be extended to reason about path logic for inspection, welding, wire-EDM, etc.