Fixture Planning in a Feature Based Environment

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Declaration

I certify that the work presented in this thesis, except where explicitly credited to others, is of my own commission in both substance and composition.

Ser Chong Chia

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Finally, I'd like to thank my parents for their understanding, love and selfless support that they have given me. Thanks, Mom and Dad.

ABSTRACT

Fixtures are used to constrain workpieces during machining processes. Fixtures locate and hold the workpiece in position and ensure that it is in a state of equilibrium, and that dimensional accuracy is maintained throughout the manufacturing operation. Traditionally, design and manufacturing problems were solved by means of a sequence of design and planning stages followed by manufacturing. However, the recent emergence of Concurrent Engineering has prompted companies to solve the problems associated with each stage in parallel. This has lead to the increase in research into process planning. Fixture planning being part of process planning however have been neglected by researchers for many years, as it was always thought to be too complex to automate. Due to the decline in the number of experienced fixture planners, the long lead time for traditional manual design and the rapid progress in the field of Computer Aided Engineering, researchers have started to look into fixturing in recent years.

It has been identified that the use of feature concept together with geometric reasoning could greatly enhance the fixturing planning process. Therefore the aim of this research is to establish the functionality of a geometric reasoning system for fixture planning; to define the relationship between fixture planning and geometric reasoning; to explore the success of geometric reasoning function in supporting fixture planning; and finally to build and establish a fixture planning system. The introduction of features and geometric reasoning prove to be critical in fixture planning by simplifying many fixturing procedures that might otherwise be very complex to implement. The advantage of geometric reasoning is in its ability to detect relationships within the model which is crucial to the fixture planning process, for example, the relationships between faces and features; the location, dimension, orientation and shape of the features in the model; the relationships between each features; the tool access direction, etc. This thesis also reports on the successful development and implementation of FixPlan. The main strength of FixPlan lies in its ability to interrogate and analyse the solid model through the use of geometric

reasoning. The information and data gathered is then used for fixture planning. This work is unique as it utilises geometric reasoning and a fully embedded 3D solid modelling representation of the parts to enable spatial reasoning functions in enhancing the fixture planning process.

FixPlan is a fixture planning system that consists of three separate modules; a Feature Based Design System, a Geometric Reasoner, and a Fixture Planner. The fixture planning module is made up of three sub-modules; one to determine the number of set-up required for the part; one to determine the locating, supporting and clamping faces and points; and finally one to retrieve the appropriate fixture elements from the database.

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CHAPTER I

1. Introduction

The recent emergence of the concept of concurrent or simultaneous engineering has influenced the way engineers solve design and manufacturing problems. The traditional methods of solving design and manufacturing problems were by means of a sequence of design and planning stages followed by manufacturing. However in today's manufacturing environment, the pressure to reduce product design and development time is leading companies to conduct design, development, analysis and the preparation of manufacturing information in parallel, refer to Figure 1-1. Thus the term concurrent engineering is used, it is also sometimes called simultaneous engineering.

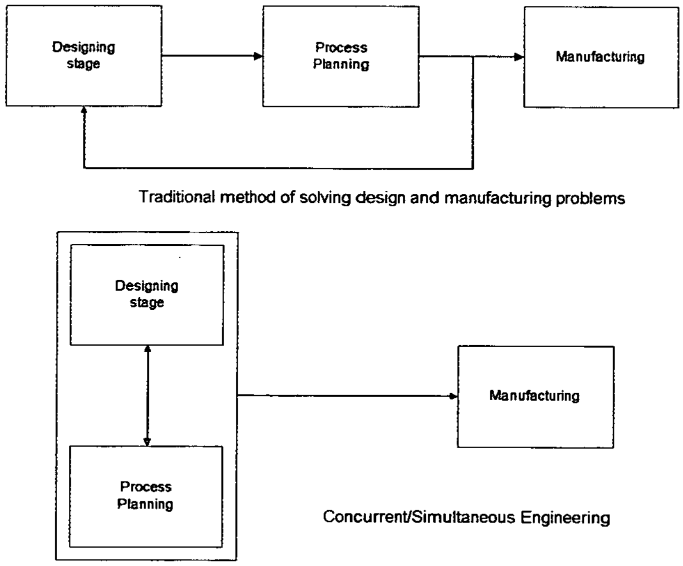


Figure 1-1 Traditional method of problems solving compared to concurrent/simultaneous method.

In concurrent engineering, as the product design progresses, various aspects that will affect the final product are taken into account simultaneously. For example the manufacturing, packing, maintenance, and disposal of the product. The early development of manufacturing capability in the process plan allows trade-offs between design and production to be made. In other words, the principle of concurrent engineering requires the availability of specific knowledge in the fields mentioned above.

Process planning modules within a concurrent engineering environment provide the means to evaluate the manufacturability of a product design. By evaluating the manufacturability of the product design in the early stages, designers can be warned of machining features, such as holes, slots and pockets etc., which may cause difficulties during manufacturing. As such, with the integration of the design activity and process planning, design flaws that may result in high manufacturing costs can be prevented through the early detection of these problems. The availability of data in a concurrent engineering environment places great emphasis on process planning. Thus since the eighties, lots of research have been carried out on process planning. However within process planning, fixture planning has always been neglected by researchers and it is not until recent years that they take notice of it.

1.1 Computer Aided Process Planning (CAPP)

Process planning can be defined as the procedure undertaken to produce a list of steps, or a set of instructions, to manufacture (or assemble) a part which will satisfy the functional and design specifications [Zhang94]. Process planning can be very complex and time consuming as many factors and data have to be taken into consideration. There are two approaches to Computer Aided Process Planning (CAPP), variant and generative.

The variant approach is very similar to the traditional manual approach whereby an existing plan is modified to satisfy the requirement of new parts. Group technology is applied to variant approaches, where all the parts are grouped according to their types and characterised by similarities, for example, in manufacturing methods. The variant approach reduces the time and labour needed to complete a process plan, it also improves the management of the information needed for process planning.

In the generative approach, process plans are generated by considering the rules of manufacturing and equipment capabilities and availability. Involvement of the human process planner is kept to the minimum in the generative approach. The part data is usually input through a CAD system or solid modeller. The main advantage of the generative approach is that it is possible, in theory, to fully automate.

In process planning, apart from the configuring of the various steps or sets of instructions to manufacture the part, one of the most important activities is the design of the fixtures to position, locate and secure the part during machining. Many CAPP systems do not take fixture planning into consideration as it is viewed by many as being too difficult to implement and automate due to the large amount of heuristic knowledge associated with it. However due to the increasing computing capabilities there have been many recent attempts to automate fixture planning [Trappey90, Hargrove94].

1.2 Fixture Planning System

The major emphasis of fixturing research is towards the elimination of human intervention through increased automation. As stated above, fixture planning is one of the most important aspects of computer aided process planning. Therefore research into the automation of fixture planning systems will further improve present computer aided process planning systems. This will in turn enhance the potential for a true concurrent engineering environment. In general, automated fixture planning research considers issues such as fixture configuration, fixture assembly and, finally, fixture verification [Trappey90].

It is recognised that there are four general requirements for a good fixture set up [Hargrove94][Sakurai92], namely, accurate location of the part, total restraint of the parts movement during machining, limited deformation of the part during machining and avoidance of interference between securing and cutting tools. The major emphasis of automated fixture planning research is on the configuration stage, where the set-ups, location and supporting points, clamping points, and the types of fixture elements themselves are determined according to the specified process information. Several systems have been developed to date.

Chou & Barash [Chou86, Chou89] applied "Screw Theory" [Ohwovoriole81] to study the kinematic constraints of fixturing the workpiece. Other researchers also use kinematic analysis.

Mani & Wilson [Mani88], used lines of restraint and a rating scheme to determine the kinematic freedom of workpieces which is then used to search for sets of points for locating the workpiece.

Menassa & DeVries [Menassa89, Menassa91], used kinematics for identifying locating, supporting and clamping points by applying an optimisation procedure to minimise workpiece deflection using finite element analysis.

Gandhi & Thompson [Gandhi86] proposed a methodology for automated design of modular fixtures based on spatial relationships. Polyhedral surfaces and envelopes are used to describe machining faces as well as candidate directions for locating, supporting and clamping the workpiece.

The main emphasis of all the above research is on the selection of the locating, supporting and clamping points for fixturing. They do not consider issues such as set-up configuration, selection of suitable locating and clamping faces and the selection of fixture elements.

Nee [Nee87, Nee91] applied Artificial Intelligence (AI) techniques and CAD concepts to develop a computer aided fixture design system. This greatly improved the way fixtures are designed, however it is not a fully automated system. Human interaction is required in creating, retrieving or updating fixture element selection, location and assembly.

Ong [Ong94, Zhang95] applied fuzzy set theory along with production rules and object representations for set-up configurations. High level feature based part descriptions have to be provided by the user in order to configure the number of set-ups required.

Pham & Larazo [Pham89, Pham90] developed an automated fixture design system called Autofix, which uses a rule based language and solid modelling CAD package. Knowledge rules in Autofix were adequate for fixturing of only single operations although the approach could be extended to allow sequential operations.

Young [Young91] proposes a methodology which combines fixturing strategies with technological and geometric information within a product modelling environment to automate set-up planning for machining. Machining capability representations and product model analysis techniques are used to generate the set-up plans. Standard fixtures such as a machine vice are assumed to be capable of fixturing the whole component. The machine type is restricted to a three axis vertical machining centre.

Boerma [Boerma88, Boerma89] developed a computer aided planning system for the selection of set-ups and design of fixtures in part manufacturing. The system, called FIXES, uses geometrical relationships to determine the sequence of operations and number of set-ups required to machine the part. The system, however, does not consider the selection of locating, supporting and clamping points nor the selection of the corresponding fixture elements.

As can been seen from the research works mentioned above, the limitation of the system developed by the various researchers leaves lots of room for further improvement and integration, for example the integration of the various stages of fixture planning, such as set-up configuration, selection of locating faces and points, clamping faces and point, as well as the selection of fixture elements itself.

1.3 FixPlan Environment

FixPlan is an automated fixture planning system developed within a feature based design system. It allows a designer to design prismatic components using its feature based design system, analyse the component with its geometric reasoning module and finally generate a fixture plan for each set up required to manufacture the component.

FixPlan is written in SCHEME (Martin94, Springer93) and uses the ACIS 3D Toolkit (ACIS94a, ACIS94b), a 3D Solid Modeller toolkit from Spatial Technology Inc., as its CAD interface. In the feature based design system, the component descriptions are stored and accessed using the Component Description Language (CODL). CODL is a compact text based language [Salmon94] that captures all the design information entered into the feature based design system by the designer. It includes a definition of the blank, the features to be machined from the blank and any additional features or relationships derived from the design.

FixPlan is made up or three separate modules, namely the feature based design module, geometric reasoning module and the fixture planning module. All three modules, including the common data base, are linked to the graphical user interface (refer to Figure 1-2).

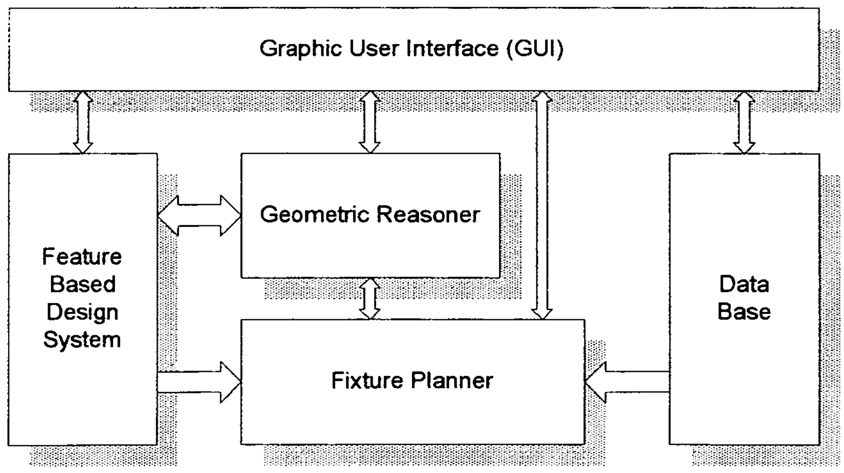


Figure 1-2 Schematic diagram of FixPlan.

The feature based design module, allows the designer to design the desired component. The geometric reasoning module enables the system to retrieve vital information needed by the fixture planning module. With the information extracted by the geometric reasoning module, the fixture planning module is able to determine the sequence of set ups required to manufacture the component. This is followed by selecton of the appropriate faces for locating, supporting and clamping that are required by each set up.

The fixture planning module generates a set of locating, support and clamping points and retrieves the appropriate fixture elements from the data base. The output from FixPlan is a set of fixturing data that contains the fixture information required to produce the part. This information could then be transferred to another process planning function, thereby providing the integration of fixture planning with process planning. However FixPlan is limited to fixturing in the manufacturing of prismatic parts on machining centres. The domain of FixPlan and its various modules will be addressed in more depth in chapters IV and V.

1.4 Aims and Objectives of the Research

For the past decade, researchers have been working on various aspects of fixturing and many fixture planning systems with limited capabilities have been developed. Several researchers' work has been mentioned earlier and others will be discussed throughout the thesis. Initial attempts in fixture design systems were mainly interactive, however recently developed systems are capable of automatically generating a partial or complete fixture solution. However, there still remains a void in fixture research in terms of combining many narrowly focused research activities into a comprehensive and complete fixture design system. Much effort is therefore needed in order to integrate the various partial solutions.

It is therefore the aim of this research to investigate the development of a fixture planning system that is capable of integrating the various narrowly focused research activities. The system developed would therefore be required to produce a fixture configuration given a feature defined component. This implies that the system must be integrated with, or at least be implemented within, a feature based design system. It was also identified that the full potential of geometric reasoning has, to date, not been fully exploited by most researchers. Hence, the application of geometric reasoning to fixture planning through solid modelling forms the main focus of this research.

The main aims of this research are therefore:

- to establish the functionality of a geometric reasoning system for fixture planning.
- to define the relationship between fixture planning and geometric reasoning.
- to explore the success of geometric reasoning function in supporting fixture planning.
- to build and establish a fixture planning system.

The area of research investigated has been limited to the fixturing of prismatic components on a three axis machining centre. The use of kinematics for the verification of the generated fixture plan was not considered. Deformation and distortion of workpieces under their own weight, clamping forces and cutting forces were also not considered in this research.

1.5 Overview of the Thesis

Chapter II outlines the fundamental aspects of feature based modelling. Features are introduced as well as the methods of representing them. The types of solid modellers as well as the application of geometrical reasoning to fixture planning are also discussed in this chapter.

Chapter III starts with an introduction to fixturing. The principles of fixturing, its criteria and strategies for fixture design are discussed in this chapter. The detail of the various types of fixturing hardware are also provided in this chapter. The chapter concludes by looking at the computerisation of fixture planning/design systems.

Chapter IV deals with the principles and strategies used in the development of FixPlan. The various modules ranging from geometric reasoning, set-up planning to the selection of fixture elements in FixPlan are discussed. The application of geometric reasoning to fixture planning is highlighted in this chapter.

Chapter V deals with the implementation of FixPlan. The various modules in FixPlan are discussed. The chapter starts with an introduction to the computer language and solid modeller used to develop the system. The development of the interfacing mechanism between the various modules is also detailed.

Chapter VI presents the conclusions and recommendations of this research.

CHAPTER II

2. Feature Based Modelling

The recent emergence of feature based modelling is viewed by many researchers [Bronsvoort93, Joshi90, Mill93, Tonshoff94] as the key to a genuine integration of many aspects of design and planning for manufacturing. The first attempts to integrate CAD and CAPP were made in the eighties [Alting89], which resulted in the introduction of the feature concept [Joshi88, Jared89]. Current CAD systems do not easily lend themselves to engineering and manufacturing activities due to the fact that they only support limited types of product information.

To fully represent a product model, product definitions such as geometry, topology, tolerances, surface finish, form features, process specification and material properties are required. Product data such as process specifications and tolerances for example are non-geometrical and can be rather abstract, thus making them difficult to represent.

Most CAD systems currently in use are only capable of producing product models with no more than the nominal geometry, thus they have deficiencies in supporting topology, tolerances, machining processes, etc. Features, higher level entities that do have some engineering meaning, are therefore currently being explored in CAD and CAPP research. Feature based design methods provide a logical way of associating product geometry with high level product definitions such as surface finish, machining process, performance and operational characteristics.

2.1 Features

There are many definitions of features [Case91]. Originally, features were thought of almost exclusively in their geometric sense. Shapes such as holes, slots, steps and pockets were regarded as typical features. However it is now widely recognised that features may also include other engineering data. In fact almost any attribute of a component can be classified as a feature. Generally, features can be divided into five different groupings; design features, manufacturing features, process planning features, dimensioning features and assembly features.

In design processes, a feature is considered by designer in term of it's geometry, specifications and detail to fulfil certain functional requirements, thus the name "design feature". Examples of sure features are fixing holes, keyways and cooling slots. However, features may be viewed differently by process planners as "manufacturing features". For example, a fixing hole may be considered as a drilled or bored; a cooling slot may be considered as a general slot machined by a slot cutter, etc. Figure 2-1 shows example of features such as holes, slots, pockets and steps. Dimensioning features as their name implies are used to dimension the component, they can also include geometric tolerances and surface finish values. Examples of dimensioning features are length, diameters and height. Finally, assembly features are used to define relationships between different parts in an assembly process.

