Challenges in Feature-Based Manufacturing Research

Martti Mäntylä

Department of Computer Science

Helsinki University of Technology, Espoo, Finland

Dana Nau

Department of Computer Science and Institute for Systems Research

University of Maryland, College Park, MD, USA

Jami Shah

Department of Mechanical and Aerospace Engineering

Arizona State University, Tempe, AZ, USA

Abstract

Smooth integration of computer-aided design (CAD) and manufacturing (CAM) is vital for companies' survival in the present competitive marketplace. One key component in this effort is the representation of product designs in terms of *features*, elements that are semantically higher-level than the pure geometric elements typically used in CAD and CAM systems.

In design, features capture explicitly engineering attributes and relationships among product definition entities—information that is essential for various design tasks and analyses. In manufacturing, features can be linked to manufacturing knowledge of various types. The knowledge facilitates manufacturing process planning and generating the detailed operating instructions required by modern production systems such as CNC machines, flexible manufacturing systems, robots, and inspection equipment. As importantly, features provide a basis of organizing manufacturing information in a data repository for data reuse in new product design, production development, and quality management.

This article discusses the role of product modeling and features in product design and manufacturing, reviews the present stage of development of features, and describes some key issues and methods in applying features in manufacturing preparation and management.

CR Categories and subject descriptors: I 3.5. [Computational Geometry and Object Modeling]: Geometric algorithms, languages, and systems; J.6 [Computer-Aided Engineering]: Computer-aided design (CAD), Computer-aided manufacturing (CAM)

General terms: algorithms

Motivation

The present competitive environment of most industrial companies is characterized by a number of simultaneous developments. Products are more complex and variable than ever before, yet customers are not willing to pay more for them. Delivery lead times are shorter: companies who enjoyed six-week delivery cycles some years ago are now operating in two-week cycles, and feel pressure to cut them down even further. The rate of product development has intensified: products that used to stay in the market for five years must now be retired and redesigned after one or two years. Customers are increasingly concerned about quality, durability, maintainability, safety, and environmental performance.

These developments are forcing companies to take a critical look at their design and manufacturing activities, and to search for radical improvements over business as usual. The infamous “stone wall” between design and manufacturing must be broken to give room for concurrent engineering and multifunctional teamwork; information flow from customer order to engineering, production preparation, and manufacture must be straightened out; non-value-adding activities along the critical path from order to shipment must be eliminated.

The traditional approaches to increasing the productivity of design and manufacturing focus on one activity at a time. This has led to the proliferation of separate systems for computer-aided design (CAD), computer-aided manufacturing (CAM), production management and control, flexible manufacturing and assembly (FMS/FAS), and computer numerical control (CNC). As a result, “islands of automation” with little integration have emerged.

Faced with the present challenges, companies are observing that this approach is insufficient. In addition to improving the individual steps, attention must be paid on the overall flow of the design and production process. If information flow from customer to factory floor is not smooth, short lead times are impossible. If product designs cannot be effectively and fully transformed to production process descriptions, extensive prototyping and iteration is needed with detrimental impact on time to market and total product quality.

Feature-Based Product Modeling

In traditional industrial practice, product knowledge is stored informally in drawings, binders, manuals, and supplier data sheets. At present, these have largely been replaced by CAD models and various data bases such Bill-of-Materials data for production management or tool and machine data for shop-floor control. However, conventional CAD models for mechanical products (see Figure 1)—drafting models, or more recently, solid models [Mänt88]—are not compatible with these data. Little integration is possible without further work. Therefore, during the last ten years, research has shifted to product representations that can carry more complete product information and provide better interfacing opportunities.

