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Applications of group technology in distributed manufacturing

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This paper discusses the systematic use of group technology (GT) to support important activities of distributed manufacturing including design indexing and retrieval, variant design, variant process planning, and design critiquing. We introduce an Object-Oriented Group Technology (OOGT) scheme, which captures design data critical to the product's manufacture. Our approach uses a STEP-based product information model to generate the OOGT data automatically. The latter are then used to conduct an efficient search for similar products manufactured by selected companies and to retrieve and use information about the manufacturing processes and performance of these similar products.

Keywords: Group technology, design evaluation, distributed manufacturing

1. Introduction

Change and uncertainty increasingly characterize markets for manufactured goods. Within this environment, success reflects the ability of a manufacturing firm to reduce drastically the time needed to design, prototype, test, redesign, manufacture, and deliver to the market a high-quality product at a competitive cost. Agile enterprises achieve this by collaborating with other companies and sharing the resources, information, and process capabilities required for satisfying the market demand rapidly (Greenstein, 1994). We denote this form of agility as *distributed manufacturing*.

Distributed manufacturing involves combining the strengths of various geographically distributed manufacturing companies and forming a virtual enterprise network in order to satisfy the needs of the customer. Effective distributed manufacturing can occur only if a communication infrastructure for efficient exchange of product- and business-related information is coupled with decision support systems that address the complexity of the new environment. One obvious need of distributed manufacturing is the ability to find and retrieve products with certain design and manufacturing characteristics produced by a multiplicity of companies. This ability is important for several activities in the virtual enterprise, including:

(1) *Variant design*: Given certain attributes of a conceptual design, the designer searches the part bases of a set of firms, retrieves existing parts that comply with the search attributes, and uses the most appropriate ones as the basis for proceeding with the detailed design;

(2) *Variant design evaluation*: The designer seeks manufacturers that produce parts similar to a proposed detailed design. The manufacturing costs, cycle times, and quality attributes of these parts provide valuable feedback for assessing the merit of the new design. This is especially important if the product is to be manufactured by a member of the virtual enterprise other than the designer's firm. In this case the designer has the ability to perform plan-based design critiquing that reflects the manufacturing capabilities of the partner firm;

(3) *Variant process planning*: The process plans of parts similar to a given design may serve as the basis for developing the reference design's process plan;

(4) *Purchasing*: Purchasing personnel may efficiently identify parts that meet certain specifications and are manufactured by candidate suppliers.

Traditionally, such variant activities have been supported by group technology (GT). It is our thesis that GT has a renewed, strong relevance to distributed manufacturing. This environment, however, raises new requirements for GT:

(1) GT codes are concise product descriptors, and comparing the GT codes of two products is a quick and

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efficient way of estimating their similarity. Though GT codes allow one to conduct a rough search for similar products, richer models support powerful variant and generative activities, and allow one to focus on those similar products that offer the most useful information. This can be achieved by developing concise GT information models that capture essential design and manufacturing views of the product while supporting efficient comparison of data for design retrieval.

(2) These concise information models should be derived from standard product representations that completely and unambiguously abstract the product design. It is critical that these detailed product representations are in standard forms so that they can be exchanged freely and processed by partners of the virtual enterprise, which may employ heterogeneous information systems.

(3) In a distributed manufacturing network consisting of several companies, each producing a large number of products, physical inspection of product designs to develop the concise information models is obviously impractical, as this is a slow and inconsistent procedure. Thus the generation of the GT models should be an automated procedure.

Based on the requirements described above, we have developed a systematic approach for GT-based applications in distributed manufacturing. Our approach uses a comprehensive, standard STEP-based product representation of mechanical and electronic product designs. We have also developed an object-oriented group technology (OOGT) information model, which includes the traditional product GT code and additional critical design and manufacturing information. The OOGT information is generated automatically from the STEP product model and may be used for a quick and efficient retrieval of process plans, manufacturing costs, cycle times, and quality attributes of similar product designs manufactured by potential partners of a distributed enterprise. We have implemented our OOGT-based approach in a software system to support distributed manufacturing of a class of electronic products including microwave modules (MWMs), printed circuit assemblies (PCAs), and hybrid microwave assemblies (HMAs), as well as a limited class of mechanical products.

The remainder of the paper is organized as follows. Section 2 provides an overview of group technology (GT) and previous research in generation of GT codes. Section 3 discusses the detailed product representation, which is based on the STEP international standard. Section 4 discusses the concise OOGT information model. Section 5 describes the automated generation of the OOGT information from the STEP-based product model. Section 6 discusses the application of OOGT to automated design retrieval. Section 7 describes the implementation of the OOGT-based system for variant applications in the distributed manufacturing of mechanical and electromechanical products. Section 8 summarizes the research contributions and conclusions.

2. Background

Group technology is a manufacturing philosophy that exploits similarities in the design, fabrication, and assembly attributes of products. A group technology (GT) code is an alphanumeric string, which represents critical information about the product in a concise manner. GT codes can be used to search a database of products and retrieve the designs and process plans of those products which are similar to a given design (Nagi and Iyer, 1994), to generate new process plans automatically using a knowledge-based system (Lee *et al.*, 1994), and to perform manufacturability evaluation of a product design (Allen and Smith, 1988; Harhalakis *et al.*, 1992).

GT coding and classification schemes attempt to capture key design and manufacturing attributes of a product, including main shape, size, product features, production quantity, and material. A number of GT coding schemes have been developed for discrete machined parts (Bond and Jain, 1988; Harhalakis *et al.*, 1992), including MICLASS, Opitz, and DCLASS. On the other hand, the existing electrical and electronic GT classification and coding schemes are customized, often proprietary, systems (Ham *et al.*, 1986; Chen, 1989). The cost, tediousness, and inconsistency of manual generation of GT codes from product designs have initiated several research efforts in automating this process.

Shah and Bhatnagar (1989) developed an automated GT coding system based on the Opitz coding scheme for machined parts. The system consists of three modules: a form feature modeler for design by features, a feature-mapping shell, and a GT coding module. Each feature in their custom feature-based CAD system has a preassigned taxonomy code. The mapping shell uses the generic information captured by the taxonomy code to determine individual feature characteristics and the relationships between features and the entire part. The GT code generator uses the resulting feature information and the Opitz coding rules to determine the values for each digit of the code.

Henderson and Musti (1988) developed a system to generate automatically DCLASS GT codes of rotational products from a 3-D CAD database. Their system contains a preprocessor, a feature recognizer, and a part coder. The preprocessor converts boundary representation data into the input format of the feature recognizer. The part coder consists of a feature interpreter and a code-specific knowledge base.

Chen (1989) developed an automated GT coding system that operates on a product design described in the IGES format. The system consists of a geometry recognition algorithm to translate the IGES file into a custom product definition file. The first step in the GT code-generating process is form feature recognition, which includes searching the data file for complex shapes, decomposing these shapes into a number of simpler ones, matching all shapes with primitive form features, and redefining the feature data into information that can be processed by the GT coding rules. The second step extracts the GT code from the preprocessed information. The system is limited to rotational products only, and cannot handle internal and facial form features.

Bhadra and Fischer (1988) developed a microcomputer-based group technology system to classify and code rotationally symmetric parts. The system also includes a GT search module, which is used to retrieve one or more parts from the GT database based on several designer-specified criteria.

Harhalakis *et al.* (1992) developed and implemented a rule-based approach for generating GT codes for microwave modules from a PDES-based product information model for the purpose of manufacturability evaluation. In their approach, the processing of many GT code digits depends on information supplied by the user.

3. STEP-based product model

Data are a critical resource throughout the life cycle of a product, from design and analysis to manufacturing, support, maintenance, and disposal. Exchange of product data is essential for the integration of life cycle activities and the realization of distributed manufacturing. The STEP standard for product data representation aims at meeting these goals.

In order to support our design retrieval approach for distributed manufacturing, we have developed, using STEP resources, an integrated object-oriented product model (or application protocol) for the complete and unambiguous representation of mechanical and electro-mechanical product designs. We have specifically applied this model to microwave modules (MWMs). This model directly supports product representation, design, and rendering (Candadai *et al.*, 1994a, 1994b).

An MWM is an electromechanical product, which consists of a complex mechanical ground plane, an insulation layer, and an artwork circuitry layer. The mechanical substrate includes features such as holes, pockets, cutouts, slots and chamfers, and serves as the ground plane of the device and as a heat sink. The insulation layer isolates the artwork layer from the ground plane. The MWM carries surface- and through-hole-mounted components assembled on the substrate using soldered and non-soldered hardware.

Our STEP-based MWM product model consists of generic STEP resources and application-specific models. The model uses the STEP geometric and topological representations (ISO, 1993a) and the STEP form features representation (ISO, 1993b). In addition, it contains application features, a layered electrical product (LEP) model, and a new MWM integrated model, which uses the STEP product description and representation scheme (ISO, 1993c, 1993d) to define the relationships between the different models. The integrated product model contains a complete boundary representation of the shape of the product's substrate, a feature-based representation of the substrate, and a description of the electronic portion of the microwave module. The schemes of the constituent product information models described above were developed using the ISO modeling language EXPRESS (ISO, 1993e), and are briefly described below.

3.1. *Geometric and topological models*

The geometric and topological models provide the boundary representation of the nominal shape of the product (ISO, 1993a). The geometric model abstractly describes the shape with geometric entities such as point, vector, curve, surface, and local coordinate system. Topology describes the connectivity relationships between portions of a design. The topological model provides the information essential for geometric reasoning through fundamental entities such as vertex, edge, loop, face, and connected face set. The geometric and topological entities are used to define the boundary representation of the product. A complete listing and description of these entities is given in ISO (1993a).

