A FEATURE BASED APPROACH TO THE COMPUTER AIDED DESIGN OF SCULPTURED PRODUCTS

by

Séan R. Mitchell

A DOCTORAL THESIS

Submitted in partial fulfilment of the requirements
for the award of
Doctor of Philosophy of Loughborough University

July 1996

Abstract

Computer aided design systems offer considerable potential for improving design process efficiency. To reduce the 'ease of use' barrier hindering full realisation of this potential amongst general mechanical engineering industries, many commercial systems are adopting a feature based design (FBD) metaphor. Typically the user is allowed to define and manipulate the design model using interface elements that introduce and control parametric geometry clusters, with engineering meaning, representing specific product features (such as threaded holes, slots, pockets and bosses).

Sculptured products, such as golf club heads, shoe lasts, crockery and sanitary ware, are poorly supported by current FBD systems and previous research, because their complex shapes can not be accurately defined using the geometrically primitive feature sets implemented. Where sculptured surface regions are allowed for, the system interface, data model and functionality are little different from that already provided in many commercial surface modelling systems, and so offer very little improvement in ease of use, quality or efficiency.

This thesis presents research to propose and develop a FBD methodology and system suitable for sculptured products. An original technique for decomposing a sculptured product into an anatomy of industry specific 'extended form' (EF) features has been identified as the basis for developing product family specific FBD systems. The work described includes; conceiving, developing and proving the EF feature method for sculptured products; identifying and capturing EF features suitable for specific existing sculptured products; specifying generic data models and functionality suitable for a customisable EF FBD system; implementing prototype EF FBD systems within a commercial 3D CAD system; initial system user trial results.

The proposed EF feature based methodology has been proven as a viable approach to sculptured product design, and has demonstrated considerable benefits in terms of ease of use and design process efficiency.

Keywords: Sculptured products, free form surfaces, feature based design, computer aided design, golf clubs, shoe lasts.

ACKNOWLEDGMENTS

I owe a debt of thanks to many people, but of those that have had something to do with this research directly I would particularly like to thank the following:

Dr. Roy Jones, whose enthusiasm for the work, patience, belief in and ability to motivate me are more constant than my own. Without him this thesis would not exist.

Delcam International (Ed Lambourne in particular), Dunlop Slazenger International (especially Mike Shaw, Brian Machin and Paul Lambert) and the EPSRC (particularly Adrian Dent and Malcolm Sabin) for supporting and encouraging the research.

My wife Val, and our children Bethan and Christopher, who's patience and long suffering has created the space I needed to get things done.

And Jesus Christ, God come to save mankind, without whom there would be no real point.

Is there anything of which one can say, "Look! This is something new"? It was here before our time. There is no remembrance of men of old, and even those who are yet to come will not be remembered by those who follow. [Solomon, Ecclesiastes 1:10-11]

Of making many books there is no end, and much study wearies the body. Now all has been heard; here is the conclusion of the matter: Fear God and keep his commandments, for this is the whole duty of man. For God will bring every deed into judgement, including every hidden thing, whether it is good or evil. [Solomon, Ecclesiastes 12:12-14]

"But what about you?" he asked. "Who do you say I am?" Simon Peter answered, "You are the Christ, the Son of the living God." [Jesus and Peter, Matthew 16:15-16]

I tell you the truth, whoever hears my word and believes him who sent me has eternal life and will not be condemned; he has crossed over from death to life. [Jesus, John 5:24]

Do not let your hearts be troubled. Trust in God; trust also in me. In my Father's house are many rooms; if it were not so, I would have told you. I am going there to prepare a place for you. And if I go and prepare a place for you, I will come back and take you to be with me that you also may be where I am. [Jesus, John 14:1-3]

Now we see but a poor reflection as in a mirror; then we shall see face to face. Now I know in part; then I shall know fully, even as I am fully known. And now these three remain: faith, hope and love. But the greatest of these is love. [Paul, 1 Corinthians 13:12-13]

All quotations from:

The Holy Bible

New International Version, Hodder & Stoughton

ACRONYMS

2D	Two Dimensional
3D	Three Dimensional
B-rep	Boundary Representation
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacture
CAPP	Computer Aided Process Planning
CIM	Computer Integrated Manufacture
CMM	Coordinate Measuring Machine
CNC	Computer Numerically Controlled
CSG	Constructive Solid Geometry
DBF	Design By Features
DSI	Dunlop Slazenger International
EF	Extended Form
EFF	Extended Form Feature
EFFM	Extended Form Feature Method
ER	Entity-Relationship
FAH	Face Adjacency Hypergraph
FBD	Feature Based Design

FEA	Finite Element Analysis
FFD	Free Form Deformation
FFIM	Form Feature Integration Model
FIRES	Feature-based Integrated Rapid Engineering System
GUI	Graphical User Interface
IFS	Interactive Feature Specification
LFF	Limited Free Form
MFR	Manufacturing Feature Recognition
NC	Numerically Controlled
OODB	Object Oriented DataBase
PDES	Product Data Exchange Standard
PICASSO	Practical and Intuitive CAD for Assembly Objects
RDBMS	Relational Database Management System
SEA	South East Asia
SFOG	Shape Feature Object Graph
SSADM	Structured Systems Analysis and Design Method
STEP	Standard for the Exchange of Product Model Data

CONTENTS

CHAPTER 1. INTRODUCTION

1. THE DISTINCTION BETWEEN PRISMATIC AND SCULPTURED PRODUCTS

This thesis concerns the application of a computer aided design philosophy, user interface metaphor and modelling methods that support product description by assembling discrete product elements (namely 'feature based design') to sculptured products. Feature based design and manufacture are currently gaining in popularity for 'prismatic' products, but the differences between this work and the body of existing work concerned with 'prismatic' features stem from the difference between the two product types.

If we first define two extremes:

- A fully *prismatic* or *simple geometric* product has an external surface shape that can be defined wholly by Boolean operations on geometric primitives (many of which will be prismatic) such as a plane, prism, sphere, cone, cylinder or torus.
- A fully *sculptured* product has a shape where no sub-region of its external surface can be accurately defined by such a geometric primitive.

In 1984, in his review of solid modelling research issues and the interface between design and manufacture, Pratt noted the earlier findings of Voelcker & Requicha that "40% of the parts designed in a range of mechanical engineering companies could be ... modelled using ... rectangular blocks and cylinders ... [and with] ... the addition of further primitive types (cones, spheres, tori) ... 90% of the parts from the same companies [could be modelled]" [1984 Pratt, 1977 Voelcker & Requicha]. Thus, it is apparent that the majority of mechanical engineering products or parts are predominantly prismatic. Consequently they lend themselves to mathematical definition and so computer aided solid modelling based on constructive solid geometry (CSG) or boundary representation (B-rep) techniques.

However, products that are produced with a significant aesthetic objective, or for comfortable physical interaction with living organisms generally require more complex shapes to achieve these goals (e.g. sanitary ware and shoes). These products are predominantly sculptured and by definition are poorly supported by modelling techniques based on simple geometric primitives. Pratt noted that the remaining 10% of parts in Voelcker & Requicha's survey required "the provision of ... sculptured ... blends fillets and regions of free-form geometry ...", and that most of these parts occurred in specialised industries (e.g. aerospace, automotive and footwear industries or casting, forging and mould manufacturers).

In reality the majority of physical products populate the spectrum between fully prismatic and fully sculptured. This work is relevant to those products that are biased heavily towards the fully sculptured end of the spectrum.

2. A Review of Feature Based Design

2.1. Geometric Modelling Systems

Whilst the ubiquitous engineering drawing is still the most widely used method for describing and specifying a product, as a formalised two dimensional representation scheme it is limited in its ability to provide a unique unambiguous description of three dimensional objects, particularly for those with sculptured surface regions. This poses problems not only for specifying and communicating shape, but also in using the drawing as a basis for other activities such as manufacture and performance analysis, particularly where these activities are to be automated and aided by computers. Consequently, considerable effort has been expended to develop unambiguous 3D geometric modelling methods.

Two approaches to 3D computer based object modelling, solid and surface modelling, were developed independently. Solid modelling, fundamentally concerned with "unambiguous representations of the internal and external aspects of an object" [1986 Miller], has emerged based on two techniques. The set-theoretic or constructive solid geometry (CSG) approach is based upon Boolean operations on half-space primitives, whereas the boundary model or B-rep approach is based on face-edge-vertex adjacency graphs obeying Euler's rule. Both methods are typically used in commercial systems to describe characteristically prismatic closed or solid objects.

Surface modelling is fundamentally concerned with modelling objects with sculptured surface regions. To achieve this modelling what is inside and outside the object has been sacrificed in favour of surface definition flexibility. Typically, surface modelling employs (generally open) piecewise parametric polynomial surfaces to describe the object's outer surface. Surface adjacency topology and whether the modelled object is a closed solid or open shell are usually neglected.

As the two approaches have matured the need to combine both approaches to model objects with both geometrically primitive and sculptured surface regions has become apparent to researchers and computer aided engineering software system developers in both fields [1986 Miller]. The following section reviews research concerned with the 'product features' concept primarily associated with solid modelling. The subsequent section reviews research in the surface modelling domain relevant to the development of a sculptured product feature concept.

2.2. Geometrically Primitive Features

2.2.1. Feature Based Engineering Origins

Feature based engineering support software research and development originated from the computer aided process planning (CAPP) research in the early 1980's [1981 CAM-I]. Feature based design (FBD) research began later in the mid 80's [1984 Pratt, 1985 Pratt & Wilson, 1986 Luby et al]. FBD originated as a means for better integrating design and process planning activities[1] [1993 Salomons et al], essentially by overcoming the manufacturing feature recognition (MFR) problem by designing in terms of features to begin with. However, the potential for FBD to improve design process efficiency and quality (through better user interfaces, data transfer, design task automation, parametric design and design for manufacture) has always been a desirable consequence of adopting this approach. Furthermore, a recent survey of UK industry revealed that the application of feature based tools is more extensive within design than process planning departments [1996 Mill et al].

There is a large body of published research relating to feature based engineering support software concerning prismatic (geometrically primitive) features, mostly for mechanical engineering activities. Several review papers have been published in recent years [1996 Mill et al, 1994 Allada & Anand, 1993 Salomons et al, 1993 Rosen, 1993 Case & Gao, 1992 Feru et al, 1991a Shah,

---

[1] Although it could be argued that earlier 2D draughting parametric symbol definition capabilities supporting greater efficiency and standardisation in the design process was the other 'natural parent'.

1991 Kim et al, 1990 Dixon et al, 1989 Dixon et al, 1988 Cunningham & Dixon, 1988 Loughlin] covering several hundred other articles published in the area. Allada and Anand provide a recent list of engineering activities under consideration for support by feature based techniques, together with key articles [1994 Allada & Anand], including:

- Group technology coding
- Finite element method analysis
- Tolerance representation
- Tooling and cost evaluation
- Automated inspection
- Automated grasp formulation
- Automated assembly
- Generative process planning
- Manufacturing evaluation
- Automated machinablitiy checking
- Automated mould design
- NC code and cutter path generation
- Automated jig and fixture design and set-ups generation

Not to mention general feature based design. It is impractical to review this entire body of research in depth within the scope of this chapter, and also unnecessary given this thesis' emphasis on sculptured product design. However, the following section presents an overview of the research based on those issues considered relevant to developing a sculptured product FBD approach.

2.2.2. Feature Definitions

An early CAM-I publication notes that the word feature is derived from the Latin *factura* meaning 'the act of making or formation' [1981 CAM-I]. Whilst this provides a classical foundation to the feature concept, and perhaps reinforces the CAPP researchers' claim to its invention, it is useful to note that engineering designers and analysts adding, removing or changing features within their respective application domain part models are involved in acts of formation, albeit without immediate physical results. The concept of a design feature predates computer aided engineering, as do the 'feature views' for other engineering activities or applications. This fact might have alerted researchers to the problems of establishing dogmatic feature definitions suitable for all engineering applications, and eased some of the tensions in establishing a definition for the feature concept.

Several 'feature definitions' have been proposed:

- *[1981 CAM-I] a specific geometric configuration formed on the surface, edge or corner of a workpiece*
- *[1985 Pratt & Wilson] a region of interest on the surface of a part*
- *[1986 Luby et al] a geometric form entity whose presence or dimensions are required to perform at least one CIM function and whose availability as a primitive permits the design process to occur*
- *[1988 van t'Erve] a distinctive or characteristic part of a workpiece, defining a geometrical shape, which is either specific for a machining process or can be used for fixturing and/or measuring purposes*
- *[1989 Shah] a carrier of product information that may aid design or communication between design and manufacturing, or between other engineering tasks*
- *[1990 CAM-I] a region of interest*
- *[1990 CAM-I] any entity used in reasoning of design, engineering and manufacture*
- *[1990 Giacometti & Chang] a semantic grouping used to describe a part and its assembly. It groups in a relevant manner functional, design and manufacturing information*
- *[1990 Shah] recurring patterns of information related to a part description*
- *[1991 Pratt] a related set of elements of a product model, conforming to characteristic rules enabling its recognition and classification, which, regarded as an entity in its own right, has some significance during the life cycle of the product*
- *[1991 Wingard] a generic shape that carries some engineering meaning*
- *[1993 Salomons et al] features can be viewed as information sets that refer to aspects of form or other aspects of a part, such that these sets can be used in reasoning about a design, performance or manufacture of the part or assembly they constitute*

Reviewing this selective, but hopefully representative, definition history it can be seen that the feature concept has normally had specific geometric shape or form connotations. However as the feature concept definition has become more abstract, this type of feature has been identified as a sub-class known as *form features*. Even so, a large proportion of current features related research is still concerned with form features. Mill et al have recently restated Shah's thinking about form features [1996 Mill et al, 1989 Shah], in terms of minimum requirements, that a feature should at least:

- be a physical constituent of a part
- be mapable to a generic shape (realisable or implicit)
- have engineering significance
- have predictable properties

Mill et al also report a more recent three part feature definition arrived at during a meeting of UK academics in September 1995, resulting from an attempt to combine several earlier definitions into one that is universally acceptable [1996 Mill et al]:

- A feature is an area of interest in relation to a component or assembly
- A fundamental feature is an entity (or relationship) on a product which is used on one or more aspects of the design/manufacturing cycle and is made available to the user (e.g. features representing and specifying form, tolerance, or surface finish)
- A derived feature embodies information derived from a fundamental model (e.g. adjacency or proximity)

Even so, there still appears to be some tensions within this definition, as some fundamental features (e.g. surface finish) could be modelled as form feature attributes according to the recent Pratt-Devries definition also endorsed by Mill et al [1996 Mill et al]:

- An attribute (of a feature) is a characteristic quality or property which associates meaning to an entity, significant to a particular stage in the life cycle of a product

Shah notes in his assessment of features technology [1991a Shah] that the feature viewpoint of different communities is different, for example:

- Manufacturing: features represent shapes and technological attributes associated with manufacturing operations
- Geometric modelling: features are groupings of geometric or topological entities that need to be referenced together
- Design by features: features are elements used in generating, analysing or evaluating designs

Pratt expanded his definition of features by identifying several feature sub-classes, mostly by engineering application [1991 Pratt]:

- design
- manufacturing
- analysis
- assembly
- robotics
- overall shape
- tolerance and inspection

Mill et al also list several *diverging application specific feature definitions* [1996 Mill et al]:

- Design feature: a discrete piece of information fulfilling a function on the component and that is made available for the designer to use
- Process planning feature: a distinctive or characteristic part of a workpiece defining a geometric shape, which is either specific to machining processes or can be used for fixturing or measuring purposes.
- Manufacturing feature: a parameterised geometric object that corresponds to a manufacturing operation
- Machining feature: a subclass of manufacturing feature. A prismatic or cylindrical volume that has primitive machining operations associated with it
- Assembly feature: a feature that defines relationships between different parts in an assembly
- Solid modelling feature: a volume whose properties include translation, rotation and scaling

It is obvious that, almost by definition, there are difficulties in mapping the features relating to one application domain to another (despite the optimism of Shah's earlier definition listed above [1989 Shah]), because the necessity of direct equivalents to make this transfer simple is not enforced or desirable. This is understandable, and to be expected, given the existing linguistic, cultural and conceptual barriers between engineering disciplines. Dedicated designers, analysts, and process planners all have there own concept of 'region of interest' and so different perspectives or views of a part model. Allada and Anand [1994 Allada & Anand] note that several researchers [1988 Woodwark, 1990 Joshi, 1991a Shah] accept that feature definitions are context dependent, as did Shah in 1989 [1989 Shah], and that even within manufacturing engineering the features are process dependent. In considering a feature based approach to sculptured products it is instructive to bear this in mind, and not attempt to formulate an approach to features that is "all things to all men" [AD 53 Paul].

However, answering the need for closer integration to improve efficiency through concurrent engineering, still depends on better communication, sharing and integration of information and knowledge across disciplines. Consequently, although the features concept has yet to fully solve the CIM integration problem that fathered it, there is still considerable need and promise. Thus research activity in feature recognition, interpretation, translation and transformation is desirable to achieve closer integration of engineering disciplines.

2.2.3. Classification and Taxonomies

Within application domains, given their particular features view, researchers have generally adopted a taxonomic approach to classifying the features they identify. As well as helping the various authors to collect their thoughts and present their feature view in a formal structure, often by further elaborating what a feature might be within their particular definition, the taxonomies often suggest differences (and sometimes ordering) in the process of employing the feature classes. For example, the classification of dependent and independent features by many researchers implies that some independent features must be employed or instantiated in some way before dependent ones. The taxonomies may also imply a natural presentation format to provide system users with access to feature functionality. They are certainly useful in developing object oriented feature system implementations (cf. Chapter 1 Section 2.2.7, and Chapter 7).

Pratt and Wilson formulated the CAM-I scheme [1985 Pratt & Wilson] later adapted and adopted by STEP/PDES (Standard for the Exchange of Product model data, or Product Data Exchange Standard) [1988 PDES]. Form features are classified under 6 types as shown in Figure 1-1. Kim et al [1991 Kim et al] propose two feature taxonomies for rotational parts, one based on the STEP/PDES classification, the other based on design features. They note that their design feature classification is more natural and effective for the designer and more concise. Although using the design feature classification requires translation to the more application neutral STEP/PDES classification for process planning, they demonstrate that this is feasible.

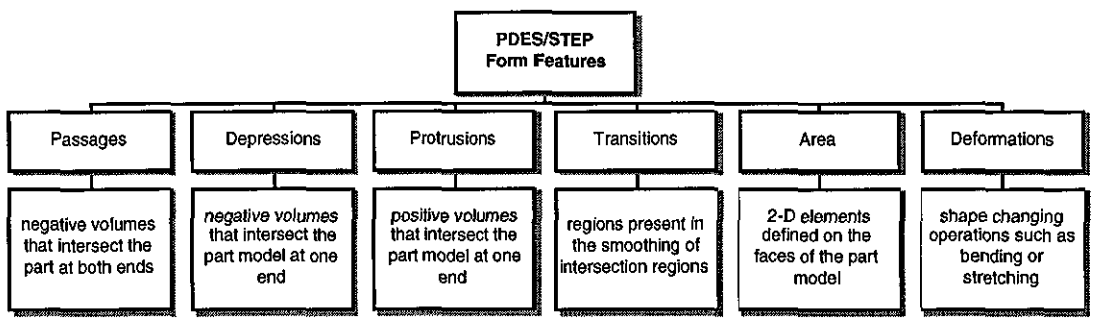


Figure 1-1 PDES/STEP Form Features Classification

Cunningham and Dixon [1988 Cunningham & Dixon] classify form features as shown in Figure 1-2, and also identify example lists of suitable feature sub-classes necessary for a variety of activities relating to several manufacturing processes (e.g. forging, casting, extrusion, injection moulding).

Shah and Rogers [1988 Shah & Rogers] classify features as shown in Figure 1-3. They include abstract product characteristics (without implied shape or geometric connotations such as material properties and operating variables) as product features. It could be argued that some of these geometrically abstract features could be better recorded as characteristics within a broad product model incorporating a form feature model, rather than as features within a multi-purpose feature model. However, abstract features defined as 'entities that cannot be evaluated or physically realised until all variables have been specified or derived from the model', as later proposed by Shah [1991b Shah], have more relevance to sculptured product design, as will be seen in subsequent chapters.

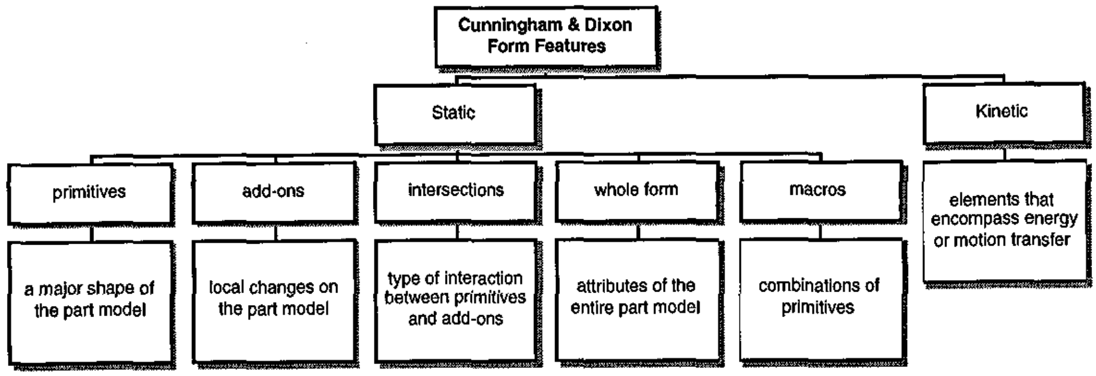


Figure 1-2 Cunningham & Dixon Form Features Classification

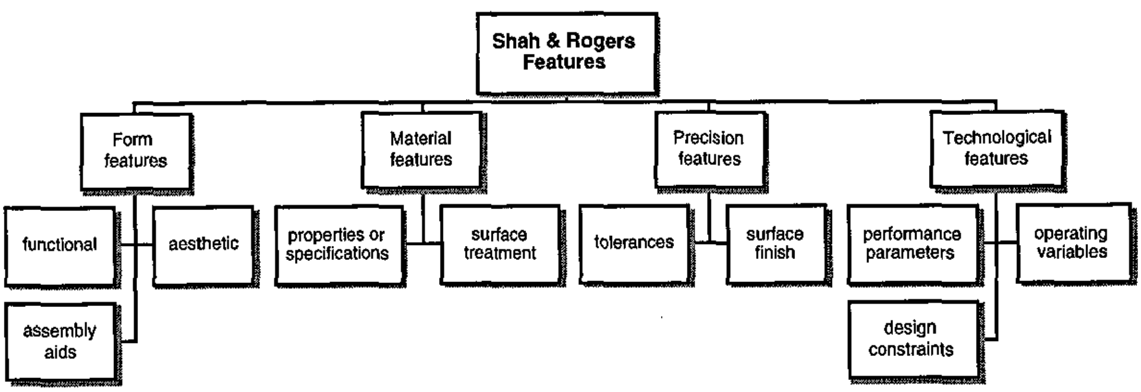


Figure 1-3 Shah & Rogers Features Classification

Gindy [1989 Gindy] proposed a feature classification hierarchy based on engineering access directions as well as geometrical characteristics, as shown in Figure 1-4. It is interesting to note that the concept of free form or sculptured features could tentatively be included under Gindy's 'real surface' feature class, except that it would not generally have 5 engineering access directions in the same sense as the other prismatic features.

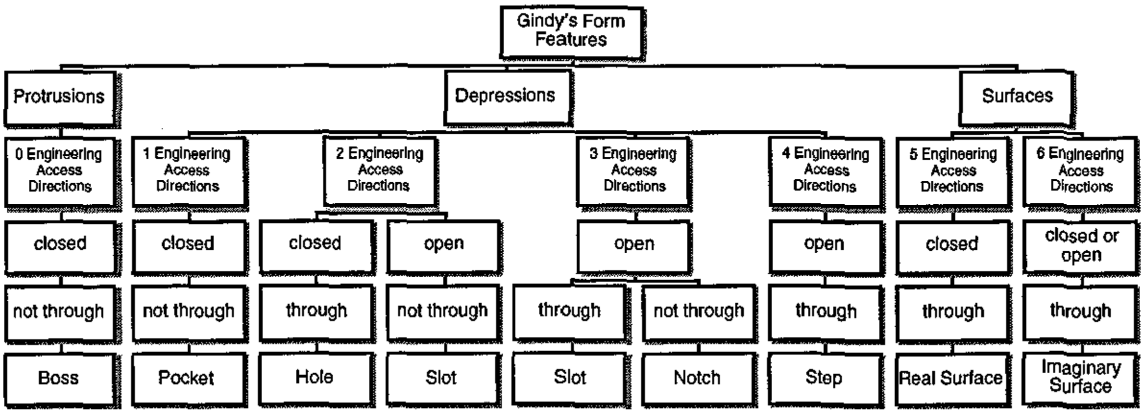


Figure 1-4 Gindy's Features Classification

Salomons et al summarise Wingard's form feature classification as shown in Figure 1-5 [1993 Salomons et al, 1991 Wingard].

Some common themes can be identified between these taxonomies. For example, STEP/PDES transition features and Cunningham & Dixon's intersection features, or Cunningham & Dixon's add-on features and Wingard's atomic modifier features, or Cunningham & Dixon's macro features and Wingard's atomic grouping features. But their differences emphasise the difference in feature views between researchers even when they share a similar interest in the same application domains.

While such flux exists within the established research community it seems reasonable to make use of the same technique to consider a taxonomic feature classification specific to the problems of sculptured product design. In this way our understanding of what features might or could be and how they can be usefully classified can be broadened before it condenses into a definitive, perhaps all encompassing, definition and approach. Hopefully it will be possible to then translate to or improve any emerging international standard using a similar approach to Kim et al [1991 Kim et al].

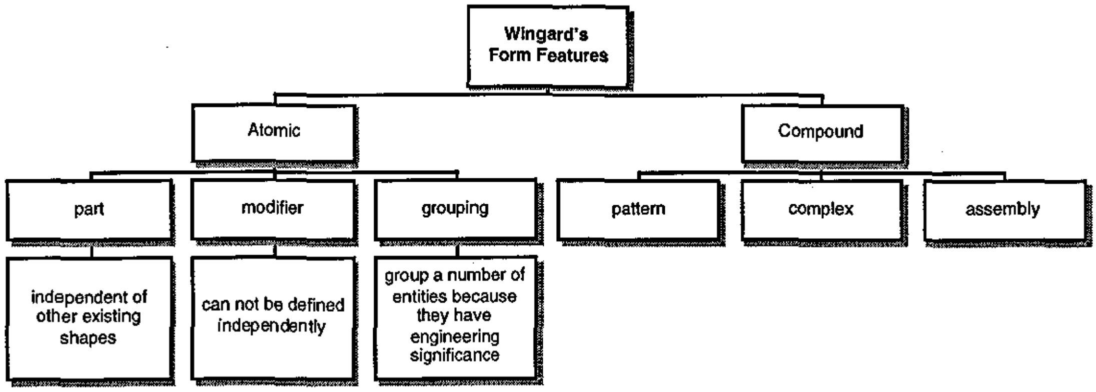


Figure 1-5 Wingard's Form Feature Classification

2.2.4. Feature Specification and Recognition

Given a well defined feature view, in the form of an overall definition and a classification taxonomy, the next obvious step is to identify and specify individual feature types for use in the particular application context. Good examples of this are the CAM-I features, classified under the extended taxonomy shown in Figure 1-6 [1985 Pratt & Wilson], and the work by Cunningham & Dixon [1988 Cunningham & Dixon, 1989 Dixon et al]. From a FBD design perspective this equates to predefining the building blocks (e.g. blocks of material, holes, slots, protrusions) from which the design is assembled [e.g. 1988 Cunningham & Dixon], or the material stock and elementary removal volumes where a destructive modelling approach is adopted [e.g. 1988 Cutkosky et al, 1988 Tuner & Anderson]. For MFR based CAPP this equates to predefining the manufacturing processes associated with a specific part form and the search criterion for the recognition process to identify that form [e.g. 1990 Joshi & Chang]. For FEA this may equate to predefining part subregions that facilitate mesh generation [e.g. 1992 Nakajima et al, 1994 Prabhakar et al].

In general, researchers have identified features they consider appropriate to their discipline, and where a part model is not predefined in these terms, features that they can successfully implement in a recognition algorithm to operate on the part's geometric model. There appears to be no reason why this should not be the initial approach to sculptured feature specification.

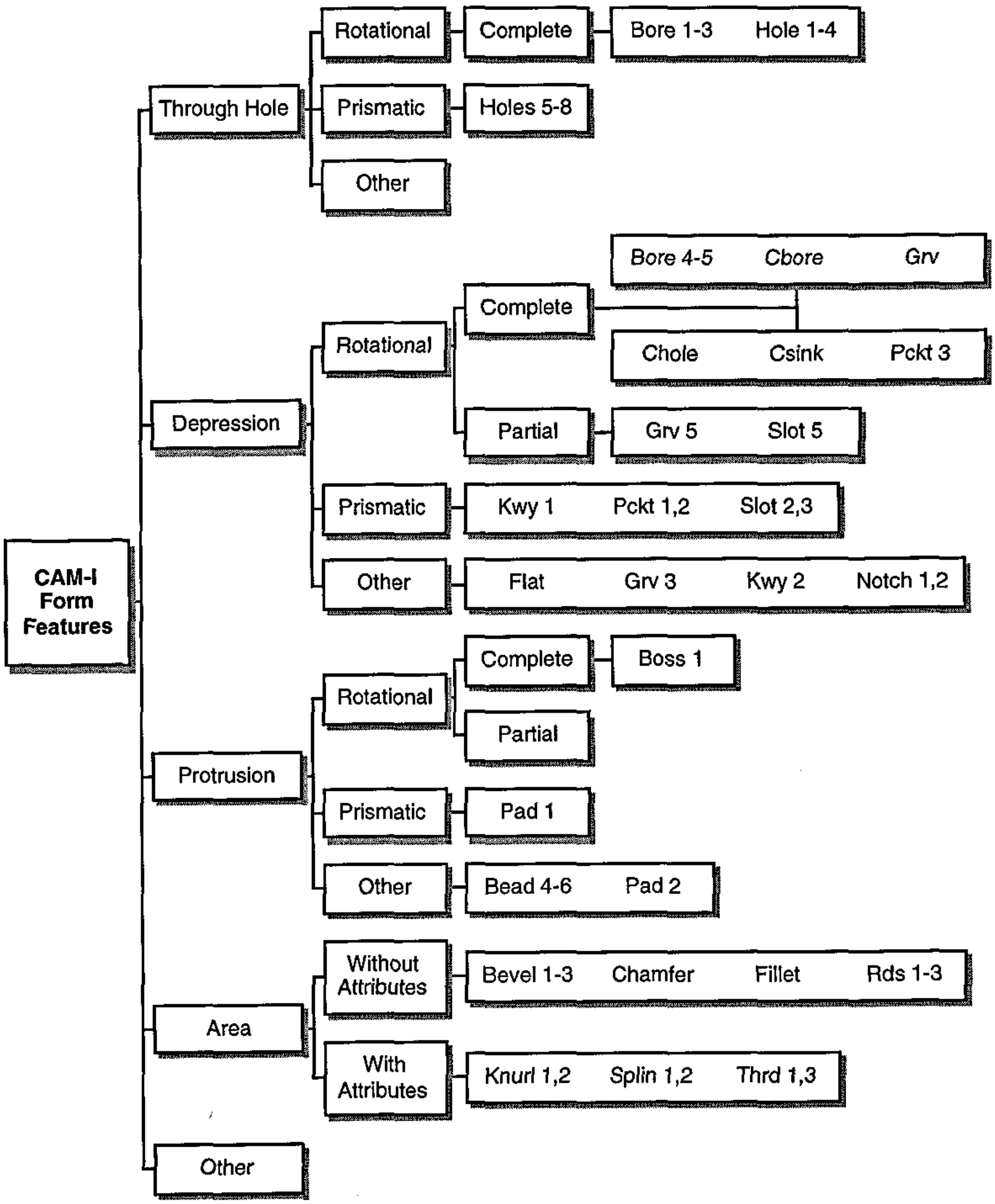


Figure 1-6 CAM-I Form Feature Classification

Where user creativity outstrips a feature based system developer's ability to predict and provide for their needs with predefined features, interactive feature specification (IFS), identification or recognition is necessary. Salomons et al [1993 Salomons et al] note that several researchers agree on the need to integrate FBD and MFR for successful feature based CAD/CAPP/CAM [1990 CAM-I, 1991 Wingard] and Sreevalsam and Shah have also identified the need to incorporate IFS [1992 Sreevalsam & Shah]. Again, this is likely to be the case for sculptured feature specification as well.

Allada & Anand published a recent review of feature based CIM [1994 Allada & Anand] primarily concerned with prismatic manufacturing feature recognition. Perhaps because of their historical perspective Allada and Anand classify design by features (DBF) as a subset of FBD, together with human assisted and automatic feature recognition. Thus DBF is presented as a CAD to CAPP/CAM feature interpretation solution for manufacturing purposes, although defining DBF in these terms is perhaps keeping the cart before the horse because it came out of the stable that way. It would be perhaps less confusing to equate FBD with DBF (maintaining the generative process implications of 'design'), and identify feature recognition (an interpretive process, with interactive human assistance or otherwise) as part of a related but different inter-application communications activity, even though some design features must first be 'recognised' to populate any FBD system.

It is also interesting to note that Allada & Anand highlight a current deficiency in the DBF approach in that blending is absent from much of the research because it is seen as a "non-feature-related activity" [1994 Allada & Anand]. Blends are one of the few 'sculptured features' common to predominantly prismatic parts, and yet are somehow considered separate and so not identified as features (despite satisfying several researcher's definition criterion). Laakko and Mäntylä are noted as possibly the only researchers to address this problem by incorporating blends in their EXTDesign FBD system [1993 Laakko & Mäntylä].

Allada & Anand comment that published manufacturing feature recognition schemes can be categorised by the solid modelling method associated with the research, and list CSG-based, B-rep-based, cellular-decomposition-based and wireframe-based automatic feature recognition approaches. Surface-model-based feature recognition is notable by its absence.

Allada & Anand comment that one of the problems with a CSG-based recognition scheme, where perhaps the primitives can almost be directly associated to manufacturing features (thus providing a quasi-FBD approach), is the requirement for the designer to understand the processes necessary to manufacture the primitives. It certainly used to be a designer's responsibility to be aware of manufacturing processes and to consider manufacturability as one of the constraints on their designs. If this responsibility is neglected, or computer based tools are intended to support designers incapable of these considerations, perhaps the problems faced by industry are not the inadequacies of computer tools but the low value placed on training, knowledge and experience. Human creative and cognitive abilities are far superior to those of the most advanced computing facilities. Thus, for the foreseeable future, feature based systems will be inadequate by comparison (e.g. in terms of feature recognition) and unable to pre-empt new feature definition or innovation. Consequently, it is perhaps better to evaluate feature based tools not in terms of whether they make incompetent engineers more competent (except perhaps to enhance usability and ensure they offer appropriate assistance) but in terms of how they increase the effectiveness of competent engineers, or in this case designers. After all, a computer based system can only really be expected to identify and prevent stupid mistakes, and not to credit the intelligent decisions of its superiors.

Allada & Anand also summarise the work of several researchers investigating surface feature recognition by graph isomorphism techniques to identify mostly depression (and in some cases protrusion) features. For example, Falcidieno and Giannini base their technique on a 'face-adjacency hypergraph' (FAH) [1989 Falcidieno & Giannini]. The FAH model has nodes representing faces, arcs representing edges and hyperarcs representing vertices of the part model. Joshi and Chang based their approach on an 'attribute adjacency graph' [1990 Joshi & Chang]. Faces are also represented within the model by nodes and shared edges by arcs between nodes, but the arcs are assigned attributes (1 or 0) to indicate convex or concave face adjacency.

The graph methods listed generally originate from attempts to make use of B-rep solid modelling concepts for feature recognition, but fall short of providing a panacea. There is an immediate problem in applying graph grammar techniques of exactly this type to identifying sculptured product features because they are typically characterised by a lack of plane faces, edges or vertices. However, given a sculptured product surface model composed of blended surface regions, using graph arcs to represent tangency curves as well as edges (together with other adaptations) yields some potential for graphically specifying the part's anatomy, as discussed later in Chapter 4. In itself this does not provide a feature class rich means for sculptured feature recognition. By adding a concavity attribute to the blends it may be possible to identify protrusion and depression features by interrogating the graph, but this provides a woefully inadequate feature set (i.e. base material, protrusion and depression features) for design purposes. If these features are considered as groups of sub-features (i.e. the modelled surface regions and blends themselves) the graphing technique can not be said to identify features, as in essence these have already been identified (unconsciously or otherwise) by the designer that specified the model composition. Instead, the graph may provide a means for depicting the results of a define-by-example approach to sculptured product anatomy and feature specification.

2.2.5. Feature Interaction and Relationships

Feature recognition problems are compounded by feature interactions, not only where several features are nested, but especially where two or more features' proximity causes them to merge into a more complex form. Shah identifies several difficulties caused by feature interaction [1991b Shah], including:

- a feature is made nonfunctional
- a non-generic shape results from two generic shapes

- feature parameters become obsolete
- nonstandard topologies are caused
- a feature disappears because of a larger one
- an open feature becomes closed

Vandenbrande and Requicha [1990 Vandenbrande & Requicha, 1993 Vandenbrande & Requicha] note that fully or partially missing feature faces and feature fragmentation resulting from feature interaction causes some B-rep based pattern recognition approaches to fail, and consequently favour a CSG tree analysis instead. Understandably, researchers are tending to adopt combined CSG/B-rep modelling approaches to resolve these and other issues [1993 Salomons et al], and we can predict the use of hybrid CSG/B-rep/surface modelling approaches in the most generally applicable systems of the future.

It is also not unreasonable to predict, even without predefining what they may be, that the provision of sculptured features (perhaps as CSG and B-rep modellers incorporate more surface modelling capabilities) will compound these issues, and it seems likely that developing a predominantly sculptured feature based design system will confront similar difficulties. For example, where two prismatic protrusions meet face to face, or overlap, it is difficult enough to identify this occurrence and suggest an alternative feature representation. Identifying tangency or overlap between a prismatic and a sculptured protrusion feature is computationally more difficult and expensive, and suggesting a sensible corrective feature substitution is similarly more difficult. Interaction between two sculptured features is more difficult again.

Some researchers have proposed modelling feature relationships such as feature nesting (or 'is-in'), adjacency (or 'adjacent-to'), and intersection [1990 Anderson & Chang, 1992 Chen et al]. Further relationships need to be specified between features, to model tolerances for example. Shah lists three instances [1991b Shah], although the second corresponds to the interaction relationships mentioned above:

- features related by parametric geometric constraints (e.g. spaced holes on a pitch circle diameter)
- features related by geometric constraints unsuitable for parametrisation (e.g. tangency)
- features grouped for convenience without geometric constraint

The first and third relationships have been embedded by other researchers within feature definitions [cf. Chapter 1 Section 2.2.3, 1988 Cunningham & Dixon, 1991 Wingard], whereas Dong and Wozny [1990 Dong & Wozny] considered the implementation of additional existence dependency and size dependency relationships in their modelling system.

Several researchers, reviewed by Shah and Miller up to 1990 [1990 Shah & Miller], and more recently Guilford and Turner and Roy and Liu [1992 Guilford & Turner, 1993 Roy & Liu], have considered different approaches to modelling geometric tolerance information and their deficiencies. Guilford and Turner in particular comment on the problems defining locations and directions for tolerances and datums within STEP, and propose attaching virtual geometry to the part geometry.

It is likely that similar issues will also be relevant to sculptured product features, and that again these will introduce additional complexity. For example, specifying a dimension and tolerance relationship between sculptured surface regions is made awkward by the difficulty in identifying datum locations on a surface where there is little or no discontinuity. Although virtual datums can be attached to sculptured features for design purposes (cf. Chapters 5 to 7), these are impossible to use for physical inspection purposes.

2.2.6. Commercial Feature Based CAD

Mill et al's recent survey of 7 UK companies using feature based engineering tools, particularly for mechanical design, reports the companies' perception of FBD's potential benefits. These are summarised in Figure 1-7. A significant proportion expected benefits from design modification ease, variational design support and the re-use of proven library features [1996 Mill et al].

However, none of the companies surveyed expected a features approach to resolve the issues of transferring data between applications.

Salomons et al [1993 Salomons et al] note that work within the STEP/PDES Form-Feature Integration Model (FFIM) refers to old draft work from 1987 coordinated by M. Dunn [1988 PDES]. Several researchers have compared the FFIM with academic systems noting differences and deficiencies [1989 Parks & Chase, 1991 Shah & Mathew, 1991 Kim et al]. Unfortunately since 1988 the work has floundered for lack of support, direction and coordination. Salomons et al note that the current consensus is that researchers are essentially not ready to establish a comprehensive and coherent features standard, and that the STEP/PDES standard should not restrict further developments in the area. In fact, Mill et al note that the feature aspects of STEP/PDES have been suspended indefinitely, so this will remain the case in the medium term.

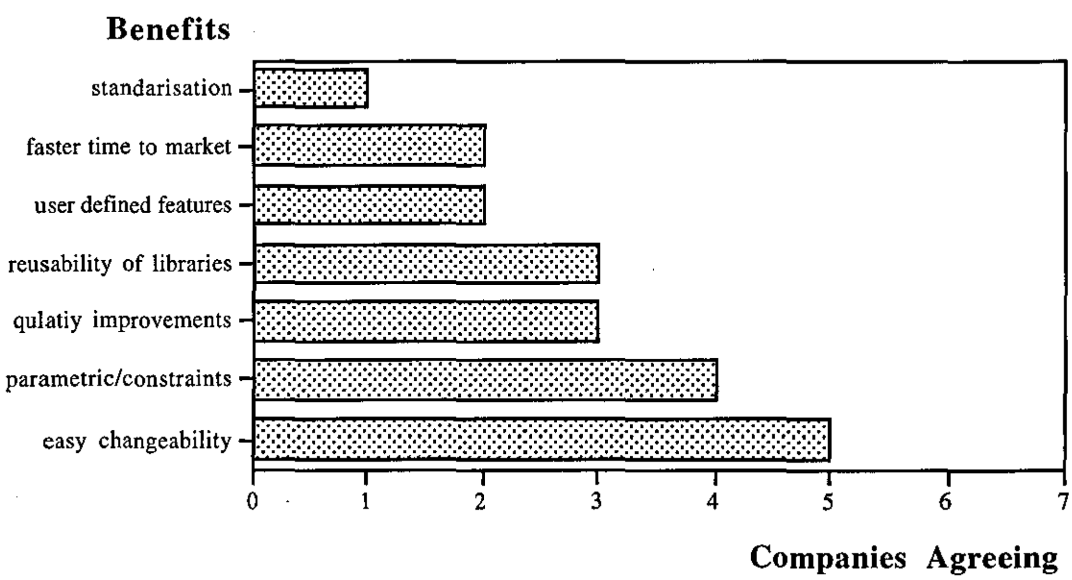


Figure 1-7 UK Industry FBD Benefit Perceptions

Salomons et al also published an extensive list of academic FBD systems. All were based on either CSG, B-rep or hybrid CSG/B-rep solid modellers [1993 Salomons et al]. However, Chamberlain et al have also published details on their hybrid FBD/MFR/IFS system, QT II, that also uses a hybrid CSG, B-rep, surface and wireframe modeller [1993 Chamberlain et al].

De Martino et al have recently published details of an architecture for fully integrating FBD, MFR and IFS [1993 de Martino et al] and potentially a range of engineering applications, based on a shape feature object graph (SFOG). They identify two important issues:

- developing intertwined data structures linking the geometric model and feature-based part descriptions
- flexibility for supporting user-defined features and procedures (in their case teach by example).

Hybrid solid/surface feature based modelling, intertwined feature and geometric data structures and user-defined feature capabilities, are being approached seriously by commercial CAD software vendors. All of the UK CAD vendors surveyed by Mill et al (CAD-Center, Camtek, CIMIO, Delcam, EDS Unigraphics, Pafec) revealed their intention to incorporate or extend the existing feature based aspects of their systems [1996 Mill et al].

Typically, advanced commercial solid modelling systems such as Unigraphics (EDS) and ProEngineer (Parametric Technology) provide parametric surface and features technology as "add-on modules" to their core hybrid solid/surface modelling systems. Table 1-1 describes the additional surface and features module functionality currently available in both systems [1996 Parametric Technology, 1996 EDS].

Mill et al note that EDS has future plans to develop design by manufacturing features, feature based design analysis and optimisation, and improved feature based tolerancing and assembly within Unigraphics. They also note that every entity within ProEngineer is called a feature, which may indicate the significance Parametric Technology attribute to feature based engineering [1996 Mill et al].

Table 1-1 Commercial CAD Surface and Features Module Functionality

System	Module	Functionality
ProEngineer	Pro/SURFACE	Parametric surfaces incorporated in the solid model or as a separate surface model. "Full associativity" between surface and other geometric/data entities.
	Pro/FEATURE	Basic feature set based on all entities. Module seems to add capability for advanced swept and blended profile features and custom feature definition
	Pro/ASSEMBLY	Assembly of feature based parts, dimension and position relationships. Targeted at variational design.
Unigraphics	UG/Solid Modelling	Geometric primitive Boolean operations and local face operations
	UG/Freeform Modelling	NURBS curves and surfaces, swept profiles
	UG/Features Modelling	Basic prismatic feature set with blending and chamfering
	UG/User-Defined Features	Custom add/remove feature definition

Given their core modeller's hybrid solid/surface modelling capabilities, it seems only a matter of time before user defined sculptured features are effectively integrated within either EDS's or Parametric Technology's CAD systems. Consequently, research considering the requirements for sculptured features within a predominantly sculptured product, not just as curiosities within a prismatic feature based context, seems both important and timely.

Delcam have plans for their suite of surface model based CAD/CAM/CAPP and inspection software to incorporate features technology. They are actively involved in feature based engineering research, notably:

- Specialised 3D sculptured milling feature recognition, for example steep, flat, and high curvature surface regions.
- Feature based design analysis and process planning (predominantly prismatic features research) [1995 FIRES].
- Feature based assembly design [1996 PICASSO].
- Sculptured product feature based design, through direct involvement with the research presented in this thesis.

2.2.7. Future Research Issues for Feature Based Engineering

In 1992 Sreevalsam & Shah [1992 Sreevalsam & Shah] noted that the features concept has failed to produce the envisaged integration of computer support tools for engineering disciplines because:

- there is no finite set of features in design
- the data management problems are not trivial
- feature recognition is still needed as some features are application specific
- it is not clear that designers design in terms of features, or if these result from other considerations

For some time now researchers have been aware of the problem areas still undermining the features concept implementation. Table 1-2 details outstanding research issues identified over the last 6 years. It is apparent that many of the same issues remain unresolved. The nature of Mill et al's publication means that most of the issues they note are biased towards the user [1996 Mill et al], but otherwise comments by all four groups indicate that the issues of feature definition, system architecture, relationships, interaction and multiple view handling are important and have remained unresolved over this period. The problems of feature library content, capturing design intent and user interface functionality, although not mentioned by all as future research areas, are nevertheless also current and important.

None of the researchers mention future research into sculptured feature issues explicitly, although their bearing on the other 7 problems identified is obviously important. It may be that some consider sculptured feature issues as a subset of the problems in providing for user defined features - the "other" features identified in many taxonomies.

Salomons et al note the use by several researchers of object oriented database structures together with solid modellers to implement feature system architectures [1993 Salomons et al, also 1993 Brandenburg & Wördenweber, 1988 Cowan et al].

The components of the object oriented approach, objects with associated attributes and methods with communication between objects, seem particularly well suited to implementing a feature data-structure, comprising features with parameters, geometry generation algorithms and inter-feature dependencies for example. Using the object class inheritance hierarchy to specify a feature definition taxonomy, and object class instances to specify feature instances, appears a natural and efficient means of implementation. The main difficulty with this approach is incorporating multiple application feature views, where typically only the design feature taxonomy class and design instance views are easily supported.

Table 1-2 Perceived Outstanding Research Issues in Feature Based Design

Issue	1990 Dixon et al	1993 Salomons et al	1994 Allada & Anand	1996 Mill et al
Feature Definition & Standards	• A formal definition for the term feature.	• Standardisation (e.g. STEP/PDES).	• Feature data exchange.	
Feature Architecture	• A systematic architecture.	• Form representation (although the trend is towards form feature based systems using hybrid CSG/B-rep solid modellers clarification is needed).	• Hybrid architecture development.	
Feature Library & User Defined Features	• The feature primitive library nature and scope. • Provision for user defined features.	• Feature description languages.		
Feature Constraints, Relationships & Interactions	• Methods to cope with feature interaction/ combination.	• Feature constraints (e.g. dimensions and tolerances for CAI applications). • Feature validation (e.g. feature interaction recognition to identify proximity/obstruction).	• Tolerancing information in the feature model. • Identification and uniqueness problems with interacting features.	• Definition of relationships between features within a part and between parts, perhaps through more intelligent features.

Table 1-2 Perceived Outstanding Research Issues in Feature Based Design [continued]

Issue	1990 Dixon et al	1993 Salomons et al	1994 Allada & Anand	1996 Mill et al
Design Intent	• A mechanism to capture the design intent for its use in managing the propagation of design changes.	• Engineering meaning representation (information additional to geometry, such as function).		
Multiple Application Views	• Use of features in conceptual assembly design systems that enable design at various levels of abstraction and in multiple functional viewpoints.	• Multiple view handling (different feature combinations & interpretations required by different applications resulting in the need for a translation activity between application-feature-space models).	• Feature mapping. • Multiple application support. • Product design optimisation, including design advice/critiquing.	• Feature interfaces between design and downstream applications. • Feature oriented cost estimating.
User Interface			• Dimension driven design.	• Improved viewing and editing of features, including the feature dependency tree. • Model view manipulation and annotation.

2.3. Sculptured Surface Features

Sculptured surface products are as diverse as; turbo machinery impellers and hip prosthesis [1993 Bauchat et al]; consumer packaging and engine exhaust manifolds [1989 Johnson]; hand held electrical appliances [1991a Roberts, 1991b Roberts]; child car safety seats [1992 Lennings]; car body panels and ceramic table-ware [1992a Cavendish & Marin]; golf clubs [1993 Jones et al, 1994 Mitchell et al]; and shoe lasts [1995b Mitchell et al].

Very little research has been published specific to sculptured product FBD issues. FBD research has almost entirely concerned prismatic products for mechanical engineering applications and has consequently been based on CSG, B-rep or hybrid CSG/B-rep solid modelling technology [1993 Salomons et al]. Perhaps because of the relatively recent incorporation of surface modelling capabilities within solid modellers, the range and depth of research issues to be resolved even for prismatic FBD, and the much greater population (and so customer base) of mechanical/prismatic product designers compared with sculptured product designers, the problems of enhancing sculptured product design by a FBD approach has received little attention from the academic community.

This does not mean that there are no sculptured product industries that may currently benefit from advanced FBD CAD software, or that this will be the status quo in the future. Although there is no expectation of a return to the ornately sculptured mechanical engineering designs of the Victorian era, there are early signs of a growing interest in more 'organic' product designs. For example, in the consumer electronics industry, previously characterised by its utilitarian prismatic designs, the growth in portable and even hand held consumer electronics, growing awareness of distress caused by human/technology interface incompatibilities[1], and the adoption of enhanced housing aesthetics as a consumer electronics product differentiator have all

[1] e.g. The growing number of repetitive strain injury claims.

resulted in new applications of surface modelling CAD software. Even a desire to achieve more optimal mechanical engineering designs in the future may herald a new interest in sculptured FBD.

Cunningham & Dixon note that "features, and their qualitative and quantitative qualifiers, originate in the heuristics that surround these activities (i.e. design, analysis and manufacturing)" [1988 Cunningham & Dixon]. Thus, the features populating the library of a FBD system for sculptured products might be expected to be predominantly dictated by the design process, more so than for general mechanical parts, as the typically used manufacturing techniques (3, 4 or 5 axis ball nose cutter machining, injection moulding or casting, and manual crafting) are so accommodating[1], and the requirements for easy analysis are often secondary to the shape goals.

Cavendish and Marin have published work on FBD for pockets, channels, beads and ribs on automotive body panels [1991 Cavendish et al, 1992a Cavendish & Marin, 1992a Cavendish & Marin]. They note that for a car containing >200 pressed sheet metal parts only 5% are smooth outer panels. The rest are functional inner panels incorporating many of the above features, and their work is primarily concerned with these pressings.

Cavendish and Marin point out that normal free form surface modelling techniques are inefficient for modelling functional panels, and propose a feature based "surface assembly" approach instead. They form functional panel surfaces "... from a given base surface, by taking pieces of known surfaces (... secondary surfaces) and smoothly blending them ... to the base surface along given curves (the feature boundaries) to create the required features." The primary and secondary surfaces are blended using a parametrically controlled transition function. The approach provides for nesting and partial superimposing of multiple features to generate complex panels from simple primary and secondary surfaces.

---

[1] i.e. Placing relatively few restrictions on product shape.

Similar work has also been published by van Elsas and Vergeest [1996 van Elsas & Vergeest].

Although it is very useful for functional sheet metal pressings, Cavendish and Marin avoid the issue of primary and secondary surface definition, as sub-features of their pocket and protrusion features, and concentrate on boundary definition, blending and interaction.

Shimada et al have also published work on designing free form functional surfaces using features employing automatic triangular mesh reconstruction [1992 Shimada et al]. The methods are based on Celniker and Gossard's earlier work on designing free form shapes using deformable curve and surface finite elements [1991 Celniker & Gossard]. The depression/protrusion feature's dimension and profile are specified by the user in relation to a triangular mesh representing the surface. The surface mesh is then reconstructed to match the desired boundary using a static force balance applied to "bubbles" related to the mesh nodes.

As mentioned previously (Section 2.2.4), the feature sets inherent in both techniques (base material, protrusions and depressions) offers only limited benefits to other sculptured products.

Several researchers have published work using various techniques to achieve localised small scale and gross distortions of underlying parametric surfaces:

- Forsey and Bartels published a method using hierarchical B-spline refinement [1988 Forsey & Bartels].
- Sederberg and Parry introduced a free form deformation (FFD) technique based on 3D parallelepipedical lattices [1986 Sederberg & Parry].
- The method was later improved by Coquillart's use of non-parallelepipedical 3D lattices to allow arbitrary deformations [1990 Coquillart].
- Kalra et al use the same technique to model facial expressions [1991 Kalra et al].

- Hsu et al proposed a direct manipulation FFD variation [1992 Hsu et al].
- Pasko and Savchenko achieve constructive solid deformation by the algebraic difference of the surface definition function and a displacement function [1995 Pasko & Savchenko].

Most of these researchers consider their deformations as 'features', but these methods essentially provide extremely flexible surface manipulation techniques, almost to the point of providing the user with 'virtual plasticene' or 'digital chewing gum' as a modelling medium. They seem particularly appropriate for modelling local surface ornamentation features [especially 1990 Coquillart], but as a broadly applicable sculptured feature based modelling approach they appear to provide too much flexibility, and generally rely on a considerable amount of tedious 3D point definition and repositioning.

It is easy to imagine that as a modelling material 'digital chewing gum' is too difficult to control, so that the iterative design modification process readily becomes unstable, and the resulting designs impossible to manufacture. Few manual craftsmen would choose such a flexible modelling material for this reason, and prefer to work in easily cut solids like wood, epoxy resin or modelling clay instead.

Roberts has published work on "feature based parametric solid modeling" associated with Parametric Technology's ProEngineer software [1991a Roberts, 1991b Roberts]. The work presented is based on a solid modeller (presumably ProEngineer) with parametric surface capabilities, feature data structures, feature parameter associativity, and "full [engineering application model] associativity".

Within the software solid geometry entities, including parametric surfaces, are combined with additional dimensional, tolerance and manufacturing information to define design features[1]. These can be assembled into a product

---

[1] e.g. holes, slots, ribs, flanges, surface drafts, blends and several injection moulding specific features such as sprues and parting lines are provided.

design with parametric associativity between features, i.e. changes to the specification of one feature affects associated feature parameters.

This provides a powerful tool for 'one-off' design and subsequent 'what-if' analysis (varying feature parameters to optimise a design) or product family generation. However, the approach is limited in its suitability for a wide range of sculptured product variation based on any one design model, as the individual features are constrained to a particular shape behaviour. Shape behaviour variation for any one feature requires the surface feature to be redefined and the model to be rebuilt.

Lee and Chang recognise the potential presence of sculptured features in industrial and consumer products [1993 Lee and Chang]. They propose a "virtual boundary" technique for isolating free form protrusions to support CAPP, cutter selection and CNC cutter path generation.

Some of the work presented in this thesis has also been published as:

- An overview of the proposed sculptured FBD method [1993 Jones et al, 1994 Mitchell & Jones].
- An initial data model for sculptured FBD [1995a Mitchell et al].
- A description of an iron golf club design system [1994 Mitchell et al].
- A structured approach to the design of shoe lasts [1995b Mitchell et al].
- As a final SERC research grant report [Jones et al 1994].

3. DELCAM'S DUCT SOFTWARE

3.1. Overview

Delcam describe their DUCT CAD/CAM software as:

> "... an aid to the design, manufacture and analysis of complex objects, many of which require patterns and moulds or dies for their manufacture. ... [DUCT] is well suited to the modelling and machining of parts with arbitrary surfaces. Parts are defined by designing individual surfaces and assembling these together, often using automatically generated blend surfaces as joints. The final geometric model represents a unique description of the component." [1995 Delcam].

Their list of facilities within DUCT include the ability to:

- "Manipulate surface data interactively on the graphics screen."
- "Create pictures of parts, or of plane sections through parts, for immediate reproduction or for plotting off-line."
- "Make colour-shaded images, with either realistic colouring or shading according to surface curvature."
- "Match or blend surfaces together."
- "Determine split lines and set draft angles for casting."
- "Calculate areas, volumes, etc."
- "Generate machining paths to mill a part from a solid block, both roughing and finishing."
- "Generate tool-paths for two-dimensional profiling, for turning or for two- or four-axis wire-spark erosion."
- "Construct finite element meshes on surfaces."
- "Add dimensions and annotation to drawings."
- "Transfer definitions of surfaces or wireframes from or to other modelling systems by means of standard interfaces."

- "Build macros (command files) to perform repeated tasks efficiently, or to create families of parts."

Although the Manufacturing Engineering Department of Loughborough University has been using DUCT for some time, and Delcam were willing collaborators for the SERC ACME research project to develop a prototype feature based approach to the design of sculptured products that funded this research, the DUCT software was chosen as the central software implementation tool because it incorporates 5 key capabilities:

- Surface model generation for feature geometry evaluation.
- An internal programming language to construct and record advance modelling routines.
- A customisable graphical user interface (GUI) allowing construction of a feature based GUI.
- Dynamic wireframe drawing, surface shading, and model rotation for realistic model viewing.
- CNC cutter path generation for model manufacture and evaluation.

DUCT uses Bézier surfaces defined using either 2D 'sections' distributed on a 3D 'spine' curve or in terms of the surface patch control points, referenced as points and vectors along 'laterals' and 'longitudinals' (the local surface isoparametric patch boundaries).

DUCT can also automatically generate intersections curves and rolling ball fillet surfaces between surfaces, within a user defined tolerance. The intersection and tangency curves are defined as a pair of local parameter space point chains matching the actual 3D curves within the specified tolerance. These 'parameter curves' can be used to specify internal boundaries to 'trim' the surface to an intersection or blend tangency point.

Recent release versions of DUCT have incorporated the ability to identify several surfaces, including blends between them, as a group or 'shell' entity. The surfaces are essentially unchanged, but the software maintains a record of the blend, intersection, bounding and trimming relationships between the constituents, so that when one element is changed associated surfaces can be updated automatically. The facility also supports Boolean operations to combine shells and surfaces, although the robustness of the capability is still improving.

The command language is the fundamental means for driving the DUCT software, and provides access to its entire functionality. The user may 'drive' DUCT directly via a command line interface, or via a menu system that actually passes DUCT commands or a series of commands to the core software in the background. The command language has programming constructs similar to FORTRAN that allow complex interactive command routines to be written. These 'command files' provide the basis for much of DUCT's high level functionality. The key capabilities in the language are as follows:

- Full access to DUCT surface modelling functionality for surface generation, interrogation and manipulation.
- A range of mathematical and text manipulation functions.
- Access to 6 general purpose system integer and real parameter stores, and 6 system binary flags.
- System and user defined lists (integer number and duct entity name sequences) and registers (real number and text character sequences).
- Conditional statements (e.g. 'if-then-else', 'do-while', 'repeat-until' constructs).
- List controlled 'looping'.
- Subroutine definition and calling.
- Limited text file disk access.

The most recent release of DUCT used for the research, DUCT 5.304, makes an internal object oriented database (OODB) available to the user. The facility was primarily introduced to allow bill of material generation from assemblies of objects associated with relevant classes. The user can define class hierarchies with lower level classes inheriting (variable or static, numeric or textual) attributes from parent classes. Multiple inheritance is supported for the lowest level classes.

Class instances can then be attached to geometry entities (including surface and shell and several wireframe construction entities) together with specific values for variable attributes.

Limited interrogation functions are provided to query the attributes attached to a named class and the values associated with them. The class of an object and attribute values can be similarly queried. There is no support for interrogating the database to establish relationships between classes.

The user interface can be customised to provide a series of menu buttons that surround the geometry display window using a text file definition scheme. Each button can be specified to activate either display of another menu element, a DUCT command string, or a DUCT command file. Either the command string or command file may also activate a user specified Motif style form. These are also defined using a prescribed text file format and allow the user to input data and activate other command strings or files as required.

3.2. Release Functionality Variation

During the pursuit of this research the DUCT software has been through 3 major revisions from the initial version 5.0. The functionality available in each release has affected the extent to which the theoretical principles could be implemented and evaluated, and also the implementation method chosen. Table 1-3 lists some of the changes in DUCT's capabilities that have most affected the research:

Table 1-3 Relevant DUCT Release Functionality History

Release	Facility	Description
5.1 & 5.0	Surface Modelling	Constant radius surface pair blending. User driven boundary curve creation.
	Programming Language	Basic conditional constructs (if-then-else). Only run time data stores supported. Text file manipulation limited to result output, command file recording and playback.
	User Interface Customisation	Single menu region with command string activation or alternative menu buttons.
5.2	Surface Modelling	Initial shell technology introduced. Improved interactive and automatic boundary creation. Interactive and multiple surface constant radius rolling ball filleting supported.
	Programming Language	Improved subroutine facilities. Extended conditional statements supported. Text file access and string manipulation.
	User Interface Customisation	Multiple menu segments possible. User definable Motif style forms available.
5.3	Surface Modelling	Shell technology robustness improved. Further improvements to automatic boundary creation. Multiple surface variable radius rolling ball filleting supported.
	Programming Language	OODB facilities available.
	User Interface Customisation	Interactive graphics selection now possible.

4. OVERVIEW

The subsequent chapters and sections present:

- A review of the need for sculptured features in relation to some example sculptured products
- The development of the extended form (EF) feature method for sculptured products
- The identification and capture of EF features suitable for specific existing sculptured products
- Functional and data models suitable for an EF feature based design system
- An EF feature based design system implementation within a commercial 3D CAD system
- The results of initial system user trials
- A description of the identified immediate benefits and those accruing from system exploitation
- A discussion, conclusions and recommendations for further work.

CHAPTER 2. SCULPTURED PRODUCTS

1. THE NEED FOR FEATURE BASED DESIGN OF SCULPTURED PRODUCTS

Sculptured products are sculptured to meet one or more design objectives, for example:

- To appeal to the aesthetic aspirations or preconceptions of a customer.
- To provide comfortable interaction with living organisms.
- To achieve optimum mass or shape for a particular level of energy transfer or constraint performance.
- To allow, generate or control a specific fluid flow regime in or around the product.
- To establish a brand image in a competitive market.

Consequently the objectives met by a sculptured product's shape are often both functional and fashionable. Because many sculptured products are for markets dominated by fashion, the design process is driven by the requirements of these markets. Typically this means:

- Regular new product design and re-design to maintain and improve brand image and so market share.
- Short NPI timescales to keep up with or ahead of the competition.
- Fast adoption of new ideas to prevent competitors taking a market lead.
- Marked product differentiation in markets with evenly matched competition, or subtle product differentiation in markets dominated by a brand leader.
- Detailed and extensive product shape specification with restricted availability to maintain and defend product ownership.

Obviously these pressures generate a significant amount of design activity. In any competitive industry where this is true the adoption of tools that improve design process efficiency or quality can provide a company with a significant competitive edge or simply mean that they remain in business.

In many cases, the design of sculptured products traditionally involves the following stages (often repeated iteratively) for completely new product design:

- Two dimensional sketching to capture and present design intent.
- Manual crafting a scaled or full sized design model.
- Modification of the model until it represents an accepted design shape specification.
- Measurement of the final crafted model.
- Manufacture and inspection of a design prototype for acceptance tests.
- Manufacture and inspection of production tooling.
- Manufacture and inspection of commercial product trials, and subsequently the final product.

For many products the majority of design activity will focus on the modification of existing designs. In this case manual crafting of the initial design model is based on modifying an earlier model of an existing product.

Three dimensional CAD tools offer the potential for significant benefit to this sort of design process.

Interpretation

- In the manual process the 2D design intent sketches are interpreted into a design model by eye and considerable skill. Using 3D CAD systems it is possible for 2D design sketches to be transformed into 3D shape definitions without user interpretation. Furthermore, it is possible to specify design intent in three dimensions directly.

Approximation

- To manufacture prototypes it is often necessary to re-scale and approximate the design model using copy machining techniques. Even when the prototype is to be cast or injection moulded to the same scale using low volume tooling, so that soft moulds can be produced by casting them around the design model as a male master, the model often needs further modification to allow for separation, provide draft angles and account for shrinkage. In some cases (notably the automotive industry) the model will be approximated using CMM measurement techniques and 3D CAD software to provide the basis for CAM CNC code generation.
- Direct 3D CAD product modelling removes the approximation element, both in terms of time and accuracy from the process. The model can be scaled and adapted to the intended manufacturing process directly and immediately.

Efficiency

- Manual sculpting or hand crafting a design model can be a lengthy process. In many cases the time taken to remove material to define the shape is less significant than the time taken to add material as the model develops and changes or corrections are made. For example manual filing is a relatively quick forming process compared to the time it takes epoxy resin to cure. Given that similar materials and techniques are used in many industries to iteratively develop a sculptured product's shape, design development can be a 'long winded' process. Using 3D CAD software redefinition of material boundaries is relatively instantaneous.
- A significant amount of time in the traditional design process does not improve the design itself, but is instead devoted to translating the design specification into a different medium (from 2D sketch to crafted model, to model measurements, to design prototype, to production tooling). Modelling the design using 3D CAD software provides a single accurate

mathematical definition of the product shape from which all other information can be derived.

Verification

- Shape verification for sculptured products is difficult. The first problem is to establish measurement datums and orientations. For a fully sculptured product this can be almost impossible, and may be resolved by introducing surface elements to identify measurement points (such as pimples or flats) or by constraining particular surface regions to have simpler prismatic geometry. Some form of custom jig is often used in an attempt to establish repeatability by holding and aligning the product in a specified way. However, even where there are sufficient prismatic features to derive a unique, repeatable datum and orientation, the traditional measurement techniques used by the craftsmen may ignore these and make use of more subjective pseudo-function related characteristics. These will often require a degree of subjective alignment 'by eye'.
- The second problem is to determine the scope of measurements to establish that the complex regions of the product surface are as intended. In small to medium sized organisations this is often resolved by specifying and measuring important derived characteristics (such as mass, a perimeter or diametric measurement) and comparison with a selection of profiles reproduced as 2D templates. In larger organisations more complicated computer based techniques may be used to compare CMM point measurements or scan data with standard measurements taken from an acceptable production model.
- 3D CAD does not resolve the datum and orientation issues for a fully sculptured product, except by making it easier to design custom holding equipment or temporary surface features that can be used for alignment and then removed after inspection. However, the disciplines involved in producing a CAD model make it easier to establish unique datums and orientations. Furthermore, a 3D CAD model is potentially a less

subjective and more accurate source for the intended derived characteristic values and can be used to produce profile measurement templates relatively simply. A 3D CAD model also makes it possible to achieve automatic generation of an objective CMM measurement scheme that directly refers to the 3D CAD shape specification.

Prediction and Optimisation

- Although the craftsman and hopefully the customer will consider the shape of a sculptured product to be a work of art, satisfying the aesthetic design objectives, the design's functional performance is often more difficult to predict due to its more complex shape. Industries or individual companies will generally resort to rules of thumb, statements of best practice, educated guesses and prototype design trials and modifications where time and money allow. Often they then make inflated performance claims in their advertising in the knowledge that it is as difficult for them to be proved wrong as it is for them to objectively establish their product's performance.
- Where a product's functional performance can be linked to characteristics simply derived from its shape, such as its inertia properties, the 3D CAD model can be used to accurately predict these. More complex performance behaviour predictions, for example failure prediction under working loads, can be achieved by applying CAE tools to the CAD geometry. This ability to predict performance makes it possible to optimise a design to achieve specific functional goals, and so reduces the need for prototype trials and unsubstantiated advertising claims.

Quality and Economy

- The potential benefits of using 3D CAD produce the knock on effect that designs can be produced and modified quicker and so more cheaply. Alternatively, the efficiency gains and improvements in the design specification's usefulness make it possible to produce better designs, that require fewer physical prototypes to test performance.

It has long been a criticism of CAD systems that they promise a great deal but in practice fail to deliver.[1] The reasons for this generally have been the hidden and apparent costs of ownership and the difficulty in actually using them. Apart from cost, ease of use prevents most industries adopting these tools. The investment in computing hardware and software is prohibitive, but small compared to the cost of recruiting and training individuals capable of driving 3 dimensional design tools using abstract mathematical concepts.[2] In many cases these personnel are additions to the design team and represent an undesirable intermediary between the design specification and the creative designer. Even when funding and personnel are available and accepted to implement 3D CAD tools their limited ease of use makes the design process less efficient than it might be.

The main goal in developing the feature based design methodology for sculptured surface products, presented in the following chapters, is to overcome the ease of use shortcomings in modern 3D CAD systems so that the potential benefits of using 3D CAD can be fully realised in relevant sculptured product industries. The desktop metaphor, implemented in current graphical user interfaces, provides personal computer users with familiar terminology and concepts with which to drive their computer's operating system. Similarly a feature based approach yields the opportunity to provide the designer with a 3D CAD interface driven by terminology and

---

[1] In Barfield et al's recent survey of 117 users from 19 companies and 3 universities, mostly using CAD for mechanical engineering design, a large proportion considered key aspects of their work worsened or unchanged by their company's CAD facilities. In particular; ~29-62% (depending on strength of opinion) considered their creativity decreased or unchanged; ~15-45% had similar perceptions of their productivity; ~27-47% thought the same about their job satisfaction; and 34-58% about the effect on their decision making abilities [1993 Barfield et al].

[2] Barfield et al reported that 83% and 72% of their sample had received in-house and short-course training respectively [1993 Barfield et al].

concepts that he recognises in relation to his product, that in turn drives the more abstract systems necessary to model the products geometry that he is normally presented with. Hopefully this places using 3D CAD within the grasp of the creative designers with minimal retraining.

The subsequent goals in developing a feature based methodology must be to make as much use as possible of the data structures to improve the efficiency of the CAD process.

2. EXAMPLE PRODUCT BACKGROUNDS

2.1. Sculptured Product Examples

Two approaches to developing a feature based modelling methodology, and subsequent design system, were considered. The first was to take a 'universal' view, assuming that the ultimate system should be appropriate for all sculptured products, and so formulate modelling methods and design tools to cope with every eventuality. This has the appeal of ultimately producing a very powerful sculptured product design system, but the research aims are too broad to achieve useful results within a practical timescale. Given the scope for variation in sculptured products, it is likely the research would produce a 'Jack of all trades but master of none'.

The second approach, adopted for this work, was to concentrate on a few extensively sculptured products with a broad range of design requirements, for example to achieve functional, tactile and aesthetic objectives together with variation of similar designs within a product range. The essential benefit of this approach was to focus the research problem so that readily applicable results could be achieved. From these product specific research results broader implications for a generic system, capable of directly supporting or adapting to most sculptured products, were to be identified and explored. The main criticism of this approach is that the research results may only be applicable to a few sculptured product types, but it is arguably better to produce research of immediate use to a few industries than to produce research of no real use to anyone.

The principal product used to develop the sculptured feature methodology was iron golf club heads. Subsequently, application of the methodology to the design of shoe lasts has been considered in detail, with golf putters and woods, ceramic table ware and sanitary ware considered as further examples. The following sections describe the backgrounds and general design issues relating to the main products referred to in this thesis to illustrate the research results.

2.2. Golf Club Irons

2.2.1. The Golf Equipment Industry

Whether you agree with Churchill that "golf is a pleasant walk spoilt", or you are addicted to the game, so that like Neil Armstrong when embarking on humankind's first trip to the moon you would be sure to take along a club and a ball in case you found time to play a round, it should be noted that the manufacture of golf equipment is a significant international industry.

World wide sales of golf equipment in 1993 totaled $5 billion, with around 52% (~$2.6 billion) attributed to clubs and 26% (~1.2 billion) to balls. The US Professional Golf Association estimated that in the USA approximately 505 million rounds of golf were played in the same year [1994 Thomas].

The UK alone has 2,400 dedicated golf equipment outlets (not counting general sports equipment and other outlets). A recent survey of these in September 1995 [1995 Golf Research Group] reports that:

- Between July 1994 and July 1995 the UK imported golf goods from 39 different countries worth £82 million, and exported golf goods to 84 different countries worth £52 million. Around 29% (~£24 million) of equipment imports were whole clubs (~86% from the USA, ~14% from South East Asia, SEA) and around 45% (~£37 million) of equipment imports were club parts (~45% from the USA, ~55% from SEA). The approximately even split of club part imports between the USA and SEA reflects the popularity of US club shafts and South East Asian club heads.
- Around 68% (~£35 million) of the UK's golf exports go to other European countries (50% whole clubs, 28% balls, 12% accessories, and 10% club parts), around 20% (~£10 million) to the USA and only ~4% to SEA (~£2 million), with a further 8% going elsewhere. Around 38% (~£20 million) of total exports are whole clubs, and around 17% (~£9 million) are club parts.

- Total sales for the dedicated UK outlets amount to around £0.5 billion. 48% (by value) of all UK sales were golf clubs, the remaining 52% being clothing, balls and bags. 60% of club sales were irons (including putters) and 40% were woods.

The same report indicates the top 50 UK golf companies alone have combined yearly sales of around £1 billion (including some equipment not directly associated with golf). The statistics indicate golf club sales are a significant proportion of this.

Golf itself is predominantly a psychological game. Mastery of the playing action, or swing, can only be achieved and maintained with both mental and emotional discipline. This is because the motion required to strike the ball effectively depends on repeatable, precise, coordinated contraction of a variety of muscles throughout the whole body, resulting in a smooth energy transfer to the club head. This is almost impossible to achieve if the player is distracted, or psychologically undermined. Consequently, there are several factors that affect a user's purchase of new clubs, for example:

- The perceived additional benefit to their game due to the club's functional improvements or tailoring to their specific needs (the actual benefits are often exaggerated, and the benefit experienced is usually due to the psychological lift from the anticipated improvement).
- The prestige, and potential one-up-man-ship, of competing with the latest and best equipment.
- The aesthetic appeal of a set of pristine condition fashionably styled clubs.
- Their cost, and the statement this makes about the owner as a successful player or businessman.

Coupled with the high profile and potentially high winnings in top professional competitions (particularly in the USA), these factors make the golf equipment industry fashion led at both functional and aesthetic levels.

The golf club head is almost fully sculptured, so golf club manufacturers have all the concerns typical of industries offering a sculptured product in a fashion dominated market (cf. Section 1). Two particular issues are perhaps paramount in the designer's mind. The first is technical invention. While club head designs are relatively stable, the market share for manufacturers remains stable. However, when technical innovation is introduced and successfully sold to players as giving them a new edge, there is often a radical redistribution of market share producing a debilitating and often fatal reduction in sales for those companies not swiftly adopting the technology. A good example of this is the introduction of peripherally weighted clubs (cavity backed irons, hollow steel traditional and 'oversized' woods) produced using lost wax investment casting techniques. Investment cast cavity backed irons currently represent 90% of golf irons sold, and so dominate a world market previously almost exclusively populated by forged 'bladed' clubs. Similarly, almost 95% of golf woods sold employ a hollow steel construction, with less than 1% being made from solid persimmon or laminated maple, the steel wood's predecessors. Oversized woods were first introduced as recently as 1990 and already represent 98% of market sales. Callaway, developers of the first oversized wood, now dominate ~42% of the UK wood club market, while no other company has more than a 10% share. [1995 Golf Research Group]

The second issue is design control and product identity. As the club market has become dominated by investment cast heads, so producing the heads has become almost entirely the province of South East Asian casting houses, with a few notable exceptions such as Ping in the USA. This is entirely because heads meeting acceptable quality levels can be produced in countries such as Taiwan at a fraction of the cost incurred in the west (~£2-£10 per head depending on design complexity and quality). This is mostly due to the relative cost of the intensive manual labour required to investment cast and finish large numbers of complex sculptured products. However, even the cost of the production wax injection tooling of $800 in SEA is much less than the £10k-£25k price in the UK.

Because 85% of the world's club heads are now produced in SEA by specialist casting houses, many brand manufacturers will have their heads made by the same company. Not only does this make it difficult to maintain the secrecy of prototype trials and new product innovations, but because of the additional time savings companies are under financial pressure to adopt 'off the shelf' head designs developed by the casting house (with the addition of their own logo). This means that, particularly at the lower end of the club market, several different manufacturers will be selling essentially the same club.

This is a potentially dangerous situation as companies may find that they loose control of the design elements that give them their market position. If this happens they become vulnerable to loss of sales due to market changes, perhaps a rivals innovation or the availability of equivalent products from a cut priced source (even the casting house itself). Around 13% of woods and 17% of irons sold in the UK can be attributed to small companies selling 'copies' of other companies clubs [1995 Golf Research Group], representing a market share for irons much bigger than any single manufacturer.

Several companies see the introduction of CAD techniques as providing a means to resolve these problems. They hope to develop in-house designs quickly, economically and of suitable quality and performance independent of the casting houses. This would allow them to innovate internally and respond to external innovation quickly. They would also be in a position to protect and control their own designs by revealing the final product to the South East Asian head manufacturers just before the production cycle rather than throughout the development cycle. With these innovation, cost and control benefits 'off the shelf' SEA designs become less attractive and economically less significant.

2.2.2. Club Development History

A golf club essentially consists of three parts; the head; the shaft; and the grip. Although the feel and mechanical properties of the grip and shaft are important their shape is currently relatively simple. In contrast, modern club heads have a complex, elegant, sculptured shape that has evolved over the last 500 years of play, trial and experimentation. It is the head shape and properties that provide an important visual stimulus, and primary product differentiation, for club set sales.

Although the game was played long beforehand, the golf club manufacturing industry was perhaps formally established with the appointment of William Mayne of Edinburgh as the Clubmaker to King James I of England in 1603. The earliest golf clubs, up until the late 1800's, were almost all hand crafted from wood, using ash or later hazel for the shafts and beech, apple, pear or thorncuts (hedge cuttings growing with natural bends from the head to the shaft) for the heads. Persimmon wood was introduced and became popular for the heads in the 1890's. Hand crafting of each element and the variation in material properties for the wood used meant that no two clubs were exactly the same. Each of the three elements were carefully refined to compliment each other and produce a unique club often specific to the needs of an individual player [1982 Henderson & Stirk].

Changes in ball fabrication techniques and materials, particularly the transition from 'feathery' (a leather pouch stuffed with boiled feathers) to 'gutta-percha' (a hard rubber produced from Malayan tree sap) after its introduction in 1848, altered the golf ball's hardness and durability. This coupled with the normal wear and tear experienced by clubs meant that face inserts of leather or bone were often used to improved a wooden club's wear resistance. But it also contributed to the increased popularity of iron headed clubs.

The first golf irons had their heads manually forged by blacksmiths from Waverley Iron bar with one end formed and welded around a mandrel to provide a tapered socket for the shaft. The hitting face's angular alignment to the socket was initially achieved by eye and later by using templates. The early irons were crude, heavy implements used often literally to dig the ball out from a difficult lie. It is clear from the names of individual irons in the mid to late 1800's and early 1900's ('cleek' Scots for hook, 'rutter', 'track' and 'spade mashie' irons) that this was often still their primary role.

However, the evolution of iron club design, for example the adoption of a deeper, shorter, flat hitting face at a larger angle to the head socket (producing a larger loft angle) with face markings (grooves or punch marks) to help impart backspin to the ball, culminating in the 'mashie' club, meant that iron clubs enabled the player to hit more accurate approach shots to the putting green. The consequent play success of the mashie, improvements to manufacturing techniques for producing sets of forged steel irons and their durability, inspired the adoption of a large range of golf irons covering the spectrum from long distance drives, through increasingly accurate approach shots, to high lofted escape shots. Whereas an early set of clubs would include six wooden clubs and two irons, there are now typically 3 types of wood (driver or 1, 3 and 5 woods) and 11 types of iron (1 to 9 irons, pitching and sand wedges) excluding the putter, that a player can choose for the set of 14 clubs they can play with in any one game.

Automating the manufacturing processes began in the late 1800's and early 1900's with the adoption of the copy turning lathe to rough the shape of a wooden head. The results produced by copy turning determined the essential shape of wooden drivers until quite recently, even with the adoption of hollow steel woods. This constancy can be partially explained by customer perceptions and the rules of golf that a club must generally be of "traditional shape" [1996 R&A], but some of this stagnation is due to the continued use of the copy turning lathe in the early stages of hand crafting the prototype model.

With the increased popularity of iron clubs, the manual head forging process became fairly organised as an industry. A large club making company, such as William Gibson's in 1907, would employ; 16 forgers (each skilled in clubmaking and only producing a single club type); several rapid club stampers; a separate head grinding, finishing and polishing shop; a permanent lathe worker producing tapers on the shaft ends; and skilled clubmakers to assemble the club, adapting the shaft flexure to the specific head as he did so. The use of stamped markings on the head (text and logos) other than face grooves or punch marks, to identify the manufacturers and club type, began with the early hand clubmakers and blacksmiths and has continued to the present day.

In 1906 Spalding pioneered using the drop-forging process to produce club heads. This enabled the production of more durable steel heads with greater efficiency and consistency in shape. Consequently it became easier to produce matched sets of irons. A set of female die pairs, providing a progressive change from a shape close to the initial blank to a shape closely representing the finished club, were manufactured for each head. A blank of metal was then forced to plastically flow into the cavity formed by both halves of each die pair in turn, under the action of repeated blows. This process produced a blade with a solid hosel (the part of the club head where the shaft is attached) that was subsequently machined to give it a tapered bore. The whole head was then finished by grinding and polishing. Initially the bore was blind, but some clubmakers adopted the practice of boring though the club to enable a firmer fit with the shaft. The forged irons, often preferred by high ranking professionals of today, are still made by much the same process.

Hickory was replaced by seamless tubular steel shafts in the 1930's. Many of today's clubs also employ wound or wrapped fibre composite shafts (predominantly carbon fibre with boron strengthening in the tips) first introduced around 1960. Both are usually glued into a parallel hosel bore using an epoxy adhesive. Also, the earlier leather grips have been replaced mostly with injection moulded synthetic rubber composite.

In the 1960's club manufacturers started to use investment casting techniques for iron heads, allowing considerably more freedom in shape than was possible with forging. This facilitated the introduction of heel and toe weighting, and peripheral weighting or cavity back iron designs that gave the club head a larger moment of inertia and consequently larger "sweet spot". The result was a more "forgiving" club for the amateur. It also enabled aesthetic and brand identification details, such as logos and names, to be cast directly into the head.

The majority of modern cast clubs are made of stainless steel, although forgings are generally made from a mild steel and plated. Some manufacturers produce injection moulded carbon fibre composite golf iron heads with metal inserts to achieve further variations in weight distribution, but their durability is currently inferior to the steel heads. There have been recent experiments, notably by Dunlop Slazenger, with composite face inserts in steel golf irons to impart greater spin to the ball, but here too the penalty is reduced face durability.

2.2.3. Current Practice

The hand crafted origins and ethos of golf club manufacture still have a marked influence on manufacturing practices and attitudes of today.

Much of the design activity for modern golf iron manufacturers is to revitalise or refine existing club set designs to keep in step with fashion, perhaps on a yearly basis. Regular development of significantly different club designs occurs over a longer cycle, perhaps every two to three years (although as with most modern products the life span of a club design is decreasing).

Figure 2-1 shows a selection of typical iron golf club heads.

Designing a set of iron clubs usually begins with establishing the 5 or sometimes 6 iron design. Beginning with a mid-iron simplifies adapting the styling as necessary to produce the progression in major head dimensions from the 1 to 9 irons. The commonly accepted significant dimensions are illustrated in Figure 2-2, although some manufacturers may use different or additional measurements (for example the width of the sole perpendicular to the face, instead of parallel to the address 'soled-out plane'). Table 2-1 lists typical variations of these parameters through a set. Each manufacturer will have its own standards for parameter variation through a set, and may vary these to achieve a particular effect on performance, perhaps to provide those characteristics best suited to a particular type of player. For example, the face offset may be progressively accentuated from the 9 to the 1 iron to help the amateur player's hands to lead their driving strokes at impact .

Figure 2-1 Example Golf Irons

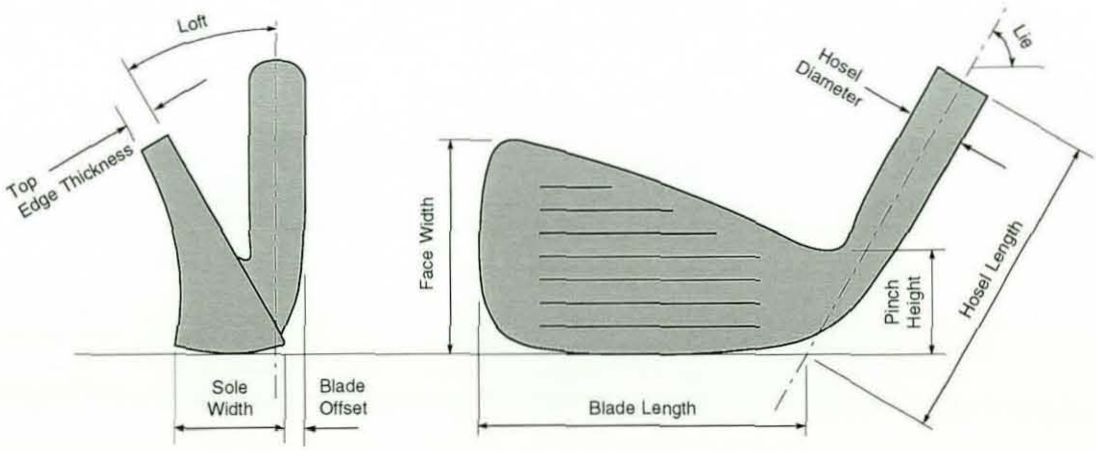


Figure 2-2 Typical Iron Golf Club Specification Parameters

Table 2-1 Typical Set Parameter Variations

Iron	Loft °	Lie °	Offset mm
1	15	57	5.5
2	18	58	5
3	21	59	4.5
4	24	60	4
5	28	61	3.5
6	32	62	3
7	36	63	2.5
8	40	64	2
9	44	65	2
Pitching Wedge	50	65	1
Sand Wedge	55	65	1

The designer's intent is usually represented as sketches, of the desired club face or back cavity profile, for example. A club similar to the intended new design will be selected as a base for the prototype model. Extra material is added by welding (where the prototype is intended for immediate play testing) or perhaps by the addition of epoxy resin. The model is then ground, filed and finished to represent the new club. Alternatively, radically new designs may be developed ad hoc by sculpting stock material using a mixture of hand shaping and milling, to remove the bulk of material and form a flat face. A full set, or alternating (1, 3, 7, 9) selection, of new irons will be produced in a similar fashion once the initial mid-iron design is accepted. The characteristic styling for the whole set is maintained mostly by eye and skill, often aided by a template for the shape, angle or curvature of particular regions. Where the set is developed by modifying an existing matched set, making similar adjustments to each of the existing clubs helps maintain a 'family resemblance'.