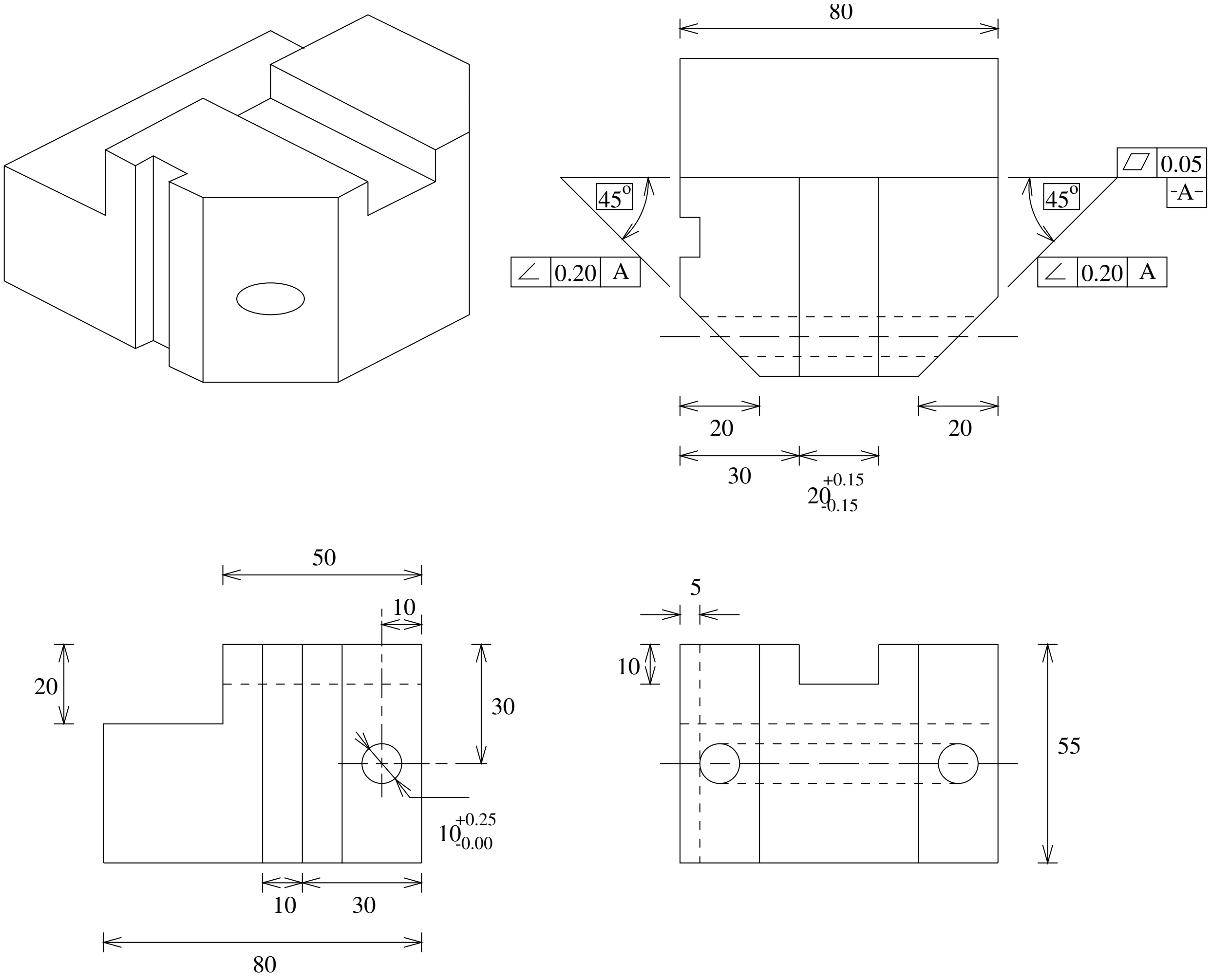

Figure 1. A typical design specification for a mechanical part (adapted from [Gupt94b]).

Product modeling can be characterized as a unified methodology for capturing and representing product information and making it available to various processes of a company. The full scale of product modeling is beyond the scope of this article. See [Owen93] (also `http://elib.cme.nist.gov:70/1/step`) for information on the Standard for Exchange of Product Data (STEP) being developed by the International Standards Organization (ISO) that aims to cover all aspects of product data.

One of the most popular product modeling approaches for manufacturing involves *features*, recurring shapes that have some fixed engineering significance [Shah95]. In brief, a feature is a parametric shape associated with *attributes* such as the intrinsic geometric parameters (length, width, depth), position and orientation, geometric tolerances, material properties, and references to other features.* Features also provide access to related production process and resource models. Thus, features have a higher level semantically than the primitive elements used in ordinary CAD systems. As shown in Figure 2, features are expected to form a basis for linking CAD with downstream manufacturing applications, and also for organizing databases for design data reuse.

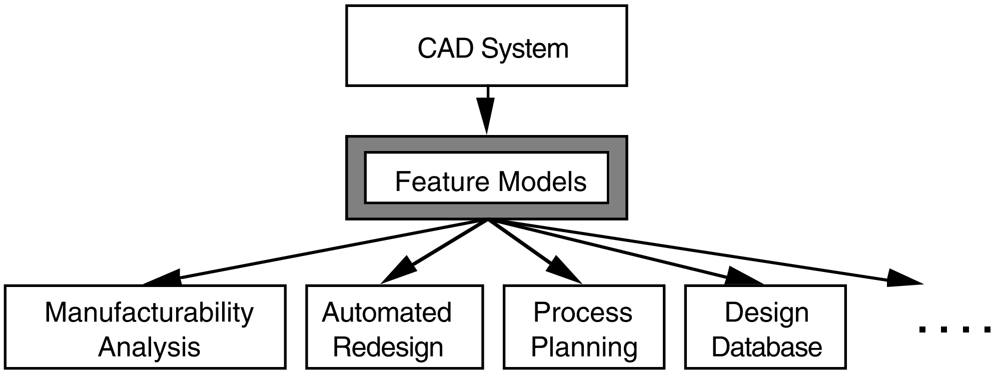

Figure 2. Features as a communication medium between design and downstream applications.

Most feature-based models are combinations of instances of *feature types*. The types are usually organized in a *feature taxonomy*, often realized via object-oriented programming as a collection of classes with inheritance. Classes contain information shared by all their instances, including procedural methods for computing properties such as volume. These concepts are illustrated in Figure 3, which shows a part, its feature model as a *feature graph*, an outline of a feature