3.2. *Form features model*

This model provides a higher level of abstraction than the geometric and topological models and contains entities from the STEP form features representation scheme, which is currently under development. This scheme provides representations for use in modeling shapes of widespread industrial interest (ISO, 1993b). However, these representations are independent of manufacturing applications such as process planning and design evaluation.

The model uses two types of sweeps to abstract form features:

(1) An axisymmetric sweep abstracts a form feature as a combination of a circular profile about the axis of the

feature and an arbitrary path perpendicular to the circular cross-section;

(2) A profile sweep abstracts a form feature as the sweep of a specified profile along an axis. The swept profile can be either closed or open depending on the position of the profile relative to the boundary of the product. Some typical profiles are the regular polygon profile (which is closed) and the rounded-u profile (open).

3.3. *Application features model*

Though the STEP-based form features scheme models shapes of widespread industrial interest, these shapes have no explicit manufacturing connotation. However, the design of the STEP scheme facilitates the development of application-specific features based on STEP form features. We have developed such a model to provide a link between feature-based product design and process-planning applications. Specifically this model describes features that are relevant to machining operations that are used to fabricate the substrate of the MWM.

Our application features model employs a combination of implicit and explicit feature representations. The implicit representation describes a feature by a number of parameters specifying the feature shape; it mimics the definition of a form feature. However, the application features have an additional explicit representation that is not supported by the STEP form features: that is, each application feature is explicitly described by the corresponding faces of the product's boundary representation. This geometric and topological description provides useful information for applications such as process planning and design critiquing.

Figure 1 describes the application features model, which includes common manufacturing features such as hole, pocket, cutout, groove, and chamfer, in the formal graphical language EXPRESS-G. In EXPRESS-G notation, each box represents an entity in the model. Thick lines represent subtype relationships, and thin ones represent attribute relationships. Note that a subtype (child) of an entity (parent) inherits all the attributes and behaviour from the parent, and may also include additional attributes and behaviour. Associated with the application features model is a description of each feature's dimensional tolerances and surface finish. In addition to these application features, the model describes circular and array patterns of features. An example of an application feature is a countersunk hole, which consists of two STEP form feature representations: a constant-diameter axisymmetric sweep represents the cylindrical hole, and a tapered axisymmetric sweep represents the sink. Another example of an application feature is a rectangular pocket, which is described by the linear sweep of a closed rectangular profile.

3.4. *Layered electrical product model*

The layered electrical product (LEP) model represents the design characteristics of a class of electronic products including printed wiring assemblies, hybrid microwave assemblies, and microwave modules. The model was originally developed in IDEF-1X by an IEEE/PDES team and is known as the Cal Poly layered electrical product model (PDES, 1987). We have completely defined all entities of the Cal Poly model in EXPRESS and have used these entities in the development of our electrical scheme.

The LEP model (Fig. 2) includes an LEP product definition, and describes the product's constitutive layers. Each layer is modeled by its material, a set of layer elements, and a set of logical subregions. A layer element is a continuous two-dimensional topological region, and may have passages with plated depositions. The device's artwork is described by a set of such layer elements. A logical subregion models the presence and type of text or voids present in a layer. The topological details of a layer element, and thus the artwork, are described by shape entities from the STEP geometric and topological models. This detailed model of the artwork topology is necessary, as for high-frequency devices such as MWMs the topological details of the artwork are significant to the electronic performance of the device.

In order to describe a complete MWM, the LEP model includes an MWM product definition, which, in addition to the LEP attributes, contains component, hardware attachment, and plating information.

3.5. *MWM integrated model*

The microwave module (MWM) integrated model relates the different schemes (geometry, topology, form features, application features, and layered electrical product) into an application scheme that describes the complete design of an MWM or other mechanical product. This integration is based on STEP schemes related to product description and support (ISO, 1993c) and representation structures (ISO, 1993d). The main modification of the STEP models was the addition of two representations: the feature-based shape representation consists of the geometric objects, topological objects, and application features that describe the product shape; and the electrical representation belonging to the LEP model includes objects related to electronic functionality such as the artwork, components, and hardware. Our MWM integrated model is illustrated in Fig. 3.

4. OOGT information model

As discussed in Section 1, the limited modeling capabilities of fixed alphanumeric GT codes restrict the power of variant and generative applications. For instance,

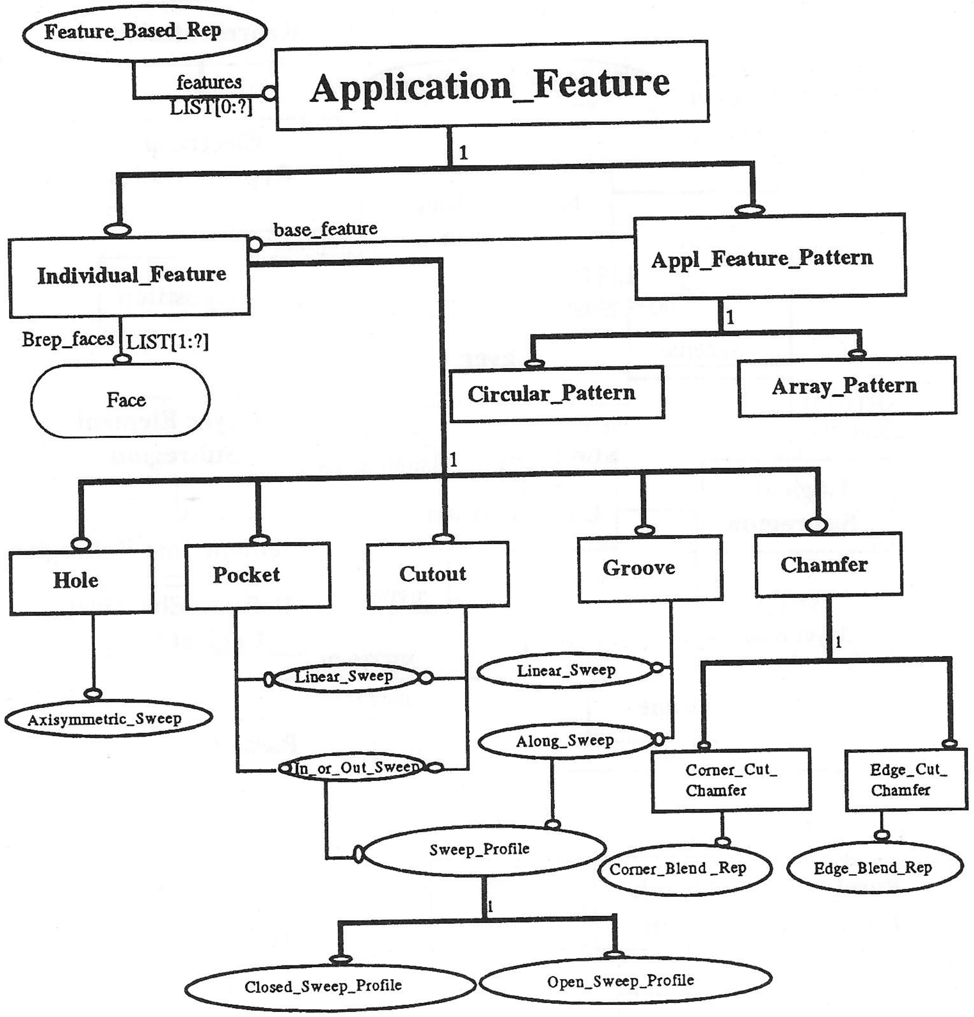


Fig. 1. Application features model: rectangular boxes denote types of application feature; oval boxes denote STEP form feature representation entities; rounded boxes denote topological entities.

although mechanical GT codes capture the presence of different types of shape features, they ignore vital information such as feature cardinality, feature dimensions, tolerances, and surface finish. Other attributes not captured by a GT code but critical for manufacturing include geometric elements such as undercuts, thin sections, abrupt changes in cross-sections, inaccessible features, and individual feature volumes. On the other hand, electrical GT codes, such as the one developed in Harhalakis *et al.* (1992), capture the presence of components, hardware, critical artwork elements, and platings, but do not describe component and hardware locations, cardinality, and values of critical electrical quantities, all of which are important to the design, manufacture, and assembly of the product. Such information is essential for retrieving meaningful and economical designs, which may be modified easily to generate a new design variant. This information is also critical for process planning (variant and generative) of a given design and effective design critiquing.

To address the need for a rich abstraction of the product information that can be used for efficient search, retrieval, variant design critiquing and generative process planning, we have developed an OOGT information model for mechanical parts and microwave modules (shown in Fig. 4). The development of this model is guided by the structure of existing GT codes: that is, the OOGT model captures the same type of attributes described by existing codes but in more meaningful detail. Thus we capitalize on the conciseness and abstraction of GT codes, while enhancing their modeling power. In deciding the additional information to include in the OOGT model, we targeted specific applications including design evaluation and process

