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Automated Generation of Group Technology Codes from a PDES Product Information Model

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ABSTRACT

Title of Thesis: AUTOMATED GENERATION OF GROUP TECHNOLOGY CODES FROM A PDES PRODUCT INFORMATION MODEL

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The design and implementation of an automated system that generates group technology (GT) codes for microwave modules (MWM) is presented. An established GT coding scheme (MICLASS) was employed to capture the mechanical attributes of MWM's, while a novel coding scheme was developed to describe their electrical attributes. The input to the automated coding system is provided in the form of a PDES product information model which describes the geometry, topology, form features and electrical characteristics of MWM's. It also includes manufacturing related data for components, hardware, platings, and passages. This information is processed by the rule-base of the coding system to yield, with minimal user input, the product GT code. Major contributions of this research include: i) the application of GT to electrical

parts, and ii) the automation of the coding process using a standard part representation. Both these issues have been limiting factors in the widespread use of GT, for reduced efforts in product and process design and for efficient manufacturability assessments of new product designs

AUTOMATED GENERATION OF GROUP TECHNOLOGY CODES FROM A PDES PRODUCT INFORMATION MODEL

by

Amy Jean Kinsey

Thesis submitted to the Faculty of the Graduate School
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DEDICATION

To Daddy

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1. INTRODUCTION

Group Technology (GT) is a methodology that takes advantage of part similarities with respect to both design and manufacturing attributes. Grouping parts that exhibit design and manufacturing similarities into families, and machines that process similar parts into cells, has favorable impact on current design and manufacturing practices, enhancing productivity, throughput, quality and overall profitability [Teicholz and Orr, 1987]. Design related applications of GT include design retrieval, part classification and design standardization. Manufacturing applications include standardization of process plans, variant process planning, plant layout and manufacturability evaluation.

The application of GT is based on part coding and classification. A GT code is a string of alphanumeric characters that represent critical design and manufacturing related attributes. Since its inception, GT has focused on mechanical parts. Hence, a large number of GT coding schemes have been developed for mechanical applications. At present, GT for electrical parts has been limited to the defense industry and, the existing GT schemes are customized and usually proprietary.

A major factor that has limited wide spread use of GT is the considerable effort required to derive the GT code for each part in a company's part base. To date, the coding process has been manual and, therefore, it is labor intensive, lengthy, allowing for inconsistencies and errors. Initial attempts to automate this process have resulted in interactive programs that require the user to answer a series of questions relating to the part's design and process plan. Although this interactive process may eliminate some of the errors and inconsistencies of manual coding, it does not offer considerable time savings.

The goal of this research is two-fold: i) to apply GT to electrical/mechanical parts, specifically microwave modules (MWM), and ii) to automate the GT code generation process using a standard part representation. Furthermore, since this system is part of a larger decision support framework focused on the life cycle engineering of MWM's, the system generates the necessary input data for the manufacturability evaluation of these parts. Considering the electrical/mechanical nature of MWM's, none of the existing GT coding schemes were found sufficient to capture all critical design and manufacturing attributes. Consequently, a novel GT scheme was proposed to capture the electrical attributes of an MWM, while the MICLASS GT coding scheme was used to describe its mechanical attributes.

The automated coding system uses a PDES (Product Data Exchange using STEP) based part information model, which captures the complete description of the product in a three level structure. A rule-based system translates the PDES feature information to the attributes captured by the GT scheme. The mechanical portion of the system is limited to classifying only flat parts, such as the substrate of an MWM. The electrical portion extracts most of the necessary data directly from the PDES database and uses various look-up tables to determine the electrical code.

This thesis is structured as follows: The remaining part of chapter 1 presents relevant research in the area of GT and GT code generation. Chapter 2 discusses the PDES model, its structure and database implementation. Chapter 3 presents the GT coding scheme that was developed especially for MWM's. Chapter 4 outlines the methodology of the automated coding system. Chapter 5 presents an application of the proposed system. The conclusions and recommendations for further work are given in chapter 6.

1.1 Background: Group Technology Coding Systems

Mechanical GT Coding Systems

Since its inception in the early forties, GT has focused on mechanical parts [Teicholz and Orr, 1987]. Several GT coding schemes have been developed for mechanical applications, including Opitz [Opitz, 1970], DCLASS [Allen, 1982], and MICLASS [OIR Multi M, 1986]. Although the actual format of each of these codes is different, they all capture six universal part attributes: i) Main shape, ii) Shape elements on the main shape, iii) Element position, iv) Dimensions, v) Tolerances and vi) Material.

The Opitz coding system was developed in West Germany for use in the traditional metalworking industry and is widely applied. The code describes both rotational and non-rotational discrete mechanical parts. It contains nine basic digits [Opitz, 1970]. The first five digits comprise the form code and capture the primary design information including main shape, rotational and plane machining, as well as holes, teeth, and forming elements. Digits six through nine comprise the supplementary code and contain manufacturing related information such as dimensions, material, raw material shape, and accuracy.

The DCLASS coding system was developed in 1979 at the Brigham Young University to facilitate various CAD/CAM applications

[Allen, 1982]. The system consists of five different classification and coding schemes including the part family code, engineering materials code, fabrication process code, fabrication tool code, and fabrication equipment code. These codes range in length from three to ten digits. For example, the part family code contains eight digits and captures information on basic shape, form features, size, precision, and material. Interactive coding software is available for this system.

The MICLASS coding system was developed by the Organization for Industrial Research (OIR) for the classification of discrete mechanical parts and basic assemblies [OIR Multi M, 1986]. It uses an 18 digit base code with additional 12 digits that can be customized by the user. The base code captures main shape, machined features, machined feature orientation, dimensions, tolerances, material, function, raw material shape, and production quantity. MICLASS also provides an interactive coding software module.

In addition to the commercially available coding schemes, many companies and universities have developed custom systems for specific applications. For example, a GT scheme for sheet metal parts was developed in Lockheed Aircraft to describe main shape contours, periphery cutouts, beads, flanges, and joggles [Bond and Jain, 1988]. Bhadra and Fishcer (1988) proposed a GT scheme for rotational symmetric parts and used it for automated GT code generation . Their code consists of eight digits and captures part aspect ratio, external shape, internal shape, circumferential holes, threads, and gears. Chen (1989) also developed a GT coding system for rotational parts and used it primarily for process planning and NC programming. The first six digits of his code capture material, tolerance, length, maximum and minimum diameters, and the total number of external form features on the part. The remaining digits of the code contain feature specific information. The code varies in length depending on the total number of features that are coded.

Electrical GT Coding Schemes

Although the benefits of GT have long been recognized in the manufacture of mechanical parts, the application of GT to electrical parts has been limited. Since design and manufacturing attributes that are relevant to electrical parts are fundamentally different from those of machined parts, the established coding schemes, such as MICLASS and OPITZ, are not applicable. The majority of GT related research for electrical parts has been conducted in the defense industry. Therefore the existing coding schemes are customized and proprietary.

One of the few systems available in the literature is the BMCode, developed by Bao and Reodecha (1986). The system caters for printed wiring boards (PWB) and was developed specifically to facilitate CAD/CAM applications in their design and manufacture. It follows the same principles and format of DCLASS, and consists of five individual coding schemes: (1) The part family code classifies all types of components assembled on the board. (2) The part assembly attribute code accounts for the specific mounting techniques for each component assembled on the board. (3) The PCB assembly layout code captures information about the board itself as well as the layout of components and hardware. (4) The process and equipment coding scheme includes information on the specific machines used in PWB assembly. (5) The supplier code contains information on particular suppliers.

The coding scheme developed by Ham, Marion, and Rubinovich (1986) in cooperation with the General Electric Co. encompasses forty different major product types, including printed wiring board assemblies, magnetic sub-assemblies, other electronic sub-assemblies, mechanical sub-assemblies, and traditional mechanical parts. Each product type uses similar manufacturing processes and corresponds to a distinct coding scheme. The attributes captured for electrical parts include board size, number of components, component mounting methods and specifications, circuitry types, testing requirements, and protective coatings. Although the methodology of the coding scheme is published, its details are proprietary.

The Organization for Industrial Research (1985) is currently developing a system to describe nine main electrical product types: discrete, integrated circuits, hybrid circuits and other components, as well as electronic components, cable, wired, electro-mechanical and other assemblies. Similar to the previously described system, each product type corresponds to a unique coding scheme. For example, the electronic circuit board scheme captures information related to the bare circuit board, the circuit type, and the assembly and testing of the circuit board. The bare circuit board portion, in turn, includes data on board type, material, shape, dimensions, maskings/coatings, and specifications. The circuit type portion describes function, input and output signals, overall specifications, and cost data. Finally, the assembly and testing portion describes component type and mounting specifications, number of components, soldering requirements, types of mechanical components (hardware), protective coatings, and testing specifications.

1.2 Background: The PDES Standard

An essential component of Computer Integrated Manufacturing (CIM) is the interchange of design data between Computer Aided Design (CAD) and other application systems. The International Graphics Exchange Specification (IGES) was the first effort to derive standard information models. It represented drawings and three dimensional wireframe product models [Yang, 1991]. In 1984, the IGES organization initiated the Product Data Exchange Specification (PDES) effort. PDES is intended to be a standard for complete product description that can be interpreted directly by computer application programs. The standard, when complete, will be able to model any product through its entire life cycle, starting from its initial design stages to full scale production and usage. In 1986, the International Organization for Standardization incorporated the PDES work in the Standard for the Exchange of Product Model Data (STEP). Currently PDES stands for Product Data Exchange using STEP [Yang, 1991].

The PDES standard is a collection of logically divided parts, each containing data on a product's physical structure and its application specific translation. Some of the individual modeling schemas include:

1. The Geometry and Topology model
2. The Form Features Information model (FFIM)
3. The Tolerance model
4. The Materials model
5. The Electrical Functional model (EFM)
6. The Layered Electrical Product model (LEP)
7. The Electrical Schematic model (ESM)

8. The Integrated Product Information Model

The geometry, topology and form features models are well established and have been implemented in this research [PDES 4.0]. The geometry and topology models are used jointly to give a physical boundary representation (BREP) of any product. The former describes the product in terms of basic geometrical entities, i.e., points, vectors, and surfaces. The latter uses those geometrical entities to develop a topological description of the product. The form features model describes individual features and their patterns parametrically, rather than geometrically, and may facilitate "design by features". Further information on all these models is given in chapter 2.

PDES currently provides three models for an electrical product. The Electrical Functional Model describes product functionality and comprises three parts: functional hierarchy, characteristics and behavior, and logical connectivity. The Electrical Schematic Model represents component parts and their electrical connections. This also includes parts with mechanical functions, e.g. heat sinks and connectors, as well as details of optical, magnetic or microwave energy transmission. The Layered Electrical Product model defines a framework for describing data about an "as-designed" electrical product, which can be topologically expressed in terms of layers. It captures the complete description of the product, starting with its geometrical and topological attributes, relating them to electrical entities and, finally, mapping them to manufacturing attributes in order to facilitate various manufacturing applications [Cal Poly, 1987, 1988]. A modified version of the latter has been employed in this work, and details are given in chapter 2 and in [Bahadur, et al., 1991].

1.3 Background: Automated GT Code Generation

A major factor that has limited wide spread use of GT is the considerable effort required in the coding of a company's part base. To date, the coding process in industry has been manual and, therefore, it is labor intensive, lengthy, and allows for inconsistencies and errors. The first attempt to make the coding process more efficient was the development of interactive computer programs. This method uses a simple decision tree corresponding to the GT coding scheme. The interactive program traverses the decision tree, prompting the user to answer a series of questions that relate to the part's design and process plan. Commercial GT systems that employ interactive software include DCLASS [Allen, 1982] and MICLASS [OIR Multi M, 1986]. Although this interactive process eliminates some of the errors and inconsistencies of manual coding, it is still subjective, requires an experienced engineer and it does not offer considerable time savings.

It has long been realized that wide spread use of GT hinges upon the efficiency and accuracy of the coding process. The need to streamline coding has prompted some researchers to develop fully automated GT coding systems that rely on part information models. To-date these systems consider mechanical parts only, and most rely on custom part models.

Recently, Shah and Bhatnagar (1989) developed an automated GT coding system based on the Opitz scheme for machined parts. The system consists of three modules: (i) a form feature modeler for design by features, (ii) a feature mapping shell, and (iii) a GT coding module. It is assumed that the part has been designed using their custom feature-based CAD system. Each feature in this system has a pre-assigned taxonomy code. The latter is a six character numeric code that classifies features in the same manner that GT codes classify parts. The mapping shell uses the generic information captured by the taxonomy code to analyze each feature, determine the relationship between the features and the entire part, and transform the part feature data into the necessary information required by the GT coding rules. The mapping shell provides generic feature information that can be used with a knowledge base of any GT coding scheme. The GT code generator compares the feature information processed by the mapping shell to the coding rules and derives the part code. To date, only the knowledge base for the Opitz coding scheme has been developed.

Henderson and Musti (1986) developed an automated coding system for rotational parts using DCLASS. This system contains a pre-processor, a feature recognizer, and a part coder. The pre-processor converts BREP solid modeling data into a customized neutral format to be used by the feature recognizer. The latter analyzes the resulting information and infers generic geometric features. Finally, the part coder consists of a feature interpreter and a code specific knowledge base. Output of the feature recognizer is processed by the coding rules embedded in the knowledge base to yield the appropriate part code. The system has been implemented using logic programming techniques and employs backward chaining to search for specific feature patterns based on a set of predefined features.

Bond and Jain (1988) developed a system to automatically generate a Lockheed sheet metal GT code from a 3-D CAD model. The part design is generated using the UCLA CADLOG Intelligent CAD system, which provides a layered set of geometric features and feature relationships in Prolog. The coding scheme rules were also implemented in Prolog.

BREP part data models were used by an expert system developed by the CAD Technology Division of the Sandia National Labs for automated part classification and coding [Ames, 1987]. The BREP models employed custom file formats based on the IGES Experimental Solids Proposal. The system targets general rotational, prismatic, and sheet metal parts. However, only the rotational portion has been fully developed. This system uses feature recognition to perform the part classification and considers overall part shape, depressions, edge modifiers (chamfers), part size, and part stock. Depressions include holes (round, profiled, blind and through), slots, grooves, and flats. The system also identifies intersecting features and patterns of features.

Automated GT code generation was also studied by Chen (1989). He used a custom part definition file which was generated from an IGES input file by a geometry recognition algorithm that accounts for fifteen types of shapes. Thus the GT code generating process comprises two steps: form feature recognition and code extraction. The first 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 feature data into information that can be processed by the GT coding rules. The second step applies the conventions of the GT coding scheme to the previously processed data. The system is limited to rotational parts only, and can not handle internal and facial form features.

1.4 Overview of the Research Approach

The objectives targeted by this research study are: i) to apply GT principles to electrical/mechanical parts, specifically microwave modules (MWM), and ii) to automate the GT code generation process using a standard part representation. The system developed is a fundamental building block of a GT-based life cycle engineering framework for microwave modules, the architecture of which is shown in Fig. 1. The entire framework is based on group technology principles, and is employed to provide feedback to the designer on the manufacturability of MWM's during the early design stages.

The automated coding system operates on a PDES-based part information model already developed in [Bahadur, 1992]. The Layered Electrical Product (LEP) model of PDES has been extended to cater for MWM's. A rule-based system translates the PDES product information to the attributes captured by the GT scheme. Considering the electro-mechanical nature of MWM's, none of the existing GT coding schemes were sufficient to capture all critical product attributes. Consequently, a novel scheme was developed in this study combining the MICLASS system, which captures the physical shape, machined features, and additional mechanical attributes of the MWM, with a new electrical code, which captures components, hardware, and other critical electrical information. The mechanical portion of the automated coding system is limited to classifying only flat parts, such as the substrate of an MWM. However, the proposed methodology is general and can be applied to the other eight part types included in MICLASS. The electrical portion of the system extracts most of the necessary data directly from the PDES

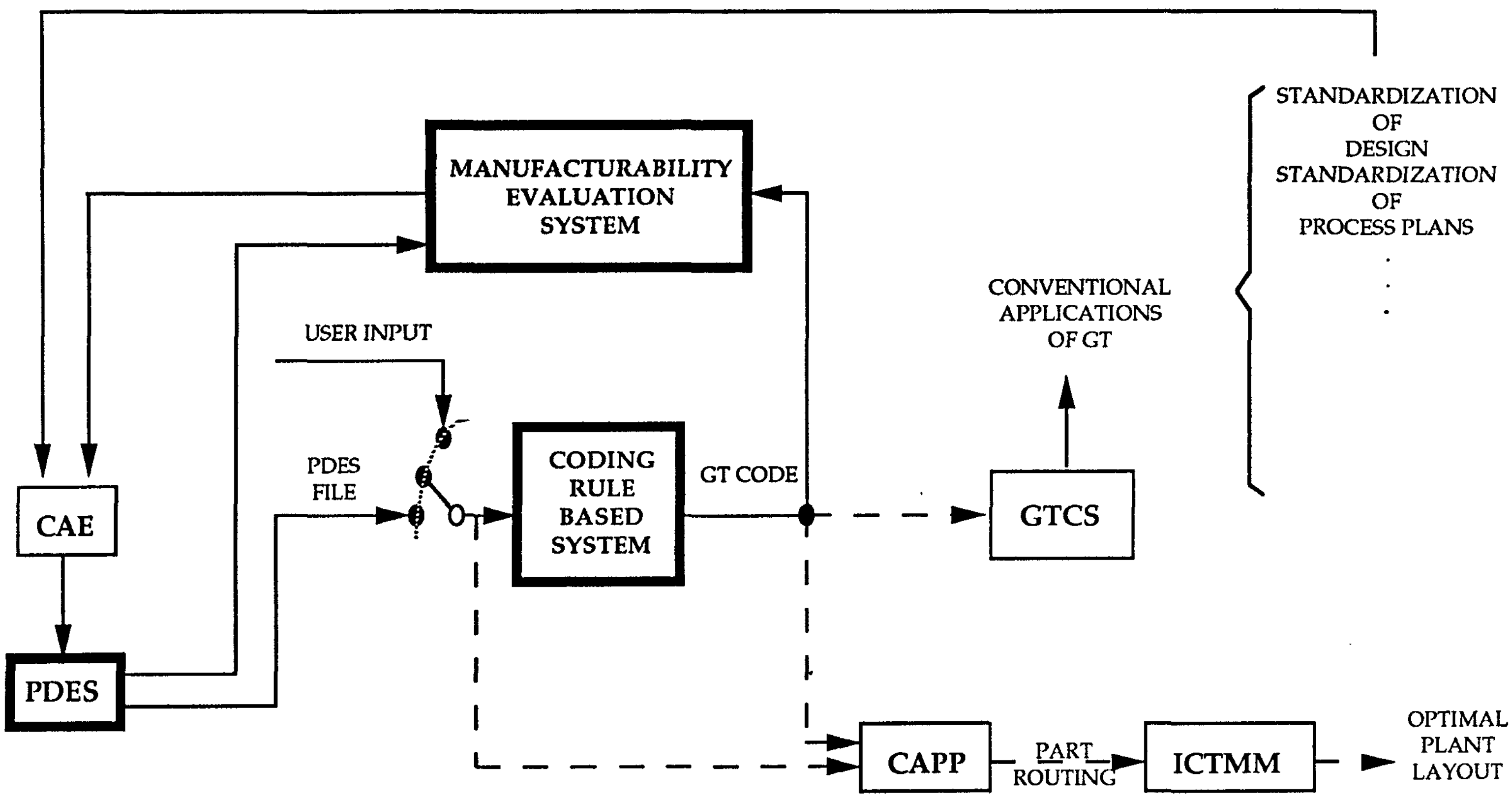


Fig. 1: Architecture of the GT-based life cycle engineering system

database and uses various look-up tables to determine the electrical code. The rule-based system provides two types of output: i) the mechanical and electrical GT codes and ii) mechanical and electrical feature files. The latter contain detailed feature information critical to the manufacture of MWM's. The GT codes and the feature files serve as the primary input to the manufacturability evaluation system [Rathbun, 1992] shown in Fig. 1. Furthermore, the GT codes can be used to drive conventional GT coding applications, computer aided process planning and optimal plant layout systems.

The significance of this work is that it addresses two critical areas of GT that have limited its use, namely:

1. A novel GT coding scheme has been developed to extend the application of GT to electrical/mechanical parts.
2. An automated GT code generation system has been developed to streamline the coding process. In contrast to similar studies, this system does not rely on custom input, but employs PDES standard part information models. It is anticipated that in the recent future commercial CAD systems will generate PDES standard outputs and, therefore, the proposed methodology may have significant impact on the integration of GT into the CIM framework.

2 PDES BASED MODEL FOR MICROWAVE MODULES

This chapter discusses the PDES information model for microwave modules that serves as the main source of product information for the GT coding system. This model has already been developed at the University of Maryland for the purposes of this research and is described in detail in [Bahadur, *et al.* 1991]. The basic characteristics of a microwave module are also overviewed.

2.1 Microwave Modules

A microwave module (MWM) is a multi-layered electrical product comprised of a layer of components, an artwork circuitry layer, an insulation layer, and a complex mechanical ground plane (see Fig. 2). MWM's carry both surface mounted and thru-hole components, which are mounted directly to the traces and pads of the artwork, a thin conductive metallic layer. An insulation layer is used to isolate the artwork layer from the ground plane. The latter is a complex mechanical part that includes features such as holes, slots, chamfers and cutouts (see Fig. 2). In addition to its electrical significance, the ground plane provides mechanical support and serves as a heat sink.

2.2 PDES-based Model for MWM's

The information model for MWM's was developed at the CIM laboratory of the University of Maryland for the purposes of this research

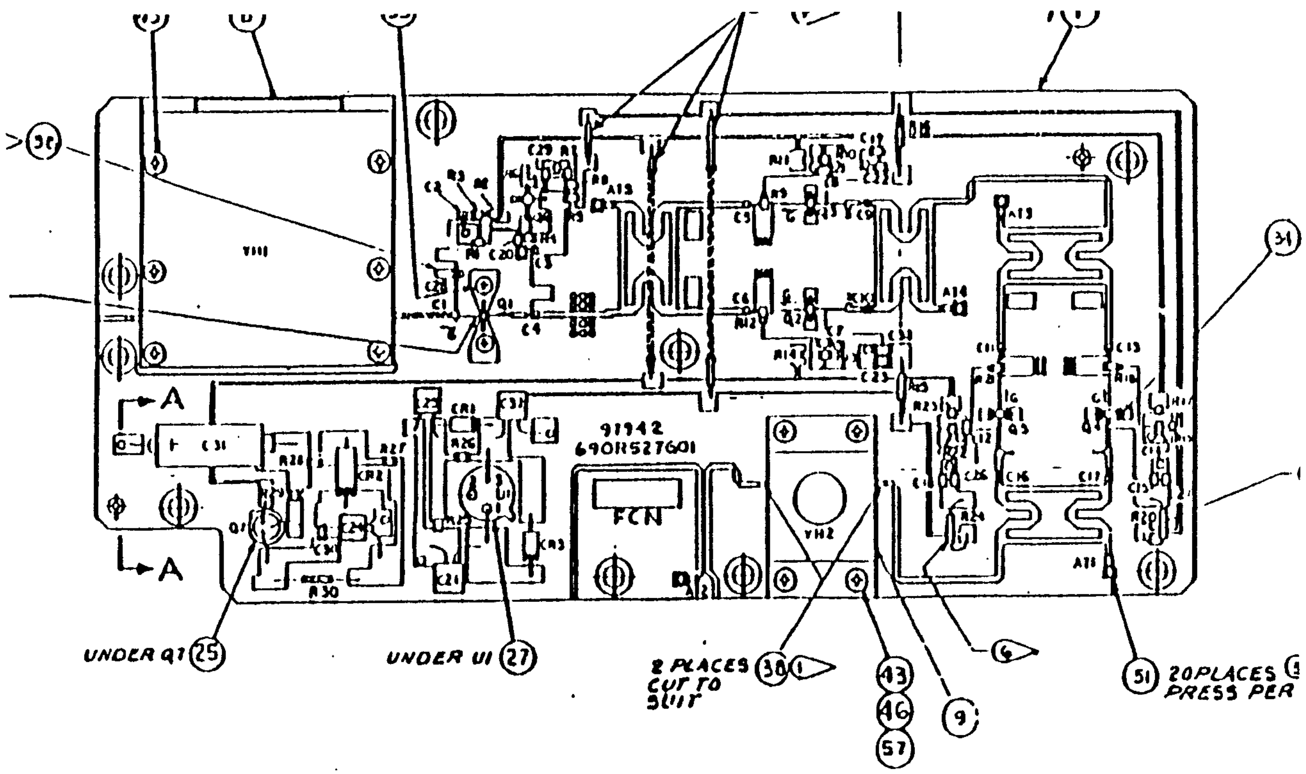


Fig. 2: Example of MWM

and is based on the PDES LEP model [Bahadur, 1991]. Figure 3 shows the structure of the model which includes three levels of abstraction. Level I describes the geometry and topology of the product envelope and its individual layers. The entities of Level I are translated into electrical entities that are represented in Level II. Level III includes design-for-manufacture information.