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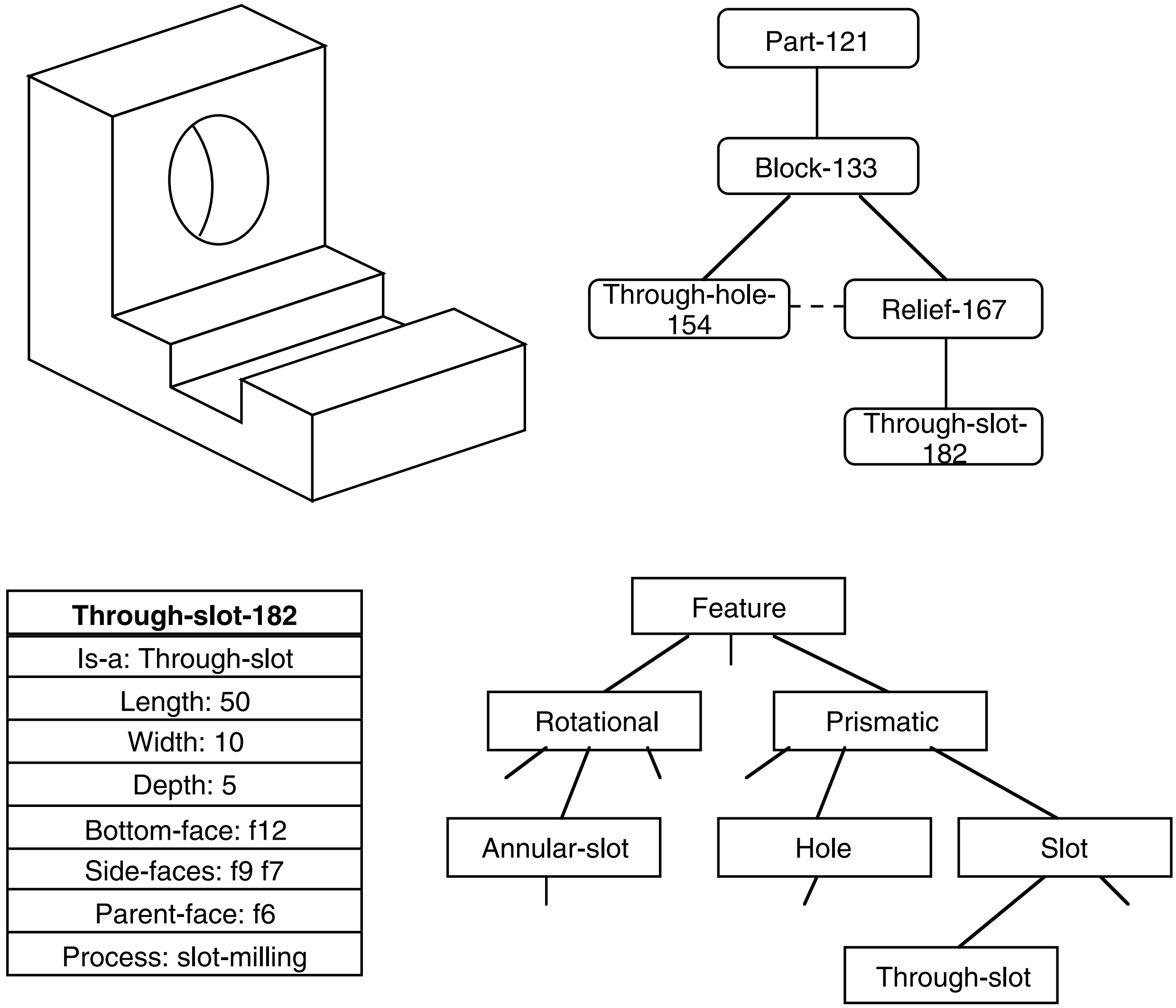
*The term “feature” is also used in pattern recognition and natural language understanding. In pattern recognition it denotes a shape of interest to some application, such as an edge of a shape (identified by sudden intensity change in an image), the overall shape of a region, or some other region characteristic (such as genus). The connotations are analogous: in both cases, features are items of interest for an application, they can be recognized from lower-level input, and they can be used to access domain knowledge.

instance, and a partial feature taxonomy. The arcs of the feature graph record neighborhood relations between the features.



Through-slot-182
Is-a: Through-slot
Length: 50
Width: 10
Depth: 5
Bottom-face: f12
Side-faces: f9 f7
Parent-face: f6
Process: slot-milling

Figure 3. Feature model concepts.

Deciding what kinds of shapes one wants to consider to be features can be difficult, and may depend on the application at hand. For example, Figure 4 shows a simple example in which one may wish to use different features for design than for manufacturing.

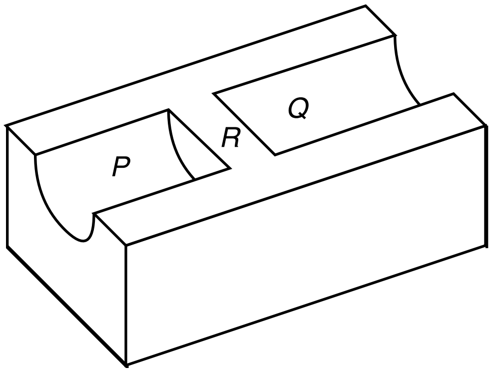


Figure 4. For design purposes one might represent this shape using a single slot bisected by the rib *R*, whereas for machining purposes one might prefer to use the two pockets *P* and *Q*.

Features in Manufacturing

The power of feature models in manufacturing applications is based on associating feature types with *manufacturing process models*. For example, the process model for a machining process would indicate the process resources (machines, tools, fixtures, auxiliary materials), process kinematics (e.g., tool access direction), process constraints (interference, spindle power), process parameters (feed, speed), and other information such as time and cost. In an object oriented implementation, process models are realized as a process taxonomy linked to various resource taxonomies.