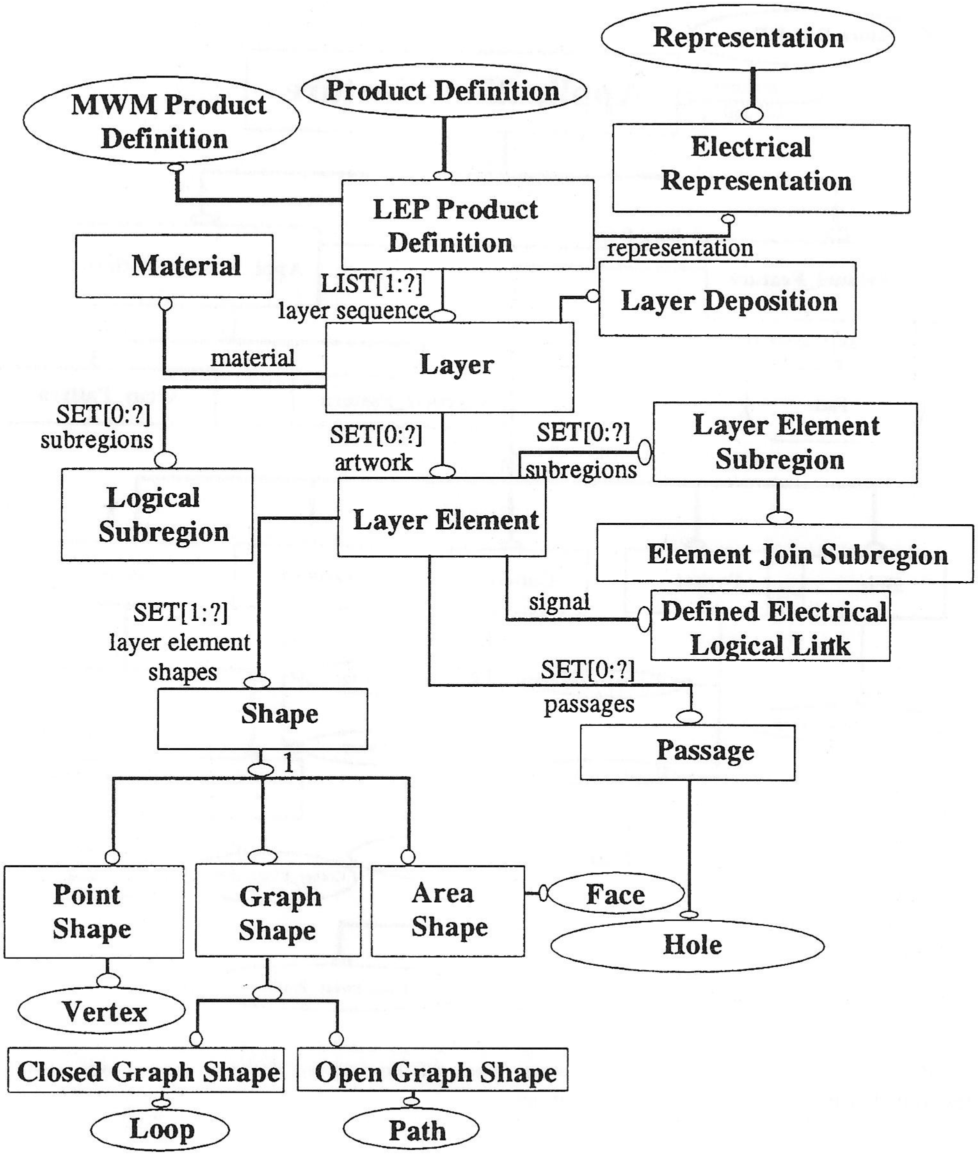


Fig. 2. Layered electrical product (LEP) model.

planning of both mechanical parts and a variety of electronic products including printed circuit boards and MWMs.

The GT coding scheme used in the development of our OOGT model was originally developed by Harhalakis *et al.* (1992). To describe the mechanical substrate, this scheme includes the 18 digits of the flat mechanical portion of the established coding scheme MICLASS (OIR, 1986), and 25 additional digits that concisely describe information related to artwork manufacture, substrate and passage plating, component and hardware assembly, and tuning and testing. Table 1 lists the attributes used in this scheme.

The mechanical OOGT information captures the following additional design-for-manufacture data: the product envelope shape; the dimensions, tolerances, and surface finish of the enveloping faces; feature descriptors such as feature cardinality, location, dimensions, tolerances, and surface finish. For each feature the model also captures the following attributes:

(1) *Feature volume*;
(2) *Minimum feature corner radius* (if appropriate);
(3) *Section thickness value*: Value of the minimum thickness of any cross-section associated with a feature;
(4) *Tool accessibility flag*: A Boolean flag, which takes a value of 1 if the feature is accessible by an appropriate cutting tool, and 0 otherwise;

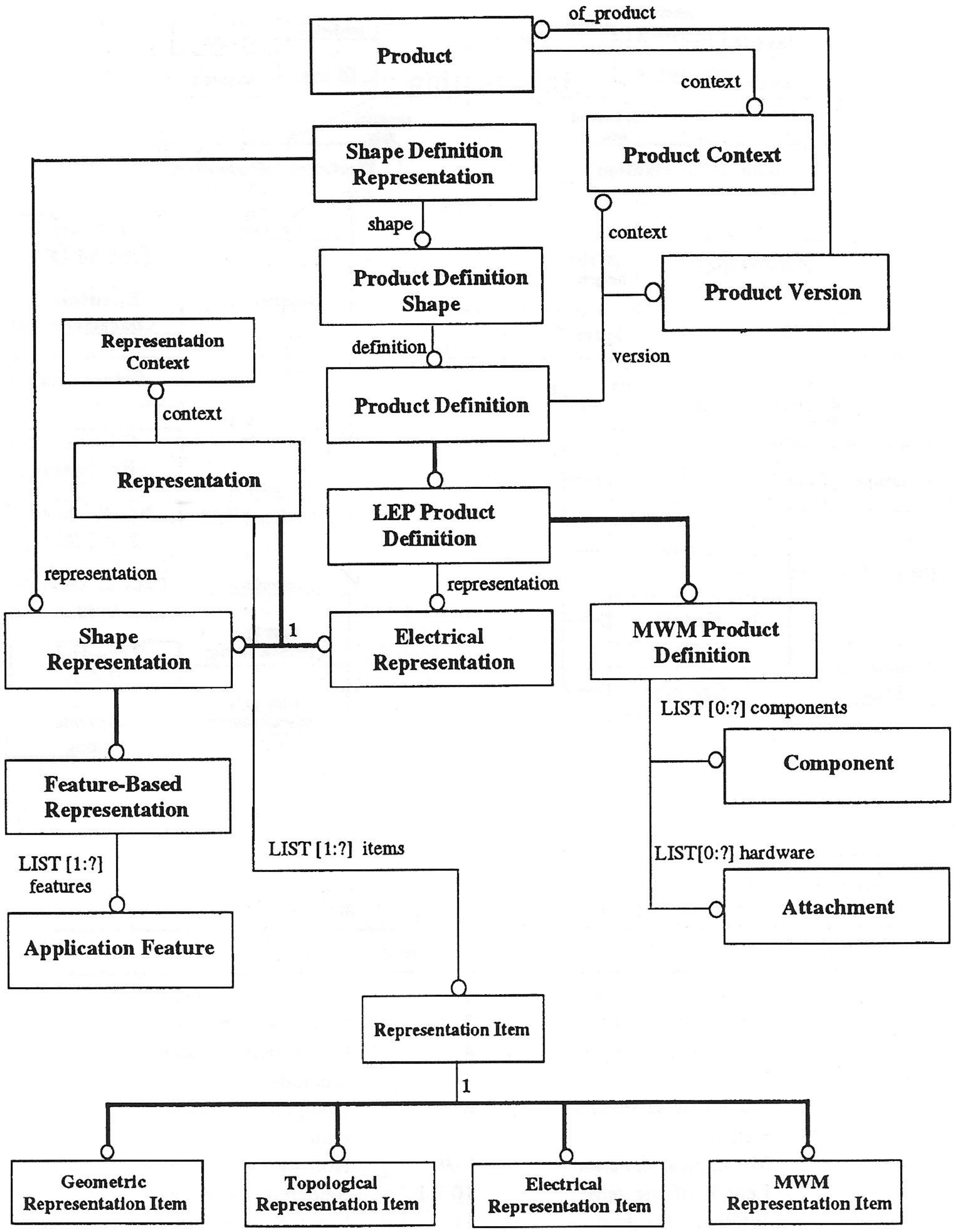


Fig. 3. Microwave module (MWM) integrated model.

(5) *Undercut flags*: Defined with respect to certain candidate undercut directions. Each Boolean flag corresponds to a given direction. A flag takes a value of 1 if the feature forms a portion of an undercut with respect to the corresponding direction, and 0 otherwise;
(6) *Section ratio*: Value of the maximum ratio of cross-sections formed by each feature.

The above information supports not only design retrieval but also generative process planning and the evaluation of manufacturing feasibility, manufacturing costs, cycle times, and quality. For example, if a product has any features that are inaccessible by a cutting tool, these features cannot be machined. Likewise, a pair of features separated by a section thickness less than a certain threshold value cannot both be obtained by sand casting. Hence alternate manufacturing processes to create these features have to be considered.

The electrical portion of the OOGT model includes information related to components, soldered and non-soldered hardware, artwork circuitry, substrate, platings,

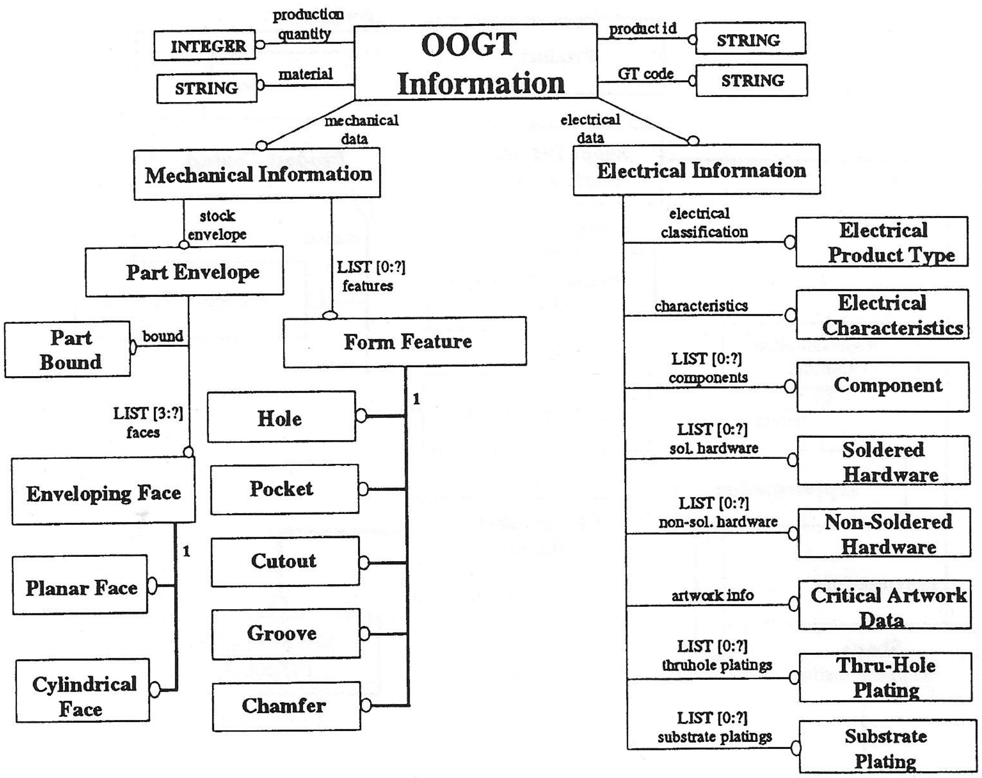


Fig. 4. OOGT information model.