After manually refining the set designs (almost inevitably iteratively), and perhaps initial play testing, the set models will be passed to a preferred casting house as masters. Usually this includes additional documentation specifying the intended loft, lie, offset and weight characteristics together with acceptable tolerances. The master set is then modified by the casting house to provide suitable draft angles for the wax moulds, and copy machined, allowing for shrinkage of the waxes and cast steel heads. The copy is then used as a core to form wax injection mould tooling by pouring a low melting point alloy or epoxy resin around it. Where the same shape is to be used with different brand logos, or where the manufacturer wants to experiment with different markings, the mould will be made with sets of removable inserts containing each variation in markings required.

At this stage further refinements to the design may be necessary to prevent loss of detail, particularly for fine text or logos on the club surface, or to overcome problems discovered with wax production. Small anomalies, such as parting lines, are often accepted and corrected by skilled workers using soldering irons. The club waxes are attached to the common tree channel core structure and then coated with several layers of ceramic slurry which is fired to form the lost wax moulds.

The cast heads are extracted from the moulds by hand. The sprue is then removed manually and ground to form the correct shape by eye, perhaps with reference to a master. The heads are then linished, often several times in different media with masking to achieve a varied or localised finish. The parallel shaft bore is then finish machined in the hosel. At this point some weight adjustment is common. When the head is finally combined with a shaft by the club manufacturer the heads loft and lie characteristics may be checked using a custom built fixture. The hosel may be bent a few degrees using the same jig to adjust for casting tolerances or to give a variant of the design specification (e.g. companies will often offer two or three standard choices of lie to suit a players height).

Including prototype modelling, play testing, and production mould development and verification, the entire design process for a new set of irons may take 18 to 24 months.

Several manufacturers have adopted CAD techniques in an attempt improve their design lead times. However, in some cases only the initial styling is proposed using CAD. The prototype models will then be machined and modified by hand (presumably because the CAD data modification overhead is too great) to produce a production master. In some privately reported cases the final result bears little resemblance to the CAD design (particularly in terms of predicted inertia properties).

DSI started using CAD for balls in 1987 and then for clubs in 1988. Their original approach was to reverse engineer existing club designs, by digitising master heads using a CMM. The digitised data is then input to Delcam's DUCT surface modelling system and refined to produce a valid model of the original club.[1] The CAD model is then adjusted using DUCT, but in a comparable manner to the manual crafting process.

Prototype models are then machined in resin. These are spray painted to appear metallic and act as visual prototypes by mimicking the intended finish. The prototype resins are then passed as masters to the casting house for them to produce a small number of play test prototypes.

Reverse engineering a complete set of irons into a CAD model may take 2 to 3 weeks. Initial modification of the CAD models generally takes 0.5 to 2 days, and so 1 to 3 weeks per set (depending on the modification extent, and whether the 1 and 2 irons or wedges are included). Major modification to the designs may require almost as much time as initial modification of the base model, and is certainly not the interactive experience DSI desire for their club stylists. Some CAD based designs have been produced from scratch, but again

---

[1] *DSI often find it is impractical to digitise some of the small blend or chamfer regions on an* existing club. Since small errors in these surface elements do not effect the club's appearance or performance they are usually approximated using DUCT's surface blending routines.

these take 2 to 3 days per head for the initial model. Despite this, the use of CAD techniques has made it possible for DSI to produce new designs within 12 months.

2.2.4. Design Specification Parameters

Maltby [1982 Maltby] and Wishorn [1987 Wishorn] have produced some of the standard texts on modern golf club design and manufacture. The most important specification parameter for a club head is its weight, since it directly affects the speed the player can generate before impact with the ball. Since most of the energy transmitted from the head to the ball is the clubs kinetic energy, it is better to swing a light head faster than a heavy head slowly. Thus, the ideal mass represents a compromise between the speed that can be generated and the accuracy a player can maintain for a given length and weight of club.

The exact weight for each golf iron head has been determined mostly by trial and error as the game has evolved. The values specified by each manufacturer will depend on their experience and traditions. It is common to specify the head weight so that when combined with a particular shaft type, length and grip all the clubs in a set will have the same "swing weight" (a measure of the weight required to statically balance the assembled club with a fulcrum 12" from the top of the shaft), even though the length of the shaft progressively decreases from the 1 to 9 iron. Typically the manufacturing tolerance on a club head's weight is ±2 grammes. Given that a 0.05 mm thick skin added to an average 5 iron would increase its weight by 5 grammes this at first appears to be a demanding tolerance. However, given the industry's current willingness to adjust head weight when necessary (without particular concern for the subsequent changes in inertia properties) by drilling the hosel bore to remove weight, or compacting lead shot in the hosel to add weight, this value must be accepted with a grain of salt, and seen as the unwillingness of companies to expend manpower on weight adjustment.

The second most important club parameters are the key dimensional parameters: loft, lie, face offset and sometimes centre of gravity. These too have a direct bearing on a club's play characteristics. The centre of gravity is generally identified in relation to the club face by balancing the head on a sharp point. The other parameters are determined more subjectively using a custom built fixture. The main problem is to establish a datum point and orientation for the head, when it is almost fully sculptured. The common solution is to mount the hosel so that its centre line can only rotate in a vertical plane. The head is then rotated in this plane and about the hosel centreline until it is in the 'soled-out' position in relation to a flat plate on the fixture. This is the nominal address position for the club at impact, with the horizontal component of the face normal perpendicular to the vertical hosel/shaft plane, and the sole tangent to a horizontal plane at its mid-point. This alignment is only achieved with considerable manual dexterity, and inevitably requires a subjective assessment (by eye) of the correct sole tangent point since this is not usually marked on the club head. In this position the loft, lie and offset values are measured. However, this assessment and any subsequent adjustment of the two compound angles can vary by as much as $\pm 1°$ for loft and $\pm 2.5°$ for lie between different club fitters.

Normally the only tolerance on club shape is that the cast head should look like the master. Sometimes this will be reinforced by a few isolated dimensions specified on a simple geometric drawing as an acceptance measure for the production tooling. However, a more subtle requirement is that the club head should not look too closely like a competitor where this would infringe any patents they hold.

In reality, despite the average player's swing variability, the club head's inertia properties (mass, centre of gravity, principle moments of inertia and principle axes) should be of paramount importance to the manufacturers as these have a direct bearing on a club's impact characteristics and 'feel', particularly for miss-hits. The key dimensional parameters should also be controlled more objectively as these do affect the impact force direction and subsequent ball trajectory. Current design trends indicate that these parameters are being taken more seriously, for example Callaway "Big Bertha" oversized irons have higher principle moments of inertia for the same mass, Titleist DTR irons are matched to have the same centre of gravity position throughout the set, Dunlop VHL irons have a progressively smaller hosel length and shafts matched to the head's inertia properties for maximum performance.

2.2.5. Existing Use of Computers

There is very little work published on the application of CAD, CAM, or CAE techniques within the golf club industry. This is understandable given the industry's competitive nature.

Much of the available scientific work is published in the proceedings of the 1st and 2nd World Scientific Congress of Golf [1990 Science & Golf, 1994 Science & Golf II], although most of this relates to shaft performance and the head/ball impact analysis.

Jones published an overview of computer based methods for the design and manufacture of golf clubs at the first congress, chiefly reporting Loughborough University's collaboration with DSI to exploit the use of a Ferranti Merlin CMM for design capture and Delcam's DUCT software for CAD and CAM [1990 Jones]. Previously, Jones et al published limited early work, attempting to use 2.5D methods for club design and manufacture [1978 Jones et al].

Thomson and Adam published crude 2D FEA of the ball/head impact at the Edinburgh Science festival [1994 Thomson & Adam]. Whittaker et al also published an analysis of club head inertia properties based on crude solid models, but hinted at more refined surface models used by his industrial collaborators [1990 Whittaker et al]. MacGregor and Cray Computing collaborated on a much more detailed FEA of driver head/ball impact to optimise the design of a hollow titanium 'wood' [1992 Braham].

The prototype iron golf club design system resulting from this research was published in detail by Mitchell et al at the first congress [1994 Mitchell et al] and also in two other more general papers [1993 Jones et al, 1994 Mitchell & Jones].

Several manufacturers have CAD facilities, and many use CAD model images in their advertising and brochures. However, private conversations with industry experts indicate that these facilities are not used extensively, or as the primary club design specification. The most complete implementation of CAD/CAM in the industry is arguably for 'precision milled' putters. These clubs are predominantly prismatic and so lend themselves to design using fairly basic 2D draughting and 3D solid modelling systems, such as AutoCAD. Many of these have basic CAM facilities for CNC code generation able to cope with the requirements of a milled putter. Manufacturers will also use traditional engineering drawing output from these systems to communicate with CNC machining contractors and provide quality inspection data.

2.3. Shoe Lasts

People have been making shoes for thousands of years. During this period most manufacturing techniques, manual or otherwise, have involved the use of a forming tool or internal support for the material used (usually leather) at some stage in the process. With few exceptions, modern shoes are manufactured using form tooling known as a "last". Lasts were first introduced in 1818, and were originally made of solid metal. In the late 19th century wood (usually maple) became more popular. Now, only the initial last model is made in wood. Modern production lasts are mostly made of plastic, generally high density polyethylene.

Figure 2-3 shows a typical modern ladies shoe last (with a heel unit supporting the heel for clarity).

A shoe last is similar in shape and size to the foot intended to wear the shoe, but it is not identical. During the shoe "upper" (usually stitched leather) and insole assembly process (known as "lasting") the upper is stretched over the last and attached to the insole. This stretching, and subsequent recovery of the upper ("fall in") once the last is removed, results in the desired shape of the shoe. Thus the last must be shaped to give the intended fit to the upper material (e.g. allowing room for the toes to flex but gripping the heel), as well as any variation from the shape of the foot required by fashion (e.g. an extended pointed toe). Modern production lasts also have a large transverse 'v' groove and a sprung hinge roughly in the middle to allow easy removal from the finished shoe.

Figure 2-3 Typical Modern Ladies Shoe Last

During the upper, sole and heel assembly process (known as "attaching") the last supports the insole from inside the shoe to provide the clamping pressure distribution necessary for the adhesion of sole to insole, and heel to sole. To do this the sole of the last is flatter and more uniform than the human foot, and has a sharper profile to distribute the load to the edges of the insole.

To make a shoe style available to a variety of people it must be made in a range of sizes. This requires production sets of last pairs manufactured to form the different shoe sizes. Initially the last is designed by a craftsman modelling a wooden last for a single size, typically to produce a size 4 (women's) or 7 (men's) shoe. The designer seldom starts from scratch.

Usually he will start with at least a part machined block that has a standard heel already copy turned from a previous design, or he will start by adapting a previous last model. The customer's design specification is usually a combination of drawings, key measurements and often a sample shoe. Sometimes a cast from the inside of the shoe will form the basis for the last shape. Once the initial model is accepted, intermediate size variations are produced by "grading" and subsequent "coordination".

Figure 2-4 shows some of the primary measurements used to specify a last. The girth measurement locations are indicated by producing raised "pips" on the last in the toe region, usually by hammering nails into the master last until they are just above the outer surface.

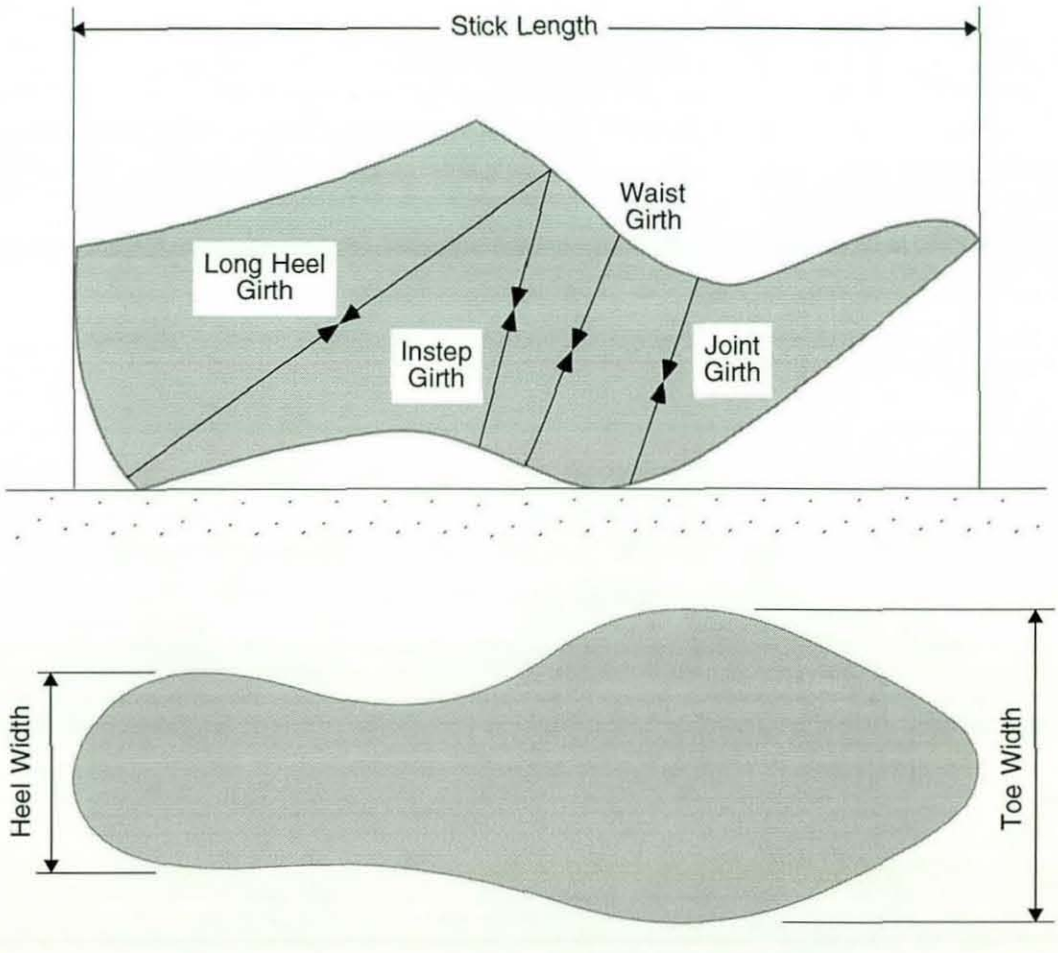


Figure 2-4 Important Last Measurements

The grading process progressively enlarges or reduces the last dimensions, and commonly involves a combination of copy turning with a magnification factor and manual adjustment. There are three approaches to grading [1989 Clark]:

- Arithmetic: The increment for a specific dimension between sizes is specified as a constant value.
- Geometric: The increment for a specific dimension between sizes is specified as a constant percentage of that dimension.
- Proportional: The increment for all dimensions between sizes is specified as the same percentage applied to each dimension.

Proportional grading is little used today even though it maintains the proportions of the last, and so its shape and style, through the size range. Figure 2-5 shows that there is little practical difference between the last dimensions produced by geometric or arithmetic grading. Both approaches allow for the length of the last to increase or decrease proportionately more than the width or girth. This produces a better fit.

To maintain acceptable comfort levels for all shoe sizes, or to reduce cost by sharing "heel units" for example, it is often necessary to manually alter the different lasts so that all sizes share key dimensions ("coordinating"). Typical adjustments involve making transverse cuts and inserting wedges to keep the "toe spring" and "heel pitch" constant through a coordinated set (Figure 2-6).

With any approach to grading, if for example a size 5 1/2 women's last is modelled the size 4 and 7 'sub-model' lasts will be copy turned from the size 5 1/2 and then coordinated. The size 8 last will then be copied from the coordinated 7. The smaller coordination errors produced by grading sub-models are usually tolerated. All other intermediate sizes are produced in a similar manner as necessary. As well as the normal range of last sizes there may also be special sizes produced for wide and narrow feet. Additional grading rules are used to generate lasts for these fits.

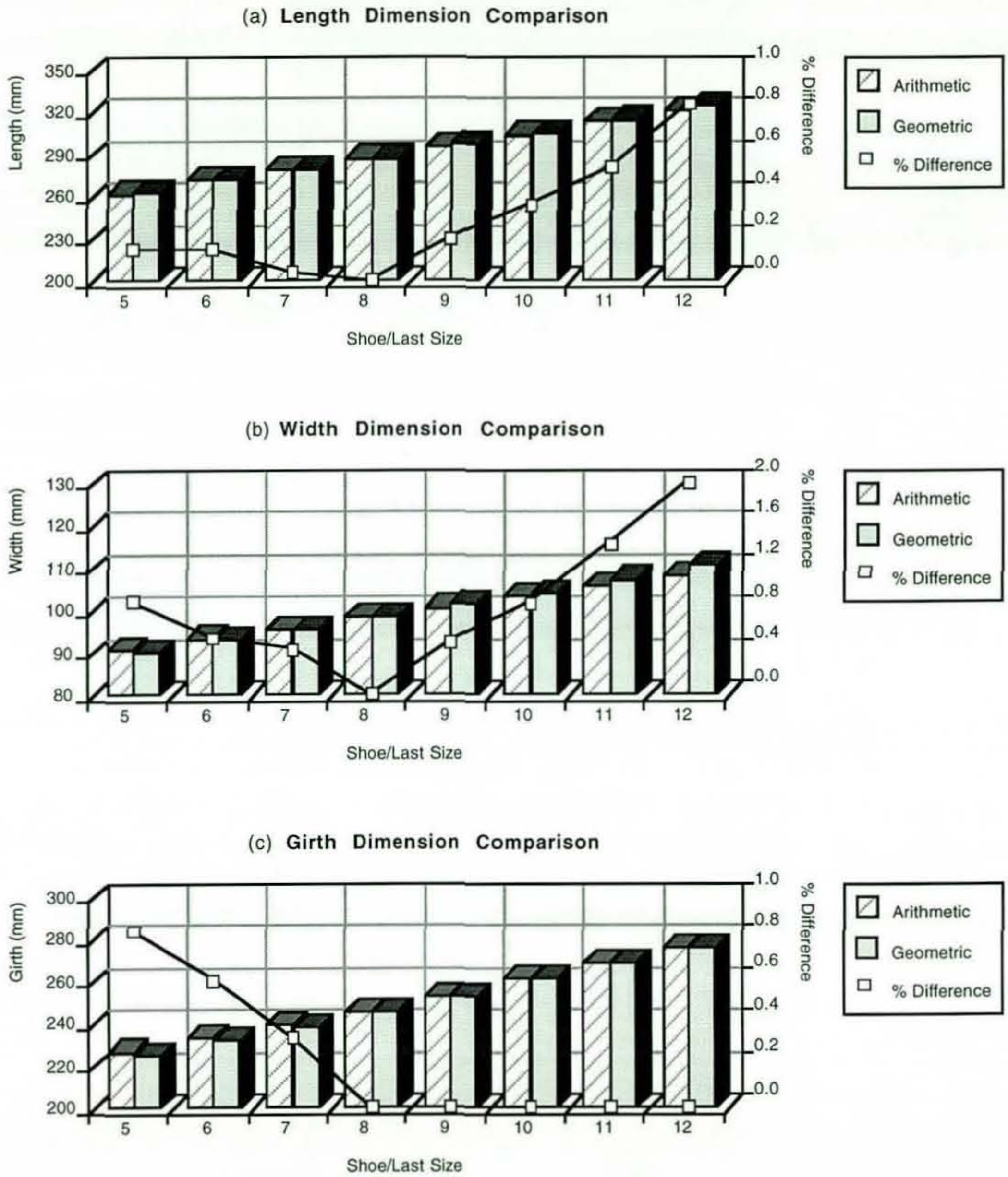


Figure 2-5 Arithmetic & Geometric Last Grading Sample Comparison

Apart from a small number of developments in grading systems [1967 Heath, 1970 Thornton, 1989 Clark] there have been few advances in last design methods over recent years. Although computer aided design methods have been applied to many aspects of shoe design, the last still tends to be made by traditional methods with a model maker developing the design model by hand.

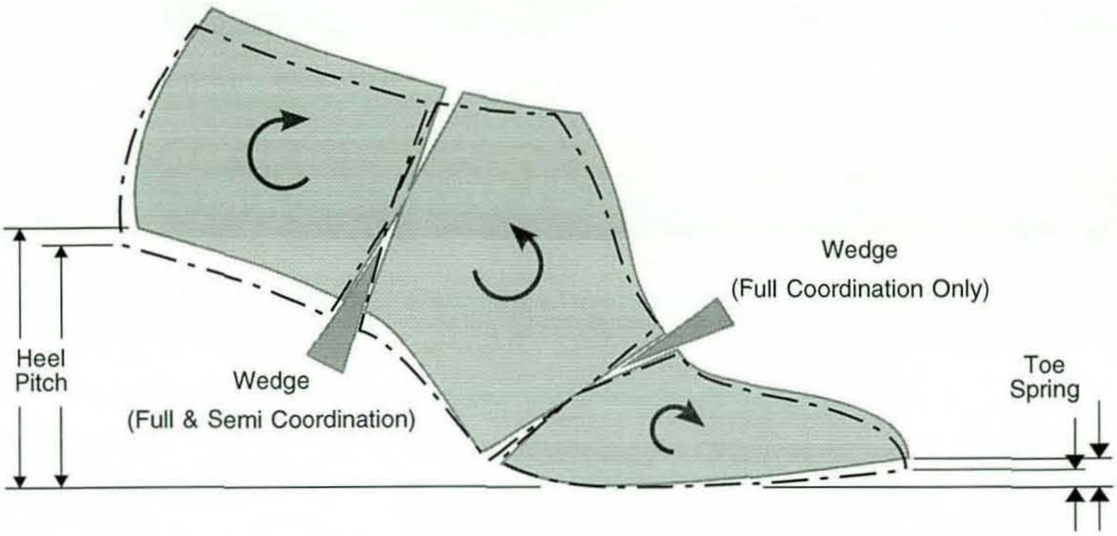


Figure 2-6 Shoe Last Coordination

For computer aided design of the shoe, the last is digitised in order to produce a CAD model on which to design the upper. The last designs captured for upper CAD systems have generally been in the form of individual single surface models. These models are difficult to manipulate if changes to the last are required. Shoe design tends to be a process of product variation rather than design from scratch, so the opportunity exists to use standard lasts and vary only those features requiring modification. Typically, the heel section will have a standard shape, whereas the toe will be varied much more, subject to the whims of fashion.

2.4. Scope for Feature Based Design Benefits

Both iron golf clubs and shoe lasts exhibit a broad range of typical sculptured product characteristics (e.g. unique shape, parametric variation through a product family, an established design culture and vocabulary, and high levels of craft based design activity) and as such provide a useful test bed for a sculptured FBD system.

Both products show a potential to benefit from a FBD approach in a number of areas. For example, both will benefit from:

- A simplified product relevant user interface.
- Efficient interactive parametric refinement of existing or prototype designs.
- A framework for selective capture of existing club features to populate a design feature resource database.
- Efficient hybrid design facilities.
- Automatic set generation.
- Mechanical and derived property prediction.
- Automated manufacturing data generation.

CHAPTER 3. A SCULPTURED FEATURE BASED METHOD

1. RESEARCH AIMS AND OBJECTIVES

The main research aim in formulating a feature based method for sculptured products (Chapter 2 Section 1) was to overcome the 'ease of use' shortcomings in modern 3D CAD systems so that their potential benefits can be more fully realised in sculptured product industries. Primarily, the intention was to place the use of powerful 3D CAD software within the reach of creative designers in sculptured product industries, with minimal retraining, by inventing, implementing and proving a 'feature assembly' metaphor for the design process. The secondary aim was to make as much additional use as possible of this approach to improve the CAD process efficiency.

More specific objectives were identified as a consequence of these aims, as follows:

(i) To devise a discretisation philosophy and method for sculptured product modelling allowing localised control of the individual features, referenced by existing industry terminology.

(ii) To implement a prototype feature based sculptured product design system including:

- (a) A range of features suitable for a trial product (golf irons).
- (b) Parametric control of a feature's shape and position, using the trial industry's existing design specification parameters where possible and inventing parameters relevant to the product context where necessary.
- (c) Automated degree zero (position) to at least degree one (tangency) boundary continuity generation between features (i.e. automatic intersection, blending and where necessary trimming)
- (d) Support for a library of existing designs and features to aid product comparison and revision.

(e) Support for hybridising design activities to revise product designs and incorporate new 'fashion features' quickly.

(f) Automated dependent feature updating in response to dominant feature changes.

(iii) To extend the prototype system's functionality to support:

(a) Automated product family generation.

(b) Automated calculation of derived property measurements important to the trial industry.

(c) Feature data extensions to enable derived property based design optimisation, and association of other process information (e.g. manufacture).

Iron golf clubs are a 'classic' example of a sculptured product family. Very little of their shape relates to 3D geometric primitives. Furthermore the need for both performance related and aesthetic product differentiation has resulted in a broad range of similar products characterised by an elegant sculptured appearance. Designing a set of clubs is a study in performance variation, while maintaining aesthetic similarity. The club market is significant and fashion based, consequently designs are changed and replaced regularly, requiring considerable time and effort. The industry itself has a developing understanding of the potential benefits of using CAD techniques and demonstrated a willingness to involve their product design facilities in this research. Consequently, iron golf clubs were identified as a suitable initial trial product.

Golf clubs generally have common shape elements and an associated vocabulary that characterise them. Figure 3-1 shows a typical iron with some of its elements itemised. A designer will emphasise or manipulate one or more elements of a new club and if this receives industry/market acceptance it will be used by competitors in their designs. A club may well be developed from a number of these concepts (e.g. the Hogan Edge cavity, the Australian Blade back). Thus it is apparent that there will be families of clubs around which designs will develop , and although there will be elements common to all clubs, there will also be those specific to a particular product family. Consequently, a feature based design system, utilising a sculptured feature library, would be very useful for the industry.

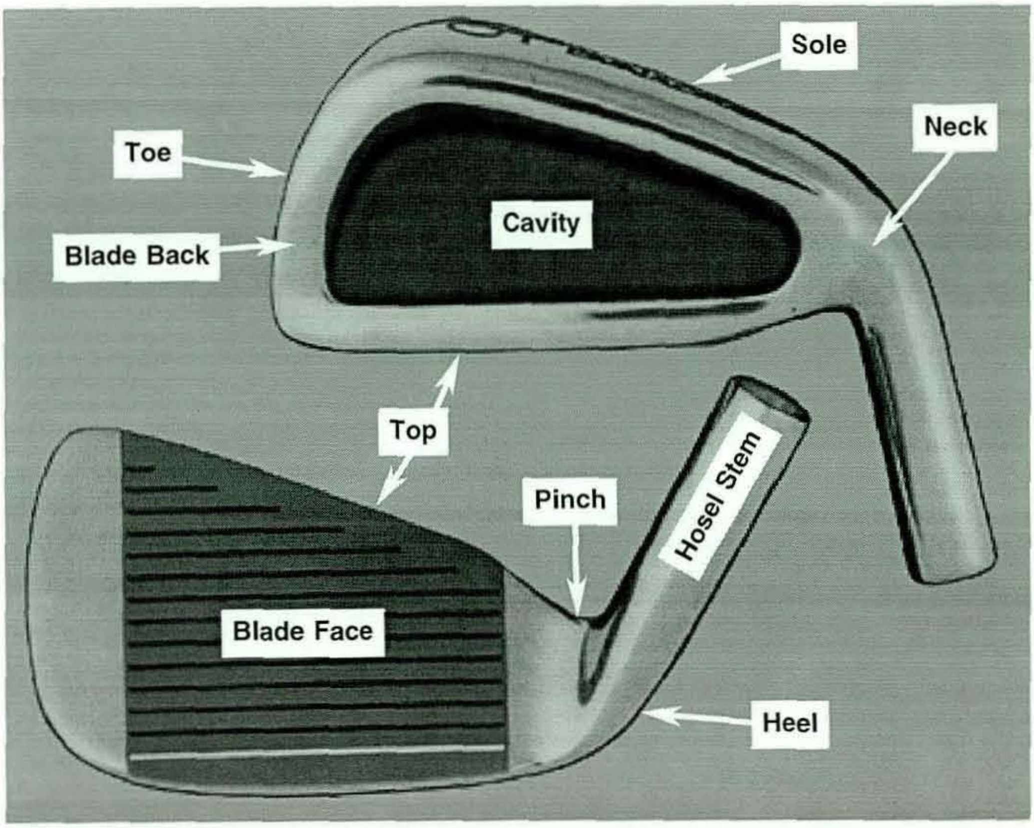


Figure 3-1 Golf Iron Vocabulary

The research results meeting the first objective are presented in the remaining sections of this chapter. Results for the second and third objectives, essentially to explore and prove the modelling capabilities of the philosophy and methods satisfying the first objective and to demonstrate their useful exploitation, are presented in subsequent chapters.

2. ALTERNATIVE APPROACHES

2.1. Two Extremes

Two approaches to identifying features dominate the related prismatic product research: the identification of design features (predominantly categorised by shape and function) and the identification of manufacturing features (generally categorised by manufacturing processes required to achieve a particular shape).

From a manufacturing perspective sculpted surfaces are almost featureless. 3, 4 or 5 axis CNC machining with a radiused tip cutter is generally the only viable approach. Furthermore, to achieve smooth transitions between surfaces any features of individual interest to the designer would probably be finish machined in groups, whether the product or its mould is being formed. It is likely that subdivision of the product surface in manufacturing process terms would primarily depend on cutter access (related to the number of degrees of freedom available for the intended CNC machine) and the cutter approach angle (to allow the cutter path strategy to be adjusted locally for a manufacturing feature group to ensure a consistent finish). Therefore, there is no logical reason for assuming that any particular group of features of interest to a designer will form a complete manufacturing feature group, or that a manufacturing feature group will wholly contain a region of individual interest to the designer.

Thus, it is unlikely that manufacturing issues will provide sufficient means for identifying elements of a sculptured product for classification as a set of features suitable for the design process. However, it is more likely that a set of design features, individually or collectively, may provide sufficient basis for manufacturing engineering reasoning.

Consequently, a feature identification and categorisation approach based on shape design issues was adopted. Essentially the design feature based approach is to simplify the design problem by subdividing the design model to achieve localised control over design elements. A design oriented definition for a sculptured product feature was devised and adopted as a starting point for formulating a sculptured feature philosophy. A sculptured feature is defined within this research as:

- **A generic element of a product design**, for which...
- ...specific instances are **defined by a set of characteristics**, so **that**...
- ...**together with other features** it **meets the** aesthetic and/or functional **design requirements**.

Sculptured products generally seem almost as featureless, in normal engineering design terms, as they are in manufacturing terms, mostly because they lack surface discontinuities. However the above feature definition establishes the goals in searching for and identifying the constituent elements of a sculptured product. Applying the definition reveals two extreme subdivision strategies:

i) Using a single feature per product defined by a complex set of characteristics. This strategy is comparable to using a single parametric surface patchwork to represent the whole product. Early experience modelling whole golf wood heads and other products indicated that even though complete products can be defined using this approach, it was too cumbersome for design manipulation. Independent control of a surface region's shape is difficult to achieve. Adequate control of unwanted surface distortions or ripples, while incorporating satisfactory levels of detail is also difficult to achieve.

ii) Using a multitude of extremely simple features, defined by relatively few simple characteristics, combined to describe a product. This strategy is comparable to the use of a multi-faceted polygon mesh, similar to those generated for shading purposes. The excessive number of features necessary to give smooth results makes this approach impractical.

The middle ground is characterised by a compromise between the number of features and their complexity. Although the two extremes offer no direct indication as to how this compromise is best achieved, the problems clearly identified at both ends of the spectrum highlight the issues relevant to evaluating any particular solution's success. In particular, several questions are implied:

- Does the method subdivide the product sufficiently, so that shape control is manageable and supports adequate levels of detail?
- Does the classification of features allow adequate independence for feature shape control?
- Does the method subdivide the product too much, so that the process of manipulating a design becomes too lengthy?

Two compromises were considered, and are described below.

2.2. Limited Free Form Feature Methods

The usual technique for golf club representation, employed by those companies using 3D CAD systems, was to specify a limited number of arbitrary free form surfaces generally 'stitched' together at their common boundaries. These surfaces can be considered as 'limited free form' (LFF) features.

The LFF feature approach originates from systematic digitising of existing products. Thus the subsequent features are good at representing a single existing product design. Typically an existing golf club would have a series of rectangular meshes drawn on its surface corresponding to the intended surface elements, with edges coincident with their neighbour's. The nodes are then digitised using a coordinate measuring machine, and input as control points within the surface modelling software. Internally, the software is allowed to fit a smooth curve through the mesh data points. Position and tangent continuity is easily achieved at the edges where adjacent meshes share the same nodes, by constraining the two meshes. Where the common edges between adjacent meshes do not share the same nodes, perhaps to represent smaller surface details within one of the meshes, position and tangent continuity is only approximate and achieved by sampling surface coordinates and normal vectors on one surface adjacent to the nodes of the other surface and constraining the later.

Changing a design is achieved by manipulating the data points, surface interpolation and boundary shapes. This is a lengthy and potentially unstable process, given that the high number of control parameters make it easy for successive design changes to diverge from the design objectives (e.g. in smoothness) rather than converging.

The benefits and limitations of this approach are best seen in relation to how the hosel neck (Figure 3-1) is modelled. This is generally the most difficult area to design and model on the club. Typically 2 to 4 separate surfaces are used in this region, as shown in Figure 3-2.

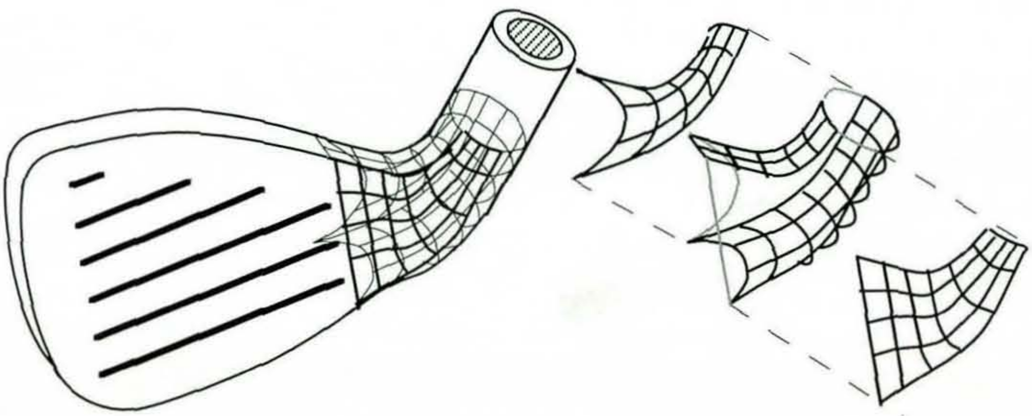


Figure 3-2 LFF Hosel Neck Modelling

The benefits are:

- This technique requires fewer surfaces to model the neck, which makes some aspects of design manipulation and mechanical property calculations easier.
- There is a direct relationship between the digitised data from existing designs and the features/surface models.

- This approach may evolve to produce a new form of club neck that reflects CAD by producing a 'featureless' or single feature hosel/blade blend. This may result in a useful product styling that denotes 'hi-tech' computer based club design to the player/buyer.

The limitations are:

- The features identified by this approach are not universal. They cannot be incorporated in a design, where neighbouring features are different, without alteration. Consequently there is no direct support for a hybrid design approach.
- It is difficult to identify feature characteristics, to use as shape control parameters, other than the number and 3D location of the defining points and the boundary surface normals. This has several implications. The routines required to manipulate the feature will be complex. Furthermore, the aesthetic contribution of the feature does not relate directly to its characteristic parameters. Thus a feature's terms of reference for designer control are difficult to interpret from the feature characteristics, and difficult to associate with existing design terminology. Thus, using the system to design clubs presents the designers with an unwanted level of mathematical abstraction to define their intentions. This makes automatic generation of clubs with aesthetic similarities more difficult.
- It can be argued that the designer does not necessarily need control over the club design in this area, or that modifications in this region are rare (this is not the case for golf clubs, but could be for a different product type). Consequently the system can be used to automatically produce an adequate neck. However, this means that the product design is heavily dependent on the system's assumptions, and designs will be characterised by the internal programming of a particular sculptured feature based system, and not the designer's styling. Experience has shown that this is not always acceptable to customers.

The first limitation listed is perhaps the most problematic. Because the features, and their behaviour, are only defined within the boundary formed by their neighbouring features, and at these boundaries the feature edges are coincident, the feature definition is context dependent. If two neighbouring features are combined from two different club designs it is extremely likely that their edges will not be coincident. This gives rise to the question 'how should the system automatically resolve this discontinuity?'[1] It is likely that forcing one feature's edge to match another, or forcing both edges to achieve some form of compromise, would corrupt the shape contribution the designer intended when introducing the features. Similarly, there is no guarantee that extrapolating the features will produce an acceptable shape or boundary to 'fill in the gap'.

The first extreme subdivision approach (use of a single complex surface feature) has similar problems. Given a single surface modelling approach utilising several surface patches with boundary constraints to achieve particular levels of continuity, the individual patches can be considered as LFF features. This approach is satisfactory for 'one-off' design descriptions. In some instance it is also manageable for modifications to that design, especially where designers are willing to accept that model dependencies may cause changes to adjacent feature shapes when a particular feature, or a boundary, is modified. However, because the individual patches are context dependent they can not be directly combined with features from other designs to produce a hybrid without modification to themselves or their neighbours. The system designer, or whoever defines the product anatomy, must also resolve the complexity/proliferation issue. Implementing a few complex features increases the complexity of mathematical abstraction required to control the features, but too many simple patch features (e.g. the number of Bézier patches required to accurately reproduce a golf club) gives the designer 'too many balls to juggle'.

---

[1] Let alone how could a designer resolve it manually.

3. THE EXTENDED FORM FEATURE METHOD

3.1. Origins

It was apparent that an alternative strategy was required to overcome the problems exhibited by LFF methods. A different rationale for subdividing the product, other than to simplify the digitising process, is needed for sculptured feature based design. Ideally it would; yield a more amenable balance between feature complexity and number; allow localised independent parametric control of the features using industry specification parameters and terms; and support feature substitution without corrupting a feature's contribution to the design.

Considering the shape and descriptive terminology associated with a single sculptured product, specifically iron golf clubs, provided some clues to a suitable strategy. Initially different iron clubs were studied to identify dominant surface shapes governing the design and common to all clubs. For example, the hosel stem is the simplest region, and can normally be modelled by extended surface forms (typically cylinders and planes), and one or two constant radius blends between these extended form (EF) features (Figure 3-3). The blends define both a smooth transitional surface and trimming boundaries between the EF regions, where they are not intersected with each other to produce a sharp edge. This combination of primary EF features and secondary blend features was perhaps the simplest example of the emerging extended form feature (EFF) modelling technique.

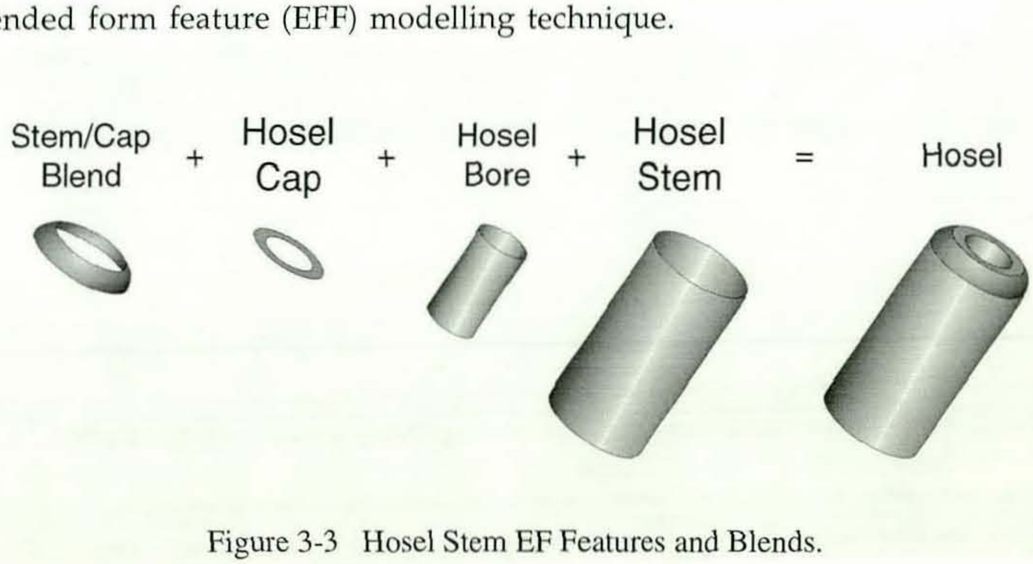


Figure 3-3 Hosel Stem EF Features and Blends.

The club blade is more complex, but the industry's vocabulary (e.g. "face", "back", "top", "toe", "sole", and "cavity") suggested potentially suitable regions for EFF modelling (Figure 3-1). A review of the manual model crafting processes, less common industry specification parameters (e.g. the radius of curvature for the surface region between the blade's top and toe elements), and the rate of change of curvature between surface regions indicated by changes in the reflected highlight patterns as the club is rotated, were used to identify potential blend features.

Finally, portions of the hosel neck were identified in terms of extrapolated form types. For example, the blade face to hosel stem blend originally had the form of a combined flat plane and constant radius fillet. Five EF features were initially identified in the hosel neck region as shown in Figure 3-4. These EF features were 'trimmed' to the boundaries of their intersections with each other, or to the boundaries of intermediate blend features, to define the hosel neck. Further analysis indicated that these early features were inadequate for producing satisfactory neck shapes, and resulted in the more mature feature set illustrated in Figure 3-5. The same clues to potential EF and blend features that were used for the club blade (e.g. surface region vocabulary such as 'pinch' and 'heel'), including discussions with expert club designers about their intentions and aspirations in this area (generally to achieve a gradual, elegant transition between the blade and stem sections), were considered in identifying these elements.

The next step was to prove that the EFF approach was capable of modelling a generic 5 iron shape (i.e. being the right shape type, having all the industry's recognised surface regions and smoothness qualities, but not necessarily being elegantly styled). This resulted in an initial 5 iron model as shown in Figure 3-6. The back cavity was initially omitted and the trimmed neck features are shown colour coded to highlight their contributions (green EF features, blue primary blends and red secondary blend). The 'neck back' and 'heel' features are also shown as white wireframe surfaces to indicate their extended shape. Using DUCT interactively, the 5 iron features were then modified to model a matching 3 iron, thus demonstrating the potential for automated set generation using the EFF method.

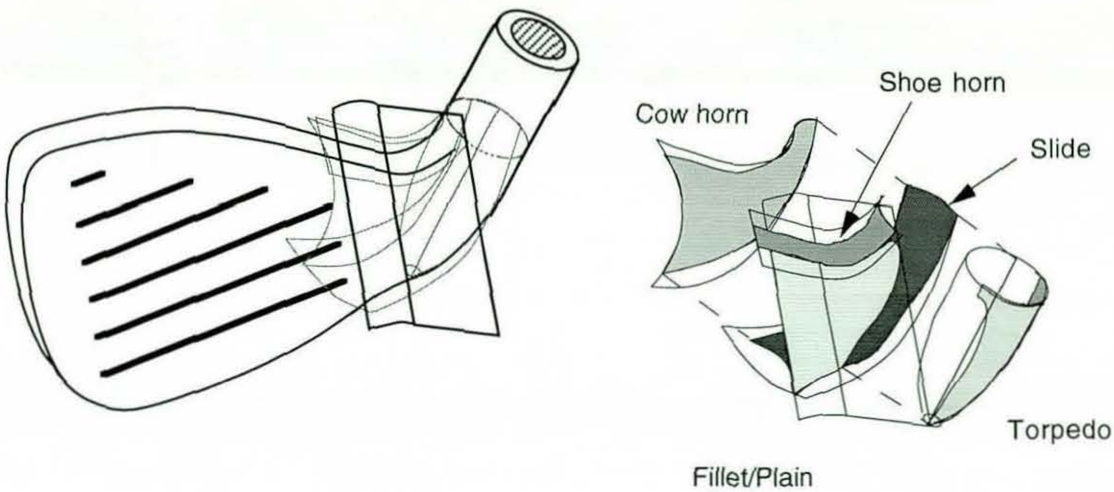


Figure 3-4 Initial Hosel Neck EFF Features

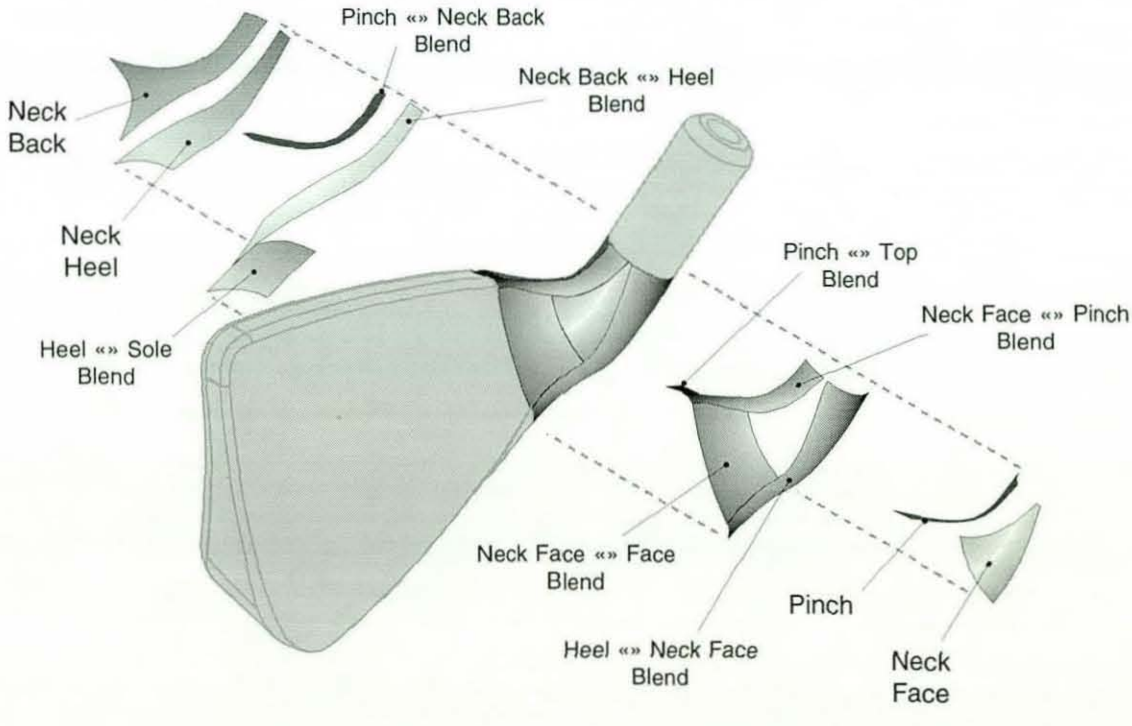


Figure 3-5 Mature Hosel Neck EF Features

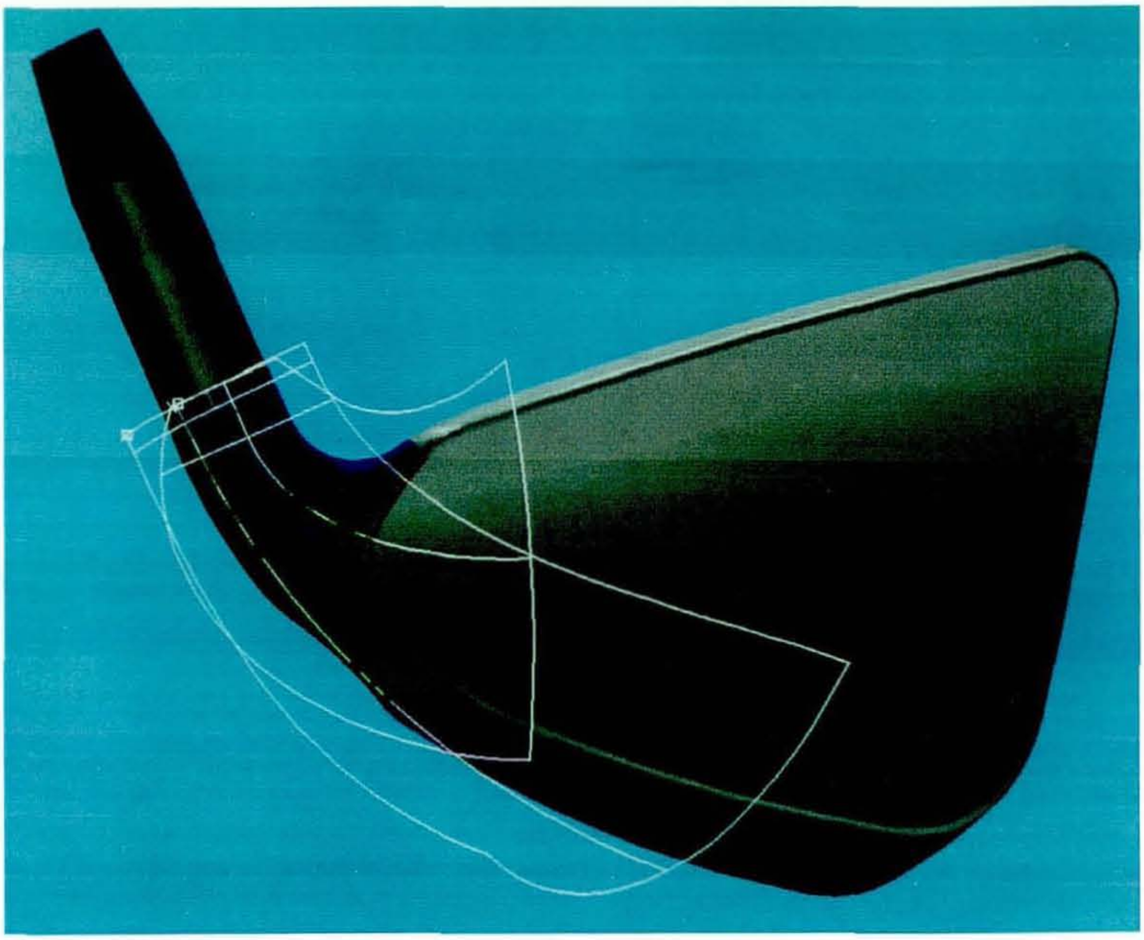


Figure 3-6 Initial EFFM 5 Iron Model.

Subsequently, a set of elementary shape algorithms was generated for the final EF and blend feature set identified. These were used to model a realistically styled existing golf iron, namely the Maxfli Tour Ltd. 5 Iron. This particular club had provided the starting point for DSI's own recent club design development activities, and so provided a good benchmark for the modelling approach. A digitised version of the Tour Ltd. 5 Iron, modelled using the LFF approach by DSI, was used as a reference for iteratively adjusting the feature shape algorithm parameters until the EFF model matched the existing design, within an acceptable tolerance. Despite the initial shape algorithms' simplicity, a surprisingly high level of accuracy was achieved with relatively little effort. Over almost all of the club surface the LFF and EFF models were matched within <0.1 mm. In the more difficult hosel neck region slightly larger errors were tolerated (<0.5 mm), because of the time taken in producing blend variations. The resulting EFF model was still indistinguishable from the existing design when compared using the naked eye.

This proved that the EFF strategy was capable of modelling industry standard club designs, accurately reproducing the styling and quality associated with their fundamental shape. The EFF method was then augmented to incorporate surface markings as a third 'ornamental' (as opposed to the 'structural' EF and blend features) feature category, using Delcam's ArtCAM software for the brand name(cf. Chapter 4 Section 2.3). The final model, illustrated in Figure 3-7 and Figure 3-8, incorporates a full set of structural and ornamental features to fully represent the original club design.

3.2. Implications

Having proved the EFF approach was capable of modelling valid club shapes, styling and ornamentation, the strategy's benefits were identified as follows:

- It used existing functionality commonly available within surface modelling software such as surface trimming, fillet surface generation, and 'shell' construction from several surfaces.
- The aesthetic contribution of the features could be described by a reduced set of parameters, controlling a custom shape algorithm. Thus the manipulation routines could be simpler and driven by terms which mean something to the designer.
- Specific EF feature shape implementations can be universally applied within designs based on a similar product anatomy. They can be easily 'bolted in and out' of a design without corrupting their shape contribution, as their general shape specification is context independent. Only the used region of an EF feature needs to be redefined and trimmed within the context of its neighbouring features for visualisation and finish machining purposes.

Figure 3-7 EFFM Based Tour Ltd. 5 Iron with Ornamental Features (Face).

Figure 3-8 EFFM Based Tour Ltd. 5 Iron with Ornamental Features (Back).

- Automatically generating a matched iron club set should be more attainable, as the features' aesthetic contributions throughout the set can be controlled directly.

The limitations of this strategy were also identified as:

- A relatively large number of surface features are required in a complete model, compared with the DSI LFF method (14 EF, 9 primary and 2 secondary blends for the EFF method as opposed to 14-16 for the LFF method). This may increase computing time in some instances and so slow the design process.
- Generating multi-intersection boundaries for the different features can be difficult.
- Intersecting multiple fillet blends can be difficult.

Given the problems with the LFF method as implemented by DSI, in particular that the parametric definition of the identified features were too complex and unwieldy, it was to be expected that a better strategy would inevitably require simpler features, but more of them. Thus, the EFF approach's limitations identified at this stage were in reality ones of processing speed and numerical error management within the geometric modelling software. The EFF principles appeared to be conceptually sound, and resulted in a new approach to golf club modelling that satisfied the feature complexity, shape independence, parameter relevance and feature swapping requirements for sculptured product design.

The EFF strategy is also more clearly defined and structured in terms of design intent than LFF methods. The three feature categories (structural EF, blend and ornamental marking) clearly reflect three levels of progressive refinement in aesthetic detail. The EF features govern the fundamental product shape; the blends control the product's visual and tactile harshness by softening its shape to produce the smooth transition between surface regions characteristic of most sculptured products; and the ornamental features add surface textural detail or product identifiers that commonly embellish sculptured products to enhance their looks and feel. Thus the EFF method should naturally support sculptured design development, and so the first research objective was met (Chapter 3, Section 1 objective (i)).

Furthermore, because the EFF approach satisfies the fundamental requirements for sculptured product modelling, and inherently allows separate consideration of these three levels of shape definition and refinement, its implementation promised to support a variety of systematic design development methods, including 'top down', 'bottom up', and hybrid strategies. The method also promised natural support for both product design and feature libraries (made possible by feature shape independence) and design automation tools (particularly product family generation, made possible by parametric shape control). Consequently, it appeared likely that a system based on the EFF method would meet the second and third research objectives (Chapter 3, Section 1: objectives (ii) & (iii)).

The approach as a whole is strongly analogous to current design by manual sculpting practices. The strong characteristic forms are created first and then smoothed or blended into each other afterwards. This analogy was considered potentially useful in developing the user interface style and terminology.

After considering the features identified by applying the EFF method, it became apparent that the specific form features are strongly product related. They have a historic content related to manufacturing methods (usually manual crafting) and gradual product shape evolution. The latter is influenced by both aesthetic fashion and the inclusion of technical features for performance enhancement. This leads to two conclusions:

- Because this trend is characteristic of other sculptured products, it is unlikely that a universal set of sculptured features, sufficient for the design of all such products, can be identified.
- There is a secondary need to link EFF CAD, CAM and CAE based performance simulation models to cover both aesthetic and performance design criteria.

This first point was initially disheartening but logical. With prismatic feature hierarchies, particularly in mechanical engineering design, the feature primitives have strong relationships with both design function and manufacturing process. Historically this is due to the symbiotic application and development of both disciplines (although geometric constraints on what designers can conveniently describe have been significant). Unconsciously, good design engineers have used 'manufacturing features' to design what can be made. Unconsciously, manufacturing engineers have developed support for 'design features' as product requirements have changed. Thus, the shape of prismatic design features are generally directly related to manufacturing processes.

Functionally, a prismatic feature's presence and the choice of shape is often dictated by a need for energy transfer or constraint with no aesthetic objective. Large safety margins are often employed, thus there is no requirement for full shape optimisation. A component's complexity is generally due to the need for it to interact with other bodies, usually other components in an assembly subdivided to simplify product manufacture and maintenance. However, the simplicity of features used to define these components, and the relatively small number of alternatives, originates in the need for cost effective design and manufacture. Using simple geometry makes the design process easier, and limiting choice reduces the range of manufacturing process capabilities needed.

Consequently, the majority of prismatic feature primitives have been relatively obvious and common to most engineering product designs.

With sculptured products the only manufacturing constraints have been general rules associated with casting, forging, or moulding technology used for economic mass production. The only other limits to product form, apart from current fashion and essential performance characteristics, have been the designers imagination and skill in wielding a manual forming tool on a prototype material. Consequently it is unlikely that there will be a useful set of free form surfaces capable of modelling all sculptured products, or a set of common parameters and terminology associated with them. For example the features required to sculpt the hosel neck region of a golf club are not present in current ceramic washbasin designs.

Theoretically universal design feature sets exist. However, for the features to be simple the set would be too large and suffer high redundancy for any one product. The development and so ownership cost for all these features are not justifiable for a single product design/manufacturer. The time taken to find a suitable feature amongst so many would also be a hindrance.

The alternative is a feature set with a smaller population. To achieve sufficient generality the features would have to be much more complex and the terminology or control parameters totally abstract in relation to any one product. The resulting design effort required to operate the system would limit its successful and rapid use. Delcam's DUCT software and other surface modelling systems, in a sense, already operate on this basis.

However, if we further consider the EFF method feature categories, it is apparent that the form features are product specific, but the blend features and the interaction between all categories are similar for all sculptured products. This leads to the conclusion that the best way to proceed is to develop a common approach to specifying and manipulating product specific EF features in conjunction with blend features that share a common generation algorithm, all supported by a generic feature trimming routine. This can then be applied to any product, by defining features and populating a feature library, as appropriate.

Lastly, the initial definition of a sculptured feature (Chapter 3, Section 2.1) implies that a sculptured product can be defined as an assembly or anatomy of features. It is likely that the members of a family of similar products will each have a version of every feature in a common anatomy, just as most human faces have two eyes, a nose, mouth chin, cheeks etc. Consequently it is also likely that the EFF based anatomy identified for one member of a product family will be suitable for other members of the same family. This gives rise to the concept that an EFF based design system for a product should begin with a definition of the products feature anatomy, establishing the number and type of EF features and their interaction, followed by definition of suitable features (and associated shape behaviour alternatives) within the context of that anatomy. This anatomy definition would also provide the basis for automatic feature trimming.

3.3. Blend Devolution within an EFF Anatomy

Further analysis of the interaction between the blend features and EF or other blends features within an EFF based product anatomy revealed that the blends can be classified as 'primary blends' that only blend between extended form features, and 'secondary blends' that blend between feature groups where at least one group contains at least one other blend. When evaluating the geometry it is apparent that there is a blend dependency hierarchy based on the primary blends and then subsequent generations or levels of secondary blends, beginning with those only dependent on primary blends (Figure 1). To produce the geometry implied by an EFF product anatomy, specified by a full set of shape algorithms and associated parameter values, the EF features must be generated first, then the primary (or generation 0) blends, followed by the secondary blends only involving the primary blends (generation 1), then the blends dependent on only these existing generation 0-1 blends (generation 2), and so on.

'Blend devolution' is based on the principle that any binary blend between two features or groups of features, within an infinitely extended EFF modelling regime, produces a zero order continuity intersection of the two feature groups as the blend section dimensions tend towards zero. Thus, for any level or generation of the blend hierarchy, and all subsequent generations, the blends may be replaced by an intersection of the relevant extended forms and blends of the previous generation (Figure 3-10). These intersections can be considered as 'devolved blends'.

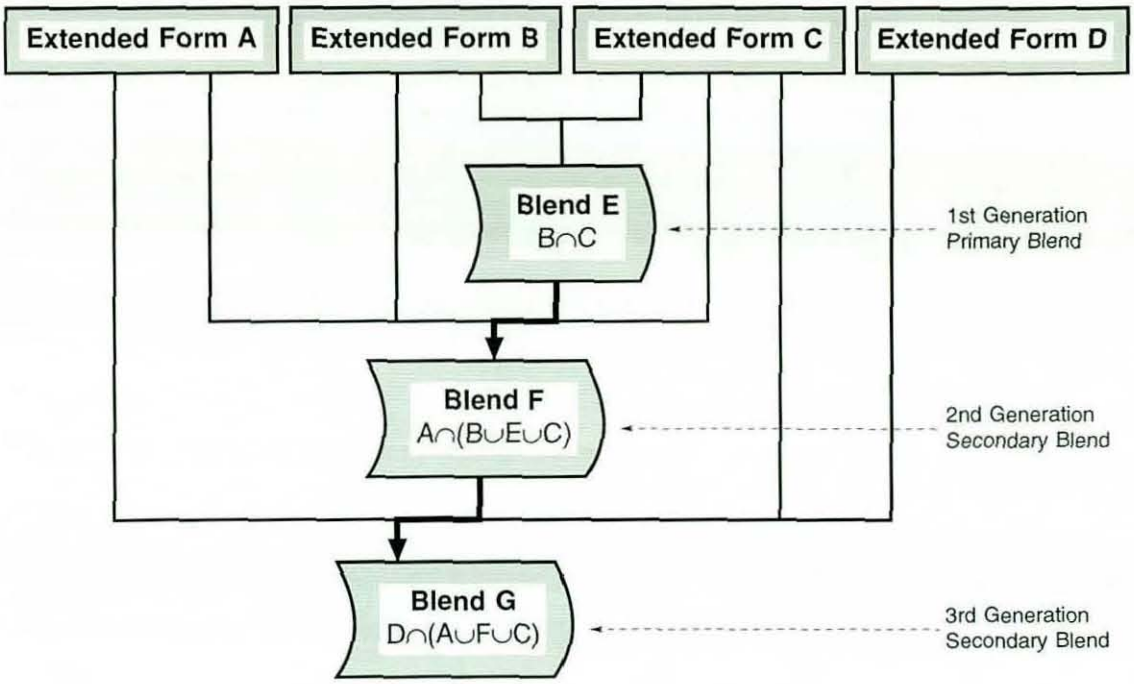


Figure 3-9 Example EFFM Blend Generations

This technique allows for the systematic removal (or development if applied in reverse) of a products aesthetic features. Applied in the extreme, the product anatomy devolves to a set of intersecting extended form features.

This definition may seem trivial in a general engineering context. The concept of blends or chamfers being applied to soften sharp edges defined by the original intersection or boundary between two features, or feature groups, has existed for some time. However, this is not the case in the sculptured product domain.

Whilst the prototype craftsmen may well be conscious of manually producing a blend between two surface regions to soften a sharp edge, the LFF CAD modelling techniques do not reflect this. Existing products have been captured as a whole, with fully developed blends, often with individual features incorporating both EF and blend feature elements in one surface region. Thus the concept of blend evolution or devolution has been lost.

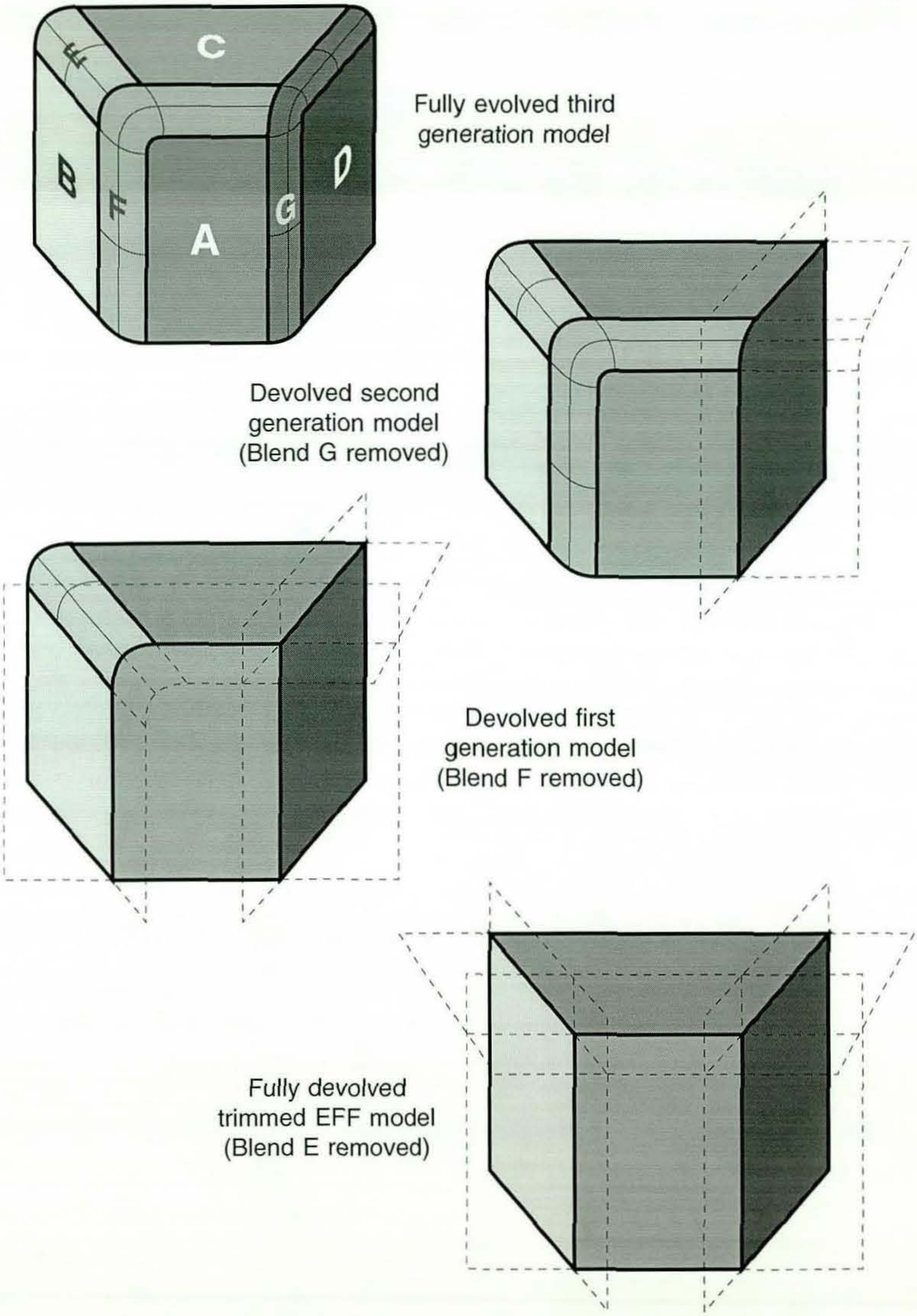


Figure 3-10 Devolved Blend Geometry Examples

Blends and chamfers in a general engineering context are also often small, usually of secondary importance, and commonly introduced for handling safety or to remove stress concentrations. In a sculptured product, the blends are often larger, more commonly fundamental structural features, and an essential factor in meeting the products more dominant look and feel objectives. In this case, the idea that the blend will not exist in a particular representation of the product anatomy has become foreign to designers. Because intersecting complex surfaces features requires more computing time than the intersecting prismatic features, surface model based CAD designers (unconsciously using EFF modelling techniques) also generally see little point in expending the effort to model a sharp edge before their intended blend. Thus, the principle of blend devolution needs to be identified and restated clearly within the sculptured product CAD context in order to promote its useful application.

Blend devolution has several implications and resulting benefits if used within an EFF modelling system:

Intermediate model trimming

- Without blend devolution, the EF features can only be limited by evaluating all associated blend geometry. This requires the definition of all relevant blending parameters and an extended pause in design development each time the blend geometry is calculated. When viewing the extended forms without blends it is difficult to visualise the essential product shape because of the confusion contributed by the excess surface regions.
- Using the devolved blend intersections to bound and trim the EF features produces a first approximation to the eventual product shape with relatively little processing time and much less confusion. Ultimately this results in faster systematic modelling, beginning with the extended forms, then the dominant first generation blends, and lastly subsequent generations of secondary blends. The design development

process, from scratch, is less confusing and more closely mimics the manual crafting process.

Anatomy definition by example

- This systematic approach to model development rigorously supports the 'anatomy definition by example' approach exemplified in DUCT's emerging shell entity technology.[1] Given the necessary data extensions and intelligence within DUCT a relatively experienced user could develop a product anatomy by providing a manually defined and trimmed example using the general DUCT interface and commands. It should then be possible for additional intelligent software routines to determine the form/blend feature anatomy automatically and potentially produce a custom interface for feature based manipulation.

Error handling

- Within a finite EFF modelling regime it is possible to select feature shape and position parameter combinations that do not allow, or only allow partial blending evaluation. To make the system more robust, by identifying this error condition, blend devolution can be used to determine the likelihood of blend success before trying to establish the blend geometry. By first checking that the devolved blend intersection can be determined as a continuous curve we can ensure that small section blend geometry can be calculated (large section blending can still fail, but this must be identified by other means).
- Given predicted failure, one of three options could be made available:
  - Partial model trimming with failed and all dependent blends omitted
  - User prescribed model adjustment to avoid the problem
  - Automatic EFF extrapolation in an attempt to avoid the problem.

[1] The ability to treat several separate surfaces as a single surface entity or 'shell' by grouping rather than approximating by a single surface.

Multiple surface blending

- Establishing the devolved blend intersection provides a spine to support the calculation of constant radius, variable radius and arbitrary section blend geometry. DUCT already uses a similar technique in its blending routines, but uses the offset surface intersection defined by the smallest blend radius. However, more extensive use of the devolved intersection as the basis for user defined blend shape transition could be made.

Finite Element analysis

- Blend devolution allows for the systematic removal of aesthetic product features. Conversely it also allows for the systematic inclusion of the dominant, or progressively more significant blends.
- It should be much more straightforward to produce finite element meshes for the fully devolved model than for the fully evolved/blended product model. The meshes should be simpler, require less computing time, and establish the regions of significance under different loading conditions. The medial surfaces for solid products in particular, should be much easier to determine.
- Systematic inclusion of the significant blends should then provide the most efficient route to increased analysis accuracy. Furthermore, it is possible that adaptation of a devolved model mesh to include omitted blends will be easier to control and automate than a more generalised re-meshing of the equivalent partially evolved model.

Mechanical property calculations and optimisation

- Calculations for the devolved model will be quicker and provide rough estimates of the product characteristics earlier in the design process. As the model evolves predictions will become more accurate.
- Using a partially devolved model for initial iterations may also reduce design optimisation time.

Manufacture

- The implications for manufacture are less significant. It would be possible to reduce the time required to produce roughing paths a little by devolving convex blends, but this would probably be nullified by the increased model manipulation time. Furthermore, concave blends must remain fully evolved to avoid gouging.
- It may be that STL mesh generation may be made easier by adapting a devolved model mesh in the same way that FE mesh generation may be improved.

Using this technique places a heavier burden on processing time if the equivalent devolved blend intersection is to be calculated and stored for each blend. However, the potential benefits arguably outweigh this penalty.

3.4. Definitive Principles

The principles of the EFF method can be summarised as follows:

- A sculptured feature is a generic element of a product design, for which specific instances are defined by a set of characteristics, so that together with other features it meets the aesthetic and/or functional design requirements.
- Similar products can be grouped in product families that share a similar anatomy. This anatomy is a conceptual framework that describes the presence and interaction of features common to members of the product family.
- The EFF based feature anatomies consist of three feature types:
  - Structural EF features that govern the fundamental product shape.
  - Structural blend features that control the product's visual and tactile harshness by softening its shape to produce a smooth transition between surface regions.
  - Ornamental features that add surface textural detail or product identifiers to enhance the product's looks and feel.

- There is no universal set of features that can be practically or usefully defined to support the design of all sculptured products. However, within a given product anatomy context it is possible to define product specific EF features, and associated shape behaviour variants controlled by existing industry terminology and relevant parameters, capable of defining a broad range of design variants within a product family.
- Any binary blend between two features, or groups of features, within an EFF product anatomy can be devolved to an intersection of the two feature groups. Thus an EFF product model can be partially trimmed before blend feature parameters have been specified, and unwanted levels of detail can be systematically removed from the model to better support engineering applications other than design.

CHAPTER 4. EXTENDED FORM FEATURE IDENTIFICATION & ANATOMY SPECIFICATION

1. EFF METHOD APPLICATION IN GENERAL

1.1. Initial System Development

Currently, there appear to be no commercial CAD systems directly supporting a generic implementation of EFF based design. Until there is one, arguably the most cost effective means for developing an EFF based facility is to adapt an existing CAD system. A suitable system, such as Delcam's DUCT software, requires; extensive surface modelling capabilities; an internal programming language with user definable data elements and structures or the ability to control the programme fully via an external process; and a customisable user interface. Given a suitable commercial CAD system to act as a geometry evaluation 'engine' and host to the EFF application routines, implementing the EFF method to provide an elementary feature based CAD system for a particular sculptured product relies on four main activities:

(i) Identifying and categorising product feature types.

(ii) Identifying and specifying inter-feature relationships within a product anatomy.

(iii) Developing suitable geometry algorithms and parameter specifications for the feature types.

(iv) Developing a custom user interface for anatomy and feature manipulation.

This chapter describes the results of applying the EFF method to iron golf clubs and shoe lasts in terms of these first two activities: feature identification and anatomy specification.

1.2. Feature Identification

At present no objective methods or tools have been developed for extracting or helping to identify candidate features for an existing product. To a certain extent, it may be expected that this process will never be fully automated, because shape interpretation is subjective in nature and shape control requirements will vary between designers in any given product industry. However, it is possible to document some guidelines for identifying suitable EF features and groups of features based on practical experience. In practice features are identified by balancing several considerations:

- *The suggestion that a feature or feature group exists from industry terminology.*

  This is most fruitful in long established industries. The information is perhaps best assimilated by talking to existing designers, and reviewing any documentation or standards relating to product specifications. Features should be given names that relate to industry terminology where possible. Where suitable terms are unavailable or inappropriate, names should be formulated to make as much sense as possible.

- *The suggestion that a feature or feature group exists from manual crafting methods.*

  Because the EFF model structure reflects progressive model refinement, it is likely that observing the manual crafting process will reveal suitable features. For example, the face and stem of a golf iron made from stock material are usually the first to be formed, by milling and turning as extended surface regions. However, with models developed by adding material, for example sculpting in clay or epoxy, the blends and forms may be produced concurrently, and so are less easy to identify.

- *The bounded EF and blend surface regions indicated by the variation of highlights on the product surface as it is rotated.*

  EF feature regions often have broad highlights, because they have low curvature, and blends will often have longer narrower highlights because of their high transverse curvature.

- *The potential for industry specification parameters to be used for feature shape control.*

  Where an industry specifies parameters that describe geometric properties at a particular point or in a particular region, this presents a potential opportunity for feature shape control and so warrants investigation of the surface region as a potential feature. Feature control parameters should be identified with existing industry terminology wherever possible.

- *The acceptable complexity level for parametric control of individual features and the total number of features.*

  This point is a reminder of the need to balance feature complexity and number in any sculptured product design system. For some product surface regions an industry's vocabulary may be limited. This may indicate that there are few features in this region, or it may indicate that the surface complexity makes it difficult to describe in words. The neck region of an iron golf club is a good example of the later. If the features identified are too parametrically complex, so that adjusting them becomes cumbersome, the surface region may need further subdivision. Conversely, if the design system is cumbersome because there are too many simple features, it may be better to combine some of them into a single feature.

- *The potential requirement for localised control of the product design.*

  This can be established in at least two ways. The first is to question existing designers about how they modify their designs, and how they expect their product designs to change in the future. The second is to compare existing designs from different manufacturers. Not only does the presence of common shape types confirm the identification of suitable features, but differences between designs in comparable surface regions indicates the need for localised control. Noting feature variability also helps indicate the relative importance of a feature, and so helps prioritise the effort in developing feature shape alternatives. However, it is important not to be dominated only by existing trends, as a change in fashion, materials or manufacturing process may focus more attention and design effort on different surface regions than are currently popular.

This entire process requires experience, consultation with existing and prospective designers, and several iterations.

1.3. Anatomy Specification

When analysing and specifying a sculptured product's features it is useful to represent the anatomy in three ways:

- As marked regions on a product example, or 2D drawings of a product depicting the features.
- As a taxonomy, representing a feature group hierarchy.
- In a modified entity/relationship style diagram, depicting all the features, groups and blending relationships.

The first two methods are most useful for capturing industry terminology and communicating with existing designers. The taxonomy approach is also useful for categorising feature types (EF, blend, or ornaments) and developing a menu interface for feature selection.

The third method is useful for anatomy/system analysis. The modified entity relationship diagram neatly specifies all the features and their blend relationships and helps to avoid looping blend dependencies. EF features are shown by a single border 'cloud' and feature groups are shown with a double border cloud. Binary and ternary blends are also suitably represented, with the blend and group relationships denoted by labeled lines between the feature objects.

The blend relationship diagrams are similar to Falcidieno et al's face-adjacency hypergraph [1989 Falcidieno et al], except that the nodes are doubly curved surface regions and the arcs represent both intersection and tangency curves, as well as membership of composite 'group' nodes.

1.4. Feature Capture

To prove the method application, for both iron golf clubs and shoe lasts, an example design was initially digitised and modelled using Delcam's DUCT software.

The digitising was performed on a Ferranti Merlin CMM using a Renishaw OP2 probe. The resulting raw data points were then transferred as a text file onto a UNIX workstation and edited manually to produce a command file that would automatically generate an equivalent surface within DUCT.

2. EFF MODELLING APPLIED TO IRON GOLF CLUBS

2.1. Identified Golf Club Anatomy and Feature Diagrams

This section describes the club anatomy implemented for the initial EFF method trials on the Tour Ltd. 5 iron. Figure 4-1 show the 2D product sketches indicating the feature surface regions, but not the ornamental markings. The anatomy is shown exploded with the EF features still trimmed in relation to their application context (i.e. limited to their boundary). Figure 4-2 and Figure 4-3 show two feature taxonomies, the first indicating the feature groupings associated with each of the EFFM type groups. The second taxonomy represents an alternative hierarchy and feature groups as another way of categorising the features within a graphical user interface (GUI), but primarily to represent blend relationship groups.

Figure 4-4 to Figure 4-6 show the feature blend relationships.

2.2. Application Comments

The features can be arranged in several group combinations. These establish different 'views' of the anatomy, reflecting the general case that an EF or blend feature will not exclusively be a member of any one group. The essential design model groups are those required to establish blending relationships between other features and a blend. Obviously binary blends require two such groups. The proposed anatomy comprises; 11 blending relationship groups; 14 EF features, 16 blends (10 primary and 6 secondary); and 8 ornamental markings.

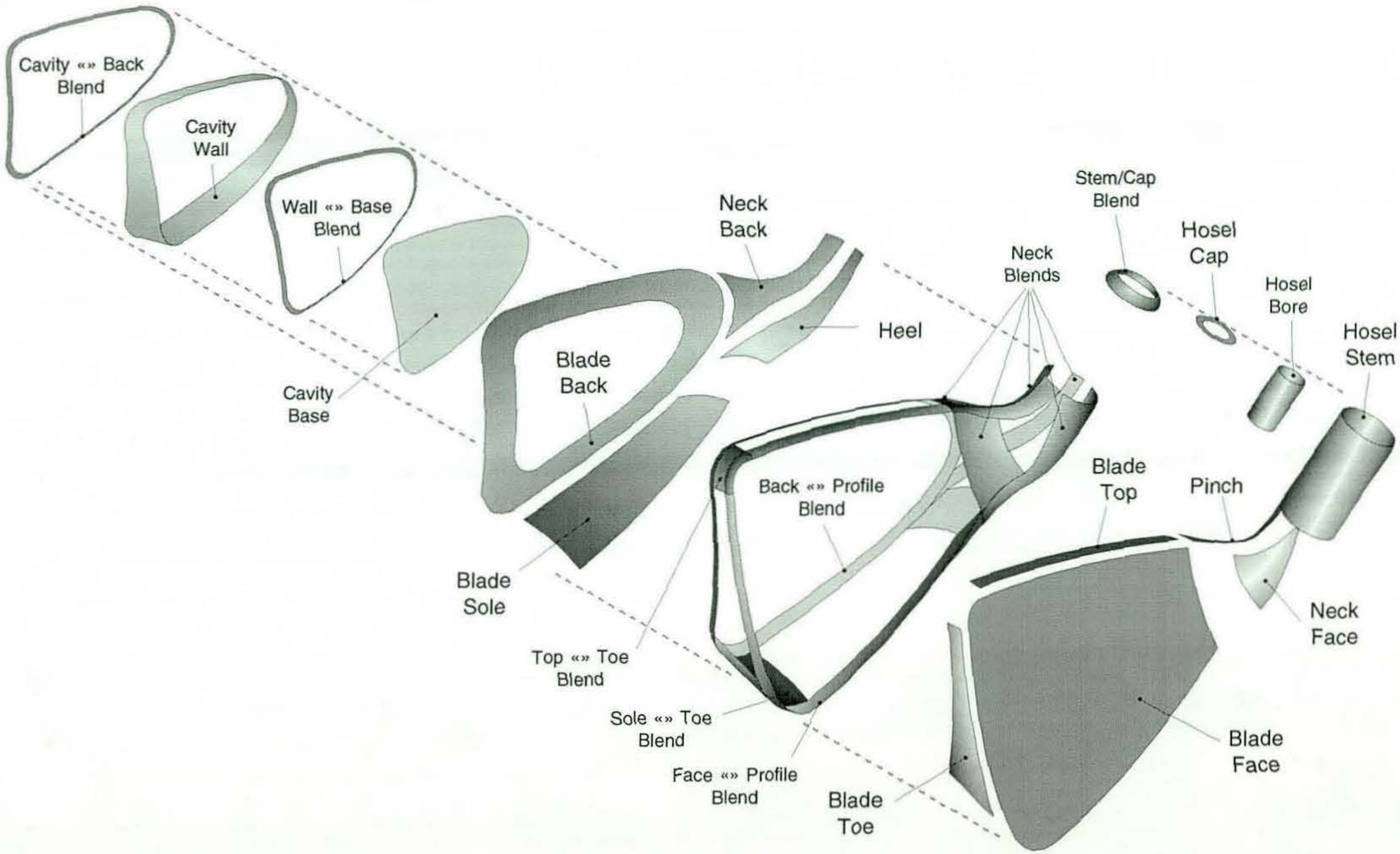


Figure 4-1 Iron Golf Club Anatomy Geometry Diagram.

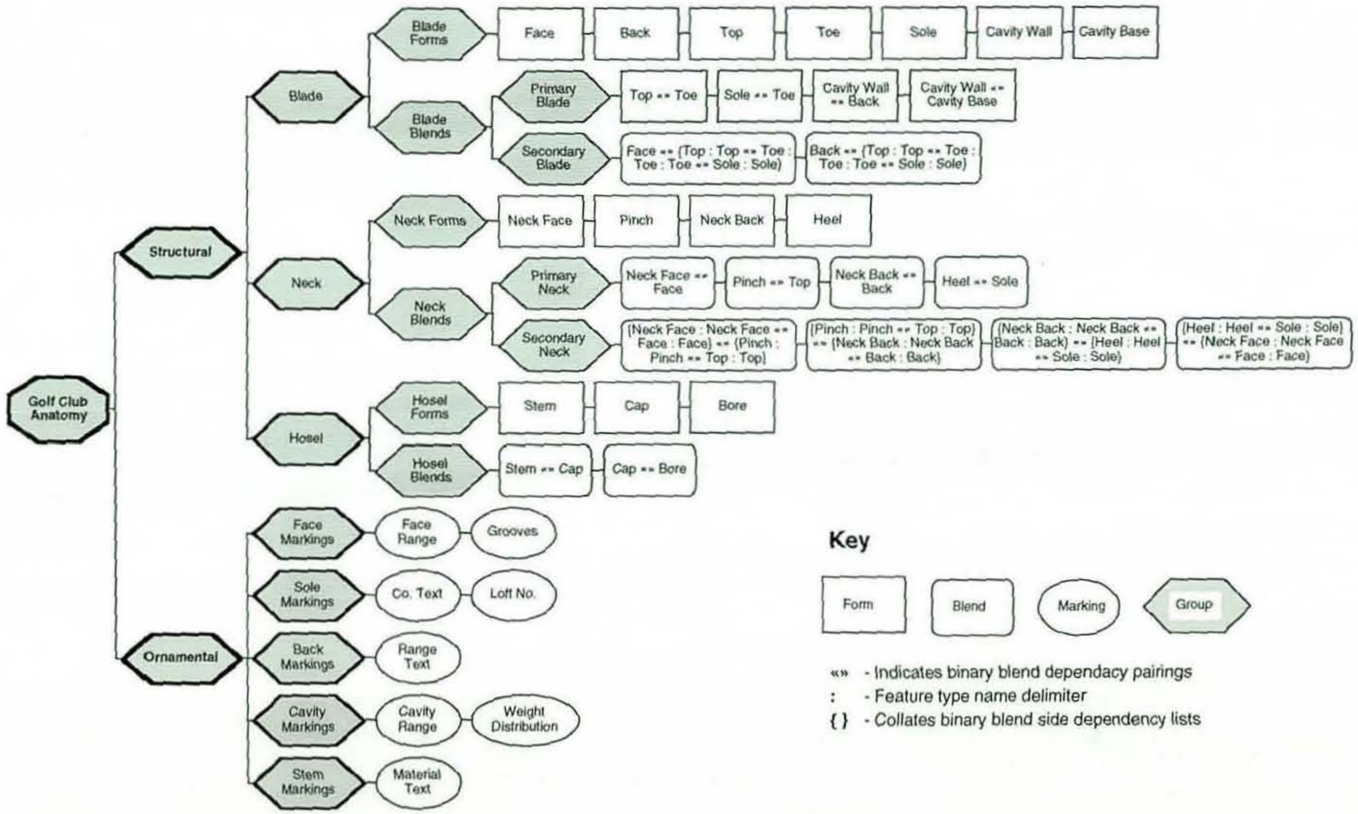
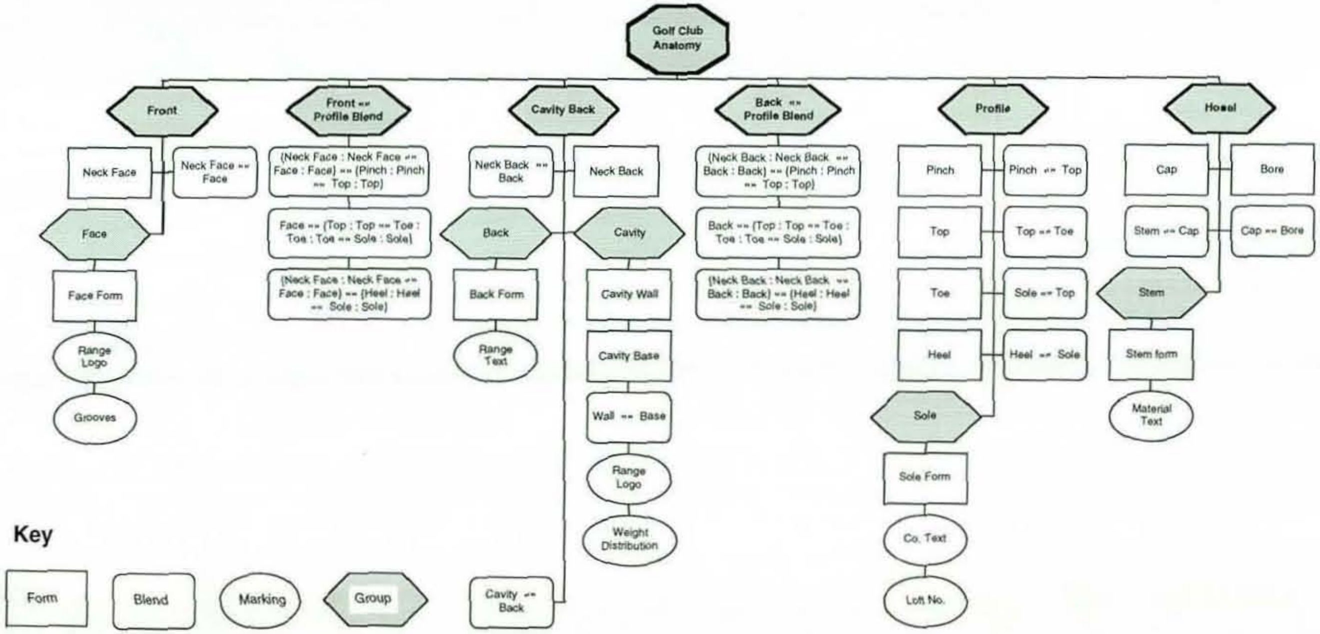


Figure 4-2 Iron Golf Club Feature Taxonomy (Feature Type Groups).