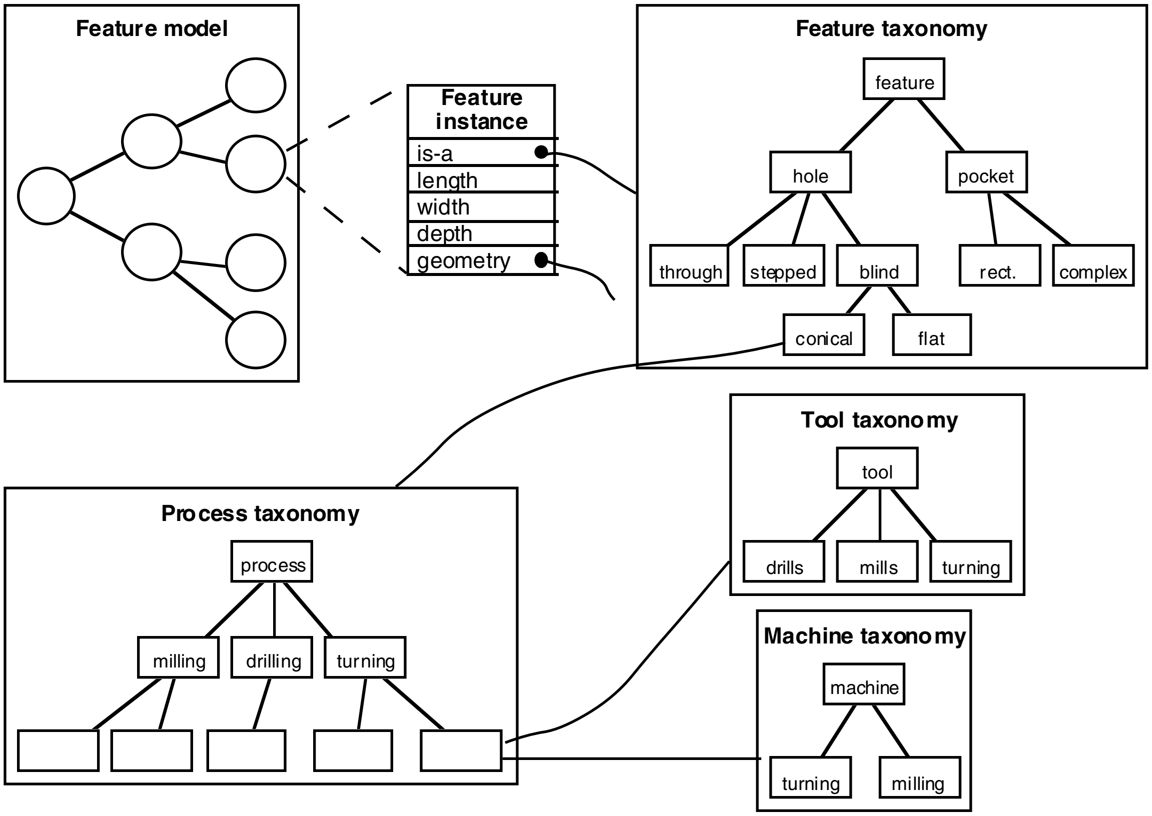


Figure 5. Feature-based manufacturing knowledge repository

Linking features, process models, and resource models leads to the manufacturing knowledge repository organization in Figure 5. Operatively, the processes potentially suited for the features of a part can be retrieved to construct a manufacturing plan for it. Strategically, the data repository supports adding new products, processes, and resources to reflect results of new product design and manufacturing process development. The following sections investigate important manufacturing applications.

Process Planning

Process planning [Chan90,Wang91] is the task of deciding what sequence of manufacturing operations to use to manufacture a part. Most research on process planning has dealt with machining processes, although there are a few examples in other areas such as injection-molded parts, stamped and die-cast parts [Wozn94], and sheet-metal parts [Bour95]. As described below, the two primary approaches for process planning are *variant* and *generative* planning.

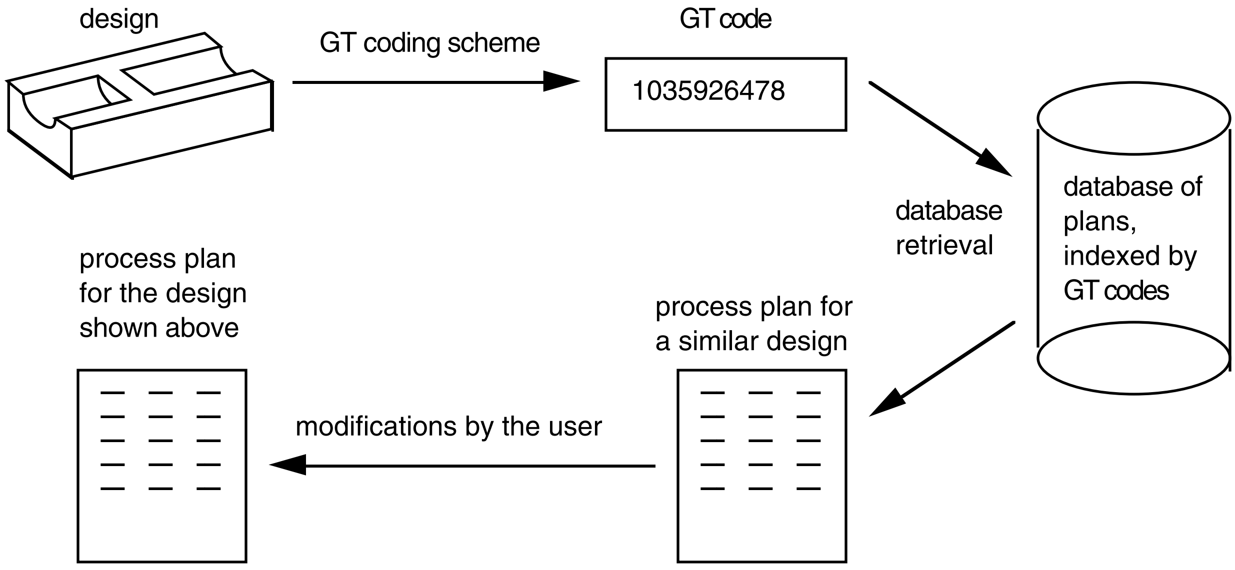


Figure 6. Variant process planning.

In *variant process planning* (see Figure 6), the process engineer uses a group technology (GT) coding scheme to map a design *D* into an alphanumeric code, uses this code as index to a database to retrieve a process plan *P'* for a design *D'* similar to *D*, and then modifies *P'* manually to produce a plan *P* for *D*. In the variant approach, the primary contribution of features is to facilitate GT coding on the basis of the explicitly recorded relationships between the feature shapes. For example, [Srik94] presents an approach for automatically producing GT codes that incorporate inter-feature relationships.

Several variant process planning systems are commercially available and have provided significant benefits, but they also have drawbacks. For example, if the process plan *P'* uses out-of-date processes, then these will propagate to *P* unless the process engineer makes a point of replacing them.

In *generative process planning*, the planning system attempts to synthesize the process plan *P* directly. For machined parts, the typical approach is to do the planning on a feature-by-feature basis by retrieving candidate processes from the manufacturing knowledge repository, selecting the feasible processes on the basis of geometric and manufacturing-related constraints, and combining the chosen processes in a proper sequence.