Table 1. GT coding scheme for flat mechanical parts and MWMs

MICLASS GT scheme		*Electrical GT scheme*	
1	Main shape	1	Electrical classification
2	Machined cutouts	2–3	Electrical function
3	Holes perpendicular to top surface	4–5	Component mounting methods
4	Machined secondary elements	6–7	Component mounting patterns
5–6	Mechanical function	8–9	Non-soldered hardware
7–8	Length of the part	10–11	Soldered hardware
9–10	Width of the part	12	Component and hardware count
11–12	Thickness of the part	13	Component orientation
13	Mechanical tolerances	14–20	Electrical dimensions
14–15	Material	21	Qualifying dimensions
16	Raw stock shape	22	Fabrication tolerances
17	Production quantity	23	Substrate type
18	Secondary element orientation	24–25	Multiple platings

and electrical tolerances of the product. For example, the component-related information includes type, cardinality, location, orientation, mounting method, and placement tolerance. This detailed information supports the analysis and evaluation of assembly processes.

We have developed the OOGT model using the EXPRESS modeling language by defining all the entities of the model, their attributes, and their relationships with other entities. Powerful object-oriented concepts such as hierarchy and inheritance, class abstraction, virtual functions, and modularity were employed in the model's development and implementation.

The most significant difference between GT and OOGT is the structure and amount of information captured by the product representations of the two approaches. From the discussion above and Fig. 4, it is clear that the OOGT product model captures significantly more information than the GT code. For example, the OOGT model captures the exact dimensions of the product's envelope; furthermore, it includes parametric information about each feature of the product, such as feature dimensions, location, and orientation. In contrast, the GT code provides only the ranges within which the dimensions of the envelope lie; in terms of features, the GT code indicates the existence of selected feature types and some important feature characteristics (such as orientation), but does not capture the dimension and location of each feature nor the number of features of each type. A direct result of the richer information content of OOGT is its increased ability to discriminate between similar products (which in some cases may have identical GT codes). This has been exploited fully by our approach while ranking products in terms of similarity (see Section 6). Other applications within which OOGT may be superior to GT include process planning (variant and generative) and design critiquing.

The differences in information content between the OOGT model and the GT code have significant computational implications beyond the obvious memory requirements. It is possible, and indeed typical, to determine GT codes manually. However, manual generation of OOGT models is clearly impractical. On the other hand, automated generation of GT codes and OOGT models requires comparable computational effort (see Section 5). In conclusion, OOGT is compatible with recent advances of information technology and more appropriate for automated processing.

5. OOGT information processing

As mentioned in Section 1, in order to exploit the attractive features of group technology in distributed manufacturing the OOGT information should be generated automatically. We have developed an approach that uses the integrated STEP-based MWM product model, described in Section 3, to generate the OOGT attribute values. Our approach consists of two types of mapping procedure:

(1) *Direct mapping* procedures generate GT digits and OOGT objects directly from the information captured in the product model. Information not contained in the product model (for example, production quantity and geometric tolerances) is provided interactively;

(2) *Indirect mapping* procedures first determine design attributes by reasoning about the product design. Subsequently, these procedures map the derived attribute values to the corresponding GT digits or OOGT objects.

Although our method focuses on flat mechanical parts and on a class of layered electrical products, it can be extended to round and sculptured mechanical parts and other electronic products, such as printed wiring assemblies, in a straightforward manner.

5.1. *Mechanical OOGT information processing*

Generating the mechanical portion of the OOGT information requires the feature-based representation of the product design. Furthermore, the boundary representation of the model is employed in many indirect mapping procedures. This section discusses the procedures for automatically generating the OOGT information about the product envelope, manufacturing features, and critical manufacturability attributes. Most of the remaining OOGT information is supplied by the designer. See Candadai (1995) for detailed descriptions of all procedures.

Consider the reference product shown in Fig. 5. The product is 10 in long by 8 in wide by 0.2 in thick (254 mm × 203 mm × 5 mm). It has four counterbore holes and four straight rectangular grooves. It is an aluminum substrate for an MWM. The production quantity is 10 000. During the discussion we shall refer to this product to illustrate the GT coding scheme and the OOGT information model. Figure 6 shows the OOGT model for this reference product. (For clarity, some details for some objects are excluded.)

5.1.1. *Product envelope*

The product envelope procedure fits a rectangular prism of minimum size around the product assuming that the product is non-rotational and is aligned properly with the coordinate system (i.e. the center of gravity is the origin of the coordinate system and the major axes of the product are parallel to the coordinate axes). For each axis, the procedure generates two planes that are perpendicular to

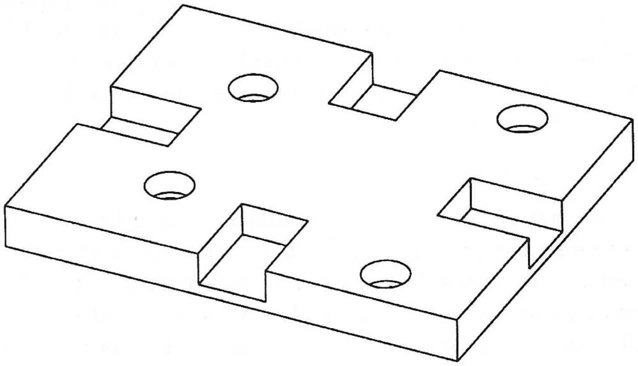


Fig. 5. Reference product.

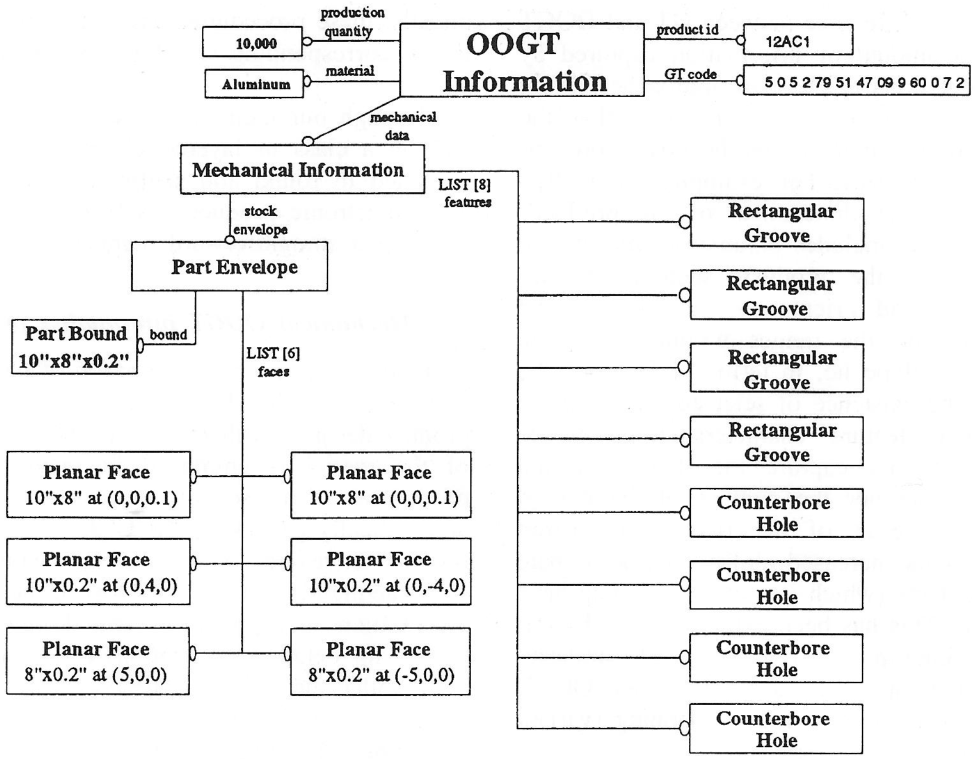


Fig. 6. OOGT information model for reference product.

the axis. Thus, a total of six planes are generated, forming a rectangular enveloping prism. Subsequently, the procedure determines the prism's length, width, and thickness. The rectangular faces of the prism form the enveloping faces in the OOGT model and provide the associated locations and orientations. Using the length, width, and thickness dimensions, the procedure derives the values of digits 7–12, which capture the approximate values of the corresponding dimensions. For the reference product, the length is 10 in, and digits 7–8 equal 51. The width is 8 in, and digits 9–10 equal 47. The thickness is 0.2 in, and digits 11–12 equal 09.

The value of digit 1, which describes the main shape of the product as flat or sculptured, is also determined from this envelope. The procedure classifies the product as flat if the envelope's thickness is less than 0.25 in; otherwise the product is classified as non-flat. Because the thickness is 0.2 in, the reference product is a flat part, and digit 1 equals 5.