2.2.1 Level I of the MWM Model

This level is built using the PDES Geometry and Topology Information Model and includes fundamental geometrical entities such as *points*, *lines*, and *directions*, as well as topological entities such as *vertices*, *edges*, and *faces*. Only the boundary representation (B-REP) of the product is described, excluding all features, such as holes and chamfers, which are included in Level III. In particular, this level describes the part envelope (*shell*) and all of the entities that make up the *shell*, i.e. *faces*, *surfaces*, *points*, and *directions*.

PDES geometry and topology follows a hierarchical structure, with the three most basic entities being *points, directions*, and *coordinate systems*. All other entities are derived from these entities. For example, i) *points* and *directions* define *curves* (*lines, circles*, etc.) and *surfaces*, ii) *curves* translate into topological *edges*, iii) a collection of *edges* becomes a *loop* or *path*, iv) *loops* and *surfaces* define *faces*, and v) a collection of *faces* define a *shell*. *Shell* is the highest entity of level I.

The first level decomposes an MWM into *layers*, i.e. the artwork circuitry, the insulation layer, and the ground plane (see Fig. 4). It describes both the geometry and topology of each *layer*. Since the artwork and insulation layers may be represented in two-dimensions, an

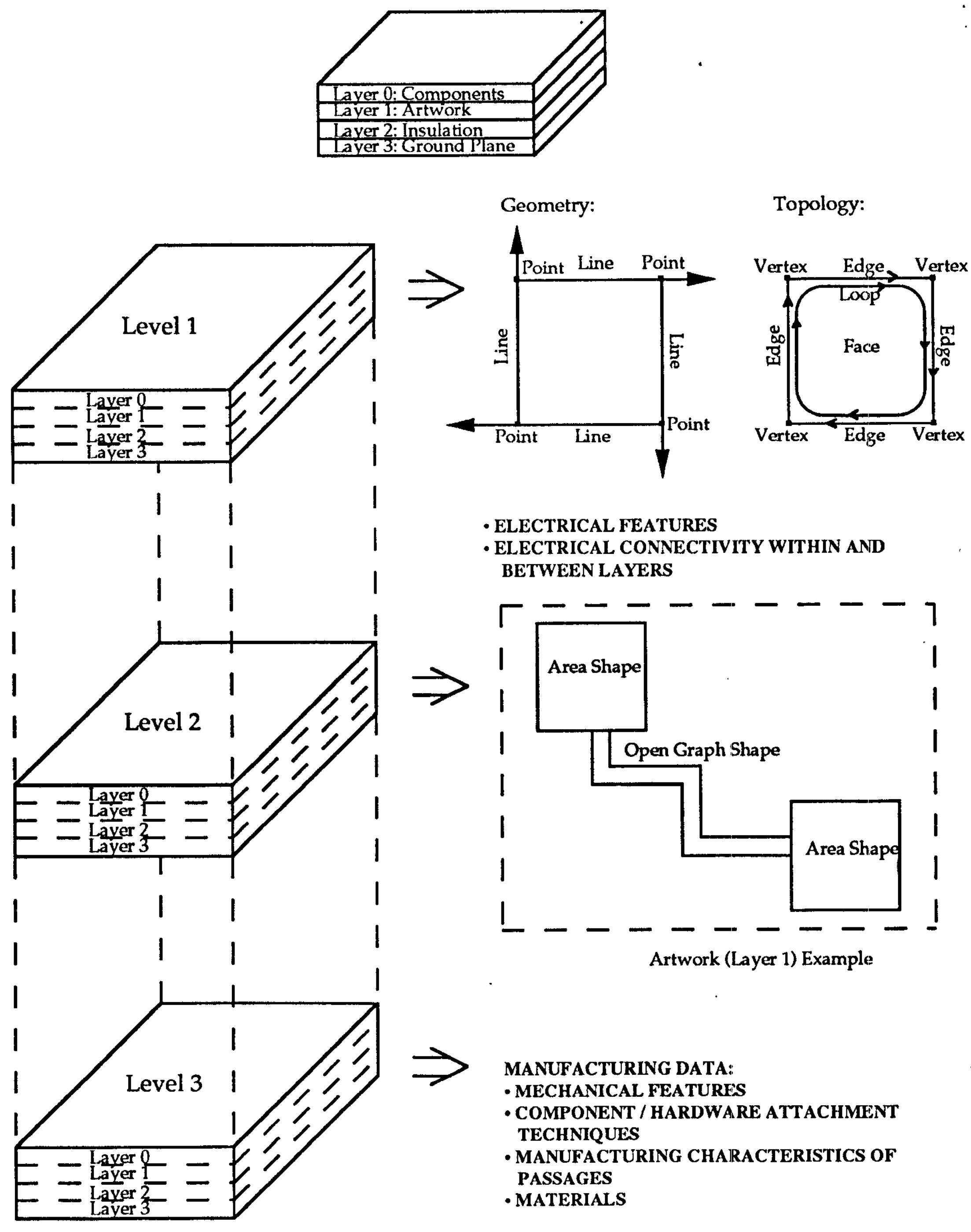


Fig. 3: PDES Microwave Module model

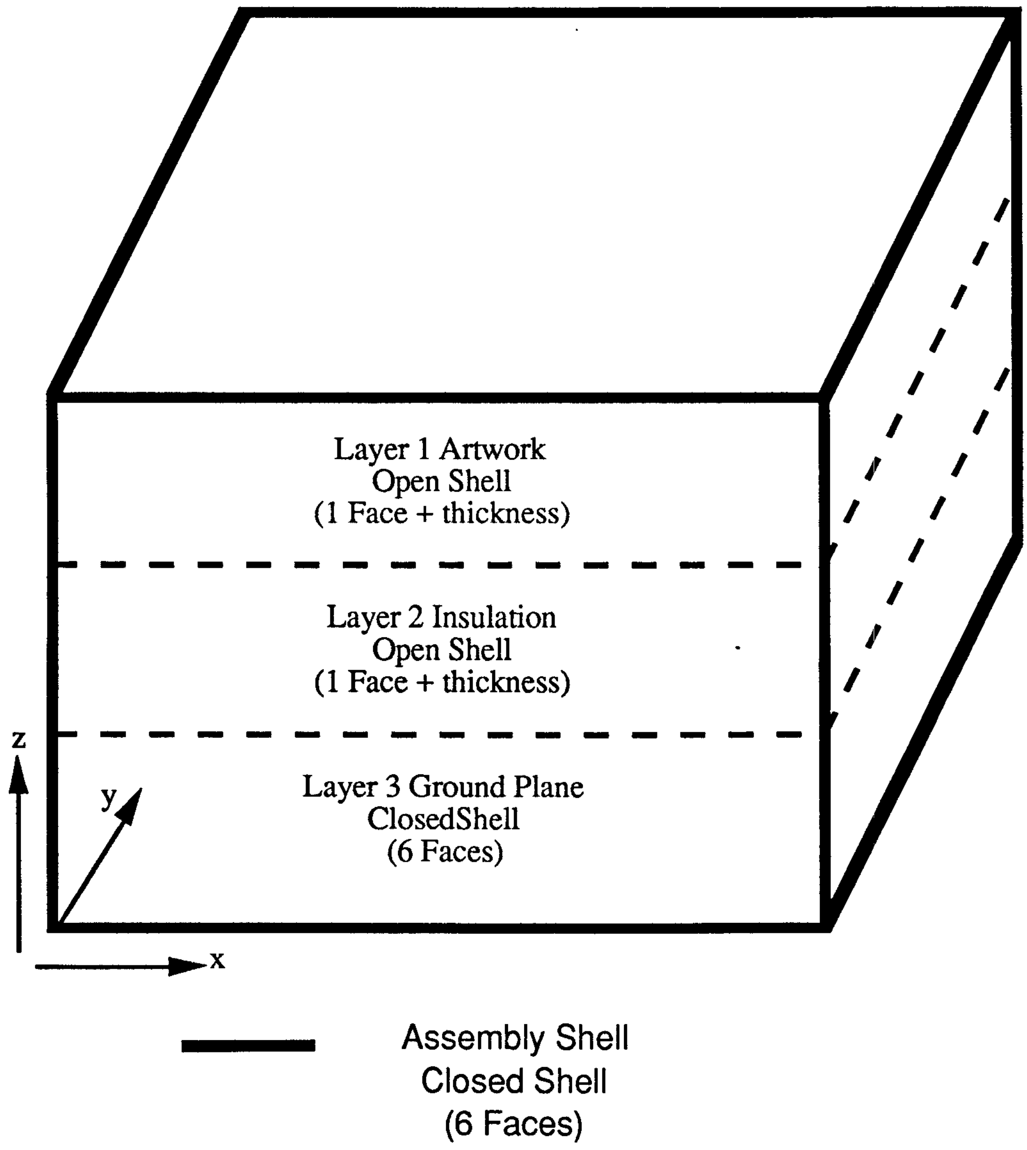


Fig. 4: Assembly shell structure

open shell is used to model them. The complex mechanical ground plane is fully three-dimensional, and therefore a *closed shell* is used to describe it. The *assembly shell*, which encapsulates the individual layers, is also modelled as a *closed shell*.

Finally, Level I describes *joins*, i.e. the physical connectivity between layer elements. The *joins* are abstracted as topological *edges* with *vertices* representing the process of joining.

2.2.2 Level II of the MWM Model

This level is the first application-specific translation of the physical description of the product. Its IDEF-1X representation is given in Fig. 5. The most basic entity of Level II is a *layer*. It is used to model the material layers that comprise the multi-layered product. Each *layer* of the MWM is represented by a topological *shell* of Level I. Geometrical and topological entities of Level I are translated into the basic elements of the artwork layer, e.g. *point shapes* (pads), *graph shapes* (traces), and *area shapes* (ground planes). *Graph shapes* are defined using the entities *path* and *loop* from Level I, while *point shapes* and *area shapes* are defined by the Level I entity *face*. Figure 6 illustrates the Level I and Level II representations of a basic artwork pattern. The highest entity of Level II is the *Layered Electrical Product* (LEP) which is an assembly of *Layers*. The coding system uses the information of Level II that is related to layer materials and electrical classification. Artwork geometry and topology is also used for determining critical artwork dimensions.

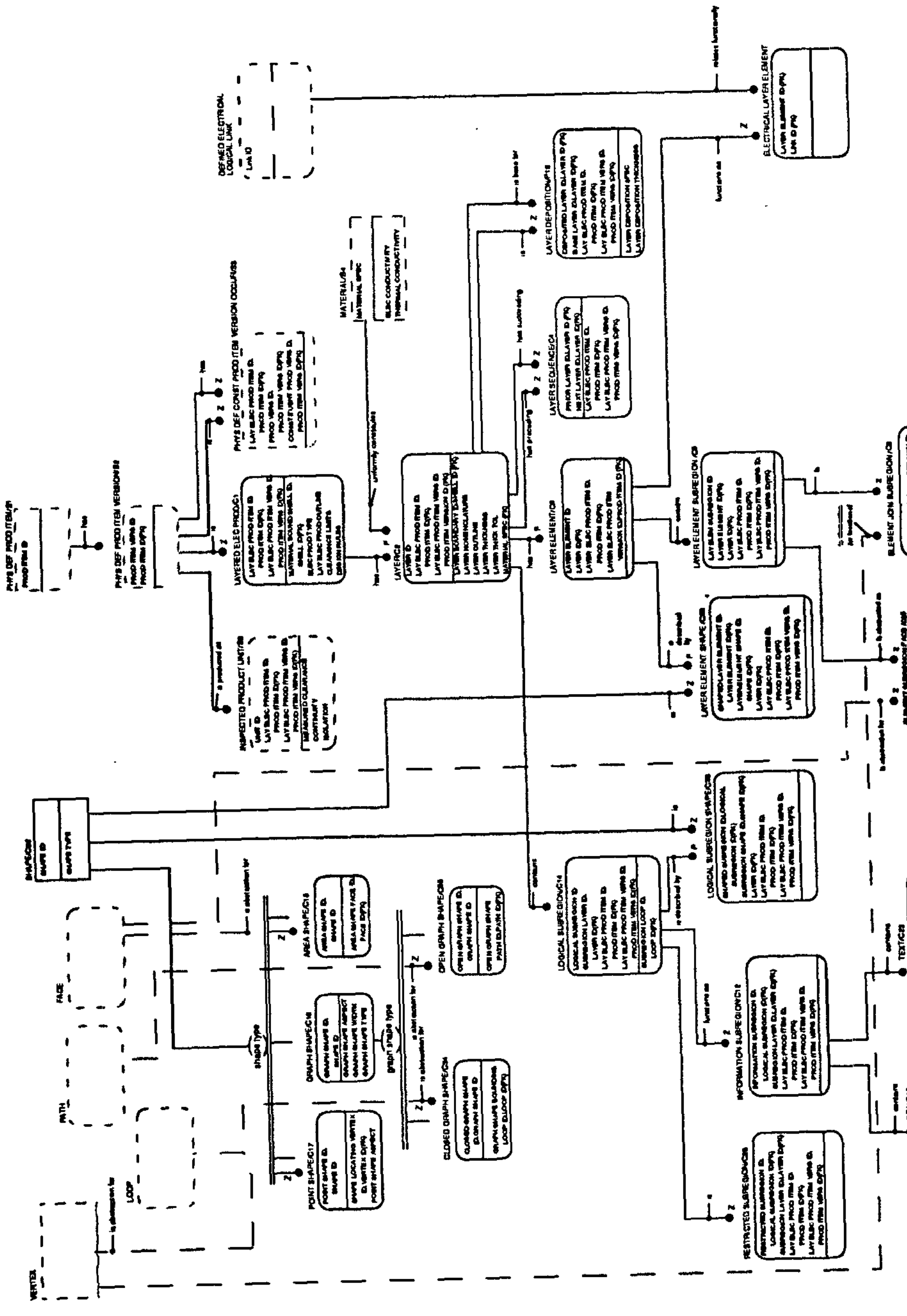


Fig. 5: IDEF-1X representation of Level II of the MWM model

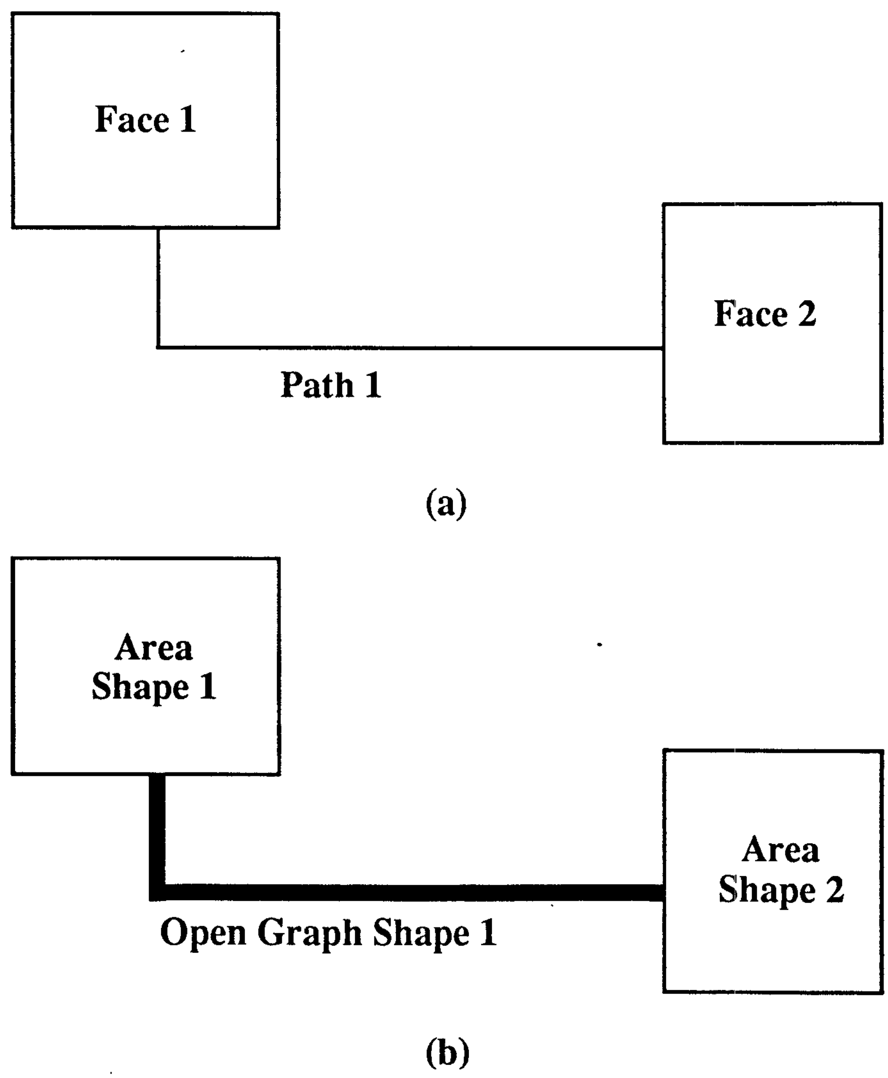


Fig. 6: PDES artwork pattern entities (a) Level I representation, (b) Level II representation

2.2.3 Level III of the MWM Model

This level the model is the second application-specific translation of the model, and was developed at the University of Maryland for the purposes of this work [Bahadur, 1991]. Figure 7 shows its IDEF-1X representation. Level III translates both Level I and Level II entities into design-for-manufacture entities. More specifically, Level III: i) models the product's features using the Form Feature Information model (FFIM) of PDES, ii) defines the part assembly which comprises each of the layer shells and all applied form features, iii) describes material attributes, iv) references electronic components and hardware as well as attachment techniques and locations, and v) captures passages and plating information. Tolerances are not currently part of this model. However, the PDES Tolerance model could eventually be used to specify the design tolerances for each feature as well as for the entire assembly.

Form features are used in Level III following the concept of constructive solid geometry (CSG), whereby features can be added to or subtracted from the BREP model of Level I. Each feature is defined separately and then applied to the product assembly shell. A *form feature* is defined by one or more *implicit form features*. The model allows for six different types of *implicit form features*: *passages, depressions, protrusions, transitions, area features*, and *deformations*. In addition, the model caters for *patterns* and *feature replication*. Figure 8 illustrates the FFIM model in a tree structure. Some feature information that is critical for the development of the coding system is given below.