«» - Indicates binary blend dependacy pairings

: - Feature type name delimiter

{ } - Collates binary blend side dependency lists

Figure 4-3 Iron Golf Club Feature Taxonomy (Alternative Blend Group Partitions).

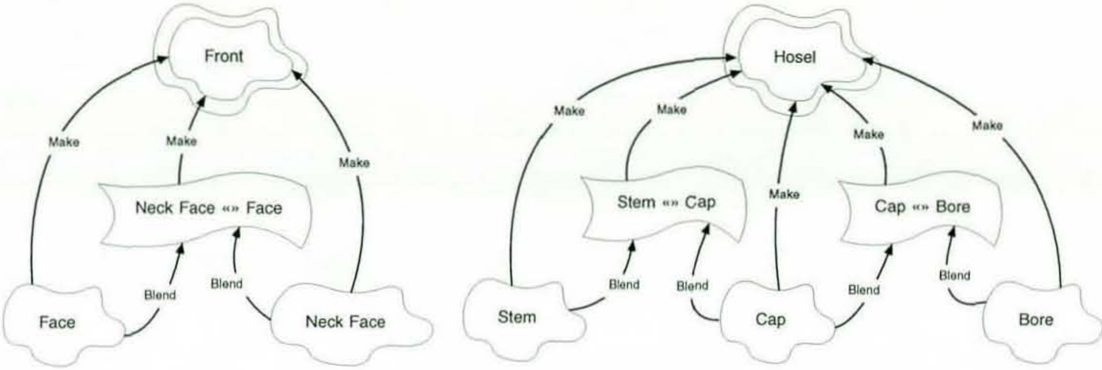


Figure 4-4 Iron Golf Club Blend Relationship Diagram (Front & Hosel).

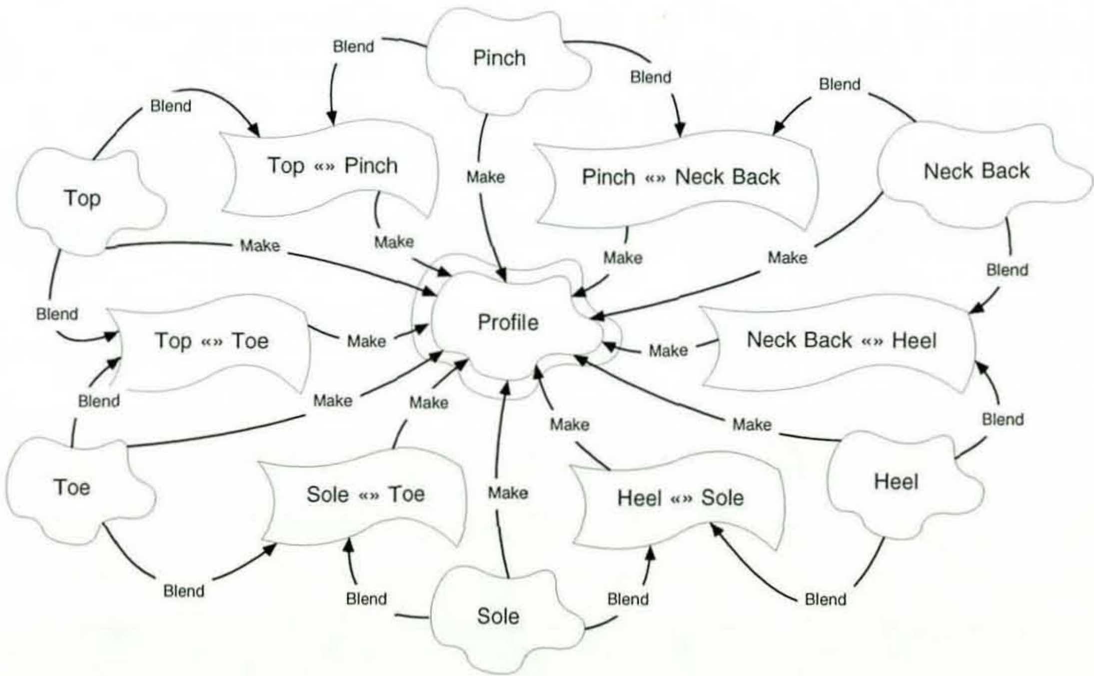


Figure 4-5 Iron Golf Club Blend Relationship Diagram (Profile).

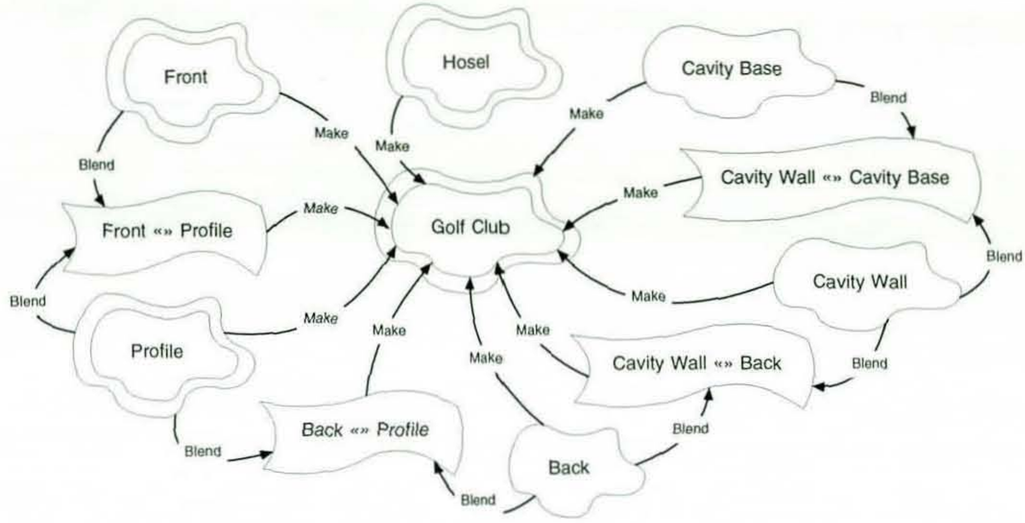


Figure 4-6 Iron Golf Club Blend Relationship Diagram (Whole Club).

The features were identified as a result of in depth discussions with DSI personnel and associated club design consultants. The features are given names that relate to industry terminology where possible. Where suitable terms were unavailable or inappropriate, names have been formulated to make as much sense as possible. For example:

- The toe blend has been called the "Top «» Toe" blend to differentiate it from the toe feature and indicate its relationship with the top feature. The "Sole «» Toe" blend has been similarly named.
- The "Profile" feature group has been so named because the features it contains determine the club outline shape (when projected onto a plane parallel with the face feature) that designers normally call the "club profile".
- The "Neck Face" surface region has no industry vocabulary associated with it. The name is chosen to indicate its location and contribution to the neck group by a combination of existing terms. The "Neck Back" feature has been similarly named.

- There is no specific vocabulary associated with many of the model blends. The names have been derived by combining the names of the blended feature groups separated by "«»" characters indicating the boundary definition's mutual dependence on both feature groups.

Some designers might argue that the profile group is an individual feature, and that it is unnecessary to subdivide it. However, some of the design changes implemented have only a local effect and are better effected by adjusting a sub-feature of this group rather than replacing the whole group. Subdividing the profile group also supports hybrid design development using either the whole group or just an element of it, whereas a single feature would not.

The anatomy does not presently cater for the variety of internal cavity styling exhibited by the industry. The range of different styles makes it impossible to identify a similar feature anatomy in each case, except the fundamental elements, namely the cavity wall, base and associated blends. This problem is perhaps best overcome by treating the cavity group as a whole "super feature" and incorporating it unchanged, except in relative depth, in every club of the matched set. This corresponds to the greater part of current practice in club design. Only where some specific inertia property optimisation through the set is required will it be necessary and worth while adapting the club anatomy to incorporate the full cavity anatomy.

However, the simple cavity feature group implemented is capable of modelling a range of popular designs, currently on the market, possessing less cluttered cavities. These represented a significant proportion of the market, and in many cases are associated with a high quality product. Arguably, they provide the best weight distribution (cf. Chapter 9 Section 1.1).

2.3. Feature Capture & Design Modification

The iron golf club anatomy was initially proven using the Tour Ltd. 5 Iron, as described in Chapter 3 Section 3.1, originally digitised and modelled in LFF format by DSI. Other club designs were subsequently modelled at

Loughborough University using the same anatomy to prove the anatomy's capacity to model a variety of club designs.

The club heads were marked with a network of suitable points to capture the models in a LFF format. The holding arrangement shown in Figure 4-7 was used to mount the club heads on the CMM. A spigot was driven firmly into the hosel bore and then held in a dividing head chuck. Several orientations were used to allow convenient access for the probe, by rotating the dividing head. The data was later transformed by an equivalent negative rotation in DUCT so that the captured surface regions were correctly aligned.

Figure 4-8 to Figure 4-11 show sample images from the completed EFF modelled Tour Ltd. 5 Iron, with a selection of features shaded blue (in their trimmed form) and superimposed as an untrimmed extended wireframe surface. The cavity used is the original multi-level club cavity (Figure 4-11), and demonstrates the comparative ease with which features suitably captured from real models can be incorporated in an EFF model.

Figure 4-12 shows several features colour coded to identify the different feature types at the back of the region (green EF features, blue primary blends, red secondary blends). The heel feature is also show as an untrimmed extended wireframe surface.

Figure 4-13 and Figure 4-14 show three ornamental marking features 'manually' instantiated on the Tour Ltd. model. The face grooves are achieved using an inset DUCT surface with the correct groove geometry, but the Maxfli text on the sole (and other features) was produced using Delcam's ArtCAM software. The 2D artwork for the logo was scanned (Figure 4-15), converted into a 3D relief (Figure 4-16), wrapped onto a triangular mesh approximation of the sole (Figure 4-17), and converted to a new triangular mesh representing the ornamental feature instance (Figure 4-18).

However, because this software was not an integrated part of DUCT at the time, implementation of the ornamental features within a prototype system was not pursued further.

Figure 4-7 Iron Golf Club Digitising.

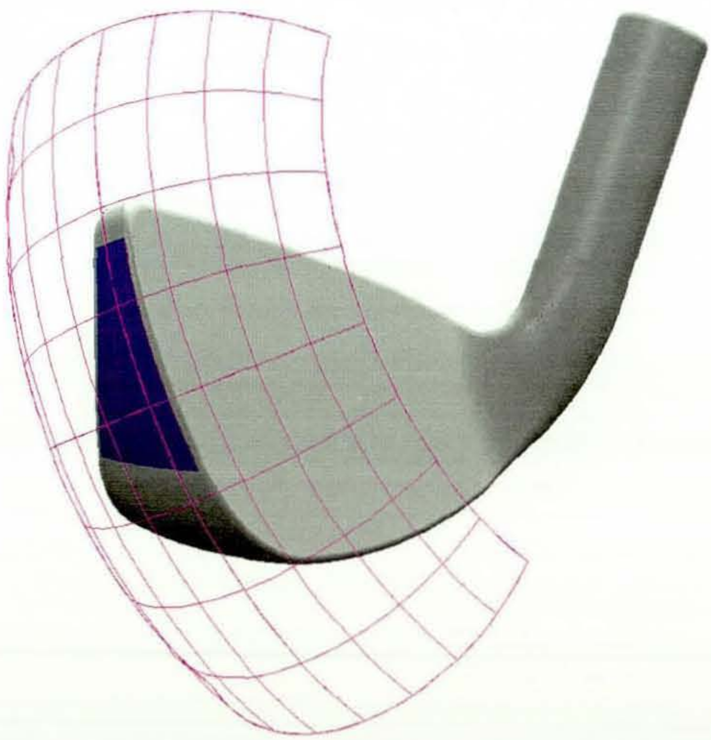


Figure 4-8 Tour Ltd. 5 Iron EFF Model (Toe feature highlighted).

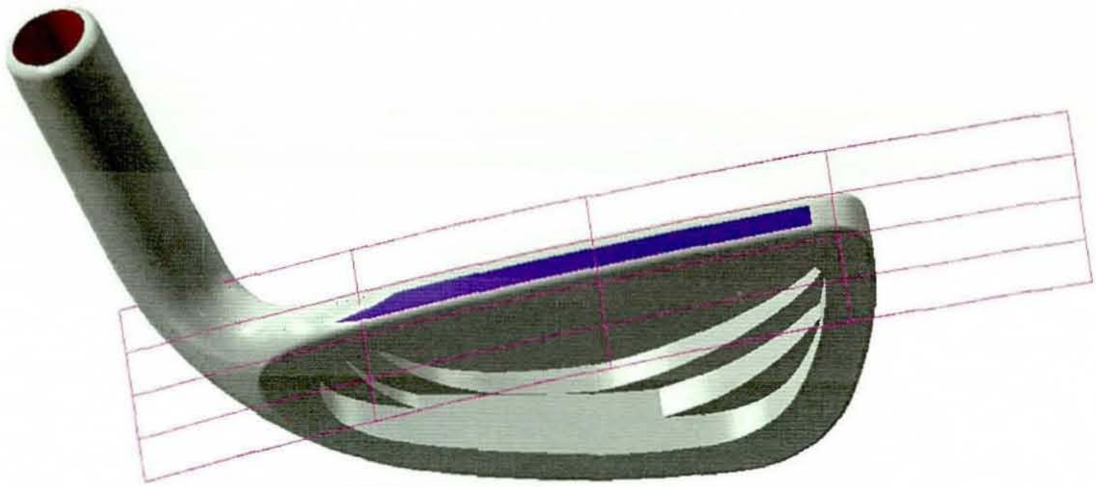


Figure 4-9 Tour Ltd. 5 Iron EFF Model (Top feature highlighted).

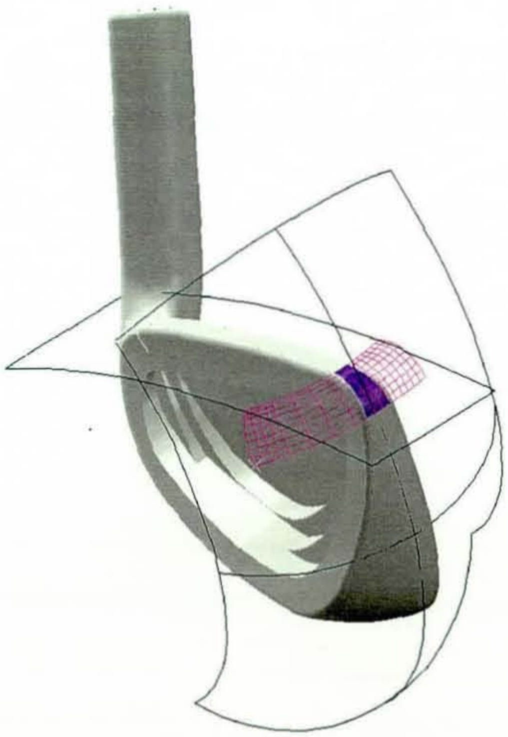


Figure 4-10 Tour Ltd. 5 Iron EFF Model (Top to toe blend feature highlighted).

Figure 4-11 Tour Ltd. 5 Iron EFF Model (Back feature highlighted).

Figure 4-12 Tour Ltd. 5 Iron EFF Model (Colour coded neck features).

Figure 4-13 Tour Ltd. 5 Iron EFF Model (Face grooves).

Figure 4-14 Tour Ltd. 5 Iron EFF Model (Sole logos).

Figure 4-15 2D Maxfli Artwork Scanned into ArtCAM.

Figure 4-16 3D Relief.

Figure 4-17 Wrapped Relief.

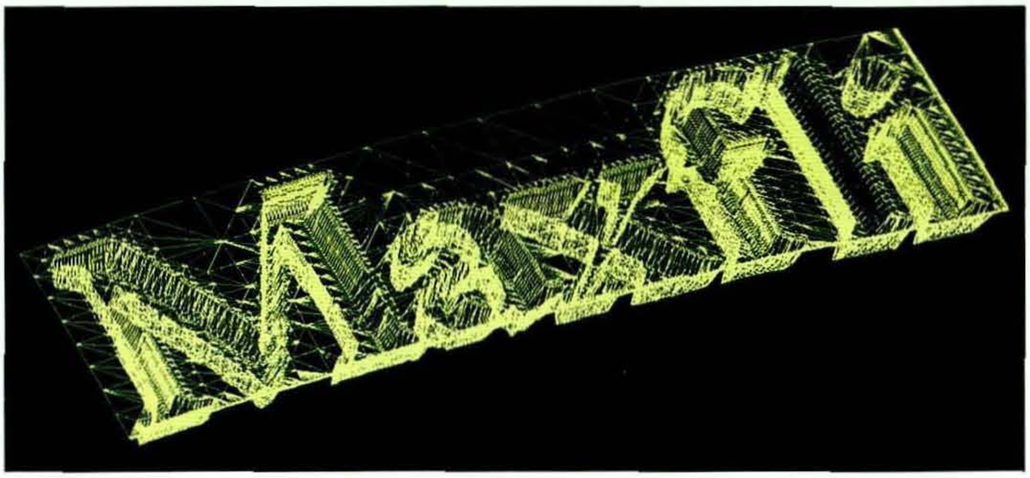


Figure 4-18 Triangular Mesh Logo.

3. EFF MODELLING APPLIED TO SHOE LASTS

3.1. Identified Shoe Last Anatomy and Feature Diagrams

This section describes a proposed anatomy of features suitable for a popular woman's shoe style, predominantly because there is a higher level of design activity for women's shoes than for men's. However, initial observations indicate the feature anatomy would be appropriate for a corresponding man's shoe. Figure 4-19 and Figure 4-20 show the 2D product sketches indicating the feature surface regions. Again, the anatomy is shown exploded with the EF *features still trimmed in relation to their application context (i.e. limited to* their boundary). Figure 4-21 and Figure 4-22 show two feature taxonomies, the first indicating the feature type groupings associated with each of the EFFM feature types. The second taxonomy represents an alternative hierarchy and model groups that again may be preferable for the system interface.

Figure 4-23 and Figure 4-24 illustrate the feature blend relationships. It is interesting to note that the anatomy relationship diagram for the last upper is symmetrical (Figure 4-24), as might be expected from the product's rough symmetry.

The proposed last anatomy comprises; 6 blend relationship groups; 12 extended forms; 7 primary binary blends; 6 secondary binary blends; and 3 secondary ternary blends (16 blends in total).

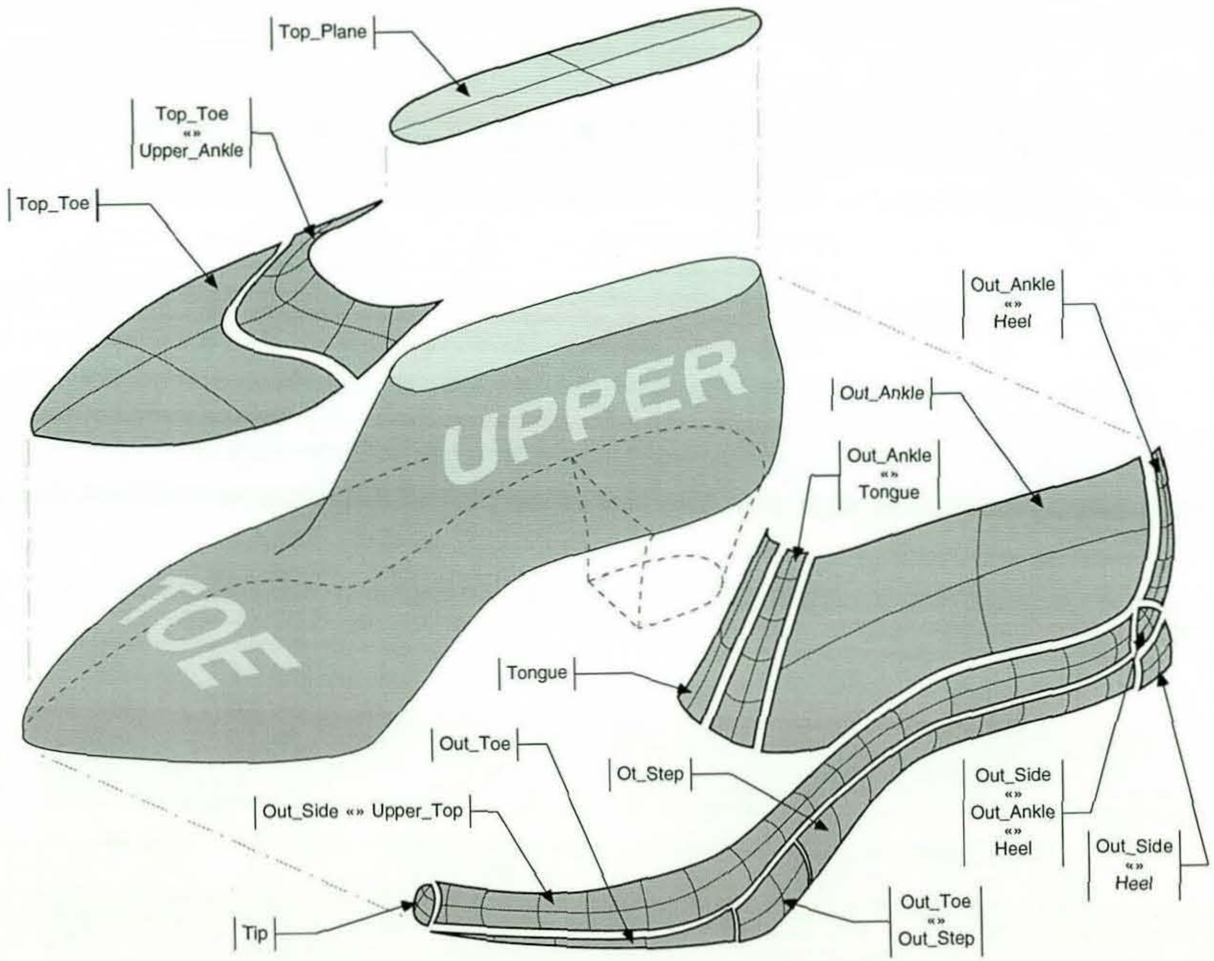


Figure 4-19 Shoe Last Anatomy Geometry (Upper view)

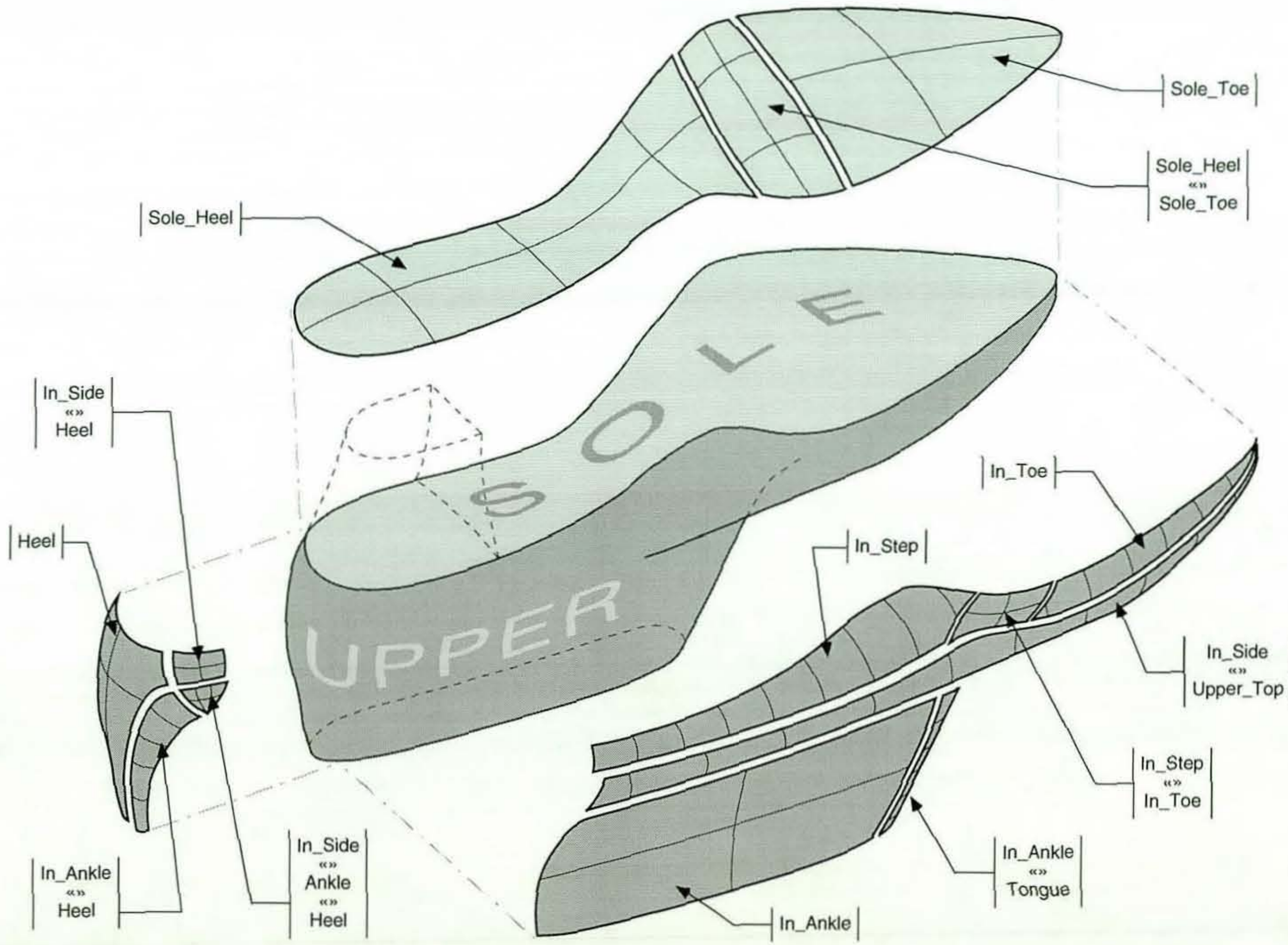


Figure 4-20 Shoe Last Anatomy Geometry (Sole view)

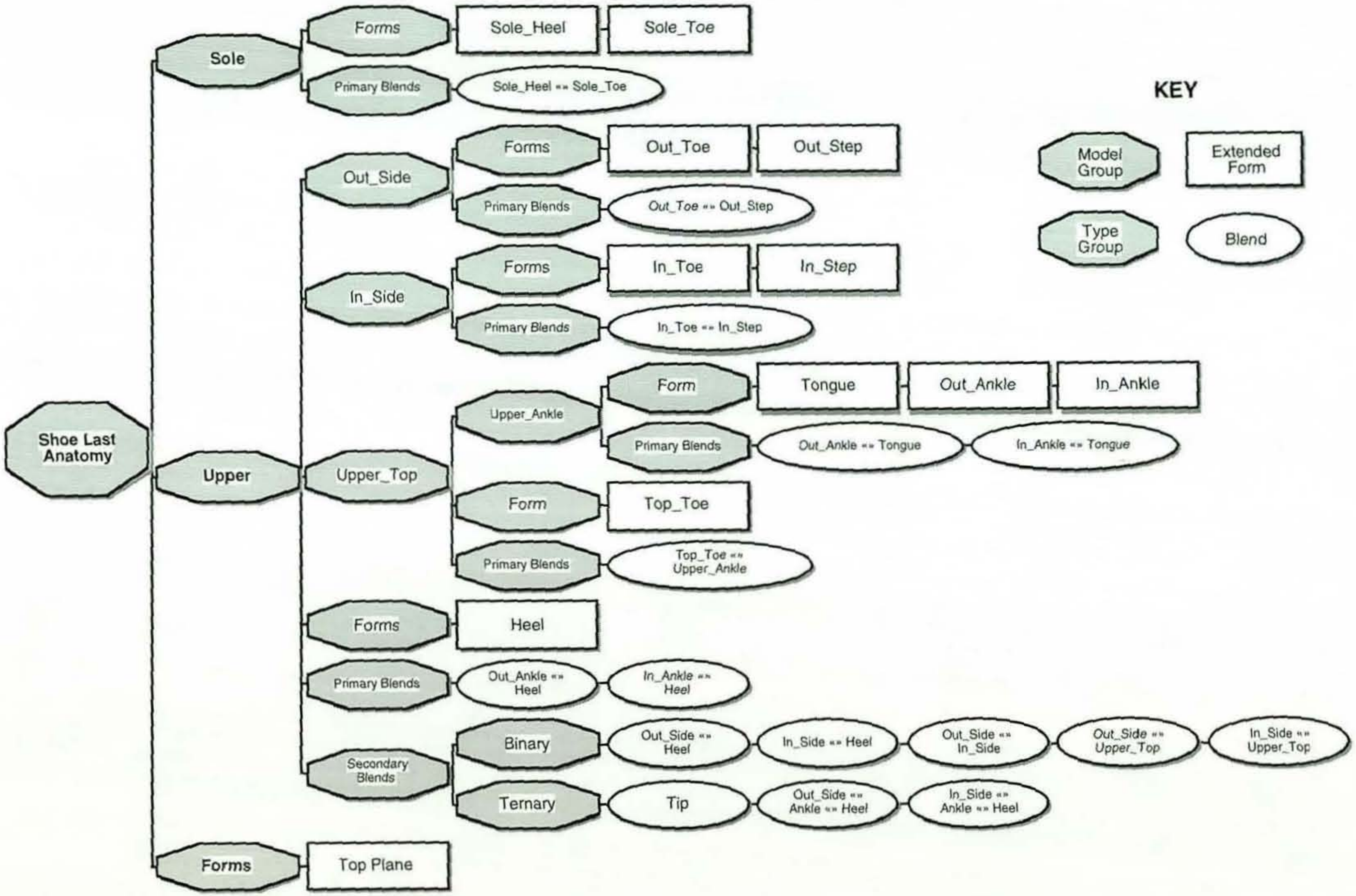


Figure 4-21 Shoe Last Feature Taxonomy (Type groupings)

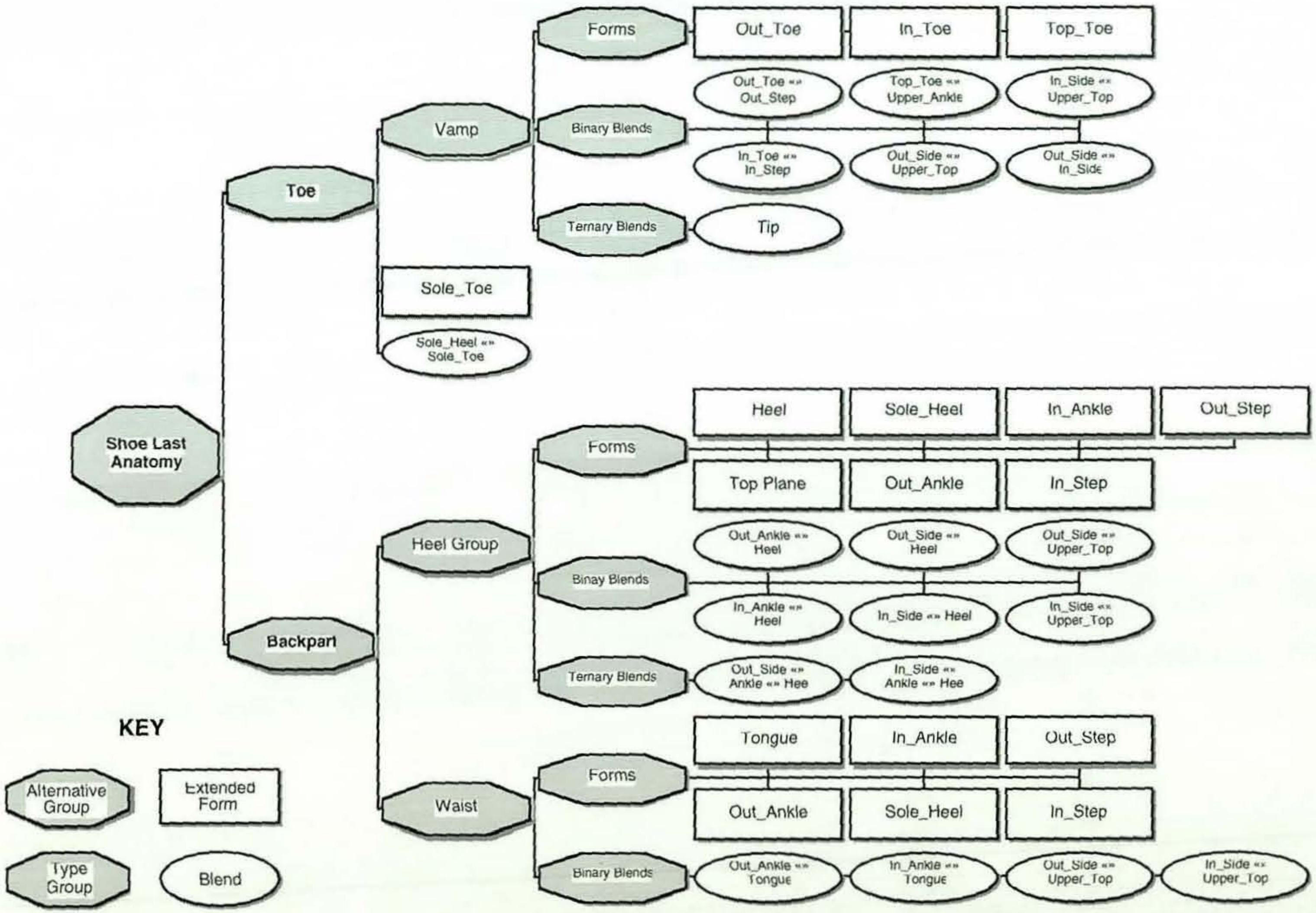


Figure 4-22 Shoe Last Feature Taxonomy (Alternative design groupings)

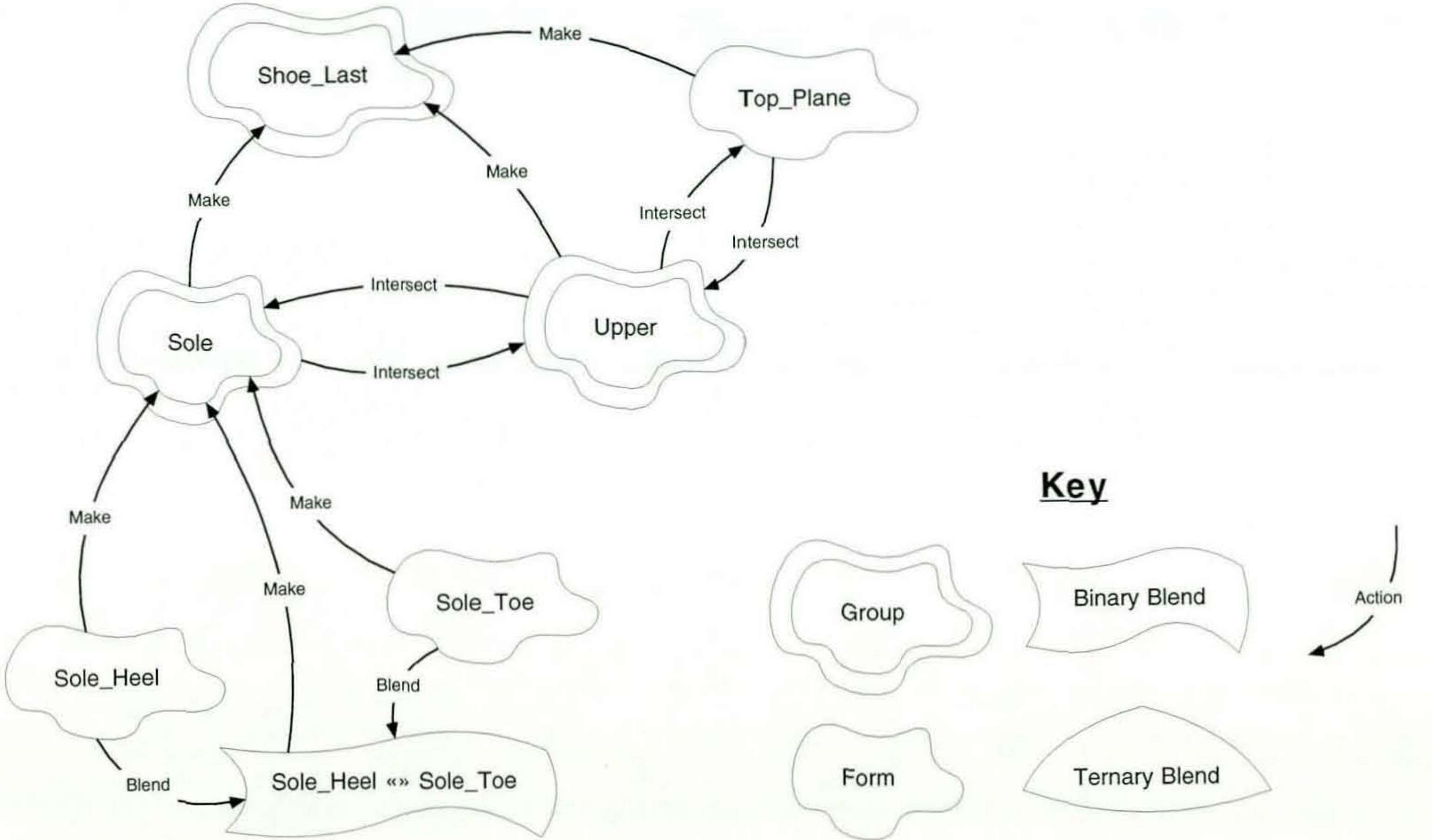


Figure 4-23 Shoe Last Blend Relationships (Top level groups)

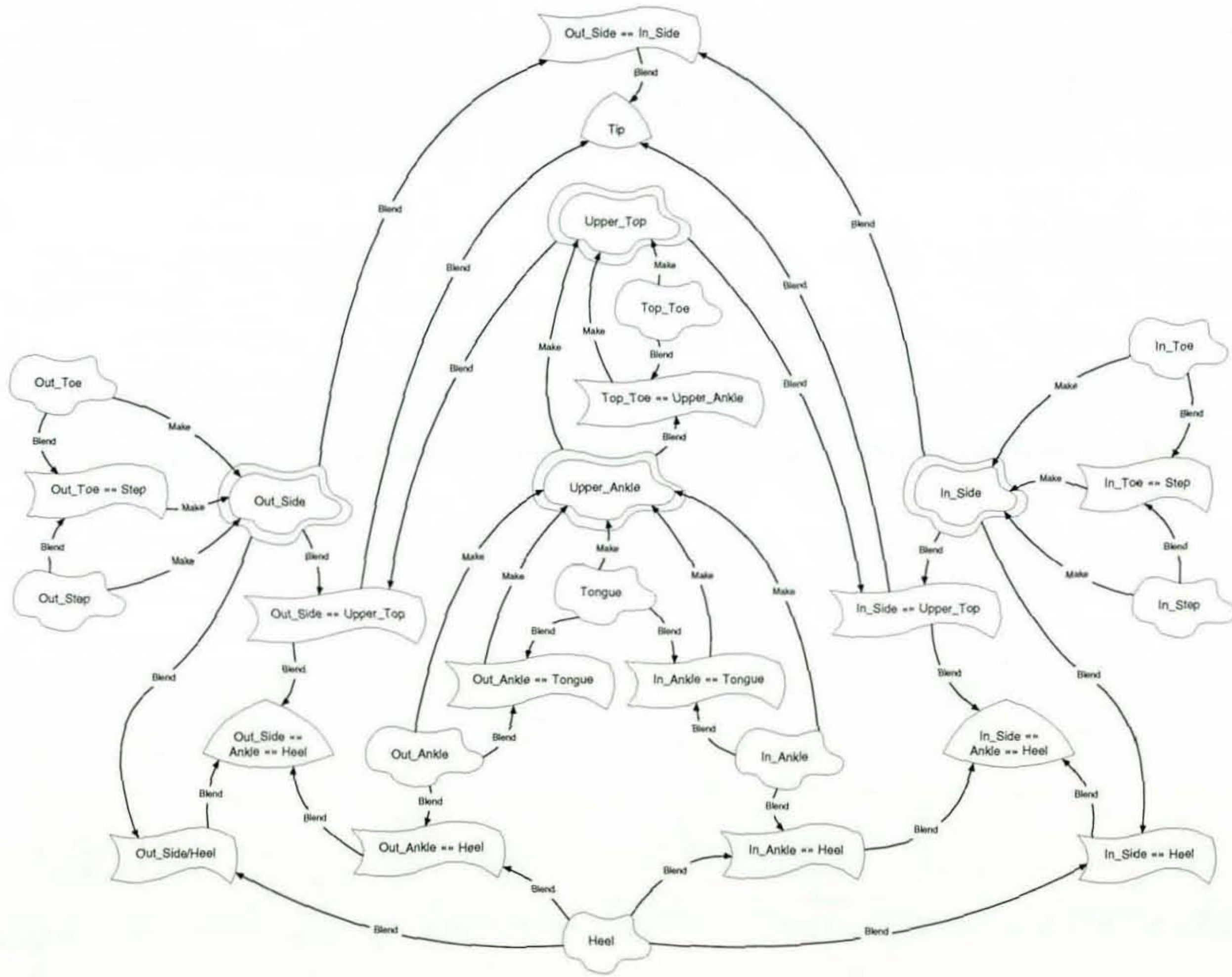


Figure 4-24 Shoe Last Blend Relationships (Upper group anatomy)

3.2. Application Comments

As with iron golf clubs the features identified were produced as a result of in depth discussions with Clarks Shoes personnel and last designers in associated last manufacture subcontractors. The features are given names that relate to industry terminology where possible. Where suitable terms were unavailable or inappropriate, again names have been formulated to make as much sense as possible. For example:

- "Out-step" is used to describe the corresponding feature on the opposite side to the "in-step".
- The "tongue" feature might have been termed the "front cone" by the shoe industry, but this would establish shape preconceptions. The feature is seldom truly conical.
- The "shank" region (roughly corresponding to the sloping region of the sole between the ball of the foot and heel) has not been identified as a separate feature. At present this is considered an unnecessary complication of the sole group, although it could be included if necessary.
- To establish feature bounding relationships it is not necessary to have a "vamp" feature or group for this particular last type. However a suitable group could be included if this aids last manipulation, for example when interchanging whole vamps between lasts. This is also true for heel, toe, and waist regions. The result would be an alternative view of feature groupings for design manipulation as shown in Figure 4-22. It is useful to note that there is some overlap between the additional groups, indicating that the model blend groupings are ultimately preferable to reduce interface redundancy, although designers may well prefer the more traditional alternative groupings in the medium term.

Obviously there is the potential for feature synonyms, for example the sole-heel and sole-toe could be called the sole-forepart and backpart respectively.

There is no reason why particular users cannot adapt or implement particular terms to suit their own preferences.

Some features have been omitted from the initial anatomy. In particular the 'v' cut and hinge details, allowing the last to bend for removal from the finished shoe (Chapter 2 Section 2.3), have been omitted at this stage. This is because they are usually produced by a dedicated machining process with little variation. They are generally purely functional, and therefore contribute little to the style of the last and so the shoe. However, it is a simple matter to add a suitable feature to the last upper anatomy should this be needed.

Shoe lasts are mostly free from tertiary ornamental marking features, except for the raised 'pips' used to indicate the position for key dimensions, such as the last girth (Chapter 2 Section 2.3). Because these markings are both simple in shape, and easily added to the model, they have also been omitted to concentrate initially on successful general shape design.

Current last designers may consider the proposed anatomy overly complex, and might argue that blended heel, waist, and toe features would be sufficient. Certainly these groups can be treated as single entities for the purpose of combining whole sections from different last designs using the EF method. However, experience suggests that shape control for the toe, for example, is best achieved by further subdividing the region. This gives localised shape control, rather than an excessively complex set of shape control parameters or routines. The latter generally makes it almost impossible to eliminate or control the side effects of making design changes to one portion of a complex feature. For example, producing a square toe and smoothly varying the severity of the internal blend regions in 3 dimensions using a single feature would be particularly difficult. These are precisely the reasons why a decomposed last feature anatomy approach is recommended instead of single surface manipulation.

It could be further argued that because the heel design changes little between last types it is unnecessary to subdivide it. Certainly a standard heel group can be introduced as one entity using the proposed features, and in most instances this will require no further change. However, it is still possible that there will be a requirement for change in the future, possibly to suit a new heel style or a new customer/population group. In this case the same arguments for subdividing the toe will apply to the heel. This highlights the need to carefully determine a product's features to allow for both future and current design requirements or activity levels.

3.3. Feature Capture & Design Modification

An example women's shoe last was marked with a network of points and manually digitised using the fixture shown in Figure 4-25. The last was attached firmly to the fixture, using a spigot driven into a tooling hole present in the last top surface, to allow complete access to the entire last surface without repositioning.

The digitised surface elements were then modelled in DUCT (Figure 4-26) and the EFF surface portions were extrapolated. The blend features were then defined using the captured blend regions as a reference to achieve an accurate representation (Figure 4-27). Finally the blended features were trimmed to their boundaries to produce a valid last model (Figure 4-28 to Figure 4-30). Figure 4-29 and Figure 4-30 show the final model shaded to clearly show the model smoothness. Figure 4-30 is also colour coded to indicate the final EF (yellow) and blend (blue) regions.

Figure 4-31 and Figure 4-32 show typical design modifications to the toe styling achieved by manually adjusting the relevant features. These illustrate the identified anatomy's capacity to support realistic design change.

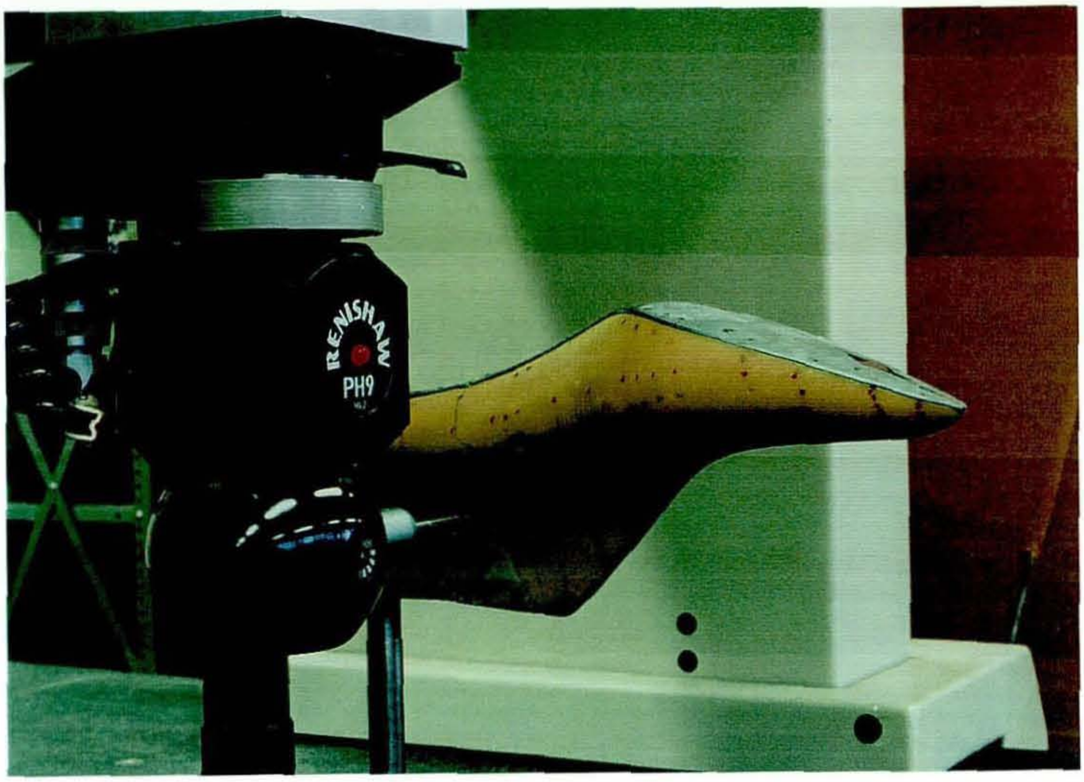


Figure 4-25 Shoe Last Digitising.

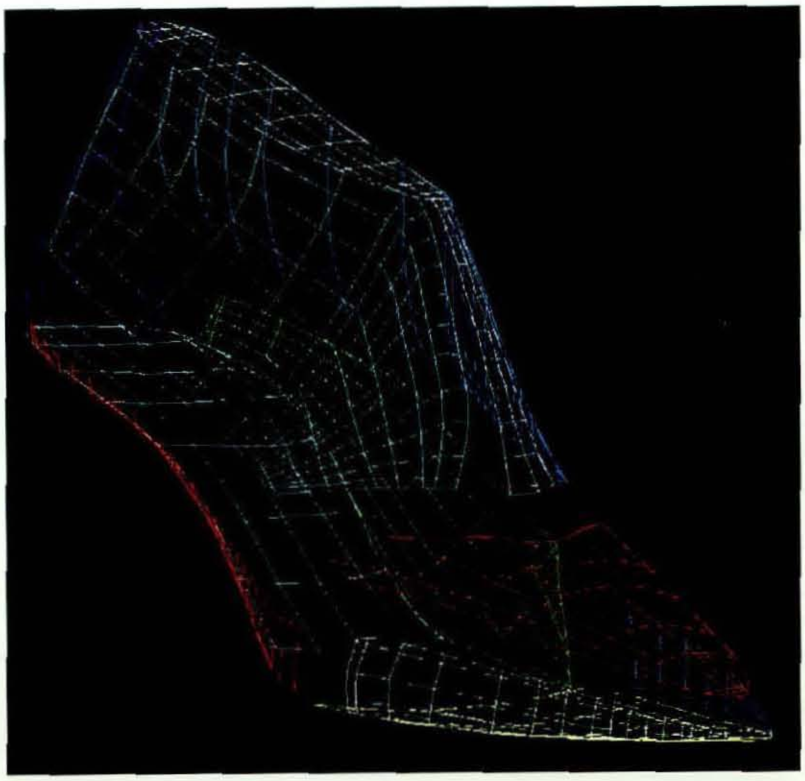


Figure 4-26 Captured Shoe Last EF Features.

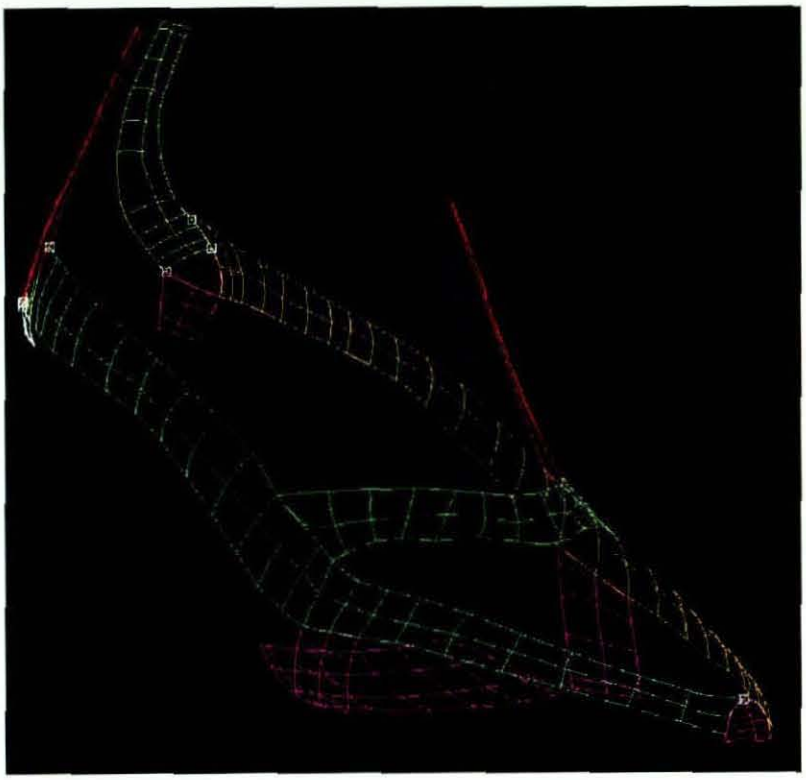


Figure 4-27 Captured Shoe Last Blend Features.

Figure 4-28 Shaded EFFM Based Shoe Last Model (Sole view).

Figure 4-29 Shaded EFFM Based Shoe Last Model (Upper view).

Figure 4-30 Shaded EFFM Based Shoe Last Model (blends highlighted).

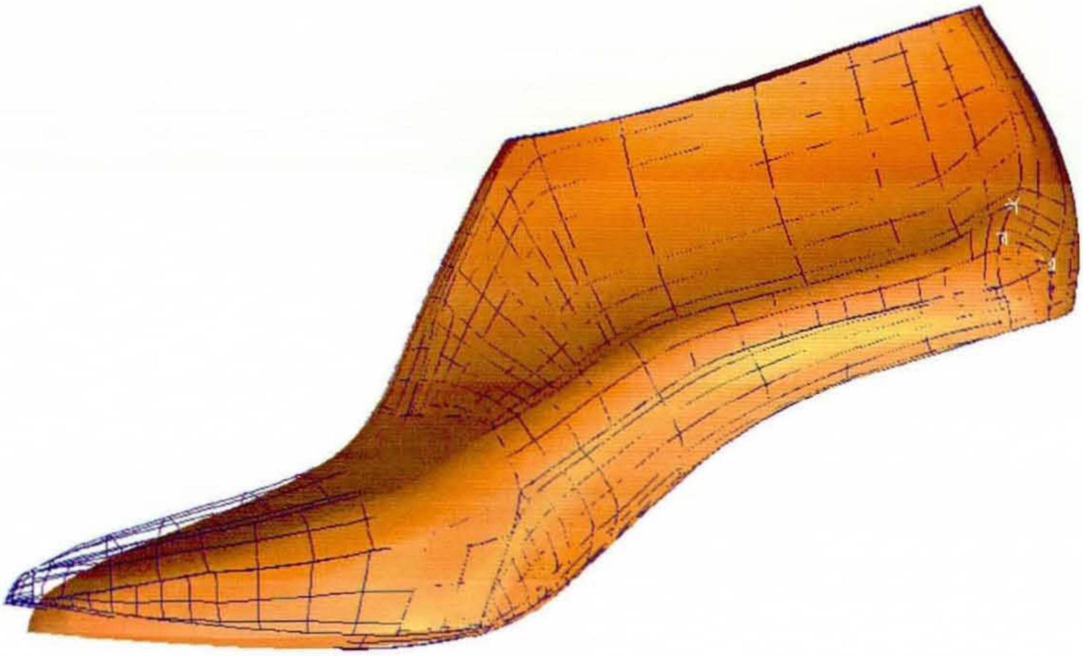


Figure 4-31 EFFM Based Shoe Last Toe Modifications (Toe spring).

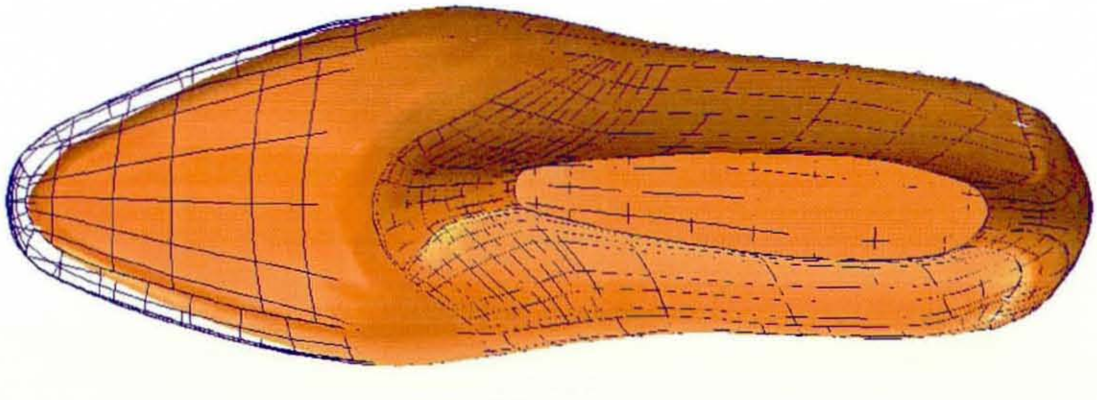


Figure 4-32 EFFM Based Shoe Last Toe Modifications (Toe width).

CHAPTER 5. EFFM BASED SYSTEM STRUCTURE MODELLING

1. SYSTEM OVERVIEW

Two apparently conflicting design approaches are implied by the research objectives.

Design from a library of existing generic designs/anatomies is a 'top down' approach (Figure 5-1). An existing high level assembly of features is used as a basis for the design process. A new design is produced by altering the characteristics of individual features within the existing design. It is particularly appropriate when the aim of design is to produce 'modest variations on a theme'.

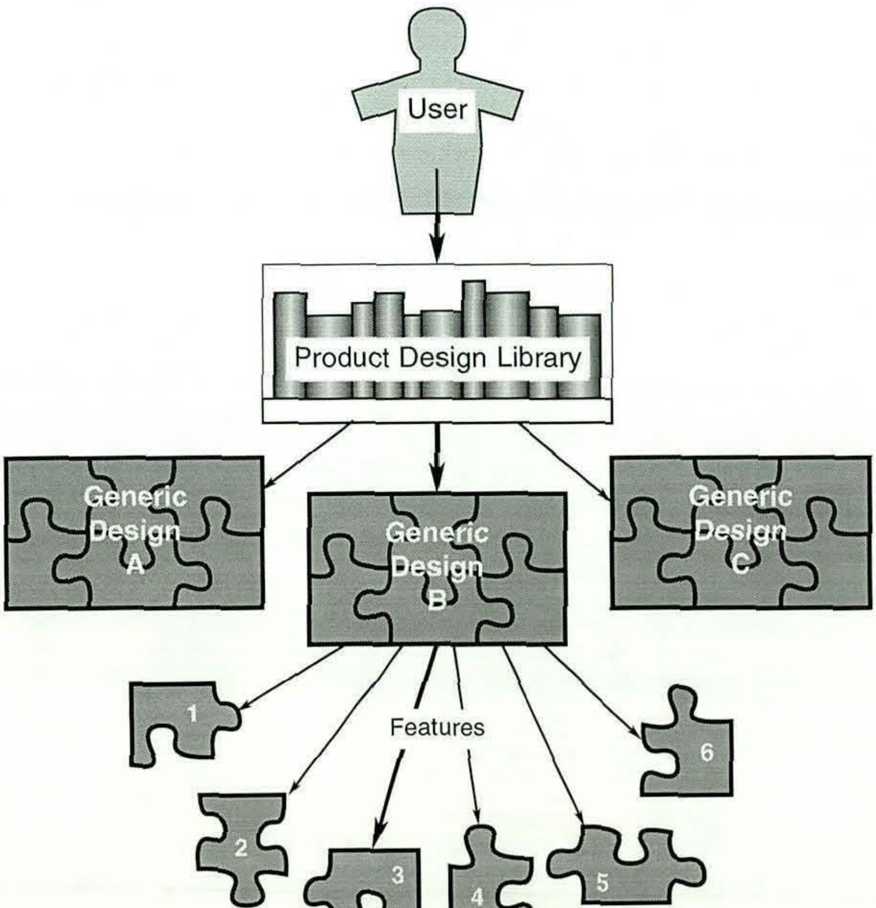


Figure 5-1 'Top down' FBD.

Design from a library of generic features is conceptually a 'bottom up' approach (Figure 5-2). A product design is produced by assembling the features necessary to create a club design. This allows more creative freedom, but may be a slower route to a variation on an existing design.

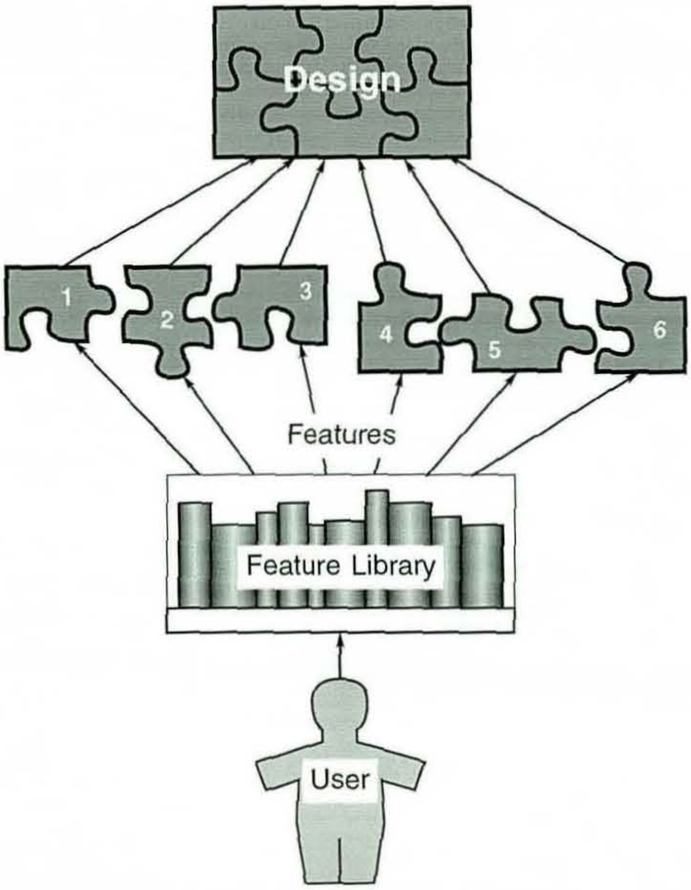


Figure 5-2 'Bottom up' FBD.

The conflict is resolved by considering the difference between design *method* and product *model structure.* A feature based design model structure allows both a library of complete models and a library of features to be stored. It is then possible to support both 'top down' and 'bottom up' methods by providing suitable facilities within the user interface. This approach also allows the hybrid design approach, where an existing design can be improved by introducing features directly from other designs.

Figure 5-3 illustrates the initial concept for the EFFM based design system framework. It supports all three (hybrid, top-down and bottom-up) design methods. The user is presented with a two stage buffer between themselves and the DUCT software. The first is a layer of custom GUI routines through which they control a second level of routines for design development, and potentially prototype manufacture and existing feature capture as well. These in turn 'drive' the DUCT geometry engine to access and manipulate custom product and feature libraries.

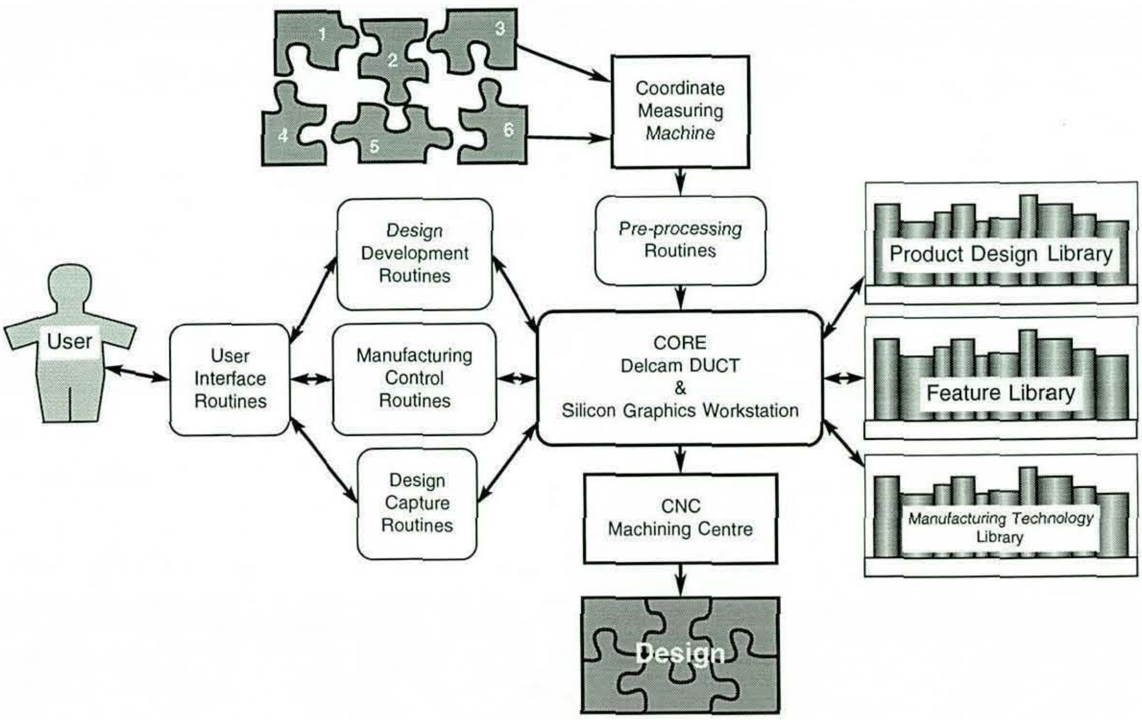


Figure 5-3 Prototype EFFM System Framework.

Although this framework was later revised and expanded (as discussed in Chapter 10 Section 3), it established the essential system structure. The following sections present the data structures (embodied in the 'feature library' and 'club design library' elements) and interface functionality (required for the 'user interface routines') required to support the system in more detail. Chapters 6 and 7 present the functionality implemented within the 'user interface' and 'design development' routines.

2. A Generic EFFM Data Model

2.1. Modelling Approach

Delcam's DUCT software depends on an internal relational database management system (RDBMS) to store geometric and associated data within a 'part' dominated taxonomy (Figure 5-4). It was originally intended that a prototype EFFM system would be implemented using the internal RDBMS functionality, despite problems with user access to these capabilities. Consequently, initial data structure requirements analysis for the system was based on Entity Relationship (ER) modelling [1976 Chen].

ER modelling provided a rigorous and concise format for describing the data structure and also yielded a convenient means for further elaborating the concepts and rules associated with the EFF method. The resulting model can be used, when combined with geometry modelling software to give combined descriptive and functional objects, to develop data structures that are capable of describing a product using feature terminology.

During the research period when the prototype EFF system was under development Delcam announced plans to incorporate the user accessible object oriented database (OODB) functionality available in their 2D drafting software into DUCT. Hinde et al had argued that object orientation is a natural extension to ER modelling and can use many of the same techniques [1992 Hinde et al][1]. Thus, the ER model for the EFFM system was maintained as a basis for implementation within the proposed DUCT OODB.

---

[1] In Mitchell et al's paper Hinde notes that the selection of the entities/objects of primary interest followed by the exploration of the interactions is a common activity, and the embodiment of a relation in executable code draws the ER paradigm even closer to object orientation. Inheritance may be viewed as an additional generator to join and so a "normalised" model would be join irreducible and also inheritance irreducible but would also exhibit cover across the domain of interest [1995 Mitchell et al].

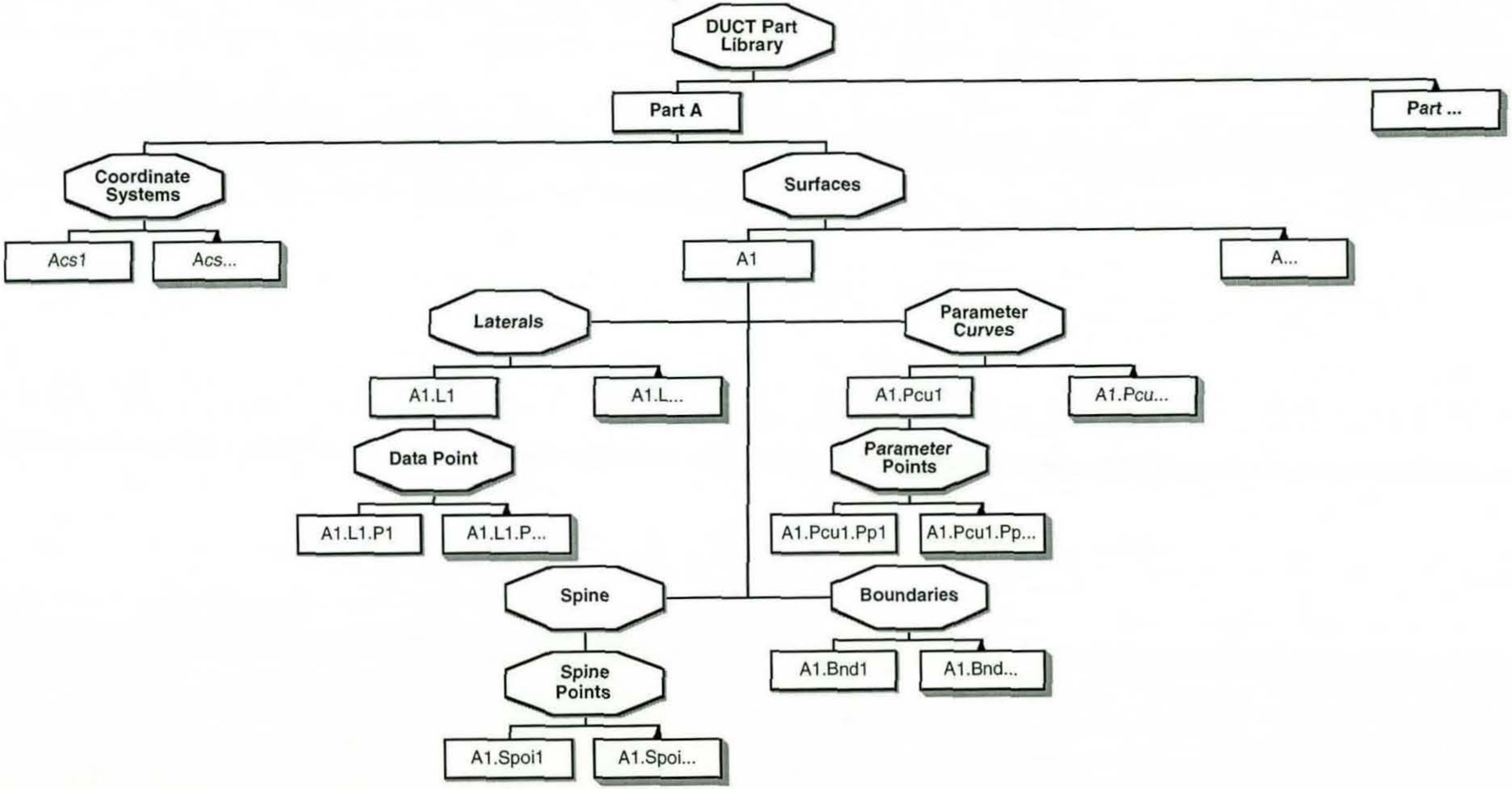


Figure 5-4 DUCT RDBMS Entity Taxonomy

The following sections use entity/relationship diagrams conforming to the ORACLE Case*Method notation detailed by Barker [1989 Barker]. The diagrams are similar to those produced by SSADM [1988 Downs et al], but have some useful additions. Figure 5-5 identifies the meaning of the different diagram elements.

Data entities are represented by round cornered rectangles with their singular names in bold capitalised type. Some of an entity's attributes may be indicated. These are in plain lower case type. The status of an attribute, whether it is always or only sometimes recorded for each instance of an entity, is indicated by a leading symbol. For example, in Figure 5-5 entity C is of standard type. It has three attributes. Attribute (i) is mandatory and is one of the entity's unique identifiers (# symbol). Attribute (ii) is mandatory (* symbol). Attribute (iii) is optional (o symbol).

Where entities are similar and share common attributes they may be grouped under a supertype containing the common attributes. Each sub entity inherits these attributes in addition to any specific to that entity. For example in Figure 5-5, entity A is a supertype and has one sub entity AA. Entity A has one attribute, a unique identifier. Entity AA has one optional attribute specific to it. It also inherits attribute (i) from A. Entity B is also a supertype and has two sub entities BA and BB. Entity B has one mandatory attribute, a unique identifier. Entity BA has one mandatory attribute specific to it, and inherits attribute (i) from B. Entity BB has one optional attribute specific to it and also inherits the unique identifier attribute from B.

The relationships between entities are represented by lines linking the round cornered rectangles. The type of line indicates the type of relationship, as shown in the key in Figure 5-5. The line labels indicate the nature of the relationship. For example entity C is related to entity A by a one (indicated by the plain line end) to many (indicated by the 'crows foot' end) relationship. Each instance of entity C is related to one or more instances of A, but an instance of A is only related to one of C.

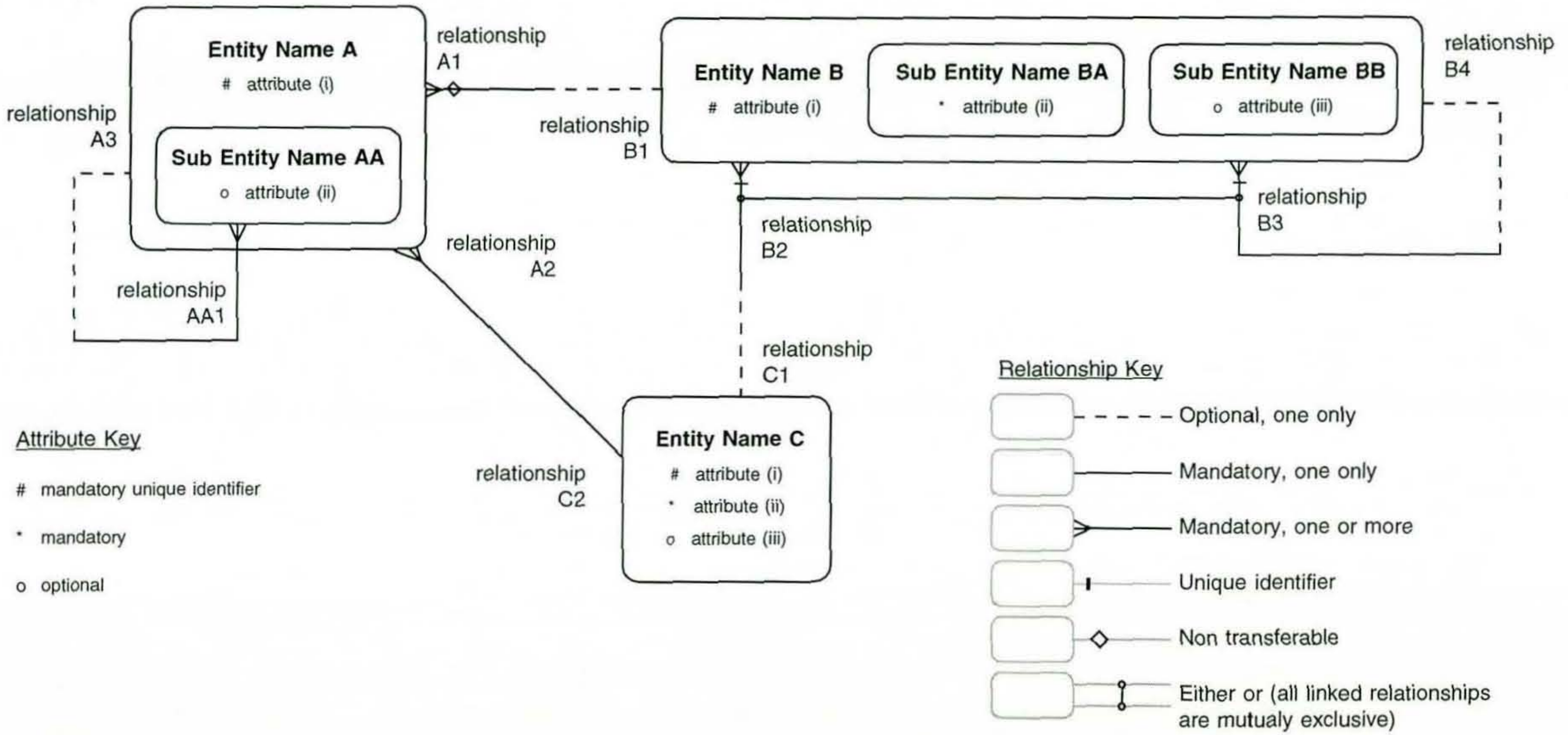


Figure 5-5 Entity Relationship Diagram Notation.

The entity AA also inherits a similar relationship with C from its supertype A.

The status of the relationship is indicated by the line quality for the section nearest the particular entity. A plain line indicates a mandatory relationship, so an instance of C must be related to an instance of A and vice versa. A dashed line indicates an optional relationship, so an instance of B may or may not be related to an instance of A or its subtype. However, entities A and AA must be associated with an instance of B or BA or BB.

Relationships between instances of the same entity type are indicated by loops such as relationship B3/B4, or A3/AA1. Where relationships are mutually exclusive this is indicated by a line linking the relevant indicators, such as those indicating relationships B2 and B3. Where relationships help to uniquely identify an instance or are non transferable to another instance this is indicated by a bar (relationships B2 or B3) and a diamond (relationship A1) respectively.

In summary, the nature of a relationship can be translated from the graphical representation into approximate English by substituting names and labels into the following phrase, and suitably adjusting the optional clauses:

- Each and every instance of a *first entity name* [must/may] be *first relationship label* [one and only one/one or more] *second entity name*, and ...
- ... each and every instance of a *second entity name* [must/may] be *second relationship label* [one and only one/one or more] *first entity name*.

For example, if entity name A were 'male child' and entity name B were 'female parent' the typical relationship labels might be 'the son of' and 'the mother of' for A1 and B1 respectively. Thus, each and every *male child* must be *the son of* one and only one *female parent*, and each and every *female parent* may be *the mother of* one or more *male child(ren)*.

Expressing the data model in this form reduces redundancy (information is stored only once) and ensures completeness (a son can not exist without a mother, hence it must be *the son of*). The model can be directly converted to linked tables within a relational database. For example, there might be a table of son's names. Each *son* instance would be linked to its corresponding *mother* in a similar table of mother's names. This link would ensure that for each *son* instance generated a link to a *mother* would be formed. This then provides the basis for searching for the *mother* of a particular *son*, the *sons* of a particular *mother*, how many *sons* a *mother* has, and so on.

With a more complex data structure it is possible to extract more detailed information. For example, in the case of the sculptured product data model, it would be possible to extract a list of all the different club designs in a category that use a particular toe shape, together with the parameter values associated with each design.

Section 2.2 presents an initial data model [1995 Mitchell et al] biased by the initial intention to implement the structure in a RDBMS context (despite the obvious change in intent reflected in the referenced paper's title when the structure was published). Subsequently, Sections 2.3 presents a revision of this model better suited to the OODB functionality now available in DUCT and incorporating further simplification and developments in understanding EFFM requirements.

2.2. Initial Model

2.2.1. Overview

Figure 5-6 shows an overview of the full model. It can be partitioned into 6 segments as shown:

- Artefact anatomy
- Parametric shape control
- Geometric representation
- Feature type interaction
- Design instantiation
- Product classification

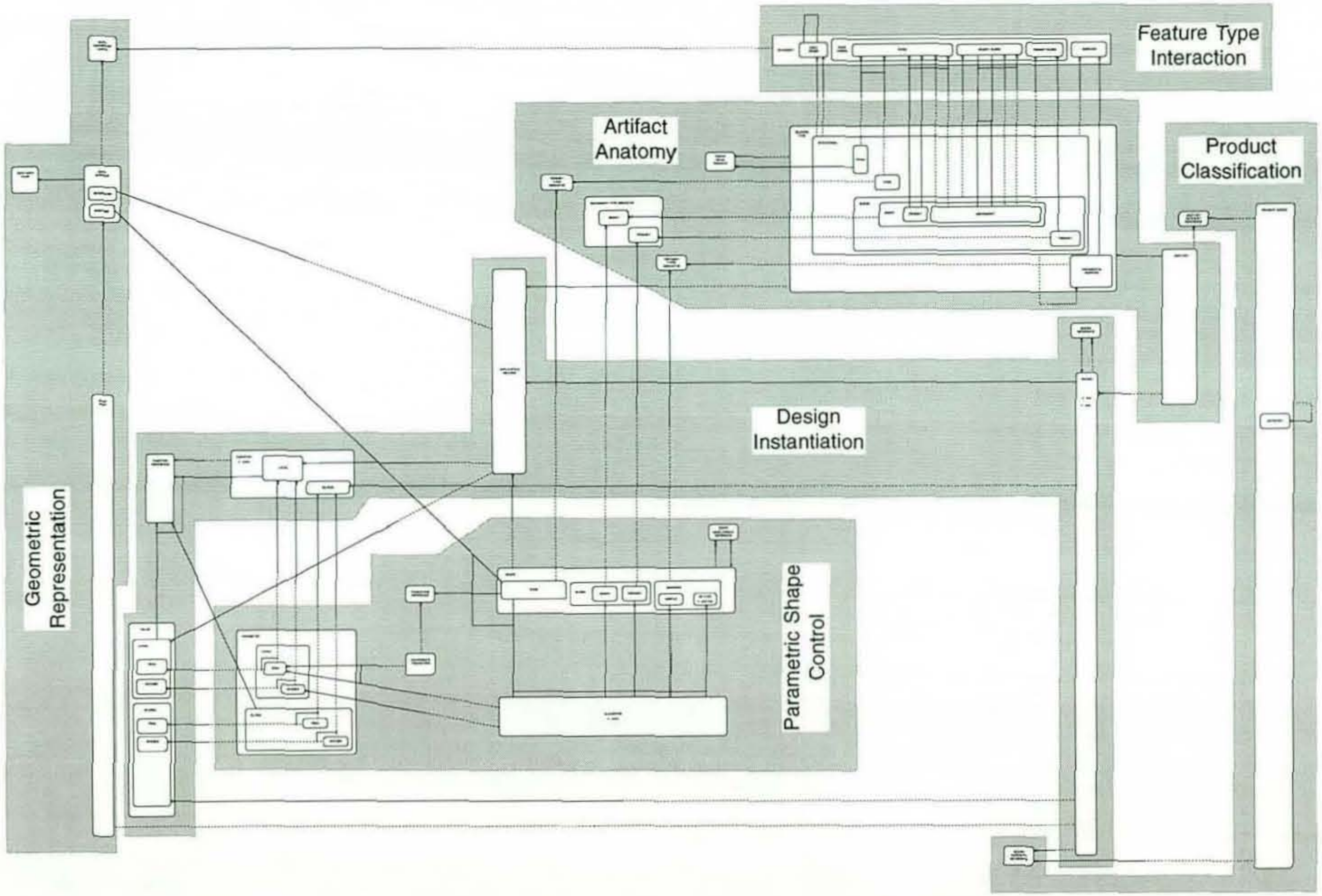


Figure 5-6 Full EFFM ER Model

These segments are discussed and illustrated in isolation, and more detail, in the following sections (2.2.2-7).

In summary, the model is founded on the entities necessary for designers to define their artefact's anatomy. Fundamentally this is a means of allowing designers to specify a language to describe the constituent elements of their designs. It is these elements that are termed 'feature types' (Section 2.2.2). Once the elements of the artefact can be referred to, the feature type interaction structures embody a means for the designer to specify the intended feature boundary inter-dependencies (Section 2.2.3).

Establishing links between the anatomy elements and potential parametric shape and position constraints within the structure allows the designer to define and explore a particular solution domain (Section 2.2.4). The design instantiation structures provide the ability to collate all the necessary data required, in relation to a particular solution domain, to specify a single solution (Section 2.2.5) and evaluate its geometry (Section 2.2.6). The product classification structures provide a means of referring to particular solution domains or solutions through descriptive product terminology (Section 2.2.7).

When the model was developed there were no standards for sculptured feature based product data models, let alone models that incorporated some functional characteristics. However, where there were some peripheral data overlaps with existing or developing standards for more generalised product data (e.g. STEP [1992 ISO, 1993 ISO]), the structure was not intended to conform to these. Nor was the model intended to support data related to product manufacture at that stage. However, the model was intended to be sufficient for the purpose of research into sculptured feature based design. Consequently the model supports the basic structures needed for the EFF approach to be evaluated, and provided the foundation for further work in the area.

In particular, the 'product classification' structures (Section 2.2.7) are presented more for completeness than for their research value. These structures are not comprehensive but support adequate functionality to conveniently implement a prototype system and evaluate the stated method's benefits to sculptured product design. This functionality needs to be extended to be appropriate for commercial use.

2.2.2. Artefact Anatomy

As discussed in Chapter 3 Section 3.2, the model is developed on the assumption that there is no generic set of features universally applicable to sculptured products. Consequently, system developers (or experienced designers) in a particular sculptured product domain need to define their own features in relation to a generic approach to modelling. The key elements of the model therefore are those that allow the definition of a generic anatomy, as shown in Figure 5-7.

Given the definition of a feature in the context of sculptured product design:

- A *feature* is a generic element of a product design, for which specific instances are defined by a set of characteristics, so that together with other features it meets the aesthetic and/or functional design requirements.

It is reasonable to identify the base entities of the structure as features, or feature types.