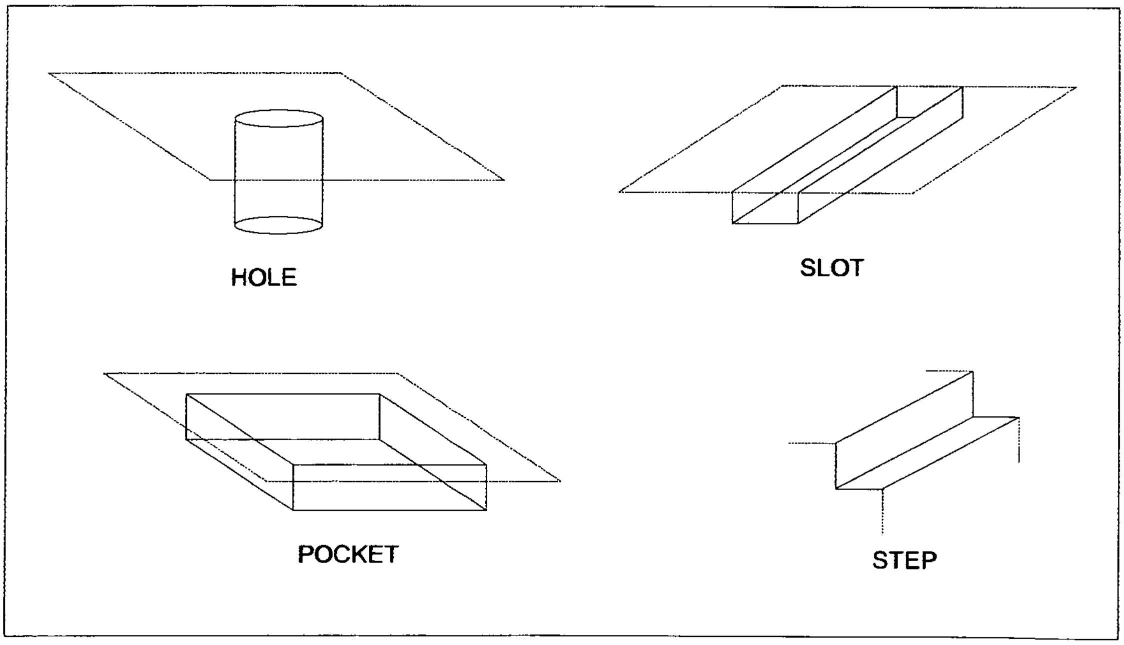


Figure 2-1 Example of features.

A geometrical feature description consists of both the feature definition as well as its corresponding parameters. The feature definition describes the geometry of the specific feature, for example the faces, edges and vertices that constitute a slot. The parameters contain information such as position, orientation, type, and feature dimensions such as length, width and height. There are basically two approaches to representing a part in terms of features; feature recognition and design by features.

Research into the use of features as a means of product model representation has allowed work to be carried out on the above mentioned aspects of representation generation introduced above [Jared89, Joshi88]. Feature recognition consists of software tools that are used to look for form features in representations that are normally created on a solid modeller [Joshi90]. Feature based design on the other hand presents the designer with a library of features to use to create the product model in mind.

2.1.1 Feature recognition

Feature recognition is the interpretation of an object to identify it so that information/data can be extracted from it. Feature recognition is based most often on boundary representation modellers because the adjacency relationships between geometric entities are explicitly defined in these systems. One approach to feature recognition is to identify the relationships between individual entities which form a face-edge graph, and try to match these to a pre-defined pattern. Therefore, the feature recognition approach requires that each feature has a pre-defined pattern primitive. This in turn limits the number of features that can be recognised.

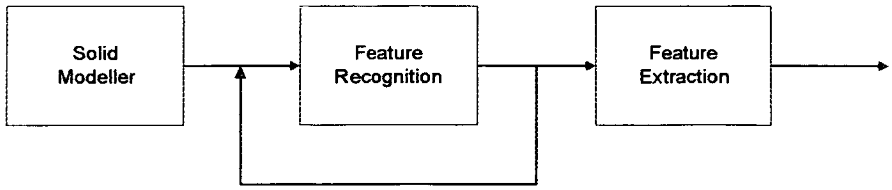


Figure 2-2 Feature recognition.

Joshi [Joshi88] developed the concept of attributed adjacency graph (AAG) for the recognition of machining features from a 3D boundary representation of a solid. The attributed adjacency graph is defined as a graph G = (N, A, T), where N is the set of nodes, A is the set of arcs, and T is the set of attribute to arcs in A, such that

- for every face *f* in F, there exists a unique node *n* in N
- for every edge *e* in E, there exists a unique arc *a* in A, connecting the nodes n_i and n_j, corresponding to face f_i and face f_j, which share the common edge *e*.
- every arc *a* in A, is assigned an attribute *t*, where *t* = 0, if the faces sharing the edge form a concave angle and *t* = 1, if the faces sharing the edge form a convex angle.

The AAG is represented in the computer in the form of a matrix. Figure 2-3 shows some AAGs of features.

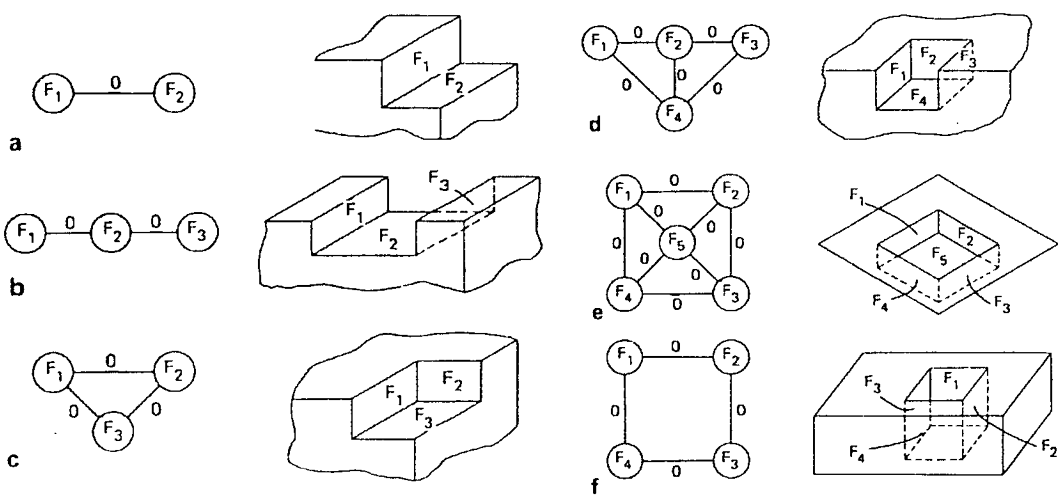


Figure 2-3 AAG of features

AAG is also used by several other researchers, e.g. Corney & Clark [Corney91, Corney91b] and Gu [Gu95], for feature recognition.

2.1.2 Feature based design

An alternative to feature recognition is design by features. Design by features is the construction of a product model using features. It is as if the user is machining with the computer. The advantage of this method is that it allows the machining operations to be checked as if they are being performed [McMahon93]. In this approach, the designer is provided with a feature library which can be used with a set of operators such as add, subtract, intersect and union to create a feature representation, for example countersunk holes and crossed slots. The feature representation maintains additional information such as feature names, taxonomy codes and attributes that are not stored in a conventional solid modeller. This eliminates the need for feature recognition.

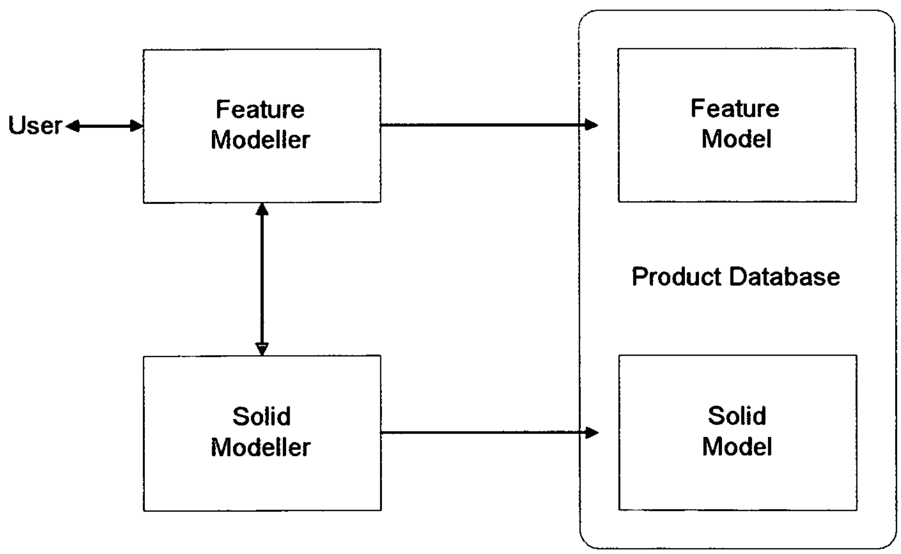


Figure 2-4 Feature based design.

2.1.3 Feature recognition versus feature based design

Feature recognition suffers from apparent drawbacks when first compared with feature based design. First, if the designer is working on a system with a feature recognition tool, they would have to constrain the design in order that it could fit with the feature definitions in existence. In such circumstances it is easy to imagine how a designer might err either by generating something that cannot be recognised by the system or by over compensating and under utilising the options available [Mill93]. In order to recognise a feature, one must first have a definition of that feature. If such a definition does exist then there is no reason why the designer could not have made use of it in the first instance. However, the advantage of feature recognition, particularly from 2-D drawings, is that there is a vast legacy of existing designs that would be expensive to redo from scratch in a feature based design system. The major advantage of feature based design is that it provides the designer with a set of high level tools that are familiar to their natural way of working. New features can be easily added to the feature library to increase the number of features available to the designers. As the feature representation is generated simultaneously with the design, it also has the advantage that it allows the designer to be advised of some manufacturing considerations without actually being constrained by them.

The use of features therefore requires a complete product model. Solid modelling is, for the moment, the only approach that has the capability to create and handle the product models required. Although most commercially available solid modellers cannot handle the requirement concerning the completeness of the product model, they can be modified and adapted to cater for the specific needs of the feature approach.

2.2 Solid Modelling

The representation of solid models has been the subject of much research over the last two decades or so, and continues to be the main focus of research as the objective of full representation of an object has yet to be achieved [McMahon93]. Solid modelling defines the geometry and topology of a product model completely and is therefore widely used in many CAD systems. Many methods for representing shapes and related data structures have been proposed for solid modelling, such as pure primitive instancing, generalised sweeping, cellular decomposition, boundary representation (BRep) and constructive solid geometry (CSG) [Jared89]. The most important of these are Boundary Representation (BRep) and Constructive Solid Geometry (CSG).

2.2.1 Pure primitive instancing

The object in this type of modeller is represented by a set of parameterised templates which define its shape and size (see Figure 2-5). For example, a cuboid can be represented in a template by its height, length and width. Primitive instancing is not very practical as a huge range of templates are required to represent all possible features. However it is very easy to distinguish the various features as each template is unique in its own sense. Thus feature recognition is not necessary as features of a family of parts could be arranged to be an inherent part of their template.

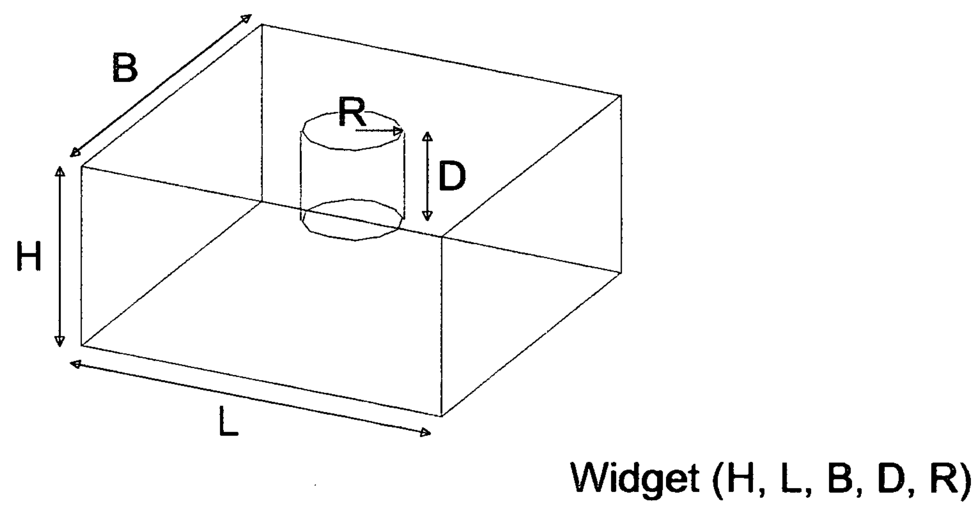


Figure 2-5 Pure primitive instancing.

2.2.2 Generalised sweeping

The object is represented by sweeping a profile along a predefined path in three dimensional space (see Figure 2-6). Models can be easily generated by this form of modeller. However, even the simplest form of profile and sweep path could result in a very complex geometry that is difficult to analyse.

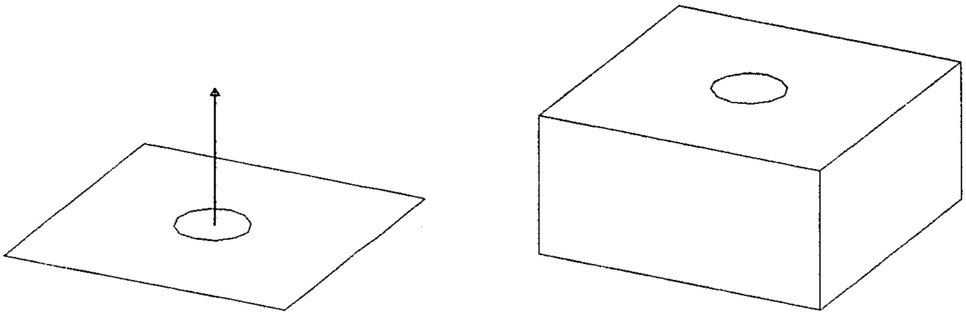


Figure 2-6 Generalised sweeping.

2.2.3 Cellular decomposition

In cell decomposition the object is described by the assembly of a number of small elements joined together (see Figure 2-7). This form of modelling is widely used in finite element analysis where complex shapes are broken down into smaller and simpler shapes for analysis (Lee86, Menassa89). Spatial occupancy enumeration is similar to cell decomposition, in that the model is divided into a number of smaller elements, but in this case it involves identifying which of a regular grid of cubic volumes are wholly or partially occupied by the object being modelled.

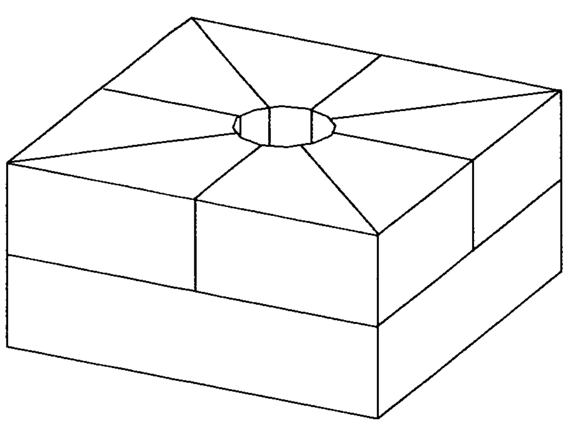


Figure 2-7 Cellular decomposition.

2.2.4 Boundary representation

Boundary representation (BRep) is based on the fact that a solid object can be considered as being bounded by a number of faces, that are, in turn, bounded by edges and these are in turn bounded by vertices. BRep models are basically graph based and all the geometric and topological information is represented in a face-edge-vertex graph. Figure 2-8 illustrates a possible boundary representation of a tetrahedron. A planar can be represented by the equation of the surface with references to its bounding edges. An edge in turn can be represented by a line equation with references to its bounding vertices. Finally a vertex is represented by its X, Y, Z co-ordinates. The data structure is a graph, with nodes for the boundary elements and the links for the references between these elements. The links represent the adjacency relations between the boundary elements.

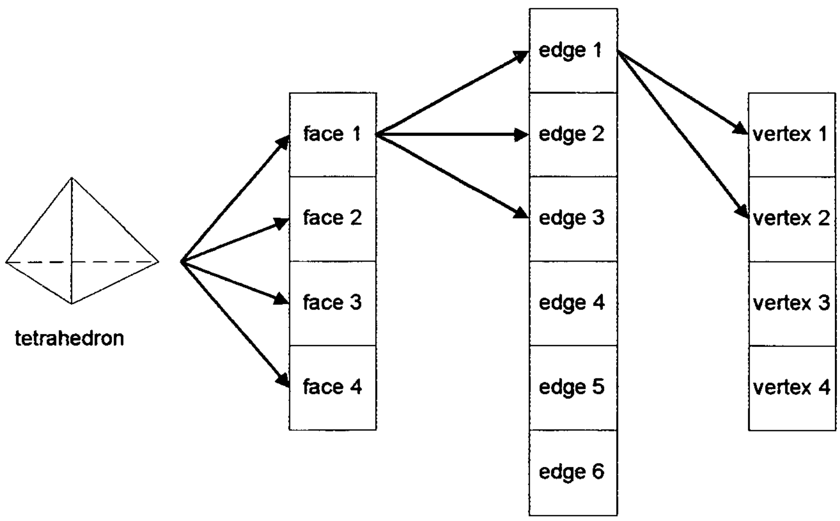


Figure 2-8 Boundary representation of a tetrahedron.

The simplest form of boundary model is one that represents all faces as flat planes or facets. A curved surface, such as a cylinder, is represented as a series of facets that approximate the surface. Such a representation is computationally relatively straightforward, and therefore has performance advantages, although it is clearly limited in the extent to which it can model 'real' shapes such as engineering components.

2.2.5 Constructive Solid Geometry (CSG)

In this approach, the product models are constructed as a combination of simple solid primitives, such as cuboids, cylinders, spheres, cones and the like. Each primitive can be combined by applying the set operations union ($\cup$), difference (-) and intersection ($\cap$) to form more complex, composite objects (Figure 2-9). The method of constructing CSG models is such that quite complex shapes may be developed relatively quickly, but only within the limitations of the set of primitives available within the system.

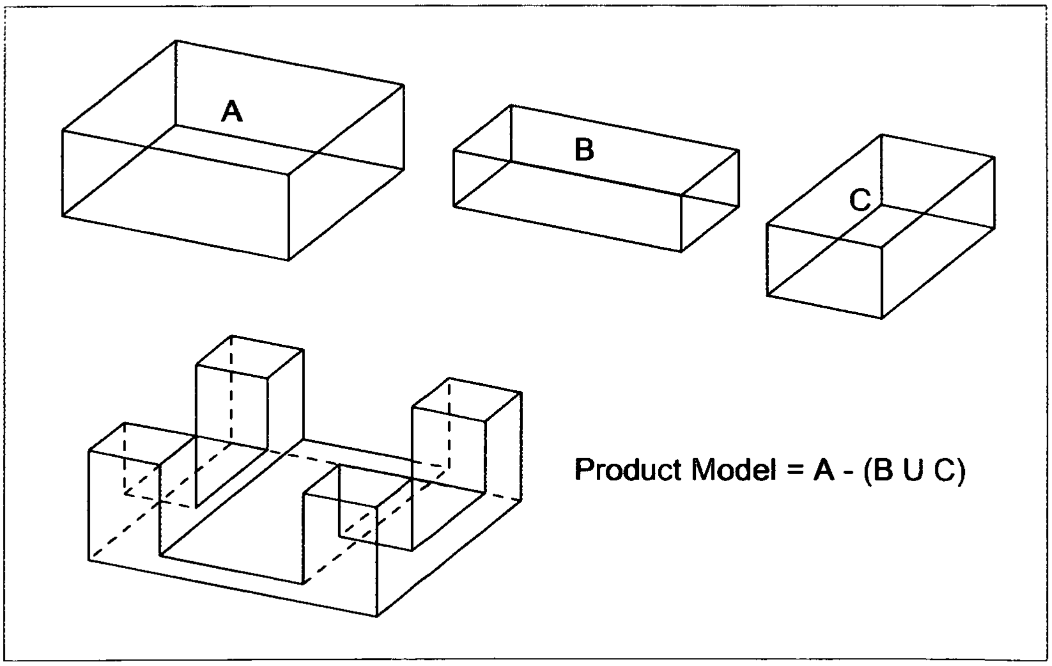


Figure 2-9 Constructive solid model of a component.