A generative process planner that provides realistic process plans for a reasonably wide spectrum of products would make a great impact on industrial practice. Thus, a great deal of research has been done on generative approaches, and a number of experimental systems have been developed for various aspects of process planning [Mänt89,Kamb93,Gupt94b,Yue94]. Unfortunately, generative process planning has proved quite difficult. Difficulties arise from interaction among various aspects of the problem, such as workpiece fixturing, process selection, and process sequencing. As a result, most existing systems work only in restricted domains, and few generative systems are capable enough to have achieved significant industrial use. A notable exception is the PART system, which is being marketed commercially (see [Geel95] and `http://www.wb.utwente.nl/pt/projects/part`).

Even in the absence of complete and comprehensive solutions to the entire process planning problem, generative process planning techniques can be useful in *design for manufacturing* [Boot94], in which the designer tries to take manufacturability considerations into account during the design stage. For example, by generating and evaluating operation plans for a part, it is possible to give feedback to designers about possible manufacturability problems with the part, or to suggest changes to the part that may improve its manufacturability [Mänt89,Gupt94b,Das95].

Assembly Planning

Most products are assemblies of discrete components; therefore, a key stage in their manufacture is to assemble those components. In light of this obvious fact, it is odd that assembly and assembly planning have received far less research attention than discrete part manufacturing.

Assembly planning can be roughly divided into the following phases:

1. *Selection of assembly method*, where the purpose is to recognize the most suitable assembly method for the product, taking into account the type of the assembly system which will be used.

2. *Assembly sequence planning*, where the purpose is to generate a sequence of assembly operations (placing an individual component in its final position in the assembly) that can be used to implement an assembly task in a given assembly system

3. *Assembly operations planning*, where the emphasis is on the details of the individual assembly steps, such as access directions, mating movements, and application of fasteners.

Assembly process problems such as poor quality, poor efficiency, or high cost (which all are interrelated) are most effectively handled at early design stage. This has resulted in the *design-for-assembly* approach [Boot94], where the most economical assembly process is selected during design, and the product is adapted to the chosen method.

Assembly sequence planning and assembly operations planning are closely related to path planning in robotics and inspection planning. For robotic assembly, operations planning involves the design of a valid sequence of rigid motions (translations and rotations) that bring a component into its final position in the assembly. Various assembly tools must also be designed, such as grippers, jigs, fixtures, pallets, and component feeders. Assembly cells must be laid out while observing the physical restrictions of robot motions.

Features are potentially attractive for many of the above tasks. A feature model can record the physical arrangement of components in an assembly, as well as attribute information on the physical fit between linked components. These data are fundamental for recognizing what assembly operations are needed and how they can be sequenced. [Bron94] addresses these and other topics in feature-based assembly modeling.

A related topic is disassembly planning, which is important for recycling and disposal of used products. Work in this area has been successful enough that a system for disassembly planning [Chen94] is being marketed commercially.

Inspection Planning

A popular current manufacturing trend is error-free "six-sigma" manufacturing, whose goal is to ensure that bad parts are almost never produced. Part inspection is vital to achieve this, not only to discard bad parts, but more importantly to provide closed-loop control on the quality of the products being produced. This means that inspection planning [Just94,ElMa94,Requ96] must be treated as an integral part of manufacturing planning.

There are several research problems still open in inspection planning. Of course, one should concentrate on the product characteristics that have the biggest influence on the product's performance, and avoid the cost of inspecting characteristics that have little significance. This means that inspection planning is deeply involved with product modeling issues, such as representations of dimensions and tolerances, assembly relationships, and, ultimately, functions and behaviors of physical shapes.

Computational Issues

Several computational issues involving manufacturing features have important consequences for how a feature-based system can be constructed and what functionality it can provide.

What Shapes to Consider as Features?

Deciding what shapes to use as one's repertoire of basic manufacturing features is intrinsically bound with the particular application at hand. The task of “featurizing” a product from manufacturing viewpoint starts by cataloging the manufacturing steps and processes of interest. This suggests a feature identification process with the following outline:

1. Decide the scope of the processes to be covered. For instance, the scope may be restricted to pure machining, or it might also include inspection and assembly.

2. Identify the individual process steps within the chosen scope. Existing company standards, process plans, process sheets, part drawings, NC programs, and manufacturing orders are useful sources of information.

3. Formalize the process steps as recurring process elements; identify process parameters and relationships between processes.

4. Identify recurring process sequences related to a certain type of geometry; formalize the relation between the geometry and the process parameters of the steps of the sequence.

5. Call the resulting shapes “manufacturing features,” draw a generic sketch for each feature identified, and name its parameters.

6. Validate the candidate features for *completeness* (identified features can create all intended parts), *unambiguity* (all parameters needed to define a feature are included), *simplicity* (only feature properties of use in some application are included), and *uniqueness* (nearly identical features are eliminated). Iterate if necessary.

The above process is not simple, and the available computational tools are rudimentary at best. Unless the scope is limited, or the production methods of the target company are well standardized and documented, identifying a good set of manufacturing features is hard work. On the other hand, the basic manufacturing processes are generic: the processes that can be executed in a CNC milling center are similar from one company to the next, even though process details vary according to the products, materials, and tools. This means that published feature sets can give a baseline for a tailored feature library. The process planning features of Part 224 of STEP are an example of such a set of features.

Features and Process Models

Several issues deal with the relation of features and process models. First, the *level of abstraction* of manufacturing features can vary. At the low end of the spectrum, features correspond directly with manufacturing processes. For example, in Figure 7a the shape of a countersunk hole is treated as a composite of low-level features “free-hole”, “reamed-hole”, and “counter-sink.” At the high end, features capture a range of shapes and processes; for instance, in Figure 7b the higher-level feature “countersink-hole” captures two alternative processes. Hence, high-level features leave more freedom to the process planner, while low-level features give control to the designer.