5.1.2. *Manufacturing features*

Recall that the OOGT model captures detailed parametric information about all product features including their locations, orientations, dimensions, tolerances, and surface finish. In addition digits 2, 3, 4 and 18 of the mechanical GT code capture the presence of different types of features as well as their orientations. An important step in developing the procedures that generate the GT feature information is relating each MICLASS feature to the application features of the STEP-based product model. This mapping is given in Table 2.

The manufacturing features procedure derives the feature parametric information from the STEP-based product model. The OOGT feature objects are identical to the STEP-based application features and contain the same attribute information. For example, Table 3 shows the attributes describing the STEP and OOGT hole entities. Thus the procedure populates the OOGT entity with the information in the STEP entity. Although their population is a straightforward procedure, the OOGT features do not point to further information, such as the form features, geometry, or topology of the design.

An important step in developing the procedures that generate the values of GT digits 2, 3, 4 and 18 is relating each MICLASS feature to the application features of the STEP-based product model. This mapping is given by Table 2. The value of GT digit 2 depends upon the presence of different types of MICLASS cutouts (rectangular, slanted, radiused, and complex). The application features corresponding to these MICLASS cutouts include rectangular, radial, L-, T- and U-shaped cutouts, and edge flat chamfers. Hence the evaluation procedure for this digit checks the feature-based STEP representation for the existence of these application features. For example, the reference product has no cutouts or edge flat chamfers, so digit 2 equals 0.

Table 2. Mapping between MICLASS and STEP application features

MICLASS feature	*Application feature*
Simple rectangular cutout	Straight square-U cutout
Radius cutout	Circular-arc cutout
Slanted cutout	Edge flat chamfer with one pre-existing face perpendicular to the *XY* plane
Complex cutout	Any other cutout (excluding those listed above)
Hole	Hole
Line pattern	Parallel array pattern
Arc pattern	Circular pattern
Machined secondary element	Hole not perpendicular to *XY* plane Non-radial groove Corner flat chamfer Edge flat chamfer with no pre-existing faces perpendicular to the *XY* plane Pocket
Flat	Corner flat chamfer Edge flat chamfer with no pre-existing faces perpendicular to the *XY* plane
Slot	Non-radial groove
Complex cavity	Pocket Complex groove

Table 3. Attributes of the STEP and OOGT hole entities

STEP attributes	*OOGT attributes*
Two constant-diameter axisymmetric sweeps:	Hole diameter
	Hole depth
Diameter	Bore diameter
Length	Bore depth
Location and axis	Location and axis
Threads	Threads
Blind-or-through	Blind-or-through
Face-surfaces	
Tolerances:	Tolerances:
Hole diameter tolerance	Hole diameter tolerance
Hole depth tolerance	Hole depth tolerance
Bore diameter tolerance	Bore diameter tolerance
Bore depth tolerance	Bore depth tolerance
Surface finish	Surface finish
	Positional tolerance

The procedure that evaluates the value of digit 3 includes the following steps. First it evaluates the cardinality of the set of holes in the product which are perpendicular to the *XY* plane (top surface of the substrate). The orientation of each hole is determined by evaluating the inner product of the hole's *Z* local coordinate axis with the global coordinate axes *X* and *Y*. If both products are zero, then the hole is classified as perpendicular to the *XY* plane. The second step of the procedure queries the diameter values of all perpendicular holes and determines the maximum diameter. The third step searches STEP application feature pattern entities for the presence of hole patterns, such as array or arc patterns. These three pieces of information are used by the MICLASS coding rules in determining the value of digit 3. For example, the reference product has four holes perpendicular to the *XY* plane. The product is 0.2 in thick, the holes have a diameter of 0.6 in, and they form no pattern. After checking the holes' orientation, the procedure for digit 3 calculates the maximum diameter and determines that it is less than five times the thickness ($0.6 < 5(0.2)$). Because the product has more than one hole, the procedure checks for patterns. Because none exist, the procedure assigns the value 5 (random holes) to digit 3. All appropriate MICLASS coding rules have been incorporated in the procedure for digit 3.

The value of digit 4 depends upon the types of machined secondary elements. The value is obtained by checking the STEP feature-based model for the presence of such elements, including holes not perpendicular to the *XY* plane, non-radial grooves (which form MICLASS slots), pockets and complex grooves (which form MICLASS complex cavities), and corner flat and secondary edge flat chamfers (which form MICLASS flats). The procedure also asks the designer for any minor deformed elements. The value of digit 4 starts at 0. If none of the above-mentioned features exists, the procedure returns a digit value of 0. If any holes are present, it adds 1 to the digit value. If any flats or slots are present, it adds 2 to the digit value. If any complex cavities are present, it adds 4 to the digit value. If any minor deformations are present, it adds 8 to the digit value. If the digit value is now larger than 9, the procedure returns 9. For example, the reference product has straight rectangular grooves, which are MICLASS slots. Thus, digit 4 equals 2.

Digit 18 describes the orientations of these machined secondary elements. The procedure, shown in Fig. 7, compares the feature's main axis with the axes of the global coordinate system by computing the corresponding inner products. The orientation of transition features (blends) depends upon the blend type and the normal directions of the faces that are being blended. Corner blends are skewed to more than one plane. An edge blend is skewed to one plane if the normal directions of the faces of an edge blend are perpendicular to the faces of the product envelope. Otherwise, it is skewed to more than one plane. The value of digit 18 starts at 0. If none of the machined secondary elements exists, the procedure returns a digit value of 0. If any of the features are perpendicular to the *XY* plane, the procedure adds 1 to the digit value. If any of the features are perpendicular to the *XZ* or *YZ* planes, it adds 2 to the digit value. If any of the features are skewed to just one plane, it adds 4 to the digit value. If any of the features are skewed to more than one plane, it adds 8 to the digit value. If the digit value is now larger than 9, the procedure returns 9. For example, the reference product's straight rectangular grooves are perpendicular to the sides (the *XZ* and *YZ* planes). Thus digit 18 equals 2.

5.1.3. *Critical manufacturability attributes*

To derive the additional OOGT feature attributes including feature volumes, tool accessibility flags, minimum section thicknesses, undercuts, and maximum section ratios, we use a solid model representation of the product design. To this end, our approach involves translating the STEP-based product model to a solid model in the ACIS geometric modeling kernel (Spatial Technology, 1993). The STEP-to-ACIS translation (Ramachandran, 1995) involves a systematic mapping between the entities of the STEP model to ACIS classes. The ACIS kernel is employed to perform the geometric reasoning that is necessary to derive these OOGT attributes. Typical solid operations in the corresponding ACIS-based geometric reasoning procedures include union, intersection, faceting, three-dimensional projection, ray tracing, and distance and volume calculations.

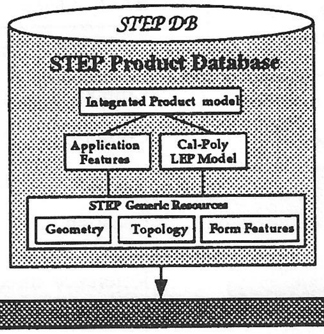
For example, Fig. 8 shows the procedure that detects undercuts in a product design. The procedure first uses the ACIS faceting function to facet the solid model of the design. Subsequently, it projects each facet in opposite candidate undercut directions (as shown in Fig. 9), examines whether both the resultant solids intersect with the product, and if so, marks the feature corresponding to the facet with an undercut flag. This procedure's computational complexity is proportional to the number of facets that the design's faceted representation has. In the reference product, each of the holes causes undercuts with respect to both the *X* and *Y* directions, and each rectangular groove forms an undercut either with respect to the *X* direction or with respect to the *Y* direction. Similar procedures generate other OOGT attributes from the solid model of the product design [refer to Candadai (1995) for details].

5.2. *Electrical OOGT information processing*

Generating the electrical portion of the OOGT information requires the electrical representation of the product design. Furthermore, the feature-based representation of the model is employed in many indirect mapping procedures. Two typical examples of electrical OOGT generation procedures are discussed below. See Candadai (1995) for detailed descriptions of all procedures.

5.2.1. *Components and hardware*

As discussed in Section 4, the electrical portion of the OOGT model captures detailed information about the components including their functions, locations, orientations, mounting methods, and placement tolerances. As shown in Table 4, the attributes that describe an OOGT component are a subset of the STEP attributes. Thus the OOGT generating procedure directly maps the component information from the electrical representation of the STEP-based product model onto the corresponding OOGT component objects in a manner identical to the mapping procedures for manufacturing features (described in Section 5.1). Digits 4–5 of the electrical GT code describe the methods employed to mount the components on the product substrate. As shown in Table 4, this information is contained explicitly in the description of the component in the STEP-based product model. The corresponding procedure queries the electrical representation of the product for components, and computes the digit values depending on the combination of methods employed for the mounting of each component. The value starts at 00. If any components have a standard surface mount, the value is increased by 1. If any components have a non-standard surface mount, the value is increased by 2. If any components have a standard through-hole mount, the value is increased by 4. If any components have a non-standard through-hole mount, the value is increased by 8.