Passages, *depressions* and *protrusions* are created by sweeping a defined profile along a particular *sweep path*. These features differ only in the extent of the *sweep path* with respect to the part envelope. A

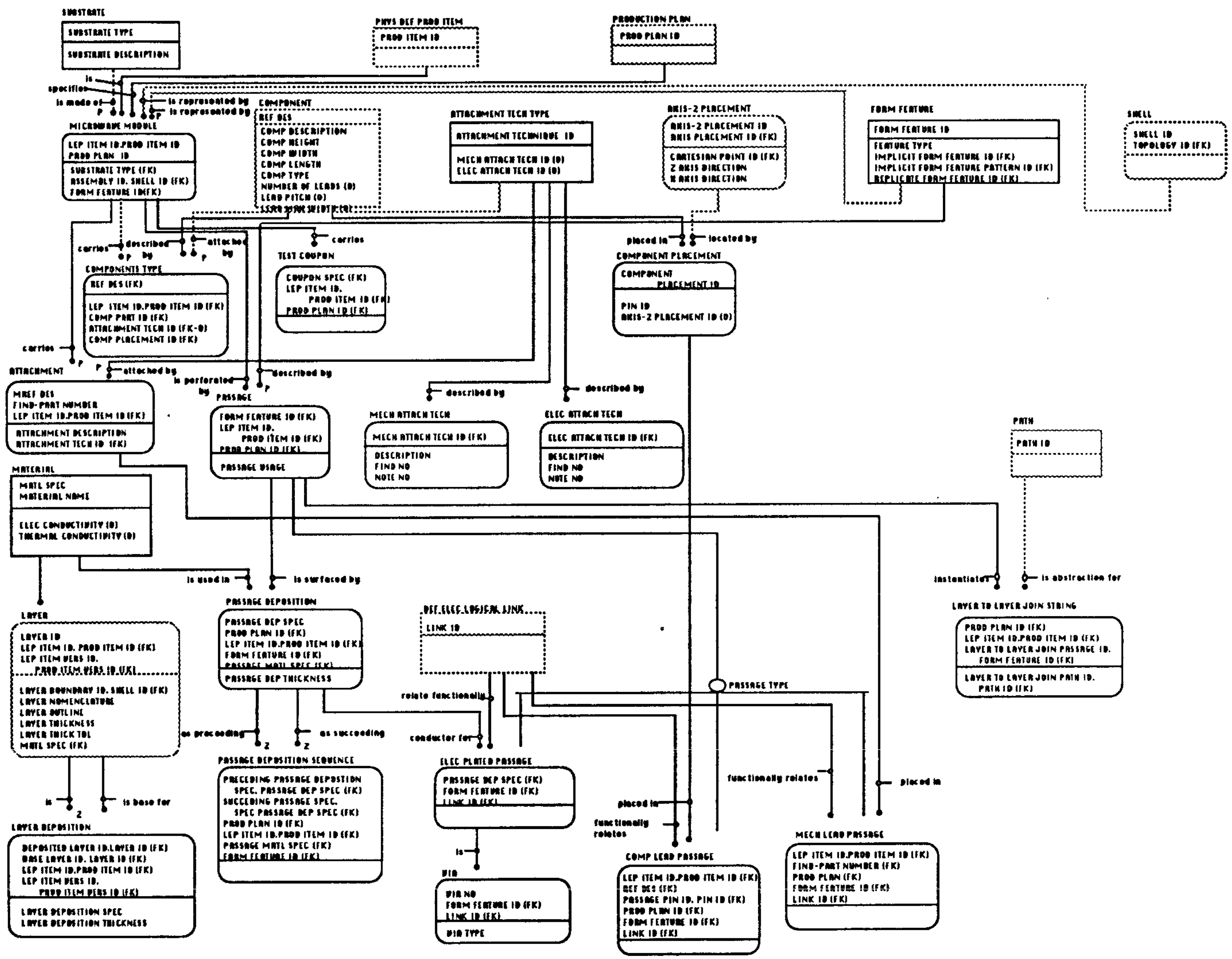


Fig. 7: IDEF-1X representation of Level III of the MWM model

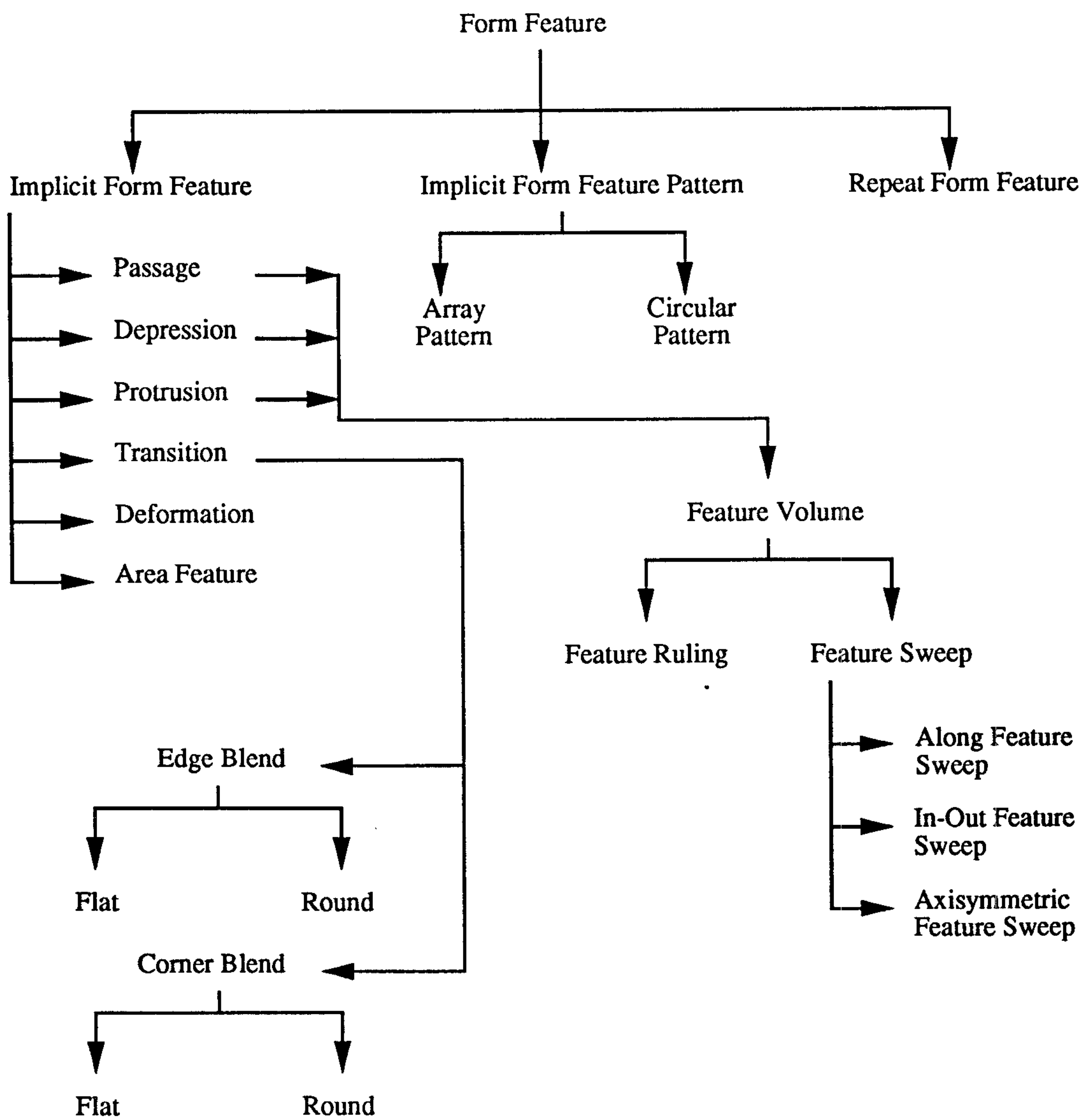


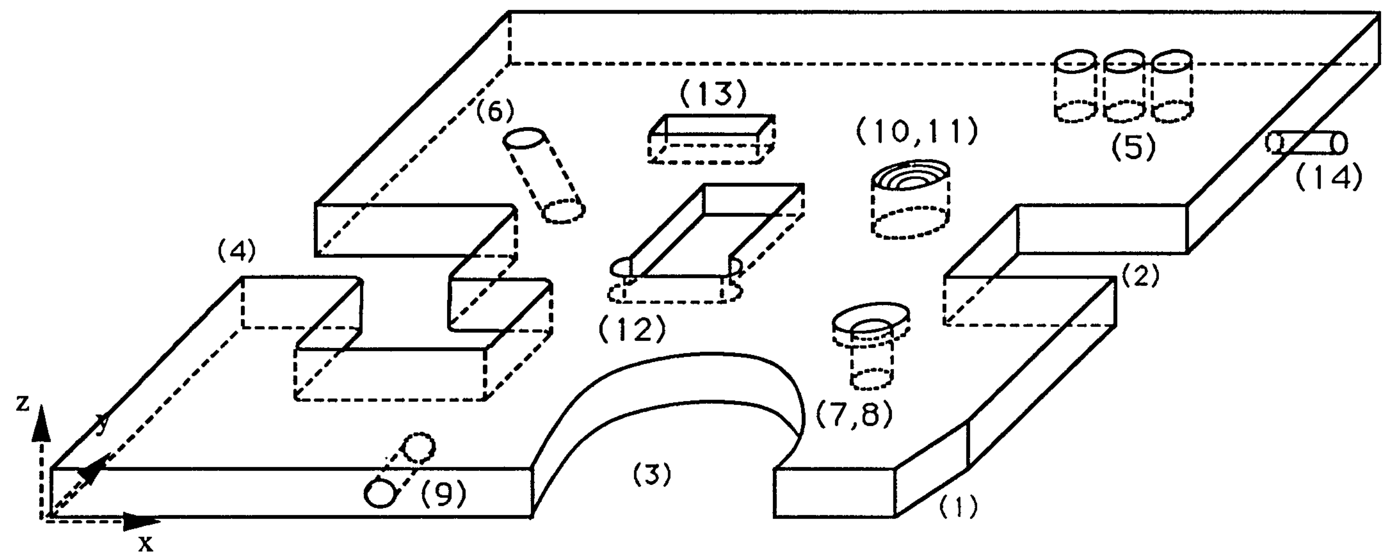
Fig. 8: Structure of PDES form feature entity

passage, in contrast to a *depression*, passes entirely through the part envelope (see Fig. 9, features 3 and 9) and a *protrusion* extends away from the part envelope (see Fig. 9, feature 14).

The *profiles* used to define the above features can be classified into two types; *open* and *closed profiles.* Both types may be defined in one of two ways; through a *predefined* or a *general profile.* The former is described by a few governing parameters. For example, the profile of a hole is defined by a radius and an *axis-2 placement* (see Fig. 10 a). An *axis-2 placement* is a local coordinate system that describes the location and orientation of individual form features, components, or pieces of hardware. Alternatively, a *general profile* may be defined by a series of *curves* contained in Level I and an *axis-2 placement* (see Fig. 10 b).

There are three different types of profile *feature sweeps*; *along sweep, in-out sweep*, and *axisymmetric sweep.* An *along sweep* is defined by an *open profile* that lies along the perimeter of the part envelope. Feature 2 in Fig. 9 shows an example of an *along feature sweep depression* with a *general profile.* An *in-out sweep* is defined by a *closed profile* that is swept along a linear path, and is located in the interior of the part (see feature 13, Fig. 9). Finally, an *axisymmetric sweep* is a profile swept in a circular pattern (see Fig. 9, feature 6, 9). Appendix A includes all of the possible feature sweep definitions for *passages, depressions*, and *protrusions.* The different types of *feature sweep paths* include: *linear, circular, spiral, surface conforming*, and *other.*

Transitions are *corner* or *edge blends* that are defined by one of two blend types and various size parameters. The different types of *transitions* are given in Appendix A. Their location is defined through the



PDES: Edge Blend Transitions: 1, Along Feature Sweeps: 2, 3, 4, In-out Feature Sweeps: 12, 13
Axisymmetric Feature Sweeps: 5, 6, 7, 8, 9,10, 14

MICLASS: Digit 2 features: 1, 2, 3, 4, Digit 3 features: 5, 7, 8, 10, Digit 4 features: 6, 9, 12, 13

Fig. 9: Types of PDES features

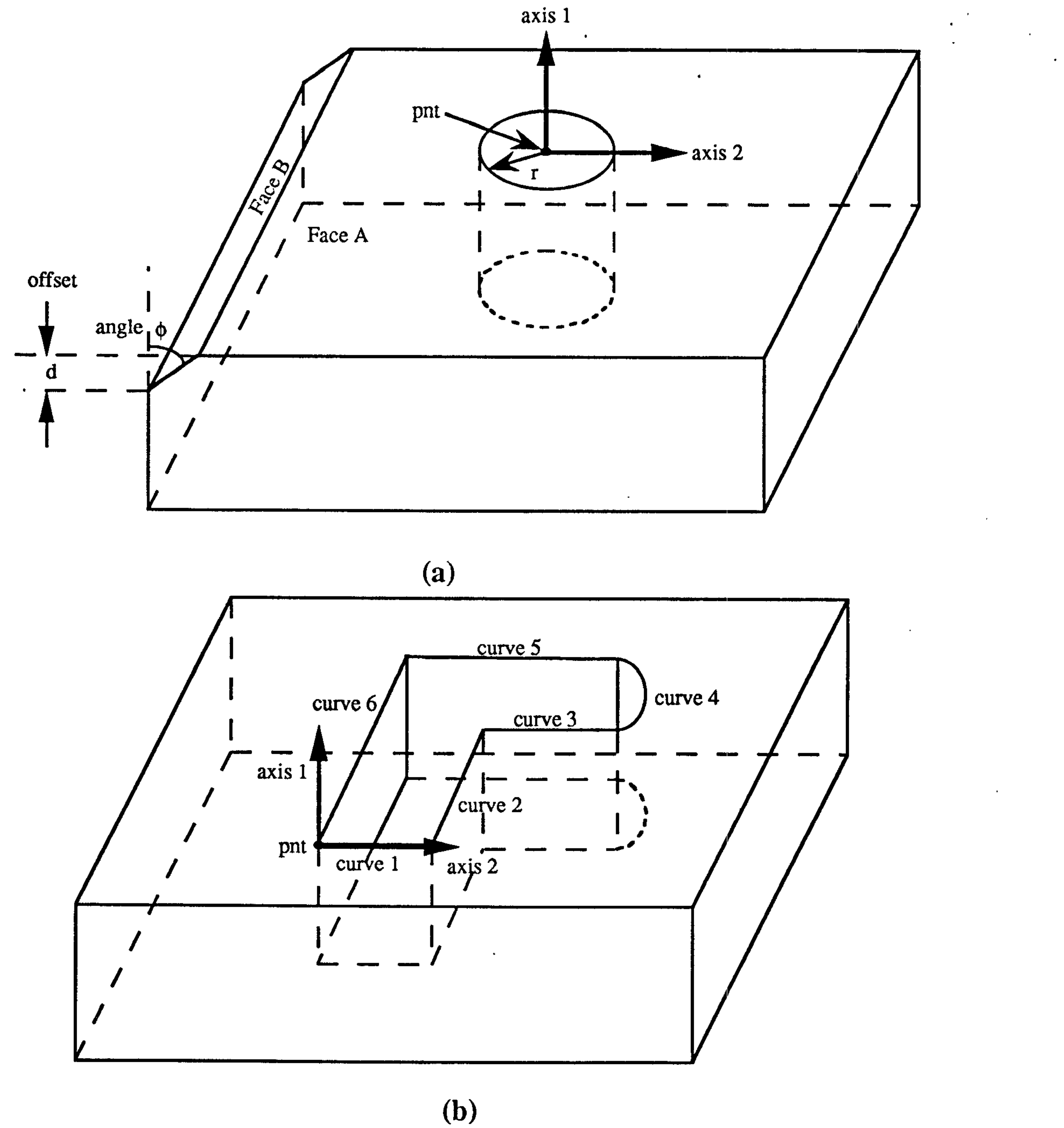


Fig. 10: (a) PDES pre-defined profile and edge flat transition, (b) PDES general profile

faces that are blended. Figure 10a shows an example of a chamfer created using an *edge flat transition.* The *transition* is defined by specifying the two *faces* (A and B), a setback distance d, and a blend angle ϕ.

Area features and deformations are defined through the *surface* that they are applied onto, and various size parameters. For example, a threaded hole is defined by specifying the cylindrical surface on which the threads are applied, and various thread dimensions such as thread type, pitch, inner and outer diameter. Appendix A illustrates the various types of area features.

There are two basic types of *Feature patterns*: *Circular patterns* and *Array patterns. Array patterns* are, in turn, classified into two types: *Parametric equal spacing*, and *parallel equal spacing array patterns.* Both types of array patterns describe sets of features with *axis placement* points located on a grid pattern. Similarly, a circular pattern describes features that lie along a circular arc. All pattern entities allow for *pattern omissions* and *pattern off-sets.*

In addition to form feature information, Level III contains pertinent information on components, hardware, and platings (see Fig. 7). Component information includes description and specifications (i.e. component type, size, number of leads, and lead pitch), assembly method (i.e. surface mount or thru-hole mount), and placement. Similar to feature placement, component placement is defined through an *axis-2 placement.* Hardware attributes described in Level III include hardware type, hardware count, and assembly method. Furthermore, plating information includes the layer to be plated, the plating material type, its thickness, and the corresponding plating tolerance.

Level III contains the majority of the information processed by the coding system. In conjunction with the entities that it references from Level I, it contains all feature data necessary for determining the mechanical GT code. It also includes all component and hardware information as well as additional plating material information required to derive the electrical GT code.

2.3 Database Implementation

The PDES-based MWM model has been implemented in the ORACLE relational database. Each entity of the model is represented in a base table, which contains all explicit entity attributes. Figure 11 shows an example of such a database table, and illustrates the relationship between super and sub-type entities. Those entities that are sub-types of a super-type entity include, in addition to the base table, an associated view-table that contains explicit attributes of the entity under consideration and all attributes inherited from its super-type. For example, the base table for the entity *Curve* contains the attributes *curve id* and *geometry id.* The entity *Line*, a sub-type of *Curve*, has a base table with the attributes *line id, curve id, point id* and *direction id.* The corresponding view table of *line* contains the attributes *line id, point id* , *direction id.* and *geometry id.*

CURVE (SUPERTYPE ENTITY) - BASE TABLE

CURVE ID	GEOMETRY ID

LINE (SUBTYPE ENTITY) - BASE TABLE

LINE ID	CURVE ID	CART PNT ID	DIRECTION ID

CONIC(SUBTYPE ENTITY/ SUPERTYPE ENTITY) - BASE TABLE

CONIC ID	CURVE ID

CIRCLE (SUBTYPE ENTITY) - BASE TABLE

CIRCLE ID	CONIC ID	RADIUS	AXIS2 PLAC ID

ELLIPSE (SUBTYPE ENTITY) - BASE TABLE

ELLIPSE ID	CONIC ID	MAJOR AXIS	MINOR AXIS	AXIS2 PLAC ID

Fig. 11: Relational database implementation of supertype-subtype relationship

3 GROUP TECHNOLOGY CODING SCHEME FOR MICROWAVE MODULES

This chapter discusses the GT coding scheme developed specifically for MWM's. It consists of two portions, a mechanical and an electrical, and contains a total of 43 digits. The first 18 digits are the core elements of the existing MICLASS code [OIR Multi M, 1986] and were used to capture information related to the manufacture of the mechanical MWM substrate. MICLASS was selected because it provides detailed feature information in a concise form. Table 1 summarizes the part attributes represented by MICLASS. A synopsis of the coding rules for flat mechanical parts is provided in Appendix B.

Since the attributes related to the electrical manufacturing characteristics of an MWM are not captured by MICLASS, a novel electrical GT scheme was developed at the University of Maryland to describe information related to photo-etching, plating, as well as component and hardware assembly. The newly created electrical code includes 25 digits and follows the GT coding principles of MICLASS. Although the present scheme encompasses MWM's only, its principles can be applied to any type of electrical product.

Although the six universal coding elements identified by Teicholz and Orr are for mechanical parts, they were used as the basic premise for the electrical code. While the mechanical coding scheme identifies attributes related to the products main shape and elements on the main shape, the electrical code identifies information related to the main product and elements assembled to the product. The following discussion of the electrical GT code has been structured following these elements.

Table 1: MICLASS GT Code (flat parts)

Code Position(s)	Part Attribute
1	Main Shape
2	Machined Cutouts
3	Holes Perpendicular to the Top Surface
4	Secondary Machined Elements
5-6	Mechanical Function
7-12	Part Envelope Dimensions
13	Tolerances
14-15	Material
16	Raw Material Shape
17	Production Quantity
18	Secondary Machined Element Orientation

The product attributes captured by the electrical GT coding scheme are given in Table 2 and each attribute is discussed below. Note that the mechanical portion of the GT code captures manufacturing information related to the MWM substrate, while the electrical portion captures information related to the fabrication and assembly of the MWM.

The structure of the electrical GT code is the same as the one followed by MICLASS. The coding scheme includes two types of tables: additive and look-up tables. Component mounting method, component mounting patterns, hardware, component orientations, mechanical dimensions, tolerances, and additional materials are of the former type, while main electrical classification, function, component/hardware count, electrical dimensions, and substrate type are of the latter. Additive tables facilitate the description of multiple product characteristics in a single code position. The values corresponding to these characteristics are added and the sum is recorded as the code value. The look-up tables allow for only one characteristic to be captured. The complete electrical GT coding book is contained in Appendix C. The basic groups of GT digits are described below.

Table 2: Electrical GT Code

Code Position(s)	Part Attribute
1	Main Electrical Classification
2-3	Electrical Function
4-5	Component Mounting Method
6-7	Component Mounting Patterns
8-11	Hardware
12	Component/Hardware Count
13	Component Orientation
14-21	Dimensions
22	Tolerances
23	Substrate Type (Insulation Material)
24-25	Additional Materials

Main Electrical Classification

The electrical product type has important manufacturing implications and, therefore, it is used as the major classifying attribute. It is captured by the first digit of the code and encompasses the following product types: i) Printed Wiring Board Assemblies (PWA), ii) Hybrid Microwave Assemblies (HMA), iii) Microwave Modules (MWM), iv) Final Assemblies, and v) Other. A final assembly is an assembly of several MWM's, PWA's, HMA's, or other electrical products incorporated in a mechanical housing (see Appendix C).

The generic function of the electronic part is captured by digits 2 and 3. For example, an MWM can function as a Transmitter, Receiver or Pre-Amplifier. A detailed list of the functions captured by the code is also included in Appendix C.

Component and Hardware Assembly

Just as each feature of a mechanical part implies certain machining operations, components and hardware of MWM's imply certain assembly operations. The GT code captures critical assembly information, such as the required component mounting method, mounting patterns, and the types of existing hardware. Information relating to artwork patterns is also included. To provide a rough measure of the number of required attachment operations, a special digit was reserved for the total number of existing components and hardware.

Component mounting method is captured by two digits (4 and 5), and includes the following types:

1. Surface Pad Mount
2. Surface Lead Mount

3. Thru-Hole Lead Mount
4. Thru-Hole Non-Lead Mount

Each mounting type implies certain manufacturing operations. For example, the surface pad mount type includes padded components, i.e. chip or die, that are attached to the substrate by soldering or conductive adhesive. The surface lead mount type includes leaded components that require lead forming, soldering of the leads to the artwork and, possibly, additional supports. The latter will also be captured by the code as hardware. The coding table for component mounting method is given in Appendix C.

Component mounting patterns and artwork patterns are described by digits 6 and 7 (see Appendix C). Both components and artwork may be classified as conforming to a grid pattern or as randomly located. The centerpoints of grid pattern components are located on grid nodes. Note that components comprising a pattern are not necessarily parallel. Artwork is said to conform to a grid pattern if the artwork traces and pads form grid squares. Artwork or components that do not conform to a grid pattern are considered as random. A single MWM may have both random artwork/components and components/artwork on a grid pattern.

Hardware is described by four GT digits and is classified into two major types; Hardware I described by digits 8 and 9, and Hardware II described by digits 10 and 11. In contrast to hardware in type I, all hardware belonging to type II requires soldering or welding. Within each type the hardware is classified by the corresponding operations required for mounting. Tables 3 and 4 give a list of the hardware type and the corresponding mounting operations for non-soldered and soldered hardware, respectively. Appendix C provides the coding tables for non-soldered and soldered hardware.

The total number of components and hardware is captured in digit 12. This digit provides a rough-cut estimate of the number of assembly operations required (see Appendix C).

Component Orientation

Digit 13 captures information on component orientation, which is critical in automated assembly operations. The component orientations captured by the GT code include: i) components parallel to the long side of the substrate, ii) components parallel to the short side of the substrate, iii) components skewed in one direction, iv) components skewed in multiple directions (see Appendix C).

Table 3: Hardware I (non-soldered)

Hardware Type	Mounting Method
Simple Adhesive	Adhesive application and short air curing time.
Supports	Simple placement operation.
Screws, Nuts, Bolts	Screwing operation.
Baluns	Heated lamination process.
Complex Adhesive,	Placement followed by a curing operation
Adhesive Preforms	(i.e. oven bake, ultra-violet, curing agent, etc.).
Other non-soldered.	

Table 4: Hardware II (soldered)

Hardware Type	Mounting Method
Ground Pins, Non-threaded Terminals	Force fit and soldering process.
Ground Screw Threaded Terminals	Screwing and soldering.
Wire Jumpers, Coaxial Cables, Isolator and Solder Preforms	Soldering.
Ribbon Jumper and Hairpins	Forming and soldering.
Lang Coupler	Parallel gap welding.
Other soldered.	

Dimensions

In addition to the geometric dimensions related to the packaging of electronic parts, electrical specifications are also described by the GT code. For example, MWM's are classified by timing, bandwidth, power density, current, operating frequency, gain and sensitivity, and voltage. Digits 14 through 20, are employed to capture these attributes (see Appendix C). The conventions for these GT digits are based on a Westinghouse study on manufacturability of MWM's [Westinghouse, 1990]. It was found that certain dimensions have a significant impact on the manufacturability of MWM's, in particular on testing and tuning.

The electrical dimensions are classified by range. The following conventions are followed by the coding system: i) Bandwidth, gain and sensitivity, operating frequency, average power density, and timing refer to the entire product. ii) Gain and sensitivity have similar impact on the testing and tuning of MWM's and, therefore, only one digit is used to capture the most severe between the two. iii) Current and voltage are classified considering the least favorable value at any point on the substrate circuit. Note that excessively high or low current/voltage present equally challenging manufacturing problems.