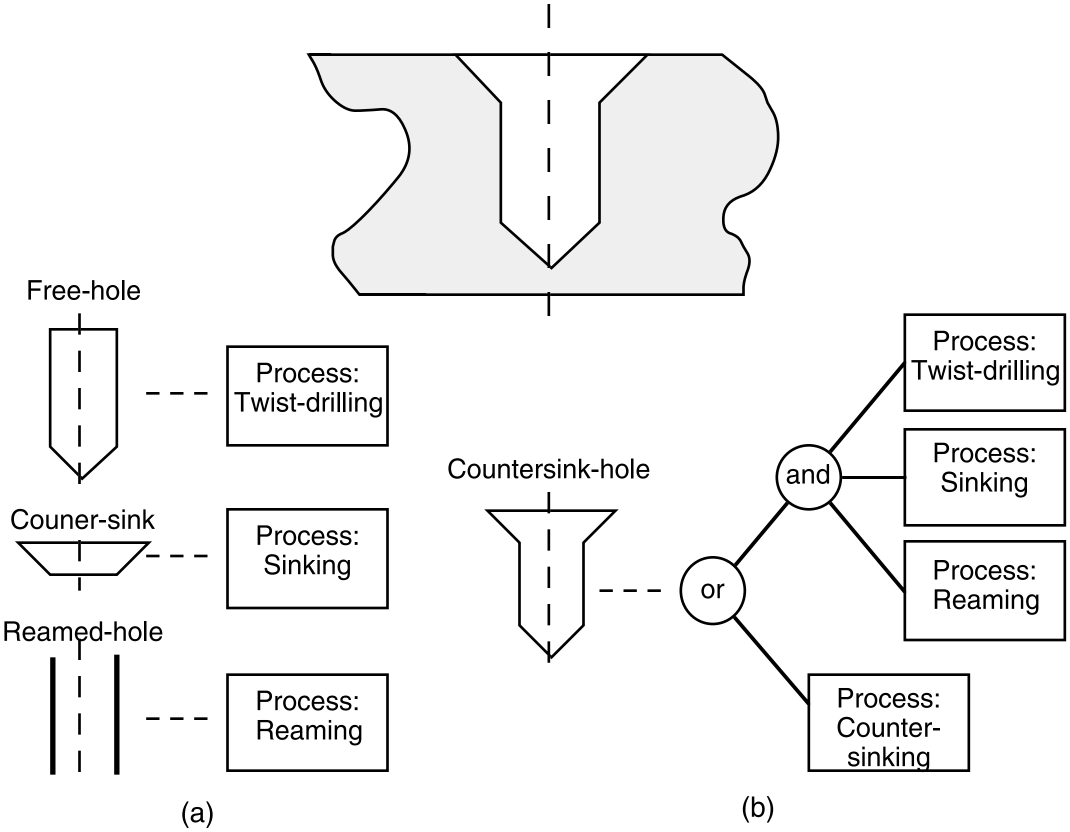


Figure 7. Features at different levels of abstraction

Related to the abstraction level is the *level of specialization*. For *generic features*, the processes are expressed in generic terms, and their parameters and resources are not precisely determined. A *specialized feature* corresponds with a precisely defined process. Again the tradeoff is between generality and user control.

Still another issue is the *completeness of the feature model*, i.e., whether the whole geometry of the part can be derived from its features. Some applications can work even if only the shape of direct interest is captured; some others require detailed geometric information on the whole part. Completeness is related to the creation method issue discussed below; typically, design by features systems give complete feature descriptions, while recognition systems can deliver also partial models.

The resolution of these issues depends on the intended use of features. If the objective is to study the producibility of a part at early stage of development, abstract and generic features are appropriate. To be useful for generating process plans and NC code (the low-level instructions used to control a machine tool), features must be fairly detailed and specialized to capture the characteristics of the processes and resources used.

Creation of Feature Models

The two main approaches to creating feature models are *design by features*, in which the designer creates the part directly as a combination of features, and *feature recognition*, which involves looking for features in a geometric model of the part. For machined parts, the goal is to find a set of features that cover the *delta volume*, the difference between the part and the stock from which it is to be machined (see Figure 8).

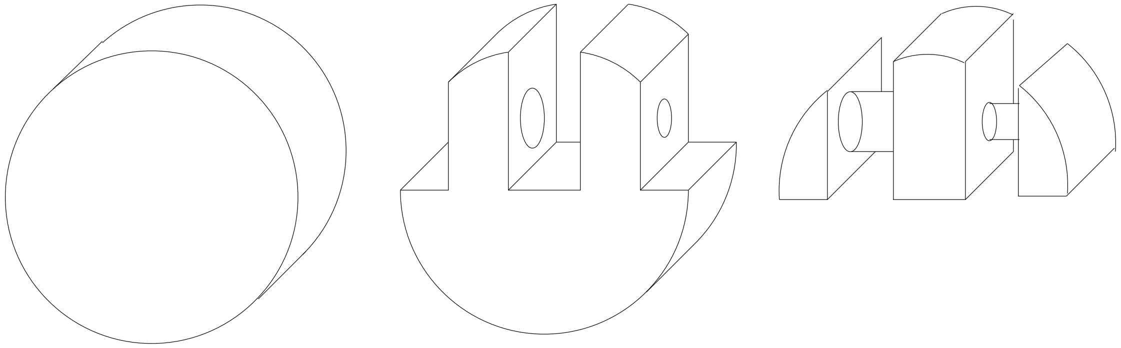

(a) stock (b) bracket (c) delta volume

Figure 8. A piece of stock, a bracket to be machined from the stock, and the delta volume.