1. Query STEP DB to retrieve the ***Feature-Based Representation*** $\mathcal{FBR}$ of product $\mathcal{P}$ from the ***Integrated Product Model.*** From $\mathcal{FBR}$ retrieve the list of ***Application Features*** $\mathcal{F} = \{f_1, f_2, \ldots, f_m\}$ of $\mathcal{P}$.
2. Initialize ***Mechanical GT Digit_18***, $mgt\_18 := 0$. If $\mathcal{F} = \emptyset$, return.
3. Query $\mathcal{F}$ to retrieve the following:
    - 3.1. List of ***Holes*** $\mathcal{H} = \{h_1, h_2, \ldots, h_k\}$ the local $\mathcal{Z}$ axis of which is not perpendicular to the $\mathcal{XY}$ plane.
    - 3.2. List of ***Pockets*** $\mathcal{PK} = \{p_1, p_2, \ldots, p_r\}$.
    - 3.3. List of ***Rectangular*** and ***Vee Grooves*** $\mathcal{G} = \{g_1, g_2, \ldots, g_s\}$.
    - 3.4. List of ***Corner Flat Chamfers*** $\mathcal{CC} = \{c_1, c_2, \ldots, c_u\}$.
    - 3.5. List of ***Edge Flat Chamfers*** $\mathcal{EC} = \{e_1, e_2, \ldots, e_v\}$ the local $\mathcal{Z}$ axis of which is parallel either to the $\mathcal{XZ}$ or $\mathcal{YZ}$ planes.
    - 3.6. Evaluate the cardinalities of these lists: k, r, s, u, v.
4. If $(k + r + s + u + v) = 0$, return.
5. Define $\mathcal{F}sme := \mathcal{H} \cup \mathcal{PK} \cup \mathcal{G} \cup \mathcal{CC} \cup \mathcal{EC}$.

6 a. If features $\in \mathcal{F}sme$ are skewed* to more than one plane, $mgt\_18 \leftarrow mgt\_18 + 8$.
6 b. If all the features $\in \mathcal{F}sme$ are skewed* to just one plane, $mgt\_18 \leftarrow mgt\_18 + 4$.
6 c. If any feature $\in \mathcal{F}sme$ is perpendicular to $\mathcal{XZ}$ or $\mathcal{YZ}$ plane, $mgt\_18 \leftarrow mgt\_18 + 2$.
6 d. If any feature $\in \mathcal{F}sme$ is perpendicular to $\mathcal{XY}$ plane, $mgt\_18 \leftarrow mgt\_18 + 1$.

7. If $mgt\_18 > 9$, return 9; Otherwise return mgt_18.

* A feature is considered "*skewed*" if it is not "perpendicular" to any of $\mathcal{XY}$, $\mathcal{YZ}$ or $\mathcal{ZX}$ planes. *Skewness* of a feature is determined by considering the absolute values of the inner products between the local Z axis of the feature and the directions of the global axes. The smallest inner product value determines the plane to which the feature is *skewed*.

Fig. 7. Example of mechanical GT code digit evaluation: digit 18.

```
Procedure Detect_Undercuts

Input  : Body B representing the solid model of part P.
Output : Undercut directions for every feature belonging to P.

Create a faceted representation F of body B.
For every candidate undercut direction (v, v'), do the following:
    For every facet f belonging to F, do the following:
        (i) Extrude f along v upto infinity. Call the extruded solid E.
        (ii) Extrude f along v' upto infinity. Call the extruded solid E'.
        (iii) If both E and E' intersect with B, then f forms an
              undercut with respect to (v, v'). Add (v, v') to the
              list of undercut directions for the feature that
              creates f.
End Procedure
```

Fig. 8. Procedure for detecting undercuts in a product.

Table 4. Attributes of the STEP and OOGT component entities

STEP attributes	*OOGT attributes*
Description (name)	
Component type	Component type
Component function	
Component leads	
Location	Location
Axis	Axis
Reference direction	
Placement tolerance	Placement tolerance
Lead pitch	Lead pitch
Component height	
Component width	
Component length	
Mounting method	Mounting method

For example, consider a product that has three components, one with a standard surface mount, one with a standard through-hole mount, and one with a non-standard surface mount. The STEP-based product model has three component entities, and each describes the mounting method (as shown in Table 4). The procedure that calculates digits 4–5 examines these entities, notes the types of mounting methods used, and calculates the value of 07 ($0 + 1 + 2 + 4 = 7$). The procedure for digit 13 compares the orientation of the axis of each component with the global coordinate system by computing the corresponding inner products between the two axes. The digit value is determined from the combination of the component orientations.

The electrical portion of the OOGT model also contains information about the various types of non-soldered and soldered hardware used for assembling the product. Again, the related procedure queries the electrical representation in the STEP product model and directly instantiates the OOGT hardware objects. The procedure simultaneously calculates the values of digits 8–9 after determining the combination of different types of non-soldered hardware employed. Similarly, for soldered hardware, the procedure for digits 10–11

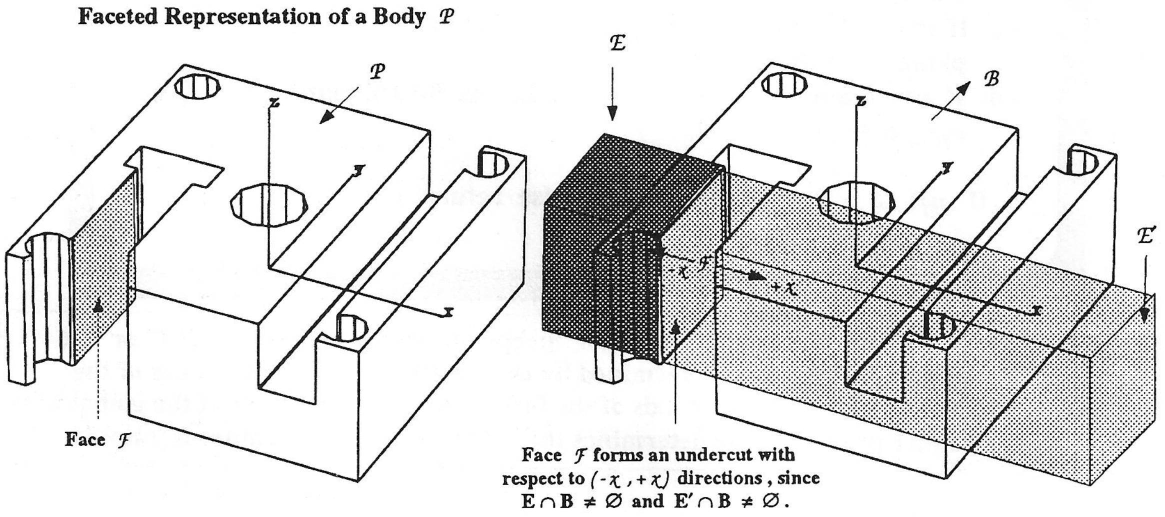


Fig. 9. Schematic representation of undercut detection logic.

calculates the digit values after determining the combination of different types of such hardware employed in the assembly. The value of digit 12 is determined by evaluating the cardinality of the set of components and hardware attachments of the product.

5.2.2. *Critical artwork circuitry information*

Recall that the OOGT model also includes critical information about the artwork, such as the absolute values of the minimum line width and minimum line spacing. The latter is the minimum spacing between two traces of the artwork, or between a trace and an edge of the top face of the substrate. Digit 21 of the electrical GT code indicates whether the values of these critical attributes lie below a predefined threshold. The minimum distance between two traces is the minimum distance between any two edges belonging to these traces. The necessary topological information includes the paths and faces forming the artwork circuit, and is obtained from the product shape model. The basic steps of the procedure that computes the minimum distance between two coplanar edges are provided in Fig. 10. The computational complexity of the procedure for digit 21 is proportional to $m^2 n^2$, where m is the total number of paths and n is the sum total of all the edges belonging to these paths.

6. Application: automated design retrieval

The OOGT model was developed to support several distributed manufacturing applications, including automated design retrieval, design critiquing, and process planning. In this section we present the model's applicability to effective design retrieval.

We have developed an OOGT-based automated procedure that retrieves, from the databases of potential manufacturing partners, products that are similar to the reference design. This procedure involves searching for similar products and sorting the products retrieved. The search exploits the concise description of the GT codes in order to identify approximately similar products quickly, and the sorting procedure uses the more detailed OOGT information to compute a more accurate similarity measure and to sort the similar products. This section outlines the approach, which is described fully by Iyer and Nagi (1994, 1995).

6.1. *GT-based search for similar products*

The search procedure retrieves products that are approximately similar to a reference product. Before describing the search, let us consider the similarity measurement approach.

To quantify attribute similarity, each digit of the mechanical and electrical GT codes was analyzed to define the similarity of each pair of values for that digit. Given a pair of values for a certain digit, a *similarity index value* (SIV) between 0 and 1 is defined; 0 represents no similarity and 1 represents identical attributes. For *binary-valued attributes*, the SIV between any pair is either 0 (if the values are the same) or 1 (if the values are different). For each of the remaining *continuous-valued attributes*, Iyer and Nagi (1994, 1995) have developed a specific mapping function that calculates, for any pair of digit values, an SIV that can take any value in the closed interval [0, 1].

Before beginning the search, the designer must generate the OOGT information for the reference design using the method of Section 5. The designer then specifies certain attributes of the product that define the search and the required level of similarity for each attribute. These selected attributes correspond to specific digits in the GT coding scheme; a product is similar to the reference design if it matches or exceeds the similarity level for every user-selected attribute (specified digit).

The specification of the search attributes and similarity thresholds requires *no detailed knowledge of the GT coding scheme*. Given the automatically derived GT code of the reference design and the desired similarity threshold values, the search procedure defines, for each specified digit, a range of acceptable values. Note that for each digit a high threshold value may confine the acceptable range of the single GT value corresponding to the reference design. On the other hand, a low threshold may correspond to a broader acceptable range for the corresponding GT digit.

The search procedure scans product databases and compares the values of the specified digits in the existing GT codes with the acceptable ranges that correspond to the similarity thresholds. If all specified digits of an existing GT code fall into these ranges the procedure retrieves the corresponding product design.

6.2. *OOGT-based sorting of similar products*

The search procedure retrieves a set of similar products but does not identify the products that are most similar to the reference design. In addition, because it uses the imprecise GT codes, the search calculates the approximate similarity between the reference and the retrieved products. The sorting procedure calculates a more accurate similarity measure and ranks the similar products accordingly.