The reason for using CSG is that it is concise, simple and is easy to edit and manipulate primitives. In Figure 2-9, the final product model is constructed using the CSG method. As can be seen, the final product model is made up of Block A subtracting the union of Block B and C forming the cross slot. A typical CSG model consists of a 'base feature', for example a blank, and several other 'features', such as holes, slots and pockets. The features can be added, subtracted, intersected or united with the base feature to form the desired model.

2.3 Feature Based Design/Reasoning in Fixturing

The apparent advantages of the features concept in CAD and CAPP has lead to the implementation of feature based design/reasoning in fixture planning by several researchers.

Dong [Dong91] outlines some of the design criteria for fixture design and how the use of features will affect it. The concept of features enhances the design of fixtures in several ways. The geometric attribute of a feature defines surfaces, orientation, area, and position, which can greatly reduce the initial problem of datum plane selection. As features carry more than just geometric specification, e.g. machining and tolerance information, it can greatly enhance the different approaches that have already been developed for fixture planning.

Liou [Liou91] developed a prototype feature-based fixture planning system for flexible assembly. Heuristic rules were used to generate the feasible solution for automated fixture planning based on the geometries of the workpiece and the nature of the selected fixtures. Both fixtures and workpieces were represented by features and a fixture process planning system was implemented using a knowledge based approach. However the prototype operation does not involve the generation of set-ups, or the selection of faces and points for locating and supporting.

Nee [Nee92] proposed a feature based classification scheme for fixtures using a 3D solid modeller, a feature extractor and an object oriented expert system shell. The features to be machined are extracted from the solid model and grouped into set-ups based on machining direction and tolerance factors. The necessary fixtures are then identified based on set-up, operation, and fixturing rules. The fixture will then be coded in a feature based symbolic representation which is then used for comparison with existing fixtures.

Dong's proposal of using features to enhance fixture planning has prompted the use of the features concept in this research. This together with geometric reasoning forms the core basis of this research. With geometric reasoning, the information carried in features can be fully utilised in the automatic generation of set-ups, selection of locating, supporting and clamping faces as well as their corresponding points. It can also provide the necessary information for the automatic selection and retrieval of fixture elements. All these will be highlighted in chapters IV and V.

2.4 Summary

In this chapter the concept of features and feature based modelling was introduced. The apparent advantages of features has prompted its application to fixture planning. The usage of features in fixture planning was also outlined in this chapter along with the work and proposal of a few researchers. In the next chapter, the concept and principle of fixturing will be addressed.

CHAPTER III

3. Fixturing

Fixturing is one of the most important tasks in a manufacturing environment. No machining process can be executed without some kind of workholding device or fixture to locate and secure the workpiece in position. The use of fixtures is not just limited to machining processes. They can also be used to locate and hold a component during an assembly or measuring process. A clamping arrangement is one that will ensure that the workpiece is in a state of stable equilibrium and that dimensional accuracy is maintained throughout the manufacturing operation while ensuring that at the same time it does not obstruct the tool path.

Similar to computer aided process planning, fixture design can be classified under two different approaches, namely variant and generative. In variant fixture design, an existing design is modified to satisfy the new workpiece. This reduces the time and cost needed to arrive at a new fixture design. However, when a similar fixture design cannot be retrieved, the generative approach must then be used.

The generative fixture design approach needs more information to come to a solution. Information needed includes workpiece geometry, process plan, machine and cutting tool envelope, fixture elements and related machining libraries.

3.1 Principles of Fixturing

As mentioned in the above section, the basic requirement of a fixture is to locate and secure the workpiece in position and maintain both its stability and dimensional accuracy. A typical fixture design for prismatic parts consists of four basic components; locators, supports, clamps and the base plate, see Figure 3-1.

Locators are used to ensure that the workpiece is in position so as to maintain static equilibrium by means of removing all its degree of freedom. Supports are used to reinforce the stability of the workpiece when the locators fail to provide adequate support. Clamps are used to secure the workpiece firmly against the locators to provide rigidity during the various manufacturing processes. Finally the element that holds all the various fixture elements together is known as a base plate. Other forms of fixture elements will be presented in a later section.

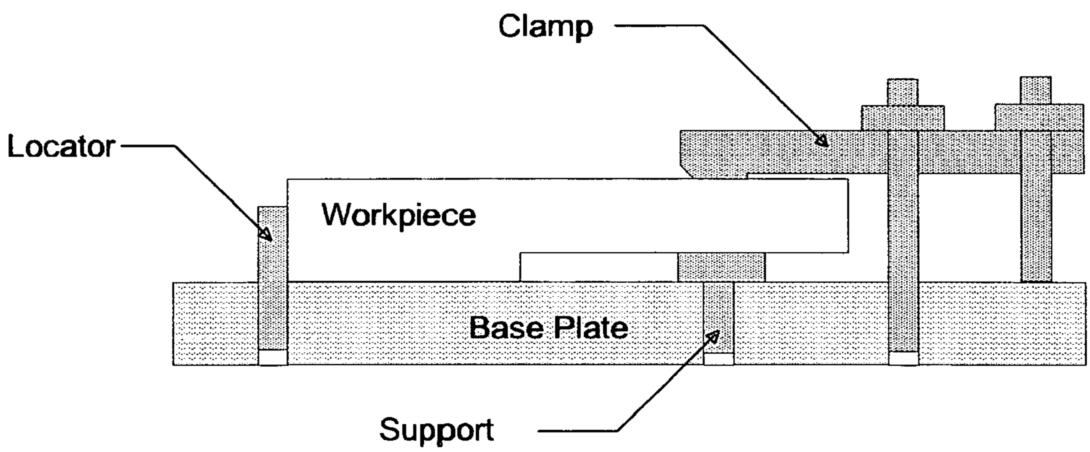


Figure 3-1 Typical fixture configuration.

3.1.1 Locating principles

A typical prismatic workpiece has 12 linear and rotational movements. These movements are as follows; six linear movements along both the positive and negative directions of the three orthogonal axes, namely X, Y and Z. The remaining six rotational movements are the clockwise and anti-clockwise rotations about the same axes (Figure 3-2). Locators and supports are capable of restricting at least nine out of the twelve movement with the remaining three being constrained by the clamps.

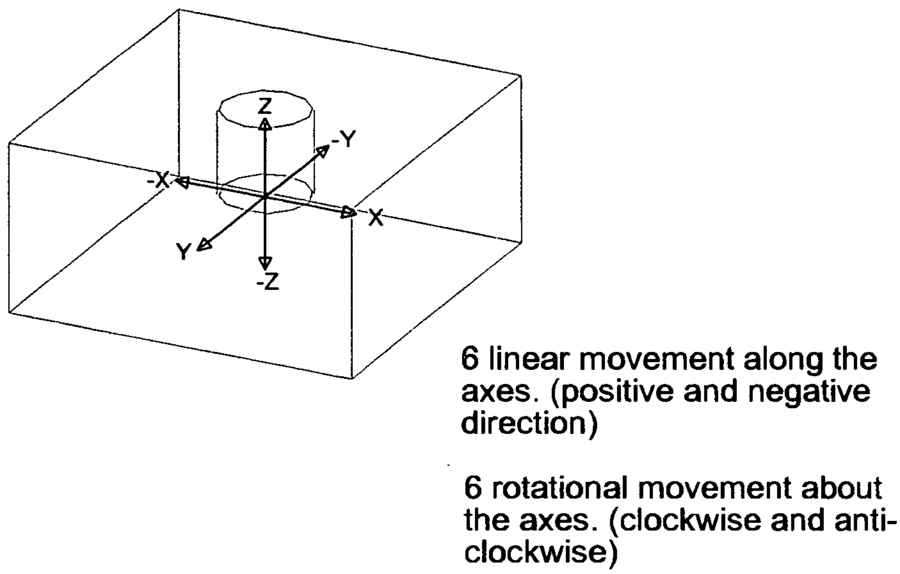


Figure 3-2 The linear and rotational movement of a prismatic part.

The 3:2:1 concept is the most common method use to locate a typical prismatic workpiece [Wilson62]. In this concept, the fixturing plane is first identified followed by its corresponding locating points. The three datum are the primary, secondary and the tertiary planes (Figure 3-3).

The three plane locators are on the tertiary datum plane. They are placed as far apart as possible to increase the stability of the workpiece, see Figure 3-4. In doing so, the linear movement in the negative Z-direction, the clockwise and anti-clockwise rotational movements about the X and Y-axis will be restricted. In total five movements will be restricted in the tertiary plane by the three locators.

On the secondary datum plane, two locators will be positioned to restrict another three movements. The three movements are the linear movement in the negative X-direction, the clockwise and anti-clockwise rotational movements about the Z-axis.

Finally, one locator is positioned on the primary datum plane to restrict one more linear movement in the negative Y-direction. This leaves only three other linear movements in the positive X-direction, Y-direction and Z-direction which are usually restrained by the clamps and the cutting force.

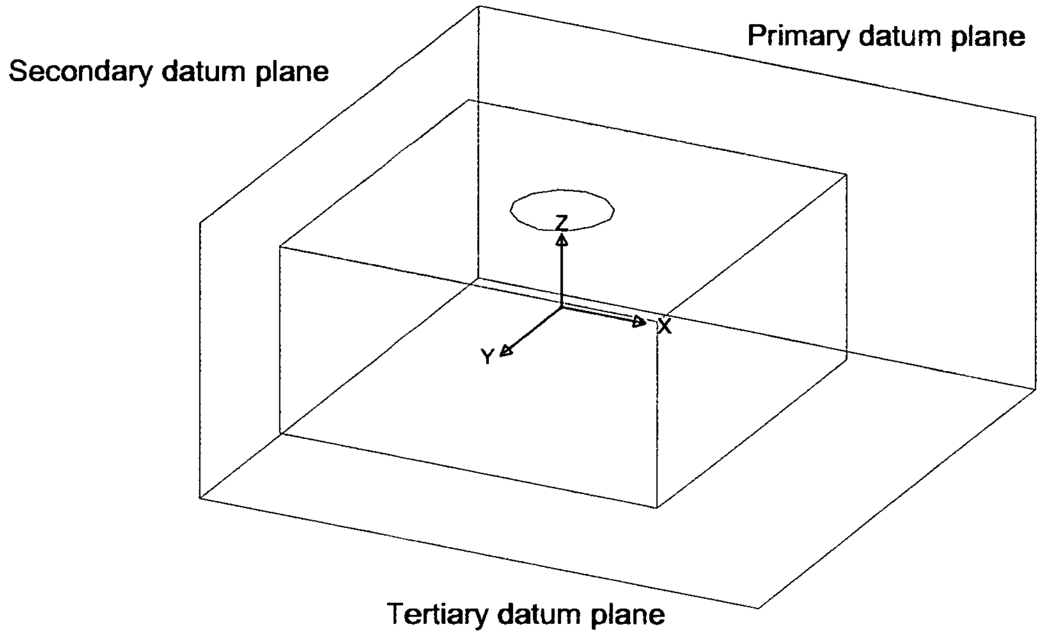


Figure 3-3 The three datum planes.

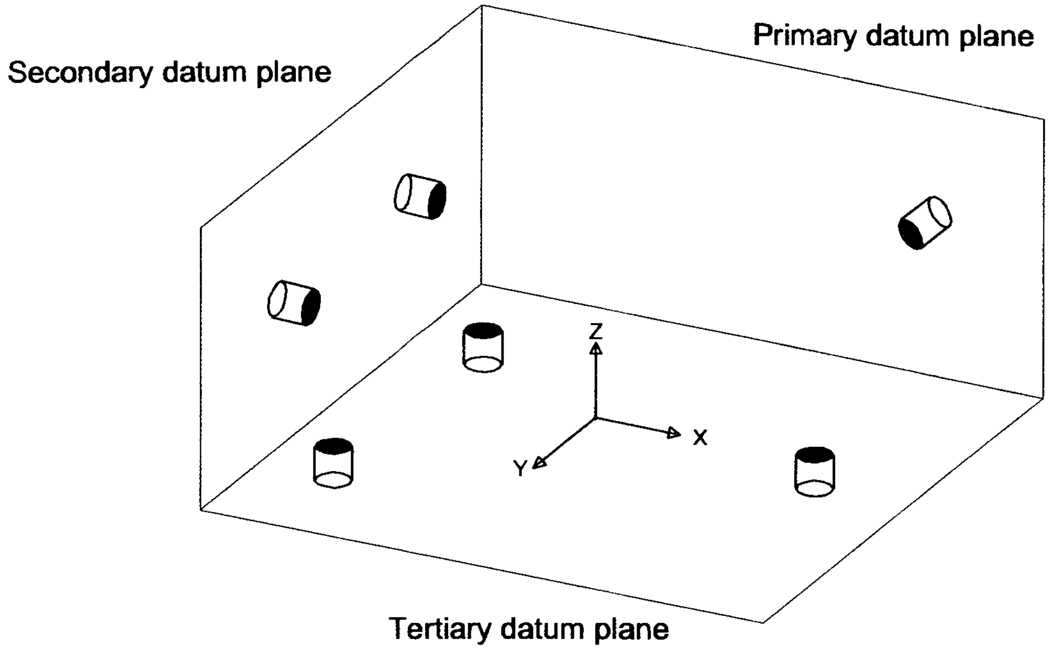


Figure 3-4 The 3:2:1 locating principles for a prismatic workpiece.

The 3:2:1 concept is not always the best method to implement a fixture design. In the situation where a prismatic part has a hole that could be used to locate the component, an internal locator may be used thus reducing the number of locators needed. The 3:2:1 concept in this case will no longer be valid.

In the example shown in Figure 3-5, the workpiece only needs three plane locators and an internal locator to restraint the nine movements, they are four linear movement along the positive or negative X and Y axes, one linear movement in the negative Z axis, and four clockwise or anti-clockwise rotational about the X and Y axes, instead of six locators. The remaining three movements, linear movement in the positive Z-axis, the clockwise and anti-clockwise rotation about the Z-axis will be restrained by the clamps. The hole used for the internal locating must be of a 'reasonable' diameter to allow the positioning of an internal locator. The diameter of the hole must at least be the size of the smallest internal locator available. It must also be perpendicular to the datum plane and open towards the datum plane. Holes on any workpiece that satisfy the above mentioned criteria will tend to reduce the number of locators needed.

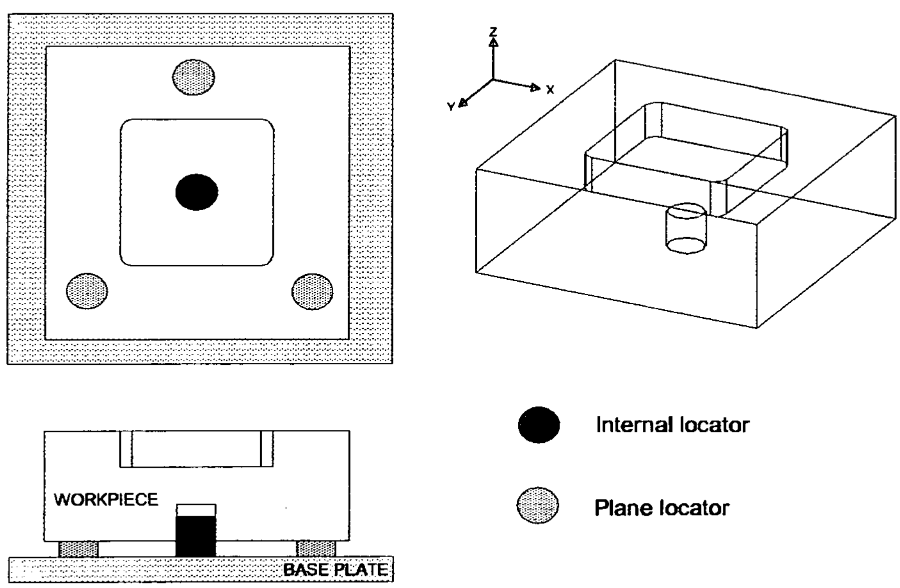


Figure 3-5 Using internal locator on a part with an existing hole.

3.1.2 Supporting principles

In most situations a locator can double as a support. However in circumstances where the locators do not provide adequate support for the component during the machining process, additional support elements have to be introduced to maintain the stability of the workpiece. In most manufacturing environments, clamping and machining loads will cause a workpiece to deflect, especially when the workpiece has a low stiffness, for example in the case where a thin wall exists. Additional supports are introduced to the fixture set-up to prevent such deflection, thus reducing any tolerance error which could result (Figure 3-6). It is also important that the support must not in anyway affect the accuracy of location.

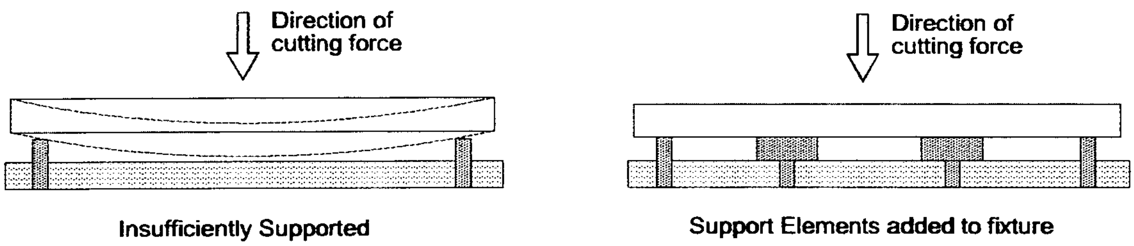


Figure 3-6 Workpiece supporting.