For design by features, a common approach is to use features that correspond directly to manufacturing operations. Although this approach is quite popular (examples include the Quick Turnaround Cell [Chan90], NEXT-Cut [Kamb93], and alpha_1 [Stur95]), one drawback is that it forces the designer to think in manufacturing terms even though he/she may find this unnatural. For example, since shapes such as pins, stiffeners, and ribs have no direct counterparts in machining operations, they often are unavailable in feature-based design systems based on machining features. Instead, the designer is required to find combinations of manufacturing features that produce the geometry (see Figure 4). Not only may the designer find this inconvenient—but since these manufacturing features are idealizations of certain manufacturing processes, this forces the designer to assume the role of a process planner. Unless the designer has ample knowledge of the processes, he/she may use manufacturing features that do not correspond to the best way to produce the part.

One way to avoid this drawback is to allow the designer to use a set of *design* features that differ from the features to be used in manufacturing the part. However, this approach means that feature recognition or conversion must be done (either by a computer or a manufacturing engineer) in order to translate the part into features appropriate for manufacturing applications. At present, feature conversion methods are still immature.

Most current methods for computerized feature recognition fall in two groups, depending on the input data required and the general style of geometric reasoning performed.

Graph-based methods (e.g., [Josh88]) work by viewing a boundary model as a graph structure such as the *face-adjacency graph* shown in Figure 9, and looking for subgraphs that correspond to various feature types. One problem with graph methods is the NP-hard asymptotic complexity of subgraph isomorphism testing required for finding search graphs. More importantly, graph methods suffer from lack of generality and from difficulty in recognizing overlapping features, and they typically produce only one feature model for a part. When features overlap, there may be more than one possible feature model for a part (see Figure 10), and different feature models usually correspond to different ways to manufacture the part. How easy it is to manufacture the part—or whether it possible manufacture it at all—may depend on which feature model is used.

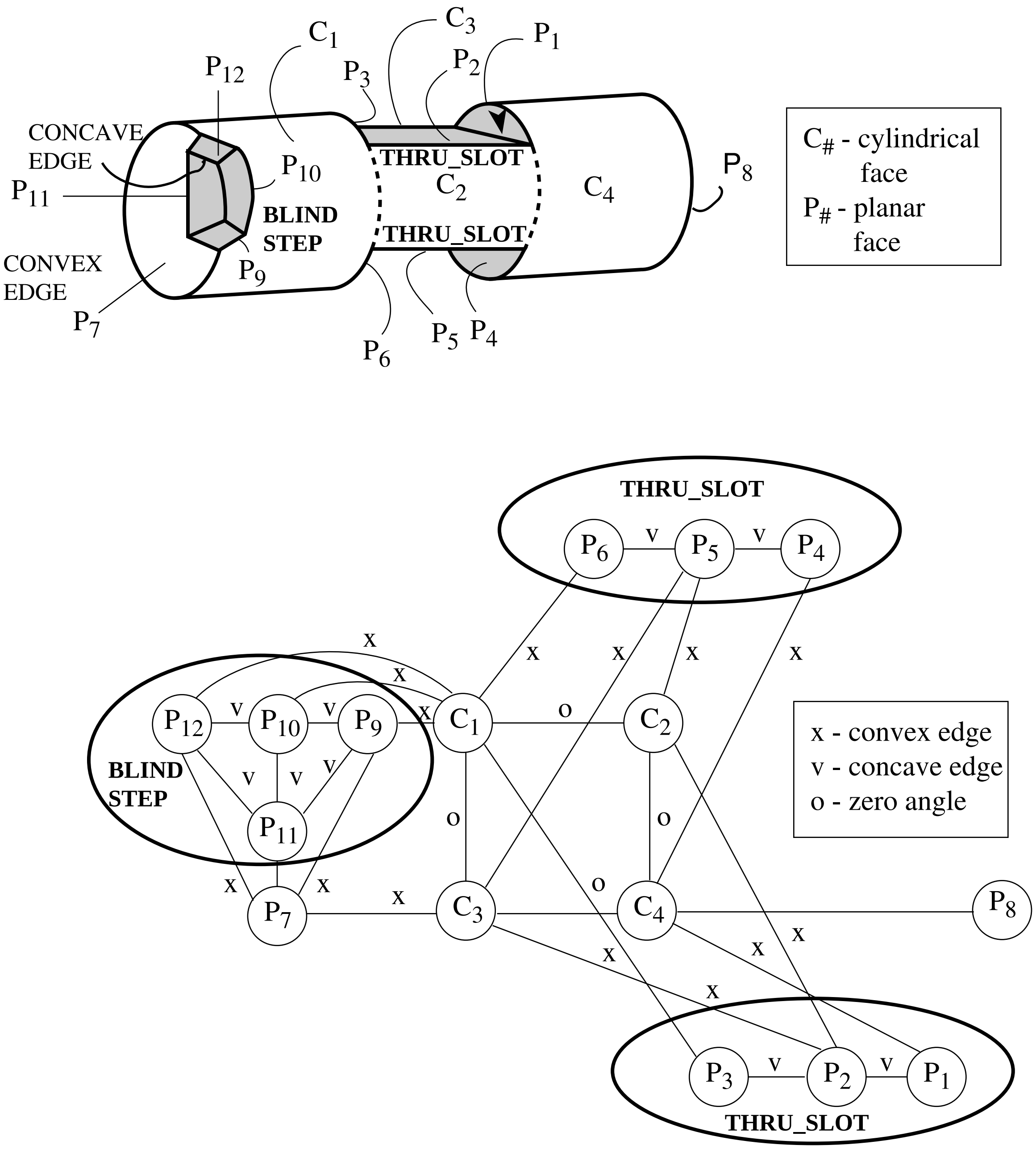


Figure 9. A part and its face-adjacency graph. The nodes represent faces and the arcs represent face-face adjacencies. The indicated portions of the graph correspond to manufacturing features.