To begin the sort, the designer selects product attributes from the set of mechanical and electrical product attributes (shown in Table 1). The sorting procedure will combine the similarity values for the user-selected product attributes to calculate an overall product similarity measure. Although the possible set of

```
Procedure Minimum_Distance_2_Coplanar_Edges

    Input : Edge E1, Edge E2 where E1 and E2 are coplanar.
    Output : Minimum distance between the two edges Dmin

    Let the end points of E1 be P11 ( x11, y11 ) and P12 ( x12, y12 ).
    Let the end points of E2 be P21 ( x21, y21 ) and P22 ( x22, y22 ).
    Let the equation of the line on which edge E1 lies be $L1 \equiv a1x + b1y + c1 = 0$.
    Let the equation of the line on which edge E2 lies be $L2 \equiv a2x + b2y + c2 = 0$.

    Define a function F( Pij, Lk, Cij ) such that given Pij and Lk, it provides Cij ,
    the point representing the foot of the perpendicular dropped from Pij onto
    Lk ( i = 1, 2 ; j = 1, 2 ; k = 1, 2 ).
    Do the following:

        1. Compute the distance D1 between P11 and P21.
        2. Compute the distance D2 between P11 and P22.
        3. Compute the distance D3 between P12 and P21.
        4. Compute the distance D4 between P12 and P22.
        5. Call F( P11, L2, C11 ). If C11 lies within* the edge with vertices P21 and
           P22 compute the distance D5 between P11 and C11. Otherwise $D5 = \infty$.
        6. Call F( P12, L2, C12 ). If C12 lies within* the edge with vertices P21 and
           P22 compute the distance D6 between P12 and C12. Otherwise $D6 = \infty$.
        7. Call F( P21, L1, C21 ). If C21 lies within* the edge with vertices P11 and
           P12 compute the distance D7 between P21 and C21. Otherwise $D7 = \infty$.
        8. Call F( P22, L1, C21 ). If C22 lies within* the edge with vertices P11 and
           P12 compute the distance D8 between P22 and C22. Otherwise $D8 = \infty$.

        Dmin = Minimum of ( D1, D2, D3, D4, D5, D6, D7, D8 ).

        Return Dmin.

End Procedure
```

* A point C lies "*within*" the edge with vertices R and S if the distance between R and S is equal to the sum of the distances between C and R, and between C and S.

Fig. 10. Computing the minimum distance between two edges.

attributes is the same as that used in the search procedure, the attribute similarity measures depend upon the more detailed OOGT information. (If the OOGT information is not available, the designer can choose a 'quick' sort. In this case the sorting procedure can calculate approximate attribute similarity measures from the corresponding GT digit values, as described above.)

For each product attribute, Iyer and Nagi (1995) have defined a procedure that maps the relevant critical design information about the two products being compared to a value between 0 and 1. (Again, 0 represents no similarity, and 1 represents identical values.) Because they use the detailed information in the OOGT information model, these procedures calculate more accurate attribute similarity measures.

To combine the individual attribute similarity measures to the overall similarity measure, the sorting procedure uses the analytic hierarchy process to derive weights from subjective information about the relative importance of product attributes. This procedure is described in detail by Iyer and Nagi (1995). Surveys were distributed to experts familiar with the design and manufacturing considerations of flat mechanical parts and MWMs. These experts compared the 13 mechanical attributes and the 13 electrical attributes shown in Table 1. For each pair of mechanical attributes and each pair of electrical attributes, these experts provided a measure of the relative importance of the two attributes to manufacturing similarity. From the set of judgments about the user-specified attributes, the analytic hierarchy process (Saaty,

1980) yields weights that measure each selected attribute's relative importance to overall product similarity.

The global similarity measure (GSM) between two products is the weighted sum of the attribute similarities. The sorting procedure calculates the GSM between the reference product and each retrieved product and ranks the retrieved products by the GSM. A more similar product has a higher GSM.

6.3. *Results and examples*

The search and sort methodology was tested by conducting trial runs on both randomly generated databases of products and industrial products. The robustness and efficiency of the system was tested by subjecting it to different search and sort specifications. Presented below is the result of an illustrative search and sort.

6.3.1. *Search example*

Consider the reference product shown in Fig. 5. We chose the following search characteristics: material (a binary feature), length (a continuous feature, threshold = 1.0), and width (a continuous feature, threshold = 0.8). Table 5 shows the set of reference product's GT code values and the acceptable target values corresponding to the search characteristics and the desired level of similarity. After examining the GT codes in the product database, the search procedure found the three products shown in Fig. 11. Table 6 displays some information about the similar products. Note that the similar products have the target values (given in Table 5) for the selected attributes (marked with an asterisk).

6.3.2. *Sort example*

We then sorted the similar products with respect to their similarity to the reference product. For this example, we combined the similarity measures for holes perpendicular to the surface, production quantity, and thickness. To compare the similarity values calculated, we conducted both a quick sort and a detailed sort. For each similar product, the sorting procedure calculated the similarity measures for the three selected attributes and combined them using the combination weights (derived from the AHP procedure) to yield a global similarity measure (GSM). Tables 7 and 8 show the two lists of sorted products. Note that the order of similarity did not change, but the GSM values did.

6.3.3. *Discussion of results*

The global similarity measures for the similar products in the two sorts differ, owing to the different attribute similarity values (as shown in Tables 7 and 8). The quick sort uses the GT codes to compute these values, and the detailed sort uses the OOGT information. The additional detail in the OOGT information model allows the detailed sort to calculate more accurate similarity measures. In

Table 5. Search characteristics

Characteristic	*Candidate part code value*	*Similarity level*	*Code values*
Dimension length	79	1.0	79
Dimension width	51	0.8	41–61
Material	60	(binary)	60

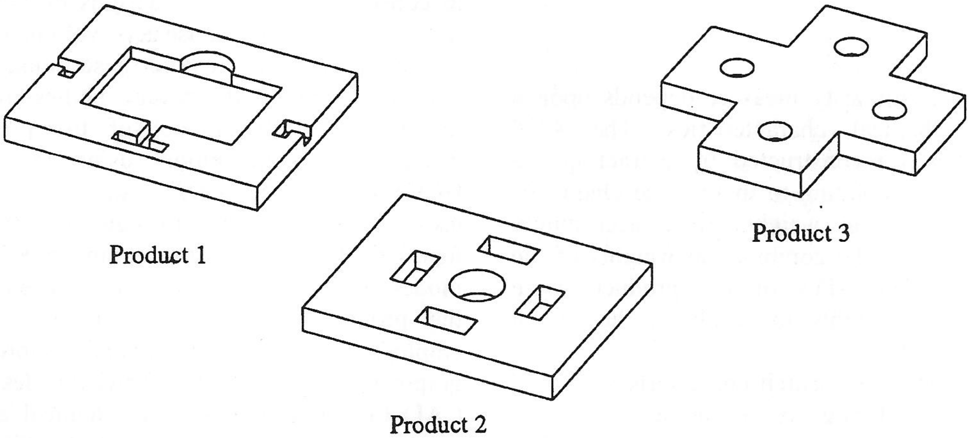

Product 1
Product 2
Product 3

Fig. 11. Similar products.

Table 6. List of similar products

Reference product	*Thickness*	*Quantity*
Mechanical Code 5 0 5 2 79* 51* 47 09 9 60* 0 7 2	0.2 in	10 000
Similar products	*Thickness*	*Quantity*
Product 1		
Mechanical code 5 0 6 4 79* 51* 47 09 9 60* 0 6 1	0.2 in	3000
Product 2		
Mechanical code 5 0 6 4 79* 51* 47 09 9 60* 0 4 1	0.2 in	500
Product 3		
Mechanical code 5 1 5 4 79* 51* 51 09 9 60* 0 7 1	0.2 in	10 000

Table 7. List of similar products: quick sort

Similar product	*Hole SIV*	*Thickness SIV*	*Quantity SIV*	*GSM*
Product 3	1.000	1.000	1.000	1.000
Product 1	0.200	1.000	0.889	0.827
Product 2	0.200	1.000	0.667	0.801

Table 8. List of similar products: detailed sort

Similar product	*Hole SIV*	*Thickness SIV*	*Quantity SIV*	*GSM*
Product 3	0.500	1.000	1.000	0.900
Product 1	0.100	1.000	0.787	0.795
Product 2	0.100	1.000	0.476	0.759

Table 9. Mechanical combination weights

Characteristic	*Combination weight*
Holes	0.199 81
Thickness	0.683 34
Quantity	0.116 85

both sorts, the global similarity measure depends upon a subset of the mechanical characteristics. The AHP comparison matrix was reconstructed by extracting the rows and columns corresponding to these three characteristics, and the combination weights were accordingly calculated. Table 9 shows the combination weights of the three characteristics. The SIVs of the products were combined using these weights to result in the global similarity measure (GSM).

Choosing a different set of search characteristics would result in a different ordering. If no single product is similar to the reference product on all important characteristics, the designer can iteratively exploit the sort flexibility to find similar products that give insight into different aspects of the new design.

7. Implementation

A distributed manufacturing network consists of manufacturing firms, each of which is capable of designing or producing a portion of the candidate product. The companies of this network share and freely exchange product-, process-, and business-related information, all of which are represented in a standard format.

The OOGT approach described in this paper is part of a decision support toolset being developed for this environment. Using the variant portion of this toolset (see Fig. 12), a designer can create a product design through a CAD tool, store the design in the STEP-based product model, automatically generate the OOGT information of the product, and retrieve similar product designs and associated feedback information on process plans, production cost, quality, and cycle time.