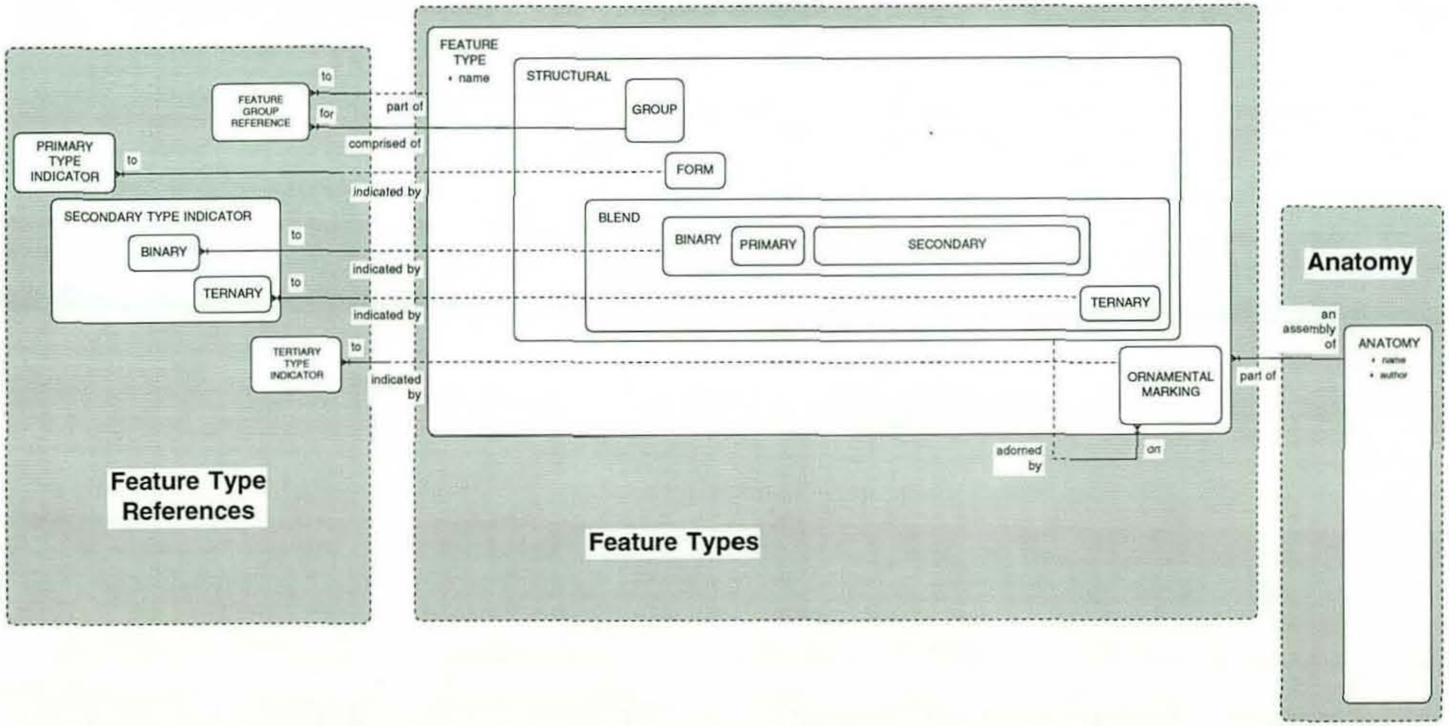


Figure 5-7 Artefact Anatomy Data Elements

The term 'artefact anatomy' embodies the concept of the full set of features needed to describe a complete object. This becomes a product type when it is given a specific market persona, and becomes the definition of a real product when combined with the data required to fully specify the design. This reflects the thinking that although it is necessary to distinguish between, for example, a 'Tour Ltd. 5 iron' and an 'XTC 3 iron' at a product level, if their anatomy is the same (although their appearance is different) there is no need to duplicate it.[1] Furthermore, maintaining the knowledge that the designs are conceptually the same better supports future hybrid design activities where a design can be drawn from a particular class rather than a single instance.

In essence, the artefact anatomy is the skeleton on which a sculptor would mould his clay. At the point of definition it is a means of capturing design intent - 'the product is to consist of this set of features.' After this it becomes a means of constraining design to a particular product type - 'the product must consist of this set of features.' However, because the relationship between feature type and geometric shape is relaxed, this does not imply 'the design must be of a particular shape.' This is a subtlety, and reflects the perception that sculptured product industries, such as the golf industry, need to have a wide variation in possible shape within their use of feature terminology. To facilitate this the emphasis that 'a feature is something that will have particular geometry' [e.g. 1991 Wingard] needs to be displaced so that a feature is only something of individual shape relevance within the design - such that the designer requires localised control over it.

In other words, the shape of the feature may be arbitrary, its existence and interaction with other features is not. Furthermore, a particular shape may be relevant to more than one feature type, as well as a type having the potential for more than one generic shape.[2] This removes a level of abstraction from

---

[1] This absence of duplication leads towards the idea of classes and inheritance of object oriented design.

[2] Hence the type indicators for parametric shape control, discussed further in section 2.2.4.

the language a designer specifies for the parts of the design, avoids redundancy, and rightly maintains the distinction between a feature's ultimate shape and the way it interacts with its neighbours. For example, a golf club's sole and toe features may have mathematically similar shapes, although different orientations. However, the feature language required by the designer includes 'toes' and 'soles' but not the mathematical term for their potential shape. There may also be other shapes these features share in common, and some they may not. Both features also interact with a different set of features within the whole design.

Design in sculptured product industries is usually strongly influenced, in a manner that superficially seems contradictory, by both tradition and fashion. Golf clubs generally have a particular type of feature anatomy because the rules [1996 R&A] state that they "... shall not be substantially different from traditional and customary form and make". However, given a basic anatomy there is still significant scope for feature shape variation, and even some anatomy mutation (slight variations of the feature anatomy, such as the use of multiple back cavities), where fashion demands innovation and differentiation, and taste allows. The decision about why the basic golf club anatomy has a certain type of feature (e.g. face, sole, or hosel) has already been made, tested, and generally accepted. The reasons have become ingrained in the designer's thinking, and industry standards, so that a feature type's design relevance and the designer's intent are already established. Even a particular feature's shape, or an anatomy mutation, always depend on the balance of two fixed criteria; 'what looks good (this year)'; and the opportunity to claim, often scientifically tenuous, innovation and performance gains.

Consequently, the important issues of recording design relevance and intent[1] in general mechanical CAD situations, where product anatomy and functional variability is high and feature shape variation relatively low, is of

---

[1] e.g. That a particular hole is present in a certain place, with a certain shape and tolerance, because it is needed for a particular bolt to fix this component to another in an assembly suitable for certain working conditions and performance criteria.

far less importance. The central issue for sculptured product industries to benefit from CAD techniques is not how to efficiently store and make sense of all the 'reasons why'. Instead it is how a product should be modelled to allow simple, efficient, and rapid design variation by a product craftsmen (not engineers, mathematicians or computer scientists), in response to constantly changing fashions.

Consequently, the proposed model exhibits little support for design intent and relevance knowledge, although, given the nature of the model, an extension of the work for those industries for which it may be more relevant is achievable . If the structure correctly models the actual structure of the object being designed then the semantics of these objects can be attached. Conversely if the semantics are naturally associated with a range of objects in the model described here then their attachment will be more difficult.[1] The time and effort spent with designers to initially define a product anatomy should ensure that such semantic integrity is naturally achievable.

The feature types exhibit an inheritance hierarchy shown in Figure 5-8. Within this hierarchy a distinction is made between structural and ornamental features. The structural features are those that are essential to describe a physically valid artefact, whereas the ornamental markings are surface embellishments of the structural features, for example engraved or embossed text and logos. The ornamental features are of particular importance in sculptured product design, both aesthetically and functionally. For example, Wedgewood's Jasperware pottery is characterised by a complex white ceramic relief on a darker product surface, and the markings and logos typically found on a golf iron affect the head weight by more than twice the design weight tolerance.

---

[1] Although achievable if for example they relate to a group of features associated by a group feature in the anatomy.

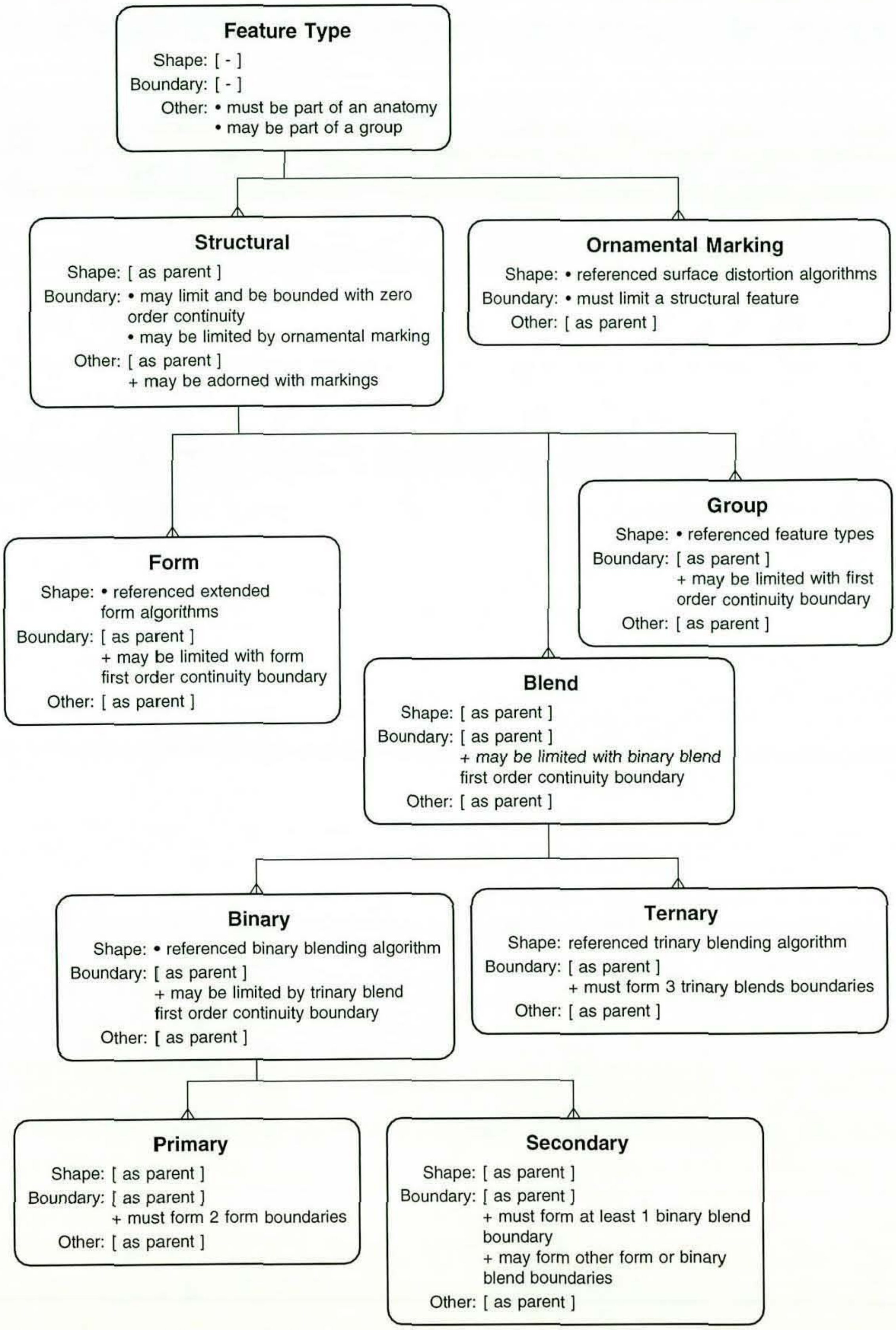


Figure 5-8 Feature Type Inheritance Tree

However, only the structural features need to be considered initially to evaluate the essential design geometry. Consequently, it will be reasonable to insist that all structural features are fully specified at an early stage within the design process. Details of the ornamental features of an anatomy can be left until later, and even omitted where an ornamentation is not needed for a particular design.

The remainder of the inheritance structure distinguishes between the potential for different shapes, and the potential for different boundary interaction. Thus the structural feature types are subdivided into groups, forms, and blends. Structural form feature types are equivalent to the extended form features that control the 'bulk' product shape, as discussed previously. Similarly, the blend feature types are those that achieve a particular aesthetic transition between the boundaries of other structural features.

Groups are shown as a special case of the structural feature type. They share a mandatory unique name, the potential for markings, and the potential for zero order continuity boundaries with other structural features. Like form features they also have the potential for first order 'form' continuity boundaries derived from primary binary blends. However, this belies their true nature as 'super-features'. The sculptured feature definition (Chapter 3 Section 2.1) certainly applies to the group entity.[1] However, the group feature type is really a collection of other lower level features or groups. This reflects a designer's need to have more than one level of feature language - a high level that refers to large complex portions of the design in a simplistic way (e.g. 'blade', Chapter 4 Section 2) and a lower level that reduces complexity and allows control at a detailed level (e.g. 'top«»toe blend', Chapter 4 Section 2).

---

[1] There are also some similarities with the 'set of faces' feature definition employed by Faux and Wingard's grouping features [1986 Faux, 1991 Wingard].

Type references provide a link between a feature type and suitable shapes, and vice versa. There is no shape reference for a group as the group's potential shape is dependent on its constituent features.

It could be argued that the anatomy entity itself is a 'super group', and should be modelled as a special case of the feature group type. Doing this would reflect the potential to design individual sub-assemblies as parts of a larger assembly, for example, the club head as part of the entire club.

However, ignoring the fact that there is no need to model the relatively simple shape of the shaft and grip together with the golf club head in an EFFM system, this approach is considered to introduce unnecessary complexity to the data structure model. Generally, a sculptured product anatomy concerning an individual user is finite and requires a custom interface for manipulation. Implementing an anatomy entity within the structure enforces these limits, and prohibits the complexities and difficulties of providing for any further extension to incorporate higher level assemblies. These are arguably better dealt with in additional dedicated systems, not by making an existing system more cumbersome.

2.2.3. Feature Type Interaction

The feature type interaction structures, shown in Figure 5-9, essentially provide a means for specifying how the feature types define each other's boundaries. For example all structural features have the potential to have part of their boundary defined by an intersection with another structural feature. Only zero and first order continuity boundaries are shown within the structure. This is adequate for the products used to evaluate the method and lies within the current capacity of the DUCT software.

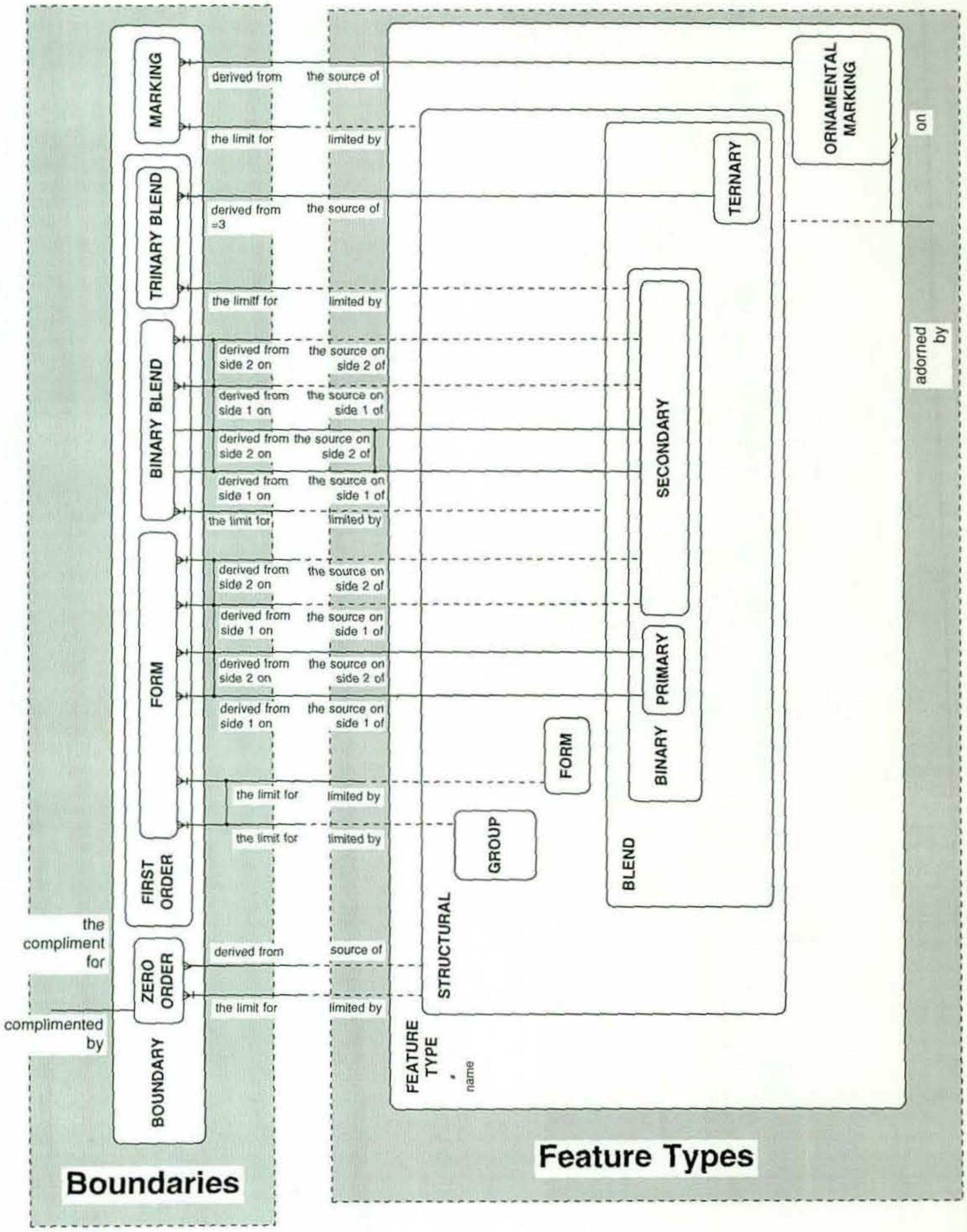
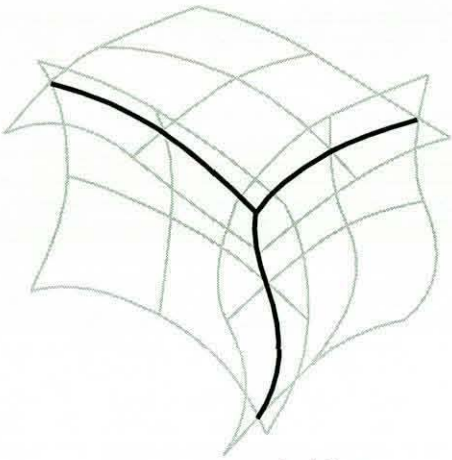


Figure 5-9 Feature Type Interaction Data Elements.

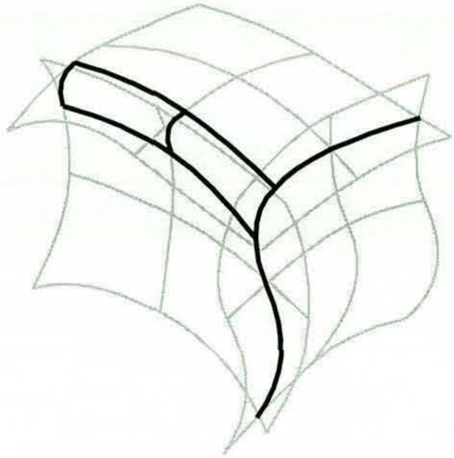
The types of first order continuity boundary are distinguished from each other to provide a logical sequence for evaluating the artefact's geometry. Primary (generation 0) blends are only based on existing forms. Secondary blends (generations > 0) are dependent on at least one other existing primary or secondary blend. Ternary blends are dependent on three existing (primary or secondary) binary blends. Finally, the evaluation of group feature boundaries is obviously dependent on the prior evaluation of its constituent features' geometry.

There is no relationship shown linking a binary blend with its corresponding devolved blend intersection. This could be modelled, but introduces unnecessary complexity. Adding the relationship between the 'Binary Blend' and 'Zero Order' boundary entities would not ensure in itself that the relevant side one and two blended feature groups were related properly to the corresponding boundary. This would have to be implemented within the systems functionality. However, if the intersection is considered as an instance of the blend with zero sectional dimensions, then the devolved blend intersection and its corresponding feature boundaries are adequately modelled by the existing entities and relationships.

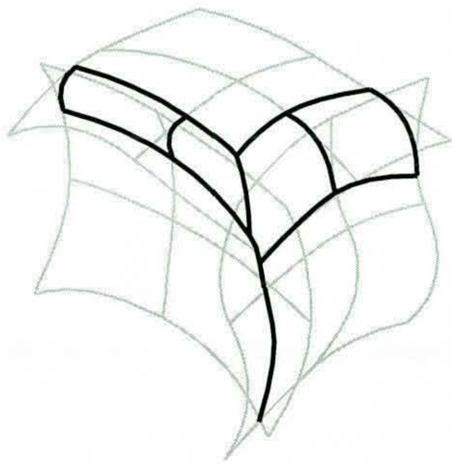
Figure 5-10 shows simple illustrations of the types of blend configuration supported by the model structure. The current data model does not support a single 'vertex' blend of higher order than the ternary case. This is a pragmatic limitation of the research scope, and not a deficiency in the method concept.



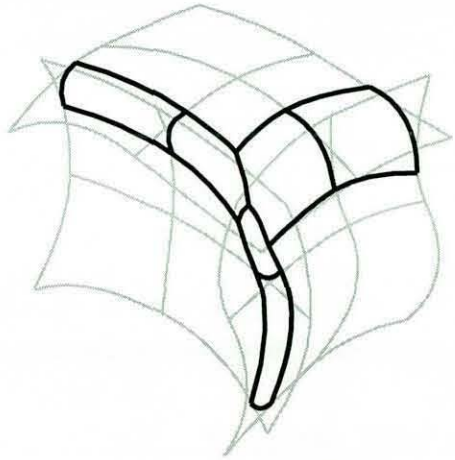
(a) Three extended forms all intersected.



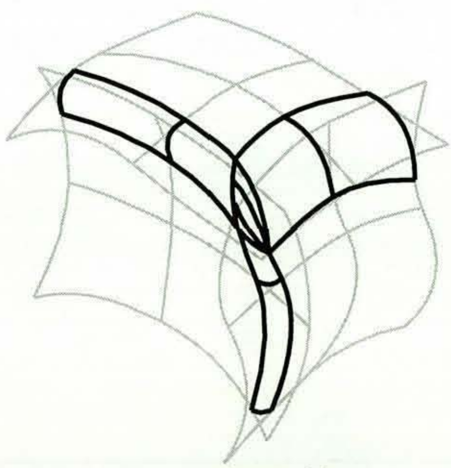
(b) One primary binary blend, blend and remaining forms intersected.



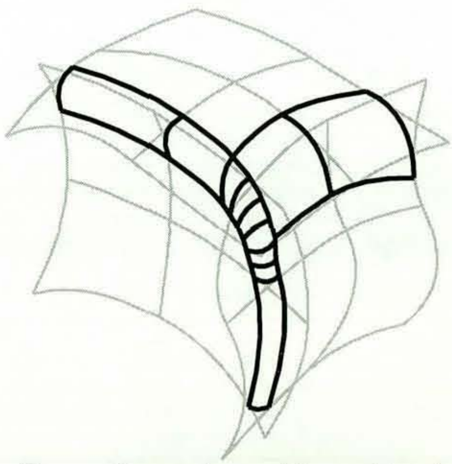
(c) Two primary binary blends, blends and remaining forms intersected.



(d) Three primary binary blends, all blends intersected



(e) Three primary binary blends, one ternary blend.



(f) One primary binary blend, one secondary binary blend

Figure 5-10 Blend Configurations.

2.2.4. Parametric Shape Control

Although the model supports the definition of feature shapes using static surface data (perhaps a digitised region of an existing product), there is much to be gained by the use of parametric algorithms (methods) for shape control. One example is the time saved by automatic generation of a complete set of golf irons from a mid-range club by variation of fundamental club design parameters.

Figure 5-11 shows the data entities and relationships necessary to provide parametric control of the feature's shape. The potential feature shapes are subdivided into form, blend, and marking categories and referenced to suitable feature types using type indicators.

Referring to potential shapes is a problem. There are three options suitable for the designer, depending on his familiarity with the intended system.

- By experience - access to a potential shape is via a previous implementation.
- By example - access to the shape is via a catalogue of visual examples.
- By name - access to the shape is through a unique term.

The latter is certainly desirable within the data structure, as a unique identifier, but is not immediately appealing to a casual user. However, given a unique term for each shape, the proposed model allows for the other two alternatives to be built transparently into the functionality of a sculptured product design system.

Each shape is dependent on a single geometry generating algorithm, which in turn is dependent on parameters specific or local to the shape. Within this research these take the form of parametric surface generating macros, written in DUCT's command language. Currently only constant and variable radius first order continuity binary blending algorithms are supported. Arbitrary section and higher order continuity blending are both areas in which the method needs to be developed.

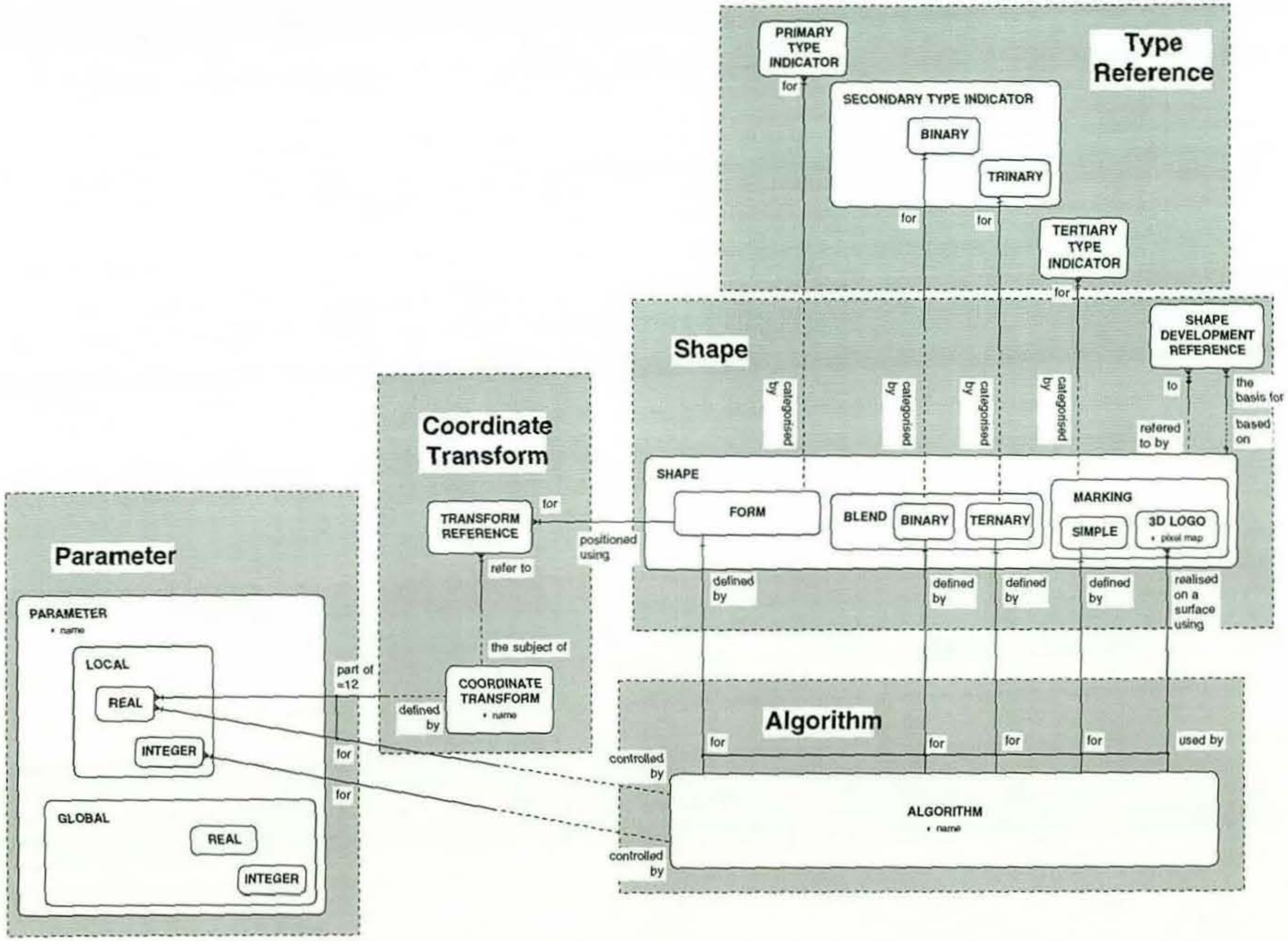


Figure 5-11 Parametric Shape Control Data Elements.

Form feature shapes also depend on a reference to one or more local co-ordinate transforms, which are in turn dependent on 12 parameters (a position and three axis direction vectors in global coordinates). This provides a way to relate the geometry algorithm to a consistent co-ordinate system, and then to position the shape in relation to another (perhaps global) reference system, and so in relation to the other features. The co-ordinate transforms are not uniquely linked to one shape, and so can exist independently as reference points for other transforms.

Generally the parametric form provides a simplified means of manipulating bi-parametric surfaces by reducing the number of degrees of freedom, and interpreting those remaining via meaningful design parameter values. These values need not be presented to the user numerically. In some instances the value will be qualitative, for example somewhere on a scale between 'sharp' and 'soft', where the numeric values of these extremes are predefined. The obvious use of this facility is to allow users to re-configure the design interface in terms of feature parameters relevant to their products. As well as enhancing usability, the resulting features will be constrained to behave in a manner that is relevant to the specific product.

2.2.5. Design Instantiation

Figure 5-12 shows the additional structures required to assign shapes to feature types, and values to the respective shape parameters. It is intended that a design should wholly define a realisable product exhibiting a particular anatomy. To this end it provides the focal point for relating the application of suitable feature shapes to all the associated feature types within the anatomy together with the values assigned to all relevant parameters.

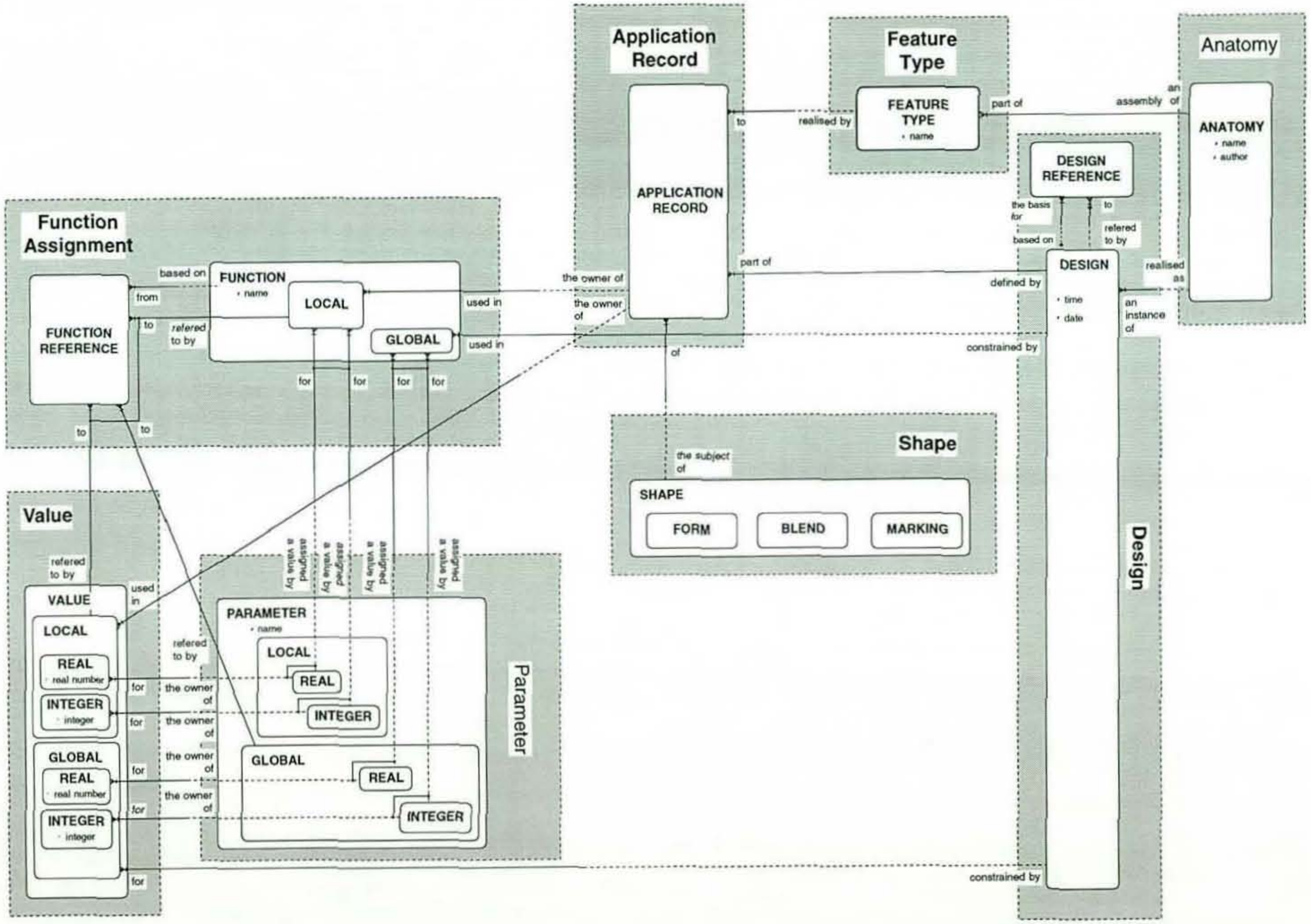


Figure 5-12 Design Instantiation Data Elements

In this model global parameters exist independently, and are assigned values in relation to a specific design either directly or indirectly via a function definition dependent on other parameter values. There is some argument for linking global parameters to specific anatomies - a particular type of product will often vary in relation to a series of identifiable parameters. However, it was thought that this over constrains and so biases design activity. For example, the horizontal distance between the sole's horizontal plane tangent point and the toe extremity on a golf club is commonly specified as a design parameter. However, the suitability of this parameter for controlling the design of all clubs of a particular anatomy is dependent on the sole having one tangent point, which it may not.

Local parameters are assigned values in one of two ways, by either:

- direct value assignment, in relation to the application of the shape to a particular feature type within a specific design.
- function assignment, in relation to the application of the shape to a particular feature type within a specific design, and dependent on the values of other parameters specified within the same design.

The latter allows the designer to specify the behaviour of features both in relation to global parameters and other features. There are no entities within the model dedicated to the controlled variation of a design through a product range. However, it is intended that this facility will be added, and the current model is sufficient to support this.

2.2.6. Geometric Representation

A geometric representation of a design is achieved by links to DUCT surface entities, as shown in Figure 5-13, although the principles are applicable to surface modellers with equivalent capabilities.

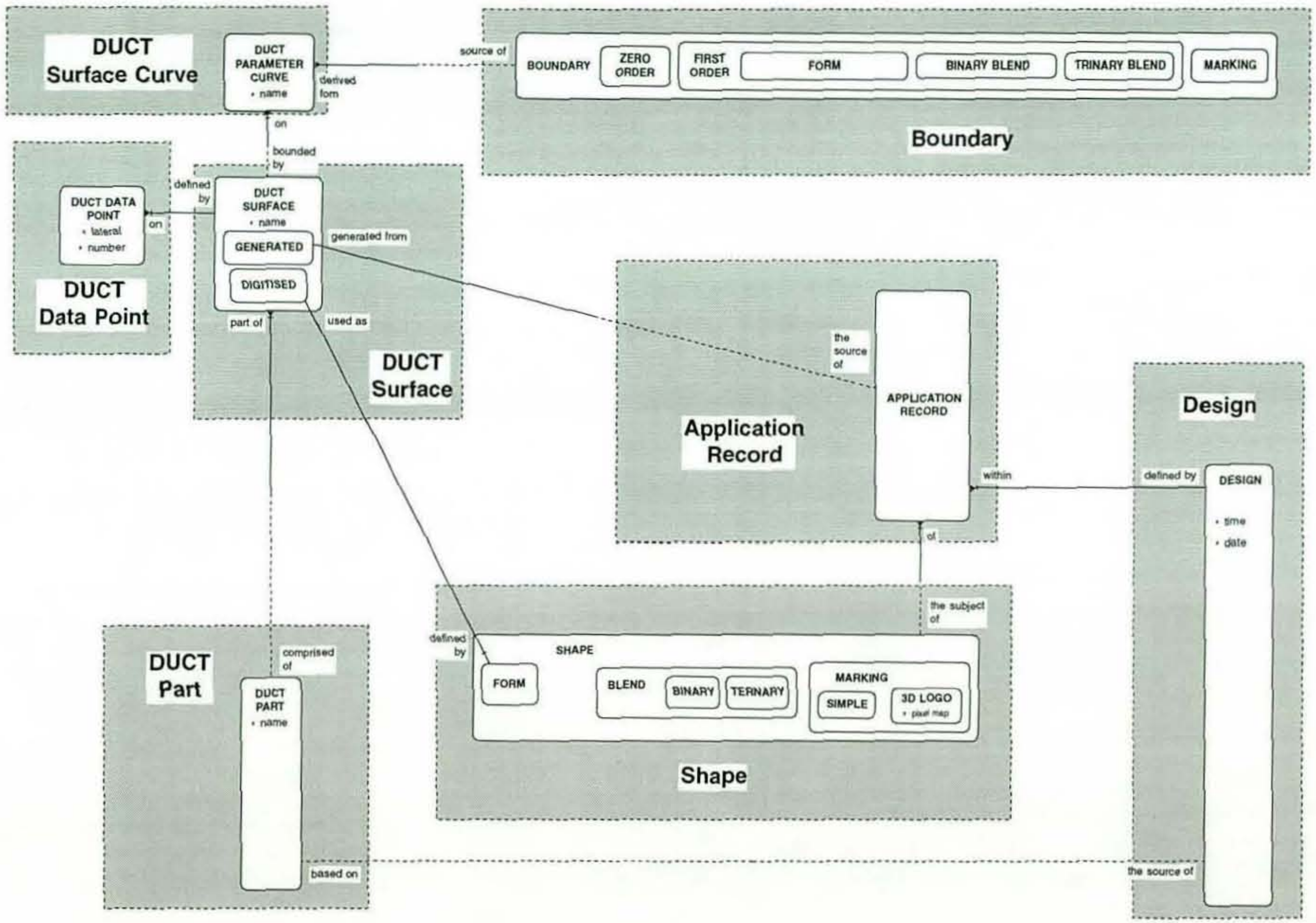


Figure 5-13 Geometric Representation Data Elements

The potential for a form feature to be based on a bi-parametric surface instead of a parametric algorithm is shown in this model by the alternative relationship with a DUCT surface. This is intended to be used to quickly capture existing designs and allow the use of their feature shapes for hybrid design. However, without resort to interactive surface editing[1] only the orientation of the feature can be altered. This limits the usefulness of the feature, and ultimately indicates the need for a suitable parametric alternative to be developed if the feature shape's use justifies it. Extrapolating the digitised surface for use as an extended form feature also gives rise to some problems, such as wrinkles and surface convolutions. Some care, and experience in laying out control point nets, are required when capturing surfaces to avoid this.

2.2.7. Product Classification

Figure 5-14 shows the structures used to classify both anatomies and designs. The intention is to allow the user to develop a classification for cataloguing and accessing existing design information. Design or anatomy membership of more than one category is possible, to allow for a realistic mix of different classifications (e.g. performance related such as '9 iron', and market name such as 'Maxfli Synergy'). Although membership of more than one category poses potential problems in general, in this case multiple inheritance will not cause inconsistencies to arise as the classifications add orthogonal information. The multiple inheritance chain could be made single line, however this would pre-judge the order of assignment of characteristics which in turn would restrict design freedom.

---

[1] There is no reason why a universally applicable general parametric surface feature algorithm (NURB, Bézier or based on another surface type) together with interactive surface editing routines should not be associated with all EF feature types as a valid shape algorithm. This could be used as the basis for all digitised features. However, regularly using and adjusting a digitised feature in this condition is not the most efficient long term solution, as it prevents the potential gains in efficiency available from prescribing more specific shape behaviour.

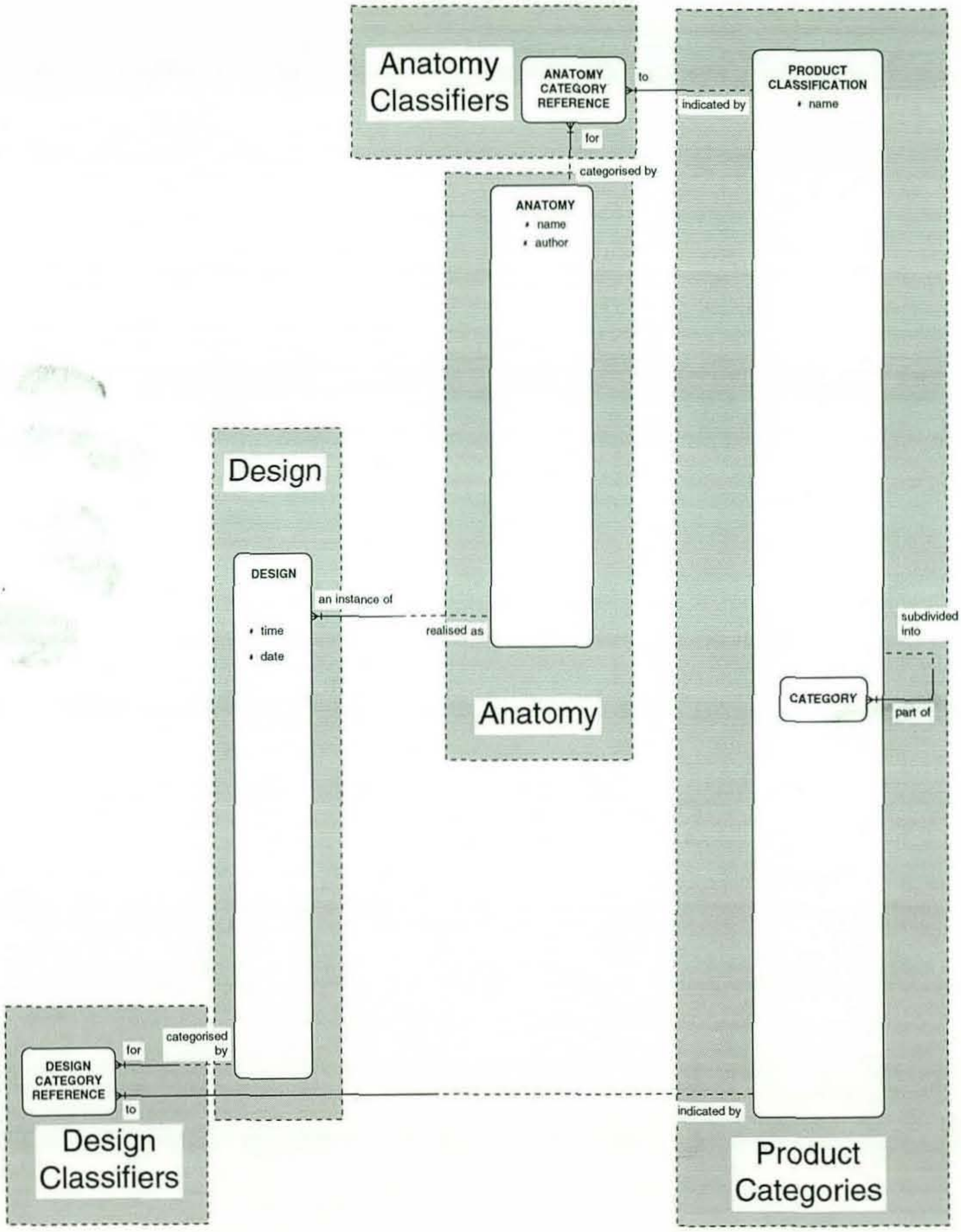


Figure 5-14 Product Classification Data Elements

It is intended that the anatomy should provide the means by which feature types are related to define a complete artefact. As such the anatomy could be defined as a unique collection of feature types. This poses some practical problems for storing and accessing anatomies and features. The feature types only make sense in an anatomy context, and a complex anatomy would be cumbersome to identify. Another alternative would be to uniquely identify the anatomy via product categorisation. In a large product range complex classifications would also be too cumbersome. Consequently, it seems justifiable to require each anatomy to be appointed a unique name, and relax its dependence on classification for uniqueness.

To this end the data model supports classification rather than enforcing it. In particular, the arguably logical classification of a design by a product category subtype characterised by the associated anatomy is not mandatory. However, it may be that in some instances the user would benefit from this kind of constraint. It is intended that the link between an anatomy and a design is via a direct relationship, not by a category association - although logical use of design and anatomy classifications should provide the means for retrieving either easily. To this end, the product groups should be seen as a means of holding user related terminology and references to anatomy, design, and ultimately feature libraries. It is expected that the user will make intelligent use of this facility. However, it is likely that some functional constraints will be introduced to reduce error in application systems.

Figure 5-15 shows a typical golf club product classification tree, and how this could be used to assign a product description to a particular design. It should be made clear at this point that Figure 5-15 demonstrates a spanning tree over a graph of relationships and properties, a simple example of the relationships which exist is that the selection of a 'forged back' implies forged manufacture. Typically there would be many spanning trees, each denoting a particular viewpoint.

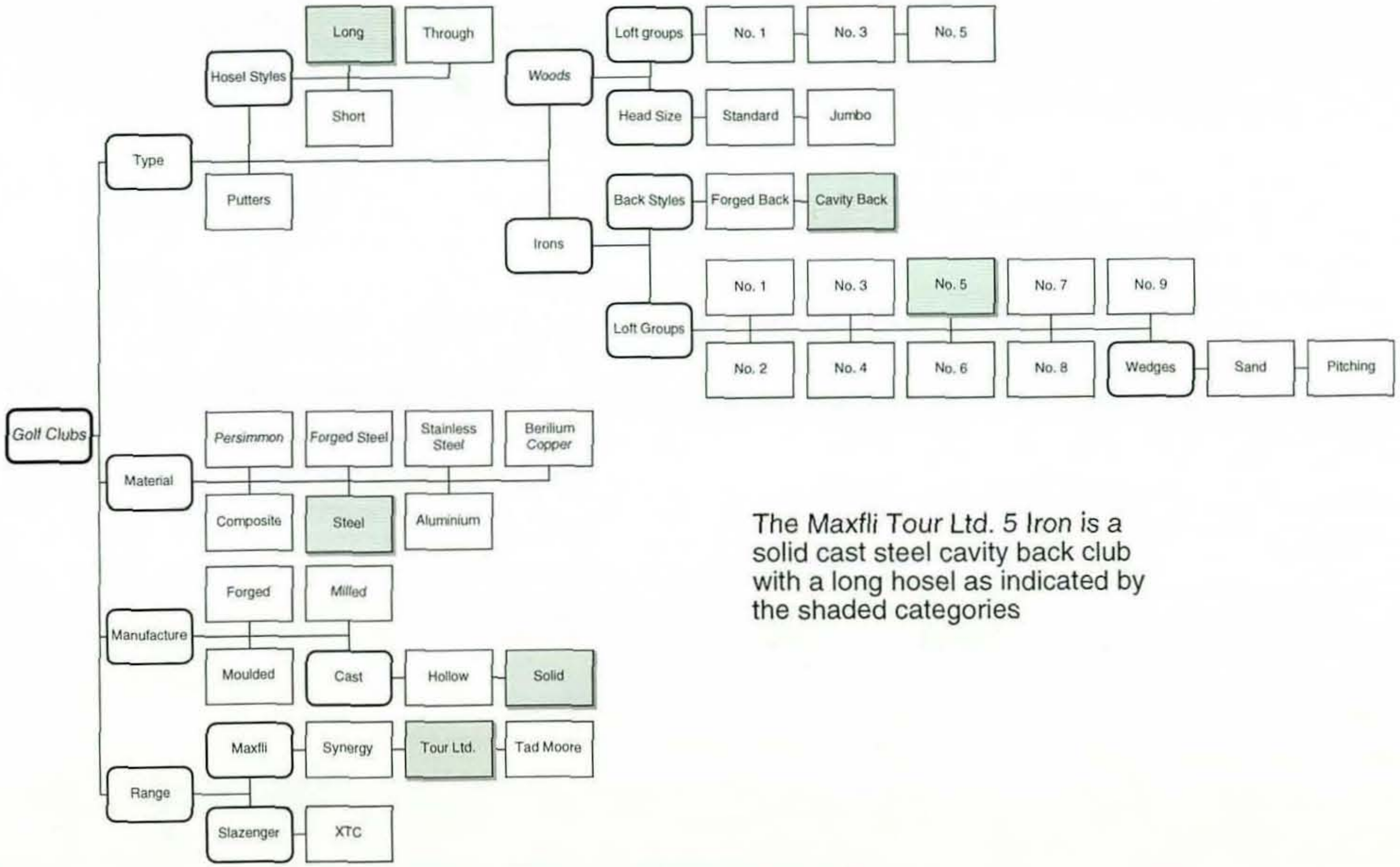


Figure 5-15 Product Classification Hierarchy

The possibility of many different viewpoints is crucial in exploring the relationship between design and manufacture. The model presents an initial language for describing design concepts with the elements of the language consisting of sets of features and relationships between them. It is likely that transforming the groups of features into a corresponding manufacturing language would produce a very different spanning tree associated with manufacture. At the moment the assignment of terms associated with manufacture, such as materials and processes, is only a means of recording design intent, and is not enforced. This would not be the case where design and manufacturing engineering are to be concurrent, but was sufficient to support research in the design domain.

2.3. Revised Model

2.3.1. Artefact Anatomy and Shape Dependency Revisions

The revised data model shown in Figure 5-16 is not fundamentally different from the original. The most significant changes reflect a simplification of the way in which parametric shape control data is stored and consequently the structures through which a design is instantiated. The most obvious change in the complete model, apart from reduced complexity, are the entities and relationships establishing a feature type's dependency on other entities to establish shape and positional behaviour.

Figure 5-17 shows these model elements in isolation. The 'anatomy' and 'feature type' super entities remain unchanged, as does the entity establishing group structures within the anatomy. However, the primary, secondary and tertiary type indicators that establish the relationships between a feature type and suitable shape algorithms now share a common super entity: the 'type indicator'. From the parent entity, the three type indicators inherit the possibility of an additional relationship with a new entity, the 'dependency indicator'. This entity, and its associated relationships, make it possible to record a feature algorithm's dependency on the instantiation of other structural features within a given anatomy, to establish shape and or position.

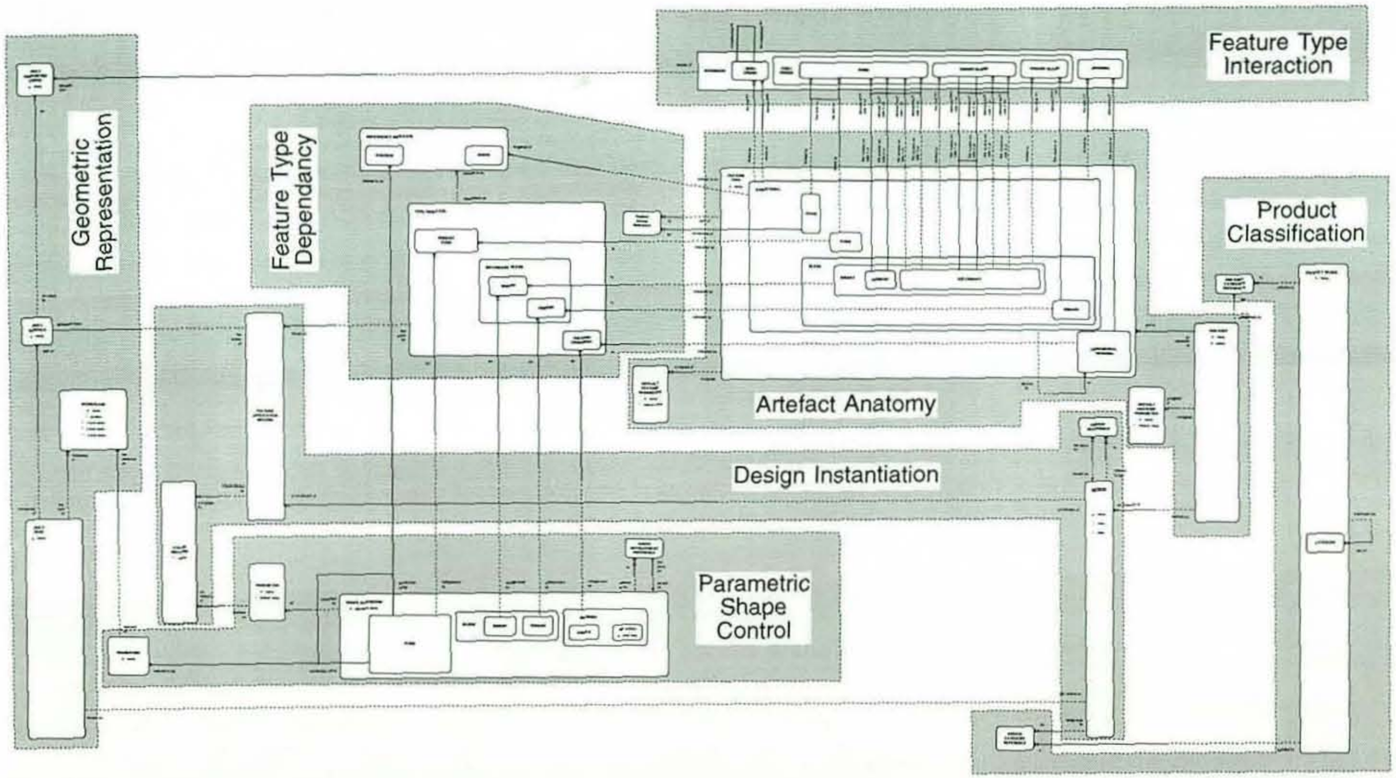


Figure 5-16 Revised Data Model.

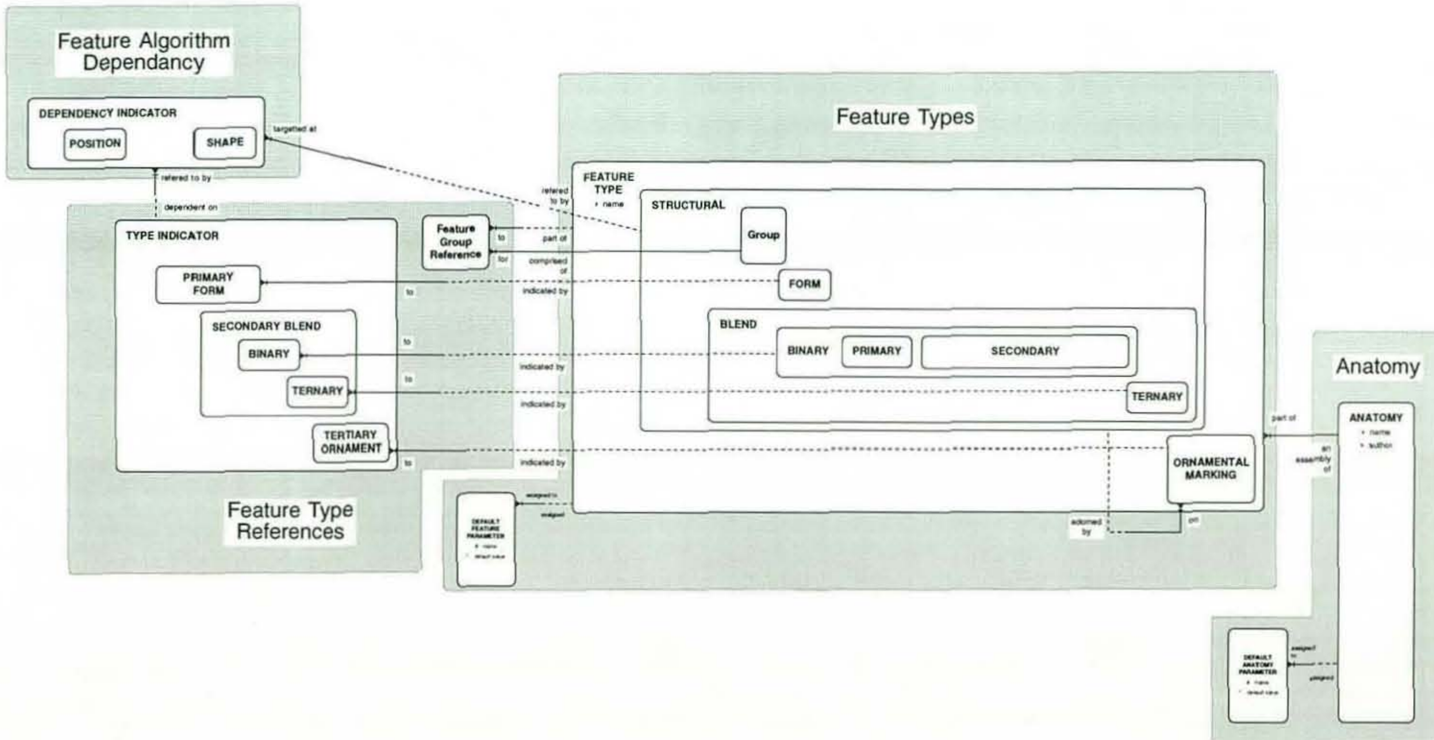


Figure 5-17 Revised Feature Type Dependency.

For example, an iron club's cavity wall profile may be defined by a 2 dimensional curve, but to ensure that this shape is achieved when blended with the club back feature, this curve must be mapped onto the actual 3 dimensional back surface before developing a suitable draft surface for the cavity wall. Thus, it makes sense to produce a shape algorithm that is dependent on the back feature type's instantiated shape, and recording this dependency by reference to the back feature type within the golf club anatomy. Similarly, a cavity base feature shape algorithm could be made conveniently dependent on the club face for positioning, perhaps to ensure a particular material thickness.

The 'ornamental marking' feature type could have its adornment relationship to other structural feature types in the anatomy modelled using the 'type' and 'dependency' indicators, but this has been left unchanged to better reflect the mandatory nature of this relationship. The 'type' and 'dependency' indicators allow algorithms to be developed that are dependent, but do not insist that this is the case for all suitable shape algorithms. This is useful. For example, it may not be necessary to insist that all cavity wall shape algorithms are dependent on the back feature. Some could be independent, perhaps to allow a common insert to be used in the wax injection moulds for the cavity details in an entire set, whereas others could be dependent on the blade profile features as well to ensure the cavity profile mimics the blade profile.

It could be argued that dependent shape algorithms are ultimately dependent on features in a particular anatomy context and so on a particular anatomy, thus destroying the many to many relationship between feature types and shape algorithms. However, this argument ignores the potential to write adaptive algorithms that react to the anatomy context by accessing the dependency indicator to determine the feature(s) in the specified anatomy context it is to depend on. It also ignores the possibility of dissimilar anatomies sharing equivalent feature groups that make the shape algorithm relevant to both anatomy contexts. This is an important aspect to maintain within an EFFM based design system to minimise algorithm redundancy or system structure changes as an industry's product, and so its anatomy, evolves.

2.3.2. Revised Shape Parameter Structures

The most striking change to the parametric shape control structures isolated in Figure 5-18 is the combined shape and algorithm entities. This is achieved by removing the potential for the shape of 'form shape algorithms' to be dependent on an existing DUCT surface instead of an algorithm. Instead of incorporating digitised EF features as DUCT surfaces these are now to be embedded in a suitable shape algorithm that regenerates the digitised surface. These static regenerating shape algorithms require no external shape parameters, only internal control point positional data. In general the form shape algorithms require both, and these are catered for by direct relationships with simplified transform (mandatory) and parameter (optional) entities, except where the algorithm is dependent on another 'feature type' for position. In this case the model reflects the option of a mandatory 'position dependency indicator'.

The coordinate transform is now directly related to the shape algorithm by a many to one relationship. This reflects a simplification of the use of coordinate transforms. In the initial model they were allowed an independent existence, to make it possible to have 'virtual datum features' within a design referred to by several shape algorithms. While these are arguably desirable, they are an unnecessary complexity. Implementing a system with the potential for manipulating different datum sets depending on the choice of feature shape algorithm was thought to be too cumbersome and too much to attempt in an initial EFFM prototype system. It is arguably easier, and more transparent to the user, to implement shared datums through establishing feature algorithm dependency rather than what was effectively a different class of anatomy feature.

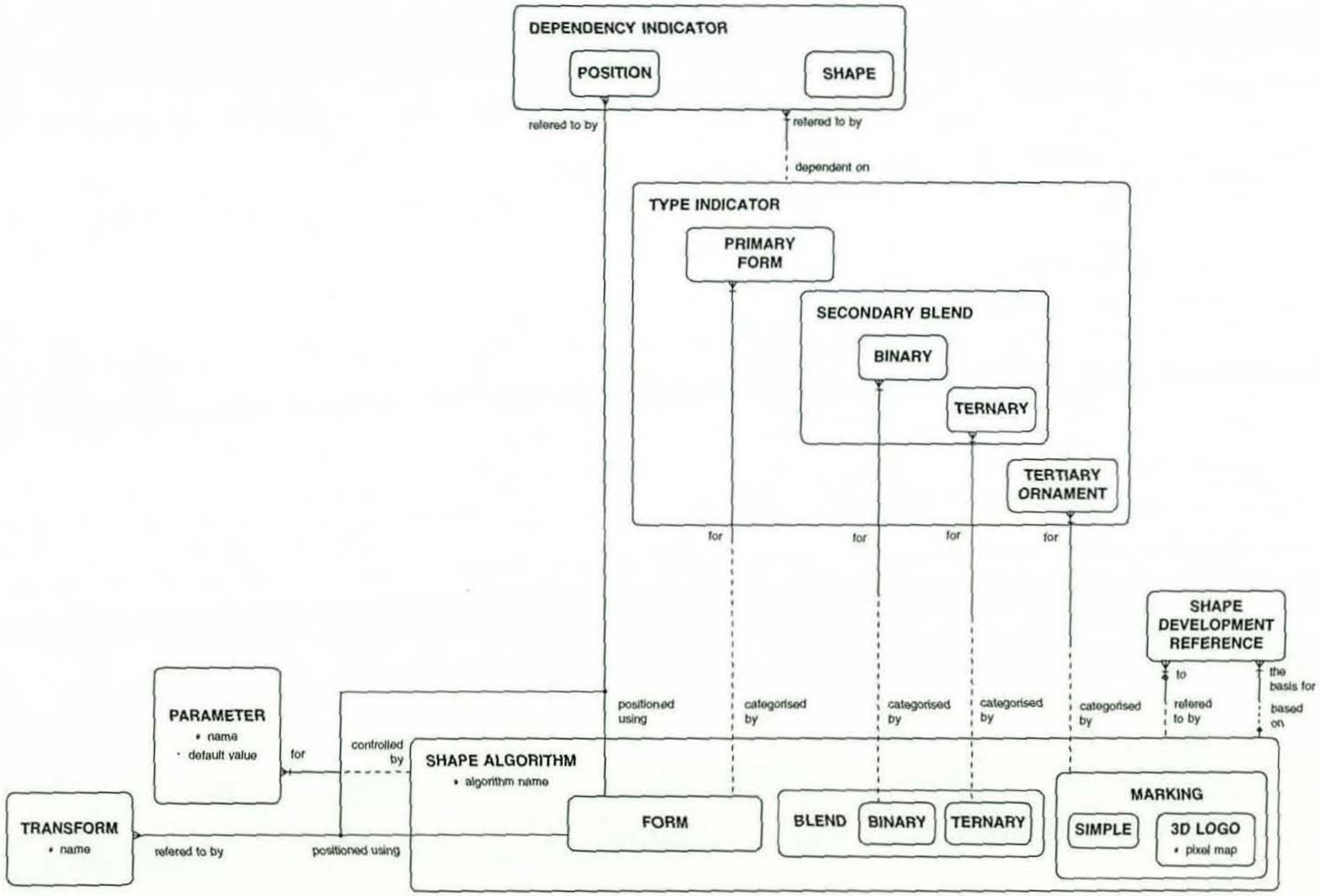


Figure 5-18 Revised Parametric Shape Control.

The transforms are still available as virtual datums, but as part of a specific structural feature (on which others may depend) rather than as a 'virtual feature'. Consequently the system would still support an interface allowing the user to move the virtual datum as a means of editing features.

The transform entity no-longer has independent parameter values associated with it. The position and orientation of a particular transform are now the result of the parameters input to its parent shape algorithm.

The 'anatomy' and 'feature type' entities may also have 'default feature parameter' and 'default anatomy parameter' entities attached respectively (Figure 5-17). Where a shape algorithm is based on a similarly named 'parameter' the default value can be resolved from these two new entities according to the specific anatomy context. Otherwise if a default value is attributed to the 'parameter' entity this may be used instead.

Although it is possible to implement this functionality within an RDBMS based system, this is an obvious application for class attribute inheritance within an OODB based system. The result is that the user may specify custom default behaviour within a multiple anatomy system rather than re-specifying parameter defaults each time one of the available anatomies is used.

2.3.3. Revised Design Instantiation and Geometric Representation

Figure 5-19 illustrates the further simplification of the parametric control structures. The feature application record is now associated with a particular type indicator, instead of both shape algorithm and feature type directly. This is a more direct means of ensuring the correct pairing of algorithm and feature type within the design's anatomy context.

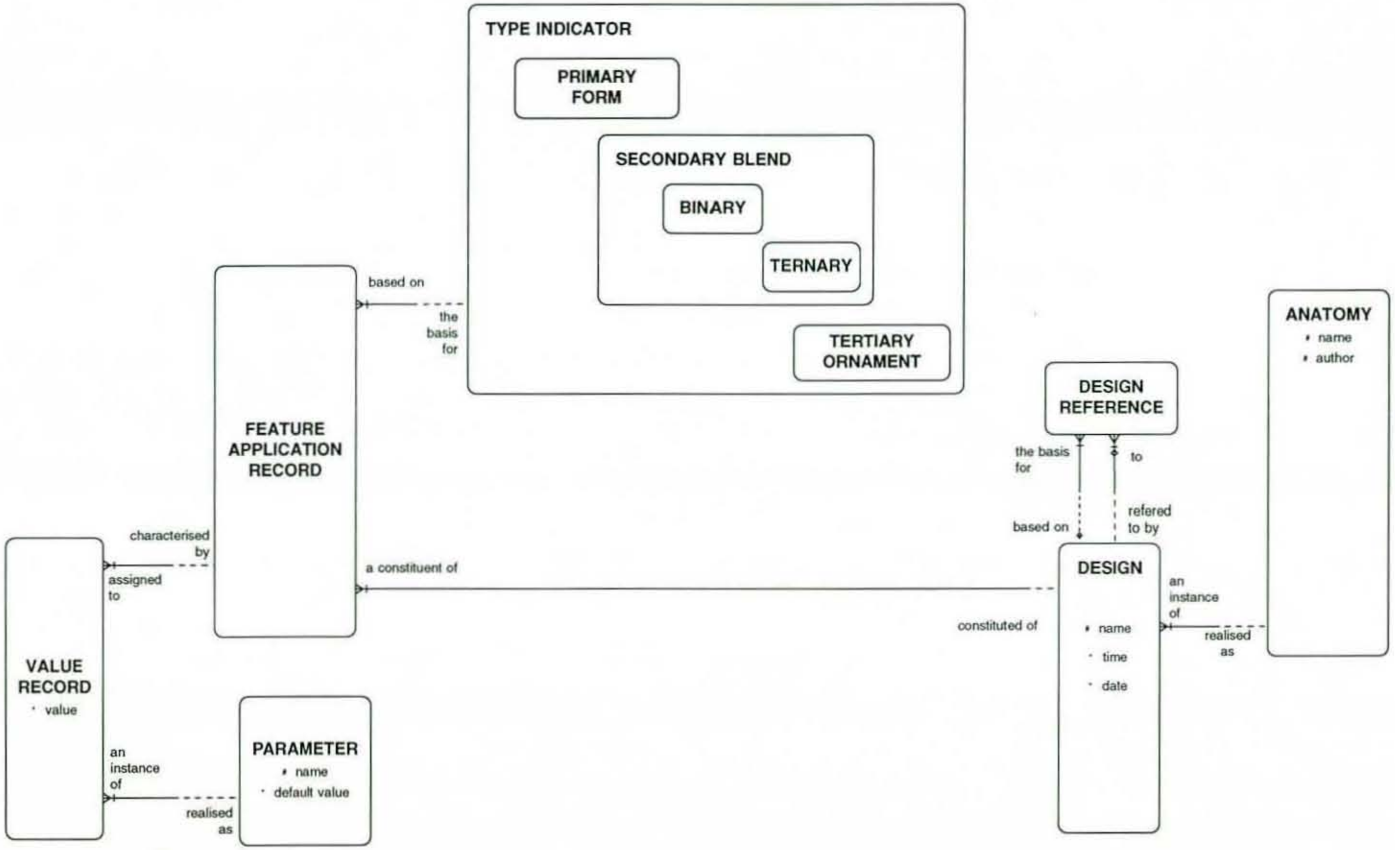


Figure 5-19 Revised Design Instantiation.

The function and global parameter entities have also been removed. Instead, a value for a shape algorithm's parameters is now directly associated with the application record. The initial model possessed these entities to allow the potential for user configured feature shape and position inter-dependency. Again, this was thought to be unnecessarily complex and too much to achieve in an initial implementation. Instead, the functionality of global parameters can be achieved (with less flexibility) by suitable feature algorithm dependencies. The facility for complex parametric dependency embodied in the function entity is then better incorporated within the shape algorithms themselves.

This does mean that shape algorithms need to be implemented carefully so that they have the correct properties needed by other algorithms dependent on their output. For example, for a cavity base to be successfully dependent on the loft and lie parameters of the club face, all club face algorithms must have associated loft and lie parameters for these values to be extracted from the application record. Given that design activity is already constrained by the use of a particular anatomy, the benefits of using feature algorithms adapted to an anatomy's parametric context in this way is now thought to outweigh the hindrance of the additional constraint.

In the case cited in Section 2.2.5, of anomalies in determining a golf club sole's tangent point, if all sole algorithms have suitable parameters associated with them, then the tangent point position can be determined without ambiguity by interrogating these properties rather than by analysing the geometry. This allows a meaningful interpretation of potential geometric anomalies, such as virtual datums, to be embedded in the algorithm definition.

The relationships between DUCT geometric entities and the EFFM data elements are little changed, as shown in Figure 5-20, except that a transform instance is recorded by a DUCT workplane with associated properties, further negating the need to associate independent parameters and values with the transform entity.

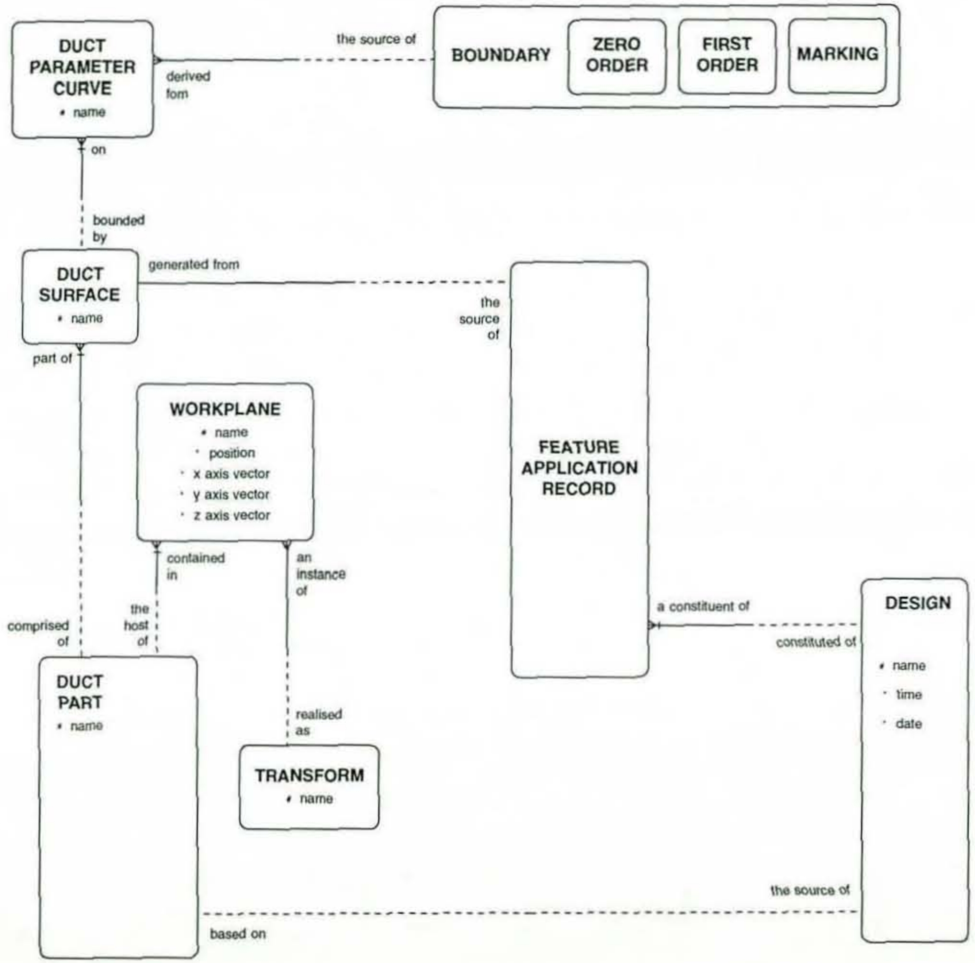


Figure 5-20 Revised Geometric Representation.

2.3.4. Anomaly Avoidance

To avoid anomalies in the data stored using the data model structure, some rules must be embedded in the system software that are not enforced by the data structures. For example:

- Generally, any 'dependency indicator' must refer to structural features of the same anatomy as that implied by the associated 'type indicator'. For any 'position dependency indicator', referred to by a particular 'shape algorithm', the related 'type indicator' must also correspond to the same 'shape algorithm'.

- For any 'feature application record', the 'anatomy' implied by the associated 'type indicator' must be the same 'anatomy' on which the 'design' is based.

- All 'feature types' corresponding to a particular 'boundary' must be constituents of the same 'anatomy'.

- All 'values' associated with a particular 'feature application record' must be for 'parameters' of the same 'shape algorithm' as indicated by the related 'type indicator'.

- Each 'group reference' must refer to features corresponding to the same 'anatomy' as the associated 'structural group feature type'.

3. Interface Functionality

It is immediately obvious that the fundamental requirement of any commercial EFFM based sculptured product design system is the facility to specify a product anatomy and its associated features within a generic EFF modelling framework. However, to consider the requirements for a generic product definition facility before establishing an EFF modelling framework was thought to be 'putting the cart before the horse', and considering both together was thought to be too nebulous a problem. Therefore, a fixed anatomy was assumed, and the elementary functional interface requirements for manipulating this anatomy analysed.

Figure 5-21 shows the top level functionality for the system, based on manipulation of a product design library.

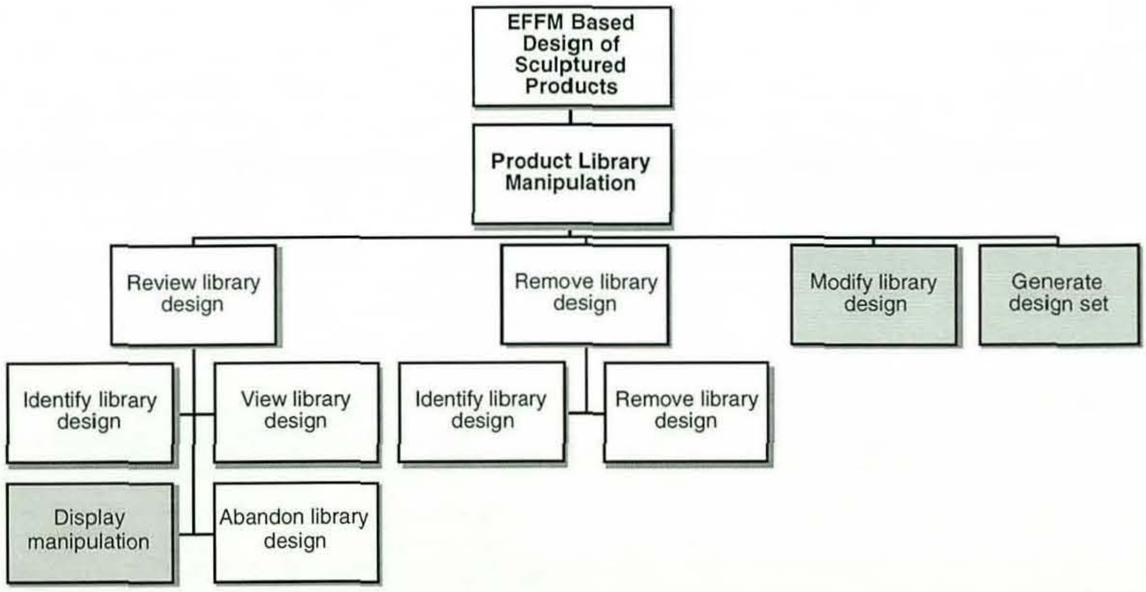


Figure 5-21 *System interface functionality*

Four major activities are identified:

- Reviewing a design.
- Removing a design from the library.
- Modifying a design.
- Automatically generating a set.

Figure 5-22 shows the functionality needed to manipulate a graphical display of the product, rendered or wireframe, at the design review and as part of the design modification functionality (Figure 5-23).

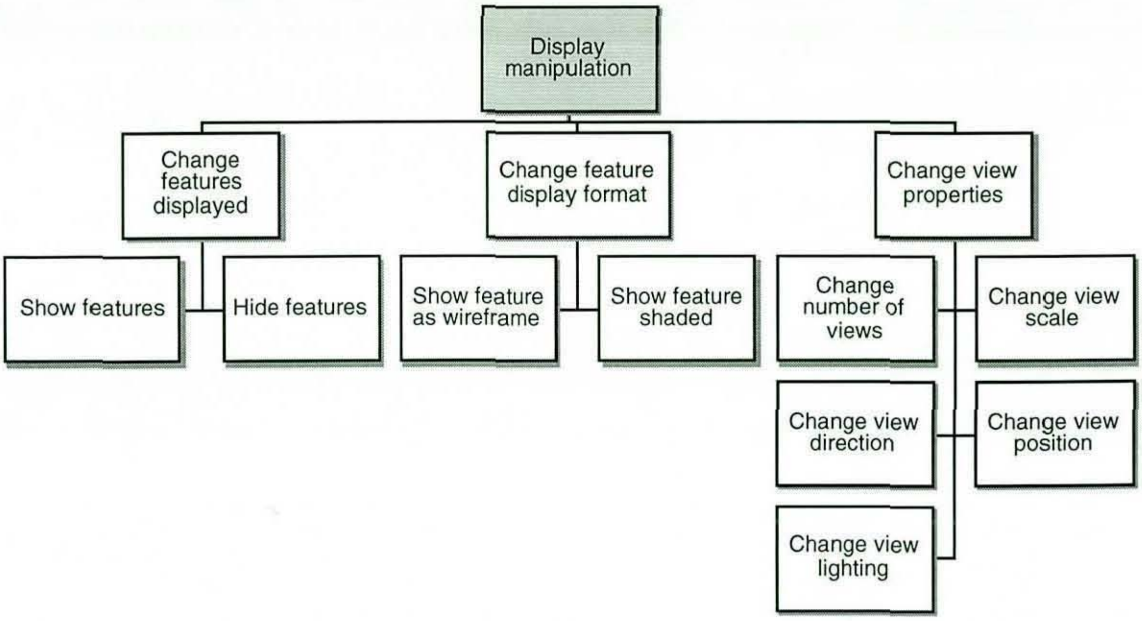


Figure 5-22 Display Manipulation

Figure 5-23 shows design modification functionality divided into 'bottom up' (new design from scratch), 'top down' (new design from template) approaches for new design development as well as the facility to modify an existing design. All three of these support hybrid design activity at the feature manipulation level, where existing feature variants can be introduced from the feature library (Section 1).

Figure 5-24 shows the design manipulation functionality required by all three design development approaches in Section 1. Essentially, for each feature type in the anatomy a suitable shape must be selected, and then a variant (default or existing) introduced. Each feature may be adjusted to suit the designer's objectives, or removed and replaced with an alternative variant or shape if necessary.

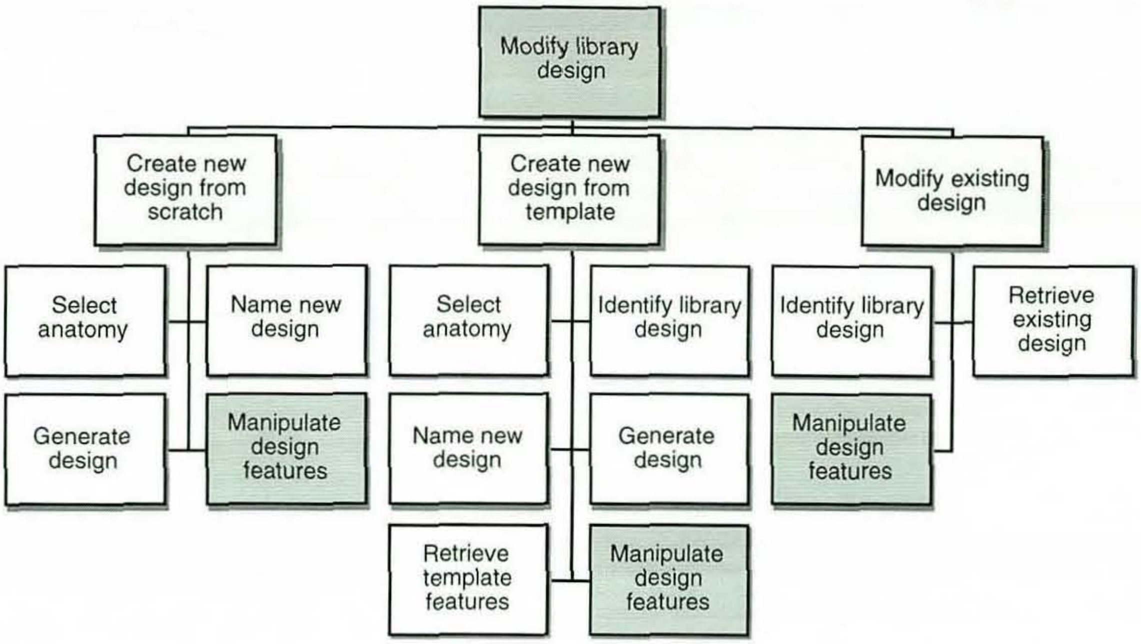


Figure 5-23 Design modification functionality

Ideally, as each feature's shape is defined or adjusted the system should automatically resolve the blend and bounding relationships to produce the explicit fully trimmed product geometry. However, given that this takes a significant amount of time using modern workstations[1] this causes an undesirable delay before the effects of a design change can be visualised. This delay can be postponed by requiring the user to initiate trimming and maintaining two versions of a feature within the design model: an existing trimmed version and the proposed revised version. By displaying both the user is given the opportunity to visually predict the proposed change's likely effects before committing themselves to the model processing time delay.

[1] ~1 minute using a 150 MHz R4400 Silicon Graphics workstation rated at 97.7 SPECfp92, 91.7 SPECint92.

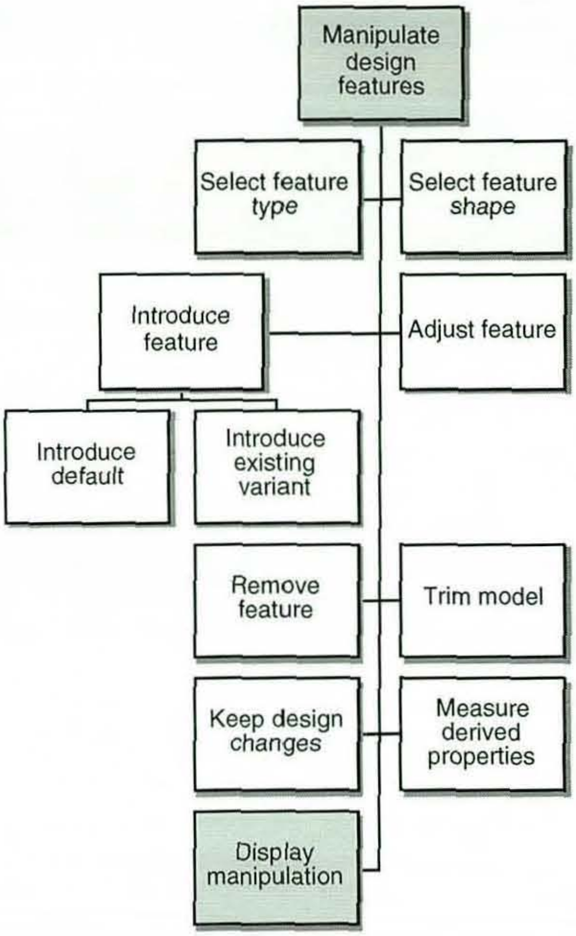


Figure 5-24 Design manipulation functionality.

Figure 5-25 shows the interface functionality required to generate a set automatically from an existing design given the set parameter variation criteria. A facility to compare the set designs concurrently is included to allow the user to evaluate the results.

As a whole this functionality scheme defines the requirements of an elementary interface adequate for a prototype EFFM system.

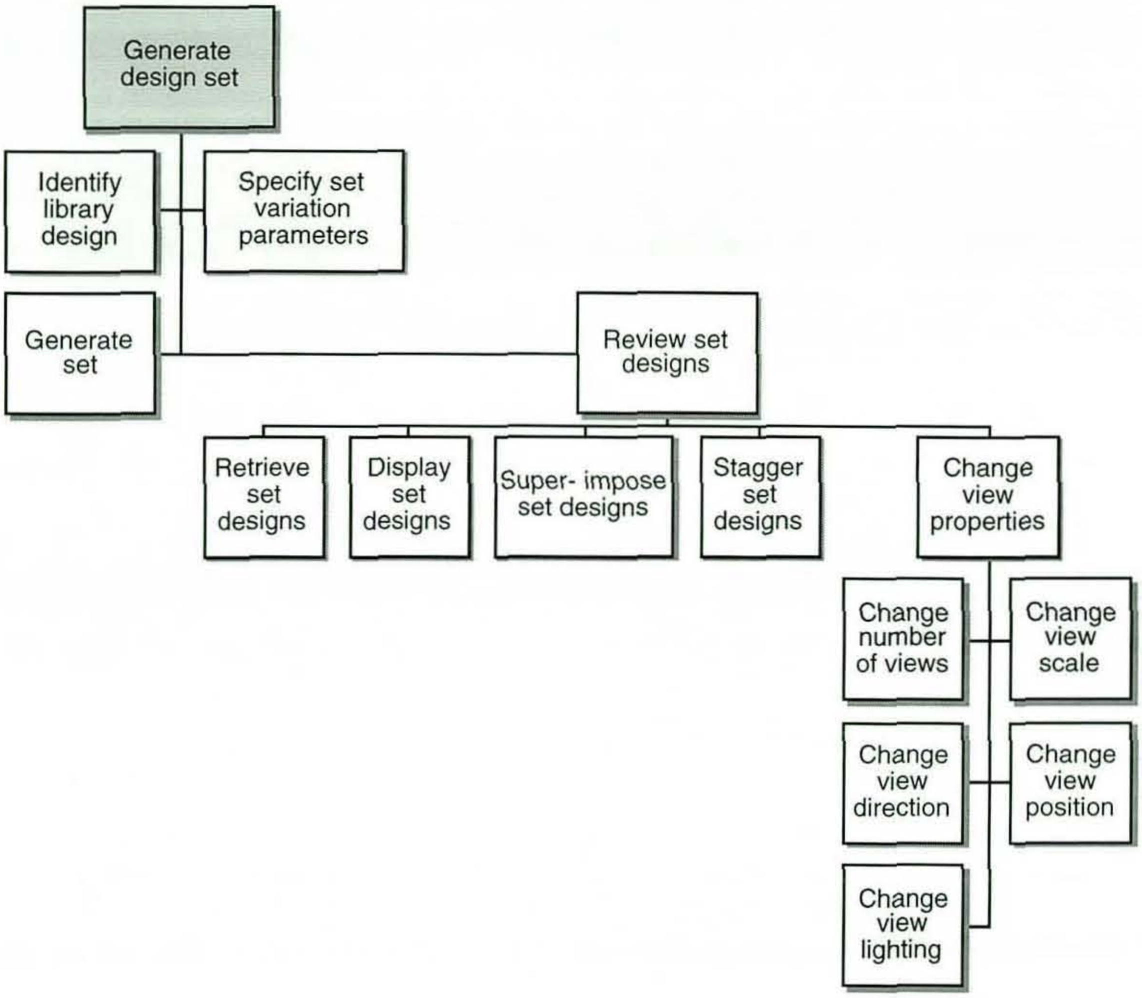


Figure 5-25 Set generation functionality.