Digit 21 of the GT code describes qualifying values for the lead pitch, component spacing, and circuit (artwork) dimensions (see Appendix C). These attributes are included due to their significance on producibility. For example, the level of difficulty associated with mounting a multi-leaded component is dramatically increased if the lead pitch is less than the qualifying value of 0.030 inches. Only those mechanical dimensions that have values less than or equal to the qualifying dimension value are recorded.

Lead pitch is defined as the minimum spacing between successive leads on a multi-leaded component. Component spacing describes both the distance between adjacent components and the distance between a component and a substrate edge. Finally, artwork dimension describes line width, spacing between lines, or spacing between a line and a substrate edge.

Tolerances

Digit 22 of the GT code capture tolerances (see Appendix C). For electronic parts, the tolerances that are critical to fabrication and assembly include component placement accuracy, artwork etching dimensions, and circuit or substrate plating thickness. The tolerance convention followed by MICLASS is adopted here. That is, only tolerances beyond a company specific qualifying value are represented in the GT code. The specific qualifying value chosen should reflect a level of manufacturing difficulty.

Material

Material is important for a number of applications, including design retrieval, and producibility evaluation. MWM's can be distinguished by their dielectric (insulation) layer, since the latter implies specific manufacturing operations. Additional materials such as pre-tinnings and platings are also important due to their added process implications. Thus besides the material of the insulation layer (digit 23), the electrical GT code uses two digits to capture plating and tinning materials (digits 24 and 25).

The insulation materials captured by digit 22 include i) Poly Tetra Flouro Ethane, ii) Polyimide, iii) Prefired Ceramic (thick film), iv) Prefired Ceramic (thin film), v) Cofired Ceramic (Greentape), and vi) Other. As new technologies are developed, this digit can be expanded to include four more materials (see Appendix C). Pre-tinning information for both component leads and component pads is captured by digits 24 and 25. In addition, plating information includes: single and multiple substrate platings, single and multiple circuit (artwork) platings, as well as thru-hole platings.

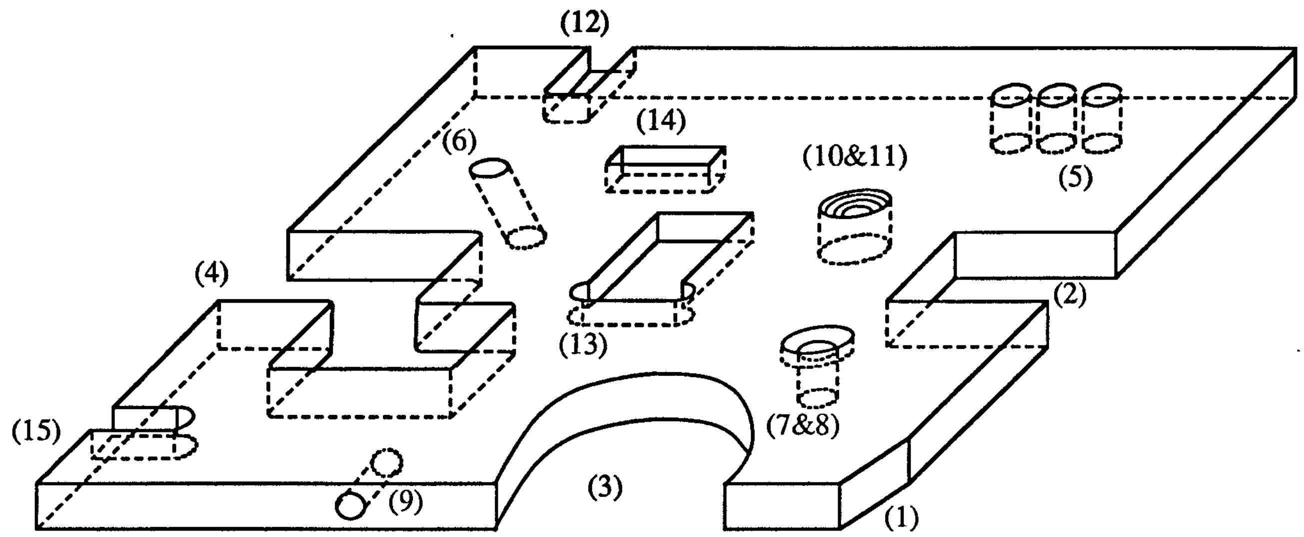
4 AUTOMATED GT CODE GENERATION

This chapter discusses the automated GT code generating system. The principal input to the system is the PDES information model (see chapter 2), which has been implemented in the ORACLE relational database. The user is queried for any information that is not available in the model. Reflecting the structure of the GT code, the system consists of two main parts; the mechanical and electrical GT code generators. The output of the system is the 18 digit MICLASS GT code, the 25 digit electrical GT code, as well as detailed information on the attributes captured by the two portions of the code. The latter is used by a manufacturability evaluation system described elsewhere [Rathbun, 1992].

Figure 12 shows a sample part that is used to illustrate some key procedures of the system. This part was also used to test the system. The corresponding PDES information model was implemented in ORACLE and contains 26 tables. The GT code obtained is shown in Fig. 12, and the output files containing the detailed information on the mechanical and electrical design attributes of this part are given in Appendix D.

4.1 Mechanical GT Code Generation

The mechanical code generator considers the overall geometric shape of the MWM, its features and their orientation, as well as its geometric dimensions, mechanical function, tolerances, material, raw material shape, and production quantity. With the exception of tolerances and mechanical function, all static design information is available from the



MICLASS DIGIT #:	1	2	3	4	5 6	7 8	9 10	11 12	13	14 15	16	17	18
MICLASS CODE:	5	9	7	3	0 1	5 1	3 7	0 9	_	0 8	5	_	7

ELECTRICAL CODE #:	1	2 3	4 5	6 7	8 9	10 11	12	13	14 15 16 17 18 19 20 21 22	23	24 25
CODE VALUE:	3	0 3	0 3	1 0	0 9	0 9	3	7	____________	2	1 3

Fig. 12: Mechanical Test Part

PDES model. As discussed in chapter 2, most of the required information is contained within Levels I and III.

The system assumes that the part is designed by features, i.e., starts from a basic part envelope and uses constructive solid geometry (CSG). As defined by Boothroyd and Poli (1980), the part envelope is the smallest cylinder, regular prism, or rectangular prism that can completely enclose the part. Since MWM substrates are flat parts, the part envelope is assumed to be an equilateral triangle, a solid cylinder, a solid cube or a rectangular prism. Any other type of envelope may be derived by subtracting the appropriate features from one of these primary shapes. Further assumptions made will be discussed in the remaining part of this section where the system is described in more detail.

The general approach employed is: i) to translate each MICLASS feature definition into a set of possible PDES definitions, ii) to use the translation rules to search the database for the existence of PDES features that are described by the MICLASS code, and iii) to assign the proper code value based on the MICLASS rules and using the PDES feature data. It is emphasized that there are numerous ways of describing each feature in PDES. Therefore, considerable effort was devoted to account for the most frequently used representations. However, the rule-base developed is not all inclusive, and its robustness to the different feature descriptions within PDES may only be assessed through applications.

Table 5 presents the MICLASS to PDES feature translations. Note that due to the domain of application, protrusions are eliminated from the possible choices of available PDES features. Table 5 was used to develop the rules for the first step in the automated coding process.

Table 5: MICLASS - PDES Feature Translation

MICLASS Feature	PDES Feature
Cutouts (Digit 2)	• Along feature sweep passages perpendicular to the AB plane • Edge blend transitions perpendicular to the AB plane
Holes (Digits 3 and 4)	• Constant axisymmetric feature sweep • Tapered axisymmetric feature sweep • In-out feature sweep (circular profile)
Flats (Digit 4)	• Edge flat transitions not perpendicular to the AB plane • Corner flat transitions • Along feature sweep passages not perpendicular to the AB plane
Slots / Complex Cavities (Digit 4)	• Along feature sweep passages not perpendicular to the AB plane • Along feature sweep depressions • In-Out feature sweep passages and depressions
Deformations (Digit 4)	• Implicit deformations

The coding rules reflect the MICLASS conventions outlined in Appendix B (see also OIR Multi-M, 1986). Based on these conventions the system derives the appropriate value for each digit of the mechanical

GT code. The detailed procedures developed for automated coding of each GT digit are presented below.

4.1.1 Digit 1: Main Shape

The main shape of the product is determined by querying the database for the geometric entities related to the product envelope. The latter is represented by the topological entity *shell,* which is comprised of several faces. Since the geometry and topology of the part are created using CSG, the topological *shell* contains only the bounding faces of the substrate envelope, excluding its features. Five steps are employed to determine and code value representing the main shape.

<u>Step 1</u>

The Id of the assembly *shell*, which encapsulates all three layers of the MWM, is determined first. Its Id is defined in the attribute *shell id* of the entity *Microwave Module* of Level III (see Fig. 7). Subsequently, the faces that comprise the *shell* are determined by querying the entity *Closed Shell* of Level I. By examining the *surface type* of the corresponding faces, the system evaluates whether these faces are planar or cylindrical. If any cylindrical faces are identified, the system follows a routine for round MWM substrates. The latter is simpler than the routine for prismatic parts, since it only analyzes one pair of parallel faces, the top and bottom ones.

<u>Step 2</u>

All pairs of parallel faces are determined by examining their normal directions. This is accomplished by creating a database view that, for each face of the assembly shell, contains the *face id*, the corresponding *surface id* and the surface normal *direction id*. The system compares the face normal directions to determine the pairs of parallel faces. If three such pairs are identified, the system recognizes a prismatic part envelope. On the other hand, if only one pair is found, then the system considers the remaining face(s) to determine whether the product envelope is cylindrical. For prismatic parts, face perpendicularity is examined forming the inner products of the face normals. In the case of rectangular prisms, the inner products that do not correspond to parallel faces are zero. For cylindrical parts, perpendicularity is only checked between the pair of parallel faces and the cylindrical surface.

<u>Step 3</u>

For each pair of parallel faces, the corresponding separation distance, which defines the appropriate product shell dimension, is determined. It is noted that in order for the part to qualify as flat according to MICLASS, its smallest dimension should be less than 0.25 in. A simple algebraic expression is used to determine the distance between two parallel faces, given the coordinates of a point and the direction normal for each corresponding surface. Both these attributes are directly extractable from the entity *axis-2 placement* used to define each surface. The diameter of cylindrical parts is defined by the attribute *radius* of the entity *cylindrical surface.*

<u>Step 4</u>

Existing deformations in flat parts are determined from the entity *form feature* of Level III. If the system identifies a major deformation, then the part is not within the scope of the coding rule-base and the user is notified.

Step 5

The orientation of the global coordinate system is examined and compared to the face normal directions. Inner products are evaluated between the face normal direction for each pair of parallel faces and the global x, y and z axes. The rest of the coding rules assume that the part envelope is aligned with the x, y and z global axes. In particular, the x-axis of the coordinate system is assumed to be aligned with the thickness of the part (see Fig. 9).

For the sample part shown in Fig. 12, the procedure described above examined the six faces of the part assembly shell, identified the three pairs of parallel faces, recognized that the part is rectangular, calculated the separation distances of face pairs, and classified the part as flat (Digit 1 = 5).

4.1.2 Preliminary Feature Classification

Critical information on the geometric features of the mechanical substrate is captured by digits 2, 3 and 4 of the MICLASS code. All feature types described by MICLASS are illustrated in Fig. 9. Specifically, digit 2 of the code describes cut-outs along the perimeter of the part which are perpendicular to the x-y plane; digit 3 describes patterns and diameter of holes that are perpendicular to the x-y plane; and digit 4 describes all remaining features. Since the PDES model is feature based, it caters for the required feature analysis.

In order to simplify the database interaction, each feature is first classified to one of the MICLASS feature types given in Table 5. The initial feature recognition process: i) distinguishes between cut-outs and secondary machined elements (passages and depressions), ii) identifies feature location (interior or perimeter), and orientation (perpendicular or not perpendicular to the x-y plane), iii) performs preliminary feature classification of holes, transitions, deformations, and other cavities, and iv) recognizes intersecting features such as counterbore holes (see Fig. 9, features 7 and 8). This procedure relies heavily on the information included in the form features model of Level III and those entities of Level I that are referenced by the form feature model. If the system encounters a protrusion in the database, a message is provided to the user and that feature is ignored. The major steps of the preliminary classification procedure are:

Step 1

All passages and depressions are identified and classified according to sweep type, i.e., along, in-out, or axisymmetric sweep. The system creates a database view for each type of passage sweep and each type of depression sweep, such as along depression, along passage and in-out depression. The resulting six views contain the attributes *feature id*, *sweep id*, as well as *axis-2 placement* and *profile id's*.

The above information is used to classify the features into cutouts (digit 2), holes (digit 3), and secondary machined features (digit 4). In some cases this information is sufficient to complete the classification of the the features in the MICLASS types. Other cases, however, require further processing. For example, all in-out passages and depressions, as well as along sweep depressions are captured by digit 4 of the GT code and are classified as such (see Fig. 12, features 12, 13, 14, and 15). However, in order to classify along sweep passages and axisymmetric sweeps, additional position and orientation information is necessary (see Step 2 below).

Step 2

Since MICLASS allocates a special digit for holes and cutouts perpendicular to the x-y plane, it is necessary to determine the location and orientation of each feature for classification. The location and orientation of a passage or depression is determined by examining the corresponding *axis-2 placement* and *sweep direction* . The normal direction of the feature profile is determined and it is classified as either perpendicular or not perpendicular to the x-y plane. Direction 1 of the *axis-2 placement* coincides with the normal direction of the feature profile.

Those along sweep passage features that have feature normals perpendicular to the x-y plane are further processed by the procedure corresponding to digit 2, while the remaining ones are processed by the digit 4 procedure. Similarly, axisymmetric sweep features are processed by the digit 3 and digit 4 procedures (see Table 5).

Considering the example of Fig. 12, this procedure assigns features 2, 3 and 4 to be further processed by the digit 2 procedure, features 5, 7, 8 and 10 by the digit 3 procedure and features 6 and 9 by the digit 4 procedure.

Step 3

Transitions, deformations, and area features are identified within the PDES model. Although area features, such as threads and dimpling, are not captured by the MICLASS code, the system processes these features and transmits the corresponding information to the manufacturability module of the life cycle engineering framework. Deformations are directly classified as features to be processed by the procedure of digit 4.

All corner blend transitions are also processed by the procedure of digit 4. However in order to classify the edge blend transitions, further orientation information is required and is determined by examining the normal direction of the two faces blended by the transition. If the normal directions of both faces lie in the x-y plane, then the transition forms a cutout and is further processed by the procedure of digit 2 (see Fig. 12, feature 1). Otherwise, the transition is further processed by the procedure of digit 4.

Step 4

This step examines feature interactions. PDES defines all features by the entity *form feature*. A form feature is defined by one or more *implicit form features* (see chapter 2). If a *form feature* consist of more than one *implicit form feature*, then the *implicit form features* are assumed to interact by definition. However, since PDES only allows for a single level of feature hierarchy, it is necessary to determine the interaction between different form features. Such interactions are determined by examining each feature's *axis-2 placement*.

For example, counterbore holes may be defined by an axisymmetric sweep depression and an axisymmetric sweep passage. The directions of the *axis-2 placement* of both features are identical. However, the coordinates of their locating points are offset by a distance equal to the depth of the counterbore in the direction of the hole axis.

In the case of interacting holes, the system first identifies the *axis-2 placements* and compares their normal directions. If these directions are identical, then the locating points of the *axis-2 placement* are evaluated. The cartesian coordinates of the first point are subtracted from those of the second point to yield the direction of the line connecting the two points. If this direction corresponds to the hole axis direction, then it is possible that the two features interact. If one of the holes is described by a passage, then the two holes do interact since a passage passes completely through the part. If both holes are described by depressions, then the sweep starting points and sweep lengths must be evaluated to determine if the two features intersect.

4.1.3 Digit 2: Cutouts

The value of digit 2 is determined by examining the profile of those PDES features that have already been designated by the preliminary classification procedure to be MICLASS cutouts (see section 4.1.2). For those features that are characterized by predefined PDES profiles (see chapter 2 and Fig. 10a), appropriate profile dimensions are evaluated in order to classify each feature to one of the four types of MICLASS cutouts: i.e., rectangular, slanted, circular, and complex (see Fig. 9, features 2, 1, 3 and 4 respectively). Table 6 indicates the relationship between the MICLASS cutouts and the PDES feature profiles.

All four types of MICLASS cutouts may also be defined by a PDES general profile. In this case, each of the curves that create the profile are examined to determine the profile shape (see Fig. 10b). This procedure: i) determines the shape of individual curves, i.e., linear, circular, or other, ii) checks for parallelism and perpendicularity, iii) examines curve connectivity, and iv) classifies the profile shape. It should be noted that small radii, less than 0.125 in., are neglected according to MICLASS rules. Steps (i), (ii), and (iii) are accomplished by querying the geometry of Level I for the appropriate information. For example, if the profile consists of only one curve and this curve is found to be linear, the cutout is classified as slanted. If this curve is circular with a radius greater than or equal to 0.125 in., then the cutout is radiused. Any other type of single curve profile belongs to a complex cutout.

Table 6: MICLASS/PDES Profile Relationships for Cutouts

Cutout Type	PDES Pre-Defined Open Profile Type
Rectangular	• Square U open profile • Vee (45 degrees) open profile
Slanted	• Edge blend transition
Radiused	• Circular arc open profile
Complex	• Rounded U open profile • Tee open profile • Ell open profile • Vee open profile • Line plus Radius open profile • Obround open profile

In the case that a general profile consists of more than one curve, curve connectivity is considered. For example, if a profile consists of three linear and two circular curves, it may or may not be a rectangular cutout. First the radius of the circular curves is evaluated querying the Level I entities *curve*, *conic*, and *circle*. If the radii are less than 0.125 in., then the orientation of linear curves is evaluated. If two of the lines are parallel, the third line is perpendicular to the parallel pair, and is connected to its members through the circular curves, then the cutout is classified as rectangular. If these conditions are not met, then the cutout is classified as complex. Figure 13 illustrate rectangular and complex cutouts formed by the same set of five curve types, respectively.

In the sample part of Fig. 12 all four types of MICLASS cut-outs are present, i.e. rectangular, slanted, radiused, and complex. Thus, the above procedure assigned the value 9 to GT digit 2.

4.1.4 Digit 3: Holes Perpendicular to the XY Plane

Digit 3 classifies holes perpendicular to the x-y plane. Consequently, axisymmetric feature sweeps and in-out sweeps of a circular profile are only considered in this procedure (see Table 5). The value of digit 3 is determined in two steps. First the hole diameters are evaluated, and classified as greater than, equal to, or less than, five times the part envelope thickness. The hole diameter is determined through the attribute *sweep size* of the entity axisymmetric feature sweep, or the *radius* of the circular curve defining the general profile of an in-out feature sweep. The resulting diameter value is compared with the part envelope dimensions calculated previously by the procedure of digit 1.

In the second step, the existence of hole patterns is examined. The PDES form feature model accounts for two types of feature patterns: array patterns and circular arc patterns (see chapter 2). Array patterns are features that lie on a rectangular grid pattern, while circular patterns are features that lie along an arc. Note that the system does not account for a pattern of features unless the designer has specified it as such. The resulting data are processed by the rule-base and the proper value is assigned to digit 3.

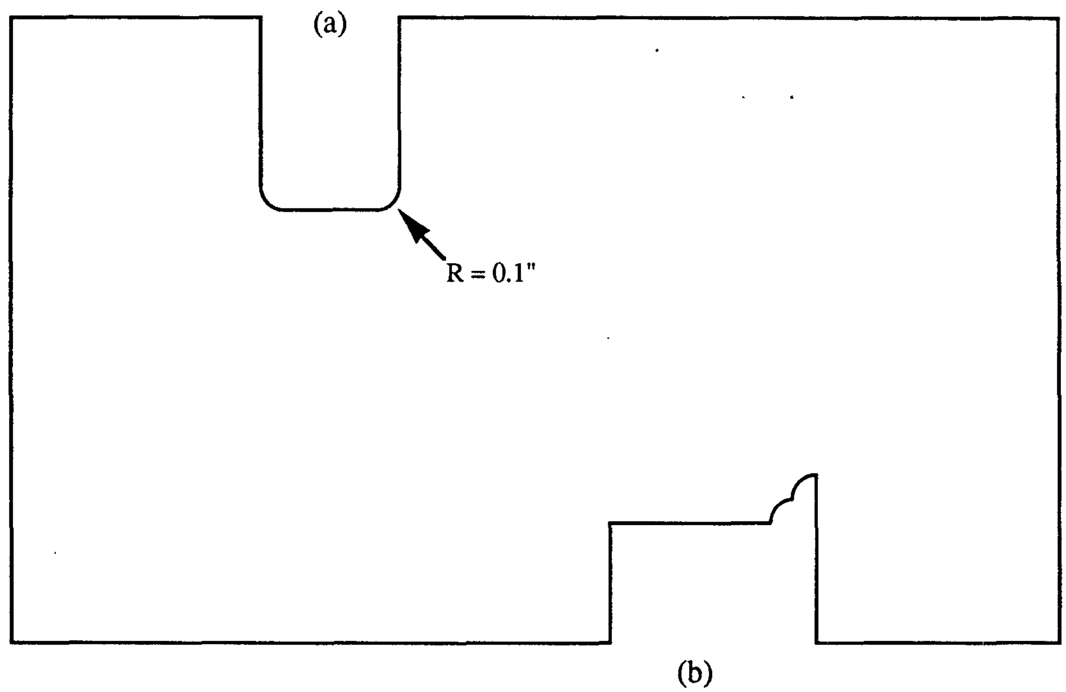


Fig. 13: Rectangular and complex cutouts formed by the same set of curves

The value 7 in digit 3 of the sample part denotes that both a line pattern of holes and a hole with a diameter greater than five times the part thickness were determined.

4.1.5 Digit 4: Secondary Machined Elements

Flats, slots, complex cavities, holes not captured by digit 3 and minor deformations are described by the MICLASS digit 4. Some of the corresponding PDES *form features*, i.e. *transition* and *axisymmetric feature sweeps* and *deformations* (see Table 5) are recognized by the preliminary classification procedure described in section 4.1.2. The remaining PDES features, *along* and *in-out passages* and *depressions*, are processed by the procedure of digit 4. The profiles of these features are processed in a manner identical to the one described in the digit 2 procedure for cutouts. Additional analysis is required in some cases to distinguish between slots and complex cavities according to the MICLASS conventions. This analysis includes: i) querying the geometry of the corresponding curves to calculate line lengths, parallelism, and curve radii, and ii) querying the form feature database tables for the specific feature sweep information. Radii less than 0.125 in. are neglected.

Table 7 relates the open profiles of the PDES along feature sweeps to the MICLASS features of digit 4. On the other hand, a predefined closed rectangular profile, the length of which is not equal to its width, corresponds to a MICLASS slot. All other predefined closed profiles correspond to complex cavities.

General profiles require a more detailed analysis to determine the profile shape. The analysis for both open and closed general profiles is similar to the one presented in section 4.1.3.