Using ACIS, a geometric modeler with an open architecture (Spatial Technology, 1993), we have developed a feature-based CAD tool that allows the designer to construct new product designs by defining the product features. This tool constructs volumetric features based on the parametric feature descriptions entered by the designer, subtracts the feature bodies from the part stock to obtain a solid model of the product shape, and displays the solid model using the graphical system HOOPS (HOOPS, 1992). An ACIS-to-STEP translator uses the solid model to construct the geometric and topological entities in the complete STEP-based product model. The designer also enters the electrical data about the product using a menu-driven user interface that employs SUIT, an open domain subroutine library for graphics (Conway, 1992). Thus the designer can use the CAD tool to design both mechanical and electromechanical products. The entities of the STEP-based product model have been defined as C++ classes and implemen-

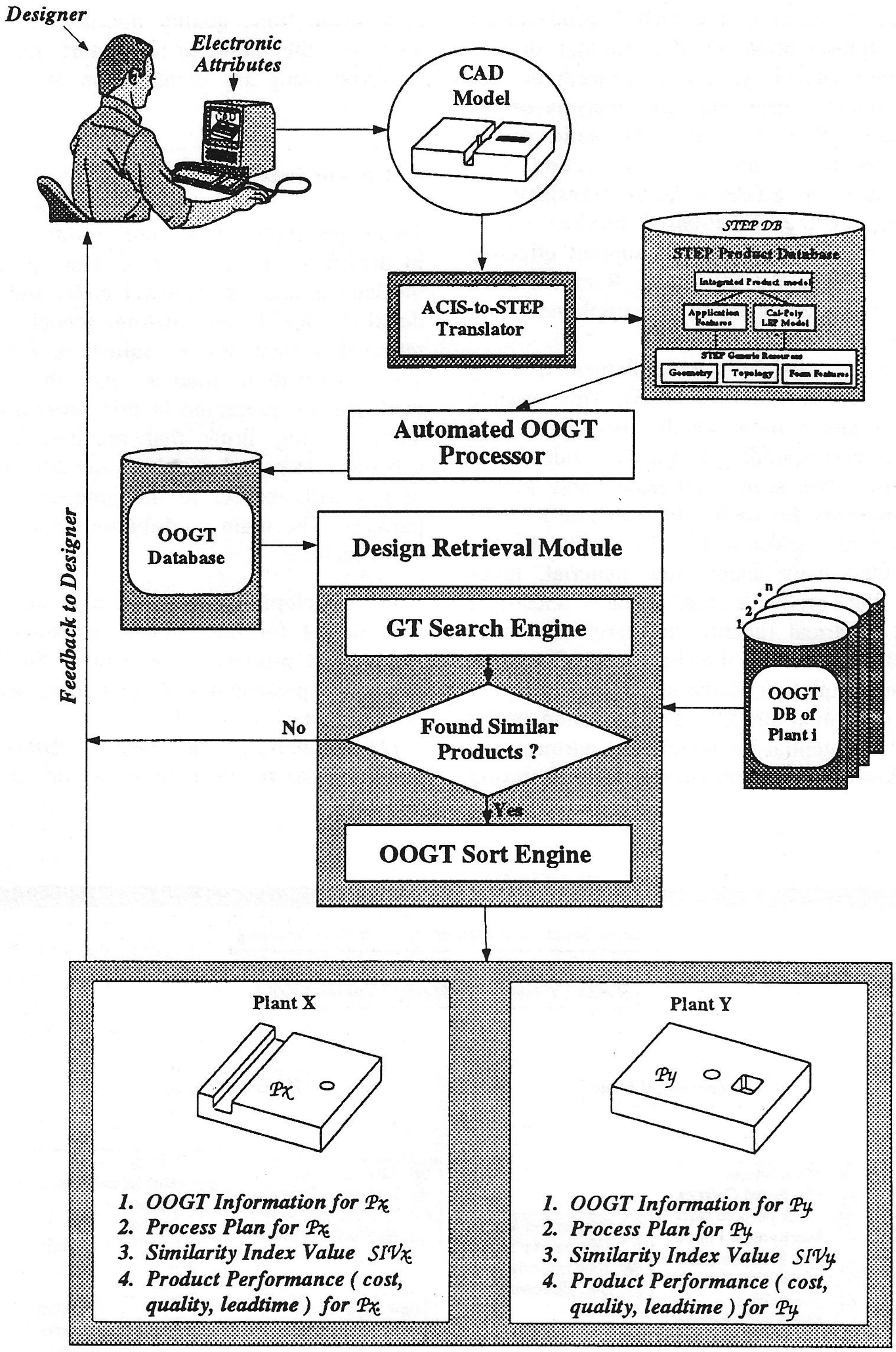


Fig. 12. Design retrieval system to support effective distributed manufacturing.

ted in the ObjectStore object-oriented database management system (ObjectStore, 1993).

The OOGT model defined in EXPRESS was also implemented in an object-oriented database. We have developed the automated OOGT processor using C++ and the ObjectStore data manipulation language (DML). This processor rapidly generates the OOGT information of the candidate design and stores these data in the OOGT database. The primary input to the OOGT processor is the STEP-based representation of the product design. However, for certain OOGT generation procedures that involve intense geometric reasoning and analysis of the product, it is more efficient to use the solid model representing the design (as discussed in Section 5.1). Hence we developed a STEP-to-ACIS translator to convert the entities of the STEP-based product model to a solid model representation that can support effective geometric reasoning. Minis (1995) and Ramachandran (1995) give additional details about the implementation and the translators.

The design retrieval module was implemented using C++ and ObjectStore (ObjectStore, 1993). This module presents to the designer a menu of the mechanical and electronic attributes corresponding to the GT code digits. The designer selects the search attributes and sets a desired level of similarity for each. The user interface for the selection procedure is given in Fig. 13. In Fig. 13, the designer has selected main shape, raw material, holes perpendicular to the product's top surface, electrical classification, and electrical function as search attributes. For the holes, a 0.50 similarity threshold value has been selected. Upon the completion of the search, the designer can view the list of similar product designs found in the product databases of potential manufacturing partners and view critical feedback information such as manufacturing cost, cycle time, quality metrics, and process plans. In addition, the designer can sort the similar products retrieved using any combination of the search attributes.

8. Conclusions

This paper explored the applicability of Group Technology in distributed manufacturing. Our approach uses concise mechanical and electrical GT codes and an extended, more detailed OOGT information model to support design retrieval, variant design evaluation, and process planning. The information models and the design processing methodology presented in this paper are targeted towards manufacturing firms that maintain a set of potential subcontractors and need to quickly assess a candidate design with respect to the process capabilities of these partners. The main contributions and conclusions of this work include:

(1) Developing a robust, integrated STEP-based product model for mechanical and some types of electromechanical products. This model facilitates neutral and efficient representation, interchange, and manipulation of product data;

(2) Developing the OOGT information model, a powerful design abstraction, to aid distributed manufac-

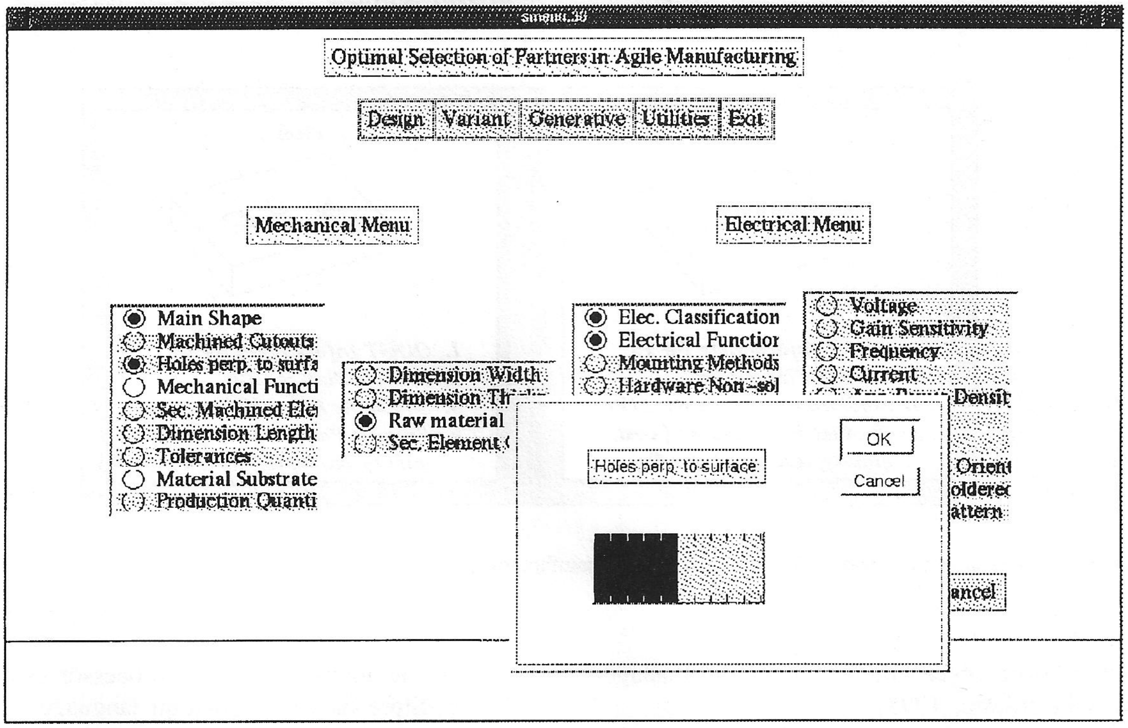


Fig. 13. User interface for specifying desired level of product similarity.

turing applications including automated design retrieval, design critiquing and process planning;

(3) Developing an automated design processor for quick and efficient generation of the OOGT information from the STEP-based product model. This overcomes the tediousness and inconsistencies of existing manual and semi-automated coding procedures;

(4) Using OOGT for automated design retrieval in distributed manufacturing. The retrieved designs may be used for product redesign, or the related information may be used for applications including design critiquing and manufacturing partner selection.

Acknowledgements

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