CHAPTER 6. INITIAL SYSTEM IMPLEMENTATION

1. DATA STRUCTURE IMPLEMENTATION AND SYSTEM PROGRAMMING

1.1. A 'Hard Wired' Approach

The initial system implementation was achieved using DUCT 5.0 and 5.1 releases. Chapter 1 Section 3 describes facilities available to the user in these versions, but they were inadequate for a full implementation of the data structures described in Chapter 5.

As mentioned previously, the internal DUCT RDBMS was unavailable for user customisation. According to Delcam engineers it would have required additional code for the DUCT database and recompilation of the entire DUCT program to affect any changes to support an EFFM system. Delcam were understandably reluctant for the research to adopt this approach unless absolutely necessary, and until the method was proved further. Using an independent third party RDBMS with suitable input and output channels to DUCT was considered, but presented similar problems because at the time DUCT had no facilities for synchronising, and an almost non existent means for communicating with external processes.

DUCT's fundamental limitation was the lack of user definable permanent data entities within the command and macro programming language. Although during any single session it was possible to assign values to a limited number of system parameters and a virtually unlimited number of user defined lists (8 character names or integer series) and registers (20 characters of text or a real number series) these were forgotten as each session ended. DUCT's text file manipulation capabilities at the time, in essence the facility to record and run a series of DUCT commands or to record calculation results to a file, were also inadequate to overcome these limitations.

Thus, to implement a prototype EFFM based system using these releases of DUCT a 'hard wired' approach was pursued. The data structures were implemented, a little obtusely, in 5 ways:

i) Minimised user interface functionality.

ii) Temporary data registers and lists, for run time parameter values.

iii) Permanent parameter value data stores using 'dummy' geometry elements.

iv) Shape algorithm coding.

v) Custom model assembly or trimming routine coding.

These are described in more detail in the following sections.

1.2. Minimised User Interface Functionality.

A single anatomy, and single set of representative shape algorithms for each feature type, were implemented instead of the structures to represent any anatomy and suitable feature shape/type pairings. Apart from the effect this had on the user interface functionality (removing the need to select a specific anatomy and the shape algorithms suitable to its feature types, Chapter 5 Section 1.3), this allowed the other system routines to be written assuming a particular data set, instead of providing the unpopulated data structures and the routines to populate and extract information from them.

The product classification structures for different anatomies were therefore unnecessary, in that all designs produced by the system were cavity backed irons. The potential for other classifiers concerning the type of iron represented by the anatomy or any particular design was omitted.

1.3. Temporary Data Stores for Run Time Parameter Values.

When initialising the prototype EFFM system a command file is activated to initialise a series of custom 'run-time' registers and lists containing default parameter settings for all the feature algorithms. If used these values would replicate a typical 5 iron design, similar in style to Dunlop Maxfli's Tour Ltd. club. This particular design consequently acted as a point of reference for all design activity.

The registers also contained space for fast access to user specified parameter settings. These are updated when a DUCT part is retrieved, to reflect the status of any feature instances in the design, or when a proposed feature value is changed interactively by the user.

No global parameters were implemented, although several feature algorithms were controlled by a commonly named parameter, such as loft, lie or offset. This allowed the presence of global parameters to be simulated by using suitable interface routines for each pseudo-global parameter to manipulate all features controlled by that parameter concurrently.

1.4. Permanent Parameter Value Data Stores

To overcome the problems of cataloguing golf club designs produced using the system, and storing the parameter values used to generate a specific feature's shape together with its evaluated geometry in a particular design, 'dummy' geometry entities with suitable characteristics were generated within the DUCT database.

A dummy 'library' DUCT part was generated and used to contain dummy surfaces named to represent the golf club designs produced by the system. A weakness in the DUCT database meant that it was impossible to query the existence of a design as a DUCT part, even though there was logical parity between the design entity, as an assembly of feature instances, and a DUCT part as an assembly of DUCT surfaces. By maintaining the library part surfaces as a record of a design's presence it was possible to query the part database indirectly by querying the surfaces in the library part.

Although only the name property of the surfaces was used in the initial prototype, it would have been possible to assign data points to each surface with coordinate values corresponding to parametric characteristics of the particular design. This would have provided a fast means for interrogating the design database for designs matching specific parametric criterion. For example, if the x coordinate of point 1 on lateral 1 of each of the dummy design surfaces always corresponded to the loft parameter for the associated design, searching for designs with a particular loft would be more quickly achieved by interrogating the dummy design surface geometry in the library part, than by retrieving all of the actual design assemblies individually and interrogating their face features.

Within the actual design part the DUCT surface names corresponded to the feature types in the single anatomy implemented. Conveniently, this meant that actions on any given feature would be associated with actions on a DUCT surface with a similar name. Starting with an empty part, a design could be specified by introducing a surface representing a single instance of each feature type, and then trimming them to produce a valid club shape. However, to modify an existing design or feature, it was apparent that it would be useful to have both the existing trimmed and proposed untrimmed feature side by side for comparison. Providing this facility means that the time spent iteratively refining a design, re-trimming the model after each change, can be reduced by predicting a modification's acceptability using a visual comparison.

In order for two versions of any given feature, an existing trimmed version and an untrimmed proposed version, to coexist in the same design part the two surfaces were named slightly differently. The trimmed version was named after the anatomy feature type. The untrimmed version's surface name was the same but prefixed with the letter 'n'.

To store the parameter values associated with both versions of a feature two dummy surfaces were generated, so that their control point position vectors corresponded, in a predefined order, to the feature's shape algorithm parameters. The dummy 'parameter' surface for the trimmed feature was named using the feature type name prefixed with the letter 'p', and similarly the untrimmed version's dummy surface name was prefixed with the letters 'np'.

Each time a particular design was accessed by the system, a preprocessing routine was activated to extract the parameter values from the dummy feature parameter surfaces and update the run-time registers. After a feature was changed the dummy surfaces and run-time registers were updated accordingly. Both run-time registers and dummy surfaces were maintained during an interactive session for two reasons. The run-time registers for parameter values provided faster access and update times than was supported by interrogating and redefining the dummy surfaces. Thus, the run-time registers best supported a responsive GUI. However, the dummy surfaces provide the only permanent data record. Generating the dummy surfaces was a relatively small overhead for the shape algorithm surface generation routines, and so went unnoticed by users as the system responded to their input. The run time registers are used within the GUI until the user commits the system to evaluating the geometry, at which point the permanent dummy surface record is generated.

1.5. Shape Algorithm Coding

Each shape algorithm was implemented as a DUCT command file capable of generating the required feature surface geometry from the values stored in the appropriate run-time registers. Each EFF shape algorithm also generates DUCT workplanes corresponding to the necessary coordinate transform entities. These are named in the same way as the trimmed and proposed feature surfaces, with the feature type name, prefixed with the letter 'n' for the proposed version.

Each shape algorithm command file follows a common procedure, as follows:

- Remove existing/conflicting geometry entities.
- Initialise internal registers.
- Generate EF feature workplanes (local coordinate system) if necessary.
- Generate surface geometry (interrogating existing surface geometry if necessary).
- Generate dummy parameter record surface.

The blend command files are more complex since they have to accommodate 4 blending scenarios. The first is to regenerate an existing blend, using existing parameter settings, where the blended features have been replaced by new versions. This is a mode only accessed internally by the model trimming routine to update a blend where new versions of the blended features have been absorbed, but no new version of the blend feature is specified.

The other three modes represent the potential blending scenarios for proposing a new blend feature. If both trimmed (old) and proposed (new) versions of the blended features exist when generating a new blend the user is given the option to generate the blend between any logical pair (i.e. old-to-old, new-to-new, old-to-new or new-to-old versions of the blended pair). This allows all three features to be changed and then trimmed in one operation, without an intermediate stage where the existing trimmed blend is regenerated to match the new blended features, thus saving time.

The 5.0 and 5.1 DUCT releases had only limited multi-surface constant radius blend facilities and no multi-surface variable radius blend routines, although these were under development for later releases. This meant that the initial prototype system could not be used to generate the blade profile and neck blends automatically. The profile blending problem was overcome by not continuing the blend into the neck region, and splitting the remaining surface feature into a chain of single surface pair blends. The resulting separate blade and hosel feature groups were then blended by a temporary custom super-blend routine, dedicated to achieving an acceptable transition between the two. This meant that the actual anatomy implemented within the system was as shown in Figure 6-1 and Figure 6-2.

Table 6-1 describes the behaviour and lists the control parameters for the various anatomy features implemented.

Very little feature shape dependency was implemented, except within the shape algorithm for the cavity wall, which was dependent on the back feature. No position dependency relationships were implemented explicitly, except for the cavity wall with respect to the blade back, although common parameter names meant this could be simulated manually or through the system interface.

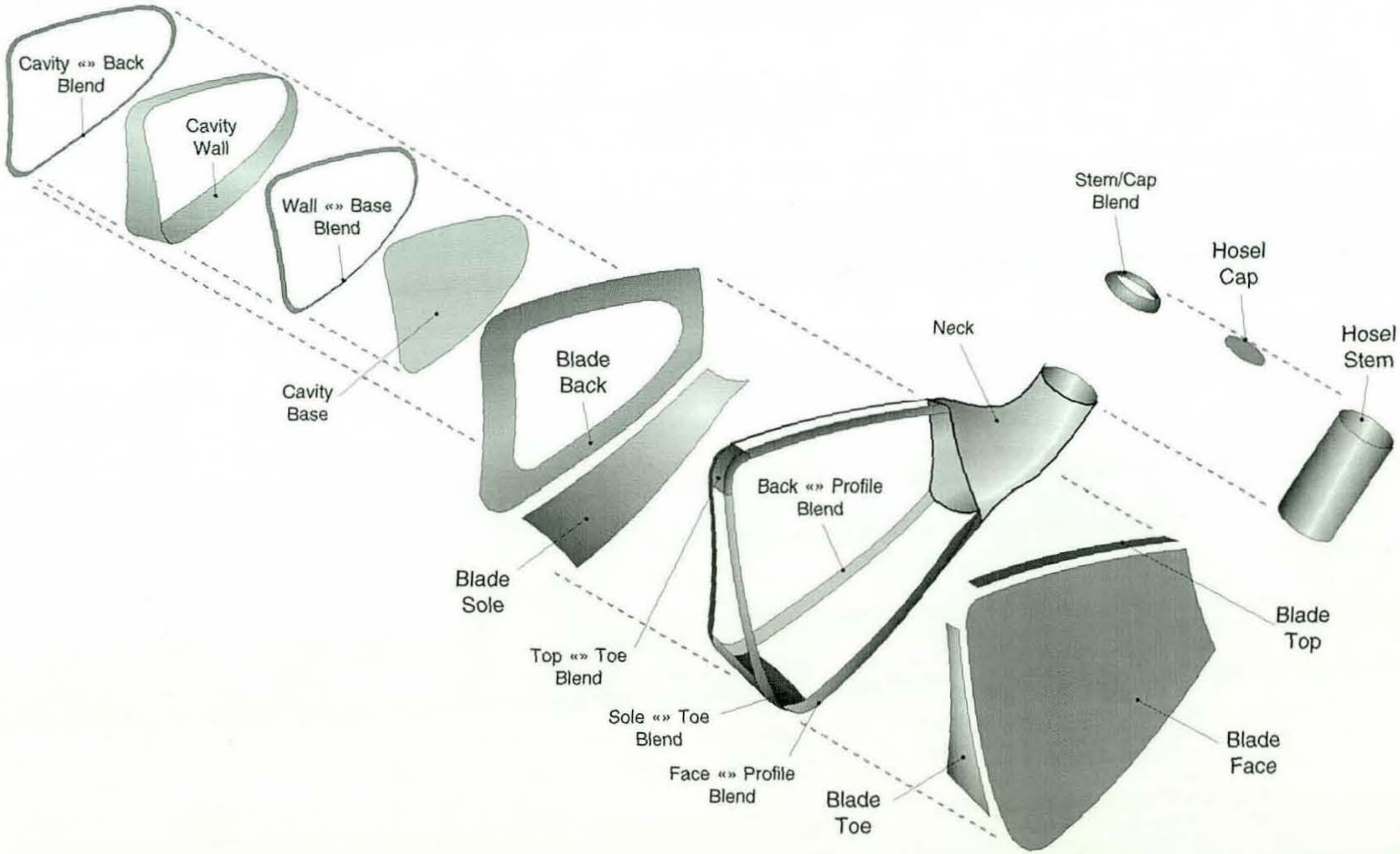


Figure 6-1 Implemented Golf Club Anatomy (Geometry diagram).

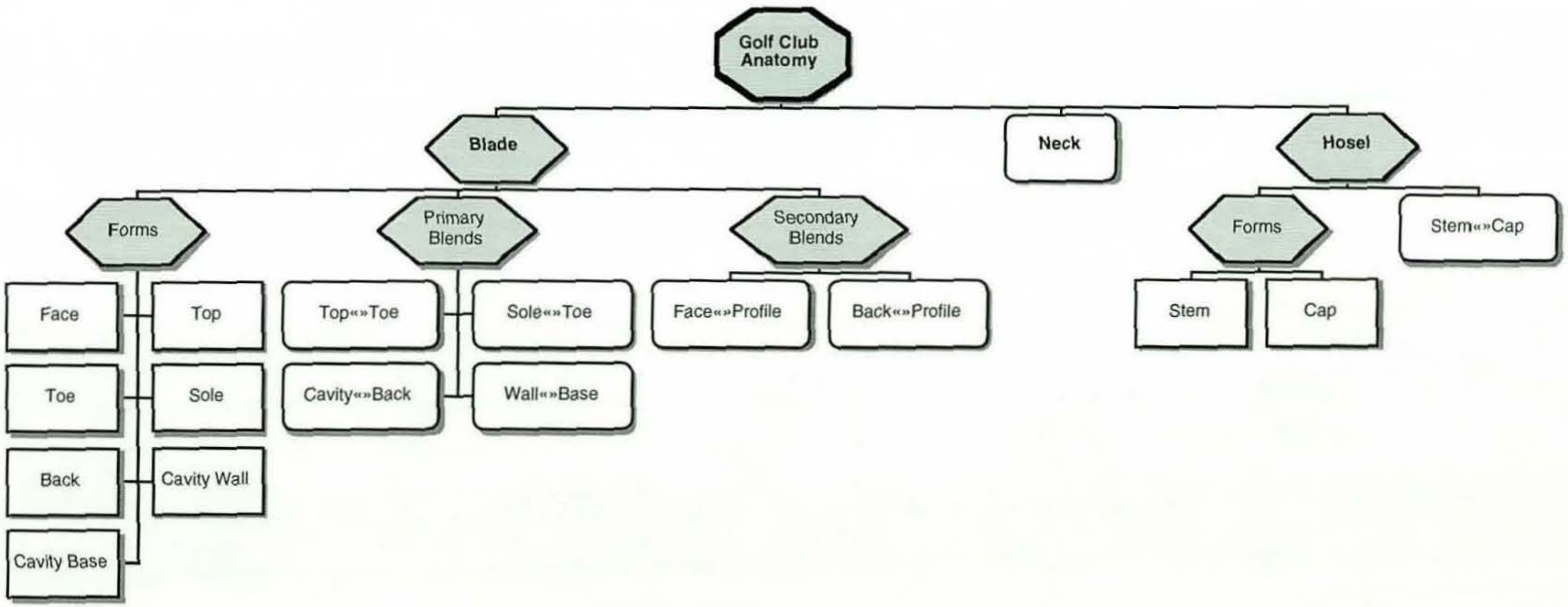


Figure 6-2 Implemented Golf Club Anatomy (Feature taxonomy).

Table 6-1 Implemented Feature Parameters and Shape Behaviour.

Feature	Shape Parameters	Position Parameters	Shape Behaviour
Face	-	Loft, offset.	Flat plane.
Back	Pinch height, chord angle, top width, top drop, sole width (toe), sole width (heel), base angle.	Loft, offset.	Smooth scalloped surface with flat land region running nominally parallel to the top feature chord angle. Developed to control nominal sole heel and to widths.
Top	Top heel-toe radius.	Loft, offset, pinch height, chord angle.	Ruled surface face to back, with curvature from heel to toe and tilted by the chord angle.
Toe	Face-back radius, sole-top radius.	Loft, offset, heel-toe offset, sole-toe offset, face-back offset.	Doubly curved surface, positioned and tilted in relation to the face position with the datum point tangent to a *yz* plane.
Sole	Face-back radius, heel-toe radius.	Offset, heel-toe offset, face-back offset.	Doubly curved surface always with the datum point at the tangent to the *xy* plane.
Cavity Wall	Draft angle, 2D Bézier profile.	Loft, offset, heel-toe offset, sole-top offset, face rotation angle.	Complex closed profile mapped onto the back feature and developed to achieve the specified draft angle.
Cavity Base	-	Loft, offset, blade thickness.	Flat plane.
Stem	Diameter.	Lie, start height.	Cylinder.

Table 6-1 Implemented Feature Parameters and Shape Behaviour (continued).

Feature	Shape Parameters	Position Parameters	Shape Behaviour
Cap	-	Lie, cap height.	Flat plane.
Top«»Toe	Top«»Toe radius.	-	Constant radius rolling ball fillet.
Sole«»Toe	Sole«»Toe radius.	-	Constant radius rolling ball fillet.
Cavity «»Back	Cavity «»Back radius.	-	Constant radius rolling ball fillet.
Wall«»Base	Wall«»Base radius.	-	Constant radius rolling ball fillet.
Stem«»Cap	Stem«»Cap radius.	-	Constant radius rolling ball fillet.
Face«»Profile	Face«»Profile radius.	-	Constant radius rolling ball fillet.
Back«»Profile	Back«»Profile radius.	-	Constant radius rolling ball fillet.
Neck	8 stem anchor points corresponding to the face-top, top-back, back-sole and sole-face blade blend boundaries. 8 corresponding stem vector magnitudes, and blade vector magnitudes.	-	Complex custom blend routine 'stitching' an 8 patch Bézier surface between the stem and the blade.

1.6. Custom Model Assembly

For a full EFF system implementation, the trimming routines would need to interrogate the anatomy feature type entity relationships to ascertain the blend and boundary dependencies. It would then be possible to identify the feature sets required to define complete boundaries for each individual feature. The trimming routines could then identify and trim those features for which a complete bounding feature set was present.

In a system for a single anatomy it is possible to code these feature sets directly into a custom trimming routine for the particular anatomy.

Because of the naming convention enforced by the shape algorithm command files, it is relatively straightforward to identify all new proposed features to be trimmed by searching the DUCT part for the presence of particular named surfaces. Similarly the presence of features dependent on a particular feature for their boundaries, and conversely the subset of these features that define its boundary, can be also be ascertained. Thus, given two feature set lists for each individual feature, those affected by its absorption and those affecting its boundaries, the features for which revised boundaries are necessary and complete boundaries are achievable can be identified and the corresponding bounding routines activated.

For the initial prototype this was achieved within a single command file. The routine's procedure was as follows:

- Identify all new untrimmed features.
- Identify blends to regenerate as a consequence of new feature absorption.
- Identify features to re-trim as a consequence of new feature absorption.
- Remove all features to be replaced or regenerated.
- Rename the surface features, workplanes and dummy parameter record surfaces for each new feature (the trimming routine itself enforces the

naming convention for trimmed features and their associated dummy data entities).

- Identify all features that can not be bounded because of an incomplete bounding feature set.
- Regenerate all affected blends, beginning with the primary blends and then subsequent generations of secondary blend.
- Generate the new boundaries for all affected features with a complete bounding feature set.

This routine is capable of assembling a partially trimmed model, where as many of the defined features are trimmed as possible. This is useful, as it allows subgroups of the design to be instantiated and visualised before specification of the entire model. For example, the blade face and its bounding feature set can be specified without the blade back feature. When the model is partially trimmed in this condition, as shown in Figure 6-3, the face boundary can be completed even though the blade profile features can not. However, the face boundary itself gives a good indication of the final club profile. Typically, this profile is the primary concern of the designer, thus initial profile refinement can proceed without the computational overhead necessary to re-trim the entire model.

The native commands available in the 5.0 and 5.1 DUCT releases for boundary assembly from a series of intersecting surface parameter curves were elementary. Because the anatomy was fixed, it was possible to overcome this by writing custom routines to intersect the local surface parameter curves and assemble a boundary for each individual feature. However, for a more flexible system it would be possible to write a routine capable of forming the boundary for any feature, given a set of intersecting surface parameter curves forming a closed chain. The later DUCT revisions attempt this within a 'native' version of the boundary creation command.

Figure 6-3 Partially Trimmed Blade

Even with the restrictions imposed by pursuing this implementation approach, it was possible to hold the data necessary to design a variety of clubs based on the particular anatomy and feature shape algorithm set chosen, thus demonstrating the successful application of an EFF based modelling strategy. A large proportion of different existing cavity back designs conform to the anatomy chosen, thus the system was quite capable of producing acceptable design variants within this domain.

2. INITIAL PROTOTYPE INTERFACE

2.1. General description

Figure 6-1 shows the golf club design system's customised DUCT interface. The computer screen is divided into a geometry display region; a command line interface; and 5 pull-down/pop-up menu selections. These cover 5 separate elements of interface functionality:

i) Feature selection.

ii) Design library access and manipulation.

iii) Simulated global parameter editing.

iv) Feature display settings.

v) A simple context sensitive help facility.

These reflect the functionality identified in Chapter 5 Section 3.

The system was implemented using DUCT 5.0 and 5.1 software releases, and then revised for the DUCT 5.2 release to make use of the additional Motif interface elements that could be programmed in this later version.

Because of the restrictions in DUCT's interface customisation capabilities in the version 5.0 and 5.1 releases the menu elements are always present, even if the current context means they have no relevance. Although this means the interface is more cluttered than desirable, it is still a major improvement for golf club design compared to the generic DUCT interface.

Figure 6-5 shows typical output from the help menu in several different situations. This facility is provided to help new users regain a sense of their current progress and the nest activity 'expected' by the system.

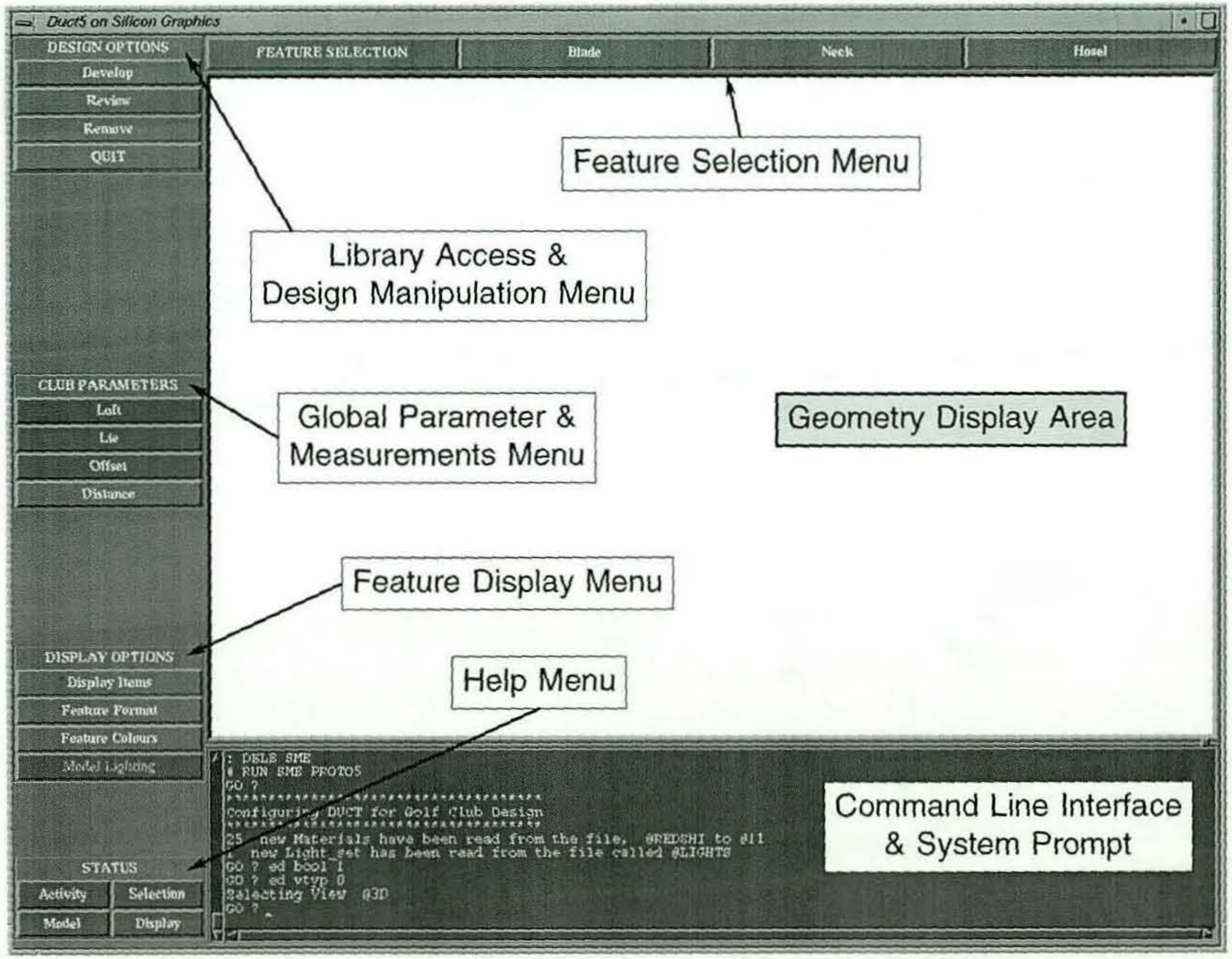


Figure 6-4 System Interface Overview.

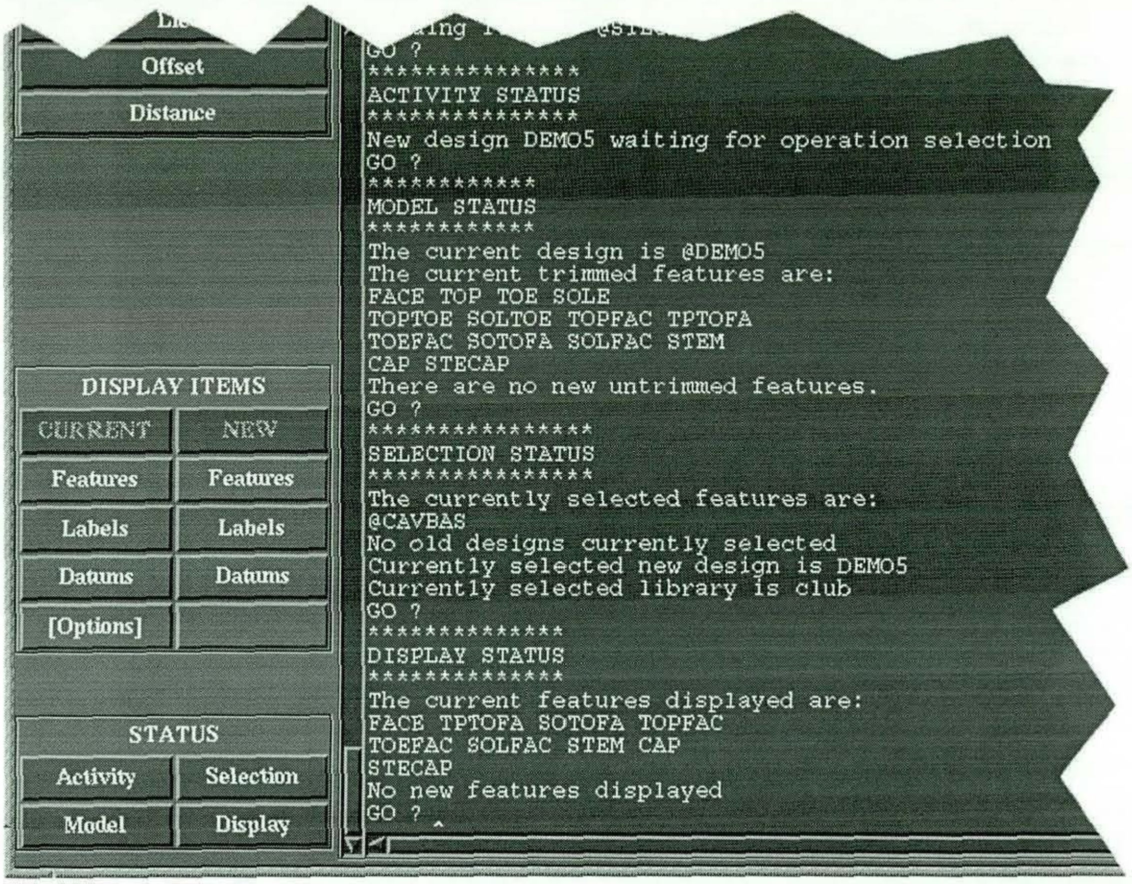


Figure 6-5 Example Help System Feedback.

Figure 6-6 shows the design options menu for library access and manipulation initially presented to the user. Clicking with the mouse on the 'review' or 'remove' buttons brings up the two sub-menus in the same screen position. These sub-menus are also illustrated in Figure 6-6 together with the design selection form (available in the 5.2 DUCT release) used for both activities. At the bottom of the retrieve and remove sub-menus (and all other sub-menus) is a button that will return the user to the parent menu.

The 'retrieve to view' command retrieves the selected design from the library, allowing the user to view it in the geometry window using the 'feature selection' and 'display option' menus, without the ability to change the design.

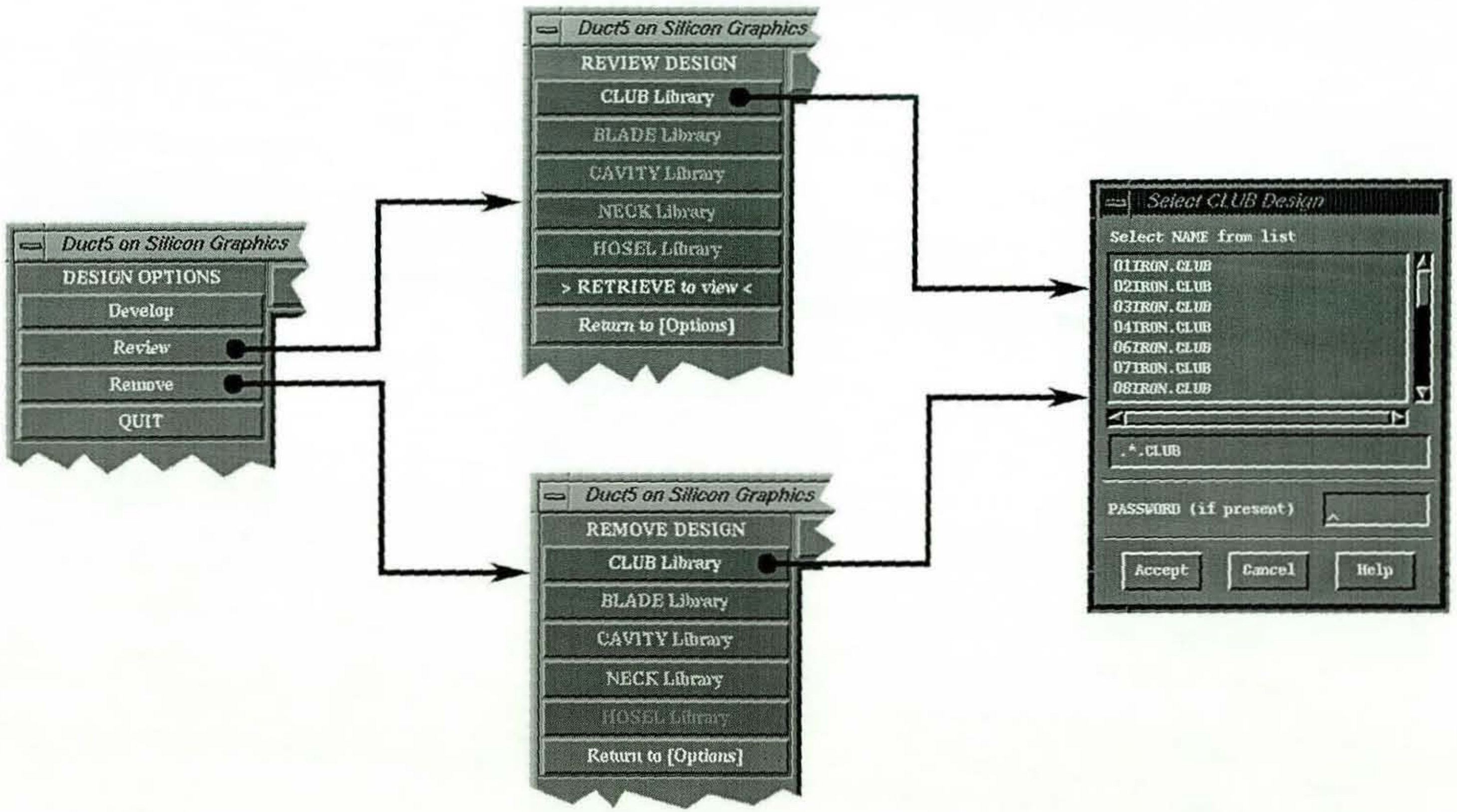


Figure 6-6 Design Options Menu Library Access.

2.2. Feature selection, display and view control

Figure 6-7 shows a sample of the pull down menus for the main feature selection group headings. Clicking on a feature or group at the bottom of the menu hierarchy (in this case approximating the anatomy hierarchy shown in Figure 6-2) informs the system which features are to be acted upon by subsequent commands. Within the design reviewing environment only the display and view control commands are available, but the feature editing commands are informed in the same way within the design manipulation context (as discussed below).

Figure 6-8 shows the various sub-menus that provide display control functionality to the user through the 'display options' menu. The user can show or hide features and their workplanes, change the format in which they are seen (shaded/wireframe trimmed/extended) and the colour with which they are displayed in wireframe or shaded modes. Essentially these menus control what the user sees in the geometry window. The geometry elements themselves do not possess display properties, so the current display settings for all feature types are held in run-time display property lists. However, these revert to the default settings when the lists are initialised each time the design system is activated.

Figure 6-9 shows the geometry window view scale, direction, layout and position sub-menus available from the 'view control' popup menu. This menu is recalled by a special mouse key combination (middle and right hand buttons pressed simultaneously) with the mouse pointer in the geometry window, and essentially controls how the user sees the displayed geometry.

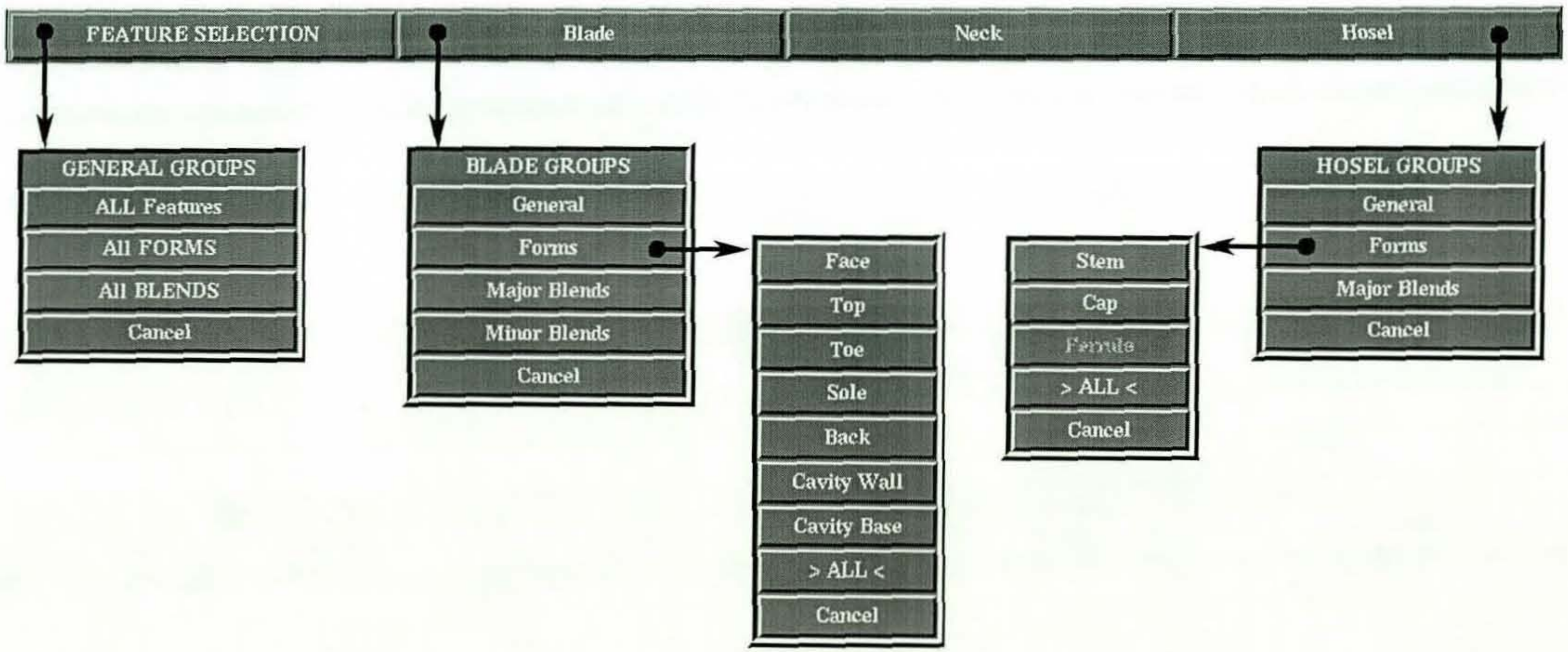


Figure 6-7 'Pull Down' Feature Selection Menus.

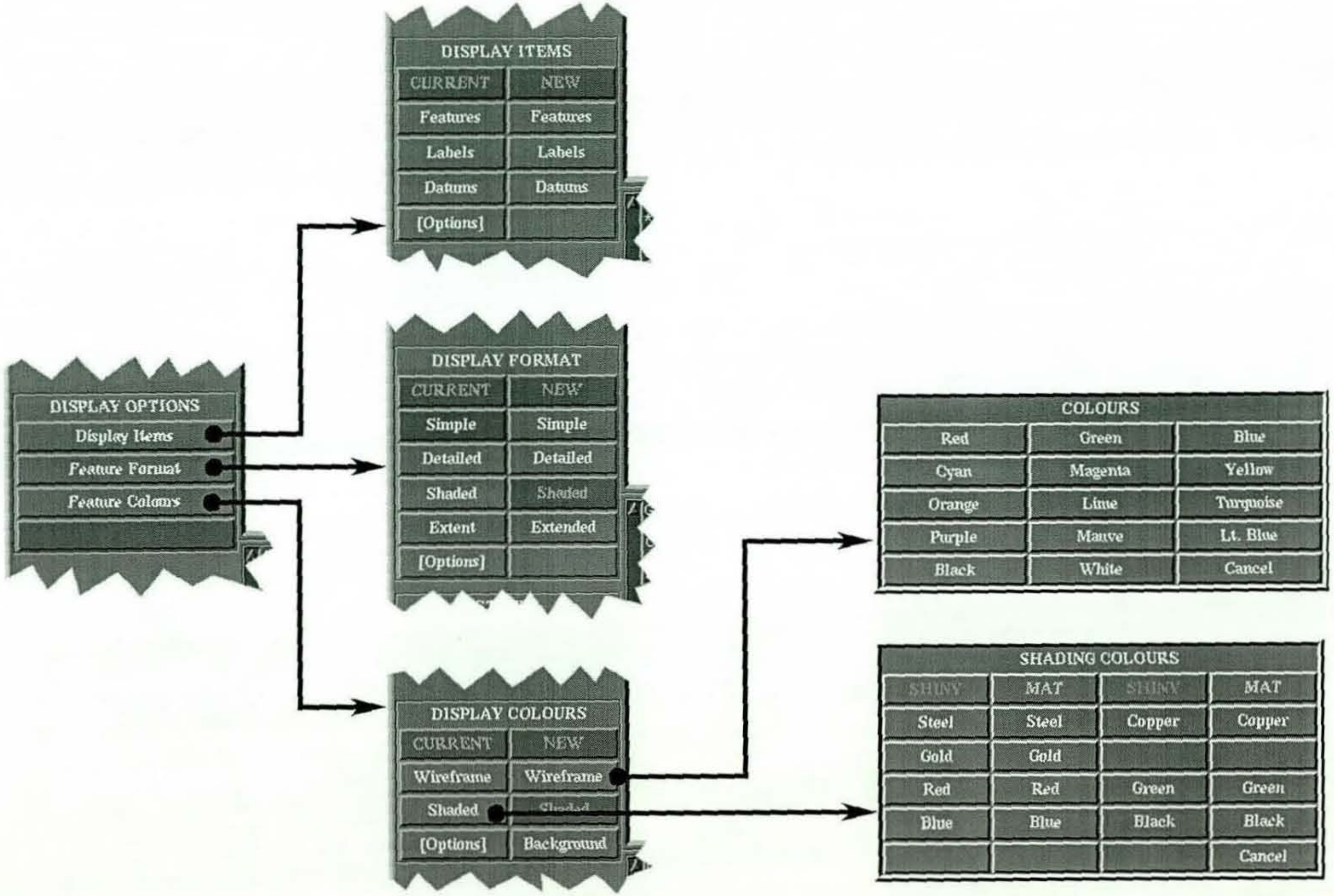


Figure 6-8 Display Menus.

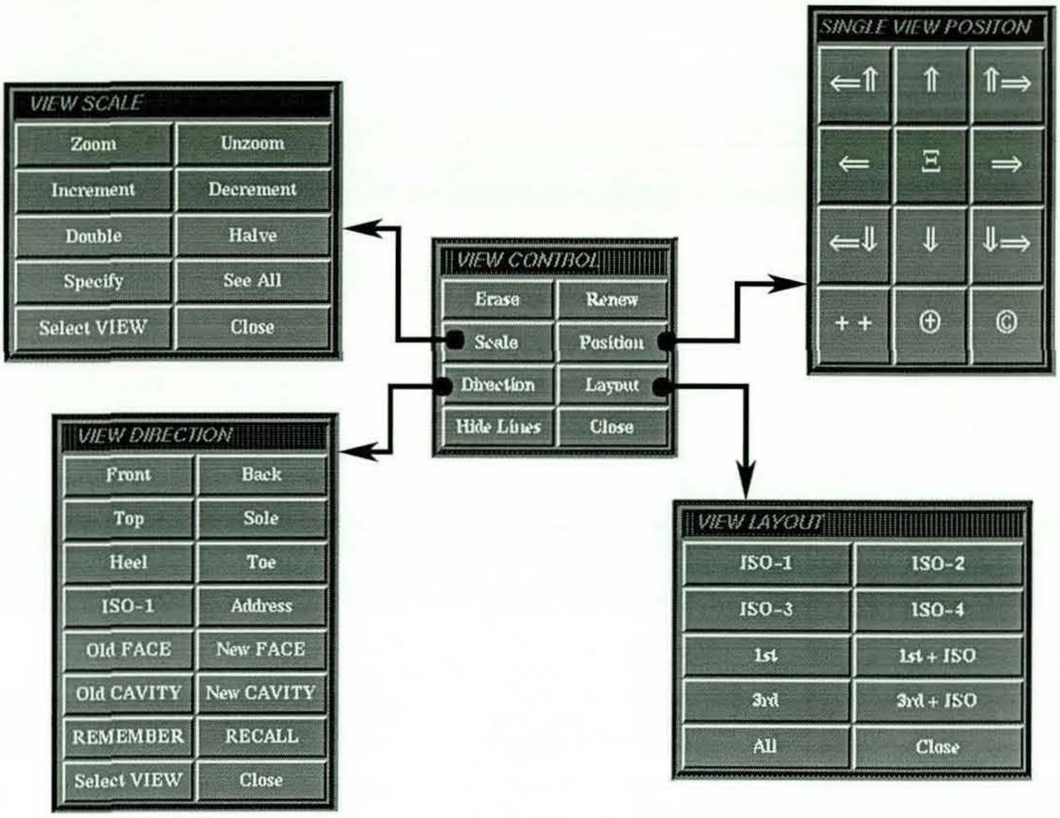


Figure 6-9 View Control Menus.

2.3. Single Design Development

Figure 6-10 shows the 'design development' menu, activated from the 'design options' root menu, for access to the design library. It also shows the sub-menus activated from the 'design development' menu to indicate the intention to produce a new design, from scratch or a 'template' existing design, or to continue previous work (cf. system interface functionality Chapter 5 Section 3). In the DUCT 5.1 release version of the club design system new design naming and existing design selections are achieved through an interactive command line dialogue. In the DUCT 5.2 release version the Motif style forms shown in Figure 6-10 are used. Figure 6-11 shows a flow diagram describing the activities and progress typical in using the system to gain access to the library to design a single club.

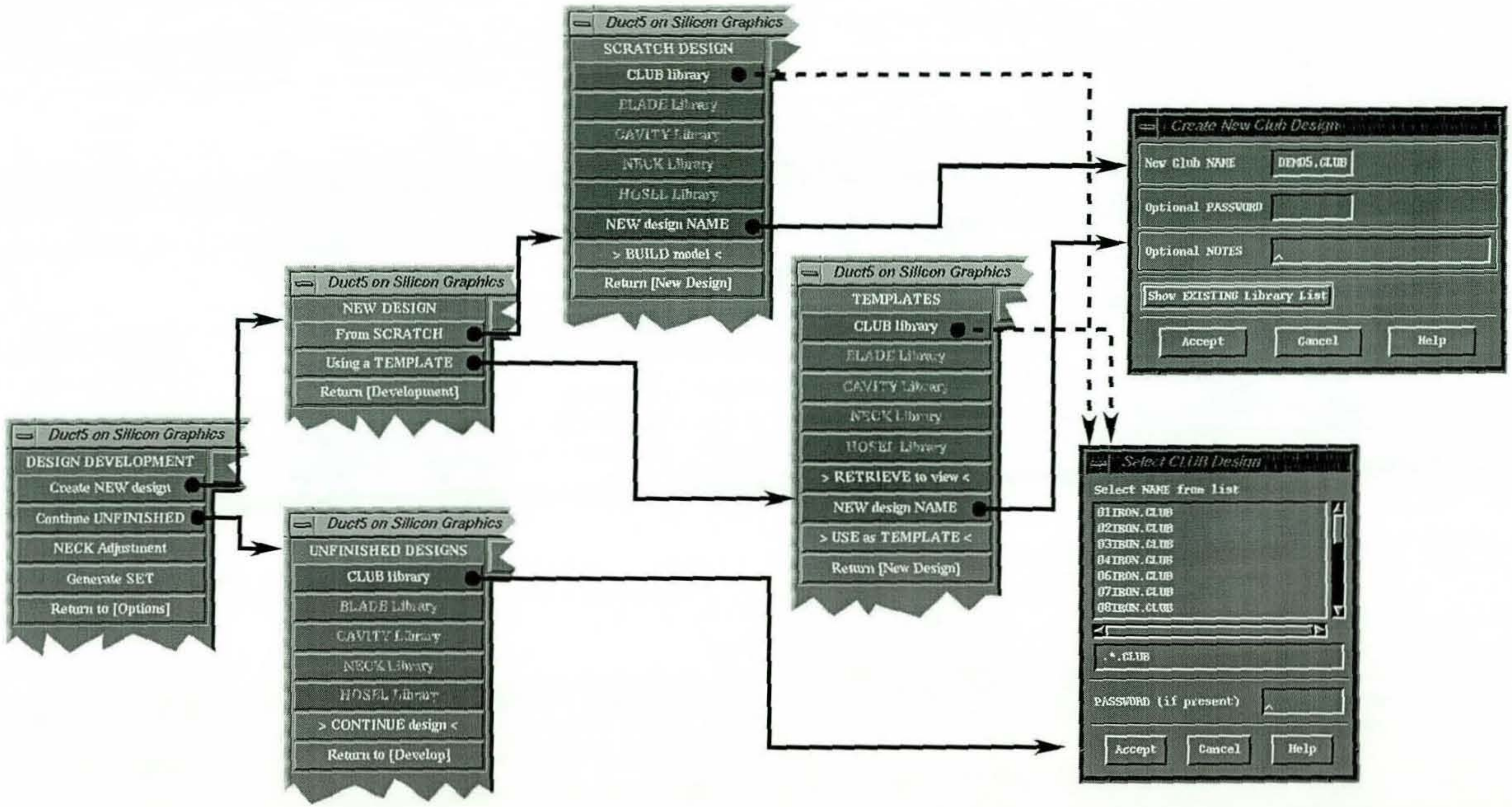


Figure 6-10 Library Access Menus and Forms.

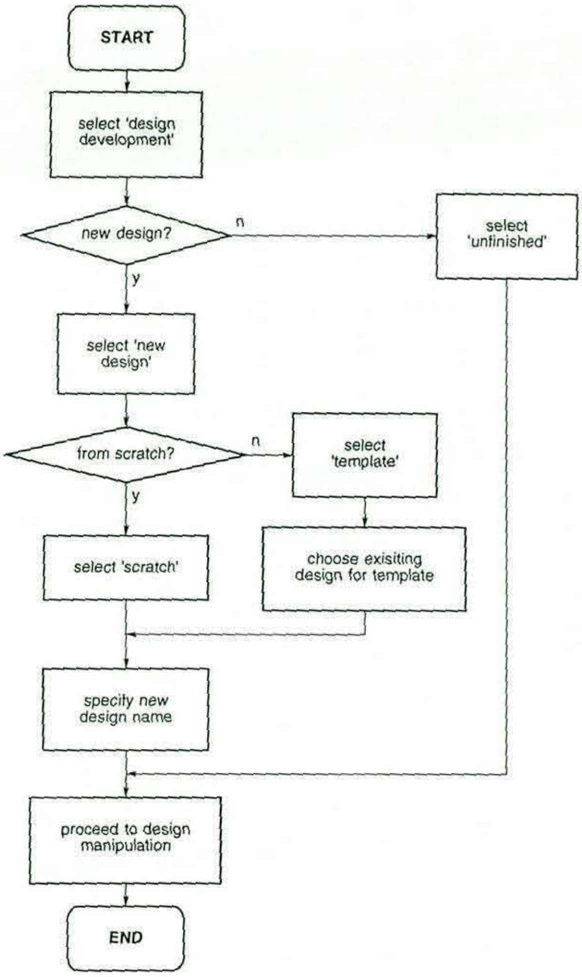


Figure 6-11 Library Access Flow Chart.

Because this prototype system used a single 'hard wired' anatomy data structure, there was no need to implement the functional interface elements needed to identify the intended club anatomy, as required in a fully functional generic EFF based system.

Clicking on the proceed buttons on any of the scratch, template or unfinished design sub-menus brings up the 'design manipulation' menu shown in Figure 6-12. The 5 pop-up design manipulation sub-menus are also illustrated. These cover:

i) Feature introduction. ii) Feature adjustment.

iii) Feature removal. iv) Model trimming.

v) Library storage confirmation.

Essentially, features identified using the selection menu are introduced, adjusted or replaced using these menus. The model is then 'assembled' and trimmed to form a valid geometric definition of a club. Ultimately changes are stored permanently in the design library. Figure 6-13 shows a more detailed flow chart of typical design activity using these menus.

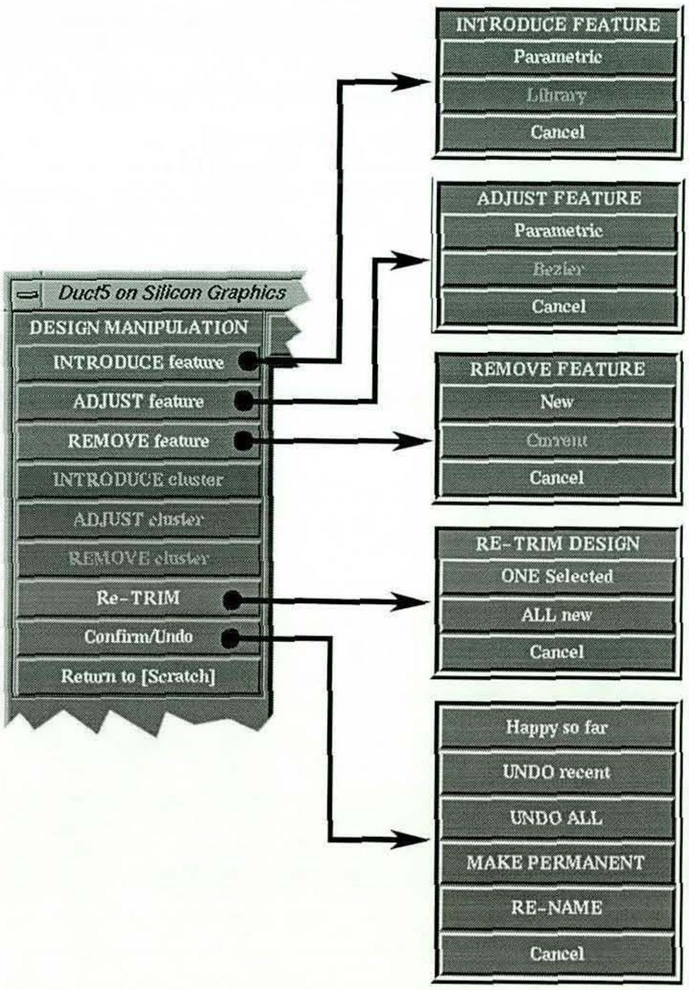


Figure 6-12 Design Manipulation Menus.

The parametric feature adjustment command activates a command line interactive dialogue in the DUCT 5.0 and 5.1 release system versions. The command line parameter adjustment command files each contain the common components illustrated in the flow diagram presented in Figure 6-14. Figure 6-15 shows a snapshot of a typical interactive session.

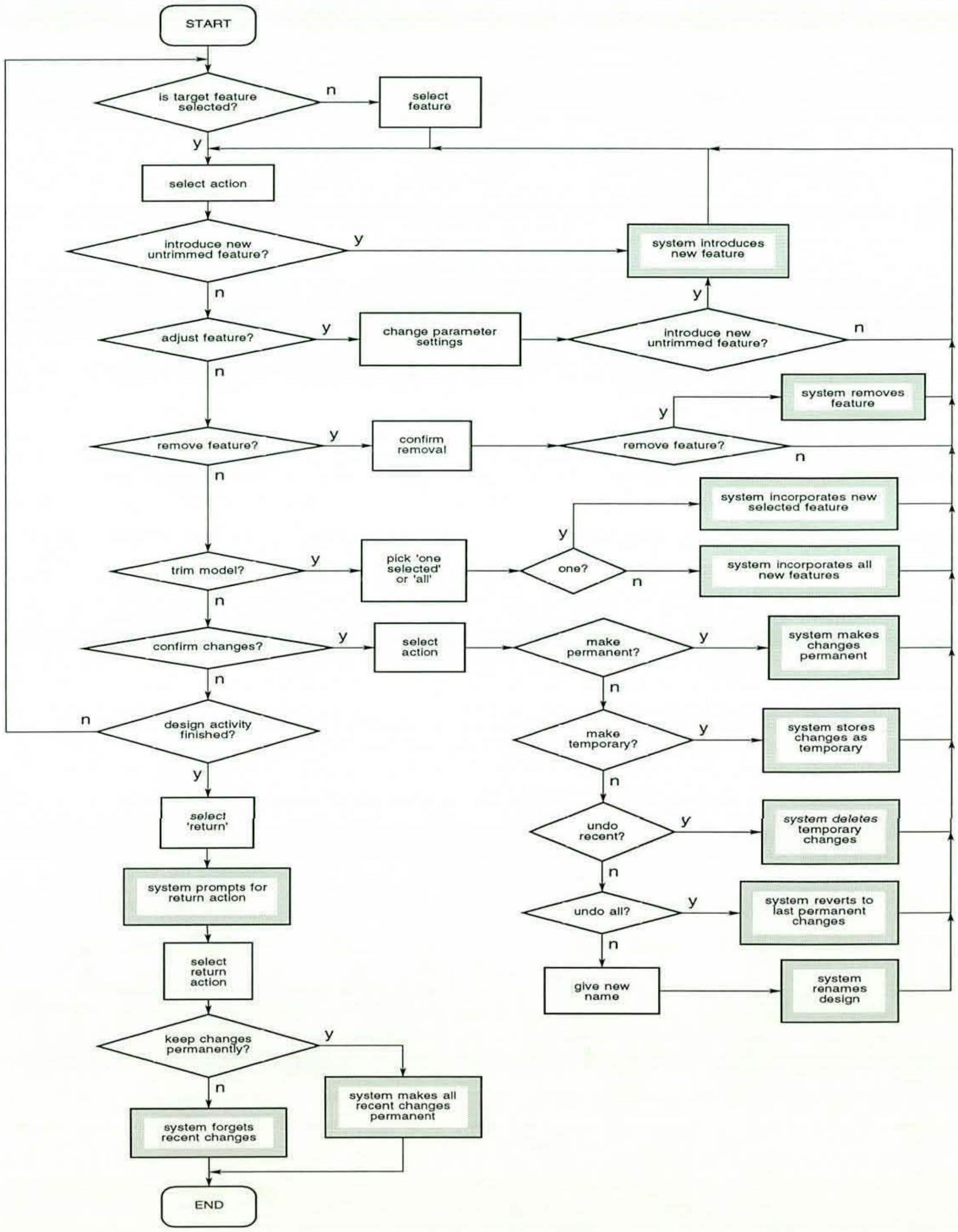


Figure 6-13 Single Design Activity Flow Chart.

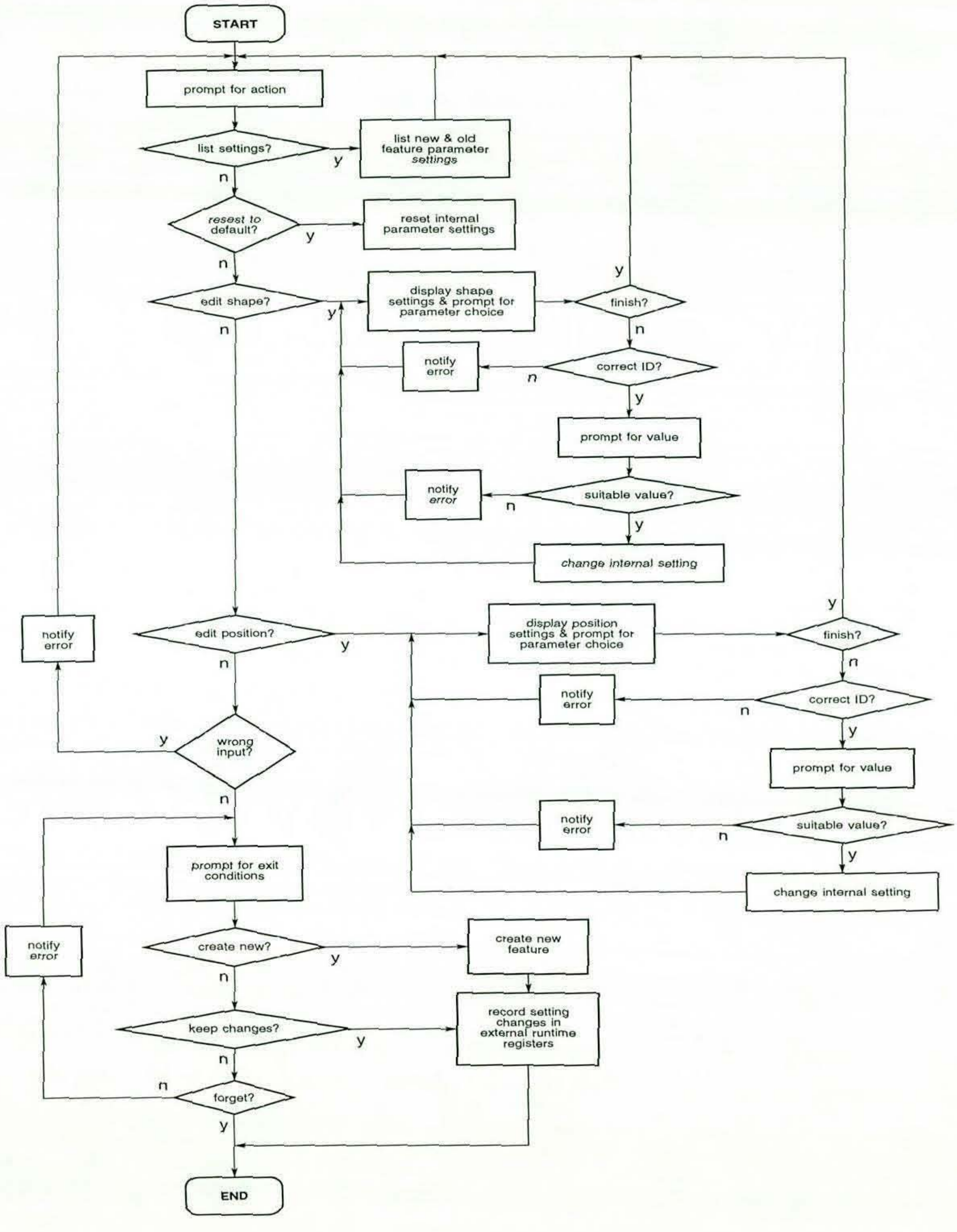


Figure 6-14 Command Line Dialogue Feature Parameter Editing Flow Chart.

The DUCT 5.2 release system revision presents the user with Motif forms for parametric adjustment. Figure 6-16 shows typical DUCT forms defined for the 'toe' and 'top«»toe' features. The parameters may be edited by moving the slide bars between extremes specified in the custom form as indicated by the arrows in Figure 6-16.

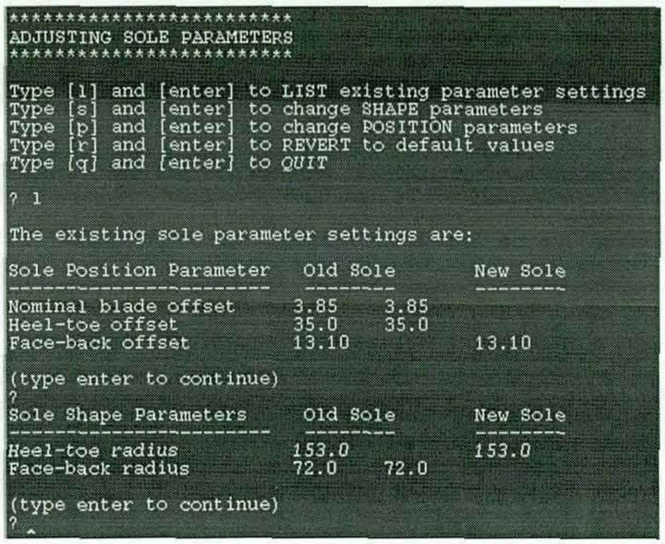


Figure 6-15 Command Line Dialogue Feature Parameter Editing Example.

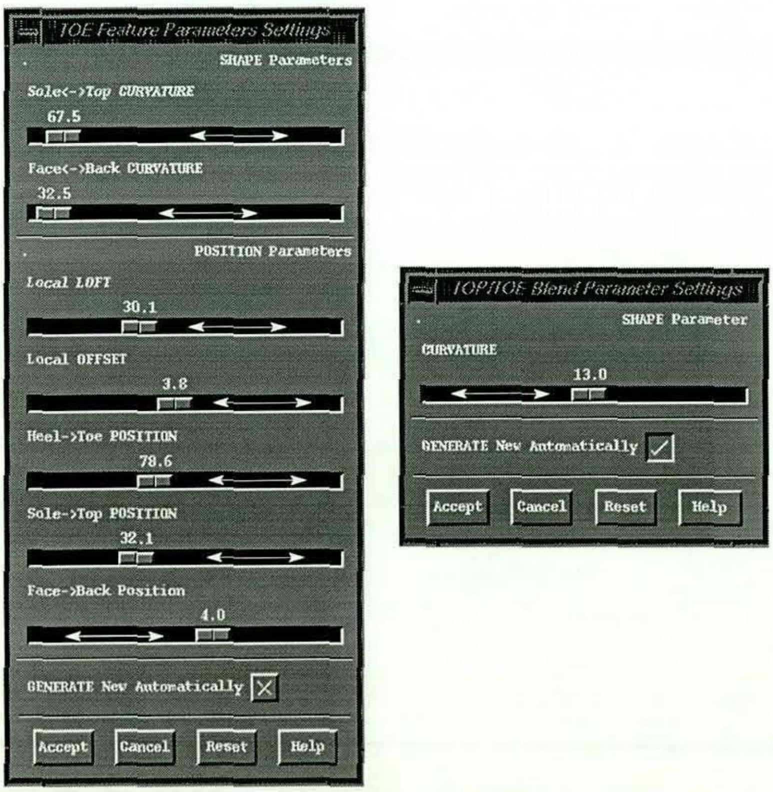


Figure 6-16 Motif Style Parameter Adjustment Forms.

Global parameter editing occurs in the same way, using the global parameter menu, but the settings of all affected features are changed together. No feature selection is necessary as the interface is written assuming that all those features controlled by the chosen parameter are to be changed.

Similarly, the interface makes no provision for using different shape algorithms for any particular feature, as this initial prototype incorporated only a single algorithm set.

2.4. Automatic set generation

Once a design has been completed, automatic set generation is accessed from the 'design development' menu (Figure 6-10). Figure 6-17 shows the 'set generation' sub-menu, together with the pop-up 'club set list' menu for accessing the parameter settings for each club. Figure 6-17 also shows the form used to edit the settings for a 3 iron available within the DUCT 5.2 system revision.

Typically, an existing club will be selected from the design library using a standard motif form (Figure 6-10). The parameter variations will be specified using the club set forms, and the automation options will be set using the form illustrated in Figure 6-17. This last form performs 4 functions:

i) It allows the user to identify the base club as a specific member of the set.

ii) The user can specify whether the individual clubs will be displayed as they are created, or whether the routines will run 'silently' (obviously requiring less processing time, but preventing the user from viewing progress).

iii) The user can specify a range of 3D 'snapshot' images (including 3D wireframe and shaded models) to be stored for comparing the results later by simultaneously displaying all set clubs (normally DUCT will only allow the surfaces of one 'part' to be displayed at a time).

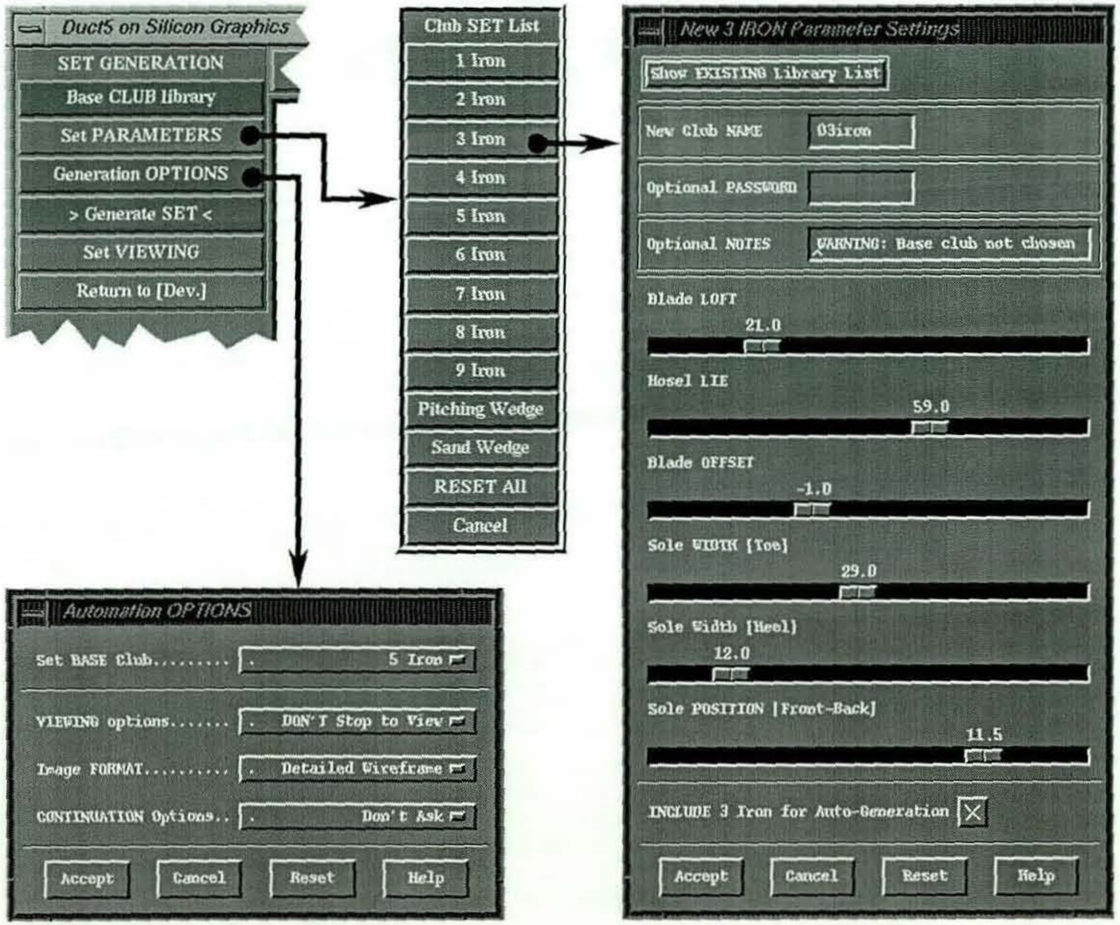


Figure 6-17 Set Generation Menus and Forms.

iv) The user can also force the routines to pause after generating each club, and wait for the user to confirm their desire to continue. This is useful if the base design is unstable and its variants produce invalid feature interactions.

Once the automation options are set the 'generate set' button activates the process, after warning the user of the likely computation time required. Figure 6-18 shows a more detailed flow chart of a typical automatic set generation activation process.

The set generation routine itself retrieves the base club design from the design library and extracts the parameter settings for each feature from their dummy parameter surfaces. A new 'empty' library design is then created for each required club in sequence. New versions of all the club anatomy features are generated for each club according to the parameter settings extracted from the base club, except where these are superseded by parameter variations specified by the user. The model trimming routine is then run automatically, the required 'snapshot images' stored in external files, and the complete model saved in the design library.

Once the set has been generated the user can use the 'set viewing' button to activate the sub-menu illustrated in Figure 6-19. Figure 6-19 also shows the pop-up forms, activated by the 'set viewing' menu buttons, used for retrieving, displaying, colour coding and staggering/superimposing the set images concurrently.

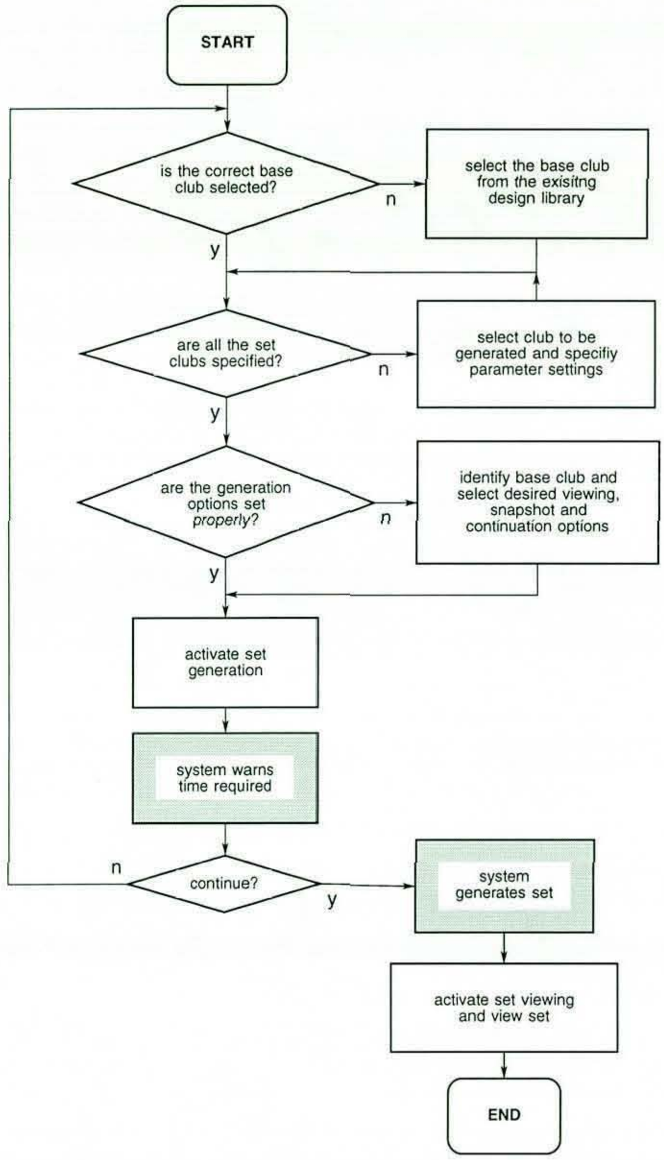


Figure 6-18 Automatic Set Generation Activation Procedure.

2.5. Actual system use

Figure 6-20 to Figure 6-22 show additional images of the system in use, to better convey the user's impression of the interface.

As a prototype EFFM based design system this initial implementation provided a successful golf club design environment suitable for performing user trials of the method (Chapter 8).

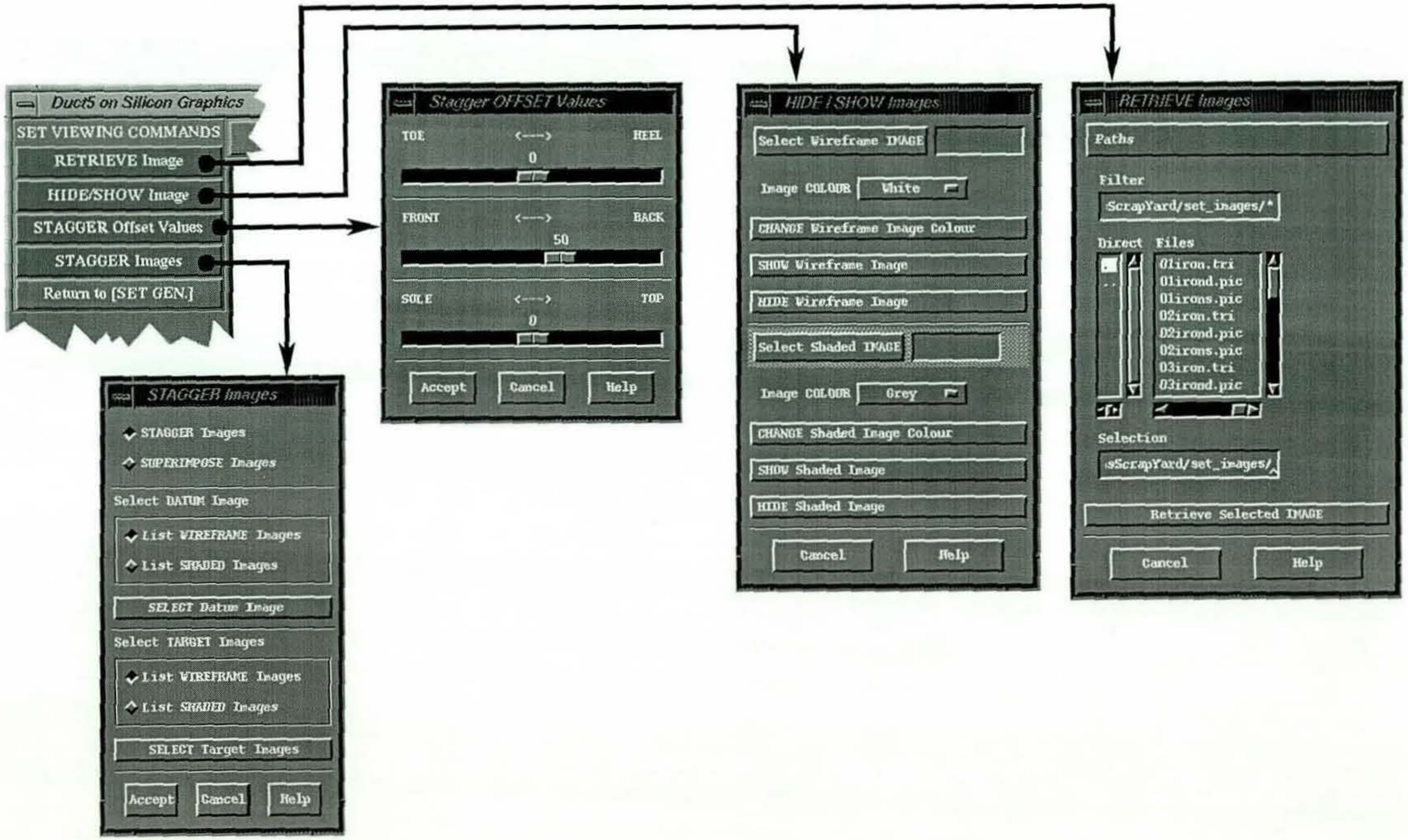


Figure 6-19 Set Viewing Menu and Forms.

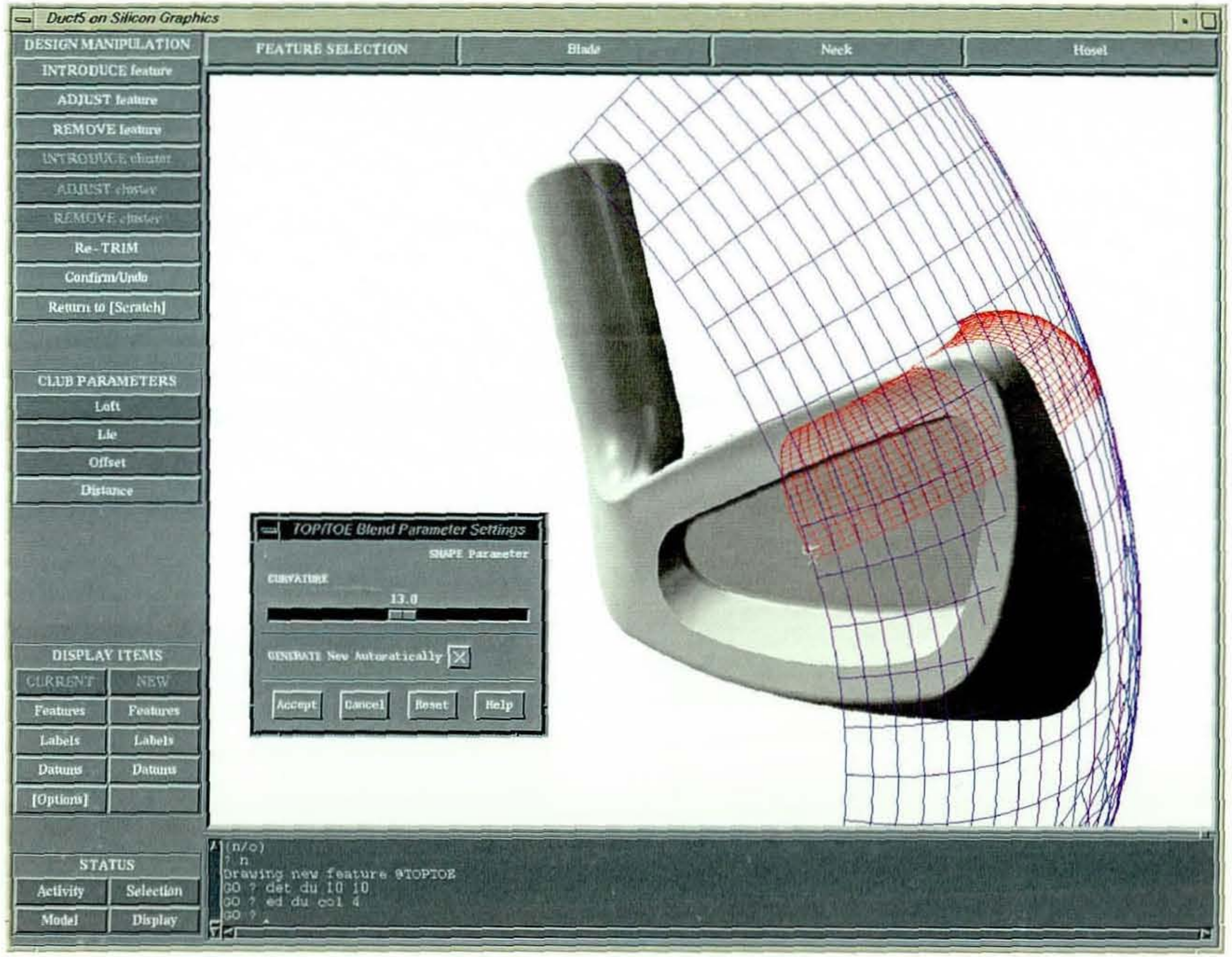


Figure 6-20 System Use (Design Modification).

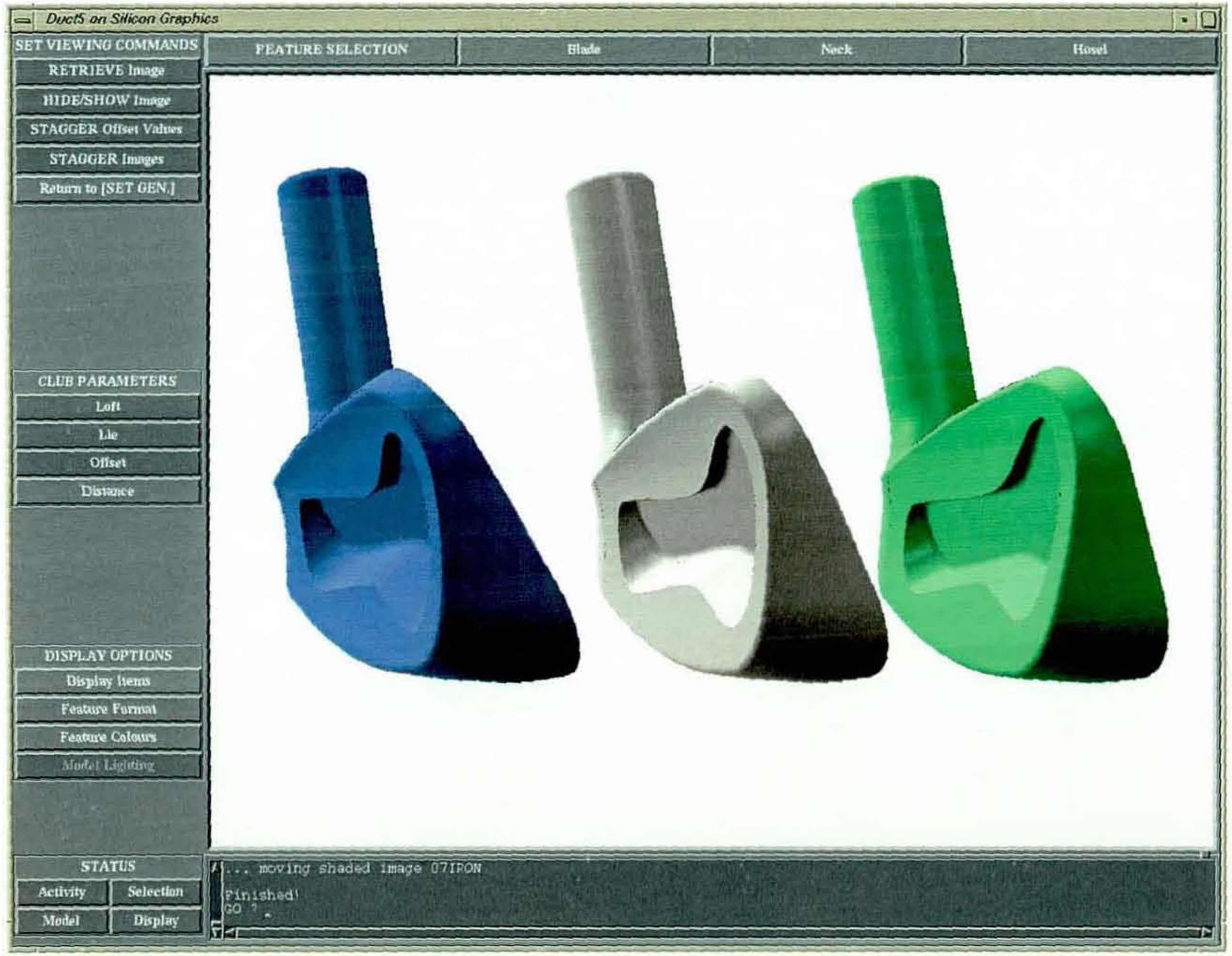


Figure 6-21 System Use (3 and 7 Iron automatic set generation results).