3.1.3 Clamping principles

Clamps are the moveable parts of a fixture, their purpose is to provide a holding force to restrict the possible movement of a workpiece that is not completely bound by the supports and locators. The clamping force secures the workpiece against the locators and supports by preventing motion in the opposite direction, or provide a moment preventing rotation about the axes. Generally there are two basic methods of clamping; vertical and horizontal. In clamp design, consideration should ensure that the clamping pressure does not distort the workpiece. It must also maintain the desired dimensional and positional accuracy of the workpiece in relation to the locators and supports.

3.1.3.1 Horizontal clamping

A horizontal clamp is one that is applied in the horizontal direction. It is usually applied on the faces that are opposite the primary and secondary datum planes, so that the clamping force will oppose and counteract the locating forces (see Figure 3-7). The most rigid area is selected for clamping to avoid deformation and cracking of the workpiece during the machining process. The best position is therefore the one opposite the locators as it will provide the rigidity and support that is required. However this is not always true as can be seen in Figure 3-7, instead of three horizontal clamps, that is one for each locator, two of the clamp can be replaced by a single clamp as show in the figure, thus reducing the number of clamps required.

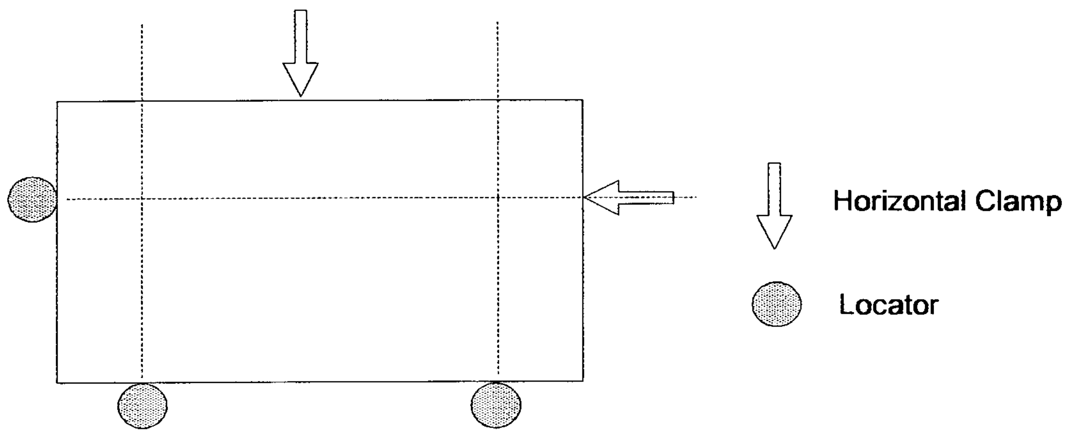


Figure 3-7 Horizontal clamping.

3.1.3.2 Vertical clamping

A vertical clamp is one that is applied in the vertical direction. It is usually applied on faces that are opposite the tertiary datum plane, so that the clamping force will oppose and counteract the locating forces on the tertiary plane (see Figure 3-8). As in horizontal clamping, the most rigid area is used as the clamping position to prevent deflection and deformation. The best position is therefore one on the plane directly above the locators on the tertiary datum, as can be seen from Figure 3-8. However this might not always be possible and therefore the best position will have to be selected from the region of stability. Clamping forces outside this region will upset the balance of the workpiece thus causing it to be unstable, unless more clamps are used to counteract the forces that are causing the workpiece to be unstable.

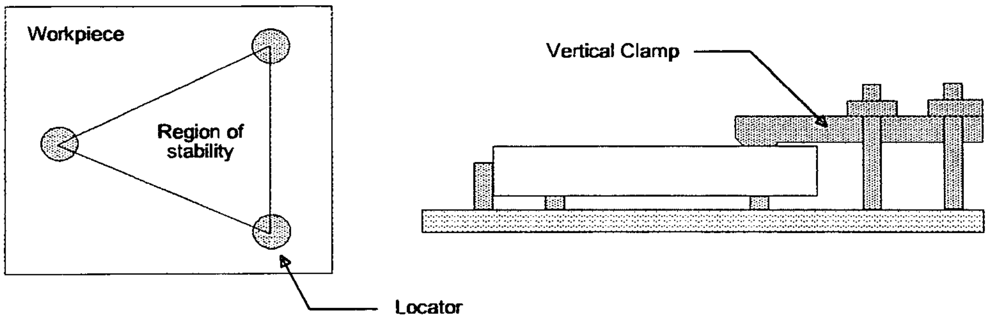


Figure 3-8 Vertical clamping.

3.2 Fixture Criteria

A good fixture is one that will ensure that the workpiece is manufactured in accordance to the design specification. Hargrove [Hargrove94] identified four general requirements to ensure a good fixture; accurate locating of the workpiece, total restraint of the workpiece during machining, limited deformation of the workpiece, and no machining interference between the fixture and the cutting tool. Other criteria that have to be considered include ease of use and cost.

3.2.1 Accurate locating of workpiece

The locating error must be recognised and minimised at all time. Locating errors are directly related to the geometrical properties of the component, such as the dimensional accuracy of the component. Locating errors occur when the locator is unable to keep the component in the pre-defined position and orientation under clamping and machining load. If the locating error is too large, a different locating face must be selected to replace the chosen one, or the tolerance of the locating face must be tightened.

3.2.2 Total restraint of the workpiece

A fixture must ensure that the workpiece is secure under all external forces generated during the machining process. Therefore it is necessary for the clamping force to be strong enough to locate and restrain the workpiece against the locators. Kinematic analysis is one way to ensure that the workpiece is properly restrained and that the clamping force is not more than what is required as over restraint may cause the workpiece to deflect or deform.

3.2.3 Limited deformation and deflection of workpiece

Permanent deformation and deflection of the workpiece must be avoided. A good fixture will never allow deformation and deflection to exceed the specified limits. These limits are determined from the given tolerances of the workpiece. Additional supports are often employed to limit such deformation and deflection. Finite element analysis is an excellent tool for detecting any deformation and deflection of workpiece.

3.2.4 No machining interference

The tool path during the machining process has to be obstruction free at all times. This is to prevent any collision between the fixture elements and the cutting tool. This will in turn prevent damage to the tools, the fixture elements and most importantly the workpiece itself. A good fixture will never allow any interference between the fixture elements and cutting tools during machining.

3.2.5 Ease of use

Fixtures must be safe and easy to use. Factors to be considered include health and safety regulations, access to clamps, minimum use of tools, ease of cleaning, ease of adjustment and repair, and the size and weight limitations of the fixture.

3.2.6 Cost

Keeping cost to the minimum is one of the main criterion in most manufacturing operations as long as the specification of the final product is not compromised. The cost of fixturing any workpiece must be kept to the minimum. Fixturing forms the major part of costs incurred in most manufacturing environments. Some estimates have placed it as high as one third of the total cost [Nee95], thus any reduction in fixturing cost will result in a significant cut in the total production cost.

3.3 Strategy for Fixture Design

The basic strategy for fixture design is to evaluate all the factors influencing the fixture layout and configuration. All the factors must be made available to the designer before any design or planning can be carried out. The geometry, topology, tolerances, surface finish, form features, process specification and material properties, as well as other data that relates to the characteristics of the workpiece, are major factors that will influence the fixture design strategy. The types of fixture tools available also play an important part in influencing the fixturing strategy.

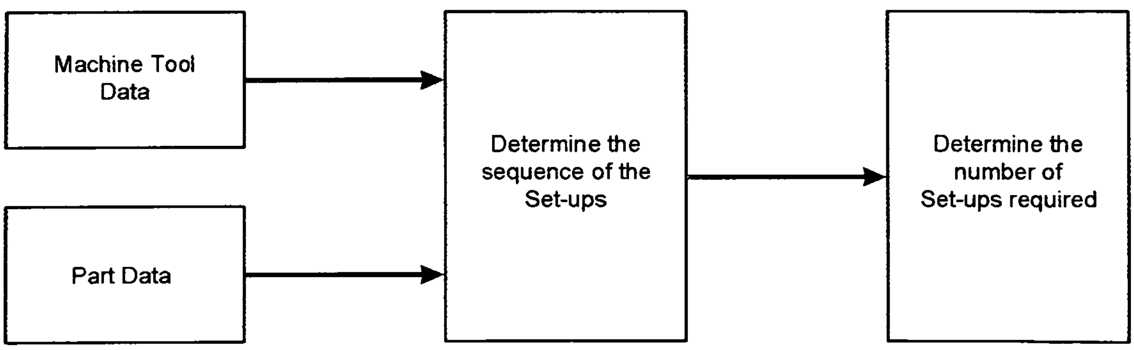


Figure 3-9 Selection of set-ups.

The first step in fixture design is to ascertain the number of set-ups that are required to manufacture the desired product. Evaluation of the part's geometry and topology has to be carried out first to obtain information that is associated with the part. This information together with machine tool data (the type of machines and cutting tools available) will enable a fixture planner to work out the number of set-ups required (see Figure 3-9). Once the number of set-ups has been determined, the next step is to sequence them. The priority of each set-up depends very much on their relationship with other set-ups as well as the design specification, such as geometric tolerances, and the relationship of the machining features in each set-up. The procedure, criteria and various factors that affect the selection as well as sequencing of the set-ups will be discussed in the next chapter.

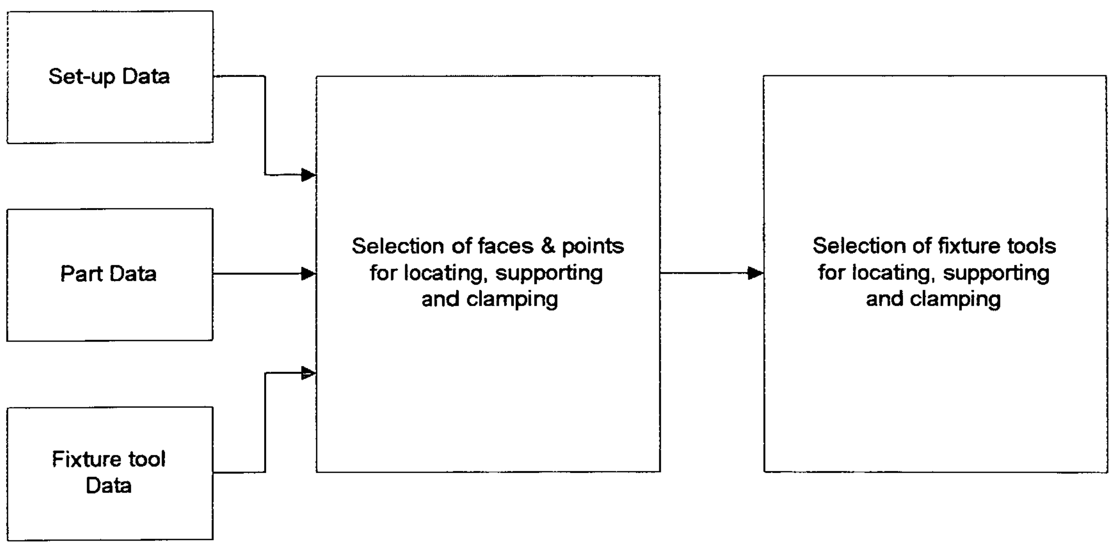


Figure 3-10 Basic fixture design procedure.

The design of fixtures requires three types of input data; set-up data, part data and fixture tool data (see Figure 3-10). The geometrical relationships of the part are first evaluated so that all possible faces that can be used as a locating face are identified. With all possible locating datum identified, the most suitable one is then selected. The selected faces are usually faces that have the most critical relationship with the features to be machined as well as showing a configuration in accordance with the 3:2:1 principle. Next it is necessary to check if the workpiece is adequately supported by the locators, if not then primary support faces will have to be selected. It must be noted that in most cases the selected locating faces may at the same time serve as the primary support face.

Once all the necessary faces/datum have been selected, the planner will proceed to select all the corresponding locating and supporting points. Finally the clamping faces and points are selected so that clamping forces can be applied in order to secure the part against the locating and support faces. Excessive deflection of the workpiece is then checked. If necessary additional faces are selected for additional support. Finally with all the faces and points selected, the planner will select the appropriate fixture tools based on the properties of the corresponding part faces and loads.

3.4 Fixturing Hardware

Fixturing has been in use by manufacturers for as long as there has been machining operations. Fixturing hardware can be classified into three general categories; modular, dedicated and hybrid. The traditional method of fixturing was to design and create a dedicated fixture for the manufacture of one single product. However, the trend towards greater flexibility in production volume and product variety has led to more multi-purpose fixtures.

3.4.1 Dedicated fixture systems

Tailor made fixtures for specific products are known as dedicated fixtures. The design cost of dedicated fixturing is usually very high, and it also takes longer to fabricate which indirectly contributes to the rise in the overall cost. The range of dedicated fixtures is almost infinite, as they are specially designed for the manufacture of specific components. Dedicated fixtures will always out-perform flexible/modular fixtures because they are specially designed and optimised to satisfy the design specification of the product. The time and cost involved in making dedicated fixtures can only be justified when the quantity of production is high or the product sales can cover the cost of making the fixture. Therefore dedicated fixtures are most suitable for mass production environments where they can be discarded at the end of the product life and their costs absorbed by the large number of products manufactured.

3.4.2 Modular fixture systems

The concept of modular fixtures was first developed by John Wharton in the 1940s [Koch89]. However they were not widely used in industry until the introduction of computer numerical controlled (CNC) machine tools and flexible manufacturing systems (FMS) to the manufacturing environment. In contrast to dedicated fixtures, modular fixtures are designed for a wide variety of workpieces. These types of fixtures are most suitable for small to medium batch production and job-shop environments where they can be used to fixture many different products.

Lim [Lim91, Lim92] highlighted the following factors that lead to the increase in popularity of modular fixtures in a modern manufacturing environment:

- Trend in industries
    - Faster changes of customers' demand
    - Trend to move from large volume to small scale customised production
    - Rapid design obsolescence, changes and modification
    - Short lead time for manufacture
    - Stiff market competition in both price and delivery
- Advancement in the machine tool industries
    - Increase in machine tool capacity and performances

    - Automated operation by CNC
    - Increase in the price of machine tools
    - Enhancements and changes in machine tool configuration.
- Labour shortage
    - Retirement and lack of skilled designers, engineers and tool makers
    - Job hopping of workers
    - Pressure to reduce the number of working hours
    - Increase in labour cost
- Operational efficiency
    - Maximum utilisation of capital intensive machine tools
    - Minimise wastage of material, set-up time and lead time
    - Simplification of job contents for unskilled workers
    - Higher quality products with lower machining tolerances
    - Maximisation of productivity and cost effectiveness

Modular fixtures are constructed using principles very similar to an adult 'Lego set' [Nee95]. Interchangeable fixture elements such as locators, supports and clamps are assembled on a standard base plate to form the desired fixture (see Figure 3-11). Modular fixtures are much more popular as they offer most of the desirable features of dedicated fixtures with the added advantage of re-assembly for a wide variety of workpieces.

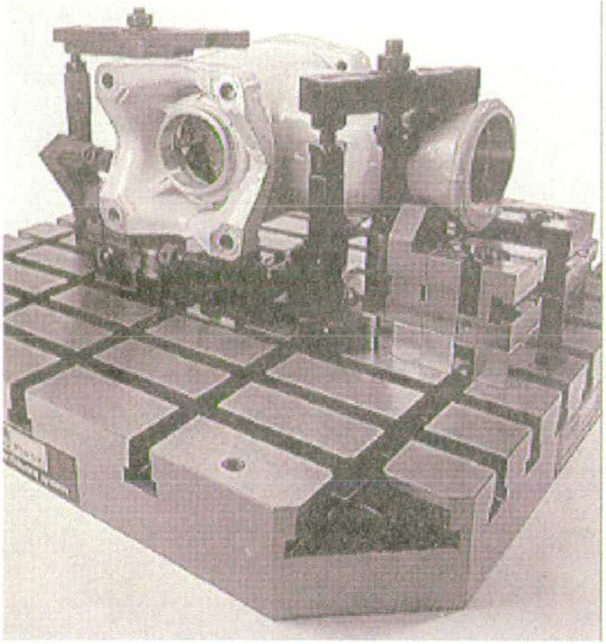


Figure 3-11 Typical modular fixture assembly (courtesy of WDS).

Modular fixture systems can be classified into two different categories; slot based and hole based. Hole based systems have accurately positioned holes on the base plate, which are used for fastening and locating fixture elements. Since these systems use screws to build the fixture, re-arrangement of the elements is easily achieved. However, this system is only able to provide discrete adjustment of mounting position. Chips generated during machining tend to accumulate in the holes and are often difficult to be remove. This can be prevented by using caps to plug the unused holes.

In contrast, slot base systems have slots running parallel and perpendicular to one another on the surface of the base plate. The attachment of each elements is done by inserting a tee-clamping block in the slot and then firmly clamping it in place with a bolt. The main advantage of slot based systems is that they provide infinite adjustment of mounting positions and the chips generated during the machining can be easily remove from the base plate. Both hole and slot based modular base plates can be seen in Figure 3-12 and Figure 3-13 respectively.

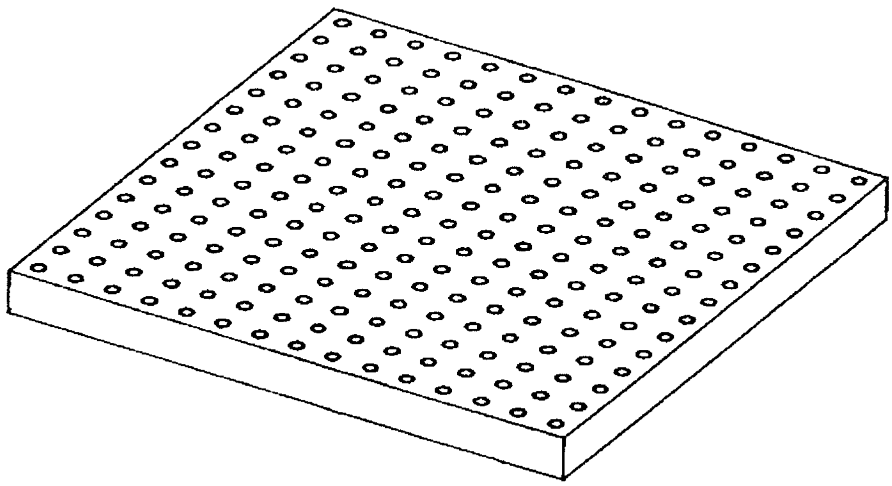


Figure 3-12 Base plate of a hole based system.