Table 7: MICLASS/PDES Profile Relationships for Secondary Machined Elements

MICLASS Feature	PDES Pre-Defined Open Profile Type
Slot	• Square U open profile • Vee open profile • Rounded U open profile
Complex Cavity	• Circular arc open profile • Tee open profile • Ell open profile • Square U open profile (length=width) • Vee open profile (length=width) • Rounded U open profile (length=width) • Line plus Radius open profile • Obround open profile

Based on the evaluation of the sample part feature profiles, the procedure of digit 4 classified features 10, 11, 12, and 13 as slots (see Fig. 12). The curved edges of these features were found to be less than 0.125 inches. Furthermore, features 6 and 8 were characterized as holes not perpendicular to the top surface. Thus, according to the MICLASS coding rules the value 3 was assigned to digit 4.

4.1.6 Digits 5-6: Mechanical Function

These digits capture the function of the bare substrate or board without any components or hardware. Coding is performed through user input.

4.1.7 Digits 7-12: Geometrical Dimensions

Digits 7-8 describe the length of the part envelope, while digits 9-10 and 11-12 capture its width and thickness. MICLASS look-up tables are used to derive the values of these code digits from the envelope dimensions calculated by the procedure described in section 4.1.1. Note that for a cylindrical flat part, the length and width are interchangeable.

For the sample part of Fig. 12 the values of digits 7 through 12 are 5, 1, 3, 7, 0 and 9, which correspond to the envelope dimensions 10 in. , 5 in. and 0.2 in. determined by the procedure of digit 1 and the MICLASS look-up tables.

4.1.8 Digit 13: Geometrical Tolerances

Since the PDES model, in its present form, does not include tolerance information, this coding procedure is interactive. The user is prompted to provide the necessary data about fifteen tolerance types; length, position, diameter, flatness, roundness, cylindricity, straightness, concentricity, profile, perpendicularity, angularity, parallelism, true position, and run-out. A company-specific threshold is employed for each type to signify the severity of the corresponding tolerance. Only those tolerance specifications that exceed these thresholds are captured. The system assigns the appropriate value to digit 13 based on the MICLASS conventions (see Appendix B).

4.1.9 Digits 14-15: Substrate Material

The coding system queries the entity *layer* of PDES Level II and the entity *material* of Level III for the material types of both the insulation layer and the ground plane. The resulting combination is compared with a MICLASS look-up table to determine the proper code values. Digits 14 and 15 of the sample part in Fig. 12 indicate that the MWM comprises a polyimide insulation layer and a 6061 aluminum ground plane.

4.1.10 Digits 16-17: Raw Material Form and Production Quantity

The raw material form is company-specific and is not included in the PDES model. The user is prompted to select it from an appropriate list. The production quantity, a production related variable, is also provided by the user.

4.1.11 Digit 18: Secondary Machined Element Orientations

This procedure determines the orientation of the form features captured by digit 4; i.e., holes, slots, flats and complex cavities. It considers orientations that are perpendicular to the top and bottom envelope faces, perpendicular to one of the side faces, skewed to one face, and skewed to more than one face. Based on the resulting feature orientations, the rule-base assigns the appropriate value to digit 18 (see Appendix B).

Feature orientation for passages and depressions is determined by comparing the normal direction of their profiles, which is evaluated by the preliminary classification procedure described in section 4.1.2, to the face normal directions of the part envelope: i) If the normal direction of the feature profile is parallel to the z direction, the orientation of the feature is perpendicular to the x-y plane (see Fig. 9, features 12 and 13). ii) If the normal direction is parallel to one of the side face normals, then the feature under consideration is perpendicular to one of the side faces (see Fig. 9, feature 9). iii) If the profile normal is parallel to either the x-y, y-z, or x-z planes, but does not belong to one of the two previous cases, the feature is skewed to one plane . iv) All other features are skewed to more than one plane (see Fig. 9, feature 6). Some features defined by an along feature sweeps may have two possible orientations (see Fig. 14). The system considers the orientation of these features to be perpendicular to the sweep direction.

The orientation of transition features is determined by analyzing the type of blend and the direction normals of the faces that are being merged. If the transition is a corner blend, the feature is skewed to more than one plane. For an edge blend the normals of the corresponding faces are examined. If they are perpendicular to the faces of the shell, then the feature orientation is skewed to one plane. Otherwise, it is skewed to more than one plane.

The value 7 in position 18 of the sample part shows that the features described by digit 4 are perpendicular to the x-y plane, perpendicular to one of the side surfaces, and skewed to one plane. These results are consistent with Fig. 12.

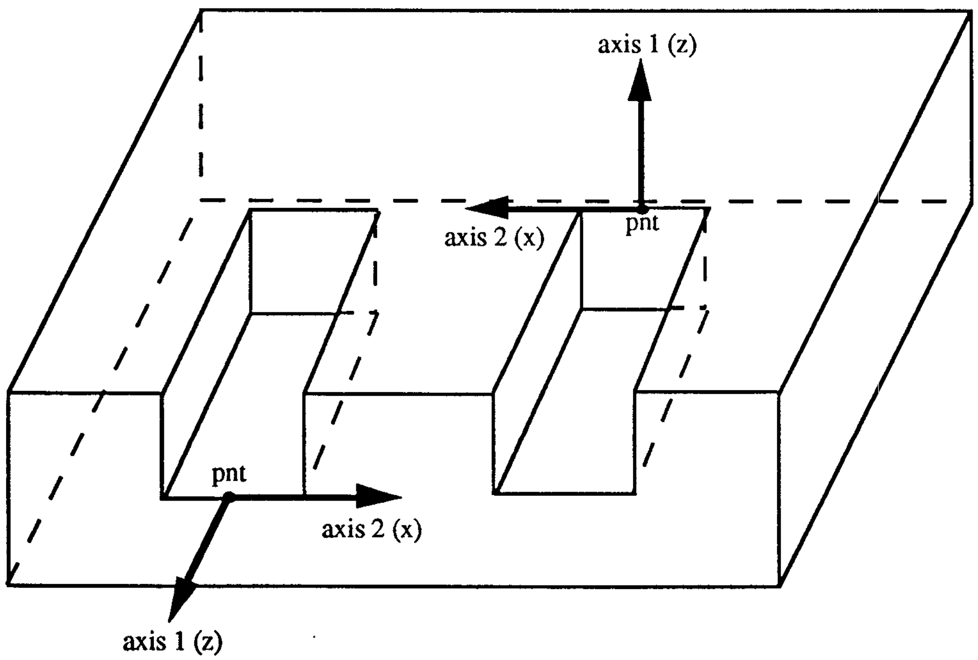


Fig. 14: PDES Along Feature Sweep Depression perpendicular to a side (left side), PDES Along Feature Sweep Depression perpendicular to the top (right side)

4.2 Electrical GT Code Generation

The electrical code generator considers the following part attributes: i) main electrical classification and function; ii) component and hardware mounting methods, patterns, orientations, and total number; iii) electrical dimensions, artwork and plating dimensions and their associated tolerances; iv) substrate, plating and tinning materials. Level III of the MWM model contains most of the information required by the electrical code generator. The system also queries Level II, the functional model and the user. Since information related to the type, number, and placement of components and hardware is less abstract than mechanical feature information, the electrical coding system is considerably less complex. With the exception of mounting patterns, tolerances, dimensions and pre-tinnings, all the necessary data are available from the PDES model.

Three types of procedures were developed to determine the values of the electrical GT code. The first uses look-up tables to compare the model data with the conventions of the GT scheme. This type of procedure is employed for digits 1 (Main Electrical Classification), 2 and 3 (Electrical Function), 23 (Substrate Type), 24 and 25 (Additional Materials). In the second procedure type, more elaborate processing of the model information is performed to determine the appropriate GT code values. Digits 4 and 5 (Component Mounting Method), 8 through 11 (Hardware), 12 (Component/Hardware Count) and 13 (Component Orientations) are determined by such procedures. The third procedure type relies exclusively on user information. Such procedures are used for digits 6 and 7 (Component and Artwork Patterns), 14 through 21 (Electrical Dimensions) and 22 (Tolerances).

Table 8 indicates the PDES entities used in the determination of each GT digit. Digits not shown in the table rely on user input. The following paragraphs describe the coding procedures digit-by-digit.

4.2.1 Digit 1: Main Electrical Classification

The main electrical classification is described by the attribute *electrical product type* of the Level II entity *Layered Electrical Product.* A string comparison is used to match the product type provided by the database query with one of the electrical classifications captured by the code. A value of 3 in the first position of the code for the sample part in Fig. 12 indicates that the database query determined the entry of the *electrical product type* to be an MWM.

4.2.2 Digits 2-3: Electrical Function

A string comparison is also performed here to match the function provided by the appropriate database query to the pre-defined functions of the coding scheme. The information required by this procedure is not contained in the PDES MWM model, but it is accessed from the PDES functional model. In order to provide a link to the MWM model, the functional model was modified to include the entity *Defined Functional Unit Occurrence.* This entity is similar to the *Defined Functional Sub-unit Occurrence* that already exists within the functional model. It was introduced to relate the *Functional Unit Id* of the entire product from the functional model with the *Production Item Id* of Level II of the MWM model. The electrical function of the product is described by the attribute

Table 8: PDES Entities Used in Determining the Electrical GT Code

GT Digit	Code Attribute	Corresponding PDES entity	Model Level
1	Main Electrical Classification	• Layered Electrical Product	II
2-3	Electrical Function	• Defined Functional Unit Occurrence	functional
		• Defined Functional Sub-unit Occurrence	functional
4-5	Component Mounting Method	• Component	III
		• Component Type	III
		• Attachment Technique Type	III
		•Mechanical Attachment Technique	III
		• Electrical Attachment Technique	III
8-11	Hardware	• Attachment	III
		• Attachment Technique Type	III
		•Mechanical Attachment Technique	III
		• Electrical Attachment Technique	III
12	Component and Hardware Count	• Component	III
		• Attachment	III
13	Component Orientations	• Component Placement	III
21	Other Dimensions	• Component	III
		• User	
23	Substrate Type (insulation material)	• Layer	II
		• Material	III

Table 8: cont

GT Digit	Code Attribute	Corresponding PDES entity	Model Level
24-25	Additional Materials	• Layer	II
		• Layer Deposition	III
		• Passage Deposition	III
		• Passage Deposition Sequence	III

Functional Unit Id of the entities *Defined Functional Unit Occurrence* and *Defined Functional Sub-unit Occurrence* of the Functional model. For the sample part digits 2 and 3 received the values of 0 and 3, respectively indicating that the part functions as a pre-amplifier.

4.2.3 Digits 4-5: Component Mounting Method

All information required by this procedure is contained in Level III of the PDES model (see Table 8). The attribute *component type* of the entity *Component* describes the specific type of component; i.e., chip, die, axial, radial, etc. This information, coupled with the *attachment technique* captured by the entities *Component Type* and *Attachment Technique Type* provides all the necessary information to determine the component mounting method. For example, if the *component type* provided by the database query is "axial", and the *attachment technique* is "surface mount", then the mounting method is "non-standard surface mount" (see Fig. 15a). However, if the *attachment technique* provided by the database query is "thru-hole mount", then the resulting component mounting method is "standard thru-hole mount" (see Fig. 15b).

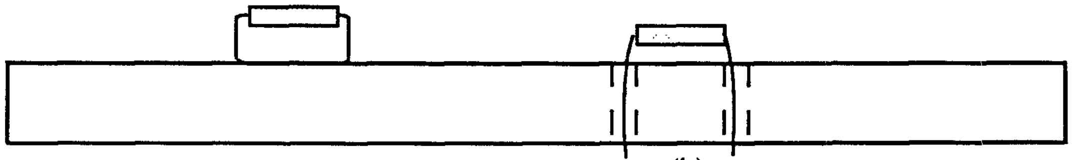


Fig. 15: Example of component mounting methods
(a) non-standard surface mount,
(b) standard thru-hole mount

The analysis of the entities *Component type*, *Component* and *Attachment Technique Type* yielded values of 0 and 3 for digits 4 and 5 of the sample part, respectively, indicating the board contains both standard and non-standard surface mounted components.

4.2.4 Digits 6-7: Component and Artwork Patterns

The entity *Component Placement* of Level III of the PDES model uses the attribute *axis-2 placement* to capture the location and orientation of components. Considering that the location of the component is defined by a point on one of the component leads and not a point on the actual component, and that the component lead dimensions were not described in the model, component patterns can not be derived from the PDES information. Furthermore, using the geometrical description of the artwork, a complex analysis would be required to determine artwork patterns. This was deemed outside the scope of this work and coding is performed through user input. The coding system assigns the proper code values based on the user's response and the coding scheme rules.

4.2.5 Digits 8-11: Non-Soldered and Soldered Hardware

As already discussed in chapter 3, hardware are classified into two types. The first type contains hardware that is attached mechanically, while the second hardware type requires electrical attachment. All necessary hardware information is captured by Level III of the PDES model (see Table 8). The first step of this procedure is to distinguish between soldered and non-soldered hardware by querying the attribute *electrical attachment technique id* of the entity *Attachment Technique Type*. If this query provides a specific id, then the hardware is soldered; if it returns a null value, then the hardware is non-soldered. The hardware type is extracted from the attribute *attachment description* of the entity *Attachment*. A string comparison, similar to that in the procedure of digit 1, is used to compare the *attachment description* with the specific types of hardware captured by the coding scheme.

For the sample part in Fig. 12 this procedure yielded values of 0, 9, 0 and 9 for digits 8 through 11, respectively, indicating the existence of both soldered and non-soldered hardware. The identified non-soldered hardware (digits 8 and 9) included i) screws, nuts, bolts, and/or rivets, and ii) spacers, stand-offs, cups, washers, housings, and/or FET mounts. The values of digits 10 and 11 show that the soldered hardware procedure determined the existence of i) ground pins and/or non-threaded terminals, and ii) ribbon jumpers and/or hairpins.

4.2.6 Digit 12: Total Number of Components and Hardware

This procedure performs three simple queries to the database. The existing instances of the entities *Component Type* and *Attachment* are counted. Furthermore, the functional artwork "components" are determined from the attribute *component type* of the entity *Component*. The total number of components and hardware, minus the number of functional artwork "components" is compared to the appropriate look-up table to provide the value of digit 12.

The results of this procedure for the sample part yielded a total of 8 components, 1 functional artwork "component" and 10 pieces of hardware on the substrate. Based on the look-up table in Appendix C, digit 12 assumed the value of 3.

4.2.7 Digit 13: Component Orientation

This procedure relies entirely on the data of PDES Level III. Note that the attribute *axis-2 placement* of the entity *Component Placement* indicates the location and orientation of each component with respect to the substrate. This procedure i) queries the entity *Component Placement* for the *axis-2 placement* of every component, ii) compares the *axis-2 placement* directions to the global coordinate system, and iii) assigns the appropriate value to digit 13 based on the GT code conventions. The value of 7 in digit 13 of the sample part's electrical code indicates components that are positioned in only three distinct orientations: parallel to the x axis, parallel to the y axis and skewed in only one direction.

4.2.8 Digits 14-20: Electrical Dimensions

Electrical dimensions include Timing, Bandwidth, Average Power Density, Current, Operating Frequency, Gain, Sensitivity, and Voltage. Since the PDES model, in its present form, does not cater for these dimensions, this procedure relies on user input. The user is prompted to select a particular range for each dimension from an appropriate table. The value of timing, bandwidth, average power density, operating frequency, gain and sensitivity, correspond to the entire module. For current and voltage, the maximum and minimum values encountered in the module are captured.

4.2.9 Digit 21: Other Dimensions

Dimensions described by digit 21 include lead pitch, component spacing, and artwork geometrical quantities. Only those dimensions that are less than or equal to a specific threshold value are captured.

Lead pitch is an attribute of the Level III entity *Component* and, thus, it can be extracted directly. However, the information contained in Level III on component dimensions and component placement is not sufficient to determine the spacing between adjacent components, nor the spacing between components and the substrate edge. Therefore, this information is provided by the user. Finally, artwork dimensions such as line width and line spacing are also provided by the user. Although Level I of the PDES model contains sufficient geometrical information to determine the latter, this was deemed beyond the scope of the present study.

4.2.10 Digit 22: Tolerances

This procedure also relies on user input to capture component placement accuracy, artwork etching tolerances, and plating tolerances. The user is prompted to input the minimum value for each existing tolerance type. The input is compared to pre-defined thresholds to yield the value of digit 22.

4.2.11 Digit 23: Substrate Type (Insulation Material)

This procedure queries the Level II entity *Layer* and the Level III entity *Material* (see also section 4.1.9) A string comparison is performed to match the resulting information with a list of insulation materials to determine the appropriate GT value. For the sample product of Fig. 12 the insulation layer material was determined to be Polyimide and the a value of 2 was assigned to digit 23.

4.2.12 Digit 24-25: Additional Materials

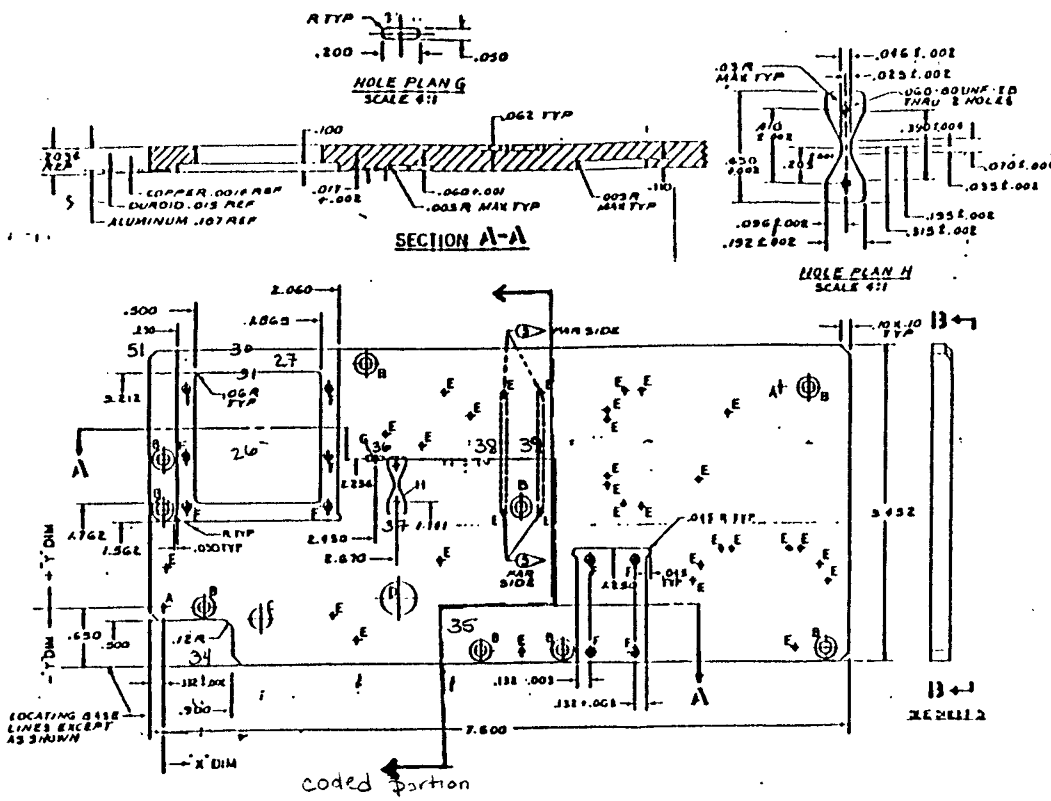
These digits capture plating and pre-tinning materials. Since pre-tinning information is not included in the PDES model, these data are provided by the user. In contrast, extensive plating information is captured in Level III (see Table 8). The entity *Layer Deposition* captures substrate and circuit plating information, while the entity *Passage Deposition* captures thru-hole plating information. In addition, the entities *Layer* and *Passage Deposition* contain information on both the layer being deposited (plating), as well as the layer being plated (base). The system queries each *Layer Deposition* entity, identifies the base layer, and uses the coding scheme rules to assign the proper code value. Furthermore, each *Passage Deposition* is related to a particular form feature. The system verifies that the form feature is a thru-hole (passage) and determines the appropriate GT value for passage plating. The values of 1 and 3 in digits 24 and 25 of the sample part code indicate the presence of pre-tinning, as well as circuit and substrate additional platings.

5 APPLICATION

The mechanical drawing of the bare substrate of an RF pre-amplifier manufactured by Westinghouse ESG is shown in Fig. 16. The product's mechanical GT code is also shown in Fig. 16. The assembly drawing of the RF pre-amplifier is shown in Fig. 17 along with its corresponding electrical GT code. The corresponding PDES database consists of 26 tables. In addition to the GT codes, the system provides detailed information on the attributes captured by the codes. The latter is used in the manufacturability evaluation module of the concurrent engineering framework [Rathbun, 1992]. Specifically, an itemized list of all features and tolerances, as well as components and hardware information, electrical dimensions, tolerances and additional materials are in the appropriate output files. These files for the RF pre-amplifier are given in Appendix D.