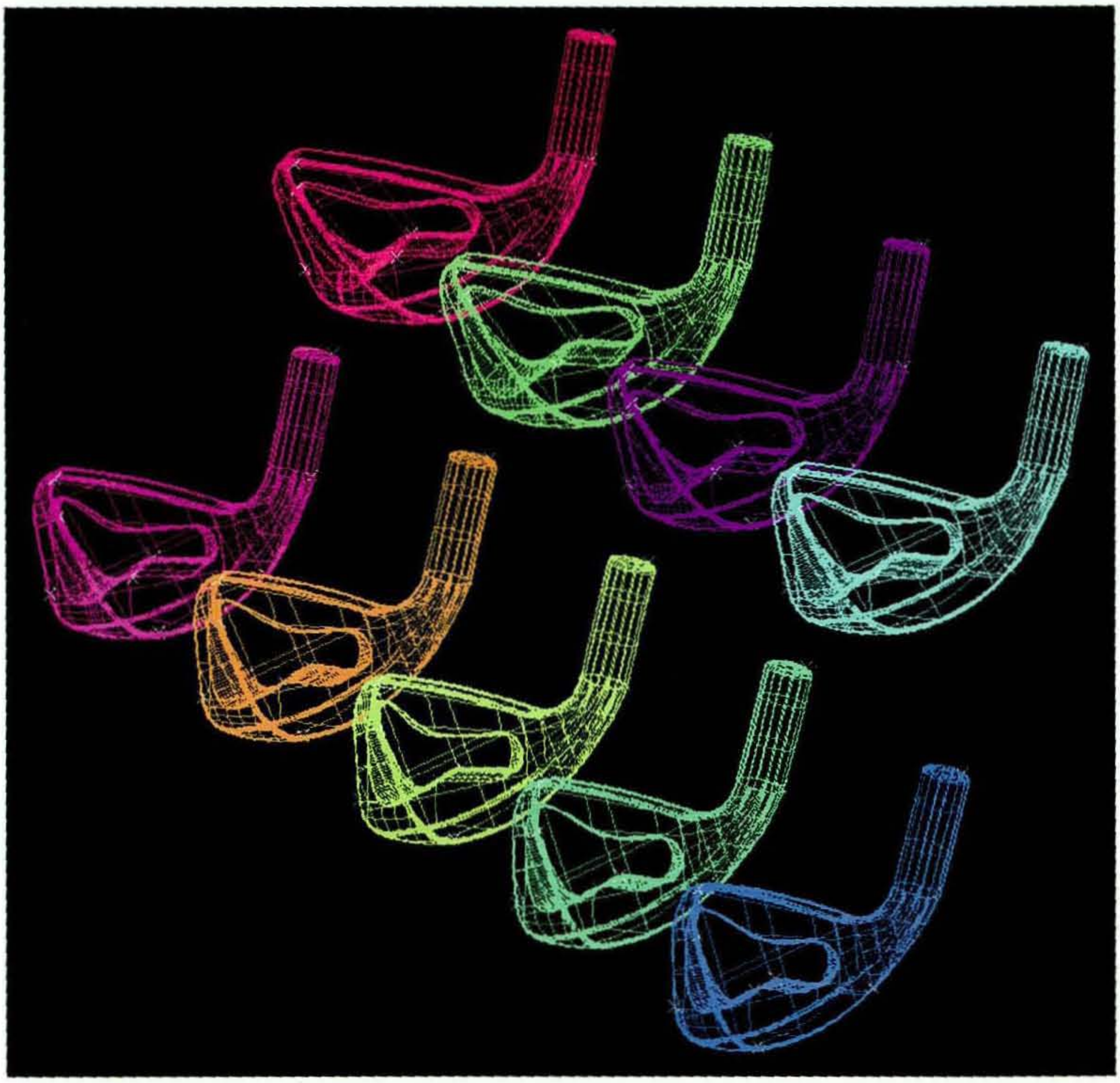


Figure 6-22 Generated Set (full set generation results).

3. Generic Applicability

Given successful implementation for a particular product anatomy it is not unreasonable to expect similar dedicated EFF based design system implementations for a single anatomy of another product to be possible. For example, the shoe last anatomy presented in Chapter 3 Section 3.1 could be hard wired into comparable trimming command files supported by a set of suitable shape algorithms, with the design data stored in comparable geometry and dummy data surface entities.

Adapting the user interface to suit other dedicated systems is relatively simple, as much of the functionality is common to them all. Primarily the feature selection menus need to change, to reflect the elements of the particular product anatomy. Any custom measurement routines and view orientation menus also need changing. Then, given new form definitions appropriate for the parameters controlling each of the new feature shape algorithms, and for specifying their variation through a set, the system would be capable of supporting single design development and automatic set generation for a different product.

CHAPTER 7. REVISED SYSTEM IMPLEMENTATION

1. OODB DATA STRUCTURE IMPLEMENTATION

1.1. Overview

The second system implementation involved a complete revision of the system routines and data structure to make extensive use of the OODB facility available within the DUCT 5.304 version release. Chapter 1 Section 3 describes in more detail the additional facilities available in this release, but the essential difference was the ability to define classes, attributes and inheritance structures, using the DUCT software, that remain from one session to another. These classes can be assigned to DUCT geometry elements, most usefully DUCT surfaces themselves, together with specific attribute values. The geometry entity combined with these extensions embodies a class instance or object.

Although the additional DUCT facilities made a more extensive EFF based system implementation possible, limitations in the internal OODB still prevented a full implementation. The data structure modifications made necessary by these restrictions are discussed further in the following sections, but primarily they made it difficult to implement concurrent anatomy variants, i.e. more than one anatomy containing similarly named feature sub-classes. Thus, the revised system data structures still only supports a single anatomy, at any one time.

1.2. Anatomy Feature and Type Classes

Within the revised EFF data model (Chapter 5 Section 2.3) the 'feature type' entity and its sub-entities suggest implementing a type class hierarchy as shown in Figure 7-1. The four feature types identified within the EFF method, and their sub-types, are denoted by different shapes.

The relationship between a specific 'feature type' entity and its 'anatomy' suggests anatomy feature classes inheriting properties from both 'anatomy' and 'type' metaclasses, so that the anatomy feature classes are instances of a 'type class'. This supports the anatomy features inheriting bounding/trimming behaviour from their 'type class' and a bounding context from their 'anatomy class'.

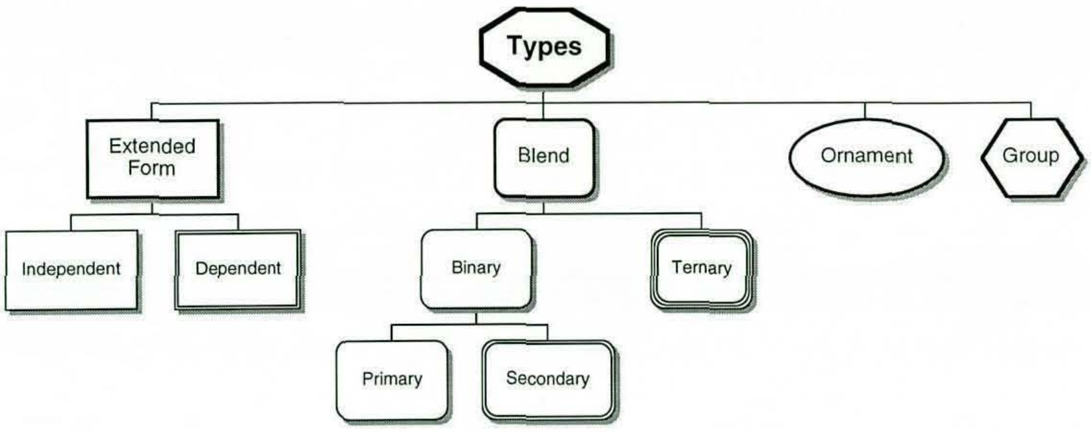


Figure 7-1 Feature Type Classes.

Within the DUCT OODB each class must have a unique name, as they can not be referred to by a full declaration of their provenance. To implement anatomy variants, a feature class common to several variants would have to be a subclass of more than one anatomy or exist with several different names for each anatomy. The multiple inheritance restrictions within DUCT make the first option impossible, and class name length restrictions make the second option undesirable. The feature classes themselves need to be metaclasses, but the DUCT OODB will not allow metaclasses to have multiple parents, thus the anatomy feature metaclass can not also be a subclass of a number of anatomies. Therefore, the EFF system anatomy feature class implementation within the revised system only holds one anatomy variant current at a time, and even anatomies for dissimilar products with similarly named features can not be held concurrently (e.g. steam iron, golf club and shoe last sole features would result in conflicting class names, unless the feature names were a concatenated version of the features provenance, for example steamIronSole, golfIronSole, and shoeLastSole).

Table 7-1 lists the attributes assigned to the type class instances within the revised system implementation. The bounding relationship between blend features and the associated blended features is established by generating blended feature groups that are then referred to by the blend side one, two, or three group attributes as appropriate. The group features themselves are a named class possessing item number attributes that indicate the members of the group.

The feature classes could also inherit global property/parameters and default values from the anatomy, if this were relevant to the particular product. It is unlikely that this would be a convenient method of assigning default shape control parameter values to an anatomy's features, except where the control parameter was relevant to the majority of features (e.g. some form of scaling attribute could be implemented for shoe last design in this way). Where this is not the case many of the anatomy's features would inherit a redundant attribute (e.g. although loft and offset parameters might be relevant attributes for a golf club's blade features, they are irrelevant to the hosel features). However, if a given anatomy was designed to usually represent a polished forged steel club, it might be convenient for all the anatomy's features to inherit a default display property that ensures that when the surface geometry is shaded the features appear polished, unless otherwise specified by the user.

The group feature relationships could be implemented by establishing the group as a metaclass and its constituents as subclasses. This might offer some benefits similar to those for global parameter inheritance from the anatomy metaclass. However, it is common for a feature to be a member of more than one group. Although this could be modelled using multiple inheritance, DUCT's capabilities in this respect prevent using this approach, just as they prevent a feature class belonging to more than one anatomy class. DUCT's current inability to identify the sub-classes of a metaclass also restrict the usefulness of this implementation approach for interrogating the data elements to support the blending and trimming routines.

Table 7-1 Type Class Inheritance and Attributes

Class	Parents	Attributes		
Type	-	SurfaceName	'Unique 7 character surface name'	
		BoundaryCode	'Unique 3 characters'	
ExtendedForm	Type	DefaultShape	'unspecified'	
		ShapeComf	'unspecified'	
		MaxCurvComf	'General'	
IndependentEF	ExtendedForm			
DependentEF	ExtendedForm	FeatureGroup	'unspecified'	
Blend	Type	DefaultShape	'unspecified'	
		ShapeComf	'unspecified'	
		MaxCurvComf	'General'	
Binary	Blend	Side1Group	'unspecified'	
		Side2Group	'unspecified'	
PrimaryBB	Binary	Generation	0	
SecondaryBB	Binary	Generation	'unspecified' (>0)	
Ternary	Blend	Side1	'unspecified'	
		Side2	'unspecified'	
		Side3	'unspecified'	
		DefaultShape	'ternary'	
		ShapeComf	'ternary'	
Ornament	Type	SurfaceName	'Unique 7 character triangle name'	
		EditComf	'ornament'	
		FeatureGroup	'unspecified'	
		TriangleFile	'unspecified'	
		PositionX	'unspecified'	variable
		PositionY	'unspecified'	variable
		PositionZ	'unspecified'	variable
		DirectionX	'unspecified'	variable
		DirectionY	'unspecified'	variable
		DirectionZ	'unspecified'	variable
		Twist	'unspecified'	variable
Group	Type	SurfaceName	'Unique 7 character shell name'	
		NumberItems	'unspecified'	
		Item1	'unspecified'	
		Item2	'unspecified'	

1.3. Type Indicators and Shape Algorithms

Figure 7-2 shows examples of typical golf club feature classes as instances of the 'Golf Iron' anatomy class. Bounding behaviour inheritance from a type class is indicated by the shape assigned to each feature class (Figure 7-1). Figure 7-2 also shows how the type indicator entities in the revised data model (Chapter 5 Section 2.3.1) are natural instances or subclasses of the feature class, although they would also need to inherit behaviour, attributes and default values from associated shape algorithm metaclasses.

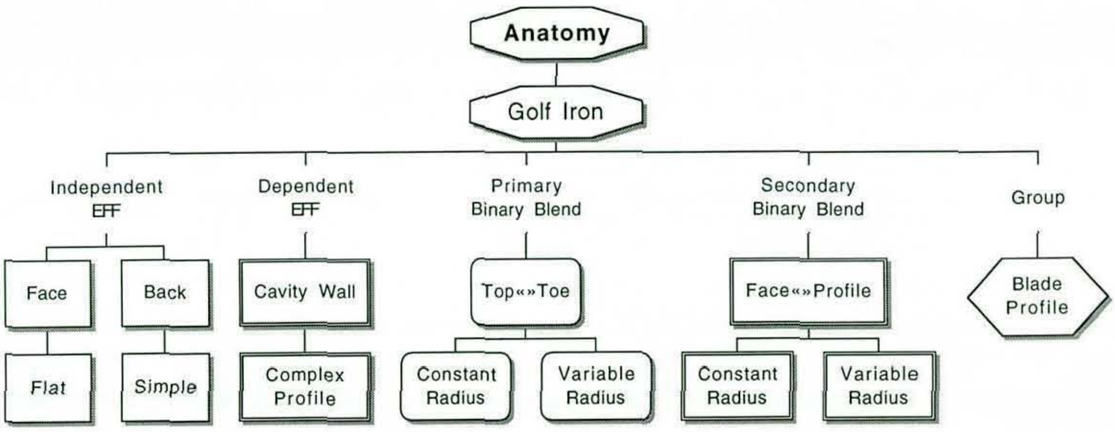


Figure 7-2 Golf Club Anatomy Feature Type Classes

The parameter entities and their relationship to a particular shape algorithm (Chapter 5 Section 2.3.2) are conveniently implemented as attributes of a shape algorithm class. The transform entities can be implemented as before within the shape algorithm command file routine identified as an attribute of the shape algorithm class.

1.4. Product Classification and the Design Default Environment

The data model product classification structures shown in Chapter 5 Section 2.3.7 suggest the class structure shown in Figure 7-3. The diagram shows that a design instance, while obviously being a subclass of the design metaclass, is also an instance of an anatomy and possibly more than one product classification class. This establishes the relationship between a design and its corresponding anatomy[1], and also allows the design to inherit a product context from its classifiers. Ideally the design class would be attached to the corresponding DUCT part, but since this is not possible in the 5.3 release the parts and classes are given corresponding names so that the assignment can be simulated.

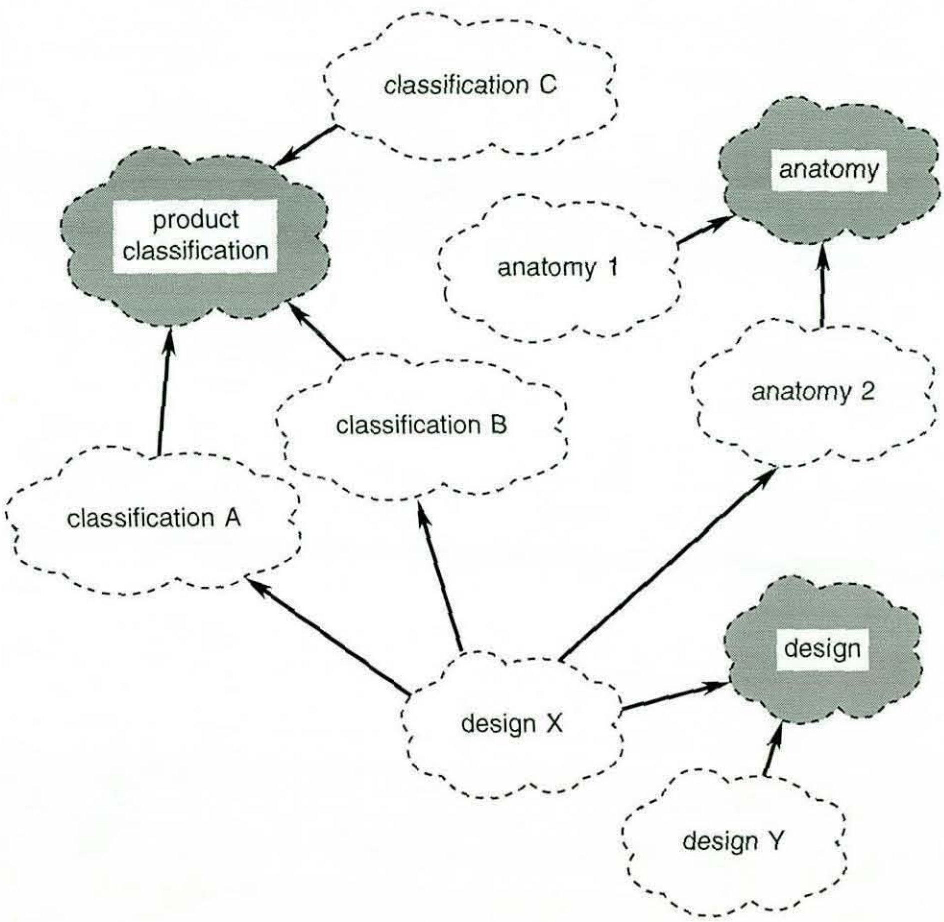


Figure 7-3 Product Classification Classes.

The product classification design context provides a useful means for establishing standard product specification defaults for a design. The 'hard wired' system implementation only supported a single set of defaults, initialised at the beginning of each session, suitable for a 5 iron based on a

---

[1] Inheritance is the only class relationship that can be specified within the DUCT OODB.

particular anatomy. The selection of multiple product classes allows the user to refine the parameter default environment beyond that associated with an anatomy type and related feature type algorithms. Predefining product classes and attributes corresponding to a company's standard parameter specifications for each member of a set provides the user with the means to specify hybrid reference environments for design development.

For example, for golf club design it is convenient to specify a product class for each iron in a set, with associated default attribute values for loft, lie offset etc. Thus by assigning, for example, the 6 iron class to a design class, the anatomy and general shape algorithm parameter defaults can be overridden to mimic those of a company standard 6 iron. It is also convenient to predefine classes and attributes to characterise each of the members of a brand set. Thus by also assigning, for example, the Tour Ltd. 6 iron class to the same design the shape algorithm parameter defaults are further refined to mimic the styling of the Tour Ltd. range as well. This provides the designer with an efficient means to focus design development, essentially by allowing them to communicate their initial intent, in this case to design a club based on the company 6 iron specification similar in styling to the Tour Ltd. 6 iron.

Table 7-2 lists a selection of 'product classification' classes implemented within the golf club system, showing a range of attributes defining default set specification and brand styling parameter values.

The revised data model (Chapter 5 Section 2.3 indicates that the anatomy classes themselves could be classified in the same way. As previously discussed, this approach could be used for global parameters controlling most if not all of the features (e.g. for assigning a default shoe last parameter standard to an anatomy) and for assigning non-geometric attribute defaults to the anatomy (e.g. a standard material representation). This would allow designers quicker access to a default design environment, as selection of a particular anatomy would infer a default product classification, thus allowing them to avoid further unnecessary classification selections. However, DUCT's restrictions on multiple inheritance for metaclasses prohibit this approach.

Table 7-2 Typical Product Classification Classes

Class	Parents	Attributes		
ProductClasses				
ParameterStandards	ProductClasses			
default1iron	Parameter-Standards	loft	15	variable
		lie	57	variable
		offset	-3	variable
		TSwidth	25	variable
		HSwidth	10	variable
		solFBoff	10	variable
default5iron	Parameter-Standards	loft	28	variable
		lie	61	variable
		offset	1	variable
		TSwidth	33	variable
		HSwidth	14	variable
		solFBoff	13.0	variable
BrandSets	ProductClasses			
TourLtd	BrandSets	pinchHgt	26.2368	variable
		chordAngle	20.3301	variable
		toeSTradius	67.5	variable
		soleHTradius	153	variable
		topToeRad	7.0	variable
		soleToeRad	16.9	variable
TourLtd1iron	TourLtd	loft	16.2	variable
		offset	-2.1	variable
		solFBoff	10.05	variable
TourLtd5iron	TourLtd	loft	30.1	variable
		offset	3.8458	variable
		solFBoff	13.0958	variable

1.5. Feature Instantiation

The most obvious means for a feature instance class to possess the default attribute values resolved within the design instance class is inheritance. Combined with the other inheritance structures described previously, tempered by the DUCT restrictions already discussed, it seems the most natural data model implementation is to have a class structure exemplified by the inheritance relationships for a particular feature instance shown in Figure 7-4. The ultimate feature instance class would inherit behaviour based on its type, an anatomy context, an associated shape algorithm, and the specific design context. Attaching this class to the DUCT geometry created by the shape algorithm would establish a permanent feature application record (Chapter 5 Section 2.3.3).

However, this inheritance structure also requires that metaclasses (the anatomy feature, type indicator and design classes) have children (the type indicator and feature instance classes), and so it can not be used within DUCT. Furthermore, for the feature instance class to inherit default parameter attributes from the design class would introduce the control parameter redundancy previously avoided by careful selection of the global parameter attributes attached to the anatomy entity.

Therefore, the class structures illustrated in Figure 7-5 were implemented instead.

Because the system can only hold a single anatomy variant at one time there is less reason to have anatomy independent shape algorithm classes. Only the potential to avoid redundancy where features can have similar shapes within the same anatomy still makes this class structure desirable. However, the additional benefits of anatomy feature specific parameter names for the EF shape algorithms, and a reduction in class structure complexity lead to the conclusion that the EF shape algorithm classes are best implemented as anatomy feature instances (given the current limitations in DUCT). Only the blend shape algorithms have independent classes, listed in Table 7-3, that are inherited by the various blend feature shape instances.

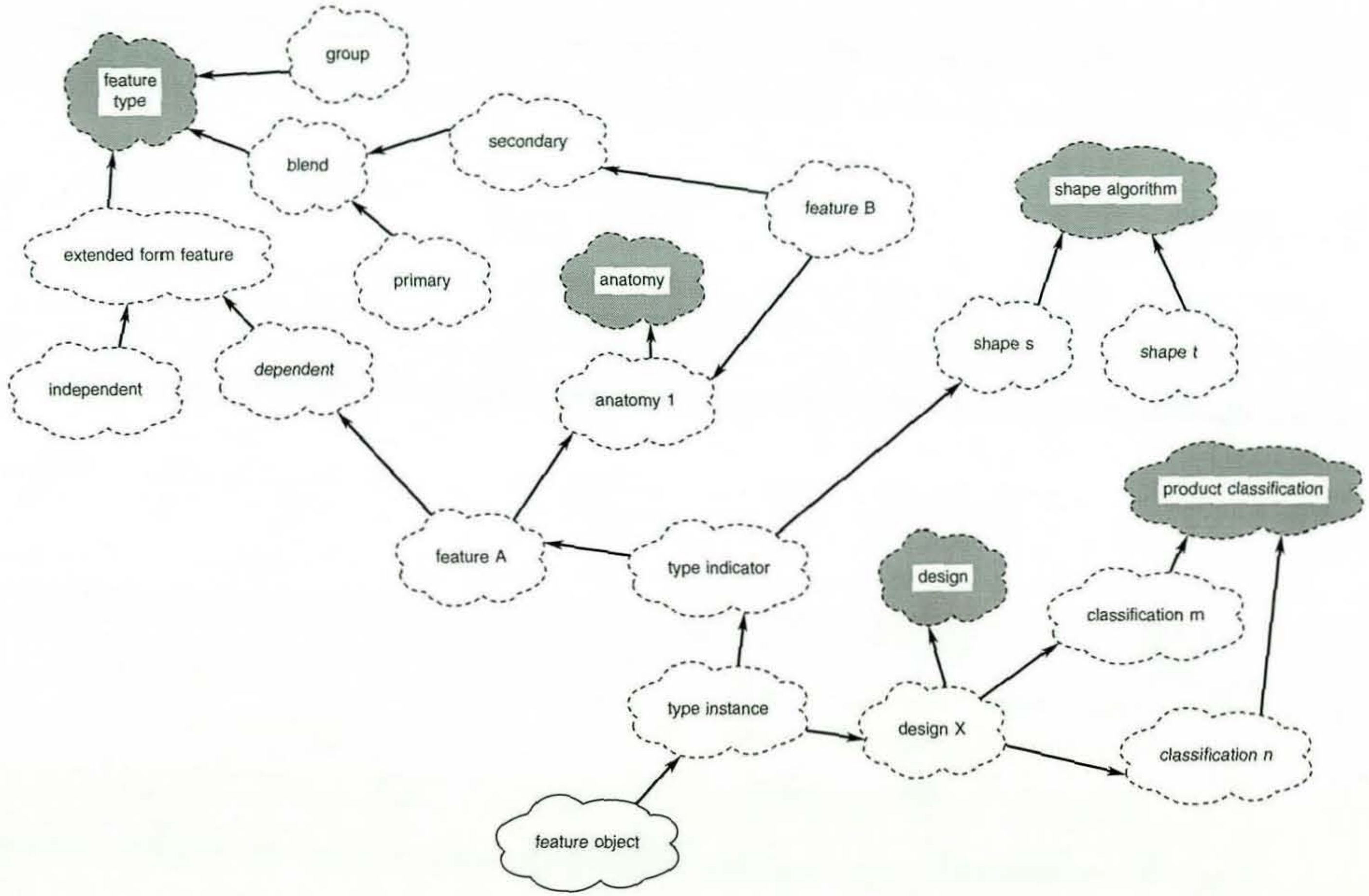


Figure 7-4 Natural Class Inheritance

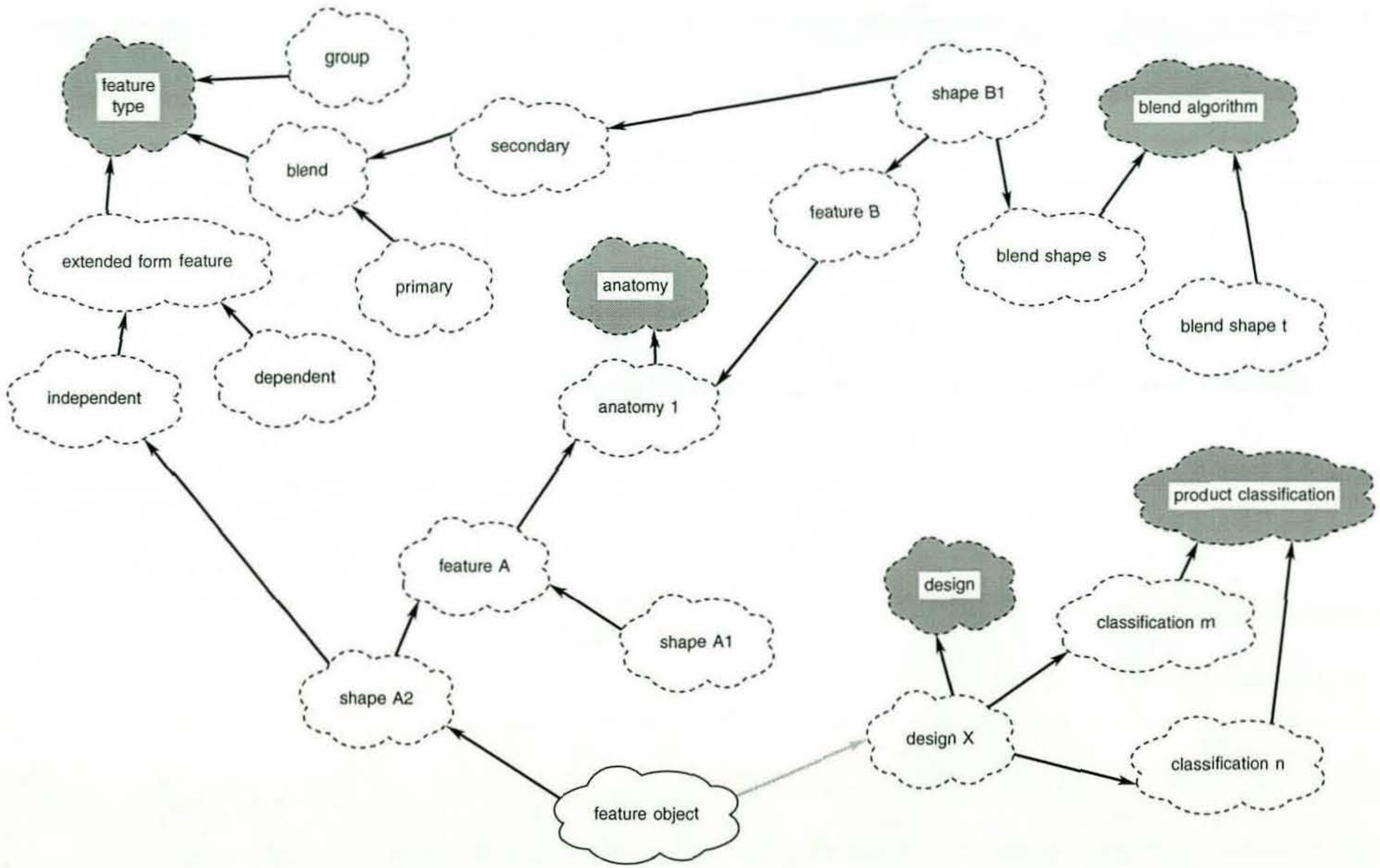


Figure 7-5 Actual Class Inheritance

Table 7-3 Blend shape algorithm classes

Class		Parents	Attributes		
BlendAlgorithms					
	ConstantRadius	BlendAlgorithms	Radius	'unspecified'	variable
			ShapeComf	'ConstantRadius'	
			MaxCurvComf	'ConRadCurv'	
	VariableRadius	BlendAlgorithms	LawCurve	'unspecified'	variable
			ShapeComf	'VariableRadius'	
			MaxCurvComf	'VarRadCurv'	
	NeckBlend	BlendAlgorithms	ShapeComf	'NeckBlend'	
			NstmPos1	'1.6 2.4 2.5 3.3'	variable
			NstmPos2	'3.4 3.95 4.05 1.5'	variable
			NstmMag1	'3 3 3 3'	variable
			NstmMAg2	'3 3 3 3'	variable
			NbldMag1	'3 3 3 3'	variable
			NbldMag2	'3 3 3 3'	variable
	SimpleTernary	BlendAlgorithms	ShapeComf	'ternary'	

Because the anatomy feature subclasses can not have multiple parents and type indicator children, the anatomy feature class has an attribute indicating its type classification. Each instance of the anatomy feature is then forced upon definition to inherit type behaviour from the indicated type class directly. Furthermore, because the EF shape algorithms are implemented as anatomy feature class instances, EFF dependency is easily modelled using the type attributes in Table 7-1. If an EF feature is an instance of the dependent type class it automatically inherits dependent behaviour and a reference to a dependency anatomy feature group.

DUCT's metaclass multiple inheritance limitations also prevent the creation of a shape instance class inheriting attributes from both the shape and design classes. Instead, the anatomy feature shape class is assigned to the feature surface geometry as the object class. The design default properties are resolved within the system software, rather than by OODB inheritance, so that the control parameter defaults for each feature presented to the user are the fully resolved combination of both feature shape and design class default parameter values. This approach has the added benefit that it also avoids assigning redundant control parameters to a feature instance.

With hindsight, while it is perhaps philosophically desirable that a particular design should be an instance of an anatomy class, this introduces limited redundancy to the model, since any feature instance will inherit the anatomy's attributes from both its anatomy feature class and the design instance class. Although this is how the data structure is implemented in the revised system, the specific anatomy might be more economically assigned to the design instance class as an attribute rather than a parent.

In summary, the anatomy feature shape class assigned to the feature surface geometry with control parameter values derived from the resolved design defaults and any values specified by the user embodies the feature object, and is equivalent to the combined application record and DUCT surface entities in the revised data model (Chapter 5 Section 2.3.3).

Table 7-4 lists the classes and attributes for several typical golf club anatomy features, showing type inheritance, shape classes and default parameter settings for a range of feature types (independent EFF, dependent EFF and primary blend).

1.6. Additional Classes & Attributes

Figure 7-6 shows the main classes implemented in the revised system. There are two classes, Display Properties and Volume Properties, not previously discussed.

Table 7-5 shows typical attributes for specific display property class instances. Table 7-4 shows that the shape classes all inherit attributes from a related display class. These attributes provide a means for permanently storing indices to indicate a feature's display characteristics (i.e. whether they are shown trimmed or untrimmed, in a wireframe or shaded format, using a particular colour or material, and the number of divisions used in the wireframe mode).

Table 7-4 Golf Club Anatomy Feature Classes

Class	Parents	Attributes		
GolfIron	Anatomy			
Face	GolfIron	Type	'IndependentEF'	
		DefaultShape	'FlatFace'	
		SurfaceName	'FACE'	
		BoundaryCode	'FAC'	
FlatFace	Face	ShapeComf	'FlatFace'	
	IndependentEF	MaxCurvComf	'Flat'	
	DisplayFace	loft	30.1	variable
		offset	3.8458	variable
CavityWall	GolfIron	Type	'DependentEF'	
		DefaultShape	'ComplexProfileCW'	
		SurfaceName	'CAVWALL'	
		BoundaryCode	'CWL'	
		FeatureGroup	'Back'	
ComplexProfile-CW	CavityWall	ShapeComf	'ComplexProfileCW'	
	DependentEF	MaxCurvComf	'ComplexProfileCW'	
	DisplayCavityWall	proFile	SimpleProfile'	variable
		draftAng	5	variable
TopToe	GolfIron	Type	'PrimaryBB'	
		DefaultShape	'ConstantTopToe'	
		SurfaceName	'TOPTOE'	
		BoundaryCode	'TPT'	
		Side1Group	'Top'	
		Side2Group	'Toe'	
ConstantTopToe	TopToe	Radius	7.0	variable
	ConstantRadius			
	PrimaryBB			
	DisplayTopToe			
VariableTopToe	TopToe	LawCurve	'TopToeDefault'	variable
	VariableRadius			
	PrimaryBB			
	DisplayTopToe			

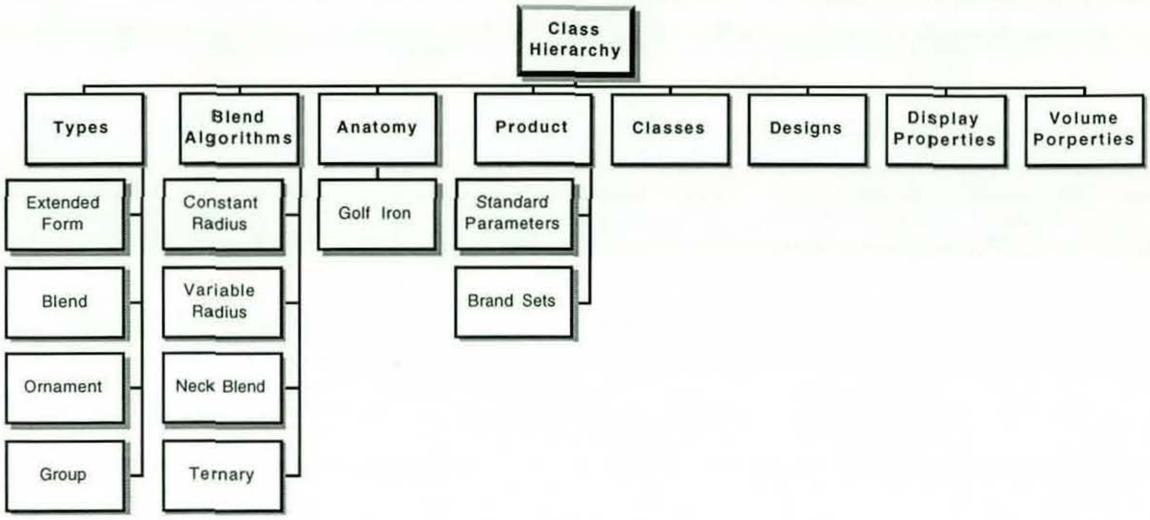


Figure 7-6 Main System Classes

The indices are assembled into a single attribute string to avoid exceeding the maximum number of attributes allowable for a single class.

The volume property class provides a means of assigning attributes as a permanent store of the results from volume property contribution calculations for an individual feature. Although these properties would be ideally inherited by the anatomy feature shape class as well, the real number attributes can not be concatenated into a small enough string to avoid exceeding the attribute limit. Instead, the class is assigned to dummy surface objects within the design part, using the corresponding feature names prefixed with the letter 'v'. Table 7-6 shows the attributes assigned to the class.

Table 7-5 Display Property Class Attributes

Class		Parents	Attributes		
DisplayProperties		-	displaySettings	'0 0 0 1 1 5 5'	variable
	DisplayFace	DisplayProperties	displaySettings	'0 0 0 11 1 5 5'	variable
	DisplayBack	DisplayProperties	displaySettings	'0 0 0 5 1 5 5'	variable
	DisplayTop	DisplayProperties	displaySettings	'0 0 0 6 1 5 5'	variable

Table 7-6 Volume Property Class Attributes

Class	Parents	Attributes		
VolumeProperties	-	calcTol	'unspecified'	variable
		volumex	'unspecified'	variable
		volumey	'unspecified'	variable
		volumez	'unspecified'	variable
		cofgx	'unspecified'	variable
		cofgy	'unspecified'	variable
		cofgz	'unspecified'	variable
		Ixx	'unspecified'	variable
		Iyy	'unspecified'	variable
		Izz	'unspecified'	variable
		Ixy45x	'unspecified'	variable
		Ixy45y	'unspecified'	variable
		Iyz45y	'unspecified'	variable
		Iyz45z	'unspecified'	variable
		Izx45z	'unspecified'	variable
		Izx45x	'unspecified'	variable

1.7. Trimming Routine

Because only a single anatomy is permissible within the system, a custom trimming routine is still used to assemble the model. Although this is partly to ease implementation, the routine follows a generic structure suitable for all EFFM based models. Since a custom routine is more efficient than a generic routine that needs to interpret the anatomy class database each time it is activated, it is likely that a future generic EFFM implementation will incorporate a generic routine for generating custom trimming routines for each anatomy (when the anatomy is created or modified) instead of a generic trimming routine.

Within the routine, feature bounding and trimming is ordered first by type, then by blend generation attribute. Figure 7-7 shows the procedure as a flow chart.

The devolved intersection for each blend is held current within the model together with the blend boundaries. The curve entity naming conflicts are overcome for specific surface parameter curves by a naming convention based on a short code property for each surface.

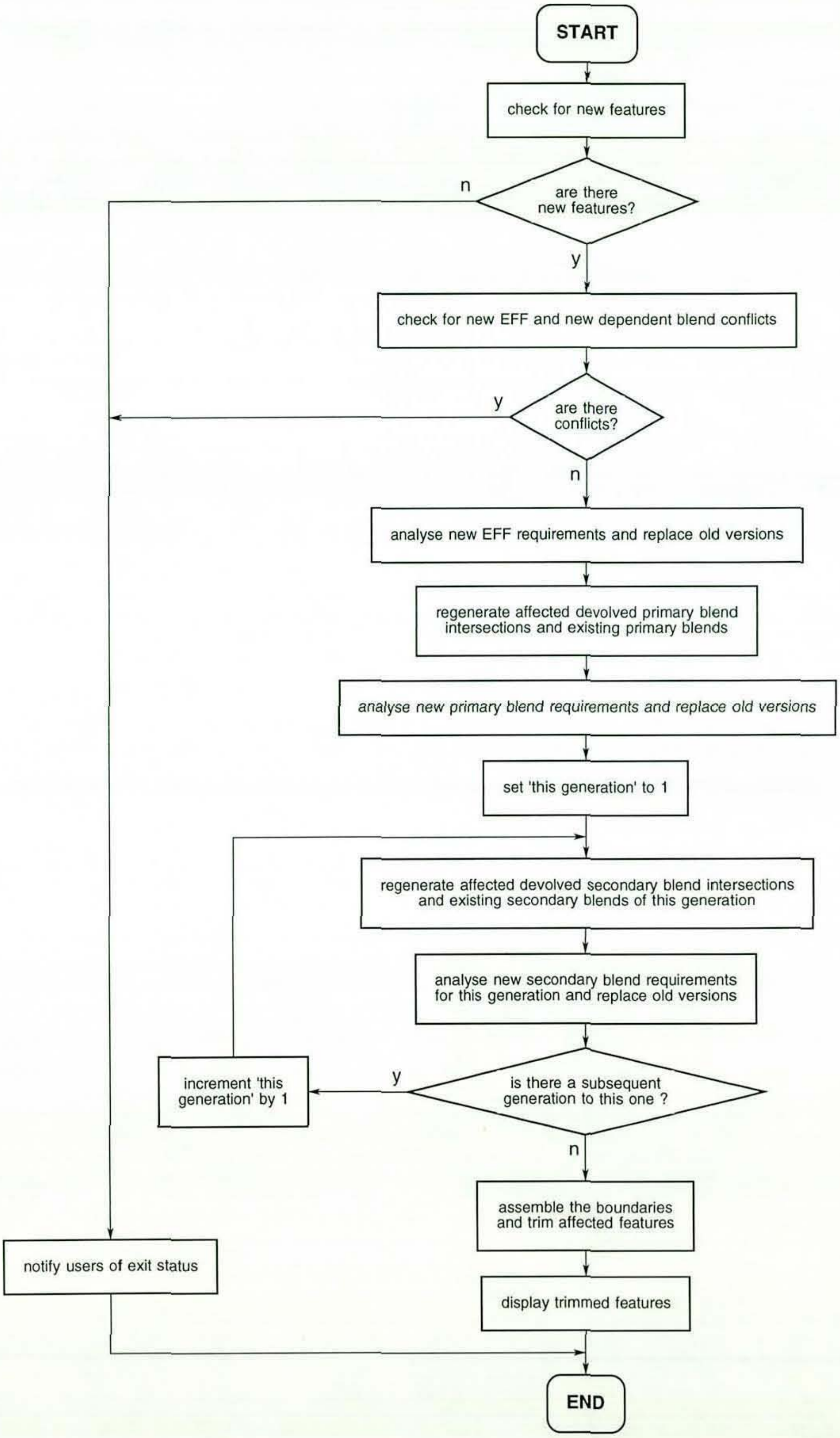


Figure 7-7 Revised Trimming Routine Flow Chart

2. REVISED USER INTERFACE

2.1. General Description

The user interface for the OODB based system implementation differs from the initial hard-wired prototype interface. The majority of changes were made to incorporate improvements identified during user trials and demonstrations of the initial prototype, to make use of additional interface customisation facilities within the DUCT 5.3 release, and to make available the additional functionality supported by the OODB data structures.

The same screen menu subdivisions are used, as shown in Chapter 6 Section 2.1, including the pop-up menu for view control available within the geometry view area. However, the separate functional regions for feature selection, library access and manipulation, global parameter editing, feature display and help, have now been programmed to be context sensitive. Thus they are only available to the user when they are functionally relevant. For example, Figure 7-8 shows the OODB implementation's startup interface. Only the library access and help menu portions are available to the user. The feature selection, display control and global parameter regions are hidden. The obvious result is a less cluttered, easier to understand interface.

The remaining significant changes are related to the interface's single design library access, design manipulation, feature selection and feature display functionality, and model trimming.

2.2. Single Design Library Access

As before, access to the system's design development functions is achieved via the 'Develop' button on the 'Library Options' (previously 'Design Options') menu on the startup screen. This activates the 'Design Development' menu from which the 'Single Club Design' menu is available.

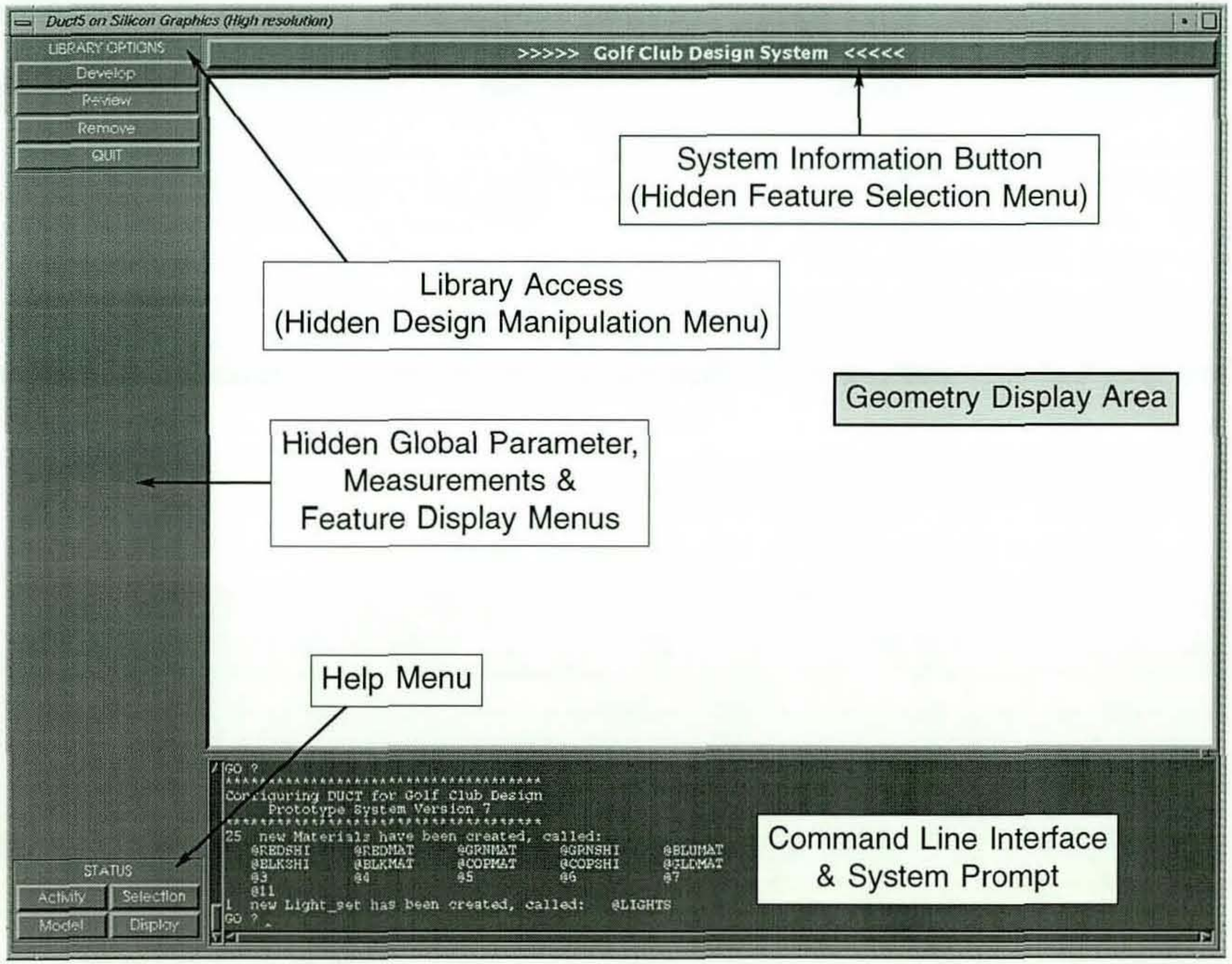


Figure 7-8 Revised Startup Interface

The previous hierarchy of menus to achieve access to a library 'space' for scratch, template based or unfinished design work has been replaced by a simpler 'flatter' interface. A single menu allows the user to activate a choice of Motif style forms for describing the type of library access required. Figure 7-9 shows the three forms corresponding to all three access modes. The last form used determines the access mode and data used to describe the design when the 'Proceed' button is activated next, thus allowing the user to change his mind without traversing through the library access menu hierarchy.

The new design forms (scratch and template based) both have scrolling selectable lists allowing the user to easily associate a predefined parameter standard and brand set class to the design, to configure the initial parameter defaults as previously discussed (Section 1.4).

Figure 7-10 shows a flow chart detailing the process of accessing a single library design for design manipulation.

2.3. Design Manipulation

Once library access is confirmed by clicking the 'Proceed' button, the user is presented with the full design manipulation and display interface shown in Figure 7-10. If an existing design (either as the unfinished subject or template) has been selected it is automatically displayed, according to the previous feature display properties now associated with each feature.

The design manipulation menu now has a 'Pick Feature Shape' button. This activates a Motif form for the currently selected feature that allows the user to select a suitable shape algorithm from a scrollable list. Figure 7-12 shows an example for the blade toe EF feature, with the default double radiused shape algorithm selected. Selecting an item from the list and clicking 'Accept' informs the system that the next new toe feature introduced should be based upon the indicated algorithm.

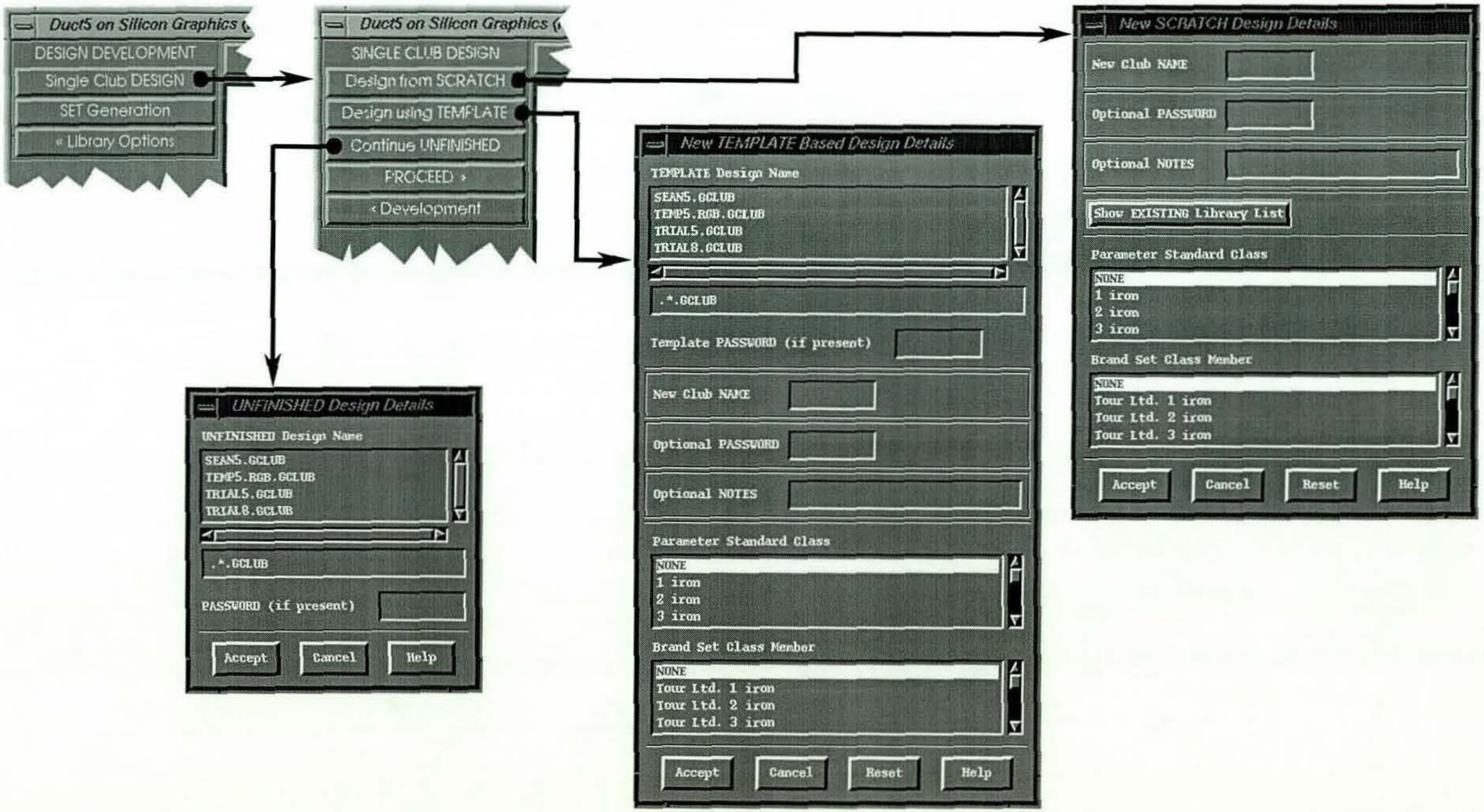


Figure 7-9 Revised Single Design Library Access.

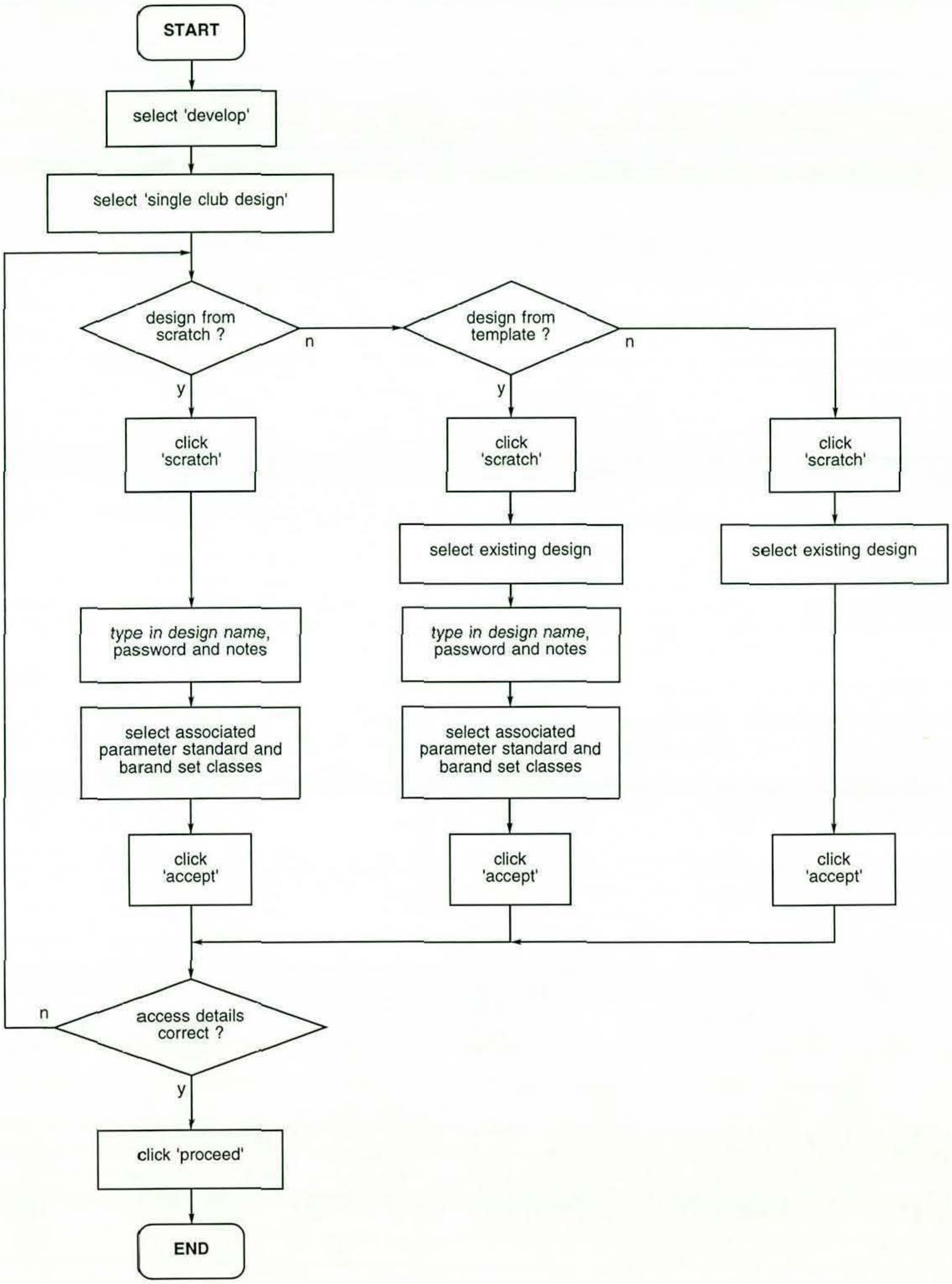


Figure 7-10 Revised Single Design Library Access Flow Chart.

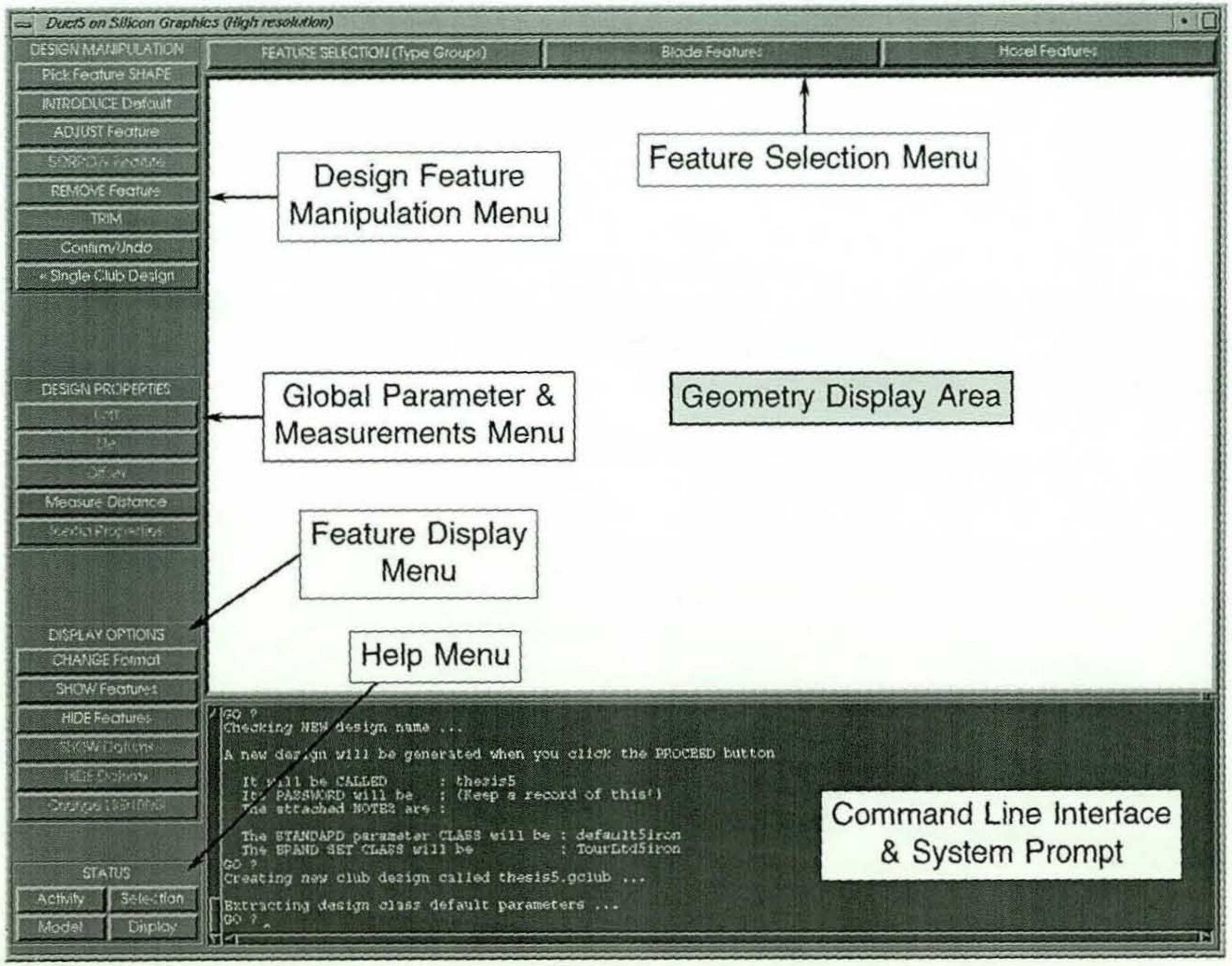


Figure 7-11 Revised Design Manipulation Interface.

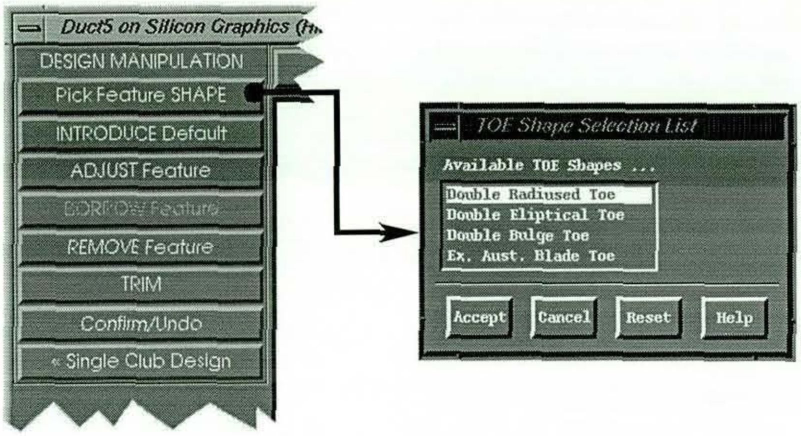


Figure 7-12 Toe Shape Algorithm Selection.

The 'Adjust Feature' button also operates differently. This command automatically introduces a new default version of the selected feature based on the selected algorithm, if one does not exist. A form is then displayed giving the user access to separate shape and position parameter manipulation forms, specific to the selected shape algorithm. Figure 7-13 shows examples corresponding to the double radiused toe algorithm. These operate in a similar way to the original parameter editing forms, except the 'Apply' button immediately changes the new feature, without removing the editing form.

Two reset options are provided on both parameter forms. The first resets the form values to the parameter values resolved from the shape algorithm, then parameter standard, and then brand set classes (the subsequent class properties having priority). The second reset option returns the parameter values to those current when the form was originally opened, thus providing a convenient means to undo recent changes.

Figure 7-14 shows a variation on the shape editing form peculiar to the cavity wall. Not only can the profile be adjusted as a 2D Bézier curve (Figure 7-15), but pre-defined profiles (equivalent to large shape parameter sets) can also be used.

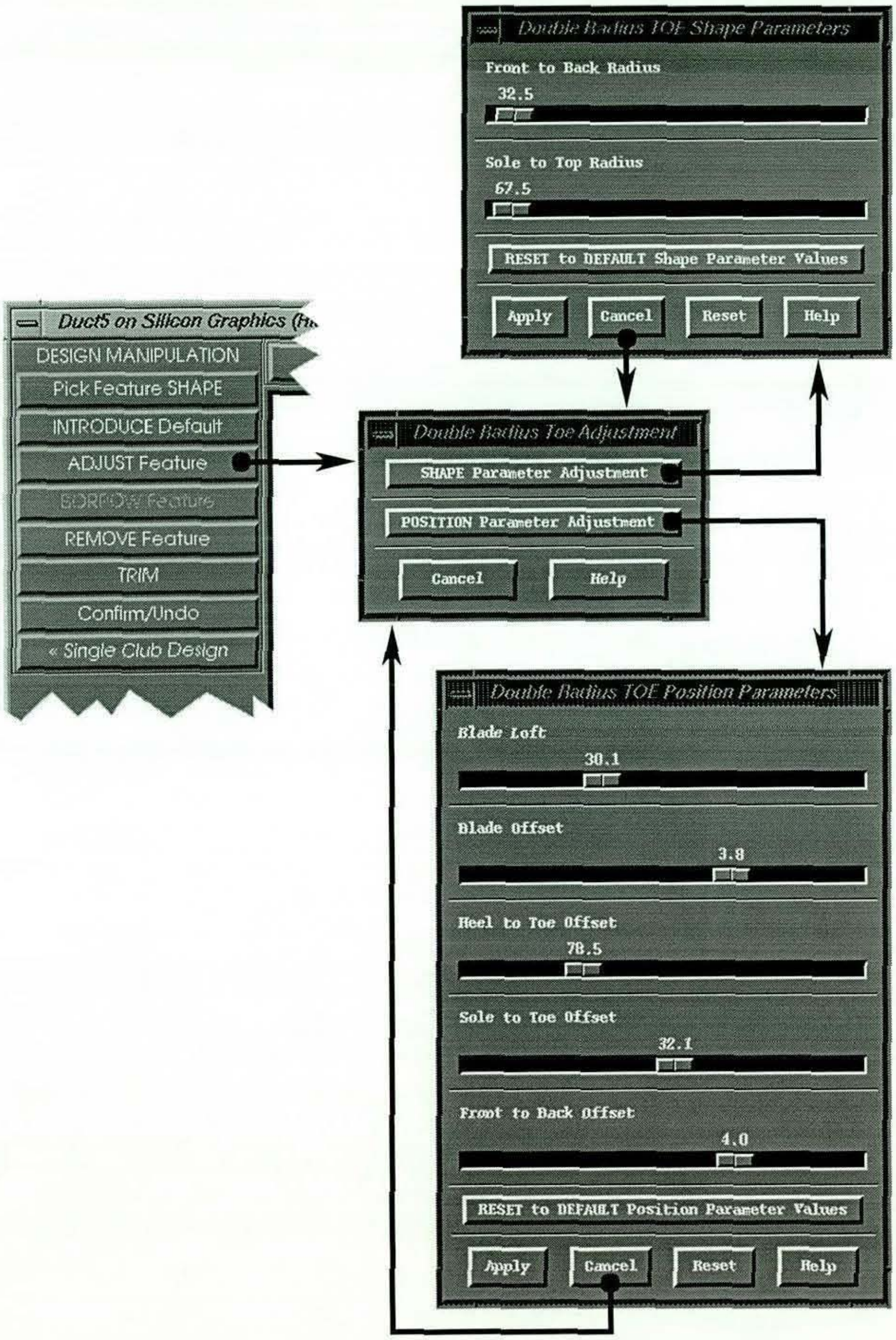


Figure 7-13 Revised Toe Feature Adjustment.

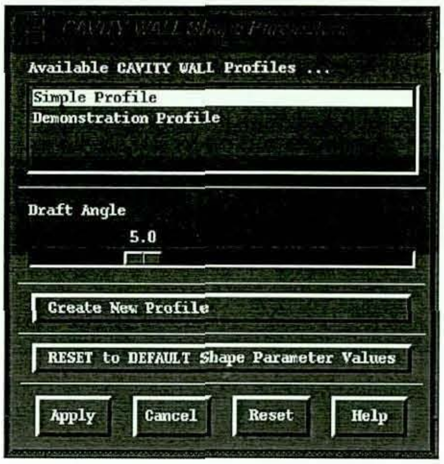


Figure 7-14 Cavity Wall Shape Form.

Figure 7-15 Cavity Wall Profile Editing.

These changes improve the interactive quality and feature adjustment speed by implementing small operation iteration loops for the adjustment process stages (algorithm selection, shape adjustment, and position adjustment). The flow chart in Figure 7-16 shows the subsequent revisions to the feature adjustment process in more detail. Otherwise the total design manipulation process is the same as that indicated in Chapter 6 Section 2.3.

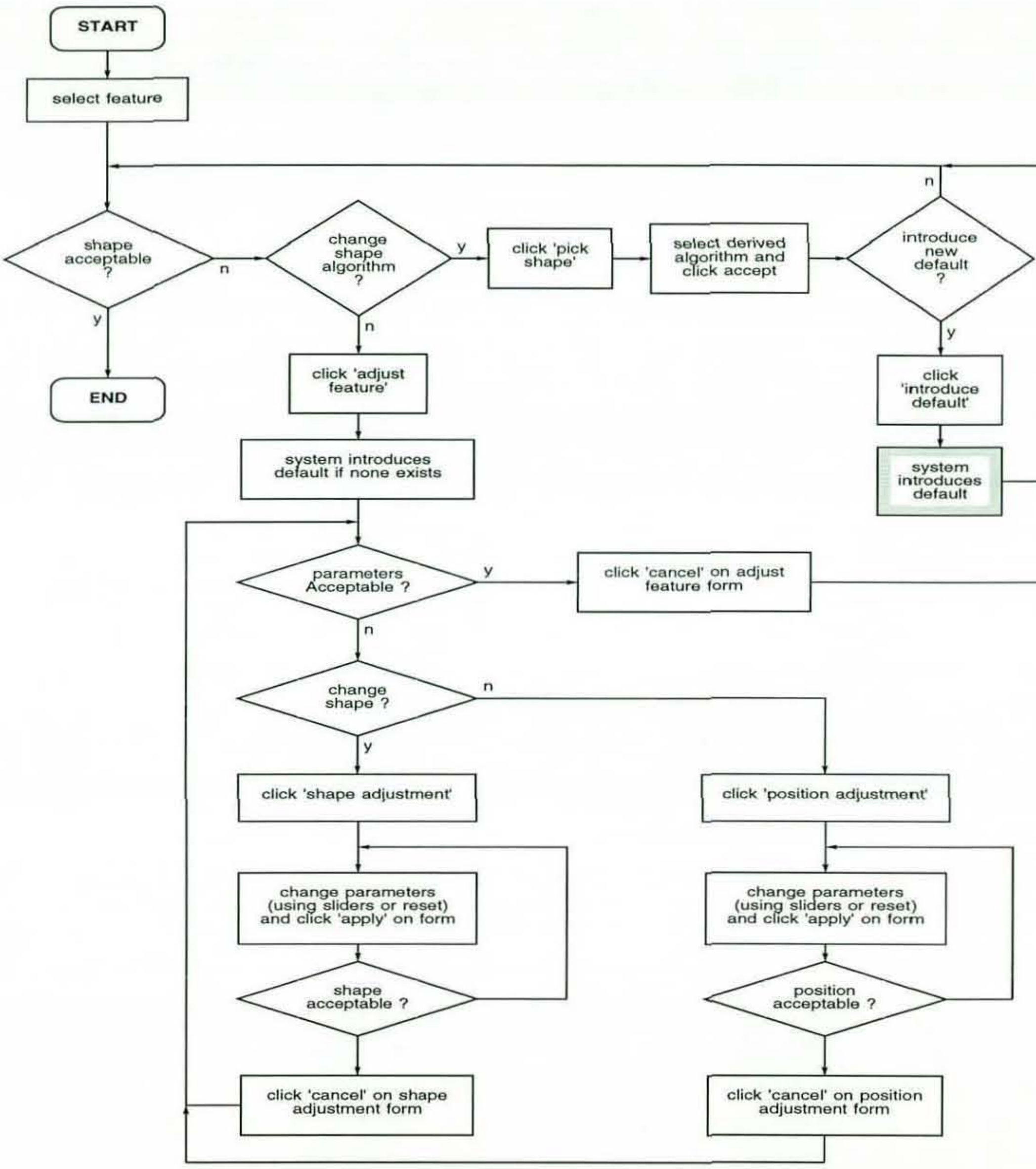


Figure 7-16 Revised Feature Adjustment Flow Chart.

2.4. Feature Selection

The feature selection menus operate under the same principles as before, except the revised OODB interface implements a slightly different hierarchy. Figure 7-17 shows examples of the pull down menus available.

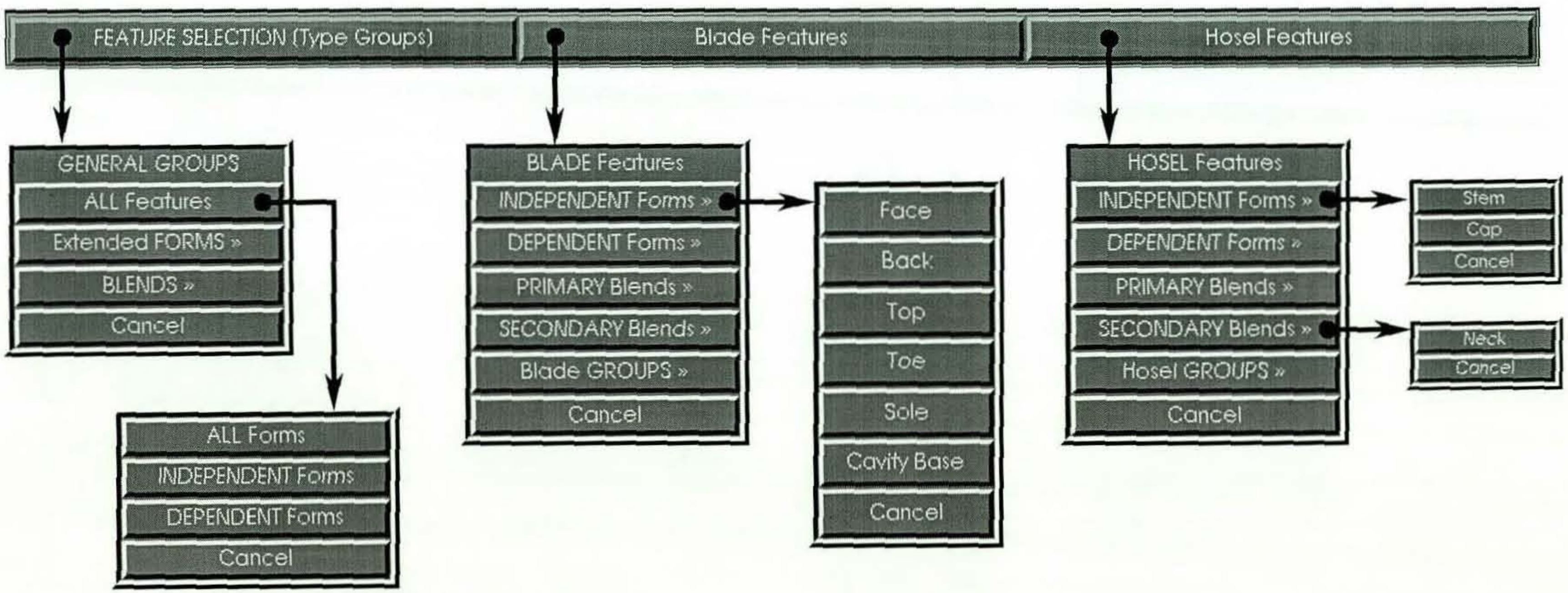


Figure 7-17 Revised Feature Selection Menus.

The 'Neck' supergroup has been removed from the top level of the menu. The neck blend feature is accessible as an item on the secondary blend sub-menu of the 'hosel features' group menu. This reflects the implementation of a complex neck blend instead of a group of EF and blend features within the neck area, made necessary by the current multi-surface variable radius filleting algorithm's limitations (as discussed in Chapter 6 Section 1.6).

The EF features have also been subdivided within the menu structure into independent and dependent classes. This classification may not be true for all algorithms associated with each feature type, but is intended to reflect the majority status for the relevant algorithms to bias the feature selection/adjustment order. The user is reminded, by the feature groupings, to consider that associated independent features may need specifying or changing before the potentially dependent ones.

Only the cavity wall and hosel bore features are indicated as being normally 'dependent' in this implementation, although several other features in the blade could usefully be classified in this way.

Figure 7-18 shows an anatomy hierarchy corresponding to the menus implemented.

2.5. Feature Display

The feature display menu has also been changed to make the menu hierarchy flatter, and so easier to use. Figure 7-19 shows the revised menu options.

The 'Change Format', 'Show Feature' and 'Hide Feature' buttons all activate a similar popup menu to the one shown, allowing the user to indicate that the target selected features are the new untrimmed or old trimmed versions. For the show and hide feature commands the new or old buttons on the popup menu directly activate the necessary display routines.

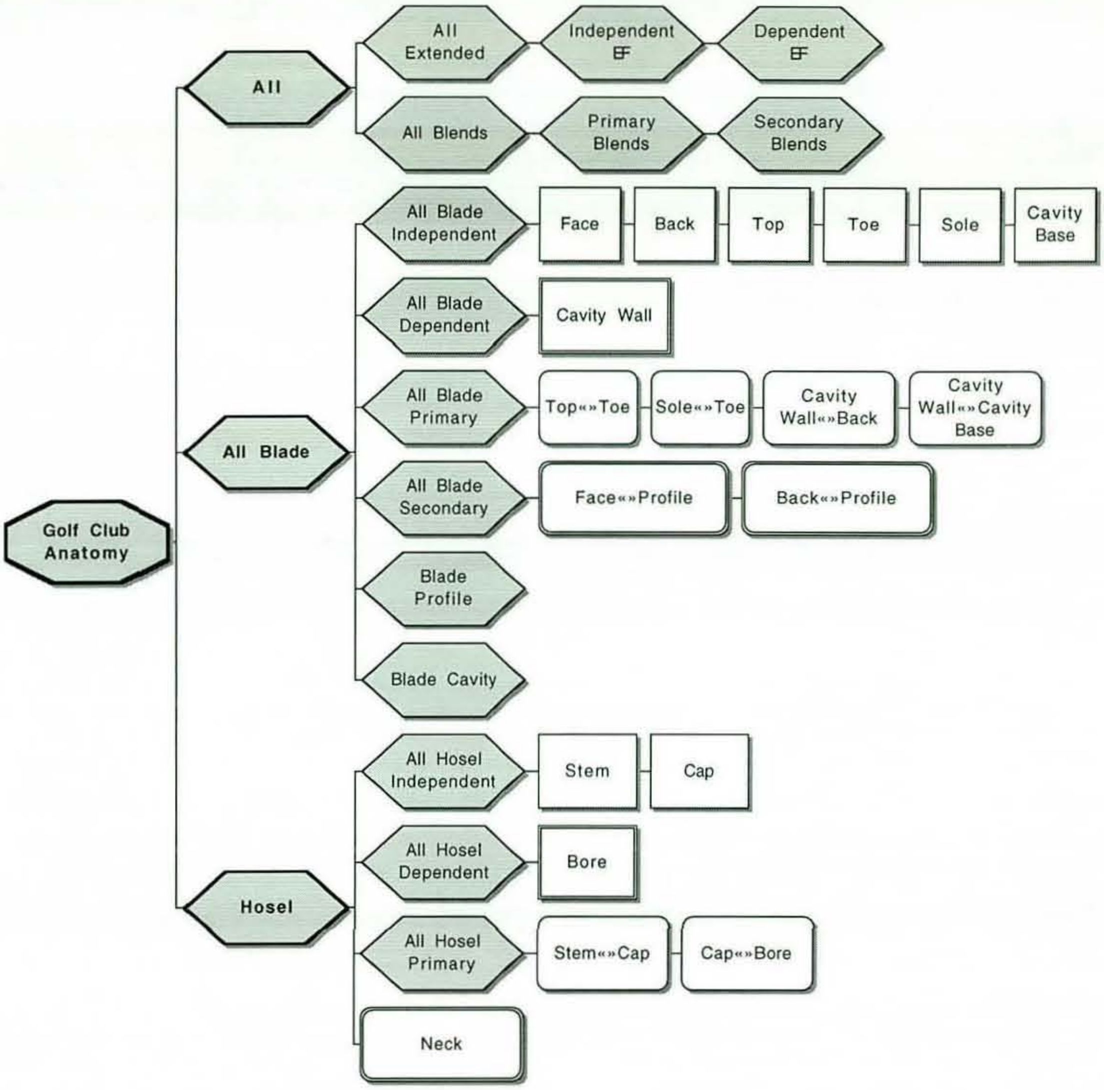


Figure 7-18 Feature Selection Menu Anatomy Hierarchy

For the change format command a format setting form is activated, also shown in Figure 7-19. This provides a more compact means for specifying the display parameters required. Activating the accept button at the bottom of the form implements the changes by passing the parameter settings to the relevant display routine. This then updates the geometry display and the properties associated with each of the currently selected features.

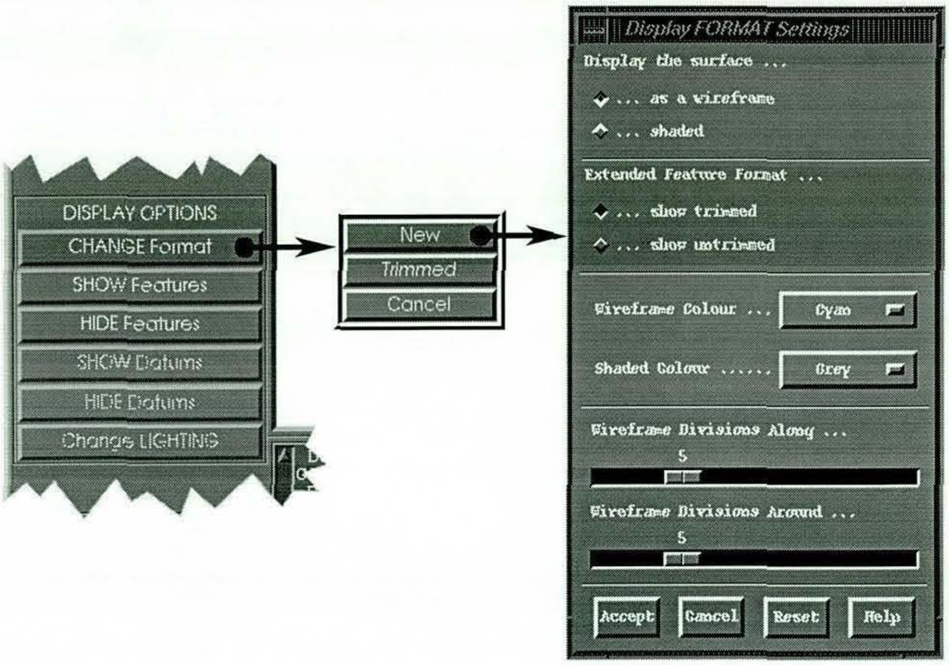


Figure 7-19 Revised Feature Format Settings Menu.

2.6. Model Trimming

Although the model trimming interface itself is unchanged, the operation of the trimming function is significantly different, and this has repercussions for the entire feature introduction/trimming process.

The initial prototype system allowed the specification of all new features at the same time and the trimming routine would automatically combine as many of the specified features as possible, introducing default blends where these were unspecified, and producing a partially trimmed model where EF features were unspecified.

The revised OODB system only permits a dependent feature, whether it is a dependent EF or blend feature, to be introduced (and so specified) when the features it depends on are already present in a trimmed state. To achieve this the independent features must be defined first and then trimmed. The new trimming routine produces a trimmed model using the devolved intersection of the missing blends. The dependent EF features can then be introduced and similarly absorbed into the model. The primary blends, and subsequent generations of secondary blends can then be introduced and also trimmed into the model.

This approach appears to dictate a rigid design process order, which at first seems at odds with the goals for the design system. However, although a logical sequence is enforced, based on feature dependency, there is still some latitude for the designer. The order in which independent feature algorithms, or the features in other anatomy subgroups such as the blade or hosel, are specified is still flexible. Only the reasonable constraint of ensuring all associated features are defined before considering a particular dependent feature is enforced. The resulting design process arguably better mimics the manual sculpting process, where for example it would usually be undesirable to style a cavity wall profile before considering the blade profile, and impossible to model without forming the back surface first.

This staged approach to model trimming has several additional benefits:

- The user is able to see the club shape develop gradually, without the need to interpret a confusing combination of extended features. This allows them to predict the ultimate shape more accurately before committing themselves to the computationally more time consuming later generation dependent EF and blend features. Consequently, the earlier generation features are more likely to be acceptable once blending is complete. This reduces the number of full model refinement iterations, and so makes the refinement process more efficient.

- Although the additional computing time required to calculate the devolved intersection increases the total amount of time the designer actually waits for the system to trim a model, only the later trimming operations take as much time as the original 'full model trimming' implemented in the initial prototype. The trimming process is much quicker in the early stages[1]. This results in a better interaction response

[1] 28 seconds for all the independent forms, instead of 70 seconds for the full model using the first prototype.

time. This further reduces the creativity 'bottle-neck', allowing the designer to quickly experiment with and refine different ideas.

- Because the trimming process is fragmented into quicker stages, the user is presented with the illusion of model trimming efficiency. The benefits of staged trimming in this way arguably outweigh the total time penalty, and in the hands of a good designer it is likely that the reduction in full model trimming iterations resulting from better predictive information will outweigh the additional 'hidden' processing time[1].

Figure 7-20 to Figure 7-23 show several different trimming stages in the development of a typical golf club. Figure 7-23 shows all the features trimmed and colour coded by type (grey independent EF, light blue dependent EF, green primary blend, mauve generation 1 secondary blend and crimson generation 2 secondary blend features).

[1] The revised system takes 30 seconds on average to re-trim the model at any stage, 10-30 seconds to generate each primary blend and 45 seconds for the secondary blends. The inital prototype took 70 seconds to blend and trim the entier model. Obviously generating multiple surface blends is increasing the total time in the revised system as well as the additional intersection calculations, but the waiting is split into smaller chunks.

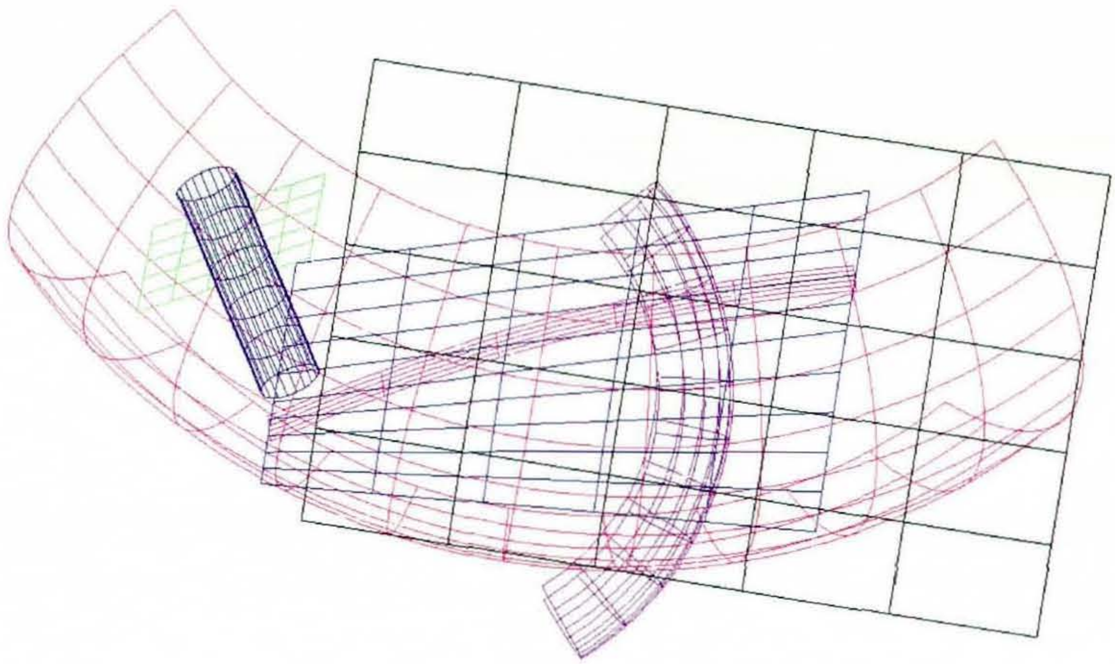


Figure 7-20 Untrimmed Independent EF Features.

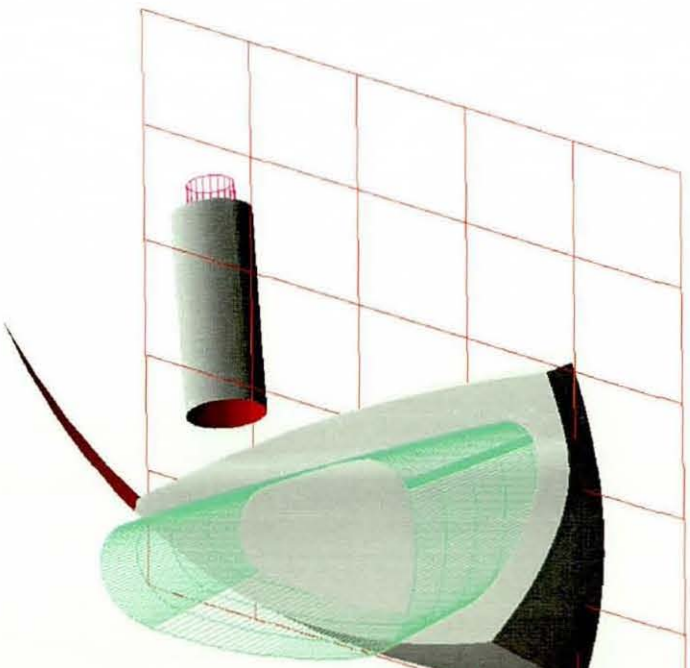


Figure 7-21 Trimmed Independent EF, Untrimmed Dependent EF Features.