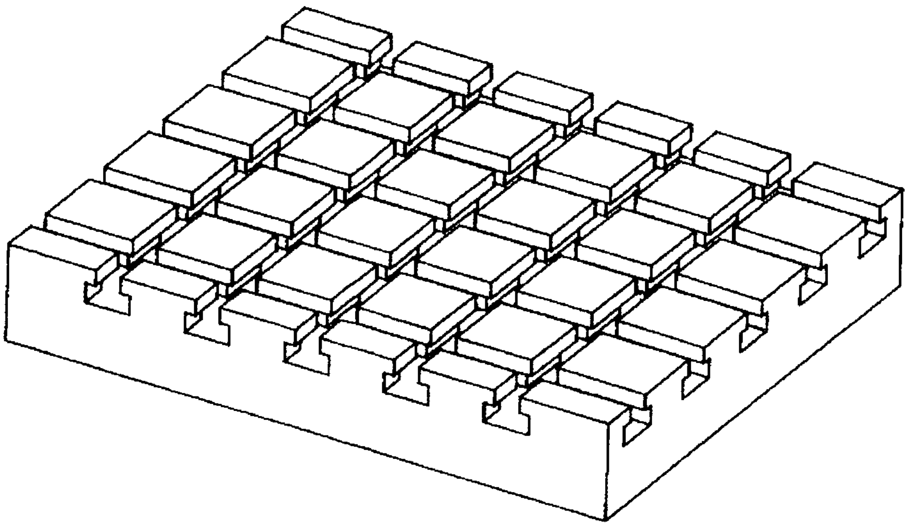


Figure 3-13 Base plate of a slot based system.

Although the positional, geometrical and dimensional accuracy of modular fixtures are lower than dedicated fixtures, they tend to reduce the need for storage space as well as designing time and cost. Several commercially available modular fixture systems are listed below:

- Hole Based Systems
    - Bluco Technik, Germany
    - SAFE (Self Adapting Fixture Element) System, USA
    - Venlic Block Jig System, IMOA Corporation, Japan
    - Kipp Modular Flexible Fixturing system, Germany
- Slot Based Systems
    - Halder Modular Jig and Fixture System, Germany
    - Wharton Unitool, UK
    - CATIC (China National Aeronautical Technology Import and Export Corporation) System, China

3.4.3 Hybrid fixture systems

This approach is a combination of both modular and dedicated fixture systems. Fixtures are assembled using selected modular fixture elements if suitable ones are available. Otherwise, some special purpose fixture components will have to be fabricated according to the workpiece geometry. Being a hybrid system, it has all the advantages of both the modular and dedicated systems. However, the disadvantages of a hybrid system are the resulting increase in cost, design time and storage space.

3.5 CAD Systems for Modular Fixture Design

The planning of fixtures using manual techniques requires a lot of paperwork, experience and a high degree of manual skill. These are some of the many reasons that give rise to the introduction of CAD systems for fixture planning. However, most CAD systems that are capable of fixture design merely use the draughting capabilities of a CAD package to produce drawings. Although such systems reduce the amount of drawings and drawing time, the disadvantages however far out strip the advantages. The disadvantages of CAD systems are:

- A high degree of expertise is still needed for fixture planning.
- A large CAD library containing all the necessary fixture elements is required.
- The fixture models are created using 2D drafting facilities, which imply problems in the design are difficult to detect, for example collision of machining tools and the fixture elements.

These are some of the main factors that gives rise to the development of automated fixture design system.

3.6 Computerised Fixture Design Systems

Over the years, a great deal of research has been carried out to improve the way fixtures are designed through the use of computers in view of the declining availability of expertise. In general, computerised fixture systems can be classified into three main categories; interactive, semi-automated and fully automated.

In interactive systems, the user is expected to use their knowledge and expertise in fixture design to select the appropriate elements from a CAD library as well as deciding the exact position to place them in to arrive at the final design. Interactive systems merely replace the need for manual drawing, which means that the full potential of computers is not fully utilised. This results in the development of semi-automated systems.

Semi-automated systems demand far less experience and knowledge from the designer to generate a fixture. However it still needs some level of human interaction to arrive at any particular solution. The increase in computer capabilities and the progress in the field of CAD in recent years has prompted many researchers in the field of fixturing to work on fully automated fixture design systems.

Automated systems do not required any human intervention to arrive at a solution. Most automated systems are integrated with some sort of CAD system to provide a product model which can be interrogated to obtain the necessary information for fixture design. The information obtained can then be used by a knowledge/rule base system to generate a suitable fixture for the product.

Researchers have applied various techniques and concepts to eliminate human intervention and increase computerisation in the design of fixtures. Techniques and concepts such as knowledge/expert based systems, artificial intelligence and kinematics form the main focus of automated fixture design research. Although many systems have been developed in the past, most of them have limitations and cover narrow domains. The next few sections will highlight some research works on fixture planning and their limitations.

3.6.1 Artificial intelligence and knowledge/expert based approach

Artificial intelligence and in particular knowledge based systems can be defined as computer programs that are designed to solve complex problems which normally would require human intelligence. The increased capabilities of artificial intelligence and expert systems has prompted many researchers to explore the possibilities of using them for designing fixtures. In these types of system, rules and facts regarding the design of fixtures are stored in a knowledge base designed to solve a domain specific problem using an inference engine, also known as the reasoning mechanism.

Markus [Markus84] is one of the earliest researchers to use expert systems for fixture design. A system called MOBUILD was developed in which modular fixtures can be designed for prismatic parts. The expert system is written in Prolog, a computer language for logic programming. It is an interactive system, where the designer has to provide a set of locating points so the appropriate fixture elements can be selected by the system. The inputs to the system include the description of the workpiece geometry, the machining parameters and the co-ordinates of the locators, supports and clamps.

Ferreira [Ferreira85] developed a system called AIFIX that also uses expert rules to determine the fixture configuration of a workpiece on a milling machine. The fixture is designed in two stages, stage one determines the suitable orientation of the workpiece and stage two designs the fixture around the selected orientation. This system works well with parts that have flat surfaces, however it is difficult to extend the rules to design fixtures for more complex parts. The designer has to provide the system with the appropriate information so that it can generate and evaluate the various fixture designs. The input information includes the workpiece description, the machine description, and a list of operations to be performed on the workpiece.

Pham and Larazo [Pham89, Pham90] developed an automated fixture design system called Autofix, which uses knowledge based reasoning and a solid modelling CAD package to design, analyse, and represent fixtures. The system configures complex fixtures from a database of modular fixture elements. If standard ones do not exist it is capable of designing special elements. Finite Element Analysis is then used to compute the deflection of the workpiece and to determine the optimum position of the supports. This system, however, does not have the capabilities to perform set-up planning.

Darvishi and Gill [Darvishi88] proposed a knowledge representation database for the development of a fixture design expert system. In this proposal, the knowledge of manufacturing methods and machine information is used to influence the design and selection of fixtures.

Kumar and Nee [Kumar92] developed an automated fixture design system using a rule/object based approach. A CAD model, generated by the HP-ME30 solid modeller, is used as an input to the system. The machining features are first recognised and then grouped into appropriate set-ups. Suitable locating, supporting and clamping points are identified using the rule base and finally, the appropriate fixture elements are selected. However the system is limited to prismatic parts with very simple machining features.

Nnaji and Alladin [Nnaji90] developed E-CAFFS which is a rule based expert system for fixturing on a CAD system using flexible fixtures. The system codes fixture elements into part families by using group technology concept and represents them as solid models on the CAD system. It is an interactive system whereby the user selects the appropriate fixture element from the data base for each of the points. Set-up planning is also not considered by the system.

3.6.2 Kinematics approach

Kinematic analysis provides a means of accurately representing cutting forces as well as the locating and clamping of a workpiece. This makes it a very useful tool for the analysis of fixtures.

Asada and By [Asada85] proposed a fixture design method that uses the stability and accessibility of the fixture elements and the workpiece as the criteria for designing the fixture. Analytic tools were developed for the fixture layout design through kinematic modelling, analysis, and characterisation of the workpiece fixturing. The system employs re-configurable fixture elements to locate and hold various workpieces for assembly. The main focus of this research is on the generation of the locating and clamping points.

Other researchers that use kinematic analysis are Chou & Barash [Chou86], Mani & Wilson [Mani88], and Menassa & DeVries [Menassa91]. Their works were briefly detailed in Chapter I, section 1.2. Artificial Intelligence, knowledge/rule bases and kinematics are only some of the most common techniques used by researchers.

3.6.3 Other approaches

Trappey and Liu [Trappey93] used a projective spatial occupancy enumeration (PSOE) to determine the fixturing location. In this technique, the workpiece is projected onto the grid plate of the fixture and decomposed into a number of cells. Empirical rules are then used to conduct a heuristic search to determine the fixturing locations.

On the other hand, Lee [Lee94] considered friction as the main factor of fixture design since many fixture arrangements rely on friction to hold the workpiece. Limit surfaces in force/moment space are introduced as a convenient formalism to check whether workpieces will slip and therefore help specify clamping forces. This approach uses rules, numerical procedures, and symbolic reasoning to determine the fixture layout.

Several other researchers have also proposed and discussed various methodologies, and techniques ranging from the use of machining forces to the use of phase change fixturing [Lim91, Lim92, Koh92, Kwasny93, Hazen90, King93, Bidanda90, Chou90, Lange89, Youcef-Toumi89].

3.7 Summary

In this chapter, the principle of fixture planning was introduced followed by the different approaches used by researchers to automate fixture planning. Their works was also highlighted in this chapter. It was noted that most have limitations, some of which this research tries to resolve. It was identified that most of the work only caters for certain stages of the fixture planning process, such as set-up planning, locating and clamping point selection or fixture planning for a single operation. Most of the work does not use geometric reasoning for fixture planning, therefore its the main focus of this research is to implement it. The next chapter will highlight the development of a fixture planning system using geometric reasoning.

CHAPTER IV

4. FixPlan: A Planning system for fixturing

Chapter III focused on the principles and strategies of fixturing. Various CAD and computerised fixture planning systems were introduced. In this chapter, the main emphasis is on the structure and strategies of the developed fixture planning system. FixPlan can be split into three basic modules, namely the geometric reasoning module, the fixture planning module and the feature based design module. The feature based design module strictly speaking should not be part of the system, however it is essential for this research as a means of creating the solid model as an input to the system. It was therefore necessary to include the development of the feature based design module into FixPlan. The geometric reasoning module forms the core engine of the entire system for without it, the whole system would not be able to function. In this chapter as well as the next, the importance of the geometric reasoning module will be highlighted. Geometric reasoning also makes FixPlan unique compared to the other systems mentioned throughout this thesis. The fixture planning module is made up of four sub-module, namely, set-up planning, selection of positioning, supporting and clamping faces, selection of locating, supporting and clamping points and finally the selection of the fixture elements. All the four sub-modules work closely with the geometric reasoning module to gather the necessary information.

The main function of a fixture planning system is the selection of set-ups and the design of the corresponding fixtures (see Figure 4-1). Fixture planning starts with the selection of set-ups based on the number of machining features within the workpiece, their geometrical relationships and corresponding machining information.

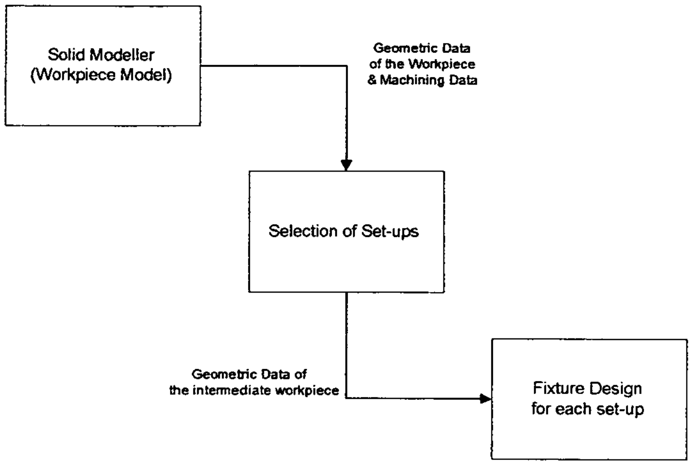


Figure 4-1 Functions of a fixture planning system.

A group of set-ups are then sequenced accordingly based on the relationships between each set-up. For each set-up a fixture will be designed depending on the geometrical relationships of the features within the intermediate state of the workpiece. It is therefore crucial that the planning system is able to interrogate the workpiece model to obtain all the necessary geometric data, at any stage, to assist in the set-up planning as well as fixture design. Thus geometric reasoning is one of the most important aspects of fixture planning and design.

4.1 Geometric Reasoning

Geometric reasoning is the only means available to extract vital information and data from a 3D solid model to assist in the selection of set-ups and subsequently the design of fixtures. The following are main functions the geometric reasoning process:

- Face-Feature relationships
- Compound Faces
- Split Faces
- Tool Access Directions

- Alternate Tool Access Directions
- Locating and Clamping Face Detection
- Locating and Clamping Point Generation

Other types of information include the size of the workpiece, its position and orientation, the number of faces it has, and the position and orientation of its features.

4.1.1 Face feature relation

All workpieces are made up of a number of faces, each face is either created by a machining feature or belongs to the blank, thus it is possible to establish their relationships. The face feature algorithm is used to determine the 'owner' of the faces. The owner in this case could either be a slot, pocket, hole or blank. Once the owner is identified, all the information associated with the face can be passed on to the corresponding faces and vice versa. Thus by selecting any face, the planner is able to access all the data that is attached to the feature that it belongs to. Figure 4-2 shows a flow chart of the face feature algorithm.

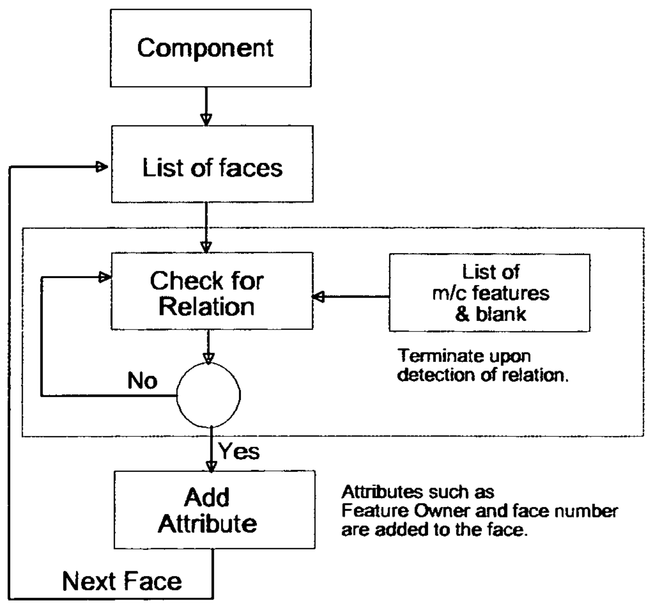


Figure 4-2 Face feature relation algorithm.

Faces are checked for intersections with machining features, such as a slots or pockets, which are present in the workpiece. When an intersection occurs, it implies that the face belongs to that feature. In other words the face is created by the intersecting feature. Attributes can therefore be added to that face to establish a link between the face and feature so that data defined for the feature can be accessed through the face. Faces that do not intersect with any feature will be cast as a blank_face, which means that the face belongs to the blank and no machining process is involved with that face. Machining processes on the blank_face, such as surface finishes or squaring up, are not considered in this research. As can be seen from Figure 4-3, faces 1,2 and 3 belong to the blank, whereas faces 4 and 5 form the step of the workpiece. The algorithm is therefore able to detect that both faces 4 and 5 belong to the step. It is common practice for CAD users to add attributes such as tolerances and surface finishes to faces on a CAD model. Hence with a face feature algorithm, it is possible to transfer such attributes to the feature concerned, thus enabling the planner to form relationships between features which will be used during set-up planning and sequencing.

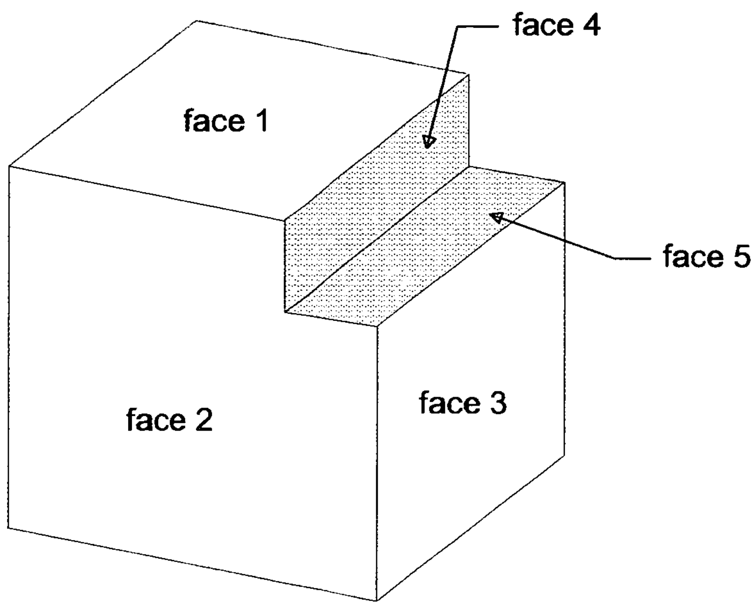


Figure 4-3 Face feature relation of a workpiece.

4.1.2 Compound face detection

Compound faces are faces that are produced by more than a single machining feature. An example of compound faces can be seen in Figure 4-4. As face 5 intersects with both slot 1 and slot 2, the algorithm will therefore classify it as a compound face and in doing so forms a relationship between it and the features. The main advantage of a compound face is that any attribute added to the face will be automatically be transferred to its features, in this case both slot 1 and 2. If a designer were to select face 5 as the reference face for another face, and that belongs to a feature, for example a pocket, it will indirectly imply that both slot 1 and 2 are reference features for that pocket.