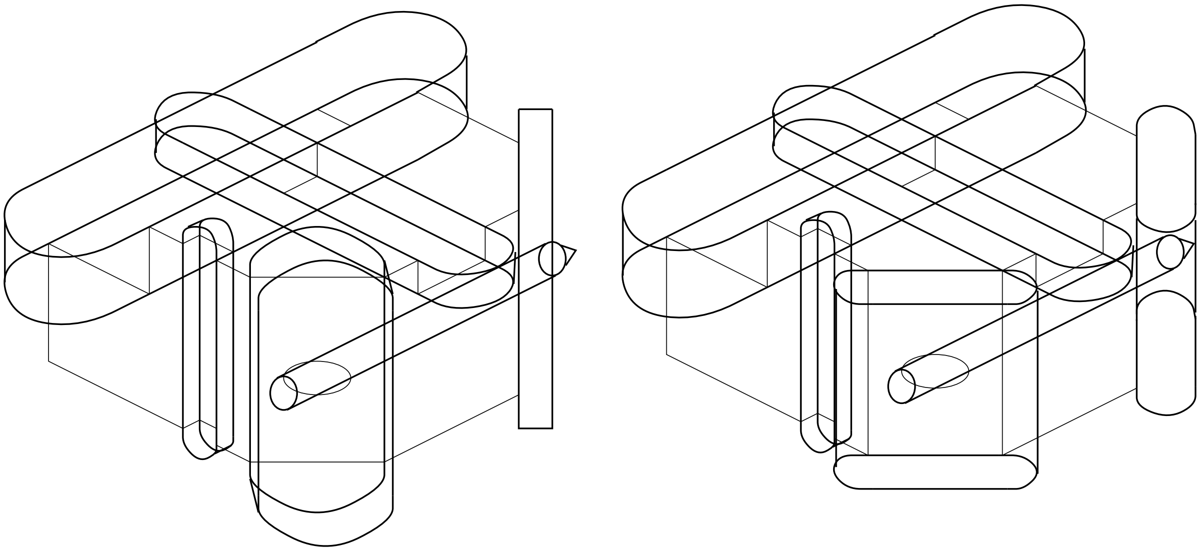


Figure 10. Two different feature models for the part shown in Figure 1 (adapted from [Gupt94b]).

Volume-based methods can produce overlapping sets of features like the ones shown in Figure 10. Two popular approaches are *cellular decomposition* and *trace-based* methods. Cellular decomposition [Saku94,Shah94] partitions the delta volume into convex cells, then combines these into manufacturing features (see Figure 11). Trace-based approaches [Gupt94a,Requ96] look for patterns of faces and edges in the delta volume that might have been produced by various types of features, and use these traces to construct instances of those features.

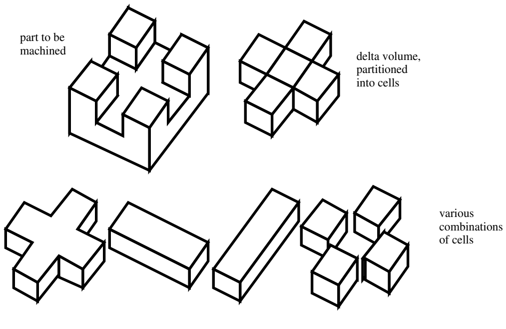


Figure 11. Feature recognition by cell decomposition

Despite promising research, many problems in feature recognition remain unsolved. Various specialized features capturing special manufacturing processes cannot yet be recognized, nor surface features needed to model manufacturing processes such as face milling. The use of tolerance and surface finish information to facilitate recognition is at infancy. Current research is looking at various hybrid methods which combine basic recognition algorithms with rules or constraints to improve the accuracy of recognition. To improve recognition speed, filtering methods that eliminate inessential geometry have also been investigated.

Discussion

Features are likely to become a dominant representation technique for mechanical CAD systems in the next few years. All major CAD vendors have published or announced feature extensions to their systems. Although feature support in many cases is still rudimentary, rapid progress can be expected. Nevertheless, significant challenges to further research remains in all aspects of feature technology.

A major challenge to future system builders is to realize fully the potential of features in the larger context of the whole industrial enterprise. The biggest advantage of features may well be that they provide a basis of organizing the design and manufacturing knowledge of products in a reusable data repository. The data repository, in turn, defines clean interfaces between the various processes of the company, in particular the customer order process and the processes of product development and manufacturing system development. The realization of this vision is likely to pose entirely new challenges to researchers working on the basic modeling facilities and related algorithms.

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Biographical Information about the Authors

Martti Mäntylä is Professor of Information Technology at the Helsinki University of Technology. His current research interests include the whole range of computational aspects of engineering design and manufacture, such as product modelling, graphics, and geometry. For more information, see `http://www.cs.hut.fi/~mam`. Author's present address: Helsinki University of Technology, Otakaari 1A, SF-02150, Espoo 15, Finland; email:Martti.Mantyla@hut.fi.

Dana Nau is a Professor at the University of Maryland, in the Department of Computer Science and the Institute for Systems Research. His research interests include AI planning and searching, and computational aspects of design and manufacturing. For more information, see `http://www.cs.umd.edu/~nau`. Author's present address: Department of Computer Science, University of Maryland, College Park, MD 20742; email: nau@cs.umd.edu.

Jami Shah is Professor of Mechanical Engineering at Arizona State University. His research interests include CAD/CAM, mechanical systems design, manufacturing automation, and engineering data management. For more information, see `http://ASUdesign.eas.asu.edu`. Author's present address: Dept. of Mechanical and Aerospace Engineering, Arizona State University, Temp AZ 85287-6106; email: jshah@asuvax.eas.asu.edu.