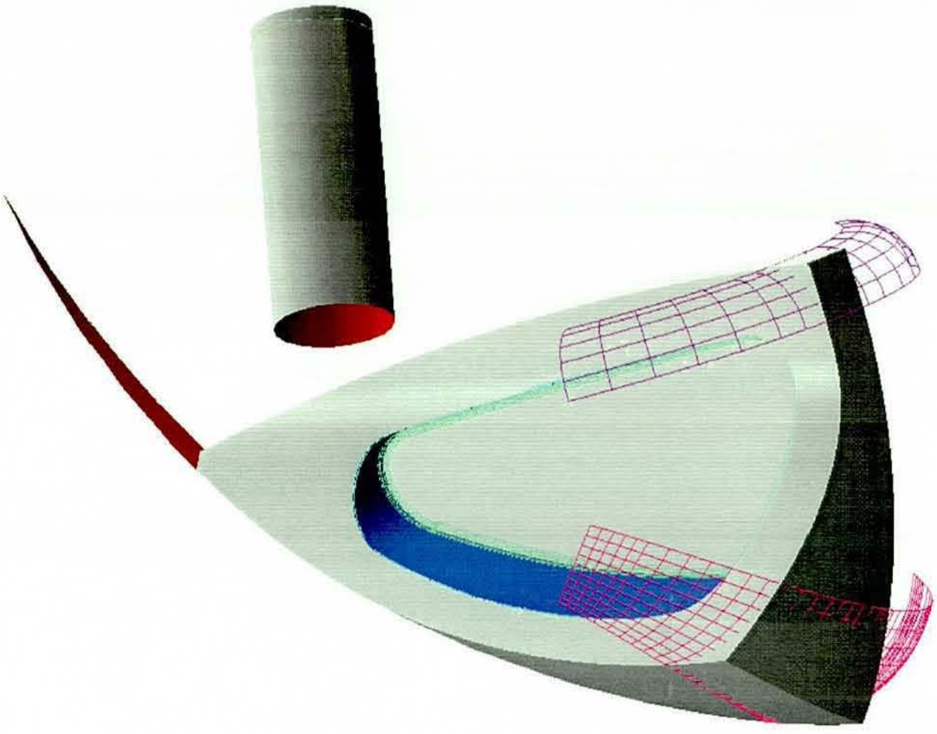


Figure 7-22 Trimmed EF Features, Untrimmed Primary Blends

Figure 7-23 Colour Coded Trimmed Features.

3. GENERIC APPLICABILITY

Again, the revised system is not a full implementation of the EFFM data model proposed in Chapter 5, but it demonstrates significant advances towards this end, particularly with regards to data storage and attribute inheritance, multiple feature shape algorithms and the trimming routine procedures.

As mentioned previously, the trimming routine is not a generic one that interprets the class database, but a custom routine specific to the particular club anatomy. In practice this could be generated as the anatomy is defined, or subsequently modified, and attached permanently to the particular anatomy class as a method. Thus it would be immediately available every time a design associated with that anatomy was manipulated.

The single anatomy restriction could be overcome in the short term by 'swapping' the current anatomy for an alternative held in an external storage area.[1] Currently this takes a long time, particularly as the DUCT OODB does not allow parent classes to be edited.

Most of the GUI elements that change between anatomies still have common elements, such as a feature selection menu definition. There is no apparent reason why these should not also be specified interactively when the anatomy itself is defined and also attached to the anatomy as a menu configuration method.

---

[1] Essentially by loading anatomy definition class hierarchies into and out of the DUCT OODB.

CHAPTER 8. USER TRIALS

1. TRIAL DETAILS

1.1. Introduction

Chapter 3 Section 1 states that the original research aims were:

- Primarily, to place the use of powerful 3D CAD software within the reach of creative designers in sculptured product industries, with minimal retraining, by inventing, implementing and proving a 'feature assembly' metaphor for the design process.
- Secondly, to make as much additional use as possible of this approach to improve CAD process efficiency.

Although the efficiency gains are easily demonstrated by comparing the effort required by an experienced DUCT user operating both the prototype EFFM based design system and using DUCT in its native configuration to achieve the same results, this does not necessarily prove ease of use.

To prove that EFFM based design systems provide the ease of use required by the first research objective a user trial was undertaken.

1.2. Subjects

13 subjects, generally with no previous use of CAD and mostly no previous exposure to the EFFM based prototype golf club design system[1], were selected for training and system operation tests. Most of the subjects were young or middle aged professionals.

7 of the volunteers were interested academics with a sports or technical background. Most of them were keen golfers. The remaining 6 volunteers

---

[1] None of the subjects had hands on experience of the golf club design system, although three of the subjects from DSI were aware of the research and its progress.

were DSI personnel, 4 of whom came from the company's marketing department. Because of their close involvement in the research, it was inappropriate for the club development engineers at DSI to participate in the trials. However, they also underwent a similar degree of training and subsequently demonstrated comparable levels of competence to those shown by their colleagues in the trials detailed in section 2 of this chapter.

It was important to DSI that their marketing personnel were involved in the trials for two reasons. Firstly, the various product range managers have considerable influence over the development of club shapes and styling, although they have no 'hands on' design experience either as craftsmen or as CAD operators. DSI management hoped that a feature based design system would make active involvement in the design process possible and even attractive to relevant marketing personnel, primarily to reduce the number of iterations normally required for a CAD operator to interpret requests from marketing personnel for a design change. Secondly, DSI hoped that hands on experience of the system would raise awareness of the design process issues, and promote acceptance of the system as an efficient means of addressing these issues.

From a research perspective, the DSI marketing personnel were the only population of subjects professionally involved in golf club design available for user trials. Their lack of experience in manual crafting, and more significantly computer based design techniques, provided an ideal opportunity to evaluate the systems intended ease of use and minimal training requirements. The other volunteers had similar computer skills. Most, although not all, were proficient with the monitor-keyboard-mouse computer hardware and point and click windows style interfaces from their use of IBM clone personal computers, but only four (R. Jones, G. Blount, R. Doyle and D. Walters) had previous CAD system experience.

Table 8-1 lists the participant's names and affiliations.

Table 8-1 User trial subjects

	Name	Department/Title	Organisation
A	R. Doyle	Manufacturing Engineering	Loughborough University
B	D. Walters	Manufacturing Engineering	Loughborough University
C	G. Blount	School of Engineering	Coventry University
D	R. Jones	School of Engineering	Coventry University
E	R. Braddon	Euro-Group Product Manager	DSI
F	P. Lambert	Golf Project Manager	DSI
G	N. Blofeld	Slazenger Euro Brand Manager	DSI
H	A. Swain	Physical Education, Sports Science & Recreation Management	Loughborough University
I	M. Smith	Maxfli Euro Brand Manager	DSI
J	N. Halliwell	Mechanical Engineering	Loughborough University
K	P. Jansen	Euro Sales & Marketing Director	DSI
L	G. Gandy	Physical Education, Sports Science & Recreation Management	Loughborough University
M	M. Shaw	Manufacture & Development Director	DSI

1.3. Tasks

The subjects participated in the trial in pairs. Where convenient one academic and one member of DSI were paired together. Generally both subjects had similar computing experience and this approach meant that at least one person was familiar with golf club design activities within the golf industry.

The trials were based on the prototype golf club design system described in Chapter 6. Each pair was introduced to the system, trained in its use through a detailed demonstration and explanation by the author, and then observed while completing a series of 6 design tasks. All this occurred on the same day according to the timetable presented in Table 8-2.

Table 8-2 Training and Trial Timetable

Time	Activity
10:30 AM	Introduction to golf club design and the principles of feature based design CAD software
11:00 AM	Full Golf club design system demonstration, including design from scratch, existing design modification, and automatic set generation
12:30 PM	Lunch
2:00 PM	First Subject Trial
3:00 PM	Second Subject Trial

The subject's were timed by an independent observer, to prevent any further system explanation or demonstration by the author. The observer was instructed to provide minimal prompts, in the form of suggested corrective action, where the subjects were unable to proceed on their own, although this was seldom necessary.

The evaluation process was based on six tasks to be complete by each user, as follows:

i) Retrieve a default 5-iron club design from the design library.

This task requires the user to navigate the system menus from the root menu to locate the library access menu for template based design activity. The user must then use the interface forms to identify the correct library design, and then activate the commands to retrieve it from the system and create a new design for the subsequent design activities. They must also identify the correct menu commands to select all the club features and display them in the geometry window as this functionality was not automatic in the initial prototype.

ii) Change the blade toe's sole to top curvature from the default value to 450 mm.

This activity requires the user to identify the blade toe EF feature as the relevant feature controlling this particular club characteristic. They must then 'select' this feature using the 'Feature Selection' menu and then activate the 'Feature Adjustment' command. Having identified the correct parameter on the Motif form displayed by the system they must then adjust its value using the 'slider' widget provided. The user must then activate the correct buttons to initiate new feature generation, and then activate the menu command to re-trim the club model.

iii) Change the top to toe blend radius from its default value to 20 mm.

This activity requires the user to identify the blade top to toe blend feature as the relevant feature controlling this particular club characteristic. They must then 'select' this feature using the 'Feature Selection' menu and then activate the 'Feature Adjustment' command. Using the single blend radius parameter 'slider' widget provided they must then adjust the feature parameter value and then activate the correct buttons to initiated new feature generation. Finally they must again activate the menu command to absorb the new blend and re-trim the affected features in the club model.

iv) Change the length of the blade from its default value to 90 mm.

To complete this task the user must again identify the blade toe EF feature as the relevant feature controlling this particular club characteristic, selecting, adjusting and generating it as before. The model must then be re-trimmed.

v) Modify the cavity wall shape to follow the new blade shape.

The cavity wall feature must be identified and selected. Using the 'Adjust Feature' menu button the user then recalls the Motif form providing access to the profile sketching functionality embedded in the algorithm interface for this feature. Typically the user will then sketch and edit the profile (in the form of a 2D Bézier curve) and generate a new cavity based on this profile. The model must again be re-trimmed.

vi) Produce a 1 and 8 iron based on the club designed in tasks (I) to (v).

To complete this task the user must first save all the changes to their new design and then navigate through the menu hierarchy to the automatic set generation commands. At this point the user must select his design as the template for set generation and use the individual club parameter variation forms to request generation of a 1 and 8 iron before activating the automation routines. After a brief wait the user may then retrieve the snap-shot images produced to simultaneously review the results of the generation process.

2. Trial Results

2.1. Native Use of DUCT

In the following sections the results from the user trials are presented with respect to a minimum time requirement based on the time taken for an experienced user to perform the same tasks using the design system. Given the user's familiarity with the system this is a close approximation to the interaction and processing time required by the system itself, as the time taken to explore the interface and interpret the commands and control element functions is greatly reduced.

However, for this benchmark to be even more meaningful it must be first compared with the time taken to achieve similar tasks using the native DUCT interface.

Firstly, to gain sufficient experience to attempt to modify a golf club model using DUCT alone typically requires 2 weeks of training with Delcam, and a further 2-4 weeks experience with the commands pertinent to modelling golf clubs using an EFF and blend approach. The user must be familiar with generating DUCT Bézier surfaces with the shape properties they require as the EF features. They must then be able use the DUCT blending facilities to produce the required blend features and also know how to produce boundaries from the blend tangency curves for the individual surface features, so that the model can be trimmed. Without this level of training it is impossible to manipulate a golf club model. DUCT itself is too powerful to allow intuitive use of its command language or interface to initially attempt anything but the simplest tasks.

The time taken to perform trial tasks for an experienced DUCT user using the native interface are as follows:

i) Retrieve a default 5-iron club design from the design library: ~45 seconds.

This is relatively quick to achieve with three typed command lines, instead of navigating a menu hierarchy. However a significant proportion of the time (20 seconds) is required by DUCT itself to retrieve the part from disk to memory and display a trimmed shaded model.

ii) Change the blade toe's sole to top curvature from the default value to 450 mm: ~30 minutes.

Firstly the user must generate a new toe surface, or edit the control points for the existing toe surface to achieve the correct extended shape. Even though the shape behaviour in this instance is fairly simple it still takes several minutes to calculate the 3D coordinate vectors and type the correct commands. Once this is done the two primary binary blends and secondary binary blends associated with the toe feature must be removed, together with their tangency curves. New top<>toe, sole<>toe, face<>profile and back<>profile blends must then be re-generated based on the new toe feature. The boundaries on the top, toe, sole, back, face, top<>toe, and sole<>toe features must then be redefined based on the new tangency curves before the model can be re-trimmed and shaded. The time taken to re-blend and re-bound the affected features is considerable.

iii) Change the top toe blend radius from its default value to 20 mm: ~20 minutes.

Because the DUCT blend algorithms can be easily controlled using a single blend radius, and there are two less features affected by this change it is quicker to implement. Otherwise the procedure is similar to that for task (ii).

iv) Change the length of the blade from its default value to 90 mm: ~25 minutes.

Apart from simply moving the toe feature the desired amount instead of adjusting its shape, the procedure for this task is exactly the same for task (ii).

v) Modify the cavity wall shape to follow the new blade shape: ~ 30 minutes.

The additional complexity of the cavity wall surface shape behaviour makes the shape adjustment more time consuming. The user must define the shape profile, project it onto the back surface and then produce the correct draft angle surface development. However, because only two other EF features and two blends are affected, the re-blend and re-trim times are reduced.

vi) Produce a 1 and 8 iron based on the club designed in tasks (1) to (v): ~ 4-6 hours

To complete this task the user must adjust all of the EF features in a copy of his new design, and consequently regenerate most of the associated blends and boundaries twice (once for each club). Even if only the position parameters for the EF features change this takes a long time.

Each of these time estimates is based on error-free non-stop command line interaction with DUCT. Generally it is not possible to maintain the level of concentration necessary to produce accurate results at this speed, even though the tasks are repetitious. However, even typing commands to a prepared script, it would take an experienced user ~6 hours of typing using DUCT's native interface to perform the six tasks described. The time estimates are also based on DUCT's revised functionality in the 5.2 and 5.3 releases. The earlier releases lacked some of the boundary definition automation tasks. Thus using the 5.0 and 5.1 releases for which the initial prototype was developed the tasks would take even longer.

DSI's own experience in modelling golf clubs using DUCT is that it takes 12-16 hours (1.5 to 2 working days) to produce a single golf club design. Any major revisions to a design would require a significant amount of that effort to be repeated, perhaps 8 hours (1 working day) for extensive modifications. Thus, in their experience, the user trial tasks might be expected to take 2 to 3 days. They would take at least 3-4 weeks to model a full set of new clubs.

For an experienced user operating the EFFM based golf club design system all six tasks can be completed in under 17 minutes. A new design, or extensive design modifications, can be produced in 15 to 30 minutes. A full set of matching irons with wireframe and shaded 'snapshot' comparison images can then be generated automatically by the system during the user's lunch hour.

2.2. Inexperienced User Results

Figure 8-1 (a) to (f) show the time taken by individuals and pairs to complete the six tasks. Figure 8-2 shows a graph of the combined times required for all 6 tasks. Figure 8-3 shows a graph comparing the minimum amount of time to complete each task compared with the average time taken by the subjects.

The trials do not represent a rigorous evaluation of the system. The subject population was small (because of the difficulty in finding suitable subjects), the test were performed in a research environment (although quiet and with reasonably lighting, the subjects were not isolated from all distraction under tightly controlled conditions) and the tests involved an element of subjective supervision and prompting. The sessions were not video recorded or analysed in any way other than to note the time taken for each task and any useful comments made by the subjects.

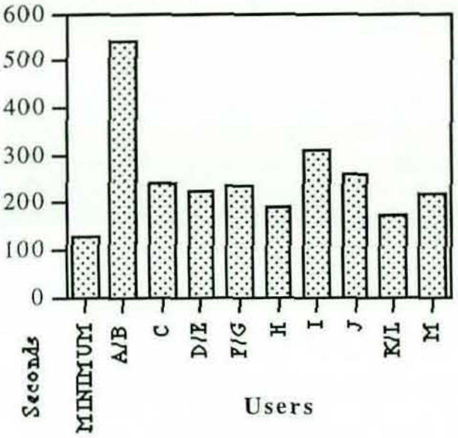
When performing each task some time is required to manipulate the geometry view to examine the results. The amount of time actually taken to do this in some cases was partly due to the user's curiosity, and not necessary to the particular task. However, this additional time has not been subtracted from the results as time taken to explore and become familiar with the system was considered part of the complete learning/task achievement process.

However, given these limitations, the trials still indicated a considerable degree of success for the system in achieving the usability research goals. All the users completed all the tasks, each of which is a realistic golf club design activity. On average the time taken to do this was a little over twice the minimum time for an experienced user, but far quicker than would be possible using the native DUCT interface. Within ~35 minutes all but one subject/pair managed to perform significant design modifications and produce two other matching clubs in the set. In fact, it would be inconceivable to give the same task descriptions to any of the subjects and expect them to complete the tasks using the native DUCT interface with the amount of training they were given.

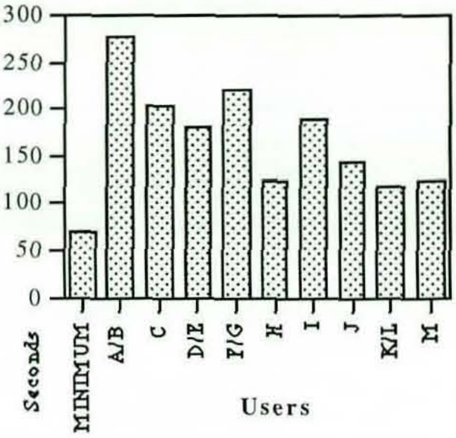
It is interesting to note that on average the time taken to produce the matching 1 and 8 irons in the set was little more than the minimum possible. This is because so much of this task is automated, and the majority of time is spent waiting for the system to respond to the commands[1]. At this point in the trial the subjects were also becoming more familiar and so more confident with the system.

It is also interesting to note that previous CAD experience seems to have had very little effect on the results, as some of the most experienced subjects took the longest time. However, there is too little data to make much of this, except perhaps to wonder if this was because these subjects had more pre-conceived ideas about how to operate the system.

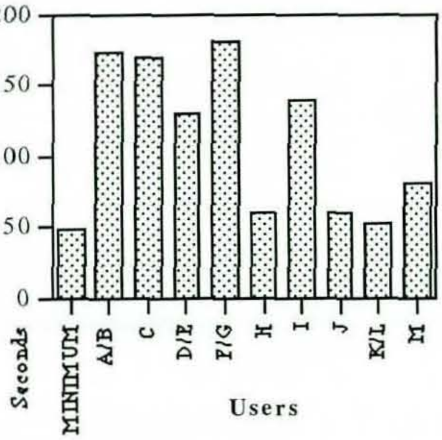
[1] ~4-5 minutes is required per club depending on the type of 'snapshot' images generated.



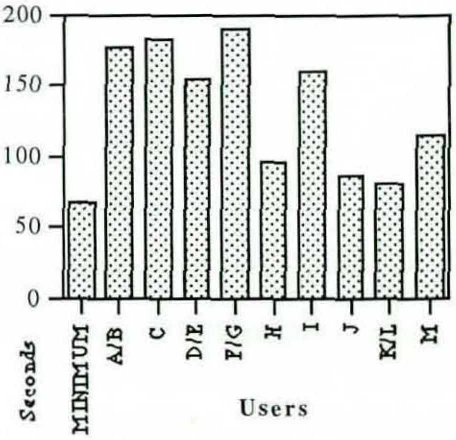
(a) Time Taken for Task 1.



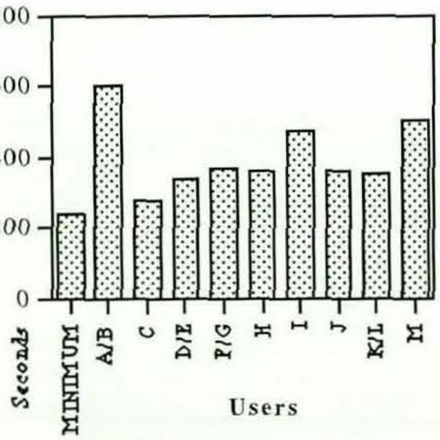
(b) Time Taken for Task 2.



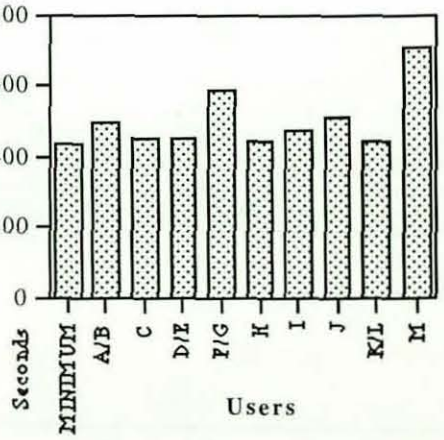
(c) Time Taken for Task 3.



(d) Time Taken for Task 4.



(e) Time Taken for Task 5.



(f) Time Taken for Task 6.

Figure 8-1 User Task Completion Times.

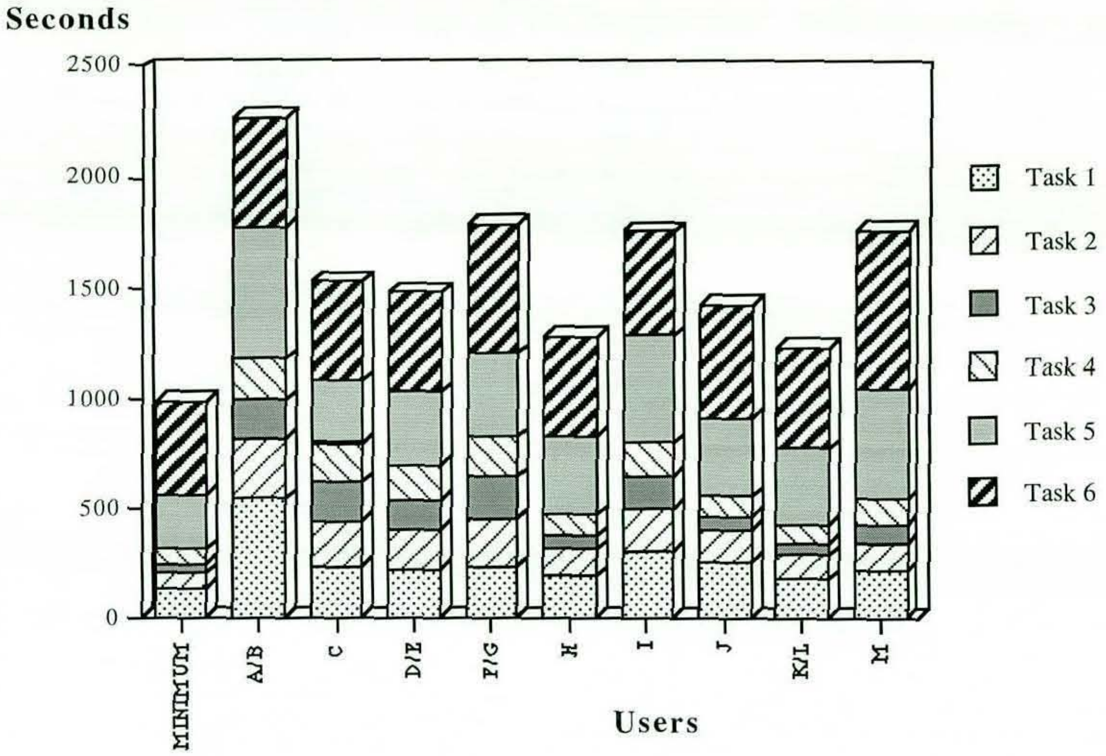


Figure 8-2 Combined times for all six tasks

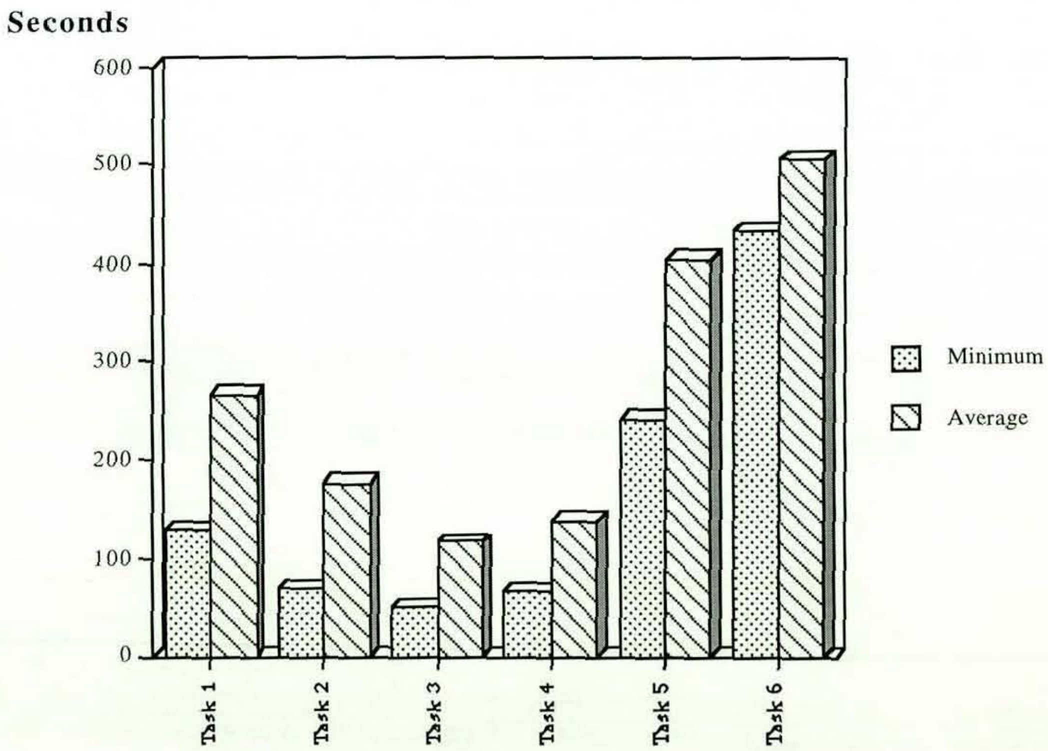


Figure 8-3 Minimum vs. average time taken

CHAPTER 9. EFFM BASED INERTIA PROPERTY CALCULATIONS

1. BACKGROUND

1.1. The Importance of Inertia Properties

The mass or inertia properties of a golf club head (mass, centre of gravity, principle moments of inertia, principle axis directions) have a direct bearing on the play/performance characteristics of the club and the loading conditions experienced by the shaft. Thus, it would be beneficial to the game and industry to be able to accurately predict these properties for a given design to assess its likely play characteristics and select a suitable shaft for prototype play testing and its ultimate game use. It would be even more useful to be able to optimise the head design to give particular play characteristics and to be able to design a shaft specifically for the head to maximise club performance, or further to optimise the characteristics of the complete head/shaft combination.

Whittaker et al, in their paper to the first World Scientific Congress of Golf, discuss the beneficial effects of controlling the club head inertia properties, and how these could be predicted using modern CAD software [1990 Whittaker et al]. Two levels of CAD model are described. The first utilises a range of crude idealised club heads, based on geometric primitives, to explore the likely effects of several mass distribution regimes. The second is apparently based on a solid model with surface modelling capabilities and is used to predict the actual inertia properties of two real head designs, although no accuracy assessment of the predictions or calculation times are given.

Generally speaking, distributing the club head mass as far from the centre of gravity as possible (peripheral weighting) increases a head's resistance to torsional loading (moment of inertia) and this theoretically yields a significant increase in the head's sweet spot size. Whittaker et al's predictions confirm this, although they suggest that the moment of inertia properties for peripherally weighted clubs will at most be 50% bigger than a bladed club with the same mass. The experimental evaluation of the accuracy and significance of their predictions is too limited to draw any further conclusions.

Johnson proposed a technique to measure an actual club head's inertia characteristics experimentally, in his paper to the second World Scientific Congress of Golf [1994 Johnson]. He compared his experimental results with crude predictions derived from a club head finite element model and independent measurements by the True Temper company. The comparison indicated agreement within 10% for the values of principle moments of inertia, and 20° for the principle axis directions. This uncertainty is unfortunate given that the variation between traditional designs predicted by Whittaker et al is of the same magnitude as the measurement discrepancies experienced by Johnson. In his presentation to the Congress, Johnson indicated that it would take several hours to make the physical measurements necessary to compute the properties of a given physical club head.

Butler and Winfield, while working with the True Temper company, patented an alternative experimental technique that they claim yields more accurate results and requires 1 or 2 hours of measurement and calculation. Furthermore, they are able to use their results to predict the momentum/energy transfer for ball impacts across the entire club face, and the corresponding stress experienced by the shaft during impact. They use these results to select or design a shaft suitable for the particular head [1993 Winfield & Butler].

1.2. Exploiting Sculptured Feature Based Methods

Given an additional facility to accurately predict a club head's mass properties from the design data before manufacture it will be possible to design and manufacture the head and shaft for a new club concurrently, with obvious advantages for bringing the club to the market quickly.

However, even though it is relatively simple to accurately calculate mass property information from a solid model based on simple geometric primitives, it is impossible to model a normal golf club's shape with sufficient accuracy to yield useful results with this 'feature set'. Using a surface model a club head can be modelled with superior geometric accuracy, but calculation of the mass properties is more difficult.

For a bicubic surface patch (bounded by limits on the defining parameters, typically between 0 and 1) it may be possible (by integration of the polynomial form of the surface equation) to calculate the volume properties of the region enclosed by the projection of the patch onto a convenient axis plane analytically, yielding almost exact computation. Thus for a closed surface model consisting of several untrimmed surface patches it is possible to accurately calculate its volume properties (and given density its mass properties) by summing the contribution of individual projected surface patch volumes. However, this type of model has been rejected for efficient head design (cf. Chapter 3 Section 2.1 (i)).

By definition the EFFM is based on 'trimmed' surface patches (additionally bounded by local surface curves, generally defined by surface intersections or blends). For a trimmed bicubic surface patch an analytical solution is generally unavailable, so an approximation is necessary. One technique is to approximate the model's surface features by a triangular facet mesh. The availability of discretisation strategies and routines to do this for surface visualisation or finite element analysis [1988 Ho-Le, 1990 Peiro et al] makes this approach economical to implement. A surface's projected volume properties can be estimated by calculating the sum of the projected volume properties for all the facets.

Triangular mesh surface approximation for visualisation, machining and volume property calculation is a technique implemented by Delcam within the DUCT software and is employed within the EFFM golf club design system. Figure 9-1 show a mesh generated to match a golf club's surface within 0.1 mm. The following sections present the mathematical basis for these triangular mesh based calculations, the accuracy achievable compared with the calculation time and the advantages of implementing feature based data storage.

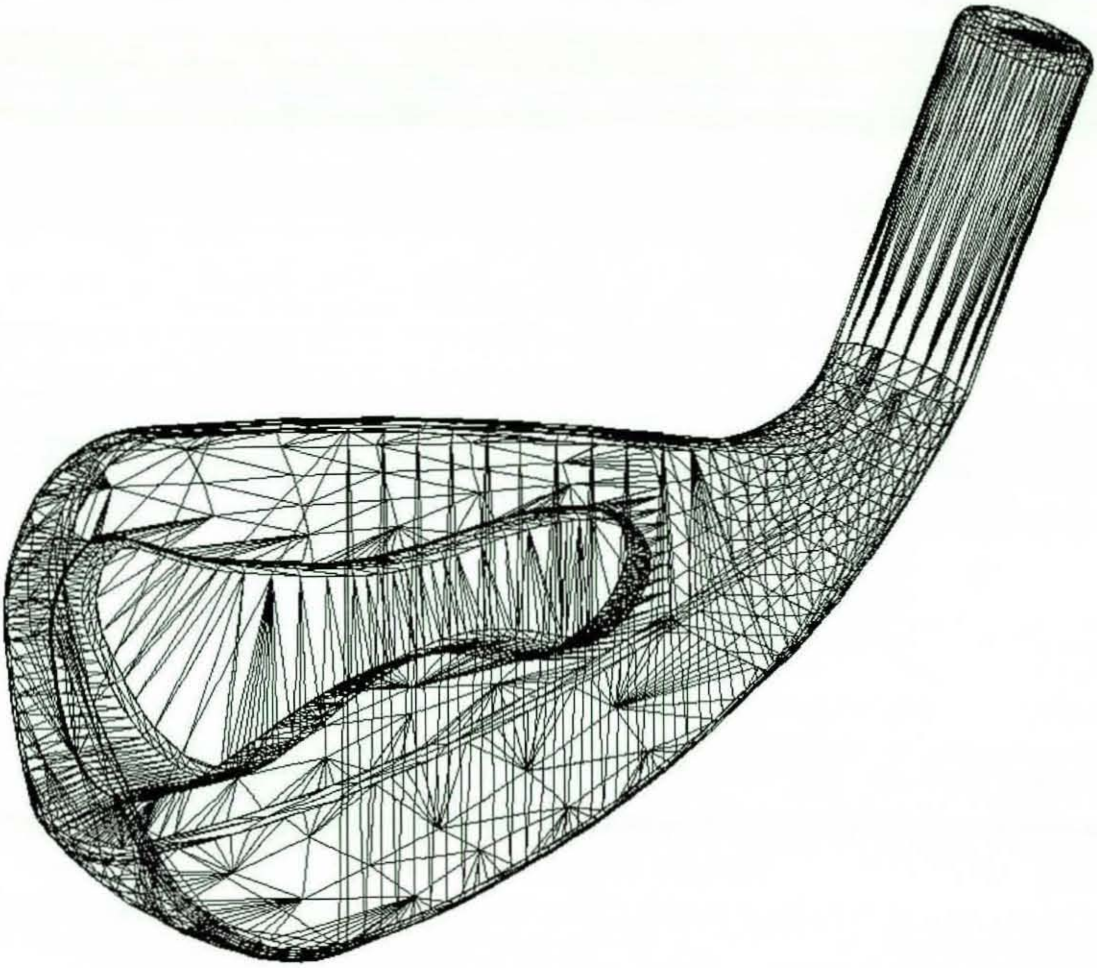


Figure 9-1 Golf Club Surface Triangular Mesh Approximation

2. MATHEMATICAL BASIS

2.1. Static Properties

2.1.1. General Case

The volume, V, of a rigid body (Figure 9-2) considered with regard to a general Cartesian xyz coordinate system, can be expressed as

$$V = \iiint_V dV \quad \text{where } dV = dx.dy.dz \qquad (1)$$

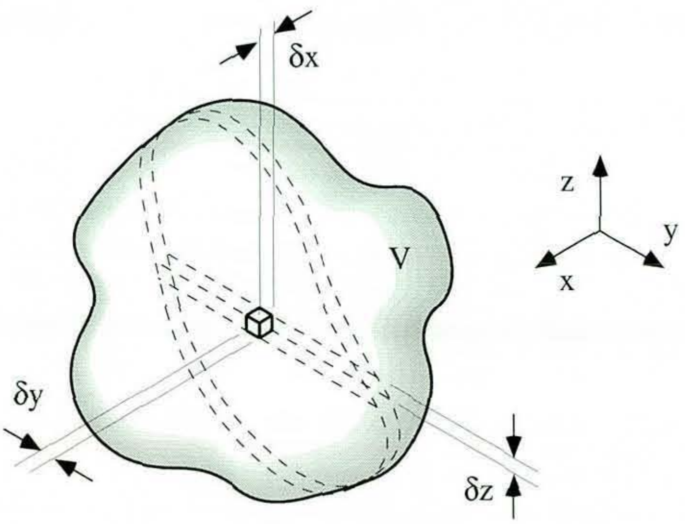


Figure 9-2 Discrete Mass Element of a General Rigid Body

The body's mass, m, is given by

$$m = \iiint_V \rho.dV \quad \text{where } \rho = \mathrm{f}(x, y, z) \qquad (2)$$

For a body made from a homogenous material where ρ is constant throughout V, the mass is given by

$$m = \rho.\iiint_V dV = \rho.V \qquad (3)$$

For such a body the volume centre coincides with the mass centre, $\mathbf{x}_c$, given by

$$\mathbf{x}_c = \begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} = \frac{1}{V} . \iiint_V \mathbf{x}.dV \quad \text{where } \mathbf{x} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad \text{......(4)}$$

2.1.2. Composite Body

For a composite body of n homogenous parts (Figure 9-3) , where the volume and density of the i^{th} part are V_i and ρ_i respectively, the total volume V, mass m, and mass centre $\mathbf{x}_c$ are given by

$$V_i = \iiint_{V_i} dV \quad \text{......(5)}$$

$$V = \sum_{i=1}^{n} V_i \quad \text{......(6)}$$

$$m = \sum_{i=1}^{n} \rho_i . V_i \quad \text{......(7)}$$

$$\mathbf{x}_c = \frac{1}{m} \sum_{i=1}^{n} \left[\rho_i . \iiint_{Vi} \mathbf{x}.dV \right] \quad \text{......(8)}$$

2.1.3 Facet Approximated Surface Feature Model

The mathematical basis for calculating the volume and mass properties for a feature based surface model are extensions of the general and composite body cases. For a body modelled by n surface features defining a closed shell, with no overlapping features, if the volume contribution of the i^{th} part is $v_{pq,i}$, the total volume of the body is given by applying equation (6)

$$V = \sum_{i=1}^{n} v_{pq,i} \quad \text{where } p, q = x, y \text{ or } z \text{ and } p \neq q \quad \text{......(9)}$$

if $v_{pq,i}$ is the volume enclosed by the projection of the surface feature onto a convenient *r=0, pq* plane (Figure 9-4) in the *r* axis direction ($p,\ q,\ r = x,\ y$ or z and $p \neq q \neq r \neq p$). Using a triangular mesh approximation consisting of t_i facets, $v_{pq,i}$ is given by applying equation (6) again

$$v_{pq,i} \approx \sum_{j=1}^{t_i} \left[\left| vt_{pq,ij} \right| . \frac{\mathbf{r}.\mathbf{n}_{ij}}{\left| \mathbf{r}.\mathbf{n}_{ij} \right|} \right] \quad \text{where } p,q = x,y \text{ or } z \text{ and } p \neq q \text{ ....(10)}$$

where $vt_{pq,ij}$ is the volume enclosed by the projection of the j^{th} facet of the i^{th} surface feature onto the *r=0, pq* plane in the negative *r* axis direction (Figure 9-5), $\mathbf{n}_{ij}$ is the facet's outward facing normal vector, and $\mathbf{r}$ is a vector in the *r* axis direction. The modulus of the projected facet volume is multiplied by $\mathbf{r}.\mathbf{n}_{ij} / |\mathbf{r}.\mathbf{n}_{ij}|$ to correct for the numbering order of the triangle vertices, so that enclosed volumes defined by facet projections out of the body are subtracted (alternatively $vt_{pq,ij}$ can be used directly, using the following equations, without correcting its sign if the vertices are numbered in an anti-clockwise sense looking along the facet normal).

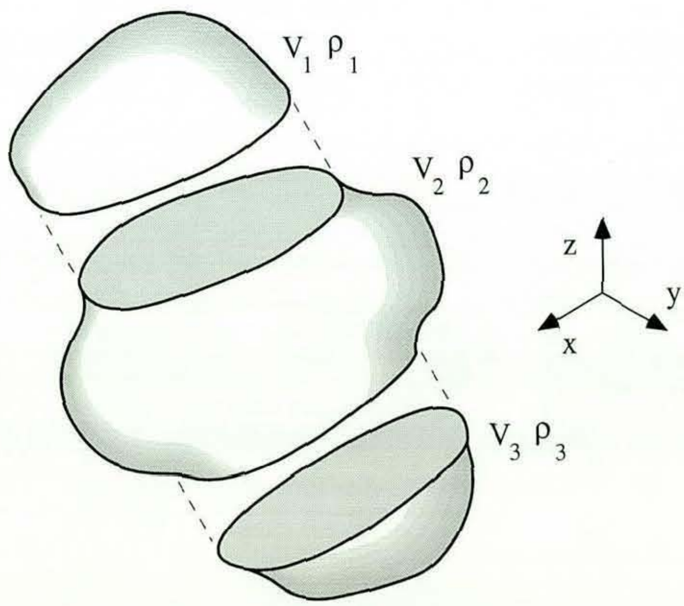


Figure 9-3 Composite Body of *n* parts ($n = 3$)

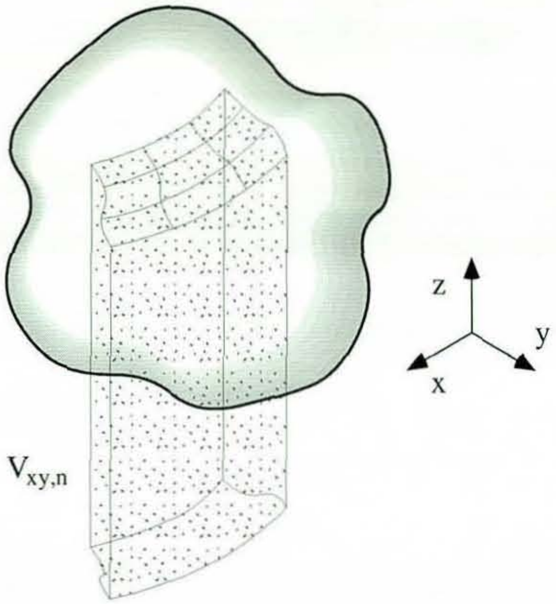


Figure 9-4 Volume Enclosed by the nth Surface Feature $r = z$ Projection

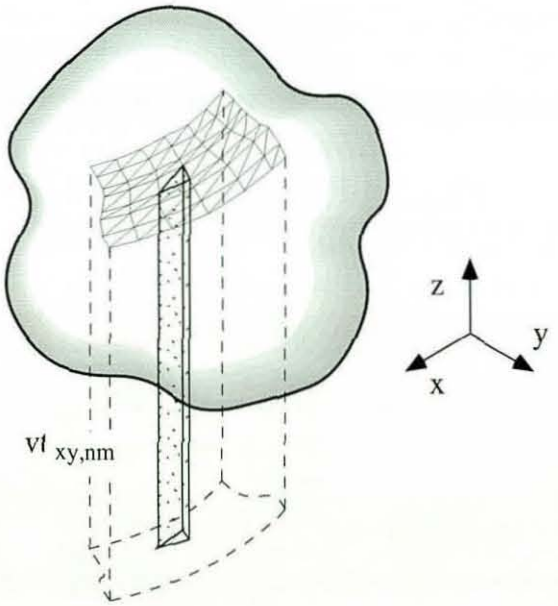


Figure 9-5 Volume Enclosed by the mth Facet of the nth Surface Feature $r = z$ Projection

If the j^{th} facet is defined by the coordinates of its three vertices $\mathbf{x}_{1,ij}$, $\mathbf{x}_{2,ij}$ and $\mathbf{x}_{3,ij}$ where

$$\mathbf{x}_{a,ij} = \begin{pmatrix} x_a \\ y_a \\ z_a \end{pmatrix}_{ij} \quad \text{where } a = 1,2 \text{ or } 3 \text{ and} \quad \mathbf{n}_{ij} = \begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix}_{ij}$$

applying equation (1) gives

$$\begin{aligned} vt_{pq,ij} &= \iiint_{vt_{pq,ij}} dr.dq.dp \\ &= \Big[\int_{p=p1}^{p2} \int_{q=0}^{m_{12}.p+c_{12}} \int_{r=0}^{k_1.p+k_2.q+k_3} dr.dq.dp \\ &\quad + \int_{p=p2}^{p3} \int_{q=0}^{m_{23}.p+c_{23}} \int_{r=0}^{k_1.p+k_2.q+k_3} dr.dq.dp \qquad \text{......(11)} \\ &\quad + \int_{p=p3}^{p1} \int_{q=0}^{m_{31}.p+c_{31}} \int_{r=0}^{k_1.p+k_2.q+k_3} dr.dq.dp \Big]_{ij} \end{aligned}$$

for $p,q,r = x,y$ or z and $p \neq q \neq r \neq p$

where

$$k_{1,ij} = \left(-\frac{n_p}{n_r}\right)_{ij}, \quad k_{2,ij} = \left(-\frac{n_q}{n_r}\right)_{ij}, \quad k_{3,ij} = \left(\frac{\mathbf{x}_1.\mathbf{n}}{n_r}\right)_{ij}$$

[the facet plane coefficients]

$$\mathrm{m}_{\mathrm{ab}} = \left(\frac{q_a - q_b}{p_a - p_b}\right)_{ij}, \quad c_{ab} = (q_a - p_a.m_{ab}) \quad a,b = 1,2 \text{ or } 3 \text{ and } a \neq b$$

[the projected facet side equation coefficients]

For a body made from a homogenous material the mass is given by equation (3). For a composite body consisting of several homogenous parts applying equation (7) gives the mass provided that each region of constant density is completely defined by a set of outward facing surface features (i.e. the body is an assembly of closed volumes or other bodies).

The mass centre of a homogenous body is given by applying equation (8)

$$\mathbf{x}_c = \frac{1}{V}.\sum_{i=1}^{n} \mathbf{M}_i \quad \text{where} \quad \mathbf{M}_i = \begin{pmatrix} M_{yz} \\ M_{zx} \\ M_{xy} \end{pmatrix}_i \qquad \text{......(12)}$$

$M_{p'q'.i}$ is the static moment of volume about the r' axis, in the $p'q'$ plane (p', q', $r' = x, y$ or z $p' \neq q' \neq r' \neq p'$) of the volume enclosed by the projection of the i^{th} surface feature onto a convenient $r=0$, pq plane (p, q, r = x, y or z and $p \neq q \neq r \neq p$). Using the triangular facet approximation

$$M_{p'q'.i} \approx \sum_{j=1}^{t_i} \left[\left| Mt_{p'q'.ij} \right| . \frac{\mathbf{r}.\mathbf{n}_{ij}}{\left| \mathbf{r}.\mathbf{n}_{ij} \right|} \right] \qquad \text{...(13)}$$

where $p', q', r' = x, y$ or z and $p' \neq q' \neq r' \neq p'$

$Mt_{p'q'.ij}$ is the static moment of volume about the r' axis, in the $p'q'$ plane (p', q', $r' = x, y$ or z $p' \neq q' \neq r' \neq p'$) of the volume enclosed by the projection of the j^{th} facet of the i^{th} surface feature onto a convenient $r=0$, pq plane along the r axis direction (p, q, $r = x$, y or z and $p \neq q \neq r \neq p$) given by

$$Mt_{p'q'.ij} = \iiint_{vt_i} r'.dr.dq.dp \qquad \text{..............(14)}$$

where $p, q, r, p', q', r' = x, y$ or z , $p' \neq q' \neq r' \neq p'$ and $p \neq q \neq r \neq p$

The expansion of the volume integral in equation (14) is similar to that of equation (11). It is not necessary for $p = p'$, $q = q'$ or $r = r'$ although it may be convenient if they do.

2.2. Dynamic Properties

2.2.1 General Case

For a body made from a homogenous material the moment of inertia about the p axis, I_{pp} (p=x, y or z) is given by

$$I_{pp} = \rho \iiint_V \left(q^2 + r^2\right).dV \qquad \text{where } p,q,r = x,y \text{ or } z \text{ and } p \neq q \neq r \neq p \qquad (15)$$

The product of inertia of the same body with respect to the p and q axes (p, q = x, y or z $p \neq q$) is given by

$$I_{pq} = \rho \iiint_V pq.dV \quad \text{where } p,q = x,y \text{ or } z \text{ and } p \neq q \qquad (16)$$

2.2.2. Composite Body

For a composite body equations (15) and (16) become

$$I_{pp} = \sum_{i=1}^{n} \rho_i \iiint_V \left(q^2 + r^2\right).dV \qquad \text{where } p,q,r = x,y \text{ or } z \text{ and } p \neq q \neq r \neq p \qquad (17)$$

$$I_{pq} = \sum_{i=1}^{n} \rho_i \iiint_V pq.dV \quad \text{where } p,q = x,y \text{ or } z \text{ and } p \neq q \qquad (18)$$

2.2.3 Facet Approximated Surface Feature Model

For the triangular facet approximated surface feature model the moments and products of inertia are given by

$$I_{p'p'} = \sum_{i=1}^{n} I_{p'p',i} \quad \text{where } p' = x,y \text{ or } z \qquad (19)$$

$$I_{p'q'} = \sum_{i=1}^{n} I_{p'q',i} \quad \text{where } p',q' = x,y \text{ or } z \text{ and } p' \neq q' \qquad (20)$$

Where $I_{p'p',i}$ and $I_{p'q',i}$ are the moments and products of inertia for the volume enclosed by the projection of the i^{th} surface onto a convenient $r=0$, pq plane (p, q, $r = x$, y or z and $p \neq q \neq r \neq p$) given by

$$I_{p'p',i} \approx \sum_{j=1}^{t_i} \left[\left| It_{p'p',ij} \right| \cdot \frac{\mathbf{r}.\mathbf{n}_{ij}}{\left| \mathbf{r}.\mathbf{n}_{ij} \right|} \right] \text{ where } p' = x, y \text{ or } z \quad (21)$$

$$I_{p'q',i} \approx \sum_{j=1}^{t_i} \left[\left| It_{p'q',ij} \right| \cdot \frac{\mathbf{r}.\mathbf{n}_{ij}}{\left| \mathbf{r}.\mathbf{n}_{ij} \right|} \right] \text{ where } p', q' = x, y \text{ or } z \text{ and } p' \neq q' \quad (22)$$

Where $I_{p'p',ij}$ and $I_{p'q',ij}$ are the moments and products of inertia for the volume enclosed by the projection of the j^{th} facet of the i^{th} surface onto a convenient $r=0$, pq plane (p, q, $r = x$, y or z and $p \neq q \neq r \neq p$) given by

$$It_{p'p',ij} = \rho. \left[\iiint_{V_i} \left(q'^2 + r'^2 \right).dr.dq.dp \right]_{ij} \quad (23)$$

$$It_{p'q',ij} = \rho. \left[\iiint_{V_i} p'q'.dr.dq.dp \right]_{ij} \quad (24)$$

where $p, q, r, p', q', r' = x, y$ or z, $p \neq q \neq r \neq p$ and $p' \neq q' \neq r' \neq p'$

The volume integrals in equations (23) and (24) can be expanded in the same way as equation (11). As with equations (12)-(14) it is not necessary for $p = p'$, $q = q'$ or $r = r'$ although it may be convenient if they do.

2.3. Dynamic Inertia Property Transformations

Generally, the centre of gravity is not known at the outset of the calculation, but a convenient set of coordinate axes can be chosen, and the inertia properties for the body calculated with respect to this coordinate system. The inertia properties at the centre of gravity can then be calculated using the parallel axis theorem. For a Cartesian coordinate system xyz with origin at point T, if the centre of gravity for the rigid body is at point C with coordinates $\mathbf{x}_c$ the moments and products of inertia at the centre of gravity are given as

$$I^C_{pp} = I^T_{pp} - \rho V.\left(q_c^2 + r_c^2\right) \quad (25)$$

$$I^C_{pq} = I^T_{pq} + \rho V.p_c q_c \quad (26)$$

where $p,q,r = x,y$ or z and $p \neq q \neq r \neq p$

If the errors in V or $\mathbf{x}_c$ are significant this obviously exacerbates the error inherent in the moment and product of inertia calculations or measurements themselves. This is partly the cause of Johnson's measurement discrepancies, as his measurements are taken with reference to a convenient coordinate system and then transposed [1994 Johnson]. Winfield and Butler's measurements are likely to be more accurate as they are taken directly along experimentally determined principal axes through the club head centre of gravity [1993 Winfield & Butler].

Delcam's DUCT software contains no routines to calculate the products of inertia, but these can be easily determined by use of the rotational transformation theorem and three additional coordinate systems produced by 45° rotations of the original system about each of its axes.

If the moments and products of inertia for a coordinate system xyz (I_{xx}, I_{yy}, I_{zz}, I_{xy}, I_{yx}, I_{zx}) are known the moments and products of inertia for any other coordinate set $x'y'z'$ at the same origin can be calculated from the following equations

$$I_{pp} = l^2_{px}.I_{xx} + l^2_{py}.I_{yy} + l^2_{pz}.I_{zz} - 2l_{px}l_{py}I_{xy} - 2l_{py}l_{pz}I_{yz} - 2l_{pz}l_{px}I_{zx} \quad (27)$$
where $p = x', y',$ or z'

$$I_{pq} = \left(l_{px}l_{qy} + l_{py}l_{qx}\right).I_{xy} + \left(l_{py}l_{qz} + l_{pz}l_{qy}\right).I_{yz} + \left(l_{pz}l_{qx} + l_{px}l_{qz}\right).I_{zx} - l_{px}l_{qx}.I_{xx} - l_{py}l_{qy}.I_{yy} - l_{pz}l_{qz}.I_{zz} \quad (28)$$
where $p,q = x', y',$ or z' and $p \neq q$

where l_{jk} is the cosine of the angle between the j and k axes.

If the $x'y'z'$ coordinate system is produced by rotating the xyz system 45° about one of the axes p, given the moments of inertia xyz (I_{xx}, I_{yy}, I_{zz}, $I_{q'q'}$ and $I_{r'r'}$ the equation for the product of inertia I_{qr} reduces to

$$I_{qr} = I_{q'q'} - \frac{(I_{qq} + I_{rr})}{2} = \frac{(I_{qq} + I_{rr})}{2} - I_{r'r'} \quad \text{.......(29a)}$$

or

$$I_{qr} = I_{q'q'} - I_{r'r'}$$
$$\text{where } p,q,r = x,y, \text{ or } z \text{ and } p \neq q \neq r \neq p \quad \text{.......(29b)}$$

Thus it is possible to calculate the products of inertia by determining at least three more moments of inertia, one for an axis at 45° to the x or y axis in the xy plane, and two more similar axes in the yz and zx planes using equation (29a). Alternatively, at the expense of more computing time, three further moment of inertia values can be determined and the products of inertia calculated using equation (29b). Potentially this has the benefit of compensating for some of the numerical errors peculiar to facet projections in a particular direction.

2.4. Principal Moments of Inertia and Principal Axis Calculations

Given the moments and products of inertia at the centre of gravity for a rigid body we have the inertia matrix or tensor, written as:

$$\begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix}$$

It can be shown that there is one unique coordinate set, $x'y'z'$, for which the products of inertia are all zero [1977 Ginsberg & Genin]. In this case the axes $x'y'z'$ are said to be the principal axes of the body and the moments of inertia $I_{x'x'}$, $I_{y'y'}$ and $I_{z'z'}$ are said to be the principal moments of inertia. The principal moments of inertia represent the maximum, minimum and intermediate moment of inertia values for the body I_1, I_2 and I_3. The corresponding principal axes $\mathbf{x}_1$, $\mathbf{x}_2$ and $\mathbf{x}_3$, represent the axes about which the body will tend to rotate as a free body. Obviously these characteristic properties are important for assessing the likely performance of a club head at impact.

For any orientation of the axes xyz it may be shown that the principal moments of inertia I_1, I_2 and I_3 and the corresponding principal axes $\mathbf{x}_1$, $\mathbf{x}_2$ and $\mathbf{x}_3$, can be found from the solution of the eigenvalue problem [1987 Meriam & Kraige, 1989 McGill & King, 1975 Meriam]:

$$\begin{bmatrix} I_{xx}-I_i & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy}-I_i & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz}-I_i \end{bmatrix} \cdot \begin{pmatrix} l_i \\ m_i \\ n_i \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad \text{.......(30)}$$

where $\mathbf{x}_i = \begin{pmatrix} l_i \\ m_i \\ n_i \end{pmatrix}$ and $l_i^2 + m_i^2 + n_i^2 = 1$

for $i = 1,2 \text{ or } 3$

Thus the principal moments of inertia I_1, I_2 and I_3 are the roots of a cubic equation. In determinate form the equation is

$$\left\| \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} - \begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} \right\| = \begin{vmatrix} I_{xx}-I & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy}-I & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz}-I \end{vmatrix} = 0 \quad \text{.......(31)}$$

Writing the cubic equation in full gives

$$I^3 + a.I^2 + b.I + c = 0$$

$$\text{where} \quad a = -\left(I_{xx} + I_{yy} + I_{zz}\right)$$

$$b = I_{xx}.I_{yy} + I_{yy}.I_{zz} + I_{zz}I_{xx} - I_{xy}^2 - I_{yz}^2 - I_{zx}^2$$

$$c = 2.I_{xy}.I_{yz}.I_{zx} + I_{xx}.I_{yz}^2 + I_{yy}.I_{zx}^2 + I_{zz}.I_{xy}^2 - I_{xx}.I_{yy}.I_{zz} \quad \text{.......(32)}$$

The cubic equation can be solved analytically by substitution. Rearranging the cubic gives

$$I_0^3 = \alpha.I_0 + \beta$$
$$\text{where} \quad I_0 = I + \frac{b}{3} \quad \alpha = \left(\frac{b^2}{3} - c\right) \quad \beta = \left(\frac{c.b}{3} - \frac{2.b^3}{27} - d\right) \qquad (33)$$

If *s=a/3* and *t=b/2* the cubic has three real roots I_a , I_b and I_c , when $s^2\text{-}t^3 \leq 0$ as follows

$$\text{for} \quad s^2 - t^3 < 0: \quad \begin{aligned} I_a &= 2.\sqrt{t}.\cos(u/3) - b/3 \\ I_b &= 2.\sqrt{t}.\cos(u/3 + 120°) - b/3 \\ I_c &= 2.\sqrt{t}.\cos(u/3 + 240°) - b/3 \end{aligned} \qquad (34a)$$
$$\text{where} \quad \cos u = s/\left(t\sqrt{t}\right), \quad 0 < u < 180°$$

$$\text{for} \quad s^2 - t^3 = 0: \quad \begin{aligned} I_a &= 2.s^{1/3} - b/3 \\ I_b &= I_c = -s^{1/3} - b/3 \end{aligned} \qquad (34b)$$

The corresponding principal axes are found by solving the eigenvalue problem equation substituting for *I* ($I = I_a$, I_b and I_c).

$$\text{if} \quad \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{bmatrix} = \begin{bmatrix} I_{xx} - I_i & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} - I_i & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} - I_i \end{bmatrix}$$
$$\text{and} \quad \mathbf{x}_{i=} \begin{pmatrix} l_i \\ m_i \\ n_i \end{pmatrix}, \quad \text{where} \quad l_i^2 + m_i^2 + n_i^2 = 1 \quad \text{for} \quad i = 1,2 \text{ or } 3$$

$$l_i = \sqrt{\frac{1}{1 + \frac{\left(a_1 - \frac{b_1}{b_2}.a_2\right)^2}{\left(\frac{b_1}{b_2}.c_2 - c_1\right)^2} + \frac{\left(a_1 - \frac{c_1}{c_2}.a_2\right)^2}{\left(\frac{c_1}{c_2}.b_2 - b_1\right)^2}}} \qquad (35)$$
$$m_i = l_i.\frac{\left(a_1 - \frac{c_1}{c_2}.a_2\right)}{\left(\frac{c_1}{c_2}.b_2 - b_1\right)} \quad \text{and} \quad n_i = l_i.\frac{\left(a_1 - \frac{b_1}{b_2}.a_2\right)}{\left(\frac{b_1}{b_2}.c_2 - c_1\right)}$$

3. Visual Representation

The numerical results produced using the volume and inertia property equations presented provide a direct means for predicting a golf club's characteristics, and so also for comparing different designs numerically.

It is also possible to display these results graphically. Figure 9-6 shows the mass centre, moment of inertia and principle axis results superimposed on a typical golf club model.

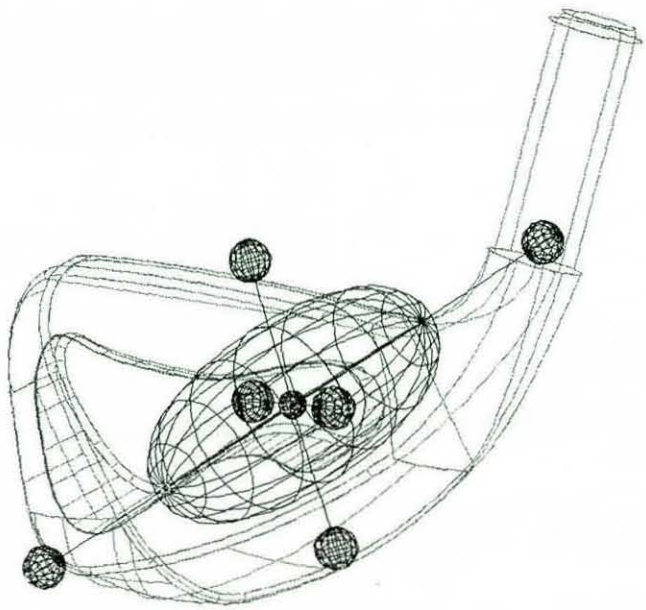


Figure 9-6 Superimposed Inertia Property Calculation Graphical Results

The mass centre is represented by a small sphere with the centre coincident with the mass centre location. The moment of inertia and principle axis results are represented in two ways. The first is by modelling a scaled inertia ellipsoid at the club's mass centre (the inertia ellipsoid is defined such that the distance from its centre in any direction is proportional to the inverse of the moment of inertia about that particular direction). The second is by modelling a scaled equivalent mass system. Six equal masses are shown, notionally as very dense spheres, positioned along the principal axes to correctly reproduce the same inertia properties.

4. Surface Approximation, Calculation Times and Accuracy

4.1. Mesh Facet Count vs. Surface Approximation Tolerance

Figure 9-7 shows the power law increase in the number of triangular mesh facets with decreasing surface approximation tolerance (<0.1 mm) for a typical EFFM based golf club model. For increasingly large tolerance values (>0.1 mm) the meshing routines do not produce a power law decrease in the number of facets as the mesh becomes more dominated by the surface boundaries than the surface curvature.

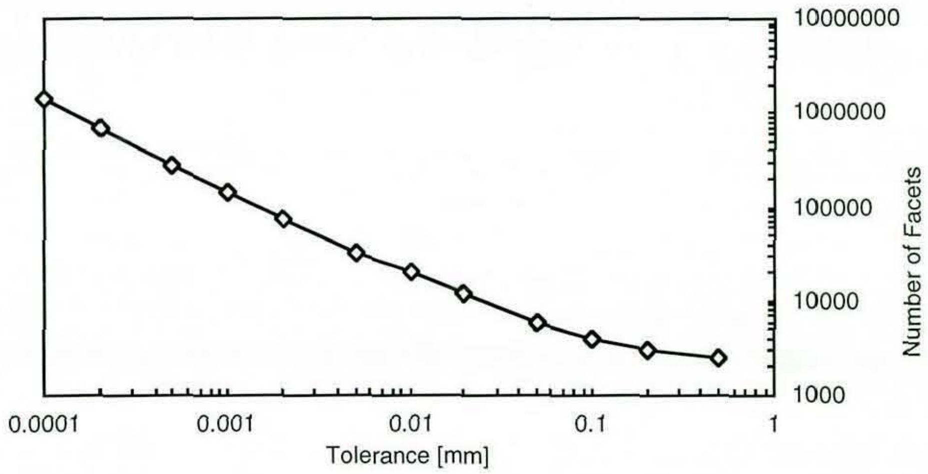


Figure 9-7 Number of Mesh Facets vs. Mesh Tolerance

The model used is a plain cavity back 5 iron produced using an anatomy of 9 extended form features and 8 blend features. No ornamental features are included. Face grooves and simple markings are typically modelled by simple surface features that tend to add a relatively small fixed number of triangular elements to the total model count. Text and logos are modelled using additions to the base feature's triangular meshes produced using Delcam's ArtCAM software and DUCT's wrapping capabilities. The logos introduce a much more significant (typically 15,500 facets for the 'Maxfli' logo used for the club models shown in Chapter 4 Section 2.3) but fixed facet count overhead.

It should be noted that the ornamental features also usually change the club mass by an amount in excess of the 2g design tolerance. However, the DUCT software currently has no compiled routines to calculate the mass contributions of triangular meshes directly, and to calculate these using DUCT's interpreted macro programming language would take a disproportionately large amount of computing time.

4.2. Calculation Time vs. Surface Approximation Tolerance

Typical results for inertia property calculation times in relation to surface approximation tolerance are given in Figure 9-8 and Figure 9-9 for the same club model. The calculations were performed on a 150 MHz R4400 Silicon Graphics Indigo2 workstation. Figure 9-8 clearly shows the power law increase in calculation time with decreasing tolerance (<0.1 mm) to be expected given that the amount of computation is proportional to the number of triangular facets.

If calculation times are divided into four categories, related to a working day:

- Real time, ≤ 10 seconds
- Almost immediate, $\leq 10^2$ seconds
- After a coffee break, $>10^2$ and $\leq 10^3$ seconds
- After lunch, $>10^3$ seconds

We can see that static properties can be calculated for a very small surface approximation tolerance *almost immediately* (~0.001 mm). Dynamic properties can be produced *almost immediately* to a coarse tolerance (~0.1 mm), and *after a coffee break* to a fine tolerance (~0.005). Dynamic property results calculated using a very fine tolerance (<0.001) are likely to be available *after lunch*.

These results mean that *real time* full inertia property prediction is beyond the computing facilities of most golf club designers, but the speed is acceptable for interactive static property optimisation and post-design static property analysis. This represents a quantum leap in the designer's ability to predict head performance and allows concurrent engineering of a suitable shaft.

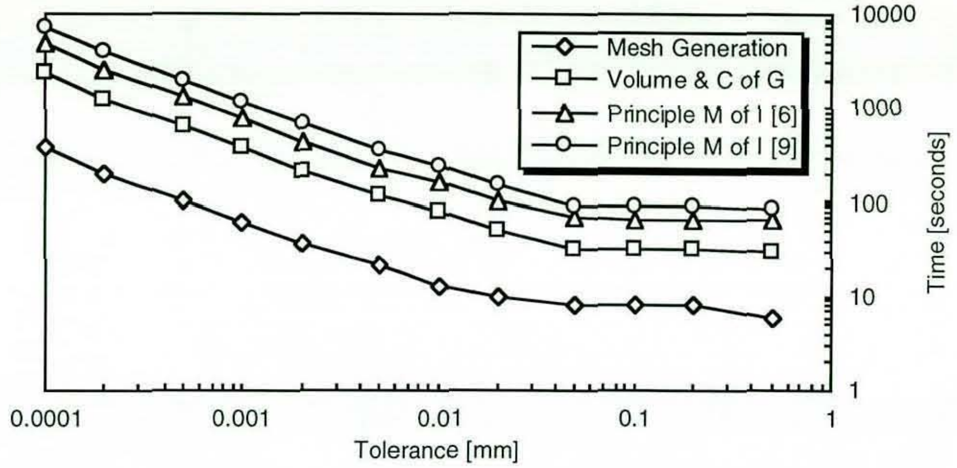


Figure 9-8 Calculation Times vs. Mesh Tolerance (log time scale)

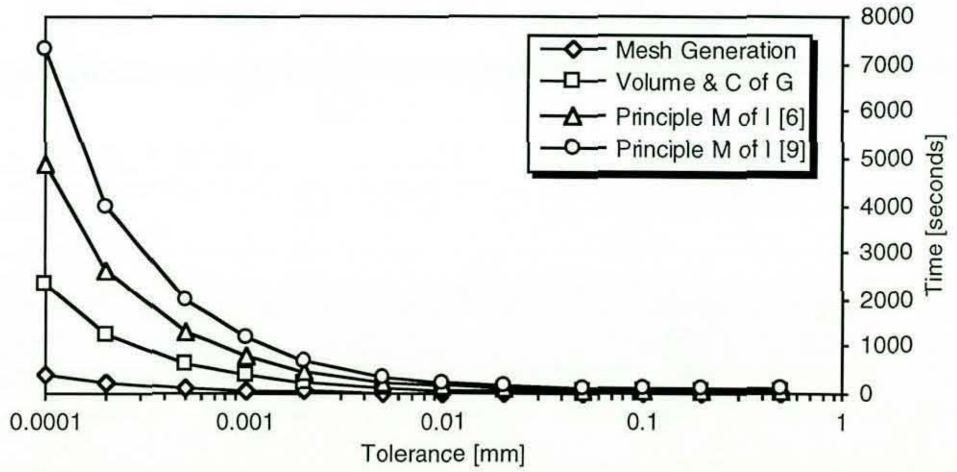


Figure 9-9 Calculation Times vs. Mesh Tolerance (linear time scale)

The times shown for volume and centre of gravity calculation include mesh generation time. The times shown for principle moments of inertia and axes calculations include the time taken to perform volume and centre of gravity calculations. Calculation times for two methods of obtaining the principle moments of inertia and axes are shown in both Figure 9-8 and Figure 9-9. The first uses the 6 moment of inertia measurements and the second uses the 9 moment of inertia measurements discussed in Section 2.

Figure 9-9 more clearly shows the increase in computing time required for the additional 3 moment of inertia measurements, and would seem to indicate this is much the same as the additional time required to calculate the other 6, and that this is almost the same amount of time required to calculate the volume and centre of gravity. However, this actually reflects the access provided to the volume integral routines within DUCT. The volume and centre of gravity calculations are based on the mean value from projections in all three coordinate axis directions. Unfortunately the routines are implemented so that a new mesh is calculated for each projection, so that the volume calculation time involves three mesh generation times. The 6 measurement principle moment and axis calculations use the same three meshes for the 3 coordinate axis moment of inertia measurements, but the 3 rotated axis measurements unfortunately result in three additional mesh generation times. Similarly, the 9 measurement calculation results in a further 3 mesh generation periods.

This is very inefficient, and means that ~45% of the calculation time is spent on mesh generation. Using routines to perform the volume integrals on a mesh generated once would produce ~30% savings on static property calculation and ~40% savings on dynamic property calculation. Although these are not an order of magnitude reduction, they would mean that coarse tolerance interactive calculations would approach the *real time* threshold.

4.3. Calculation Accuracy vs. Approximation Tolerance

Figure 9-10 to Figure 9-13 illustrate typical calculation accuracy achieved with respect to the surface approximation tolerance. Table 9-1 summarises the broad implications for calculation accuracy given a particular approximation tolerance. The 'exact' properties for the club head model were determined by extrapolating the results of very small tolerance calculations, assuming the results are of the form:

Result = *Exact Value* + *k.(tolerance)*$^{-c}$, where *k* and *c* are constants

This gives a reasonable assessment of error given the asymptotic behaviour of the results graphs.

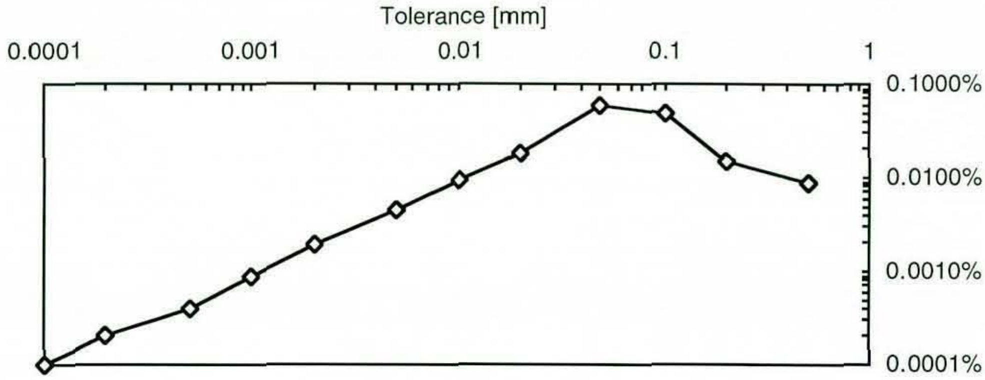


Figure 9-10 Volume Calculation Error vs. Mesh Tolerance

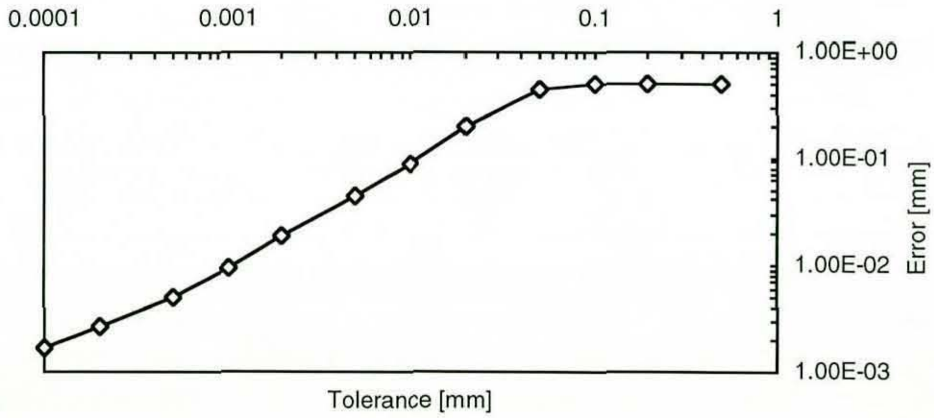


Figure 9-11 Centre of Gravity Error vs. Mesh Tolerance

The graphs and table show that given a typical industry design tolerance for mass of 2 grammes, it is possible to design for static inertia properties using a mesh tolerance of ~0.1 mm. However, given Whittaker et al's results, it is necessary to calculate dynamic inertia properties using a mesh tolerance of ~0.001 mm in order to accurately compare similar clubs [1990 Whittaker et al].

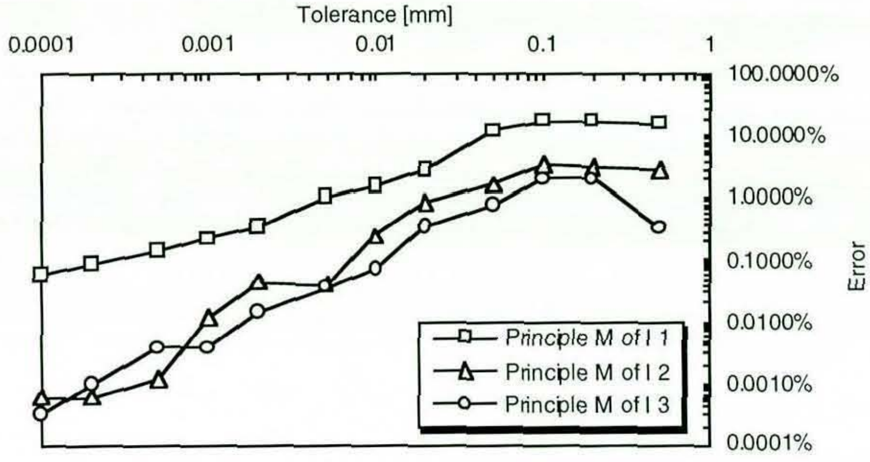


Figure 9-12 Principle Moment of Inertia Errors vs. Mesh Tolerance

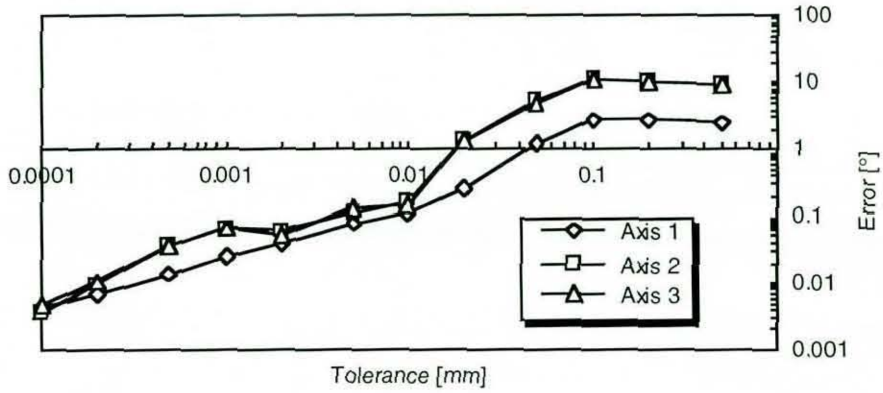


Figure 9-13 Principle Axis Direction Error vs. Mesh Tolerance

Table 9-1 Mesh Tolerance & Calculation Summary

Tolerance [mm]		~0.1	~0.01	~0.001	~0.0001
Error:	Volume [%]	~0.1	~0.01	~0.001	~0.0001
	Centre of Gravity [mm]	~0.5	~0.1	~0.01	~0.005
	Principle Moments of Inertia [%]	~15	~5	~0.5	~0.1
	Principle Axis Directions [°]	~10	~0.1	~0.05	~0.005

In practice manufacture will introduce further errors, for example due to:

- Manual cusp removal after NC machining of masters.
- Workpiece holding point removal and dressing.
- Casting process deformations.
- Manual loft lie and weight adjustment.

However, without accurate prediction of the intended properties it is difficult to specify and control these additional errors.

4.4. Calculation Accuracy vs. Calculation Time

Figure 9-14 shows a plot of calculation time vs. result accuracy for two different types of volume calculation.

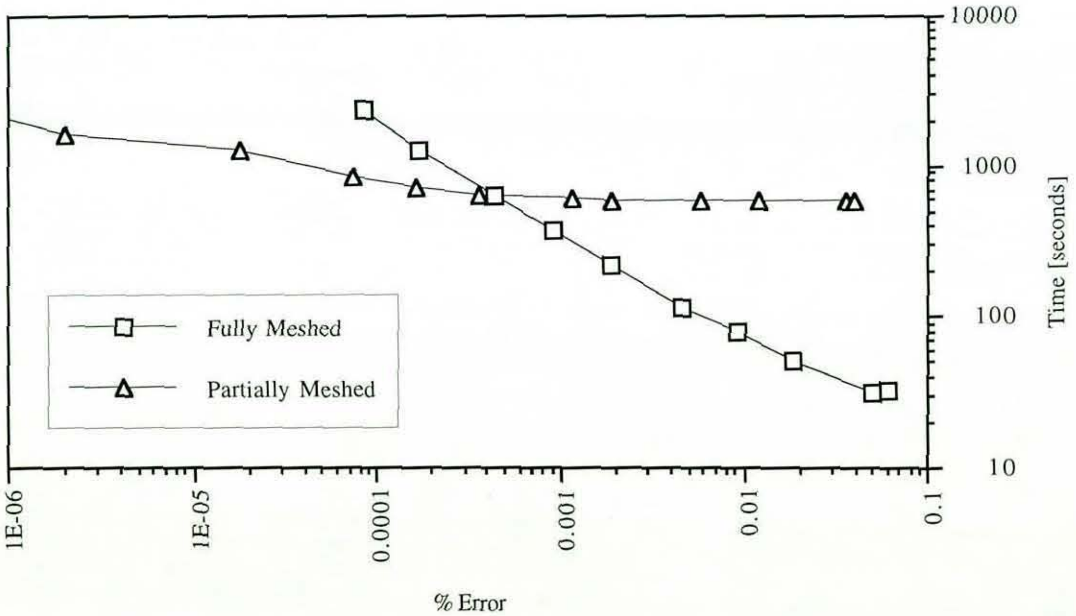


Figure 9-14 Calculation Time vs. Volume Error

The fully meshed data is from volume calculations based on the mean of results from the three coordinate axis projections. The entire surface of each feature is approximated by a triangular facet mesh. The partially meshed data is also based on the mean of the three axis projection results, but only those surface patches containing part of the feature boundary are approximated. For the complete patches the volume is calculated using the exact projected polynomial surface integral. There is obviously a time penalty involved in this calculation (similar calculations for the moments of inertia have not been implemented by Delcam as the calculation times are too prohibitive). Calculations down to an error of 0.0004% can be achieved more quickly using a fully meshed approach, but if for some reason accuracies greater than this are required the partially meshed approach yields more accurate results faster.

Figure 9-15 shows a similar graph for the centre of gravity calculation time against result accuracy, but in this case it is obvious that over the range of errors shown the fully meshed approach is more efficient. Using this approach for both volume and centre of gravity calculations very small errors are obtainable at *almost immediate* calculation speeds.

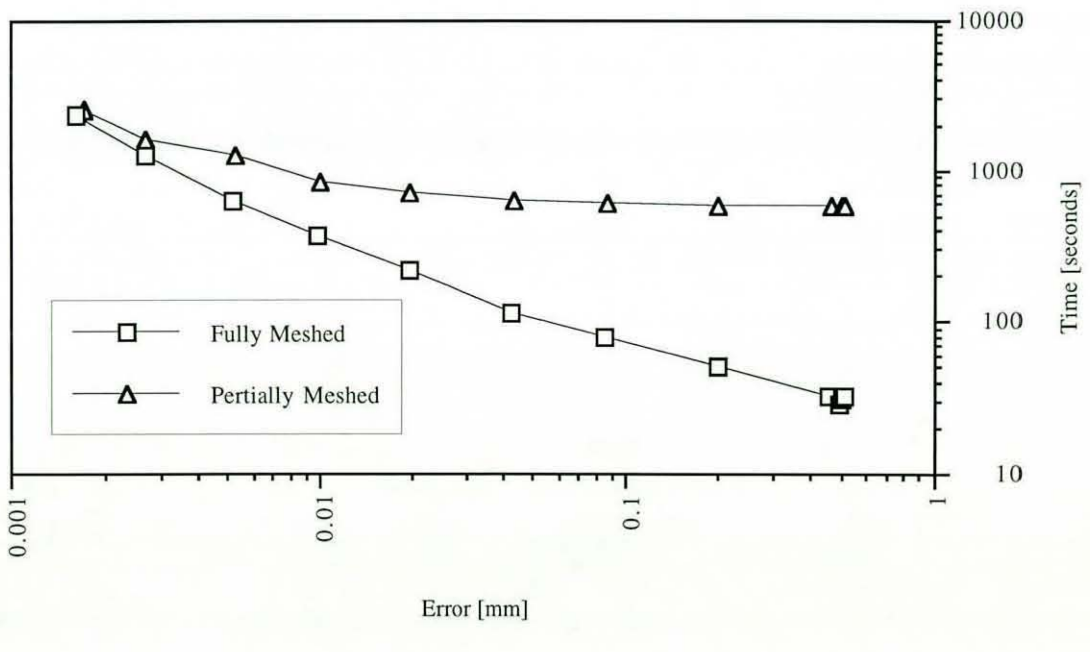


Figure 9-15 Calculation Time vs. Centre of Gravity Error

Figure 9-16 to Figure 9-18 show graphs of calculation time against result accuracy for principle moment of inertia calculations. Interestingly there is very little benefit in using a 6 measurement approach when compromising accuracy for speed, except perhaps where an error of ~5% is acceptable. Even so there is only a slight benefit. Otherwise a coarser tolerance mesh 9 measurement calculation yields results faster than a finer toleranced mesh 6 measurement approach to give the same accuracy.

Figure 9-19 to Figure 9-21 show similar graphs of calculation time against result accuracy for principle axis calculations. There is some slight benefit in using the 6 measurement approach where errors greater than 1° are acceptable, otherwise a 9 measurement approach is more efficient.

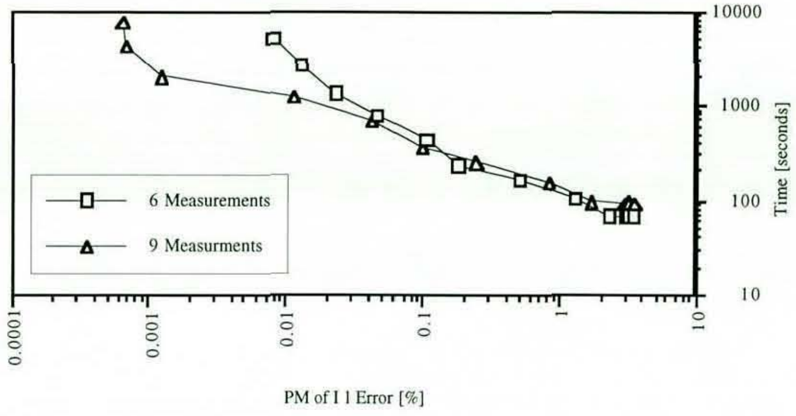


Figure 9-16 Calculation Time vs. 1st Principle Moment of Inertia Error

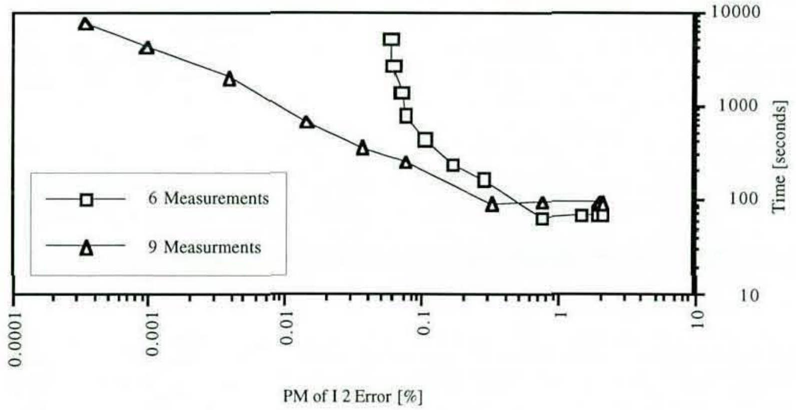


Figure 9-17 Calculation Time vs. 2nd Principle Moment of Inertia Error

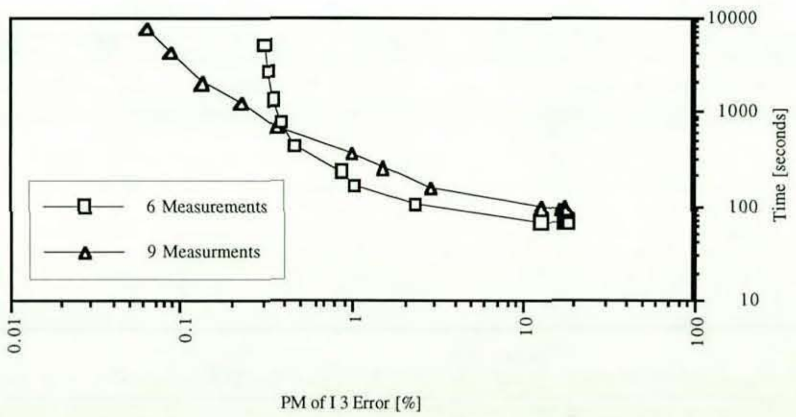


Figure 9-18 Calculation Time vs. 3rd Principle Moment of Inertia Error

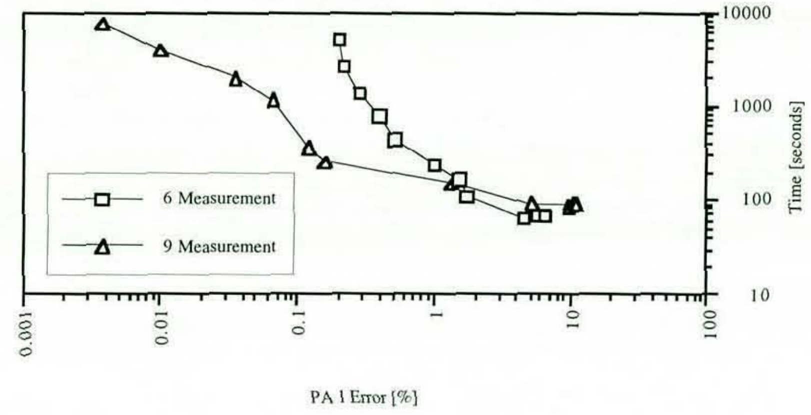


Figure 9-19 Calculation Time vs. 1st Principle Axis Error

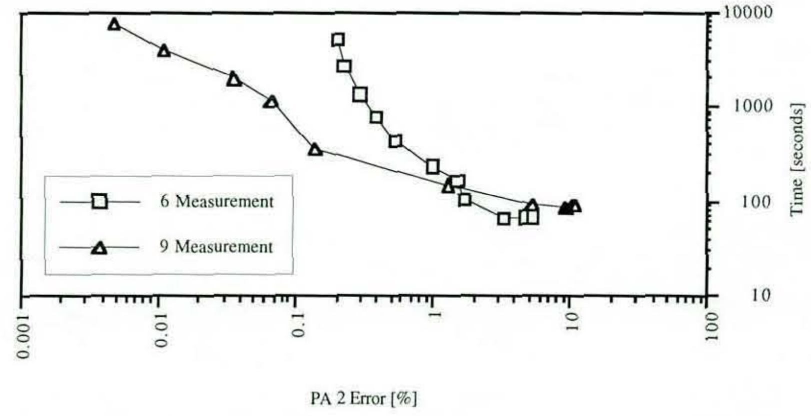


Figure 9-20 Calculation Time vs. 2nd Principle Axis Error

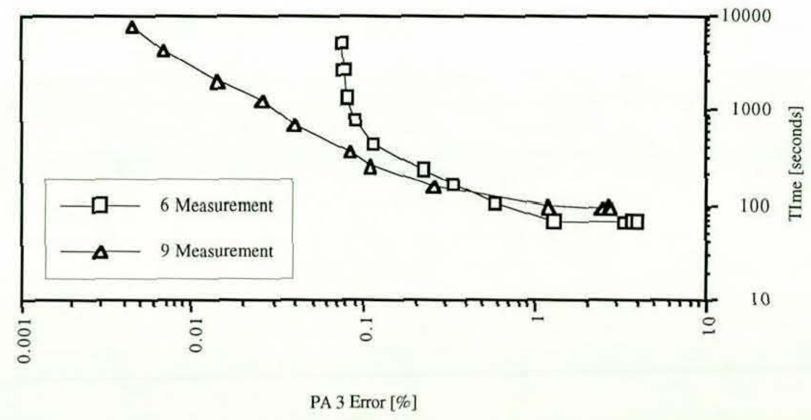


Figure 9-21 Calculation Time vs. 3rd Principle Axis Error

5. Advantages of Feature Based Data Storage

Using surface modelling software it is often the case that the designer will take 'short cuts' to achieve a geometric product model that yields correct manufacturing data (particularly CNC machining paths) with minimum effort. However, this type of model is usually flawed as a mathematical description of a valid solid object since surface regions will often extend untrimmed into the object, and small gaps may be left which will be ignored by the CNC path generation software given a large cutter size. Concave blends may also be omitted under the assumption that these will be acceptably produced by the tip radius of the specified cutter. Unfortunately models of this quality are inadequate for accurate inertia property calculation.