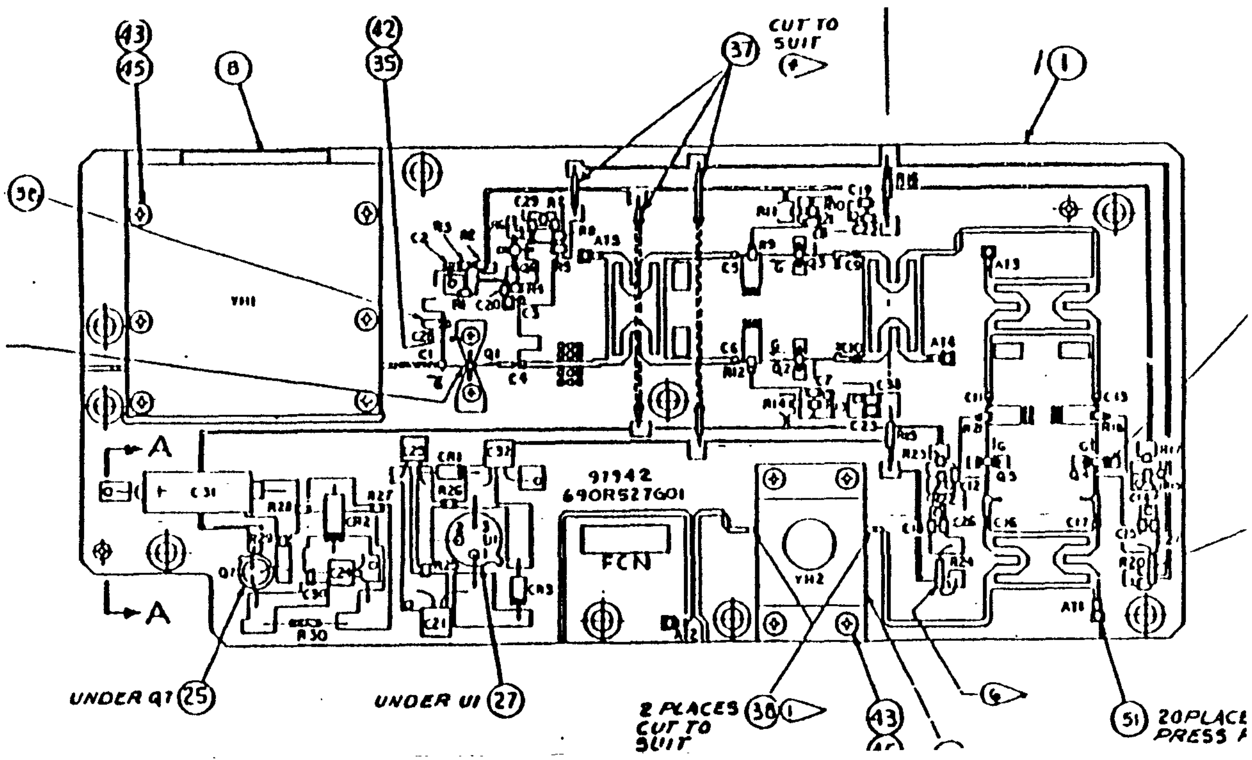
5.1 Mechanical GT Code Generation

Figure 18a shows the output provided by the system upon the completion of the digit 1 procedure. Six planar faces were identified. The perpendicularity of the face pairs was examined, and the part envelope was determined to be prismatic. Subsequently, the separation distances for each pair of faces was computed. The thickness was found to be less than 0.125 inch and, thus, digit 1 was assigned the value of 5 (flat MICLASS part). The part envelope dimensions were ordered by size and labeled as A, B, and C. An orientation check was also performed to



MICLASS DIGIT #:	1	2	3	4	5 6	7 8	9 10	11 12	13	14 15	16	17	18
MICLASS CODE:	5	9	2	6	0 1	36	3 1	0 9	7	0 2	5	4	9

Fig. 16: RF Pre-Amplifier bare substrate



ELECTRICAL CODE #:	1	2 3	4 5	6 7	8 9	1 1 0 1	1 2	1 3	1 1 1 1 1 1 2 2 2 4 5 6 7 8 9 0 1 2	2 3	2 2 4 5
CODE VALUE:	3	0 3	0 3	1 0	0 9	1 3	6	9	3 4 5 1 5 4 2 1 7	1	1 3

Fig. 17: RF Pre-Amplifier assembly

```
Number of plane faces in the assembly shell = 6
Total number of faces in the shell = 6
Number of cylindrical faces in shell = 0

This part is Prismatic


Dimension A = 4.565000
Dimension B = 3.482000
Dimension C = 0.203400

This part is flat rectangular

DIGIT 1 = 5
```

(a) Digit 1 Output Screen

```
NUMBER OF ALONG FEATURE SWEEP DEPRESSIONS = 1

NUMBER OF ALONG FEATURE SWEEP PASSAGES = 3

NUMBER OF IN-OUT FEATURE SWEEP DEPRESSIONS = 4

NUMBER OF IN-OUT FEATURE SWEEP PASSAGES = 1
```

(b) Preliminary Classification Output Screen 1

```
NUMBER OF AXISYMMETRIC FEATURE SWEEP DEPRESSIONS = 5

NUMBER OF AXISYMMETRIC FEATURE SWEEP PASSAGES = 24

NUMBER OF COUNTERBORES = 5
```

(c) Preliminary Classification Output Screen 2

```
NUMBER OF EDGE_FLATS = 3

NUMBER OF EDGE_ROUNDS = 0

NUMBER OF CORNER_BLENDS = 0

NUMBER OF PROTRUSIONS = 0

NUMBER OF AREA FEATURES = 2

NUMBER OF EMBOSS DEFORMATIONS = 0

NUMBER OF PARTIAL CUT_OUTS DEFORMATION = 0
```

(d) Preliminary Classification Output Screen 3

```
            SUMMARY OF CUT-OUTS

The following types of cut-outs have been detected:

Complex Cut-out(s)
Rectangular Cut-out(s)
Slanted Cut-out(s)


DIGIT 2 = 9
```

(e) Digit 2 Output Screen

```
SUMMARY OF HOLES PERPENDICULAR TO THE AB PLANE

The following hole features have been detected:

Holes in a Line Pattern


DIGIT 3 = 2
```

(f) Digit 3 Output Screen

```
      SUMMARY OF MACHINED SECONDARY ELEMENTS

The following types of features have been detected:

Complex Cavity(s)
Slot(s) and/or Flat(s)


DIGIT 4 = 6
```

(g) Digit 4 Output Screen

```
        SUBSTRATE FUNCTION

    VALUE        DESCRIPTION
      0              Other
      1              MWM Substrate
      2              PWB Board
      3              HMA Substrate
      4              Unknown

Enter the Appropriate Value From the Table Above:
>Description for 01 is MWM Substrate

Is Selection Correct? (y or n)
>


DIGIT 5 = 0
DIGIT 6 = 1
```

(h) Digits 5-6 Output Screen

Fig. 18: Mechanical GT code generator output screens (Digits 1-6)

verify that the part envelope is oriented properly with respect to the global coordinate system.

The preliminary classification procedure described in section 4.1.2 sorted all existing features according to the MICLASS types. Features 43, 44 and 51 were all represented in the database as *edge flat transitions*. Feature 51 was classified as a cutout to be coded by digit 2, since it blends two faces with face normals in the x-y plane. Features 43 and 44 were classified as flats to be further processed by the digit 4 procedure. Feature 42 is a corner blend transition and was designated to be processed by the digit 4 procedure. Features 34 and 35 are both along feature sweep passages in the x-y plane and were assigned to the digit 2 procedure for further processing. Feature 26, which was defined by an along feature sweep depression of a general profile, was assigned to the procedure of digit 4. Features 36, 37, 38 and 39 are all in-out feature sweep depressions of general profiles, while feature 27 is an in-out feature sweep passage of general profile. They were all assigned to the digit 4 procedure. Features 1-13, 15, 17, 19, 21, 23-25, 28, 40-41 and 45 are all constant diameter axisymmetric feature sweeps perpendicular to the x-y plane and were assigned to the digit 3 procedure for further analysis. All of the remaining features of the part, such as threads, are not captured by the MICLASS code.

Figure 18e illustrates the output provided to the user upon completion of the digit 2 procedure. A value of 9 in position 2 implies the existence of both complex and simple cutouts. More specifically, the output indicates that the part includes rectangular, slanted and complex cutouts. Both features 34 and 35 were defined by along feature sweep passages of general profiles. The detailed analysis of the profile curves identified feature 34 as a complex cutout and feature 35 as a rectangular cutout. Feature 51, the edge blend transition, was classified as a slanted cutout. These results are also contained in the output file in Appendix D.

The value of digit 3 of the code is 2 indicating the existence of a line pattern of holes all having a diameter less than five times the envelope thickness. This information is reflected in the output shown in Fig. 18f. The corresponding output file (Appendix D) indicates that 24 holes were identified, all of them perpendicular to the x-y plane. The output file also indicates that both counterbore holes and threaded holes were identified. This is indicated by the value of 5 that corresponds to perpendicular hole additions.

Figure 18g shows the output provided by the digit 4 procedure. It indicates the existence of flats and/or slots as well as complex cavities. Features 42-44 are all flat transitions and therefore were classified as flats. Features 26, 27, 36, 38 and 39 were classified as slots. All these features were defined by general profiles containing more than one curve. Therefore, a detailed analysis of the profile curves was performed to distinguish between slots and complex cavities. Furthermore, feature 37, an in-out feature sweep depression of general profile, was characterized as a complex cavity. According to the MICLASS coding rules the value of 6 was assigned to digit 4. The feature file indicates that features 38 and 39 are located at the bottom face of the substrate, while the remaining features are located at the top face.

The dimensions of the part are represented in positions 7 through 12 of the code, which assumed the values of 3, 6, 3, 1, 0 and 9 respectively. This is consistent with the part envelope dimensions calculated in digit 1.

Figure 19d shows that the database queries to the entities *Layer* and *Material* of Levels II and III, respectively, determined the materials of the insulation layer and the ground plane to be polyimide and 6061 aluminum, respectively. This material combination corresponds to the values of 0 and 2 in digits 14 and 15.

Figure 19g illustrates the results of the digit 18 procedure. Features perpendicular to the x-y plane, skewed to one plane, and features skewed to more than one plane were found. The output file, Appendix D, shows the detailed feature orientations. Feature 44 is a corner flat transition and is classified as skewed to more than one plane. The face normal analysis of the two edge flat transitions determined features 42 and 43 to be skewed to only one plane. The remaining six features classified by digit 4 were all determined to be perpendicular to the x-y plane by examining the directions of their corresponding *axis-2 placements.*

The procedures for digits 5, 6, 13, 16 and 17 are all interactive. Their user selection screens are shown in figures 18h and 19 b, c, e and f, respectively. The part functions as an MWM substrate, which results in 0 and 1 for positions five and six respectively. Since the user indicated the existence of length, positional, and diameter tolerances, digit 13 receives a value of 7. A value of 5 in position 16 implies that the raw material form is a flat plate. Finally, a value of 4 in digit 17 indicates a production quantity range of 251 to 750 pieces.

```
Dimension A =  4.565000 inches

DIGIT 7 = 3
DIGIT 8 = 6

Dimension B = 3.482000 inches

DIGIT  9 = 3
DIGIT 10 = 1

Dimension C = 0.203400 inches

DIGIT 11 = 0
DIGIT 12 = 9
```

(a) Digits 7-12 Output Screen

```
The following 15 questions pertain to the geometric tolerances on
this part.  Please answer all of the questions with 'y' or 'n'.

Does the part have Diameter Tolerance <= 2 mils? (y or n)
> Does the part have Positional Tolerance <= 2 mils? (y or n)
> Does the part have Length Tolerance <= 0.5 mils? (y or n)
> Does the part have Roundness Tolerance <= 0.2 mils? (y or n)
> Does the part have Cylindricity Tolerance <= 0.2 mils? (y or n)
> Does the part have Flatness Tolerance <= 2 mils? (y or n)
> Does the part have Straightness Tolerance <= 2 mils? (y or n)
> Does the part have Profile Tolerance <= 2 mils? (y or n)
> Does the part have Concentricity Tolerance <= 2 mils? (y or n)
> Does the part have Perpendicularity Tolerance <= 2 mils? (y or n)
> Does the part have Angularity Tolerance <= 2 mils? (y or n)
> Does the part have Parallelism Tolerance <= 2 mils? (y or n)
> Does the part have Symmetry Tolerance <= 2 mils? (y or n)
> Does the part have True-Position Tolerance <= 2 mils? (y or n)
> Does the part have Run-out Tolerance <= 2 mils? (y or n)
>
```

(b) Digit 13 Output Screen 1

```
The following tolerances have been selected for this part:

Diameter Tolerance <= 2 mils
Positional Tolerance <= 2 mils
Length Tolerance <= 0.5 mils

Is the above selection correct? (y or n)
>

DIGIT 13 = 7
```

(c) Digit 13 Output Screen 2

```
Materials :  Insulation Layer : PTFE(Duroid)
             Ground Plane     : 6061 Aluminum


DIGIT 14 = 0
DIGIT 15 = 2
```

(d) Digits 14-15 Output Screen

```
                FORM OF RAW MATERIAL

VALUE       RAW MATERIAL DESCRIPTION
0           Other
1           Round Bar Stock
2           Round Tube or Round Pipe
3           Hexagonal Bar Stock,
4           Square or Rectanguler Bar Stock
5           Sheet Stock less than or equal to 0.25 inches thick
6           Plate Stock greater than 0.25 inches thick
7           Cast or Molded
8           Forged
9           Extruded Shapes

Enter the Appropriate Raw Material Value From Table Above:
>Description for 5 is Sheet Stock less than or equal to 6mm (.25inches)
thick

Is Selection Correct? (y or n)
>

DIGIT 16 = 5
```

(e) Digit 16 Output Screen

```
               PRODUCTION QUANTITY

VALUE      PRODUCTION QUANTITY DESCRIPTION
0          Quantity from      1  --  to  --      5 parts.
1          Quantity from      6  --  to  --     25 parts.
2          Quantity from     26  --  to  --     75 parts.
3          Quantity from     76  --  to  --    250 parts.
4          Quantity from    251  --  to  --    750 parts.
5          Quantity from    751  --  to  --   2500 parts.
6          Quantity from   2501  --  to  --   7500 parts.
7          Quantity from   7501  --  to  --  25000 parts.
8          Quantity from  25001  --  to  --  75000 parts.
9          Quantity Greater than             75001 parts.

Enter the Appropriate Value From the Table Above:
>
Description for 4 is Quantity from    251  --  to  --    750 parts

Is Selection Correct? (y or n)
>

DIGIT 17 = 4
```

(f) Digit 17 Output Screen

```
SUMMARY OF MACHINED SECONDARY ELEMENT ORIENTATIONS

The following orientations have been detected:

Feature(s) Perpendicular to AB Plane
Feature(s) Skewed to One Plane
Feature(s) Skewed to More Than One Plane


DIGIT 18 = 9
```

(g) Digit 18 Output Screen

```
              MICLASS GT CODE

Digits :  0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1
          1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8

GT Code : 5 9 2 6 0 1 3 6 3 1 0 9 7 0 2 5 4 9


press return to continue
```

(f) Final Output Screen

Fig. 19: Mechanical GT code generator output screens (Digits 7-18)

5.2 Electrical GT Code Generation

The assembly drawing of the RF pre-amplifier is shown in figure 17 along with its corresponding electrical GT code. The output file that was generated for this product is given in Appendix D.

Figure 20a shows the results of the digit 1 procedure. The attribute *electrical product type* of the Level II entity *Layered Electrical Product* indicated that the product under consideration is an MWM (Digit 1 value = 3). Figure 20b shows that the MWM functions as a pre-amplifier. This information was determined from the entity *Functional Unit Occurrence* of the functional model. The resulting values for digits 2 and 3 were 0 and 3, respectively.

Figure 20c shows the output of the procedure for digits 4 and 5. The board was determined to contain both standard and non-standard surface mounted components. The resulting values of positions 4 and 5 are 0 and 3, respectively. Detailed component information was also provided to the output file (Appendix D). In this file, all components of the module are listed, along with the component type and the corresponding minimum lead pitch. The component type was provided by queries to the entity *Component*. The resulting type, combined with the attachment method, which was obtained from the *Attachment Technique Type* entity, provided the necessary data for the component mounting method classification. The lead pitch was also obtained from querying the entity *Component*.

Digits 8 through 11 represent hardware and assumed the values of 0, 9, 1 and 3, respectively. The corresponding information was extruded

```
Part type is:

DIGIT 1 = 3
```

(a) Digit 1 Output Screen

```
Product Function is: PRE
AMPLIFIER

DIGIT 2 = 0
DIGIT 3 = 3
```

(b) Digits 2-3 Output Screen

```
     SUMMARY OF COMPONENT MOUNTING METHODS

The following mounting methods have been detected:

Standard Surface Mount
Non-Standard Surface Mount

DIGIT 4 = 0
DIGIT 5 = 3
```

(c) Digits 4-5 Output Screen

```
The following 4 questions pertain to Component and
Artwork patterns.

NOTE: 1. Components lie on a grid pattern if their
         centers are located on grid points,
         regardless of component orientation.
      2. Artwork lies on a grid pattern if the
         traces and pads of the artwork border
         grid lines.

Please answer each of the following questions
by typing 'y' or 'n'.

Do any components lie on a grid pattern? (y or n)
>Are any components randomly placed? (y or n)
>Does any artwork lie on a grid pattern? (y or n)
>Is there random artwork? (y or n)
>
```

(d) Digits 6-7 Output Screen 1

```
The following component and artwork patterns have been
specified for this part:

Random Component Placement
Random Artwork Placement

Are the above selections correct? (y or n)
>


DIGIT 6 = 1
DIGIT 7 = 0
```

(e) Digits 6-7 Output Screen 2

```
                 SUMMARY OF HARDWARE

The following groups of non-soldered hardware have been detected:

* Screws, Nuts, Bolts, and/or Rivets
* Spacers, Stand-offs, Cups, Washers, Housings, and/or FET Mounts


The following groups of soldered hardware have been detected:

* Ground Pins and/or Non-Threaded Terminals
* Wire Jumpers, Solder Preforms, Coaxial Cables, and/or Isolators
* Ribbon Jumpers and/or Hairpins


DIGIT  8 = 0
DIGIT  9 = 9
DIGIT 10 = 1
DIGIT 11 = 3
```

(f) Digits 8-11 Output Screen

```
SUMMARY OF COMPONENT/HARDWARE COUNT

Number of Artwork Components = 1
Total Number of Components = 39
Number of Pieces of Hardware = 60


DIGIT 12 = 6
```

(g) Digit 12 Output Screen

```
        SUMMARY OF COMPONENT ORIENTATIONS

The following component orientations have been detected:

Component(s) Parrallel to A axis
Component(s) Parrallel to B axis
Component(s) Skewed in Only One Direction
Component(s) Skewed in Multiple Directions


DIGIT 13 = 9
```

(h) Digit 13 Output Screen

Fig. 20: Electrical GT Code Generator Output Screens (Digits 1-13)

from the entities *Attachment* and *Attachment Technique Type* of Level III. Figure 20f lists the non-soldered hardware that exist in the MWM under consideration (digits 8 and 9), i.e.; i) screws, nuts, bolts, and/or rivets, and ii) spacers, stand-offs, cups, washers, housings, and/or FET mounts. The results of the soldered hardware procedure, captured by digits 10 and 11, indicate the existence of i) ground pins and/or non-threaded terminals, ii) ribbon jumpers and/or hairpins and iii) wire jumpers, solder preforms, coaxial cables, and/or isolators. The output file in Appendix D identifies each piece of hardware.

Digit 12 assumed the value of 6, since a total of 98 components and pieces of hardware were carried by the substrate. The output of the digit 12 procedure (see Fig. 20g) shows that 1 artwork "component", 39 total components and 60 pieces of hardware were found.

Figure 20h shows that digit 13 of the code assumed a value of 9, indicating components i) parallel to the x axis, ii) parallel to the y axis, iii) skewed in only one direction and iv) skewed in multiple directions

The digit 23 procedure queries the entities *Layer* and *Material* for the insulation layer material. The results are shown in Fig. 21f. A value of 1 in position 23 corresponds to a Poly Tetra Flouro Ethalene (PTFE) insulation layer. The values of 1 and 3 in positions 24 and 25 indicate pre-tinning, circuit and substrate platings. These results were obtained from queries to the entities *Layer Deposition* and *Passage Deposition.* The output file in Appendix D, contains an itemized list of all of the platings identified in this part, as well as the corresponding plating thickness and tolerance. The output of this procedure is shown in Fig. 21g and indicates the existence of 1 circuit (artwork) plating, 2 substrate platings, as well as 24 pre-tinned component leads.

```
VALUE     TIMING DESCRIPTION

1         DC - 100 millisec

2         10 millisec <= t < 100 millisec

3         1 microsec <= t < 10 millisec

4         100 nanosec <= t < 1 microsec

5         10 nanosec <= t < 100 nanosec

6         1 nanosec <= t < 10 nanosec

7         t < 1 nanosec

Please enter the value 1-7 corresponding to the
appropriate range of the Timing for the part.
```

(a) Digit 14 Output Screen 1

```
User has selected 1 microsec <= t < 10 millisec

Is Selection Correct? (y or n)
>

DIGIT 14 = 3
```

(b) Digit 14 Output Screen 2

```
Minimum Lead Pitch: 0.020000

Please enter the smallest distance between adjacent
components (in inches).

Please enter the smallest distance between a component
and the substrate edge (in inches).

Please enter the smallest artwork line width on the
part (in inches).

Please enter the smallest distance between adjacent
lines of artwork (in inches).

Please enter the smallest distance between a line of
artwork and the substrate edge (in inches).
```

(c) Digit 21 Output Screen 1

```
The following values have been entered:

Distance between Components 0.050000
Distance between Components and Edge 0.100000
Artwork Line Width 0.025000
Distance between Lines of Artwork 0.005000
Distance between Artwork Lines and Edge 0.050000

Is this correct? (y or n)
>

DIGIT 21 = 1
```

(d) Digit 21 Output Screen 2

```
The following questions pertain to the fabrication
and assembly tolerances of the part being coded.

Please enter the smallest Placement accuracy (in inches).

Please enter the smallest Artwork etching tolerance (in inches).

Please enter the smallest Substrate Plating tolerance (in inches).

Please enter the smallest Artwork Plating tolerance (in inches).

The following tolerances have been entered:

Placement accuracy = 0.004000
Artwork etching tolerance = 0.000500
Substrate Plating tolerance = 0.000300
Artwork Plating tolerance = 0.000700

Is the above selection correct? (y or n)
 >
DIGIT 22 = 7
```

(e) Digit 22 Output Screen

```
Insulation Layer Material: PTFE(Duroid)

DIGIT 23 = 1
```

(f) Digit 23 Output Screen

```
SUMMARY OF PLATINGS AND PRE-TINNINGS

Number of Artwork platings = 1
Number of Substrate platings = 2
Number of ThruHole platings = 0

Please enter the total number of component leads and
component pads that need to be pre-tinned.

24 Component leads and pads require pre-tinning.
Is this correct? (y or n)
>

DIGIT 24 = 1
DIGIT 25 = 3
```

(g) Digit 23 Output Screen

```
                    ELECTRICAL GT CODE

Digits :  0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2
          1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5

GT Code : 3 0 3 0 3 1 0 0 9 1 3 6 9 3 4 5 1 2 4 2 1 7 1 1 3

press return to continue
```

(h) Final Output Screen

Fig. 21: Electrical GT code generator output screens (Digits 14-25)

The remaining electrical coding procedures, digits 6, 7, 14-21 and 22 all rely on user input. The output for the procedure of digits 6 and 7 is shown in Fig. 20d. The resulting values 1 and 0 indicate the existence of random component and artwork patterns. As already discussed in chapter 4, digits 14 through 22 describe electrical specifications. Digits 14 through 20 represent various electrical dimensions. Figure 21a and b shows an example of the timing output (digit 14). The user is prompted to select the appropriate timing range for the part being coded. Digit 21 captures geometrical dimensions that have electrical significance, such as component spacing and artwork spacing (see chapter 4). Although the lead pitch is obtained directly from the Level III entity *Component*, the remaining information is provided by the user. A sample screen from this procedure is presented in Fig. 21c and d. Note that the user is prompted to enter minimum values for artwork spacing, artwork line width and component spacing. Finally, a sample screen for digit 22 is shown in Fig. 21e. The user is prompted to enter specific values for various tolerance types.

The above example demonstrates the capabilities of the automated GT coding system. The results are provided by the system with minimum user interaction, are consistent with manual coding and error-free. The system also provides a detailed list of critical detailed information on the attributes captured by both portions of the GT code. The resulting output files provide the necessary input to the manufacturability evaluation module of the life cycle engineering system. It is noted that an experienced engineer would one to three hours in order to generate the GT code for the above example manually. Using the automated GT code generating system the part was coded correctly in approximately 10 minutes to run. For detailed description of how to use the above system see [Kinsey and Rathbun, 1992].

6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

6.1 Conclusions

This study applied GT to electrical/mechanical assemblies, specifically microwave modules (MWM). Since all existing GT coding schemes for electronic parts developed so far are proprietary, a novel GT scheme was developed for MWM's comprising two portions. The first portion employed the existing MICLASS scheme for flat parts to describe critical mechanical attributes. The electrical portion consists of 25 digits and was developed at the University of Maryland. It captures information critical to the fabrication and assembly of MWM's. The resulting coding scheme served as the primary input to an automated manufacturability evaluation system (see Fig. 1). However, the code could be applied to various other CIM systems such as automated process planning and plant layout, as well as the standard GT applications.

In order to streamline the coding process, an automated GT system was developed to generated the GT codes from a PDES information model. In addition to the GT code, the system provides detailed information corresponding to each attribute captured by the code. This information is used for manufacturability evaluation. Automated coding eliminates ambiguities and results in a consistently coded part base. In addition, it requires minimum human effort, which has been the impeding factor in the wide spread use of GT. This study showed that a feature based model is critical for automated coding, since the reasoning employed in GT code generation is also feature based. It is noted that translation of the coding scheme conventions to the PDES model definitions is specific to the GT coding scheme used.