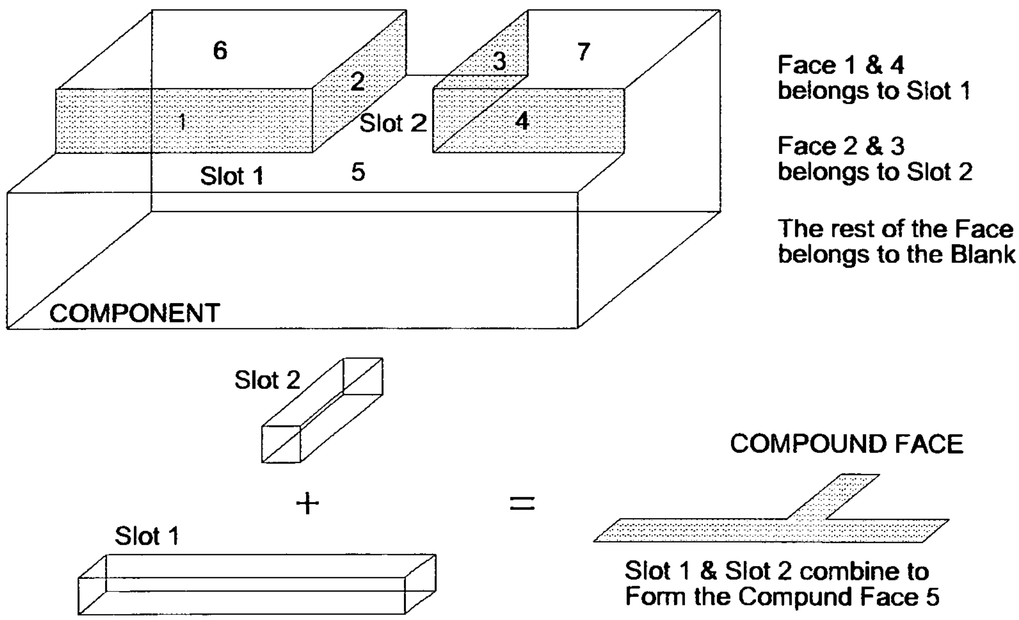


Figure 4-4 Compound face detection.

4.1.3 Split face detection

Splitting up faces is very common in CAD modelling. It happens when a designer adds a feature to a model like the one shown in Figure 4-4. As can be seen, the feature Slot 2, splits the top face of the workpiece into faces 6 and 7. The same can be said about the face that was split into faces 1 and 4. It is important to realise that these faces are related and could be classified as the same face. This will reduce the processing time needed by the planning system especially when it has to interrogate a very complex product model that is made up of a large number of faces.

In most 3D CAD system, such faces are treated as separate entities, therefore it is necessary to have an algorithm that will analyse the product model to identify such faces and relate them together. For any face to be classified as a split face, it must satisfy the following criteria:

- faces must lie in the same plane
- faces must have the same outward normal
- faces must belong to the same feature
- faces must have the same attribute, such as surfaces finishes

The ability to detect split faces becomes apparent when the fixture planning system has to select datum faces for locating, supporting and clamping.

4.1.4 Tool Access Direction (TAD)

The tool access direction is the approach in which a tool can access/create a feature without obstruction. Tool access directions are usually pre-defined when a feature is created. As all features are created by sweeping a wire-body in a pre-defined direction, that pre-defined direction will be assumed to be the tool access direction. As can be seen from Figure 4-5 the sweep direction of the hole feature defines the tool access direction of that feature, which in this case is in the negative Z-direction.

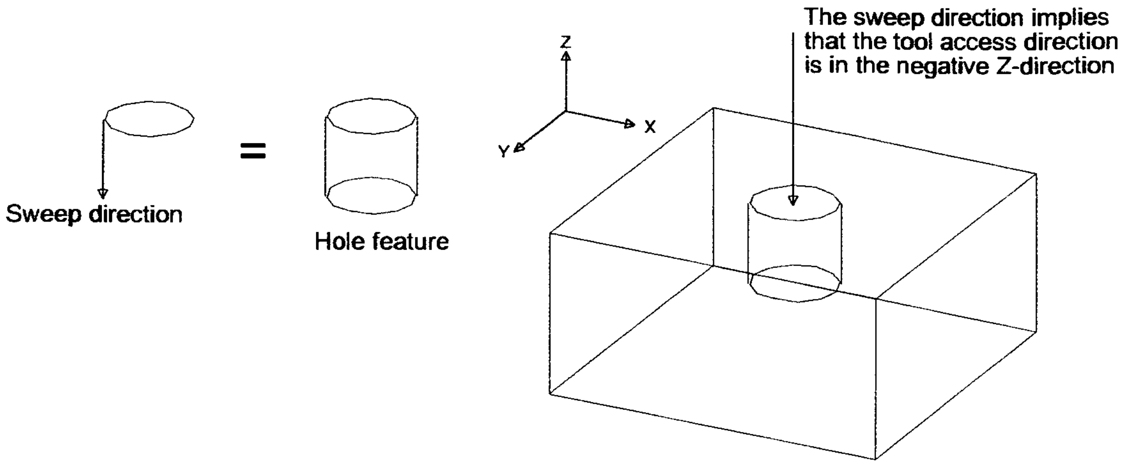


Figure 4-5 Tool access direction.

However, this is not always the case, for example a through hole has two possible access directions, one of which is the pre-defined tool access direction while the other is the alternative tool access direction. This implies that the feature, which in this case is a through hole, can be machined from either direction and that the choice of machining direction will be affected by its relationships with the other features in the workpiece model.

Once the tool access direction is determined, it is possible to generate a tool access body to check for accessibility of the feature (see Figure 4-6). The tool access body of a feature allows the planning system to detect manufacturing problems in the early stages of the design process thus avoiding any re-designing in later stages of the system. When adding features to a design, the planning system must automatically check for any intersection between the tool access body of that feature and the blank. If an intersection is detected, the planning system must immediately notify the designer so that the design fault can be corrected. In other words, the planning system must ensure that the designer does not add any feature to a design that will cause machining problems in the later stages of the manufacturing process.

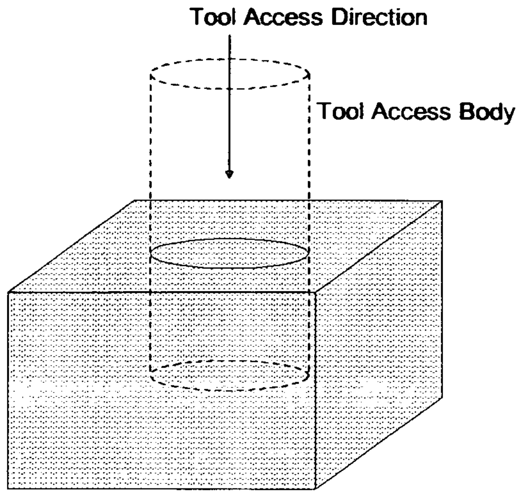


Figure 4-6 Tool access body.

In set-up planning, tool access directions are used to ensure that the features grouped in a set-up can be accessed by cutting tools from the same direction. Tool access bodies on the other hand, are used in the configuration of fixtures for each set-up. One of the most important criteria in fixture design is to ensure that none of the fixture elements obstruct the path of the cutting tool, thus preventing any tool collision. By simply ensuring that none of the elements intersect with tool access bodies during the design stage, the planner will be able to avoid manufacturing problems such as tool collision in a later stage.

The simple tool access body shown in Figure 4-6 does have some difficulties in detecting certain access problems. Figure 4-7 shows an example where the simple tool access body can not detect the access problem present. In this example, hole 2 is to be drilled through hole 1 which has the same diameter. Since the tool access body in this case has a diameter that is the same as hole 1, there will be no intersection between the two, thus implying that there is no access problem. However in a real manufacturing environment, it is impossible to machine hole 2 without damaging hole 1 in any way, unless holes 1 and 2 are either machined together or hole 2 first. Tool access bodies are used to check for collisions between the tools and fixture elements. Since most tools are held in some sort of tool holding device, such as a chucks or collets, it is important that the tool access body also takes them into account. This will result in a tool access body that is much larger than the original one.

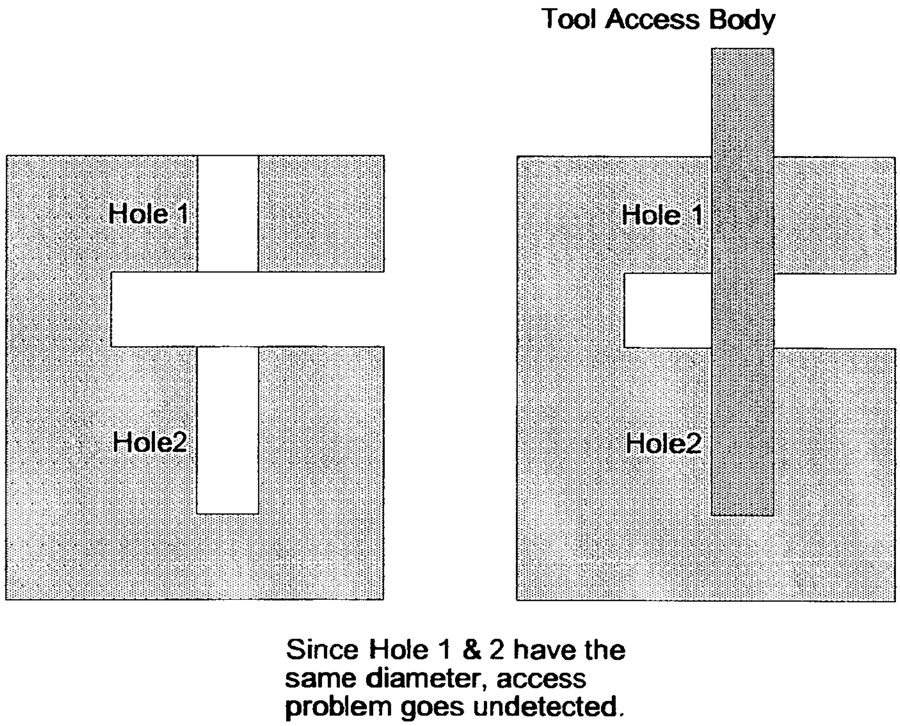


Figure 4-7 Problem in recognising an access problem.

Figure 4-8 shows an expanded tool access body that will solve the problems mentioned above. It can be seen that for the same example, there is a definite intersection between the expanded access body and hole 1, which otherwise was left undetected. The next question is how much should the access body be grown/expanded? To answer that question, the planner must be provided with information such as the type of machine tool to be used, the shape and size of the tool holder, etc. (Mill94).

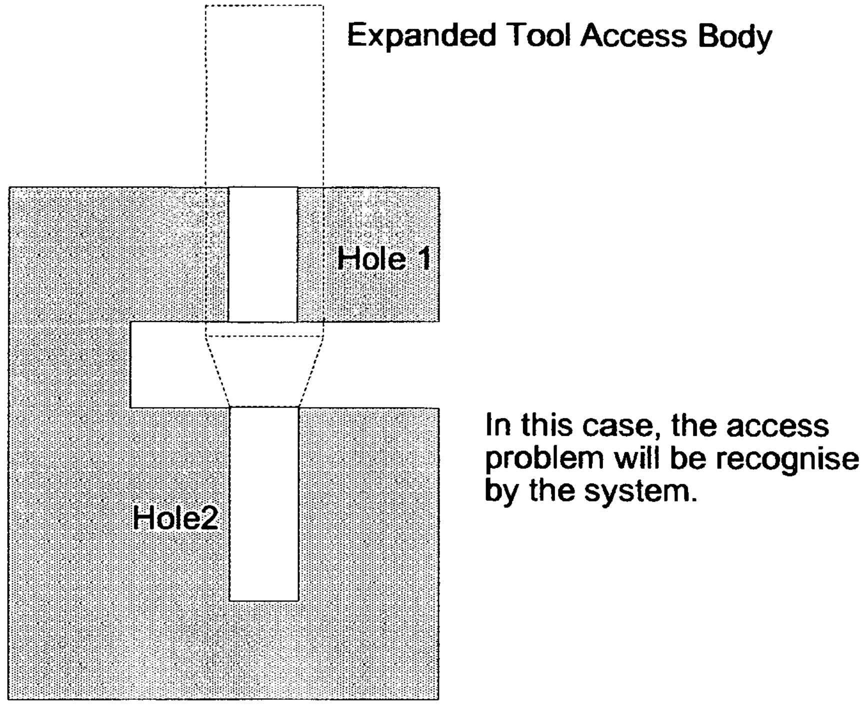


Figure 4-8 Solution to recognising access problem.

4.1.5 Alternate Tool Access Direction (ATAD)

The checking of access directions of a feature is often carried out on the assumption of a preferred access direction from which the feature is to be machined. This is true in most cases, for instance most holes will be machined from above, although through holes could be machined from either end (as mentioned in the previous section). Similarly it is very common to assume that a slot will be milled from above, but in certain instances, depending on the location of the slot, there may be more then one possibility.

For example by placing a slot on the edge of the component, thus resulting in a step, some might say that this will result in four possible tool access directions. However one could argue that depending on the type of step, its dimensions as well as the tools and machines available, the possible number of tool access direction can be reduced.

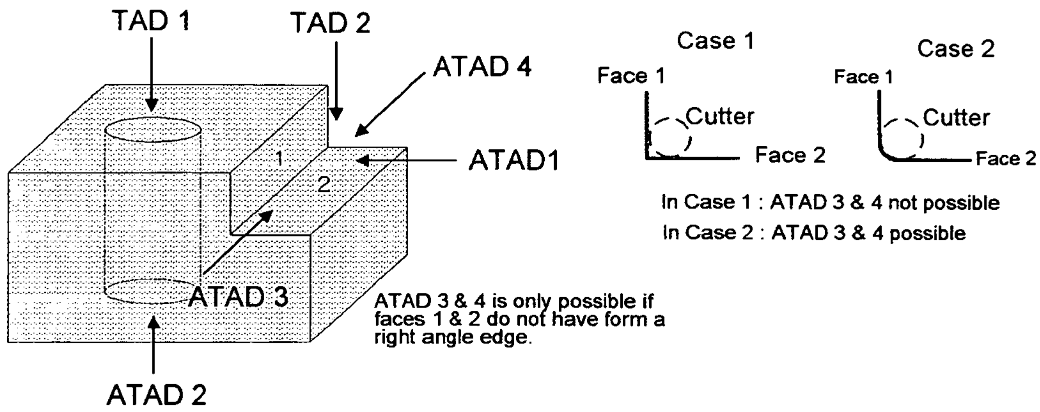


Figure 4-9 Alternate tool access direction.

As can be seen from Figure 4-9, there are two possible machining directions for the hole. The step however has two possible scenarios, case 1 shows a step with a right angled edge, which implies that there are only two possible ways of machining it (TAD2 and ATAD1), assuming that an end mill is to be used. On the other hand, in case 2 where the edge is rounded, the only way to machine the step is with an end mill through ATAD3 and ATAD4, as TAD2 and ATAD1 could not possibly create the round corner. It must be stressed that the characteristics of the machine and tool used for machining will affect the number of possible ways to create a specific feature. Thus with the right combination of tools and machines, all four access direction shown in the above example could be made possible.

The number of possible tool access directions in the machining of a feature is very crucial to fixture set-up configuration, as it is more likely to reduce the number of set-ups when features have more than one tool access direction as compared to those which have only one. The usefulness of tool access directions and alternate tool access directions will become more apparent in the set-up planning section.

4.2 Set-up Planning

Set-up planning is a function of both process planning and fixture design. It is therefore the key linkage between process planning and fixture design. A set-up plan can be defined as a collection of machining operations that will enable a part to be manufactured. It however does not define the details that are needed to produce the part. Therefore the main concern in set-up planning is with the grouping of machining features into set-ups and the sequencing of these resultant set-ups.

The cost of fixturing depends on the manufacturing cost of the fixture as well as the time required to assemble it. It is therefore assumed that reducing the number of set-ups will lead to a reduction in fixturing cost. It should be noted that this might not be the case as more expensive processes or machining methods, such as a five axis machining, could be introduced to reduce the number of set-ups but may inevitably increases the cost. Therefore the total cost of alternative configurations has to be compared before any decision can be made. This can be quite difficult under practical circumstances.

Although set-up planning plays an important part in process planning and fixture design, little research work has been carried out on the subject. Delbressine [Delbressine93] used a feature based design representation for the automatic generation of set-ups. A "Design Tree" is first derived by recording all the machining/design operations applied to the workpiece. For each operation the design tree contains information such as nominal shapes, tolerances, surface roughness, nominal position, nominal orientation as well as position and orientation tolerances. To configure the set-up plan, the design tree is converted into a manufacturing tree, given the available machines, fixturing tools and machining tools. Once completed, the manufacturing tree consists of one or more set-ups with a collection of basic manufacturing operations which define the intermediate state of the workpiece per set-up.

Zhang [Zhang95] on the other hand proposed a hybrid system which uses an optimisation algorithm coupled with rule based reasoning to perform set-up planning for the machining of simple prismatic parts. Rules and heuristics were created to determine the relationships between the machining process of features and tool approach directions. Based on the problems caused by these relationships, an optimisation approach was developed to find the optimal plan from all the feasible set-up candidates.

Ong [Ong95] proposed a knowledge modelling and formulation process for the development of an intelligent set-up planning system. The related knowledge and information required in set-up planning are modelled using object oriented modelling techniques, production rules and fuzzy sets. A fuzzy set based formulation of the problem solving procedures of the machinist is then used with this knowledge to form a coherent framework for set-up planning of prismatic parts.

All three researchers mentioned above use machining features and their relationships and/or attributes in various ways to formulate the number of set-ups required. However, none of them make use of geometric reasoning in their set-up planning which could otherwise ease the generation of set-ups as in the case of FixPlan. In Delbressine's work, the "Design tree" is derived by information that is provided rather than extracted from the feature based solid model. These argument applies to both Zhang and Ong's work whereby the information needed is not derived from the features through geometric reasoning.

Figure 4-10 shows the procedure of set-up planning. As can be seen, the feature based model of a part is first interrogated by the geometric reasoning algorithm to obtain the various relationships between features, for example the relationships between the faces and features, compound faces, split faces detection as well as to identification of the tool access directions of each feature. Geometric tolerances, tool access directions and alternate tool access directions are then used to determined the number of set-ups and sequences in this research.