Designs produced using the EFFM based system have an inherent structure that ensures a valid description of the product for inertia property calculation. Further use of this structure and its associated data storage capabilities can be made to improve calculation efficiency.

Given that calculation accuracy is dependent on the surface approximation, the approximation accuracy is dependent on the number of triangular facets, but increasing the number of facets proportionally increases calculation time, there is a need to compromise between accuracy and computation time to achieve acceptable results with an tolerable delay (using modern CAD workstations).

It would also be a particularly useful innovation for golf club designers to be able to style a club head and then have the performance characteristics optimised automatically. However, manual or automated dynamic inertia property optimisation, based on a complete recalculation for the entire model after a design change generates a heavy demand on computing time. This can be reduced in several ways, for example:

- The modelling accuracy can initially be low and then increased as the optimisation process proceeds. For initial iterations only the most significant features need have their facet approximation accuracy increased.

- Initial calculations can be based on a devolved blend model, with several generations of blends removed, and then subsequent generations of blend introduced as the optimisation process proceeds.

- A refined optimisation regime using the above techniques can be determined for a single club and applied to the optimisation of all the clubs in a matched set.

However, more significant reductions in time can be achieved by making use of the parameter storage capabilities of the feature based club model. By storing the mass property contribution calculation results for individual surface features within the feature model, only the properties of those features affected by design change need to be recalculated to predict the properties of the entire model. This means that predicting the effects of minor changes to existing designs is much faster, and certainly provides the designer with more acceptable response times for manual optimisation. Obviously the application of this technique to the set optimisation regime yields proportionally equivalent time savings.

Typical results for calculation times versus approximation tolerance are given in Figure 9-22 for recalculation based on varying degrees of design change. Obviously, for the more localised design changes the recalculation times are faster. For example a design change to the loft angle of the blade involves 14 of the 17 club features and so, for the particular club model considered, requires 94% of the original calculation time to update the results. Changing the hosel length only involves 3 of the 17 club features and so requires 6% of the original calculation time to update the results.

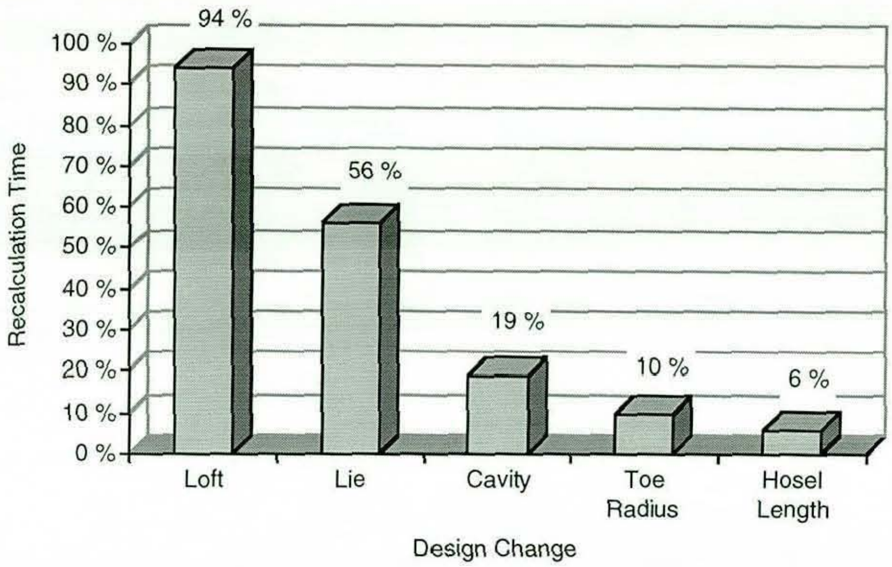


Figure 9-22 Post Design Change Recalculation Times

Obviously, inertia property optimisation that only affects a limited range of features is much more time efficient. For example, dynamic property optimisation of a 9 club set based on back cavity depth, position and orientation, with 10 iterations per club would take ~29 hours with complete recalculation at each iteration, but less than 8 hours making use of the feature model (even without using the tolerance refinement strategies listed above).

6. Summary & Recommendations

The static and dynamic inertia properties of the golf club head are important design performance characteristics. With current experimental techniques measuring these properties takes several hours, given a physical prototype, to achieve modest accuracies. The burden of manufacturing time for a prototype club head, even with relatively fast measurement times, means that extensive dynamic inertia property optimisation is impractical.

Using modern CAD facilities introduces the potential to predict inertia properties for a given club head design, and with emerging shaft design facilities this will allow concurrent engineering of the entire club.

Using a sculptured FBD system ensures the design model quality is high enough for accurate inertia property calculation. Static property predictions for a given design can be produced to exceptional accuracies almost immediately. Similar dynamic property predictions can be produced within an acceptable additional time period.

Full triangular facet mesh approximation of the surface features to a sufficiently low tolerance (0.1 mm for static properties and 0.001 mm for dynamic properties) efficiently produces accurate results and is preferable to direct integration of the surface equations. Using a 9 measurement principle moment of inertia strategy is also recommended.

Manual or automatic optimisation speeds can be dramatically improved by making use of the parameter storage facilities afforded by a feature based model and by adopting a sensible optimisation regime where prediction accuracy is increased as the solution is approached.

These facilities make club head optimisation for a full set practical, economical and desirable to improve designs before the expense of prototype manufacture and play testing.

CHAPTER 10. DISCUSSION & FUTURE WORK

1. PHILOSOPHICAL CONSIDERATIONS

1.1. Generic Applicability to Sculptured Products

The data model presented in Chapter 5 clearly supports the EFF method for sculptured FBD proposed in Chapter 3. Because there is no convenient hierarchy or taxonomy for a universal set of sculptured features, the model provides, and to some extent represents, a universal method for defining features in this paradigm. The features and their shapes are disassociated and cross referenced in a lattice structure, and this relates well to a sculptured product designer's circumstances. For example, the toe of a golf club is different from the toe of a shoe last. Similarly, the sole of a steam iron is different from the sole of a golf iron, but similar in shape to the golf iron's face. The mathematical terms for the shapes of all but the most simple features are irrelevant and cumbersome to the designer in these fields.

The data model provides the basis for a system that will allow designers to define their products in terms of interacting features they recognise, and categories that are meaningful to their organisation. Design solutions can also be explored and finally defined by means of parametric shape algorithms and values relevant to a particular product domain. Finally, the three dimensional geometry can be evaluated throughout the design activity for visualisation, analysis, and ultimately manufacture. The preliminary results from the prototype implementation demonstrate the substantial benefits achieved using this approach.

Any CAD tool based on this model requires an investment of some initial effort to capture anatomies and create suitable feature shape algorithms. For this to be cost effective the product domain must exhibit one or more of the following:

- A high level of design activity based on the same or similar product anatomies.

- A high level of design activity based on the adjustment of existing shapes.
- Product families with parametric shape relationships.

This implies that the approach is less relevant to product domains where each design is unique. This is true except where:

- Several solutions must be considered, and these form the basis for a product family.
- Shape optimisation requires several design iterations equivalent to repetitive design using a fixed anatomy of features.
- Some borrowing of features from existing designs sufficiently reduces design effort.

The data structure presented supports features in a static complex form (digitised surface) and in a dynamic simplified form (parametrically constrained surfaces). Work concerned with feature capture in both formats has uncovered problems introducing this technology into the golf industry. The problems revolve around the use of traditional product datum concepts and manual measurement alignment methods and indicate the need for a new generation of golf club fixturing suitable for a co-ordinate measuring machine. Essentially the modelling precision introduced by the use of CAD techniques, in particular the features' position and orientation in relation to each other, coupled with the need to design with a mixture of reverse engineered and computer generated features, exposes the subjective nature of the golf industry's geometric measurements and fixturing techniques. This is likely to be true for similar industries, and requires attention to the practical and cultural measurement issues associated with different products to ensure successful implementation and use of the data structure.

A prototype FBD system has been developed and proved to be effective for iron golf clubs, but the EFF method has not been applied with the same rigour to any other product. However, the feasibility of using the method for shoe last design has been considered in some depth by developing a suitable EFF anatomy and identifying those elements of the golf club system that are directly applicable to both products (e.g. design and feature library access; select, remove and adjust feature operations) and those elements that would need to change (e.g. feature selection menu content and derived measurement routines).

In general, shoe lasts exhibit characteristics in line with the fundamental assumptions underlying the EF feature method. This reinforces the assumptions and indicates that the method shows promise as a generic approach to sculptured product feature based design, as well as significant potential for shoe last design.

In particular, shoe lasts share the following characteristics with other sculptured products (such as golf club heads, consumer electronics casings, ceramic tableware or sanitary-ware) considered suitable for EF feature based design:

- The shoe last is a fully sculptured product. The design prototype is usually produced manually by craftsmen and the designs exhibit virtually no prismatic engineering features.
- Different lasts have similar anatomies and terminology. However a typical last's sole or heel feature is not equivalent in shape to those of a golf club or steam iron, for example. This confirms the need for product specific anatomies and features to support efficient sculptured product CAD.
- There are accepted parameters, properties and notional datums used to specify the last design characteristics. These are common to most manufacturers in the shoe industry, and show some promise as control parameters for individual last features and size variation.
- The notional datums are often vague and open to interpretation (e.g. the girth is measured in three positions. Their location is determined by each craftsmen and is difficult to reproduce independently). This causes

some cultural and implementation conflicts when applying CAD techniques, as a more rigorous design specification is necessary.

- Shoe lasts require typical design processes (e.g. hybrid design based on previous lasts requiring localised feature editing and swapping; automatic anisotropic set generation; and optimisation to achieve derived properties such as girth). This confirms the need for a generic sculptured feature architecture to manipulate the product specific anatomies and features.
- Design characteristic optimisation and set grading are partly based on properties that are more easily derived or measured from the design rather than used to directly manipulate shape (e.g. the girth property is more easily treated as a measured characteristic than a feature control parameter, as are a golf club head's mass, or a teacup's capacity).
- The main design goals are difficult to quantify (i.e. the last's effect on "shoe fit" and the golf club "feel" are similarly enigmatic), thus physical prototypes are required for performance assessment (i.e. a last needs leather stretching trials and a golf club needs play testing).
- There is an equivalent abundance of previous last designs, all cross referenced by the design guru, and used as the basis for current designs. This creates a common design capture, storage, classification and retrieval problem. Current research indicates that approximating Coordinate Measuring Machine (CMM) digitised data with suitable EF features and blends produces acceptable CAD model replicas for existing designs.
- Design activity levels are high to keep pace with fashion changes. Thus the investment required to develop anatomies and features is warranted. The need for economic limited volume last customisation for orthopedic purposes also supports the need for feature based CAD.
- The current designers/craftsmen exhibit low computer literacy levels.

Shoe lasts also exhibit some idiosyncrasies that raise uncommon issues:

- The shoe last is a manufacturing process form tool. It is not the final commercial product, and so may be overlooked for CAD. There is some discrepancy between shoe size measurements and last size grading parameters [1988 Rossi]. It may be expedient to rationalise these when developing CAD based grading routines.

- Last design specifications are more dependent on derived parameters than golf clubs, for example. This places a greater emphasis on dimension optimisation facilities, for both base model design and automatic set generation, once the general shape has been established. This will increase the time taken to achieve a finished design, depending on the tolerance band for accepting these dimensions.

- Existing last sets are partly generated by anisotropic scaling using a copy machining process (grading) and partly by one of three levels of manual adjustment required to eliminate some of the undesirable effects of scaling (full, semi- and no coordination). Exactly reproducing this process is complex, and probably unnecessary. Instead, given the increased flexibility in shape control provided by the EF feature approach, the grading and coordination goals are more directly achievable. Ultimately, this technology may enable an enhancement to current grading systems, for example by allowing controlled non-uniform girth variation along the last length, that will result in subtle improvements to shoe fit.

- Shoe upper CAD tools generally require the last geometry to be specified in a different format to that produced directly from EF feature modelling. This introduces an additional model conversion process.

- The last design is wholly concerned with shape and ultimately shoe fit. The mechanical strength and load response requirements are unlikely to warrant analysis, thus there is little need for analysis mesh generation (model discretisation) except when FEA packages become capable of estimating upper "fall in" to predict the resulting shoe's fit.

- The last machining accuracy is relatively low, indicating less critical precision requirements. This gives some scope for approximating existing designs and conversion to a single surface representation for upper design.
- Future generations of last designers may be more CAD literate, due to the spread of computer aided upper and unit design systems.

Finally, using CAD tools for last designs has some implications for last manufacture. Once the base model has been graded by the CAD system it is relatively easy to produce CNC machine code to manufacture a pair of lasts for each size in the set. Production last sets for each size can then be copy turned from these masters.

Alternatively, automatic CNC code generation may make it cost effective to produce low production volume injection mould tooling for each last size. This approach would remove much of the manual work in finishing the last heel and toe profiles. Currently these are used as holding points and the final shape is produced by manual grinding and shaping the residual lugs. The 'v' groove and hinge recess could also be cast at the same time to further reduce manual operations. Furthermore, it may be possible for shoes to share the same heel moulds where they use a standard heel shape, and even for shoe manufacturers to use one set of heels (foreparts) with several alternative sets of toes (backparts).

1.2. Stylist Constraint and the User Interface

Feature based design will impose some constraints on product stylists. Using an existing feature set and anatomy for their product limits their scope to some extent. This not only implies that a system's usefulness will depend on the breadth of features and anatomies supported, but also on its ability to adapt to a product's evolution. The proposed data structure (Chapter 5) is capable of supporting this evolution. Anatomies can be varied and given access to existing feature shapes where appropriate. New shapes and behaviour can be introduced as new feature algorithms, or as digitised shapes.

These can then be incorporated into other designs to update a whole product range.

In contrast it should be noted that even a simple golf club anatomy, and a single set of appropriate feature shape algorithms, is sufficient to generate a multitude of acceptable designs. There is also some merit in slowing the pace of design change where this ensures that products remain within the scope of good design and manufacturing practice. However, the ease with which a user can define new features, anatomies, and their behaviour, is likely to play an important part in the acceptance of a sculptured product CAD tool. This places a heavy burden on the developers of a suitable user interface.

There are three areas that need careful consideration to produce an improved user interface for sculptured features:

- Feature introduction - possibly based on library access, viewing, and comparison to support 'bottom up', 'top down', and hybrid design activities.
- Feature editing - including both parametric control and direct surface distortion.
- Feature definition - including shape algorithm definition (possibly using a generic language) and real surface capture.

Parametric shape control will support automatic product range generation, and so remove some of the less skilled design activity. However it is likely that individual range members will still require subsequent fine adjustment to satisfy aesthetic quality standards. Where parametric control is insufficiently refined for this activity, more detailed surface editing will be needed. This relates well to the sculpting analogy, where the forming process is iterative and increasing in refinement. The essential forms are dealt with first, then their interaction, and finally each is refined in detail. This could be seen as a prediction of failure for the parametric approach. It should be seen as a pragmatic acceptance of the desire for full control over a design, but with a reduction in development time and effort.

Given this conclusion, the feature application record needs to indicate a state change from an original digitised or parametrically defined shape to a bi-parametrically refined shape (i.e. one modified to a limited extent by suitable access to the mathematical surface parameters). This supports logical access for the user to the appropriate shape manipulation methods (the parametric shape algorithm and its parameter associations or the geometry engine's inherent capabilities) and indicates the further need for methods to transform (and so approximate) between the 3 potential shape states (digitised; parametrically defined; bi-parametrically refined).

Currently the capability for fine shape adjustment, and its ease of use, is dependent on the representation technology employed. It is likely that this will continue to be the case. A generic approach can only be a more detailed and formalised approach to parametric surface definition, and as such it is just a case of adopting the most promising representations within a standard. The shape definition algorithm, simplified parametric control, and detailed surface control can then be unified within a single schema.

Before any system is capable of emulating the subtleties of manual sculpting some significant progress in low cost computer hardware, as well as interface technology, is needed. For example, parallel processing will be needed to give shaded surface shape and intersection adjustment simultaneously in real time. Until then, a systematic phased approach to design, with some commitment to earlier design decisions, is needed to reduce the time spent in model geometry evaluation at each design iteration. Initial use of the method shows that it is not unreasonable to refine the product forms, then primary blends, then secondary blends, and subsequently surface markings, with little reiteration. Design activity based on existing designs already exhibits some commitment to earlier design decisions within sculptured product industries.

1.3. The Importance of Shape & Feature Type Disassociation

Although the disassociation of feature type and shape behaviour has been emphasised as fundamental to the EFFM data model, its importance should be considered, especially given that neither of the implementations presented actually achieves this. Without this tenet sculptured EF features could simply be implemented as parametrically controlled (constrained) free form features within a normal feature based modeller. The consequences of this are likely to be a reduction in data model complexity and a more economical commercial implementation for those systems predominantly supporting feature based design for mechanical CAD.

However, it is important to recognise that to remove disassociation, to have the different shape behaviour as instances of an anatomy feature class as in mechanical FBD, is a compromise between the flexibility of a sculptured feature based system and economy of implementation. As such it will adequately support the requirements for designing partially sculptured products, but for predominantly sculptured products a different scenario is envisioned. For a mechanical CAD system the types of feature are many, and the instances of shape behaviour are relatively few, supporting the assembly of many completely new anatomies. For FBD of a mature sculptured product the number of types is relatively few, the range of shape behaviour classes is (potentially) many, and these are associated with few anatomies that evolve far more gradually.

Mechanical feature based CAD can be seen as assembling generic shape components (and by implication generic functional and manufacturing process components) to form new anatomies capable of new functionality. Sculptured feature based CAD can be seen as specifying shape variation within known anatomies to establish some functional variation, but predominantly to bring about new aesthetic appeal.

Thus, because in mechanical CAD the focus of activity is on anatomy variation by feature type combination, the type context is always new, and so it is more convenient to classify type by shape (and so functionality and manufacturing process), as there are few types that will share common shape. However, because for sculptured CAD the focus of activity is on shape variation within stable anatomies, the type context is static but the shape possibilities endless. New shape behaviour classes are likely to be developed at a far greater rate than anatomies or even anatomy variants. To insist that features are classified by rigid shape and type associations is impractical. In an environment characterised by an ever growing shape behaviour population to insist that each type be related to a dedicated and exclusive subset of this population must introduce redundancy within the data structure, but also repetition of effort in defining new shape behaviour (algorithm) classes.

CAD systems for individual sculptured products are likely to be industry specific anatomy implementations within a generic EFFM framework. Supporting shape and type disassociation within the generic system enables greater efficiency in system implementation and evolution.

For the basic user, using a system to quickly produce design variants, the true value of EFFM approach is not in shape disassociation, but in the change in emphasis from anatomy variation to anatomy stability. This allows the user interface and model assembly and shape variation processes to be streamlined. This could be achieved by customising a mechanical CAD system given suitable interface adaptation and surface manipulation functionality. In fact, in these terms it is only the custom interface that distinguishes the current EFFM system from the parametric design functionality of other capable modelling systems. However, for the more advanced user, developing new shape behaviour classes and product anatomy variants, shape disassociation supports a more efficient evolutionary process.

By comparison with the mechanical CAD system market, CAD systems targeted at sculptured products specifically occupy a relatively small, but not insignificant niche. It seems likely that within this market sector, those companies offering a generic EFFM capability for customisation by specific product industries offer their customers greater design development efficiency than the all-purpose mechanical CAD system vendors. Similarly those all-purpose vendors offering an EFFM based sculptured feature module to extend their system's functionality to encompass predominantly sculptured products will have an advantage over those that do not.

1.4. Implications for STEP/PDES

The 'form feature' work within STEP/PDES [1992 ISO] does not cover:

- Sculptured surfaces.
- Inter-feature relationships.
- Application features.
- Features that are not of 'widespread industrial interest'.

However there are some useful points for comparison with the sculptured feature model. The working draft refers to 3 levels of feature data:

- Application feature - a shape with non-shape application specific connotations.
- Form feature - 'a (generic) shape aspect which conforms to some preconceived pattern or stereotype and is, for the purposes of some application, usefully dealt with as an occurrence of that stereotype.'
- Form feature representations - 'employed in shape modelling to represent shape properties.'

Currently the working draft aims to deal with form features and their representation. Application features are to be dealt with separately.

These definitions show an approximate equivalence in concept with entities in the EFFM data model (Chapter 5). The 'shape' entity can be seen as a form feature. The 'algorithm' entity has some similarities with the form feature representation (although there is some overlap with the definition of the form feature). The 'feature type', containing data elements and methods, is similar to the application feature, in that it embodies the non-shape feature connotations.

However, the feature type entity is significantly different in that it has no fixed relationship to shape. In a sense:

Feature type ≈ (Application feature) - (Form feature)

This disassociation is important for reasons already discussed. The shape entity is not identified as a 'feature' within the data model because it has very little use as a feature that can be presented to a user. Essentially, a form feature as defined above is only a 'data modelling feature' within the sculptured product context - a useful concept for system developers, but less so for users. This is because defining a fixed relationship between the feature type and its shape over-constrains design activities in a sculptured product context, whereas it saves time in a general mechanical design context.

The implication is that there can be no complete 'feature entity' within the data structure, without introducing redundancy. A feature is a concept presented to the designer, by the system interface, that embodies several data entities, such as:

- Application relevance - a role in the design (feature type; artefact anatomy).
- Potential shape - (shape; algorithm; surface; type reference)
- Alteration behaviour/constraint - (algorithm; parameters)
- Inter-feature relationships - (boundary; co-ordinate transform; group)
- Application instance - (application record; value; function; design)

In general mechanical design, there is more variety in anatomy and less in feature shape. Thus, the product anatomy is generally formulated by an assembled instance of features, and the feature shape can be seen as the co-ordinating concept for relevance, shape, and even manufacture. The co-ordinating key for feature ideas within the sculptured product model is the feature type within an anatomy, at the conceptual design stage. For a design instance, the co-ordinating key becomes the application record within a particular design.

These concepts have profound implications for STEP if, in the future, it is to encompass the means to exchange product data for sculptured products designed using EF features.

2. Summary of Achievements

2.1. Overview

Dixon & Cunningham stated that a successful FBD system should [1989 Dixon & Cunningham]:

- Constitute a natural set of primitives that enables designers to design complex parts conveniently with add, modify and delete operators.
- Enable a primary representation of in-progress designs to be created so the desired secondary representations can be developed easily. Feature extraction or feature decomposition, if required, should be computationally tractable.

The work presented in this thesis fulfills the first requirement for sculptured product design, and provides a basis for exploring the second requirement as future work. Considering the work in more detail, the research approach has been to establish generic principles for feature based sculptured product design by first considering a specific product's requirements (primarily iron golf clubs). The resulting assumptions, theorems and methods have then been validated through direct application to the product's design process, and subsequent extension to the broader requirements of other products (notably shoe lasts, although wooden golf clubs and ceramic tableware have also been considered and omitted for brevity). The following sections review the achievements, knowledge gained, and industrial relevance in fundamental objective areas.

2.2. Objectives and Achievements

2.2.1. Sculptured Product Design Process Analysis

Within this aspect of the research the existing manual and normal CAD based design processes were considered in relation to the full spectrum of iron golf club designs. The essential tasks were to identify the requirements for a new design system, propose a suitable architecture for a prototype, and devise an approach to sculptured features. The results can be summarised as follows:

Main Achievements

- Familiarity with iron golf club designs and design processes was established, and the need for localised control over product surface elements for product design revision was confirmed.
- The need for 'top down' (modification or revamping existing designs), 'bottom up' (design from scratch), and 'hybridising' design process support was identified.
- The need for any CAD system interface to be driven via industry specific terminology and concepts, rather than mathematical and computational jargon, was confirmed.
- The inadequacy of current prismatic feature systems, and the lack of detailed support for sculptured features was confirmed.
- A generalised design feature definition for sculptured products was adopted.
- Free form sculptured features 'stitched' together at their common boundaries were evaluated as an inadequate approach for sculptured feature based design due to their poor support for hybridising design activities and simplified parametric control. The distortions necessary to re-establish smooth joins between a new hybrid feature set undermined the shape contribution required from the feature and the general complexity of the free form features defied parametric simplification.
- The EFF approach to sculptured product feature anatomy decomposition was conceived and adopted. Product models are based on three classes of feature; primary extended forms (controlling fundamental shape); secondary blends (governing aesthetic refinement); tertiary ornamental markings (allowing detailed decoration). The EFF approach directly supports hybridising activities, parametric simplification and so automatic set generation.

- A system architecture was established using DUCT software as the geometry evaluation engine, custom routines to manipulate design and feature libraries and custom interface routines driving the feature routines and presenting relevant design process controls and results to the user.
- The inadequacy of a manufacturing feature analysis and decomposition as a basis for sculptured product design features was established, and the likely sufficiency of a set of design features as a basis for manufacturing reasoning is proposed.

New Knowledge

- The EF feature approach to sculptured product modelling.
- Sculptured features are strongly interrelated so that a cohesive approach to all feature classes is necessary.
- Primary extended form features are product specific, mainly because they originate from a craftsman's skill with a manual forming tool rather than a heavily constrained machining process. Thus it is impractical to develop a complimentary generic set of sculptured features to match the set for prismatic designs. However the method does provide a generic approach to product modelling and manipulation within which product specific features can be defined.
- The proposed EFF method is strongly analogous to the manual sculpting process where the strong characterising forms are established first and subsequently refined in shape, blended into each other and embellished with fine detail.

2.2.2. Iron Golf Club Features

With the goal of developing a prototype design system based on the EFF method it was necessary to first identify and define an anatomy for golf club irons. The resulting set of features could then be measured and reproduced as CAD geometry, and then converted or approximated by corresponding parametric feature algorithms. The project research results in these areas can be summarised as follows:

Main Achievements

- Several market studies for different golf club categories (e.g. cavity back and forged irons) were performed to establish club feature shapes, and a satisfactory iron golf club anatomy based on industry terminology and design control aspirations was proposed, refined and validated.
- A selection of existing clubs were captured by digitising using a CMM, DUCT data processing, and extrapolation to produce extended forms.
- New product datum assignment and design orientation methods were developed and adopted to overcome ambiguity in existing industry specifications.
- Parametric algorithms were developed and used to model a valid club shape, and subsequently to model digitised clubs within a satisfactory tolerance.
- The parametric algorithms were used to successfully produce valid golf iron designs and set variants.

New Knowledge

- The suitability of a feature based method to golf club modelling was confirmed.
- Because product specifications are in the main the hand crafted model, there are gaps in the vocabulary and specification parameter set that must be filled, in consultation with existing designers and stylists, to establish an adequate set of features to model and manipulate the product design in all eventualities. In some instances this requires evolving the product anatomy to model product variants beyond existing product designs.

- The nature of sculptured products makes it difficult to establish repeatable physical datums. Existing methods associated with manual sculpting are generally ambiguous and inadequate for feature based CAD. It is important to rationalise existing approaches, maintaining consistency with traditional methods where possible, to introduce the rigour necessary for complete 3D feature positioning.

2.2.3. Prototype Golf Club System Implementation

Given the club anatomy and feature shape algorithms it was possible to develop a working design prototype. The major additional elements of the system were a prototype user interface, automatic blending routines and automatic set generation routines. The prototype was initially simulated, with manual results being displayed to represent design activities. Subsequently a working prototype was implemented, and refined.

Main Achievements

- The functional requirements of the user interface were analysed. A prototype user interface allowing user control of the design and feature libraries and interactive manipulation of the feature parameters was developed based on the results.
- Automatic EF blending and trimming routines were developed and successfully implemented for the golf club anatomy.
- Manual set generation was demonstrated, and then automatic set generation routines developed and successfully implemented.
- EFFM based mechanical property calculation and visualisation facilities have been incorporated within the system. They demonstrate improved calculation efficiency due to exploitation of the feature data structure.
- In summary, the prototype system is a working sculptured product (golf club) design system based on the EFF method, supporting extended functionality to enhance design process efficiency.

New Knowledge

- The EFF model approach's success is heavily dependent on the robustness and repeatability of the blending routines. The need for a multiple surface variable radius filleting routine within DUCT (required to model the golf industry's existing neck regions) was overcome by developing a golf iron specific hosel/blade neck feature. In retrospect this can be seen as an adaptation of the original club anatomy, and the adoption of a product specific complex blend shape algorithm.

- The back cavity design facility exposes the need to support anatomy variation. The back cavity is so varied in shape and feature content that it disrupts the concept of a shared anatomy between sets. Thus, any EF feature based system for products of this kind needs the ability to evolve a product family's anatomy to handle the estimated 20% of feature content that changes to establish a new market identity.

- The back cavity design facility also exposes the need to support complex feature parametric definitions. The cavity wall's potential complexity defies simple parametric manipulation. Thus in some instances the feature shape algorithms need to be driven by more appropriate means, such as control curve sketching or direct parametric surface manipulation. Although implemented using Bézier surfaces the EFF method is not constrained to any particular surface representation or editing technique. Simple parametric manipulation of surfaces is only encouraged where this gives acceptable shapes and so simplifies the design process and task automation.

- In most cases automatic set generation produces valid models with 80% acceptability. This removes most of the 'donkey work' for set generation, and makes time for design refinements. In some instances extreme parameter variations cause model failure (mostly due to blend routine robustness or inadequate form extension) or unacceptable design distortions. In many instances the variation of additional parameters through the set markedly improves the results.

- Although the mechanical property calculation facilities can be used to establish satisfactory objective functions for design optimisation, the time taken to recalculate values after a model change for characteristics other than mass/volume (e.g. ~15-30 minutes for each principle inertia calculation) prohibits their use for immediate or gross change optimisation. With current workstation speeds optimisation of complex derived characteristics (e.g. centre of gravity positioning and "sweet spot" maximisation) require batch processing over night or implementation on more powerful computers.

2.2.4. Prototype Model Manufacture

Although developing feature based CAPP and CAM are not part of the research aims presented in this thesis, models produced using the design system have been manufactured to confirm the method's validity. Despite high quality visual displays, real time shading and model rotation, sculptured product designers still require a 3D physical prototype to evaluate shape. It has also been particularly useful for collaborators to see the physical results and success of the work to promote system acceptance and development within their own organisations. The research results in this area are as follows:

Main Achievements

- Several EFF based anatomy modelled clubs mimicking existing physical designs and several EFF system designed irons have been machined in resin (Figure 10-1).
- System designed irons have been produced using a range of rapid prototyping technologies including stereo lithography, laminated object manufacture and powder sintering (Figure 10-2).

Figure 10-1 EFFM Design Machined in Resin.

Figure 10-2 EFFM Design Produced Using Rapid Prototyping Techniques.

New Knowledge

- The prototype system produces acceptable results for both CNC machining and rapid prototyping. The physical results are acceptable club shapes.
- The modelling consistency enforced by using the design system reduces the problems in producing CNC data and STL files.
- Any sculptured feature based approach, including EFF and LFF methods, increases the difficulty in producing model output for current rapid prototyping machines. Because they all require STL file data input (a continuous triangular facet based approximation of the object surfaces) more complex and robust facetting routines are needed to approximate the individual features and match mesh nodes at their shared trimmed boundaries, than is needed for continuous bi-parametric surfaces or prismatic solid models.

2.2.5. User Trials

Users trials were undertaken to evaluate the initial prototype system. The research results can be summarised as:

Main Achievements

- The user trials demonstrate that a successful sculptured product CAD system can be developed using the EFFM strategy, providing product experts with a powerful and efficient design tool without the need for special computing skills, training or experience.

New Knowledge

- The trials indicated the potential for substantial improvements in training, design development and manipulation times. In particular:
    - After only a few hours training it is possible for a novice user to design valid golf clubs, as opposed to several weeks of DUCT training and months of experience.

- A new club design can be generated in less than 30 minutes (depending on its variation from the norm), as opposed to a days work for an experienced CAD user.
- Modifications to a design can be achieved in a matter of minutes as opposed to several hours using traditional methods (depending on the modification complexity and extent).
- An initial full set of iron club designs can be produced automatically (based on a new mid iron design) in less than 50 minutes as opposed to two weeks for an experienced CAD user.

2.2.6. Alternative Product System Prototype

The original research objectives were to first produce a design system for iron golf clubs and then golf woods. Applying the EF method to woods and a selection of other products (including shoe lasts, ceramic tableware, ceramic sanitary appliances and even a 3D criminal photo-fit system) has been considered, with some initial modelling undertaken to evaluate the feasibility and difficulty in all cases (except sanitary appliances). The results have established the EF method's generic applicability and exposed the need for product specific developments to cater for individual requirements (e.g. providing mass optimisation for golf clubs, shrinkage allowances for ceramics, and fit optimisation for shoe lasts).

Shoe lasts were subsequently selected as the subject for the second design prototype instead of golf woods. Shoe lasts exhibit greater dissimilarities to golf irons than golf woods, thus successfully applying the EF approach is better proof of generic relevance. Loughborough University's contacts with BUSM, SATRA and Clarks Shoes also made it possible to consider the product in some detail. To pursue a prototype feature based shoe last design system it was necessary to form a detailed plan for the implementation, identify and capture a product anatomy, and adapt the system interface and modelling elements to the last anatomy. The results were as follows:

Main Achievements

- Familiarisation with shoe last designs was established, and an acceptable shoe last anatomy developed for a common ladies shoe style.
- A representative set of features has been captured using a CMM and DUCT data processing.
- The necessary interface reconfiguration and model elements necessary to simulate a prototype last design system have been completed.

New Knowledge

- It is possible to decompose a shoe last into feature anatomy for EF feature based design.
- There are issues common to sculptured products, including shoe lasts, that are specifically addressed and dealt with effectively within the EF method, for example:
    - CAD tool implementation based on product specific terminology.
    - Localised and simplified shape control for sculptured product design.
    - Hybrid and variational product design.
    - Anisotropic grading of product families.
- Shoe last modelling requires more extensive multiple surface variable radius blending than golf irons, and in some cases arbitrary section blending as opposed to rolling ball fillets. With these additional facilities it will be possible to successfully design shoe lasts using an EFF approach.
- An EFF based approach shows significant potential to benefit last design efficiency, enhance size grading, and improved manufacturing processes. Last design specifications are more dependent on derived parameters than most other sculptured products. This places a greater emphasis on dimension optimisation facilities, for both base model design and automatic set generation, once the general shape has been established. This will increase the time taken to achieve a finished design, depending on the tolerance band for accepting these dimensions.

2.2.7. Generic System Implementation

To completely establish the EF feature methods generic applicability to sculptured products a definition and implementation of the fundamental generic data structure was needed. This will provide the basis for further work in this area. The work on the generic system can be summarised in brief as follows:

Main Achievements

- A generic data structure to support EF feature based sculptured product design has been established. The structure is characterised by:
  - A product classification hierarchy for design retrieval, relating parametric design variations (sets), and differentiating between product anatomies.
  - Feature type associations to collectively define the abstract (non-explicit geometry) product anatomy.
  - Feature shape associations to relate acceptable sculptured shape behaviour to anatomy features types.
  - Feature shape and type associations with specific designs relating the abstract feature descriptions and shape algorithms to instances of evaluated geometry.
  - The use of common variable associations to control parametrically constrained features with reference to designer terminology and to enable automatic set generation.
  - EF, blend, tertiary marking and group feature type associations to enable automatic blending and geometry evaluation.
- Although the generic data structure has not been fully implemented within the object oriented database in DUCT as planned, the prototype system represents a successful single anatomy implementation that conforms to the model structures.

New Knowledge

- The generic data structure is specified using entity relationship modelling. The model itself affirms the ability to conceptually decompose a product into EF sculpted features. It also exposes the reality that in the sculptured domain a feature's shape and type are not bound together (as an uninstantiated feature entity) but instead are combined at instantiation as a design entity (sculptured feature) with multiple inheritance (shape and type). This disassociation of sculptured feature type and shape is in contrast to prismatic product features, where shape and type are associated, and supports the sculptured product designer's need to use common terminology for product regions that may adopt almost any shape.

- A blend devolution approach has been identified to overcome problems with error detection, FE mesh generation, and multiple surface blending. Primary and subsequent levels of secondary blend can be ordered (1 to n). Blends at each level (i) can be replaced by intersections of the base feature groups at the previous blend level (i-1). Thus blending errors can be predicted by first establishing a successful devolved intersection, unnecessary levels of model detail for FE analysis can be removed by blend devolution, and the devolved intersection provides a 'guide' for multiple surface or arbitrary section blending.

2.3. Industrial Relevance

The 'stitched free form' feature approach to sculptured product design has several advantages over the EF method when:

- Each product design has a virtually unique anatomy.

- There is little commonality between feature shapes for a product family even though members share much the same anatomy.

- The desired product shape permits little surface feature decomposition and exhibits exceptional higher order curvature continuity.

For products that exhibit these characteristics, perhaps automotive body shapes, there is little to be gained from a full implementation of the EF method. Although they can be modelled, the effort to develop an anatomy and product specific feature sets balances or outweighs the efficiency gains for subsequent design manipulation, unless:

- High levels of design variation trials, or iterative refinement are expected.
- Anatomy and feature definition overheads can be reduced, possibly by initially following the EF approach manually and using 'define by example' routines to automatically interpret the model structure and control elements.

Otherwise, the 'stitched free form' surface approach with some Boolean operations, directly supported by most surface and now some solid modelling systems, is better for these products.

However, for sculptured products that form a family where:

- Members share a common or similar anatomies
- Members are differentiated by variations in the anatomy shape elements (features)
- Anatomy features may be controlled by a simple set of parameters
- Sub-sets exhibit parametric shape variation (e.g. a particular set of golf irons)

the EF method provides significant savings in:

- Training time
- Initial design development
- Subsequent design modification
- Automatic set generation
- Model quality

that potentially outweigh the initial investment in anatomy and feature set development.

Companies with this type of product that adopt an EFF based design approach can expect faster new product design and existing product modification. This should allow cheaper product development, greater margins for product experimentation, faster response to market fashion changes and better quality. This capability coupled with computer based manufacturing data generation, companies should have more direct control over their product's manufacture and so it's distinguishing characteristics. For the golf industry this means reclaiming control that has been transferred to the South East Asian casting houses. In the shoe last industry this might mean that custom orthopedic lasts are economically viable.

3. FUTURE WORK

3.1. Sculptured Feature Recognition and Specification

Currently, a product's sculptured feature anatomy is identified using a mixture of subjective and objective techniques (Chapter 4). A more rigorous computer based curvature analysis for existing products, using scan digitised data, could be investigated as a means of augmenting a craftsman's ability to identify surface feature regions.

Also, using existing general purpose surface modelling systems it would be useful to investigate a feature anatomy 'definition by example approach', where a computer modelled product is decomposed into features based on the algorithms used to generate them (i.e. everything that is not generated using a blending routine is an extended form). This could be used retrospectively to convert existing surface models to EFFM based models, and also as a means of interactively specifying new EFF based product anatomies.

In both cases the EFF shape algorithm library would still need to be populated, but even this process could be aided by an intelligent 'macro recording facility', i.e. software that monitors the general surface modelling commands used to generate a particular EF feature example, identifies potential control parameters, and compiles this into a shape algorithm for use within the system library. There seems no reason why an interactive dialogue with the system user should not fine tune the result, nor any reason why suitable GUI elements should not be generated automatically.

3.2. Ornamental Features

Although ornamental features are accommodated within the EFF method (Chapter 3) and proposed system data structure (Chapter 5), and the potential to combine them with the evaluated structural feature geometry has been demonstrated (Chapter 4) the capability has not been implemented within the EFFM based FBD prototype. Delcam have now incorporated the 3D relief mapping capability, previously in the UNIX version of their ArtCAM software, within their DUCT surface modelling software. Thus it is now possible to incorporate the ornamental feature class, with associated shape algorithms containing 3D relief logo definitions and methods for applying the wrapping software, within the EFFM FBD system DUCT implementation.

However, the software controlling the nature of the relief itself (e.g. whether the 2D artwork is developed as a relief or engraving) is still external to DUCT. The ornamental features would be more economically implemented if this functionality was available seamlessly within DUCT, as the parameters and methods associated with generating depth or height and slope on a 2D definition of the feature profile could be incorporated within the shape algorithm, instead of having access to predefined relief instances.

3.3. Virtual Sculpture

A future variation on the design by example alternative could be based on virtual sculpturing tools. If the user were provided with a virtual environment containing tools capable of mimicking the manual sculpting processes, it may well be possible to identify sculptured features by interpreting the virtual sculpting process. Large, and perhaps early, material removal or addition to establish fundamental forms could be interpreted as EF features. Subsequent refined blending between established surface regions would indicate blend features. The types of virtual tool used (e.g. user defined shape templates and blending balls) and even pressure patterns for 'hands on' manipulation might also indicate feature type and define suitable shape algorithms. Given such a powerful virtual tool the obvious question is why bother with a feature based model interpretation? Two answers are apparent:

- Manually producing design variants is inefficient, but automatically producing design variants requires access to variation controls. Interpreting a manual sculpture as a feature based model decomposes the model into controllable elements, reveals the means by which they can be controlled, and establishes a structure for processing change.

- Manual sculpting often results in surface imperfections. In some cases these are desirable and contribute to the products quality. In other instances they are not acceptable. Translating a virtual sculpture to a feature based model may well provide a controlled means for removing these imperfections, effectively 'cleaning up' the product model.

3.4. Anatomy Evolution

It is unlikely that any sculptured product anatomy will remain constant ad infinitum, even one as immersed in tradition as the iron golf club. Because the EFF method provides a product anatomy specific design aid solution, its future success will depend on its ability to adapt to change.

The types of anatomy change envisioned are:

- *Additions to the feature library.*

  These are easily incorporated as additional classes.

- *Additions to the anatomy.*

  These are relatively easy to incorporate as variations of the anatomy definition, although some means of overcoming the class naming restrictions or multiple inheritance problems need to be overcome if the definitions are to be held concurrently without redundancy.

- *Subtractions from the anatomy*

  These pose similar problems to additions, although not insisting on the presence of all potential features (except those with required dependents), or additional rules for optional final generation features (such as ornamental features) might provide a more efficient means for incorporating the majority of subtractions.

- *Partial anatomy revisions.*

  Theses are essentially combined subtraction and addition, and so pose the same problems.

- *Full anatomy revision*

All of these depend upon the ease of feature and anatomy definition. The model trimming routine can be made to work universally on any EFF anatomy[1], and it would be possible to have an abstract definition interface, where the anatomy and features are programmed from the top down. It would also be useful to explore a formal system development methodology, perhaps similar to SSADM, based on blend relationship diagrams (anatomy graphs), feature taxonomies, and shape algorithm functionality specifications.

Alternatively a bottom-up approach based on a 'define by example' technique (Section 4.2) may be more desirable for an experienced designer.

3.5. Error Handling

Identifying and reacting to unintentional feature interactions, and the failure of intentional ones, is one of the main weaknesses of the existing EFFM FBD system.

Failure of intentional relationships is partly due to the robustness of existing blending routines, and partly due to the extension limits of the EF features. Both of these can be overcome by 'smarter' routines.

Beyond this the failure of intentional relationships and the introduction of unintentional ones is mainly due to the inherent potential surface complexity of sculptured products. It is unlikely, given current engineering workstation computing performance, that these problems can be dealt with automatically. However, because all EFFM design is based on a predefined anatomy, any unspecified interactions are much more likely to be user errors rather than an obtuse approach to achieving a desired result. Thus, it is more likely that problems associated with feature interaction should be identified and rectified by designers, so that research effort should be focused on establishing the means for them to do this.

---

[1] Although for greater speed it would make more sense to automatically configure custom routines for each anatomy definition rather than interrogate the object database each time.

Given that most designers/craftsmen currently working in sculptured product industries do this unconsciously it seems natural to adopt this solution, and economically unjustifiable to pursue computer based solutions that will ultimately fail to match a designer's abilities.

3.6. Other Engineering Applications

Finally, the potential for exploiting the EFFM FBD model for other engineering applications such as manufacture and analysis should be explored. The benefits of the method for simple inertia property analysis are already presented in Chapter 9, but more extensive use of an EFF based design model requires more detailed investigation to identify suitable analysis, translation and expansion of the 'design view'. Work considering EFFM based CAPP, CAM and automatic FEA mesh generation is underway at Loughborough University.

Figure 10-3 and Figure 10-4 shows the prototype system architecture for EFF based design expanded and updated from the original version (Chapter 5) to reflect the additional object oriented database facilities, and initial proposals for extending the system to support design analysis and manufacturing data generation, in terms of additional interface and manipulation routines accessing the EFF based design model. Although the functionality of these elements is relatively easy to predict, the fundamental issue is the extent to which the design model can be exploited or needs to be augmented to support the additional applications.

To resolve this issue the relevance of EFFM design features must be established within other computer aided applications. Because EFFM design features relate to specific geometry they do have CAPP, CAM, CAE, CAI, DFM and DFA relevance, but they do not necessarily represent direct equivalents of features in these domains, either as groups or sole members of particular subsets.

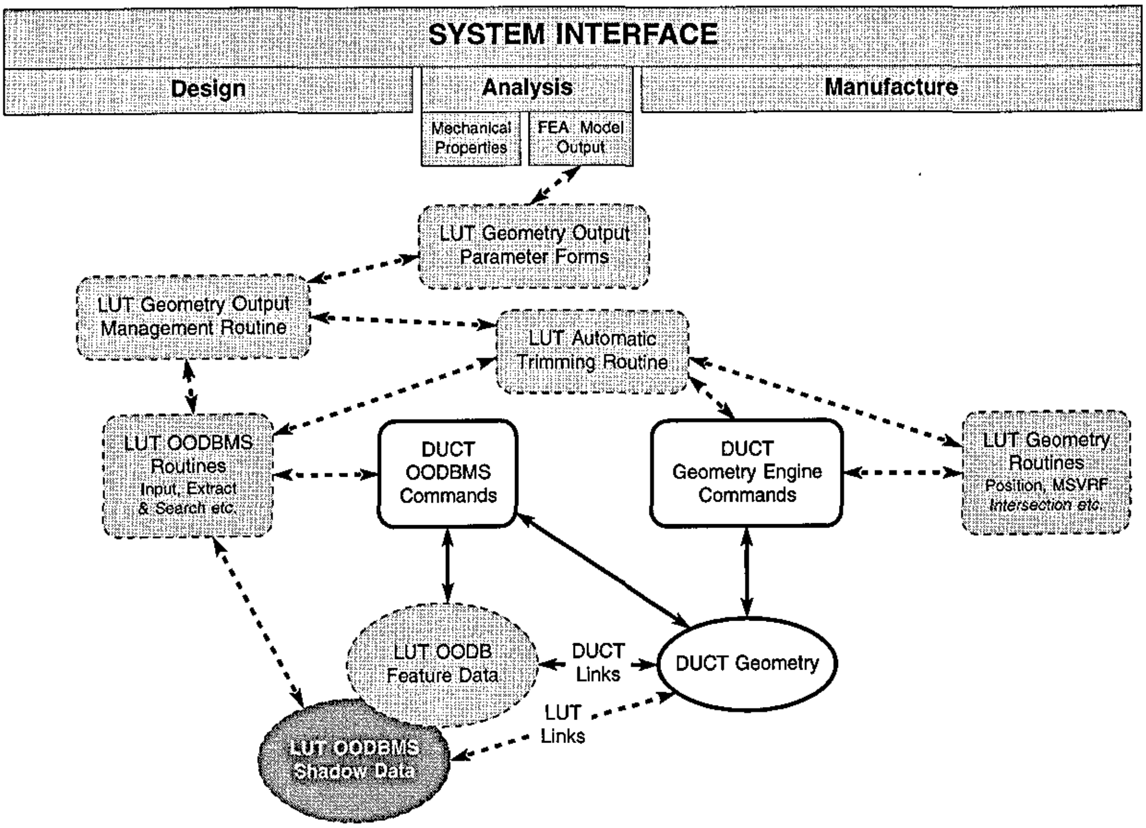


Figure 10-3 Design Analysis System Extensions

For example, although for CAE analysis each feature has potential direct relevance for mesh generation routines, the mappings between CAD features and CAM processes are less closely related than for prismatic parts, so that the concept of equivalence or direct mapping to manufacturing features has little or no use.

Considering the issue of exploiting the design model for CAPP/CAM further, Table 10-1 lists the disparities between sculptured and prismatic products that compound the exploitation problem.

Just as it is impractical (if not impossible) to find a universal set of design features for sculptured parts to support the design of any sculptured product, it is likely that a universal manufacturing process feature and or reasoning tool is impractical (if not impossible). Just as the design feature set would be too extensive, the process strategy possibilities are also too extensive. Instead, it may be more sensible to establish a 'seed' strategy, if not a ruling strategy, for a particular product manufacture scenario, that can then be optimised and instantiated to suit a particular design (just as the EFFM design approach defines a product anatomy and then produces optimum designs by variation of the instantiated feature parameters).

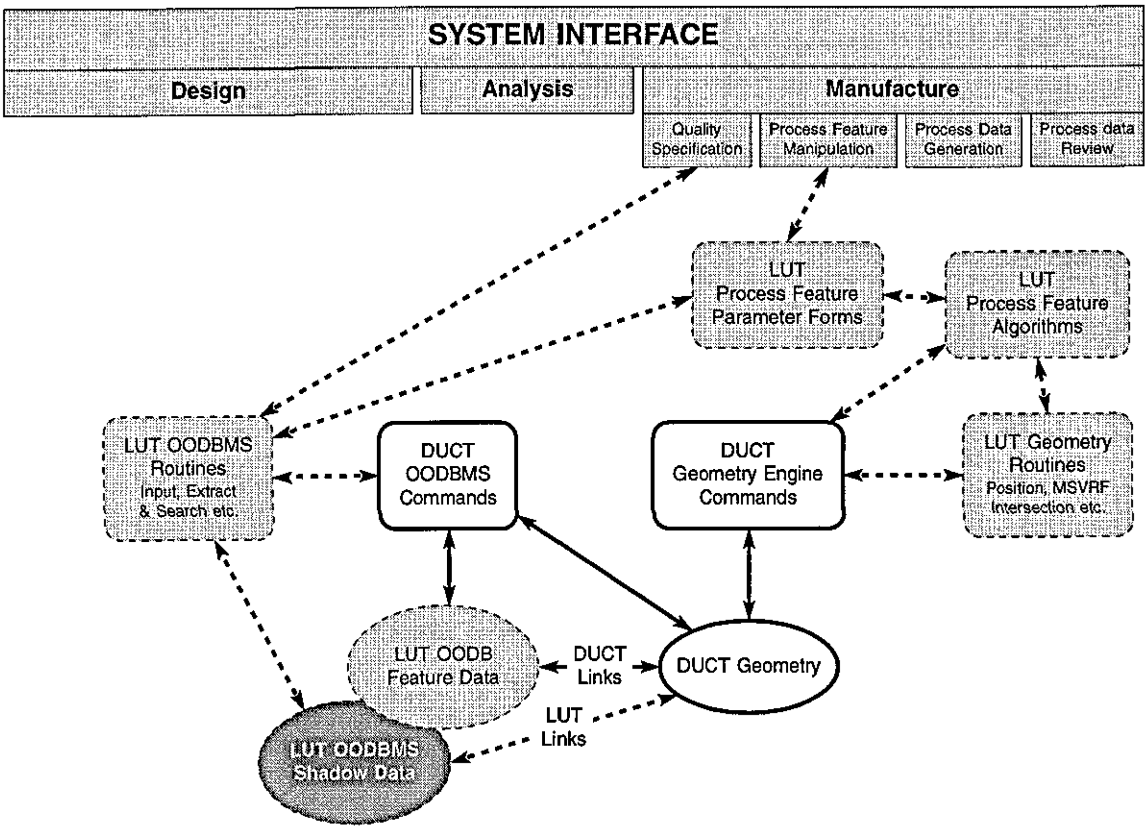


Figure 10-4 Manufacturing Strategy System Extensions

It is expected that a sculptured feature based concurrent engineering system will have a similar architecture to that proposed by Dixon & Cunningham [1989 Dixon & Cunningham] with some modifications. In Dixon & Cunningham's architecture the system interface allows the designer to access design feature and operations libraries to build a primary (design) representation from "primitive features and their legal combinations" sanctioned by a monitoring process capable of preventing feature combinations the system can not interpret. The primary representation is then translated automatically into secondary representations to support other (interactive or automatic) applications such as visual display, manufacturing evaluation or performance analysis, to provide feedback to the designer.

Figure 10-5 shows a predicted concurrent architecture for just one additional engineering application, manufacturing analysis. Like Dixon & Cunningham's architecture the user is presented with a design feature manipulation interface accessing a design feature library via feature operation procedures (although the feature library includes an anatomy library as well) to generate a primary design feature model.

The primary model includes evaluated geometry (although Dixon & Cunningham's architecture does not seem to require this) partly because the existing implementation within DUCT requires class instances and geometric objects to be combined, but also because it is inconceivable that the sculptured product design activity will progress without simultaneous geometry evaluation and visualisation. Thus there is no apparent need to separate feature object data and geometry data, or feature combination and geometry combination functionality, or to introduce a delay between the procedures involved. This is certainly true for interactive design, and for automatic set generation. Even though the geometry display process may be delayed in some set generation scenarios until full set generation is completed, the next operation on the respective models almost certainly requires evaluated geometry for visualisation or performance analysis. Using this approach 'neutral' geometry or even feature data can always be extracted independently for communication purposes if necessary.

As with Dixon & Cunningham's architecture, additional engineering applications are supported by translation to a secondary representation. This process may involve feature decomposition as mentioned by Dixon & Cunningham, but includes the introduction of additional features not present in the design model space [1989 Shah].

Table 10-1 Sculpture/prismatic part comparisons

Issue	Prismatic Part Characteristics	Sculptured Part Characteristics
Process Range	Often involves a broad range of machining processes, some of which can be allocated to reduced degree of freedom specialist machines	Almost exclusively requires a single process type (NC milling, ignoring the distinctions due to cutter types) allocated to a generalist multi-degree of freedom machine
Shape Machining	A design feature shape is often closely tied to a single or relatively few manufacturing processes and process parameters. Given a particular finish, accuracy and access requirements the choice of relationship between design feature shape and manufacturing process (even process tool) may be even more restricted. Thus the variety of shape results in a similar variety of processes	The design shape can generally be achieved by the same process type (multi-degree of freedom, ball nose cutter, CNC milling), but with a greater variety of parameter settings (cutter path cutter locations). Thus the variety of shapes results in a single process and a variety of parameter settings. The restrictions or constraints to these variables are not established by feature type (as for prismatic parts) but by inspection of the internal feature surface curvature and the problems of access to the surface with a particular tool
Surface Continuity	Parts contain a relatively high number of inter-feature surface discontinuities, suggesting discrete machining processes	Parts generally contain a relatively low number of inter-feature surface discontinuities, suggesting continuous machining processes
Degrees of Freedom & Surface Normals	The set of surface normal directions is sparsely populated. The surface regions over which a normal direction applies is often extensive and grouped with other regions so as to make concurrent machining easy. This makes solution of the orientation/access problem relatively simple and efficient machining by alignment of the workpiece surface normal with a machine degree of freedom possible	The set of surface normal directions is generally well, if not fully populated. The regions over which a normal direction applies are small, fragmented and often isolated. However, the increase in surface continuity makes process continuity more desirable. This makes the orientation/access problem more complex and difficult to solve as it requires detailed investigation of the feature surfaces. Efficient machining can only be achieved by multiple degrees of freedom allowing continuous workpiece re-orientation
Datum Points & Holding	Because the surface normal set is sparse, applied to extensive regions and grouped, there is generally plenty of scope for establishing datum and holding points	Because the surface normal set is almost fully populated, applied to small regions, fragmented and mostly continuously varying across the product, there is generally little scope for establishing datum and holding points. Thus they must be added artificially to suit the manufacturing processes

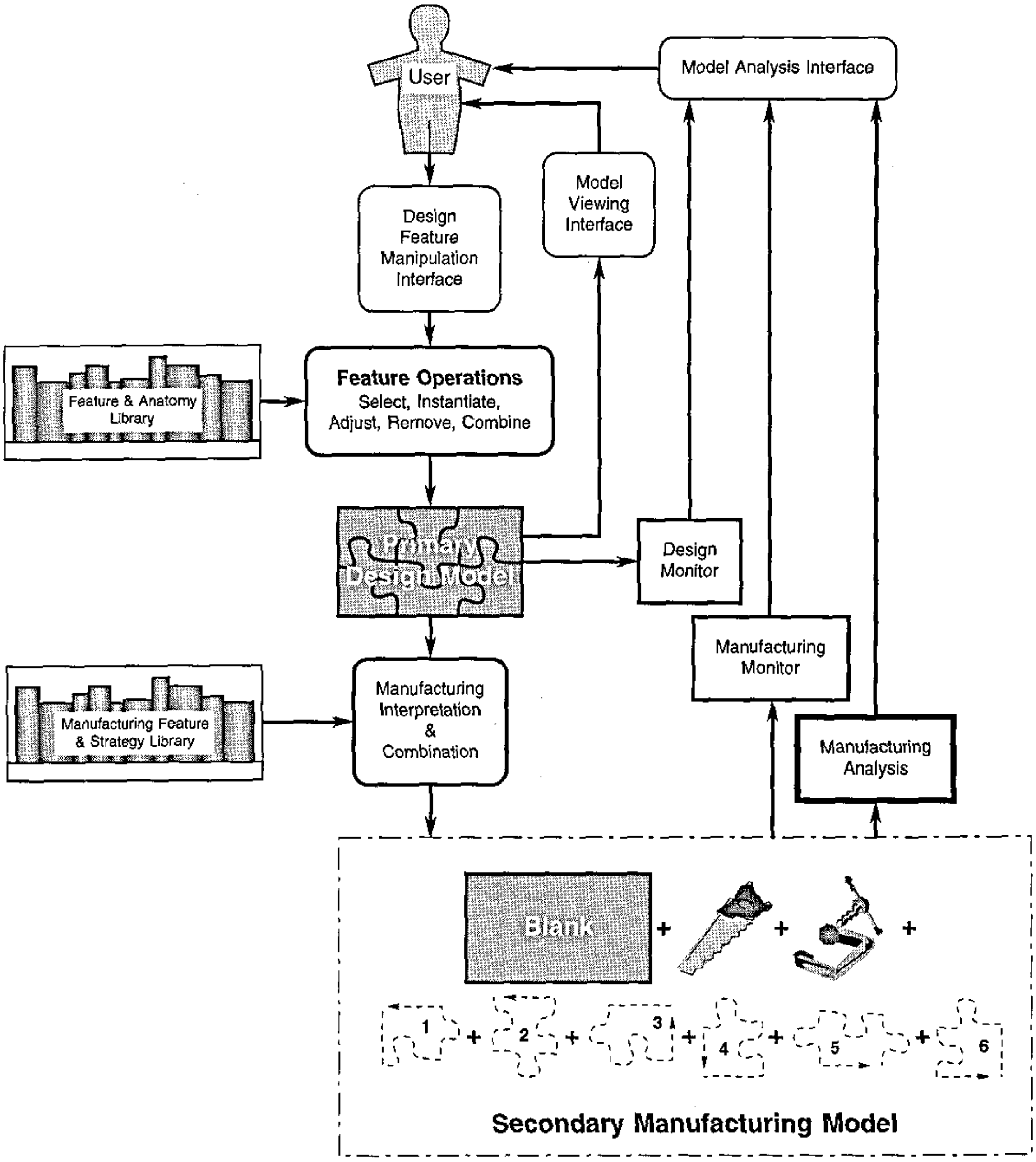


Figure 10-5 Revised System Framework

For manufacturing analysis this requires access to a manufacturing feature and strategy library. It is intended that one or more manufacturing strategies are associated with a particular anatomy and defined in terms of manufacturing features and relationships between these and the anatomy's feature types. This strategy and its features represents an abstract (uninstantiated, a priori) manufacturing view of the product, just as the feature anatomy is an abstract (a priori) design view, from which the manufacturing interpretation and combination process generates a complete manufacturing feature instance model. This manufacturing view is the basis for a manufacturing monitor process, capable of alerting the designer to design model conditions that invalidate the associated manufacturing strategies, and a more detailed manufacturing analysis application.

Other applications, such as FEA based performance evaluation, would be supported in a similar fashion. However, although the design monitor can be implemented as a concurrent process in support of real time interactive design, the secondary engineering application monitors would probably slow the system's response to an unacceptable level using current engineering workstations. Until more powerful parallel computing systems are available, it is more likely that analysis of the design model by secondary applications will be activated at discrete intervals during the design process.

CHAPTER 11. CONCLUSIONS

From the research described in the preceding chapters it can be concluded that:

(i) There is a need for FBD of fully sculptured products and existing FBD approaches are not well adapted to the problems associated with these products, particularly the potential variety of feature shape behaviour.

(ii) The proposed EFF FBD modelling approach addresses these issues specifically and as a result is fundamentally well suited to efficient sculptured product design. In particular it provides:

  (a) A CAD tool driven by product specific terminology.

  (b) Localised and simplified shape control for sculptured product design.

  (c) Efficient hybrid and variational product design.

  (d) Effective and efficient anisotropic grading of product families.

(iii) Valid EFFM based sculptured product anatomies can be, and have been, identified as the basis for successful computer based designs of a variety of real sculptured products.

(iv) A data model to support a generic EFFM FBD system has been described in detail and proven as far as possible within the constraints of the available research tools.

(v) A prototype EFFM FBD system has been successfully developed and shown to provide considerable ease of use and substantially improved sculpture product design process efficiency.

(vi) Although dedicated to a specific product, the prototype EFFM FBD system demonstrates the generic applicability of the method, and the potential for partially automated configuration of a future generic EFFM FBD system for other sculptured products.

(vii) The EFFM FBD system and product models show significant potential for extension and exploitation by other engineering applications such as manufacturing and analysis.

REFERENCES

[0053 Paul] Paul the Apostle, First letter to the Corinthians, circa AD 53, chapter 9 verse 22[English translation in "The Holy Bible, New International Version." Hodder & Stoughton, 1979].

[1967 Heath] Heath, A. "Some basic considerations in shoe last sizing systems." Leather & Shoe, August 1967.

[1970 Thornton] Thornton, J. H. "Textbook of footwear manufacture." Heywood Books, 1970.

[1975 Meriam] Meriam, J. L. "Dynamics, 2nd Edition SI Version." John Wiley & Sons, 1975.

[1976 Chen] Chen, P. P., "The Entity-Relationship Model - Toward a Unified View of Data." ACM Trans. on Database Systems, Vol. 1 No. 1, March 1976, pp 9-36.

[1977 Ginsberg & Genin] Ginsberg, J. H. & Genin, J. "Statics and Dynamics." John Wiley & Sons Ltd., New York, 1977.

[1977 Voelcker & Requicha] Voelcker, H. B. and Requicha, A. A. G. "Geometric modeling of mechanical parts and processes." Computer, Volume 10 No. 12, December 1977, pp 48-57.

[1978 Jones et al] Jones, R. Murray, J. and Simpson, G. "A digitiser NC programming system." Proceedings of International Conferences on CAM, NEL, East Kilbride, 1978.

[1981 CAM-I] "CAM-I's illustrated glossary of workpiece form features." Report R-80-PPP-02.1 (revised), CAM-I, May 1981.

[1982 Henderson & Stirk] Henderson, I. T. Stirk, D. I. "Golf in the making." Second revised edition, Sean Arnold, 1982.

[1982 Maltby] Maltby, R. "Golf Club Design." Ralph Maltby Enterprises, 1982

[1984 Pratt] Pratt, M. J. "Solid modelling and the interface between design and manufacture." IEEE Computer Graphics and Applications, 1984, pp 52-59.

[1985 Pratt & Wilson] Pratt, M. J. Wilson, P. R. "Requirements for support of form features in solid modelling systems." CAM-I report, R-85-ASPP-01, CAM-I, 1985.

[1986 Faux] Faux, I. D., "Reconciliation of Design and Manufacturing Requirements for Product Description Data using Functional Primitive Part Features." CAM-I report, R-86-ANC/GM/PP-01.1, 1986.

[1986 Luby et al] Luby, S. C. Dixon, J. R. Simmons, M. K. "Creating and using a features data base." Computers in Mechanical Engineering, November 1986, pp 25-33.

[1986 Miller] Miller, J. R. "Sculptured surfaces in solid models: issues and alternative approaches." IEEE Computer Graphics & Applications, IEEE, December 1986, pp 37-48.

[1986 Sederberg & Parry] Sederberg, T. W. Parry, S. R. "Free-form deformation of solid geometric models." Proceedings SIGGRAPH 1986, pp 151-160.

[1987 Meriam & Kraige] Meriam, J. L. & Kraige L. G. "Engineering Mechanics Volume 2: Dynamics." John Wiley & Sons Ltd., New York, 1987.

[1987 Tuma] Tuma, J. J. "Engineering mathematics handbook." Third edition, McGraw-Hill, 1987.

[1987 Wishorn] Wishorn, T. "The modern guide to Golf Club Making." Dynacraft Golf Products, 1987.

[1988 Cowan et al] Cowan, G. S. Jakiela, M. J. Kuttner, B. C. "MEX: an object oriented approach to feature-based design." ESD/SMI Expert Systems Proceedings, 1988, pp 39-50.

[1988 Cunningham & Dixon] Cunningham, J. Dixon, J. R. "Designing with features: the origin of features." Proc. ASME Computers in Engineering, ASME, San Francisco, California, 1988, pp 237-243.

[1988 Cutkosky et al] Cutkosky, M. Tenenbaum, J. and Miller, D. "Features in process based design." Proc. ASME Computers in Engineering Conference, San Francisco, USA, 1988.

[1988 Downs et all] Downs, E., Clare, P. & Coe, I., "Structured Systems Analysis and Design Method: Application and Context." Prentice Hall, 1988.

[1988 Forsey & Bartels] Forsey, D. R. Bartels, R. H. "Hierarchical b-spline refinement." ACM Computer Graphics, Vol. 22 No. 4, 1988, pp 205-212.

[1988 Ho-Le] Ho-Le, K. "Finite element mesh generation methods: A review and classification." Computer Aided Design, Vol. 20 No. 1, pp 27-38.

[1988 Loughlin] Loughlin, C.A. "Feature-based modeling." Proceedings of NCGA '88. Ninth Annual Conference and Exposition, Nat. Comput. Graphics Assoc, Fairfax, VA, USA, Vol. 3, 1988, pp 372-380.

[1988 PDES] "PDES Form Feature Information Model (FFIM)." Editor: Mark Dunn, United Technologies Research Center, June 1988.

[1988 Rossi] Rossi, WA "The Futile Search for the Perfect Shoe Fit." J. Testing & Evaluation, JTEVA ASTM, Vol. 16 No. 4, 1988, pp 393-403.

[1988 Shah & Rogers] Shah, J. J. Rogers, M. T. "Expert form feature modelling shell." Computer Aided Design, Vol. 20 No. 9, 1988, pp 515-524.

[1988 Turner & Anderson] Turner, G. P. and Anderson, D. C. "An object oriented approach to interactive, feature based design for quick turn around manufacturing." Proc. ASME Computers in Engineering Conference, San Francisco, USA, 1988.

[1988 van t'Erve] van t'Erve, A. H. "Computer aided process planning for part manufacturing, an expert system approach." Ph.D. Thesis, Twente University, 1988.

[1988 Woodwark] Woodwark, J. R. "Some speculations on feature recognition." Computer Aided Design, Vol. 20, 1988, pp 483-503.

[1989 Barker] Barker, R., "Case*Method: Entity Relationship Modelling." Addison-Wesley, England, 1989.

[1989 Clark] "Manual of shoe making." 6th Edition (R. G. Miller Editor), C. & J. Clark Ltd., 1989.

[1989 Dixon et al] Dixon, J. R. Cunningham, J. J. Simmons, M. K. "Research in designing with features." Intelligent CAD, I. Proceedings of IFIP TC/WG 5.2 Workshop on Intelligent CAD (Yoshikawa, H. & Gossard, D. Editors), North-Holland, Amsterdam, Netherlands, 1989, pp 137-148.

[1989 Falcidieno & Giannini] Falcidieno, B. Giannini, F. "Automatic recognition and representation of shape-based features in a geometric modelling system." Journal of Computer Vision, Graphics, and Image Processing, Vol. 48, 1989, pp 93-123.

[1989 Gindy] Gindy, N. N. Z. "A hierarchical structure for form features." International Journal of Production Research, Vol. 27 No. 12, 1989, pp 2089-2103.

[1989 Johnson] Johnson, A. R. "The effects of implementing a fully integrated modern CADCAM system." Proceedings of the IASTED International Symposium. Applied Informatics - AI '89 (Hamza, M. H., Editor), ACTA Press, Anaheim, CA, USA, 1989, pp 258-261.

[1989 McGill & King] McGill, D. J. & King, W. W. "Engineering Mechanics: Statics and an Introduction to Dynamics." PWS-Kent, Boston, 1989.

[1989 Parks & Chase] Parks, R. R. Chase, T. R. "Representing mechanical parts using feature specifications and positional constraints: a contrast with PDES." Engineering Database Management: Leadership for the 90's, ASME, 1989, pp 81-96.

[1989 Shah] Shah, J. J. "Philosophical development of form feature concept." Preprints. NSF Engineering Design Research Conference, Univ. Massachusetts, Amherst, MA, USA, 1989, pp 317-332.

[1990 Anderson & Chang] Anderson, D. C. Chang, T. C. "Automated process planning using object-oriented feature based design." Proceedings of the IFIP WG 5.2/GI International Symposium, Elsevier Science Pub. BV (North-Holland), 1990, pp 247-260.

[1990 CAM-I] "Proceedings Features Symposium, Boston." Report P-90-PM-02, CAM-I, 1990.

[1990 Coquillart] Coquillart, S. "Extended free-form deformation: a sculpturing tool for 3D geometric modeling." Report No. 1250, Inst. Nat. Recherche Inf. Autom., Le Chesnay, France, 1990.

[1990 Dixon et al] Dixon, J. R. Libardi, E. C., Jr. Nielsen, E. H. "Unresolved research issues in development of design-with-features systems." Geometric Modeling for Product Engineering. Selected and Expanded Papers from the IFIP WG 5.2/NSF Working Conference on Geometric Modeling (Wozny, M. J. Turner, J. U. Preiss, K., Editors), North-Holland, Amsterdam, Netherlands, 1990, pp 183-196.

[1990 Dong & Wozny] Dong, X. Wozny, M. "Managing feature type dependency in a feature-based modelling system." ASME Computers in Engineering Conference, Vol. 1, 1990, pp 125-130.

[1990 Giacometti & Chang] Giacometti, F. Chang, T.-C. "A model for parts, assemblies and tolerances." Preprints of the first IFIP W.G.5.2 workshop on design for manufacturing, 1990.

[1990 Jones] Jones, R. "Computer based methods for the design and manufacture of golf clubs." Science & Golf, Proc. 1st World Scientific Congress of Golf, E & FN Spon, 1990, pp 280-285.

[1990 Joshi & Chang] Joshi, S. Chang, T. C. "Feature extraction and feature based design approaches in the development of design interface for process planning." Journal of Intelligent Manufacturing, Vol. 1 No. 1, 1990, pp 1-15.

[1990 Joshi] Joshi, S. "Feature recognition and geometric reasoning for some process planning activities." Geometric Modeling for Product Engineering. Selected and Expanded Papers from the IFIP WG 5.2/NSF Working Conference on Geometric Modeling (Wozny, M. J. Turner, J. U. Preiss, K., Editors), North-Holland, Amsterdam, Netherlands, 1990, pp 363-384.

[1990 Peiro et al] Peiro, J., Peraire, J. & Morgan, K. "The generation of triangular meshes on surfaces." Applied Surface Modelling (C. F. M. Creasy & C. Craggs Eds.), Ellis & Horwood, 1990, pp25-33.

[1990 Science & Golf] "Science and Golf." Proceedings of the First World Scientific Congress of Golf (Cochran, A.J. Editor), E & FN Spon, 1990.

[1990 Shah & Miller] Shah, J. J. ;Miller, D. W. "Structure for supporting geometric tolerances in product definition systems for CIM." Manufacturing Review, Vol. 3 No. 1, 1990, pp 23-31.

[1990 Shah] Shah, J. J. "An assessment of features technology." Report P-90-PM-02, CAM-I, 1990.

[1990 Vandenbrande & Requicha] Vandenbrande, J. H. Requicha, A. A. G. "Spatial reasoning for automatic recognition of interacting form features." Proceedings of the ASME International Computers in Engineering Conference, ASME, August 1990, pp 251-256.

[1990 Whittaker et al] Whittaker, A., Thomson, R., McKeown, J. & McCafferty, J. "The application of computer-aided engineering techniques in advanced clubhead design." Science & Golf, Proc. 1st World Scientific Congress of Golf, E & FN Spon, 1990, pp 286-291.

[1991 Cavendish et al] Cavendish, J. C. Frey, W. H. Marin, S. P. "Feature-based design and finite element mesh generation for functional surfaces." Advances in Engineering Software and Workstations, Vol. 13 No. 5-6, 1991, pp 226-237.

[1991 Celniker & Gossard] Celniker, G. Gossard, D. "Deformable curve and surface finite-elements for free-form shape design." Computer Graphics, Vol. 25 No. 4, 1991, pp 257-266.

[1991 Kalra et al] Kalra, P. Mangili, A. Magnenat Thalmann, N. Thalmann, D. "3D interactive free form deformations for facial expressions." Compugraphics 91. First International Conference on Computational Graphics and Visualization Techniques, Tech. Univ. Lisbon, Lisbon, Portugal, Vol. 1, 1991, pp 129-141.

[1991 Kim et al] Joo-Yong Kim O'Grady, P. Young, R. E. "Feature taxonomies for rotational parts: a review and proposed taxonomies." International Journal of Computer Integrated Manufacturing, Vol. 3 No. 6, 1991, pp 341-350.

[1991 Pratt] Pratt, M. J. "Aspects of form feature modelling." Geometric Modeling. Methods and Applications (Hagen, H. Roller, D., Editors), Springer-Verlag, Berlin, Germany, 1991, pp 227-250.

[1991 Shah & Mathew] Shah, J. J. Mathew, A. "Experimental investigation of the STEP Form-Feature Information Model." Computer Aided Design, Vol. 23 No. 4, 1991, pp 282-296.

[1991 Wingard] Wingard, L. "Introducing form features in product models, a step towards CAD/CAM with engineering terminology." Manufacturing Systems Department, Royal Institute of Technology, Stockholm, Licenciate Thesis, 1991.

[1991a Roberts] Roberts, A. F. "Solid modeling: trends and new directions." AUTOFACT '91. Conference Proceedings, Soc. Manuf. Eng, Dearborn, MI, USA, 1991, pp 1-7.

[1991a Shah] Shah, J. J. "Assessment of features technology (CAD)." Computer Aided Design, Vol. 23 No. 5, 1991, pp 331-343.

[1991b Roberts] Roberts, A.F. "Next generation CAD/CAM/CAE systems." Conference Proceedings. NCGA '91. 12th Annual Conference and Exposition. Dedicated to Computer Graphics, Nat. Comput. Graphics Assoc, Fairfax, VA, USA, 1991, pp 626-631.

[1991b Shah] Shah, J. J. "Conceptual development of form features and feature modelers." Research in Engineering Design, Vol. 2 No. 2, 1991, pp 93-108.

[1992 Braham] Braham, J. "Super clubs hit the sweet spot." Machine Design, April 1992, pp 30-34.

[1992 Chen et al] Chen, Y. M. Miller, R. A. Lu, S. C. "Spatial reasoning on form feature interactions for manufacturability assessment." ASME Computers in Engineering Conference, Vol. 1, 1992, pp 29-36.

[1992 Feru et al] Feru, F. Cocquebert, E. Chaouch, H. Deneux, D. Soenen, R. "Feature-based modeling: state of the art and evolution." IFIP Transactions B[Applications in Technology], Vol. B-6, 1992, pp 29-50.

[1992 Guilford & Turner] Guilford, J. Turner, J. "Representing geometric tolerances in solid models." ASME Computers in Engineering Conference, Vol. 1, 1992, pp 319-327.

[1992 Hinde et al] Hinde, C. J., West, A. A. & Williams, D. J., "The use of object orientation for the design and implementation of manufacturing process control systems." IEEE International Symposium on Object Oriented Manufacture, Calgary, Canada, 1992.

[1992 Hsu et al] Hsu, W. M. Hughes, J. F. Kaufman, H. "Direct manipulation of free form deformations." Computer Graphics, Vol. 26 No. 2, 1992, pp 177-184.

[1992 ISO] "ISO 10303-48, Industrial Automation Systems - Product Data Representation and Exchange - Part 48: Integrated Generic Resources: Form Features." Working Draft, ISO TC184/SC4/WG3 N102 (P5), January 2, 1992.

[1992 Lennings] Lennings, A. "CAD/CAM integrations in practice: Two cases of computer aided tool making." Computers in Industry, Vol. 18, 1992, pp 127-134.

[1992 Nakajima et al] Nakajima, N.; Tokumasu, S.; Kunitomo, Y. "Feature-based heuristics for finite-element meshing using quadtrees and octrees." Computer Aided Design, Butterworth-Heineman Ltd., Vol. 24 No. 12, 1992, pp 677-690.

[1992 Shimada et al] Shimada, K. Balents, B. Gossard, D.C. "Automatic mesh reconstruction for feature-based sculpting of deformable surfaces." IFIP Transactions B[Applications in Technology], Netherlands, Vol. B-8, 1992, pp 165-188.

[1992 Sreevalsam & Shah] Sreevalsam, P. C. Shah, J. J. "Unification of form feature definition methods." IFIP Transactions B[Applications in Technology], Vol. B-4, 1992, pp 83-106.

[1992a Cavendish & Marin] Cavendish, J. C. Marin, S. P. "A procedural feature-based approach for designing functional surfaces." Proceedings: Topics in Surface Modelling, Geometric Design Publications, 1992 pp 145-168.

[1992b Cavendish & Marin] Cavendish, J. C. Marin, S. P. "Feature-based surface design and machining." IEEE Computer Graphics and Applications, Vol. 12 No. 5, 1992, pp 61-68.

[1993 Bauchat et al] Bauchat, J. L. David, J. M. Defretin, A. L. Wattellier, A. and Caignaert, G. "CAD/CAM of complex surfaces the experience of a multi-disciplinary research team." CARs and FOF. 8th International Conference on CAD/CAM, Robotics and Factories of the Future, Univ. Metz, Metz, France, Vol. 1, 1992, pp 95-108.

[1993 Brandenburg & Wördenweber] Brandenburg, W. Wördenweber, B. "Feature modelling with an object-oriented approach." Computing[Supplementum], 1993, pp 43-57.

[1993 Case & Gao] Case, K. and Gao, J. "Feature technology: an overview." International Journal of Computer Integrated Manufacturing, Vol. 6 No. 1 & 2, 1993, pp 2-12.

[1993 Chamberlain et al] Chamberlain, M. A. Joneja, A. Chang, T.-C. "Protrusion-features handling in design and manufacturing planning." Computer Aided Design, Vol. 25 No. 1, 1993, pp 19-28.

[1993 de Martino et al] de Martino, T. Falcidieno, B. Giannini, F. Habinger, S. Ovtchraova, J. "Integration of design by features and feature recognition approaches through a unified model." Modelling in Computer Graphics (B. Falcidieno & T. L . Kunii, Editors), Springer-Verlag, 1993, pp 423-437.

[1993 ISO] "ISO/DIS 10303-1, Industrial Automation Systems - Product Data Representation and Exchange - Part 1: Overview and fundamental principles." Draft International Standard, ISO/IEC, 1993.

[1993 Jones et al] Jones, R., Mitchell, S. R. & Newman, S. T. "Feature based systems for the design and manufacture of sculptured products." Int. J. Prod. Research, Vol 31 No. 6, 1993, pp 1441-1452.

[1993 Laakko & Mäntylä] Laakko, T. Mantyla, M. "Introducing blending operations in feature models." Eurographics '93 (R. J. Hubbard & R. Juan, Editors), Vol. 12, 1993, pp c176-c176.

[1993 Lee and Chang] Lee, Y. S. and Chang, T. C. "Cutter selection and cutter path generation for free-form protrusion feature using Virtual-Boundary approach." Proceedings of the Industrial Engineering Research Conference, IIE, Norcross, GA, USA, 1993, pp 375-379.

[1993 Rosen] Rosen, D. W. "Feature-based design: Four hypotheses for future CAD systems." Research in Engineering Design, Springer-Verlag, Vol. 5, 1993, pp 125-139.

[1993 Roy & Liu] Roy, U. Liu, C. "Integrated CAD frameworks: tolerance representation scheme in a solid model." Computers and Industrial Engineering, Vol. 24, 1993, pp 495-509.

[1993 Salomons et al] Salomons, O. W. van Houten, F. J. A. M. Kals, H. J. J. "Review of research in feature-based design." Journal of Manufacturing Systems, Vol. 12 No. 2, 1993, pp 113-132.

[1993 Vandenbrande & Requicha] Vandenbrande, J. H. Requicha, A. A. G. "Spatial reasoning for automatic recognition of machinable features in solid models." IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 15, 1993, pp 1269-1285.

[1993 Wallace & Jakiela] Wallace, D. R.; Jakiela, M. J. "Automated product concept design: unifying aesthetics and engineering." IEEE Computer Graphics & Applications, July 1993, pp 66-75.

[1993 Winfield & Butler] Winfield, D. C. & Butler, J. H. "Optimising post-impact conditions: minimising dispersion of a golf drive." True Temper Sports, Olive Branch, MS.38654, 1993.

[1994 Allada & Anand] Allada, V. Anand, S. "Feature-based modelling approaches for integrated manufacturing: state-of-the-art survey and future research directions." International Journal of Computer Integrated Manufacturing, Taylor and Francis Ltd., 1994, pp 222-251

[1994 Johnson] Johnson, S. H. "Experimental determination of inertia ellipsoids." Science and Golf II, Proc. 2nd World Scientific Congress of Golf (Cochran, A. J. & Farrally, M. R. Eds.), E & F Spon, 1994, pp 290 - 295

[1994 Jones et al] Jones, R. Newman, S. T. Hinde, C. J. and Mitchell, S. R. "Final Report: A Prototype Design Aid for Sculptured Surfaces." ACME Grant Code GR/G35237, Manufacturing Engineering Department, Loughborough University, 1994.

[1994 Mitchell & Jones] Mitchell, S. R. and Jones, R. "Feature based Design of Free Form Products." Autofact (Asia), Proc. 3rd Int. Conf. on Comp. Int. Manuf., World Scientific, Singapore, 1994, pp 229-235.

[1994 Mitchell et al] Mitchell, S. R., Jones, R., Newman, S. T. & Hinde, C. J. "A design system for golf club irons." Science and Golf II, Proc. 2nd World Scientific Congress of Golf (Cochran, A. J. & Farrally, M. R. Eds.), E & F Spon, 1994, pp 390 - 395.

[1994 Prabhakar et al] Prabhakar, V. Sheppard, S. D. "Knowledge-based approach to model idealization in FEM." Proceedings of the Conference on Artificial Intelligence Applications, IEEE, 1994, pp 488-490.

[1994 Science & Golf II] "Science and Golf II." Proceedings of the Second World Scientific Congress of Golf (Cochran, A.J. & Farally, M.E. Editors), E & FN Spon, 1994.]

[1994 Thomas] Thomas, F.W. "The state of the game, equipment and science." Science and Golf II: Proceedings of the World Scientific Congress of Golf (Cochran A.J. and Farrally M.R. Editors), E & F Spon, London, 1994, pp 237-246.

[1994 Thomson & Adam] Thomson, R. D. and Adam, A. "The role of the engineering properties of materials on the performance of golf clubs." Edinburgh Science Festival, February 1994.

[1995 Delcam] "DUCT 5 Reference manual." Volume 1, Delcam International, 1995.

[1995 FIRES] FIRES: Feature-Based Integrated Rapid Engineering System. European Community ESPRIT Project 6090, July 1992-5.

[1995 Golf Research Group] "1995 UK Equipment Survey." Golf Research Group, London, UK, 1995.

[1995 Pasko & Savchenko] Pasko, A. A. Savchenko, V. V. "Algebraic sums for the deformation of constructive solids." Proc. Solid Modelling '95, Salt Lake City, Utah, USA, ACM, 1995, pp 403-408.

[1995a Mitchell et al] Mitchell, S. R., Jones, R., & Hinde, C. "An initial data model, using the object oriented paradigm, for sculptured-feature-based design." Research in Engineering Design, Vol. 7, Springer-Verlag, 1995, pp 19-37.

[1995b Mitchell et al] Mitchell, S. R. Jones, R. Newman, S. T. "A structured approach to the design of shoe lasts." Journal of Engineering Design, Carfax, Vol. 6 No. 2, 1995, pp 149-166.

[1996 EDS] "EDS Unigraphics Enterprise Engineering." http://www.ug.eds.com/, EDS Unigraphics, May 1996.

[1996 Mill et al] Mill, F. Rieken, J. C. Salmon, J. C. Warrington, S. W. "Feature oriented engineering in UK industry and academia." Department of Mechanical Engineering, University of Edinburgh, April 1996.

[1996 Parametric Technology] "Parametric Technology Corporation Home Page." http://www.ptc.com/, Parametric Technology Co., May 1996.

[1996 PICASSO] PICASSO: Practical & Intuitive CAD for Assembly Objects. European Community Brite-EuRam Project 5693, January 1993-6.

[1996 R&A] "Rules of Golf." As approved by The Royal and Ancient Golf Club of St. Andrews, Scotland and the United States Golf Association, 28th Edition, January 1996.

[1996 van Elsas & Vergeest] van Elsas, P. A. Vergeest, J. S. M. "Creation and manipulation of complex displacement features during the conceptual phase of design." Proc. International Computers in Engineering Conference, ASME, USA, 1996.