PDES was found to be a very adequate source of product information to drive the automated GT coding system, as well as other CIM systems. Since PDES information models are feature based they cater for automated GT code extraction. However, this application of PDES did identify a few weaknesses of the PDES standard. In particular, the lack of a feature hierarchy, component placement and electrical dimensions.

Although the primary output of the automated coding system is a GT code, it also provides the necessary detailed information required by the manufacturability evaluation module. Furthermore, since the coding system performs a very detailed analysis of the product i.e., feature-by-feature, component-by component, and has employed PDES as its input, the automated GT code generation system could be modified in a straight-forward manner to provide the input necessary for other CIM systems such as automated process planning and plant layout.

6.2 Recommendations for Further Work

Enhancements to the GT Coding Scheme

Although the electrical GT coding scheme developed in this research was designed to be expandable to other types of electronic assemblies, it was only fully developed for MWM's (see chapter 3). Thus a natural extension of this work is to further develop the coding scheme for printed wiring board assemblies (PWA) and hybrid microwave assemblies (HMA).

Enhancements to the Automated Coding System

In the current translation, only the most common PDES feature definitions were used. In addition, the mechanical GT code generator is only developed for MICLASS flat parts. The system could therefore be enhanced to include all MICLASS main shape types.

The electrical GT code generator may also be improved to eliminate some of the user input required for artwork spacing and line width. As mentioned in section 4.2, the information available from the PDES model Levels I and II is probably sufficient to determine these dimensions. Furthermore, appropriate enhancements of the PDES model to include tolerances, electrical dimensions and more complete component placement information would reduce drastically the user input. In addition, an object oriented database would represent the hierarchical structure of the entities of the PDES model in a less ambiguous manner than a relational database and, therefore, simplify the logic of the automated GT coding system.

Finally, the automatic generation of PDES files from IGES files is a necessity for the practical use of the automated GT code generation system. Currently the National Institute of Standards and Technology has a system that will translate the IGES file of very simple parts into a PDES geometry and topology information model. However, this is only a small portion of the required coding information, and therefore, a more complete translator is required.

APPENDIX A

This appendix contains the complete descriptions of the various PDES features discussed in chapter 2.

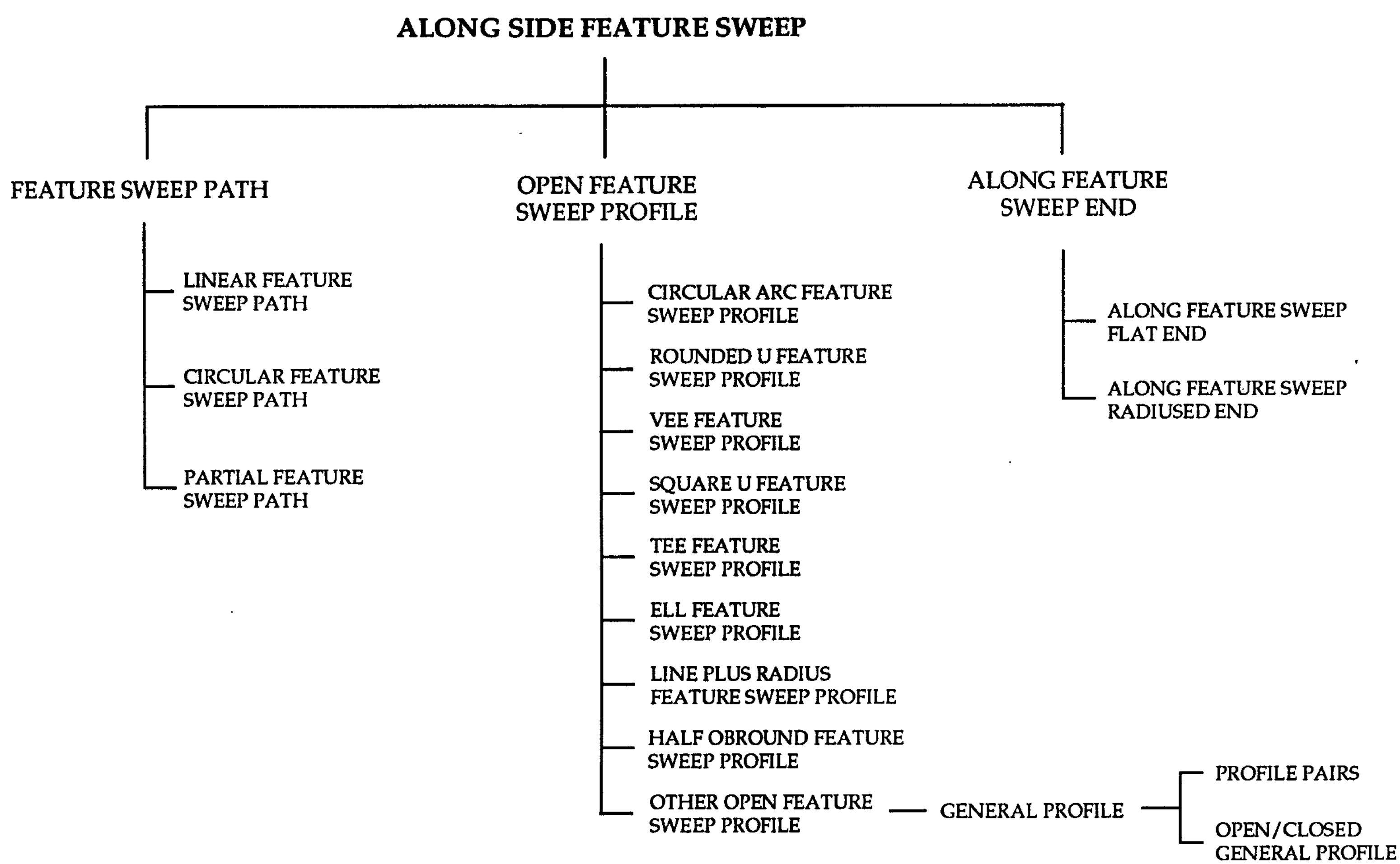


Fig. A-1: PDES Along Feature Sweep tree structure [Bahadur et al., 1991]

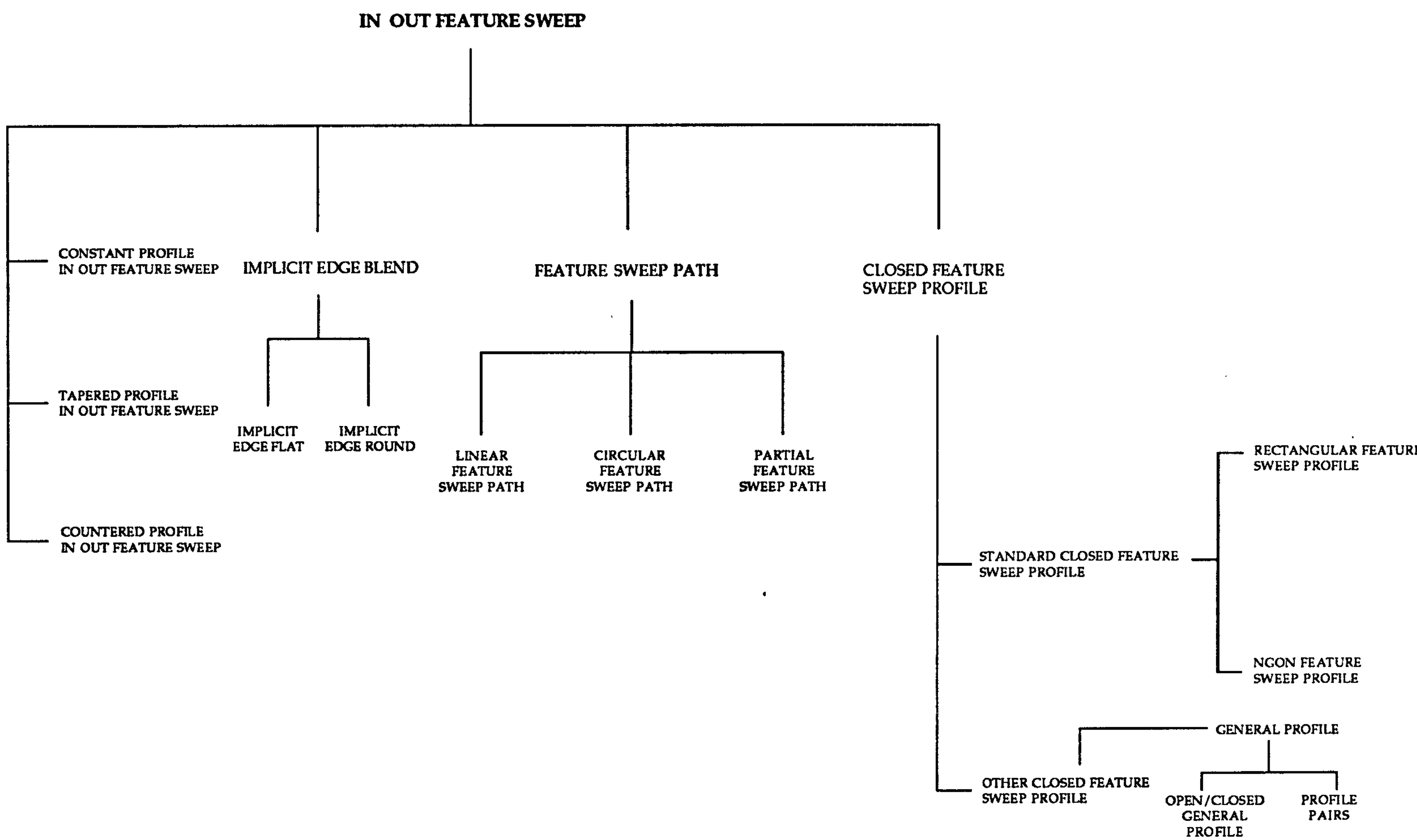


Fig. A-2: Tree structure for PDES In Out Feature Sweeps [Bahadur et al., 1991]

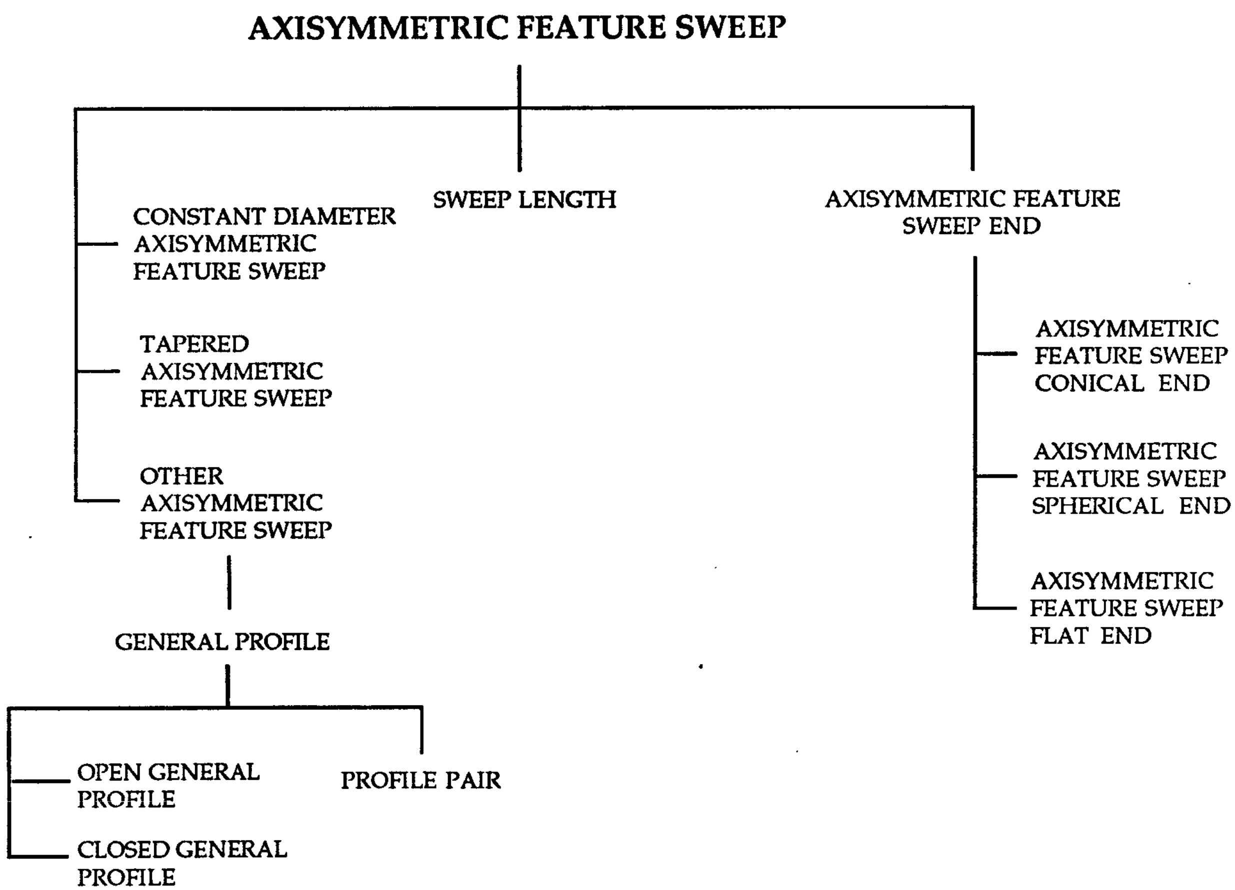


Fig. A-3: Tree structure for PDES Axisymmetric Feature Sweeps [Bahadur et al., 1991]

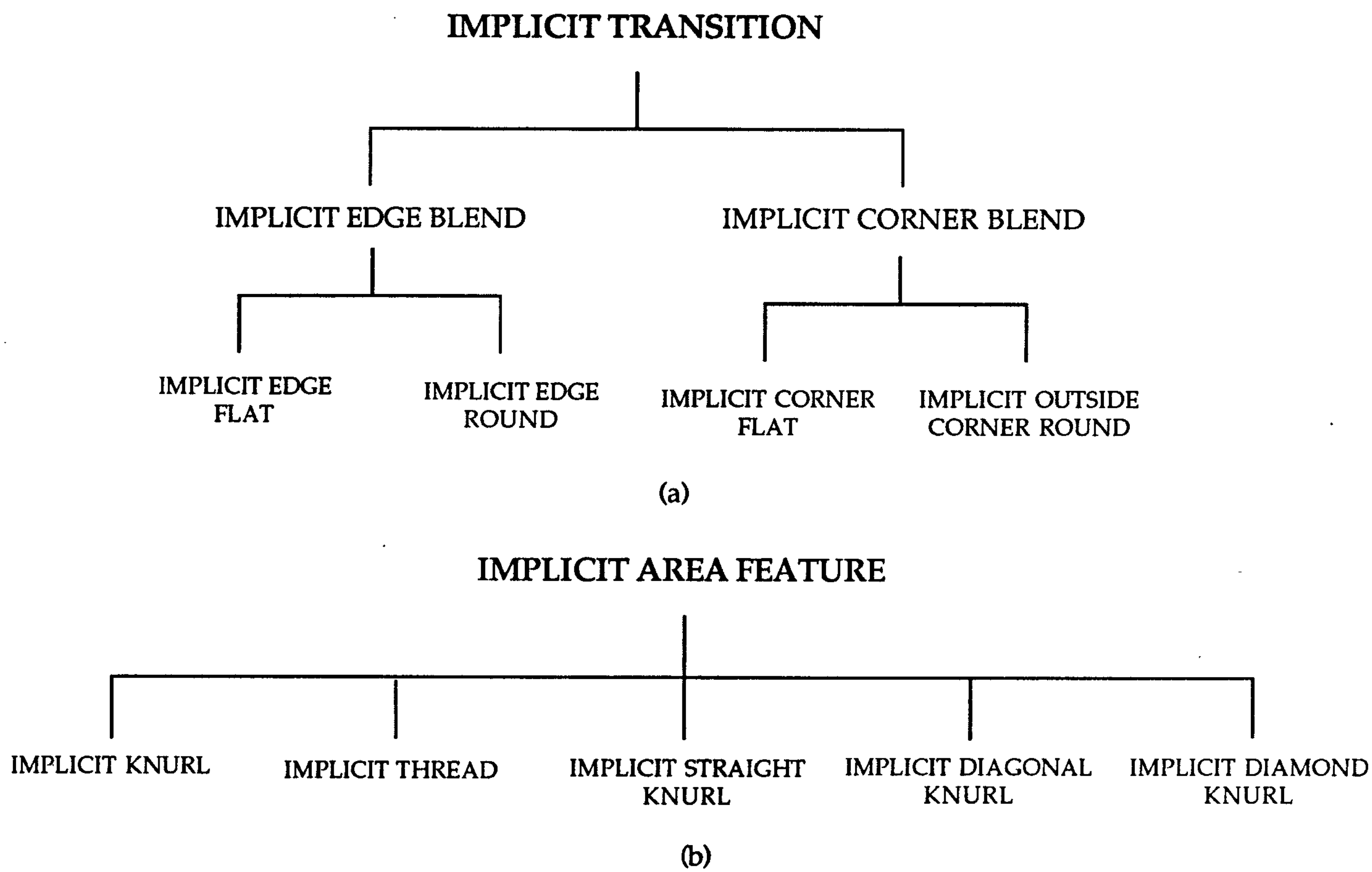


Fig. A-4: Tree structure for (a) PDES Implicit Transition, (b) PDES Implicit Area Feature [Bahadur et al., 1991]

APPENDIX B

This appendix outlines the MICLASS coding scheme for flat parts, and gives a synopsis of the MICLASS coding rules that were implemented by the mechanical GT code generating system. For more detailed information see [OIR Multi-M, 1986].

Main Shape

MICLASS has nine main shape categories, eight of which classify discrete parts and one that describes basic assemblies. Discrete parts are classified into four round and four non-round types. According to the MICLASS rules, MWM's are classified as flat parts.

A part is considered flat if it does not qualify as a round part, its thickness is less than or equal to 0.25 in. (6 mm), and it does not contain any major deformations, such as those generated by bending or deep drawing. Since the machining processes of round MWM substrates are virtually identical to those of prismatic substrates, this study does not make any distinction between the two shapes. A flat part receives a value of 5 in the first position of the code.

Cutouts

For flat parts, the second digit of the code describes the shape of the part perimeter and the existence of cutouts. According to MICLASS, "a cutout is an absence of material which alters the perimeter of a plain rectangle." The feature must be located along the perimeter of the part, pass completely through it and be perpendicular to the top and bottom faces of the part envelope. Four types of cutouts are considered: simple rectangular, simple slanted, simple radiused, and complex. Figure 9 (features 1-4) shows typical examples of slanted, rectangular, radiused, and complex cutouts. It is noted that the corner radii of rectangular cutouts should be less than 0.125 in.

Holes

Digit 3 of the code captures configurations of holes that are perpendicular to the primary plane of the flat part. Three types of hole patterns are identified; line, arc, and random. Hole patterns may contain thru-holes, blind holes and holes of varying diameter. The maximum hole diameter is also classified as either less or greater than five times the part thickness.

Secondary Machined Elements

Digit 4 of the code describes the existence of any secondary machined features that are not captured by digits 2 or 3. Secondary machined elements include: holes not perpendicular to the primary plane of the part envelope, flats, slots, complex cavities, and minor deformations (i.e. dimpling, louvering, and piercing). Secondary machined elements may pass either partially or completely through the part.

A flat is a planar surface on a part that is not created by a turning process. If two flats intersect to form a V-shaped cavity of less than 90^0, neither surface is considered a flat. If two flats intersect to form an L-shaped cavity of exactly 90^0, the larger surface is considered to be a flat. If two flats intersect to form a V-shaped cavity greater than 90^0, both surfaces are considered to be flats. Figure 10a shows an example of a flat.

A slot is defined as a cavity the sides of which are continuous and either parallel or concentric. In addition, the length of the side may not equal its width. For example, feature 2 in Fig. B-1 is a slot, while feature 4 is not. A slot may also have either ends, a bottom, or both. The definition of a slot with parallel sides and ends may also include radiused corners that create a right angle corner (see feature 1, Fig. B-1). If a cavity fails to be a slot, it is coded as a complex cavity. Features 2 and 3 of Fig. B-1 illustrate a slot and a complex cavity, respectively.

Functional Description

Digits 5 and 6 of the code capture the mechanical function of the part. Company specific functions are provided in a look-up table that includes all manufactured items of the particular company. In this study the mechanical function list has been customized to include: PWA board, HMA substrate, MWM substrate, and Other (see Table B-1). These choices represent only the bare board (substrate) without the components and hardware of the assembly.

Table B-1: Functional Description

Code Value	Functional Description
00	Other
01	MWM Substrate
02	Printed Wiring Board
03	HMA Substrate
04	Unknown

Dimensions

Digits 7 through 12 describe the principle geometric dimensions of the part envelope, i.e. length, width, and thickness. The dimensions are determined by considering the three principle planes that construct an envelope encapsulating the part. These three planes are always mutually perpendicular, and the longest dimension is labeled as A, the second longest dimension is labeled as B, and the smallest dimension is labeled as C (see Fig. B-1). For round parts the A axis should be chosen as any axis that lies in the radial direction. The B axis is also in the radial direction of the part and is orthogonal to A. A look-up table is used to associate ranges of dimensions with specific code values.

Tolerances

MICLASS accounts for fifteen different mechanical tolerances and it groups them into five distinct categories: length, position, diameter, type A and type B. Type A and B tolerances include single indicator and double indicator tolerances, respectively. Type A tolerances include: roundness, cylindricity, flatness, straightness, and profile. Type B tolerances include: concentricity, perpendicularity, angularity, parallelism, symmetry, true position, and run-out. Tolerances are described using a threshold value. If a specific tolerance is less than or equal to the threshold, then it is captured in the code. Otherwise, it is ignored. The threshold value is company-specific.

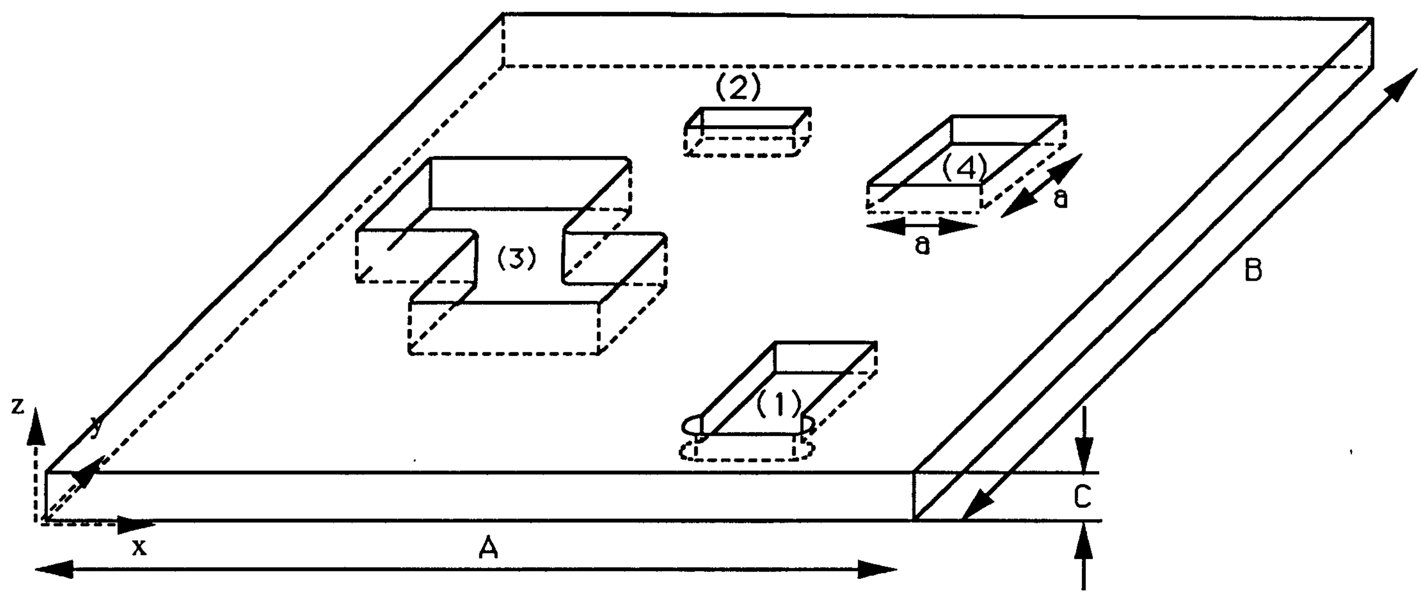


Fig. B-1: Examples of MICLASS slots and complex cavities

Material

Digits 14 and 15 describe material chemistry. A company specific look-up table is used to relate materials with the corresponding GT code values. The corresponding table that was generated for this research is shown in Table B-2.