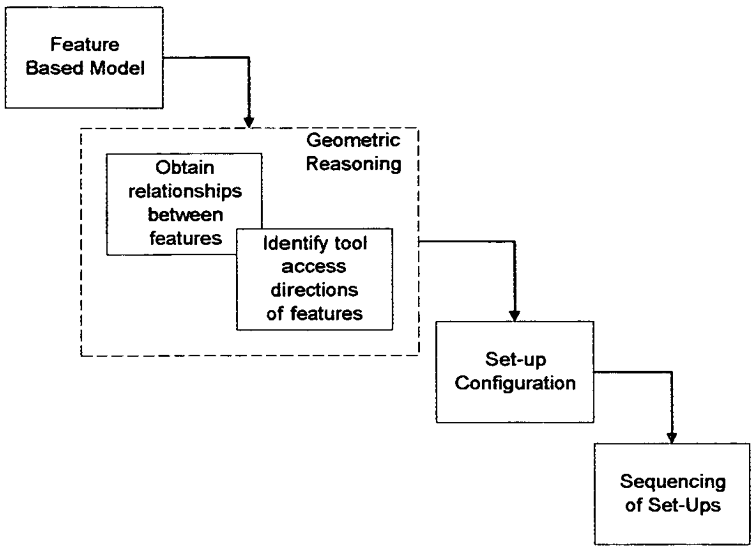


Figure 4-10 Set-up planning procedures.

Geometric tolerances are representations of the type and size of admissible deviation from nominal geometric relationships. These deviations can be both rotational and translational. Errors causing rotational misalignment are always dominant as translational misalignment can be compensated for. It is always difficult to compensate for rotational misalignment, whereas translational misalignment could be easily compensated through additional machining processes as long as it is well within the specified tolerance. This in turn implies that only rotational misalignment in the three principal axes are important in the configuration of set-up planning. Therefore a way to compare different geometric tolerances is needed. This is achieved by adopting a method developed by Boerma [Boerma88, Boerma89, Boerma90]. Boerma and Kals developed a system for the automatic generation and sequencing of set-ups using tolerance specifications of a part as the main criterion. The automatic generation of set-ups is based on the comparison of the tolerances of the relations between the different shape elements of the part. All the tolerances are converted into a non specific tolerance factor to form a converted tolerance scheme so that a comparison can be made.

4.2.1 Conversion of tolerances

As stated above, only the rotational misalignment in the three principal axes are important to the configuration of set-ups. Therefore the tolerance factor represents the tangent of the maximum admissible angle of rotation of a feature. Tolerances are converted into tolerance factors (TF) by dividing their tolerance value by their relative length. The length depends on the type of tolerance and the dimension of the part. The tolerance value is the maximum allowable deviation a feature can have with respect to its reference feature.

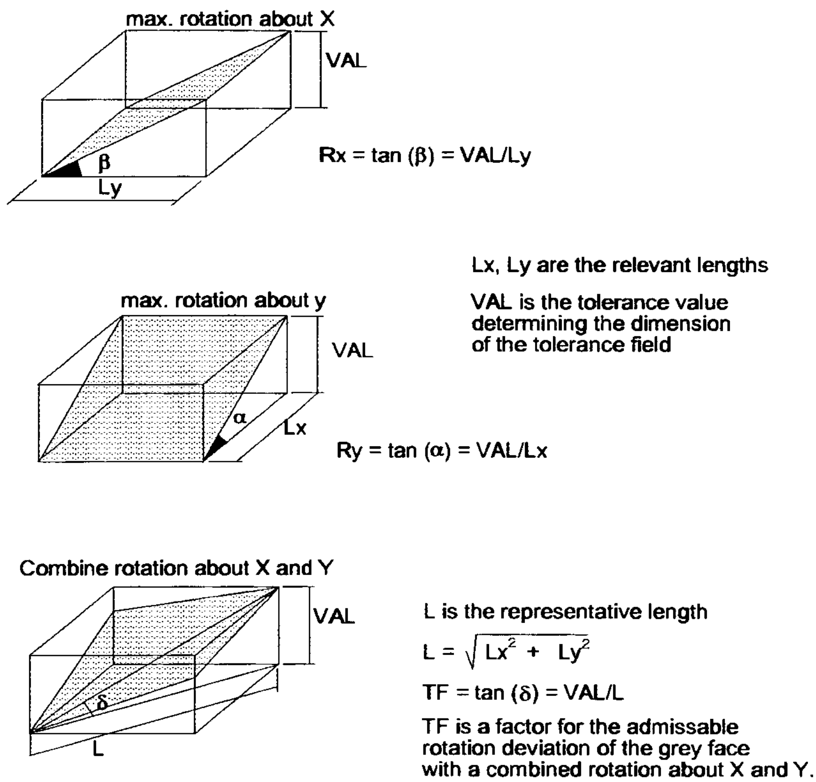


Figure 4-11 Conversion of a tolerance to tolerance factor.

Figure 4-11 shows an example of the conversion of a tolerance into a tolerance factor. As can be seen from the example, there are two possible misalignment errors, namely the rotational error about the X and Y axes. The rotational error about X axis can be represented by $R_x = \dfrac{VAL}{L_y}$, and the rotational error about Y axis is represented by $R_y = \dfrac{VAL}{L_x}$. The two errors have to be combined together so that the maximum rotational error can be obtained. When the two errors are combined, the relative length is therefore represented by $L = \sqrt{L_x^2 + L_y^2}$, and so the tolerance factor in this example is $TF = \dfrac{VAL}{\sqrt{L_x^2 + L_y^2}}$.

The conversion of the tolerance to a tolerance factor can therefore be represented by the following equation:

$$TF = MIN\left[\frac{VAL}{\sqrt{L_x^2 + L_z^2}}, \frac{VAL}{\sqrt{L_y^2 + L_z^2}}, \frac{VAL}{\sqrt{L_x^2 + L_y^2}}\right] \qquad \text{Equation 4-1}$$

where: Val - Tolerance Value

L_x - Relevant length in the X-direction

L_y - Relevant length in the Y-direction

L_z - Relevant length in the Z-direction

This conversion method is applicable to all tolerances which are used in geometric relations between features of a part. When all the geometrical tolerances between the features have been converted into tolerance factors, their relative importance can then be evaluated. The ranking of the tolerance factors constitutes the basis for the selection of set-ups.

4.2.2 Configuration of set-ups

The configuration of set-ups starts by selecting the feature with the lowest tolerance factor value, as it is the most constrained feature in the geometrical sense. Once selected, the feature is added to a set-up. The system then proceeds to search for features that are related to the one already selected. This could either be the reference feature (REF) of the chosen tolerance feature (TOF) or it might be a feature which has the same tool access direction. For example, referring to Figure 4-12, the feature with the lowest tolerance factor is hole H2 which takes reference from feature H1. Since H2 has the lowest tolerance factor, it is added to set-up 1. As hole H1 is the reference feature for H2, it is considered as a possible candidate for set-up 1. It should be noted that H1 has two tool access directions as it is a through hole. Although the initial tool access direction does not match that of H2, the alternate tool access direction does which means that H1 will be added to set-up 1.

The search then continues until all related features for this set-up are found, then the next minimum tolerance factor value, not already chosen, will then be selected to form the next set-up. It can be seen that although H3 takes reference from H1, it is not included in set-up 1 as its tool access direction does not match those in set-up1. Since H3 is the only feature left, it has to have the lowest tolerance factor which means that it is added to a new set-up. In this particular example, only two set-ups are required to produce the part.

1 is the left face of the part
2 is the back face of the part

3 is the cylindrical
face of the hole H1

Converted Tolerance Scheme

TOF	REF	TYPE	TF (e -4)
H1	1 , 2	⌖	30
H2	H1	//	20
H3	H1	⊥	30

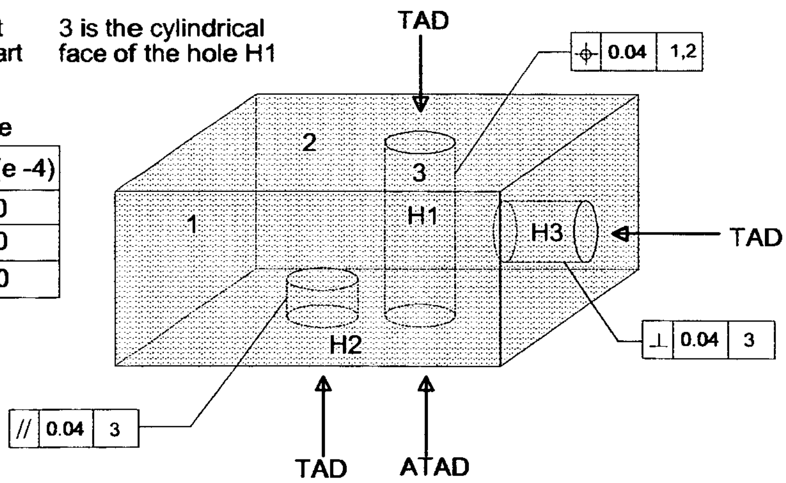
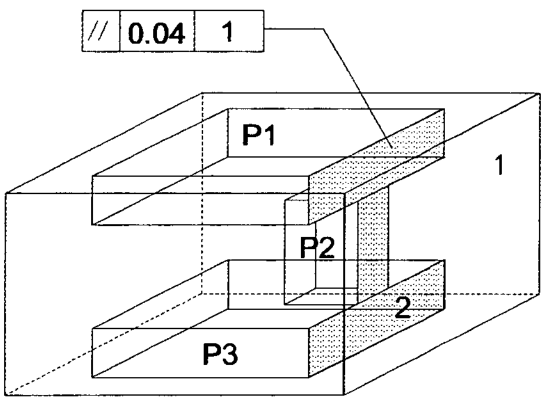
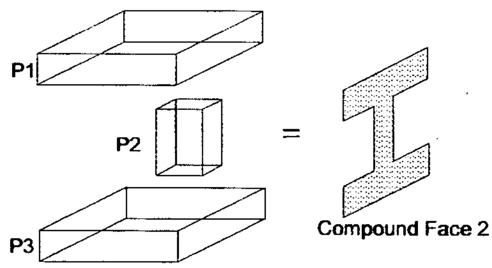


Figure 4-12 Set-up selection of part.

It is important to note that the selected feature for any set-up must not have a reference feature that will cause any conflict between set-ups. If so, a new set-up should be created for it instead of adding it to an existing one. For example, if H3 is the reference feature for H1 instead of faces 1 and 2, H1 can only be added to set-up 1 if H2 is to be machine after H3. By combining H1 and H2 into a single set-up which has to be machined first, it will cause a conflict during the machining process as H1 takes it reference from a feature (H3) that is still not present in the part. This means that in this circumstance, it is not advisable to add H1 to H2 as this implies that three set-ups are required to produce this part without any problems. The sequencing of the set-ups will be discussed in the next section.

Another important point is the way the geometric tolerance is defined/specified. As can be seen from Figure 4-12, all the geometric tolerances initially point to the faces of the features during the designing stage Through the use of the various geometric reasoning algorithms these tolerances are then transfered to the features which are then used to identify the relationships between features for the configuration of set-ups. Another advantage of geometric reasoning will be highlighted in the next example.





CTS

TOF	REF	TYPE	TF e -4
P1	1	//	20
P2	1	//	20
P3	1	//	20

Figure 4-13 Set-up selection of a part with a compound face.

In Figure 4-13, the part consists of three features that form a compound face. In this example the compound face (2) is defined as being parallel to face 1. As the geometric reasoning algorithm recognises that the compound face was created by the three pockets, the three features (pockets P1, P2 and P3) automatically inherit the tolerance. Thus implying that pockets P1, P2 and P3 take reference from face 1. From the Converted Tolerance Scheme (CTS) table, it can be seen that all three features have the same tolerance factor.

With all three tolerance factors having the same value, any of the features could be selected to form the first set-up. Since P1 is on the top of the list, it is used to create set-up 1. The search will then go on to find any feature that are in some way related to those in set-up 1. As P2 has the same tool access direction as that of P1 in set-up 1, it will be added to the set-up. It has to be noted that P2 must not in any way affect or create any conflict for the set-up. For example, if P1 takes reference from P3 and P3 takes reference from P2 than it is not advisable to add P2 into the same set-up as P1 as it will cause conflict during the sequencing of the set-ups. As the tool access direction of P3 is not compatible to those in set-up 1, a new set-up is thus created. Therefore, two set ups are required to produce this particular part.

It is interesting to note that P2 could be machined from both directions, and its alternate tool access direction is the same as the tool access direction of P3. This implies that if P3 were to be selected first, P2 will be combined with it to form the first set-up. Thus leaving P1 to form the second set-up. Although the same number of set-ups are configured, it does however contain a different combination of features in each set-up. The above examples highlight the procedure of set-up selection using geometric tolerances and geometric reasoning. With the set-ups selected, the next step is to sequence them into order.

4.2.3 Sequencing of set-ups

The sequencing of set-ups depends on the relationships between each set-up. Set-ups with features that are reference features to other set-ups will be chosen as the first ones to be machined. The set-ups that have features with the lowest tolerance factors should always be machined first as they are more sensitive to geometric tolerance errors. However this is not always the case, for instance in a situation where set-ups A and B are to be sequenced, set-up A consists of features with the lowest tolerance factor values with reference feature in set-up B. This implies that set-up B should be before set-up A. However, if set-up A consists of features that are reference features in set-up B, then the sequence is reversed even though set-up A holds the lowest tolerance factor value. The same principal applies to three or more set-ups.

However, consider a situation whereby a loop occurs, for example, set-up A takes reference from set-up B, set-up B takes reference from set-up C and set-up C takes reference from set-up A. In a situation like this, one possible solution is to select the set-up with the highest tolerance factor value as the first set-up to break the loop as it is less sensitive to geometric tolerance error.

Referring to Figure 4-12, there are two set-ups to be sequenced. The feature that has the lowest tolerance factor value is that of H2 which takes reference from H1. As can be seen from the CTS table, H1 takes reference from faces 1 and 2 which belong to the blank. Since H2 is in set-up 1, it implies that set-up 1 should be machined first. On the other hand, if either H1 or H2 were to take reference from H3, the order of the above sequence will be reversed.

In a situation where the lowest tolerance factor of each set-up are equal and there is no relationship between each set-up, the sequence of these set-ups will be of no importance. Referring to the example in Figure 4-13, the two set-ups determined do not have any relationships and all the features in the set-ups have equal tolerance factors. Set-up 1 consists of P1 and P2, while set-up 2 consists of P3. Since there is no relationship between the two set-ups, and all are equally sensitive to tolerance error, there is no reason why one set-up should be machined before the other. However, from the machining point of view, it might be more sensible to machine pocket P3 before P2 which means that set-up 2 will have to be before set-up 1, but some could argue otherwise.

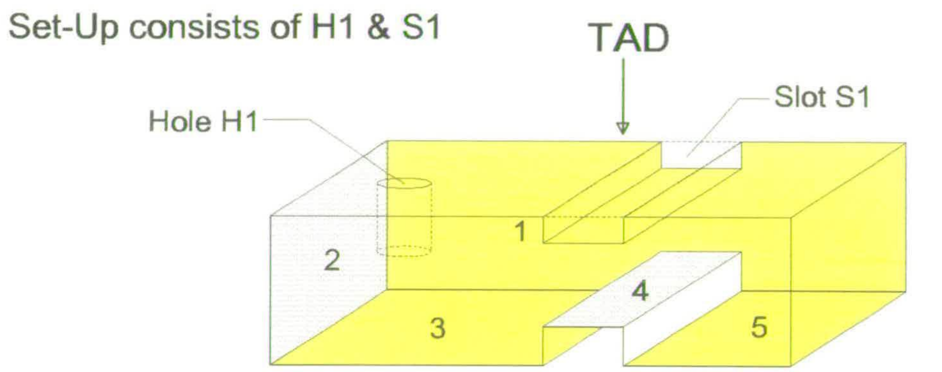
4.3 Selection of Positioning, Supporting and Clamping faces

All components have to be restrained before any machining processes can be carried out. The component must also be held in the correct position to reduce tolerance error which may result due to the machining processes. The faces that are used to locate the component are known as the positioning faces. The principle of locating a component was discussed earlier. Three locating planes are needed to locate a component. For a simple prismatic part, the three planes will be perpendicular to one another, this however may not be true in all cases. When the locating faces are not able to support the component, additional faces will have to be selected to provide the necessary support. These faces are known as supporting faces. To completely hold the component in position and maintain its orientation, the component has to be clamped. The faces where these clamps are located are termed clamping faces. The clamping faces can only be selected after the positioning and support faces have been determined.

4.3.1 Selection of positioning faces

The first datum are faces with a normal that is identical to that of the tool access direction. This is to ensure that the component is restricted from moving in that direction thus removing one of the linear movements. The second datum will be chosen from the remaining faces. However it must not have a normal that is the same as the tool access direction nor the inverse of it. Beside its normal, it is also chosen on the basis of its relation to the features in the set-up. Thus if a face is the reference of a feature in the set-up, it is classified as a possible candidate. It will also depend on the surface area of the faces, as only faces that are "big enough" for locating will be selected. If none of the remaining faces has any relationship to the features in the set-up, then the face with the largest surface area will be chosen. Finally, the third datum will be selected from the remaining faces. The procedure for the selection of the third datum is similar to that of the second except that the third must not have a normal that is the same as the second.

Figure 4-14 shows a component ready for the selection of positioning faces. As stated above, three datum are required to locate the component properly so that both its stability and dimensional accuracy will be maintained. Since the first datum is selected from faces that have a normal equivalent to that of the tool access direction, the three possible faces are Faces 3, 4 and 5. The CTS table shows that Face 4 is the reference face for slot S1, this implies that it is the best candidate for the first datum. However it has a surface area that is too "small" for locating as well as supporting the component, therefore it is rejected as the first datum. The acceptable surface area depends on the size of the smallest locating element, it at least be able to allow the locator to be place on it. Through geometric reasoning, it is recognised that Faces 3 and 5 form a single face split into two by a slot, therefore both are selected as the first datum instead of one. In a situation where both Face 3 and 5 lie on different planes, the face that has the larger surface area will be chosen. In later stages of the planning process, if the chosen face was found to be incapable of supporting the component properly, support faces would be added. The support faces must have characteristics similar to the datum that they are assisting.



CTS

TOF	REF	TYPE	TF (e -4)
S1	4	//	20
H1	1, 2	⌖	30

Face 3 & 5 - Selected First Datum
Face 1 - Selected Second Datum
Face 2 - Selected Third Datum

Figure 4-14 Selection of positioning face for a prismatic part.

Faces 1 and 2 are reference faces to hole H1, therefore both faces are suitable for the second datum. By comparing the surface area of both faces it is clear that Face 1 has a much larger area then that of Face 2, therefore Face 1 is selected as the second datum. The locating principal states that the best way to locate a component is to have the three datum planes perpendicular to one another. To ensure that the three datum are perpendicular, for this example, the only faces that are capable of achieving this are Face 2 and the face directly opposite it. Usually it does not matter which face is chosen as both faces have the same area, however since Face 2 is the reference face for one of the features in the set-up it is only natural that it should be selected to be the third datum.