Raw Material Form

Digit 16 of the code represents the shape of the raw material for the part. The appropriate values are provided by a look-up table.

Production Quantity

Digit 17 describes the production quantity for the part under consideration. A look-up table relates ranges of the production quantity to the specific GT code values.

Orientation

Digit 18 captures the physical orientation of certain machined secondary elements already captured in digit 4. It includes orientation information for holes, slots, flats, and complex cavities. Four orientations are considered: i) perpendicular to the AB plane, ii) perpendicular to one of the envelope sides (AC or BC planes), iii) skewed to one plane, and iv) skewed to more than one plane. If a feature is not perpendicular to one of the three planes of the part envelope it is considered skewed to the plane which the element is most nearly perpendicular. Figure 9 illustrates features perpendicular to the AB plane and AC plane, as well as a feature skewed to more than one plane.

Table B-2: Material Chemistry Description

Code Value	Insulation Layer	Ground Plane
00	Other	
01	Poly Tetra Flouro Ethane	None
02	Poly Tetra Flouro Ethane	6061 Aluminum
03	Poly Tetra Flouro Ethane	5083 Aluminum
04	Poly Tetra Flouro Ethane	Brass
05	Poly Tetra Flouro Ethane	Copper
06	Poly Tetra Flouro Ethane	Kovar
07	Polyimide	None
08	Polyimide	6061 Aluminum
09	Polyimide	5083 Aluminum
10	Polyimide	Brass
11	Polyimide	Copper
12	Polyimide	Kovar
13	Prefired Thick Film Ceramic	None
14	Prefired Thin Film Ceramic	None
15	Cofired Ceramic	None
16	Unknown	

APPENDIX C

This appendix contains the code book of the Group Technology coding scheme developed at the University of Maryland to describe the electrical characteristics of Microwave Modules.

Group I

Position 1

Description of Main Electrical Classification

Value	Description
1	Printed Wiring Assembly.
2	Hybrid.
3	Microwave Module.
4	Final Assembly.
5	Other.

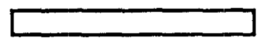
Positions 2 and 3

Description of Electrical Function

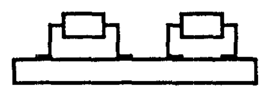
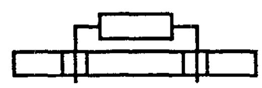
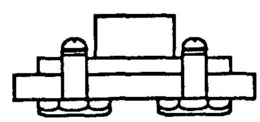
VAL	DESCRIPTION
00	Other
01	Power Amplifier
02	Low Noise Amplifier
03	Pre Amplifier
04	Mixer
05	Oscillator
06	BITE Circuit
07	Receiver
08	Filter
09	Phase Shifter
10	Combiner
11	Splitter
12	Transmitter
13	Pulse Shaper
14	Modulator
15	T/R Module (Transmit/Receive)

Positions 4 and 5

Description of Component Mounting Method

Value	Description
00	No Components. 

If more than one condition applies add the values together.

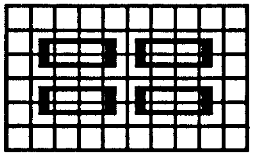
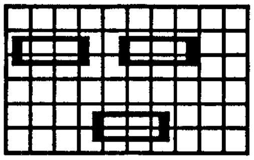
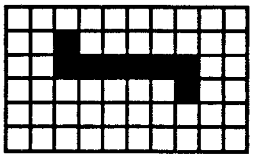
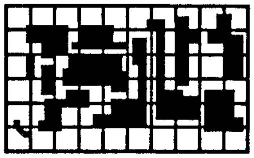
01	Standard Surface Mount 
02	Non-standard Surface Mount 
04	Standard Thru-Hole Mount 
08	Non-standard Thru-Hole Mount 

Positions 6 and 7

Description of Component Mounting Patterns

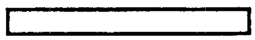
Value	Description
00	No Components or Artwork. 

If more than one condition applies add the values together.

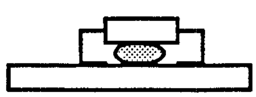
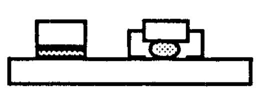
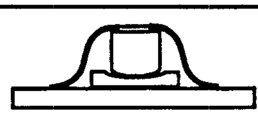
01	Components Centered on Grid Pattern. 
02	Components Randomly Placed. 
04	Artwork on a Grid Pattern. 
08	Random Artwork. 

Positions 8 and 9

Description of Hardware I (Non Soldered Hardware)

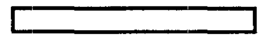
Value	Description	
00	No Hardware I.	

If more than one condition applies add the values together.

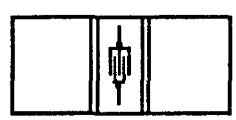
01	Screws, Nuts, Bolts, Rivets.	
02	Simple Adhesive.	
04	Complex Adhesive, Adhesive Preforms.	
08	Supports (i.e.: Spacers, Standoffs, Cup,Washers, Housing, FET Mount).	 
16	Other.	

Positions 10 and 11

Description of Hardware II (Soldered Hardware)

Value	Description
00	No Hardware II. 

If more than one condition applies add the values together.

01	Ground Pins, Non-Threaded Terminals. 
02	Threaded Terminals, Ground Screws. 
04	Wire Jumpers, Coaxial Cables, Isolator, Solder preforms. 
08	Ribbon Jumpers, Hairpins. 
16	Lang Coupler. 
32	Other

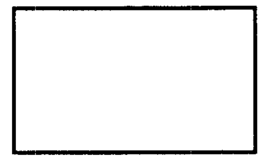
Position 12

Description of Component/Hardware Count

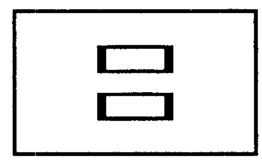
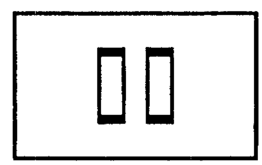
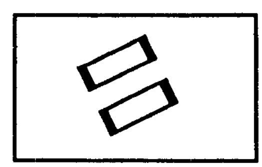
Value	Description
0	No Components/Hardware
1	1-3 Components/Hardware
2	4-12 Components/Hardware
3	13-28 Components/Hardware
4	29-50 Components/Hardware
5	51-78 Components/Hardware
6	79-112 Components/Hardware
7	113-153 Components/Hardware
8	154-200 Components/Hardware
9	> 200 Components/Hardware

Position 13

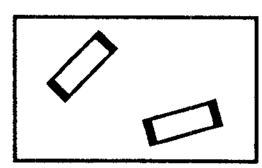
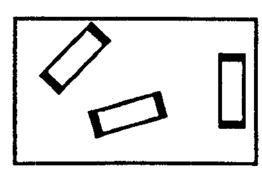
Description of Component Orientation

Value	Description	
0	No Components.	

If more than one condition applies add the values together.

1	Components with axes parallel to 'A'.	
2	Components with axes parallel to 'B'.	
4	Components skewed to 'A' or 'B', all with one orientation.	

The values below may not be added to any others

8	Components skewed to 'A' or 'B', with more than one orientation.	
9	Value of 8 Plus any of the above.	

Position 14

Description of Timing (t)

Value	Description
1	DC - 100 ms
2	10 mS $\leq$ t < 100 mS
3	1 µS $\leq$ t < 10 mS
4	100 nS $\leq$ t < 1 µS
5	10 nS $\leq$ t < 100 nS
6	1 ns $\leq$ t <10 nS
7	t < 1 ns

Position 15

Description of Bandwidth (BW)

1	BW $\leq$ 100 kHz
	100 kHz < BW $\leq$ 1 MHz
3	1 MHz < BW $\leq$ 10 MHz
4	10MHz < BW $\leq$ 100 MHz
5	100MHz < BW $\leq$ 3 GHz
6	3GHz < BW $\leq$ 6 GHz
7	BW > 6GHz

Position 16

Description of Average Power Density

Value	Description
1	1 watt/sq. in.
2	2 - 3 watt/sq. in.
3	3 - 4 watt/sq. in.
4	4 - 5 watt/sq. in.
5	5 - 6 watt/sq. in.
6	> 6 watt/sq. in.

Position 17

Description of Current (i)

Value	Description
1	$i < 100\ \mu A$
2	$100\ \mu A \leq i < 1\ mA$
3	$1\ mA \leq i < 10\ mA$
4	$10\ mA \leq i < 0.1\ A$
5	$0.1A \leq i < 1A$
6	$1A \leq i < 10A$
7	$10A \leq i < 20A$
8	$20A \leq i < 30A$
9	$i \geq 30A$

Position 18

Description of Operating Frequency (f)

Value	Description
1	f < 1MHz
2	1MHz ≤ f < 100MHz
3	100MHz ≤ f < 500MHz
4	500MHz ≤ f < 2GHz
5	f ≥ 2GHz

Position 19

Description of Gain & Sensitivity (G)

Value	Description
1	G < 10 dB
2	$10 \leq G < 20$dB
3	$20 \leq G < 54$dB
4	$54 \leq G < 60$dB
5	$G \geq 60$dB

Position 20

Description of Voltage (v)

Value	Description
1	$v < 10\ \mu V$
2	$10\ \mu V \leq v < 1\ mV$
3	$1\ mV \leq v < 10\ mV$
4	$10\ mV \leq v < 0.1\ V$
5	$0.1V \leq v < 50V$
6	$50V \leq v < 100V$
7	$100V \leq v < 500V$
8	$500V \leq v < 1000V$
9	$v \geq 1000V$

Position 21

Description of Qualifying Dimensions.

Value	Description
0	No Qualifying Dimensions.

If more than one condition applies add the values together.

1	Qualifying Lead Pitch Dimension.
2	Qualifying Component Spacing Dimension. (Spacing between components, Spacing between components and edge)
4	Qualifying Artwork Dimension. (Line width, Spacing between lines, spacing between lines and edge)

Position 22

Description of Fabrication and Assembly Tolerances.

Value	Description
0	No Qualifying Fabrication or Assembly Tolerances.

If more than one condition applies add the values together.

1	Qualifying Component Placement Accuracy.
2	Qualifying Artwork Etching Tolerance. (Line width tolerance)
4	Qualifying Plating Tolerance. (Artwork, Substrate)

Position 23

Description of Substrate Type

Value	Description
1	Poly Tetra Flouro Ethane (PTFE eg. Duroid).
2	Polyimide.
3	Prefired Ceramic (Thick Film).
4	Prefired Ceramic (Thin Film).
5	Cofired Ceramic / Greentape .
6	Other.

Positions 24 and 25

Description of Additional Materials.

Value	Description
00	No Additional Materials.

If more than one condition applies add the values together.

01	Lead and/or Pad Pre-Tinning.
02	One Substrate Plating.
04	One Circuit Plating.
08	Multiple Substrate Platings.
16	Multiple Circuit Platings.
32	Thru-Hole Plating.

APPENDIX D

This appendix contains the format for the mechanical and electrical output files generated by the coding system. The actual files for the sample part discussed in chapter 4 and the pre-amplifier application of chapter 5 are also included.

MECHANICAL GT PROGRAM OUTPUT FORMAT

"Cutouts"

Cutout ID	Cutout Type
IFF id	1: Rectangular
	2: Slanted
	3: Radiused
	4: Complex

"Holes Perpendicular to the AB Plane"

Hole ID	Diameter	Length	Location ID
IFF id			

"Perp Hole Additions"

Addition ID

0: No Additions	4: Thread
1: C'bore	5: Thread & C'bore
2: C'sink	6: Thread & C'sink
3: C'bore & C'sink	7: Thread & C'bore & C'sink

"Holes Not Perpendicular to the AB Plane"

Hole ID	Diameter	Length	Location ID
IFF id			

"Non-Perp Hole Additions"

Addition ID

(Same as Perp Hole Addition id's)

"Flats/Slots/Complex Cavities"

Flat/Slot/CC ID	Feature Type ID	Location ID
IFF id	1: Flat/Slot	
	2: Complex Cavity	

"Tolerances"

Qualifying Tolerance	Qualifying Dimension

"Orientations"

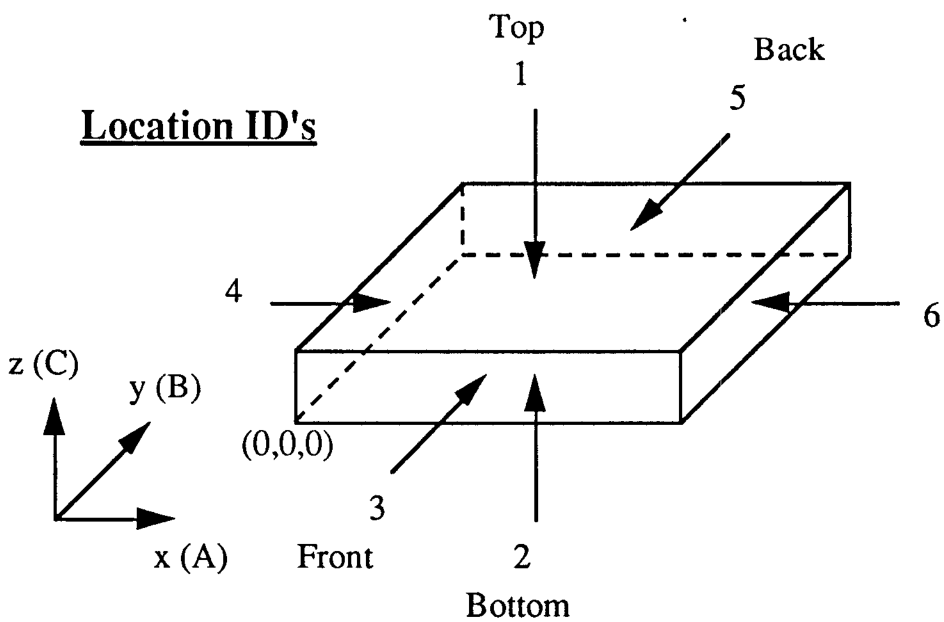
Feature ID	Orientation ID
IFF id	1: Perp AC
	2: Perp BC
	3: Skewed to One Plane
	4: Skewed to More than One Plane

"Mechanical GT Code"

Note:

All Dimensions in inches

Location ID's



Location ID 0 indicates internal feature

ELECTRICAL GT PROGRAM OUTPUT FORMAT

"Components List"

Ref. Des.	Type (chip, die, axial, etc.)	Lead Pitch

"Hardware"

Part-Find — Hardware Description ID

1	Screw	14	Ground Pin
2	Nut	15	Non-Threaded Terminal
3	Bolt	16	Threaded Terminal
4	Simple Adhesive	17	Ground Screw
5	Complex Adhesive	18	Wire Jumper
6	Adhesive Preforms	19	Coaxial Cable
7	Spacer	20	Isolator
8	Standoff	21	Solder Preform
9	Cup	22	Ribbon Jumper
10	Washer	23	Hairpin
11	Housing	24	Lang Coupler
12	FET Mount	25	Other Soldered Hardware
13	Other Non Soldered Hardware		

"Artwork"

Line Spacing (closest)	Line Width	Artwork Tol. (smallest)	Artwork Thickness

"Components Spec"

Placement Accuracy (smallest)	Pre-Tinned Leads (total #)

"Artwork Plating"

Layer ID	Material	Plating Thickness	Plating Tolerance

"Substrate Plating"

Layer ID	Material	Plating Thickness	Plating Tolerance

"Electrical GT Code"

MECHANICAL GT PROGRAM OUTPUT CHAPTER 4 EXAMPLE

97942-SAMPLE

Cutouts

1	2
2	1
3	3
4	4

Holes Perpendicular to the AB Plane

5	0.400000	0.200000	1
10	1.600000	0.200000	1
7	0.300000	0.250000	1

Perp Hole Additions

5

Holes Not Perpendicular to AB Plane

6	0.060000	0.300000	1
9	0.060000	0.300000	3

Non-Perp Hole Additions

0

Flats/Slots/Complex Cavities

12	1	2
15	1	1
14	1	1
13	1	2

Tolerances

Diameter	0.002
Positional	0.002
Length	0.005
Flatness	0.002

Orientations

6	4
9	2
12	1
15	1
14	1
13	1

Mechanical GT Code

5 9 7 3 0 1 5 1 3 7 0 9 8 0 8 5 3 7

ELECTRICAL GT PROGRAM OUTPUT CHAPTER 4 EXAMPLE

97942-SAMPLE
Components List

C31	AXIAL	0.022000
Q7	CAN	0.021000
R29	CHIP	0.020000
C30	RADIAL	0.040000
C24	DIE	0.025000
Q1	RF	0.107000

Hardware

27-424R781H09	9
1-690R526H01	11
25-424R621H01	9
35-424R785H01	12
34-434R266H09	14
34-434R266H09	14
43-NAS62032	10
43-NAS62032	10
44-NAS1635-00-3	1
44-NAS1635-00-3	1
38-	22

Artwork

0.005000	0.002500	0.000500	0.001000

Components Spec
0.000200 12

Artwork Plating

4	nickel	0.000100	0.000000

Substrate Plating

5	tin	0.000200	0.000000
6	nickel	0.000100	0.000000

Electrical GT Code
3 0 3 0 3 1 0 0 9 0 9 3 7 3 4 5 1 2 4 2 3 7 2 1 3

MECHANICAL GT PROGRAM OUTPUT CHAPTER 5 EXAMPLE

97942-690R527

Cutouts

34	4
35	1
51	2

Holes Perpendicular to the AB Plane

1	0.063000	0.203400	1
2	0.062000	0.203400	1
3	0.062000	0.203400	1
4	0.062000	0.203400	1
5	0.062000	0.203400	1
6	0.062000	0.203400	1
7	0.062000	0.203400	1
8	0.062000	0.203400	1
9	0.062000	0.203400	1
10	0.062000	0.203400	1
13	0.062000	0.203400	1
11	0.062000	0.203400	1
12	0.062000	0.203400	1
24	0.246000	0.203400	1
25	0.386000	0.203400	1
28	0.030000	0.203400	1
45	0.030000	0.203400	1
40	0.060000	0.203400	1
41	0.060000	0.203400	1
15	0.240000	0.233400	1
17	0.240000	0.233400	1
19	0.240000	0.233400	1
21	0.240000	0.233400	1
23	0.240000	0.233400	1

Perp Hole Additions

1

Holes Not Perpendicular to AB Plane

Non-Perp Hole Additions

0

Flats/Slots/Complex Cavities

42	1	1
43	1	1
44	1	1
26	1	1
36	1	1
37	2	1
38	1	2
39	1	2
27	1	1

Tolerances

Diameter	0.002
Positional	0.002
Length	0.005

MECHANICAL GT PROGRAM OUTPUT CHAPTER 5 (CONT)

Orientations

42	4
43	4
44	5
26	1
36	1
37	1
38	1
39	1
27	1

Mechanical GT Code

5 9 2 6 0 1 3 6 3 1 0 9 7 0 2 5 4 9

ELECTRICAL GT PROGRAM OUTPUT CHAPTER 5 EXAMPLE

97942-690R527

Components List

Q1	RADIAL	0.107000
YH1	DIP	0.030000
AT5	CHIP	0.020000
Q6	RADIAL	0.043000
U1	CAN	0.021000
C20	DIE	0.030000
C29	DIE	0.040000
C30	DIE	0.040000
R29	CHIP	0.020000
R3	CHIP	0.020000
R6	CHIP	0.020000
R4	CHIP	0.020000
R26	CHIP	0.020000
R5	CHIP	0.020000
R28	CHIP	0.020000
R7	CHIP	0.020000
R25	CHIP	0.022000
R1	CHIP	0.020000
R27	CHIP	0.020000
R2	CHIP	0.020000
R8	CHIP	0.020000
C1	DIE	0.025000
C28	DIE	0.025000
C4	DIE	0.030000
C3	DIE	0.030000
C2	DIE	0.030000
C6	DIE	0.030000
C5	DIE	0.030000
CR3	AXIAL	0.022000
CR1	AXIAL	0.022000
CR2	AXIAL	0.022000
Q7	CAN	0.021000
C31	AXIAL	0.021000
C24	RADIAL	0.021000
C25	RADIAL	0.021000
C32	RADIAL	0.021000
C21	RADIAL	0.021000
R30	AXIAL	0.021000

Hardware

27-424R781H01	9
1-690R526GO1	11
25-424R621H01	9
35-424R785HO1	12
34-434R266HO9	14
34-434R266HO9	14
34-434R266HO9	14
34-434R266HO9	14
34-434R266HO9	14

ELECTRICAL GT PROGRAM OUTPUT CHAPTER 5 (CONT)

34-434R266HO9	14
34-434R266HO9	14
34-434R266HO9	14
37-M16878/4BDA9	18
42-NAS620-0	10
42-NAS620-0	10
43-NAS620C2	10
43-NAS620C2	10
43-NAS620C2	10
43-NAS620C2	10
43-NAS620C2	10
43-NAS620C2	10
43-NAS620C2	10
43-NAS620C2	10
43-NAS620C2	10
43-NAS620C2	10
44-NAS1635-00-3	1
44-NAS1635-00-3	1
45-MS51957-9	1
45-MS51957-9	1
45-MS51957-9	1
45-MS51957-9	1
45-MS51957-9	1
45-MS51957-9	1
46-MS51957-3	1
46-MS51957-3	1
46-MS51957-3	1
46-MS51957-3	1
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
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51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
51-434R266H10	14
58-NAS1676CO	10
58-NAS1676CO	10
38-13404HX00220023	22

ELECTRICAL GT PROGRAM OUTPUT CHAPTER 5 (CONT)

Artwork
0.005000 0.025000 0.000500 0.001400
Components Spec
0.001000 24
Artwork Plating
6 TIN 0.000050 0.000000
Substrate Plating
4 NICKEL 0.000100 0.000000
5 TIN 0.000150 0.000000
Electrical GT Code
3 0 3 0 3 1 0 0 9 1 3 6 9 3 4 5 1 5 4 2 1 7 1 1 3
Feasible

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