The main purpose of having all three datum perpendicular to each other is to create a wedge effect that will lock the component in place preventing it from any translational displacement. It should be noted that it is not always possible to have all three datum perpendicular to each other. In fact, there are circumstances where three perpendicular datum are not the best method to locate a component. The following example will be used to illustrate this.

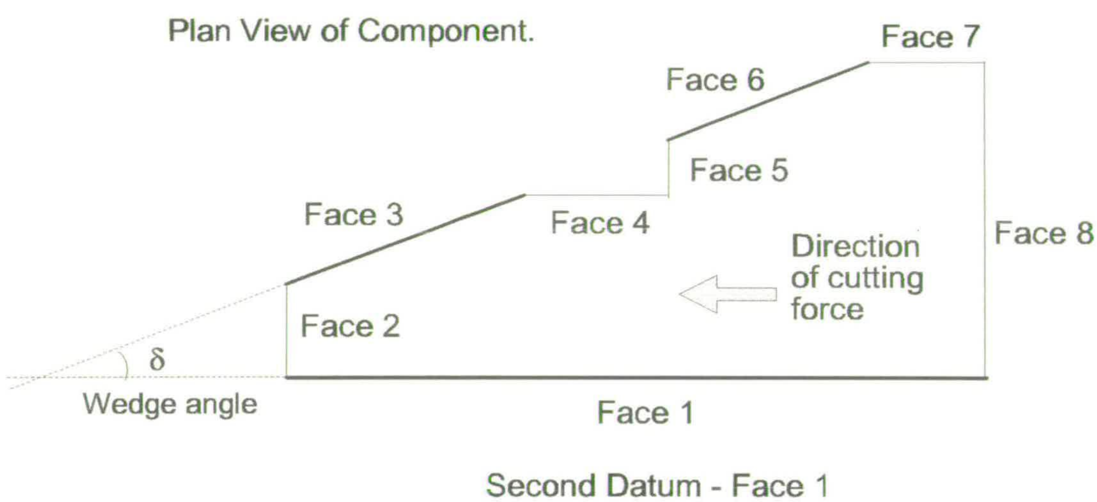


Figure 4-15 Wedge effect of datum faces.

As can be seen from Figure 4-15, Face 1 is the second datum, Faces 2, 3, 4, 5, 6, 7 & 8 are all possible faces for the third datum. Face 2 or 8 will be selected as the third datum if the rule of locating principal were to be strictly followed. However it can be seen that both Faces 2 and 8 will not be able to provide the best datum to properly locate the component. If none of the remaining faces are references to features, it does not matter which face is selected so long as it gives the best locating configuration.

Selecting Face 3, forms a better wedge effect than the one created by Faces 1 and 2 or Faces 1 and 8. If Face 3 were to be selected, it will automatically mean that Face 6 will be selected too as the geometric reasoning algorithm recognises that both Faces 3 and 6 are a split face. The angle of the effect formed by faces 1 and 3 is much smaller that the other two cases, which have an angle of 90 degrees. Face 2 is also too small for locating and if Face 8 was to be selected, it will not be able to prevent the translation displacement caused by the cutting force, unless the force is in the opposite direction. If the cutting force was to be in the opposite direction, Face 8 would be chosen although the wedge angle formed by it and Face 1 is much larger than that of Face 3. This is because the combination of Face 1 and 3 will no longer be able to restrain the translational displacement of the workpiece due to the cutting force. In this example, 4, 5 and 7 are ruled out as they are too small for locating. Faces 4 and 7 also happen to be parallel to the direction of the cutting force which means that they will not be able to prevent any displacement caused by it.

The general procedure for the selection of the third datum face can therefore be summarised as follows; a) select faces that are able to stop displacement in the direction of the cutting force, if possible chose faces that are references for the features in the set-up, b) ensure that the second and third datum form a wedge effect that has the smallest wedge angle, and c) the selected face must have a surface area big enough for locating. The direction of the cutting forces are therefore one of the major factors that influence the selection of the secondary and tertiary datum faces. However the directions of the cutting forces in machining operations is not considered in this research.

4.3.2 Selection of support faces

Support faces as their name suggest are used to support a component during machining. A positioning face can perform the same function as that of a support face. It is only when it fails to provide adequate support for the component that additional support faces are needed. After the positioning faces have been identified, it is necessary for the planner to analyse the stability of the component to determine if any additional faces are required to support the component.

The selection of support faces begins with the analysis of the features that are within the set-up. Geometric reasoning is employed to accomplish this task. The position and the orientation of each feature has to be obtained. This information will then be used to determine whether the existing positioning faces are sufficient for the supporting of the component. If not, additional faces will have to be selected to provide the support needed. The same information determined by the geometric reasoning algorithm will be used to select the necessary support faces.

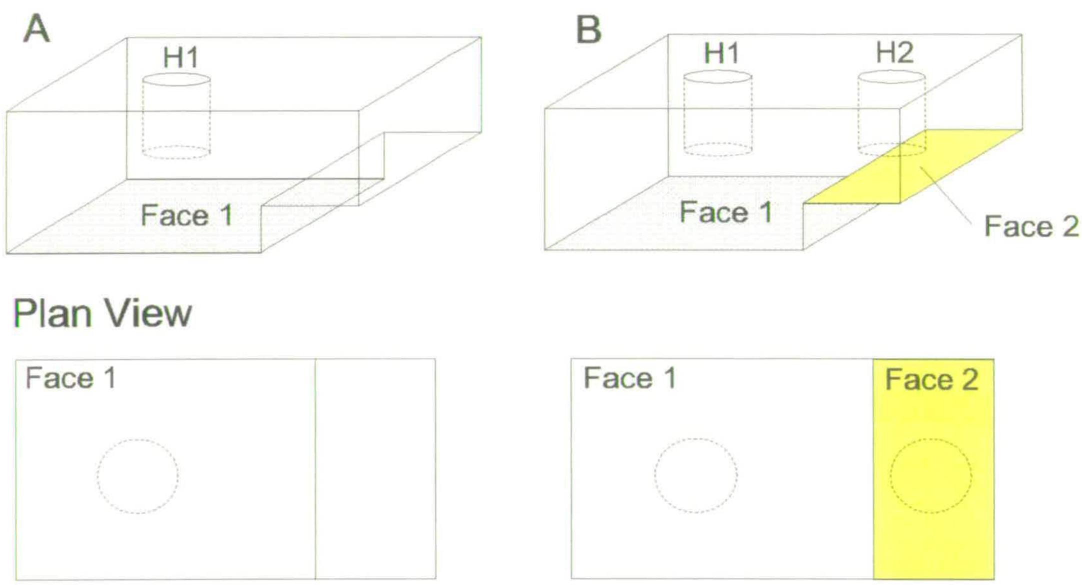


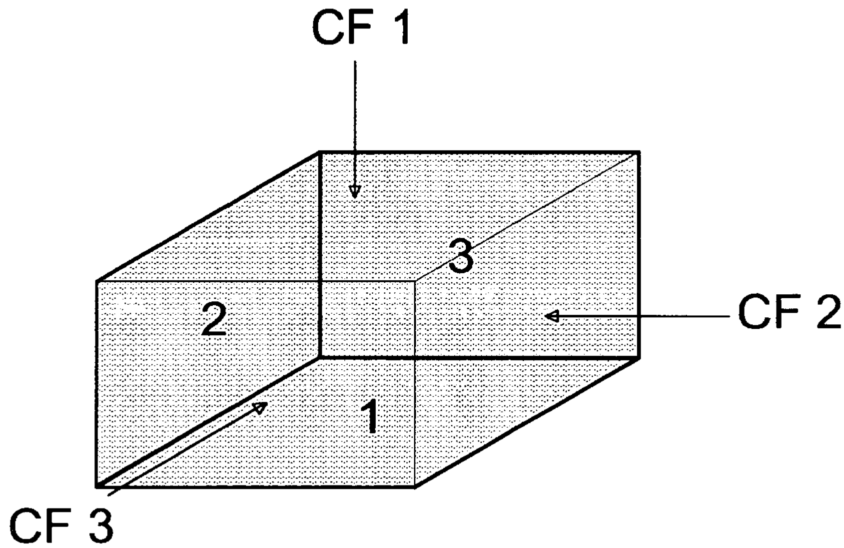
Figure 4-16 Selection of support face.

In Figure 4-16A, the position of the feature H1 is located within the boundary of the positioning face, Face 1. This implies that the hole can be machined without disturbing the stability of the component itself, thus no additional support faces are required in this set-up. However in Figure 4-16B, another feature H2 is added to the same set-up which changes the whole situation. The position of H2 is located outside the boundary of the datum face, Face 1, this in turn will cause instability of the component during the machining of the hole H2. Therefore an additional support face is needed to eliminate the instability of the component.

When selecting a supporting face, it must have similar characteristics to that of the datum face. This includes the normal of the face and its surface area. The support face must have a face normal that is the same as the direction of the datum face normal. It must also have a surface area that is big enough for the positioning of supporting elements. Looking at the example, Face 2 satisfies the above mentioned characteristics. Face 2 is selected because its boundary encloses the hole H2 thus ensuring machining stability, its surface area is big enough for supporting elements and its face normal is equivalent to that of the datum face.

4.3.3 Selection of clamping faces

With the positioning and supporting faces selected, the final task is to select the appropriate clamping faces. Several factors affect the selection of the clamping faces. Faces that are opposite the position and supporting faces are all possible candidates as clamping faces. Suitable faces are therefore selected from this list of faces. Similar to positioning and supporting faces, clamping faces must also have a surface area big enough to accept the clamps. Accessibility of the clamping tool is a major consideration when selecting the clamping faces. When positioned, the clamping tool must not in anyway obstruct the tool path. Figure 4-17 shows the possible clamping faces of a simple prismatic part. The possible clamping faces CF 1, 2 and 3, which can be seen from the figure, are directly opposite the three datum faces. However it is not necessary to use all the three faces as it might over constrain the component.



Clamping Face - CF 1, 2 & 3
Positioning and Support Face - Face 1, 2 & 3

Figure 4-17 Selection of clamping faces.

The number of clamping faces should be reduced to the minimum when applicable. The basic procedure for the selection of the clamping faces is based on the size, position and orientation of the features. Figure 4-18 shows the possible types of clamping configuration.

There are basically two types of clamping, namely horizontal and vertical. Horizontal clamping as the name implies, applies clamping forces in the horizontal direction. Cases (a) and (b) shown in the Figure 4-18 are examples of the horizontal clamping method. Vertical clamping on the other hand applies clamping forces in the vertical direction. Case (c) of the example shows the vertical clamping configuration. In Case (a), the faces CF2 and CF3 are selected as the clamping faces as they are directly opposite to the primary and secondary datum respectively. In Case (b), the two clamping forces in Case (a) are combined to form a single force thus reducing the number of clamping faces. However it must be noted that this configuration is only valid if the clamping forces can be applied in that direction. In Case (c), the selected clamping face is CF1 which is directly opposite the primary datum face F1. Regardless of the type of clamping configuration it is important to note that by reducing the number of clamping faces, it might also reduce the accessibility of the clamping tools to the faces. Case (b) is one example highlighting this problem.

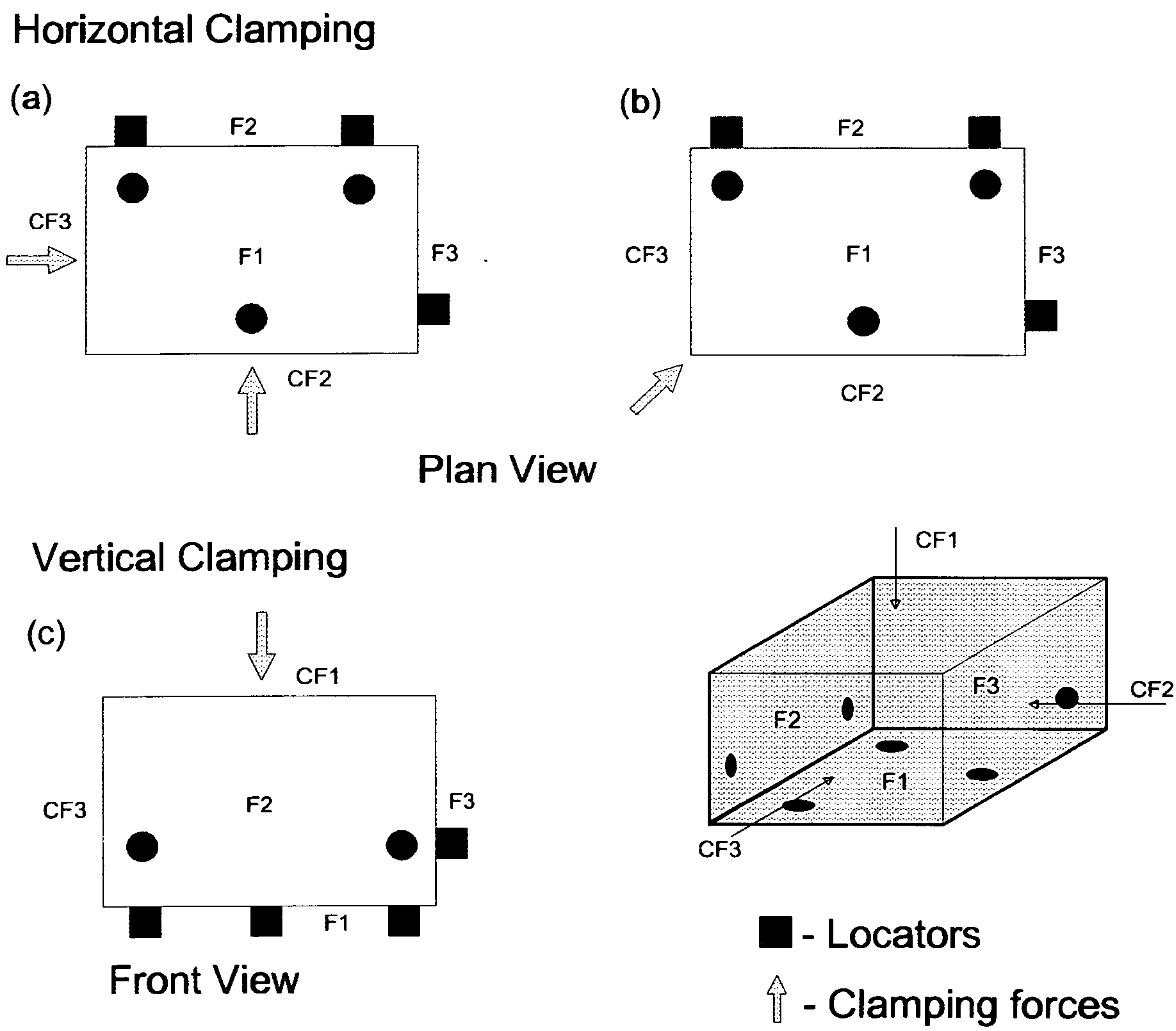


Figure 4-18 Horizontal and vertical clamping faces.

4.4 Selection of Locating, Support and Clamping Points

Locators, supports and clamps are fixturing elements used to hold the component in position during the manufacturing process. These tools are located in their respective faces on the component, namely the locating, supporting and clamping faces. Restraints against sliding are not considered since the chosen datum faces were selected to oppose the sliding field. Therefore, arresting the rotational movement of the component is the main concern.

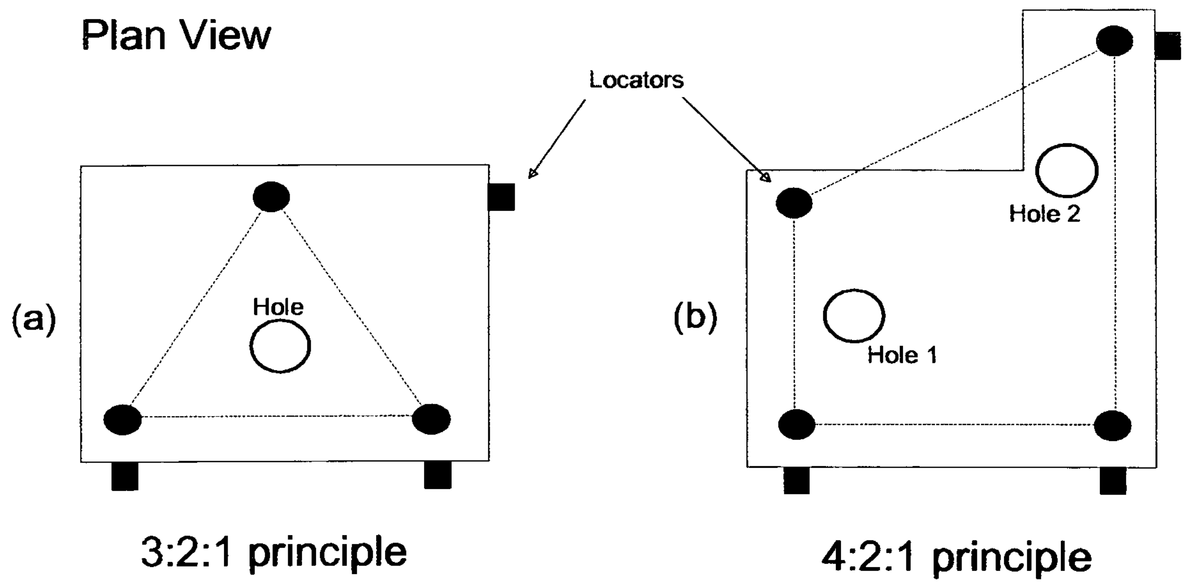


Figure 4-19 The difference locating principles.

Depending on the size and shape of the workpiece, the 3:2:1 or 4:2:1 principle could be used for the selection of locating points. Although the 3:2:1 principle is more commonly known, it however has problems locating components that have certain complexities (see Figure 4-19). Example (a) shows the 3:2:1 locating principle applied to a simple prismatic part, it can be seen that the hole lies within the boundary of the three primary locating points implying that all the machining forces are well within the boundary. If the same principle were used in example (b), it will not be able to restrain the workpiece properly as part of the holes might be outside the boundary formed by the locating points. Therefore the 4:2:1 principle has to be applied.

Similar to the selection of datum faces, it is necessary to analyse the component using geometric reasoning to obtain all the information on the features within the set-up. With this information, a field of features can be configured to determine the locating points. The field of features is a region that encloses all the machining features in the set-up (see Figure 4-20). As all the features are within the field of features, this implies that all the cutting forces are applied within this region. Since it is the location of these forces that causes the rotational movement, locators can be strategically placed outside the field to eliminate it.

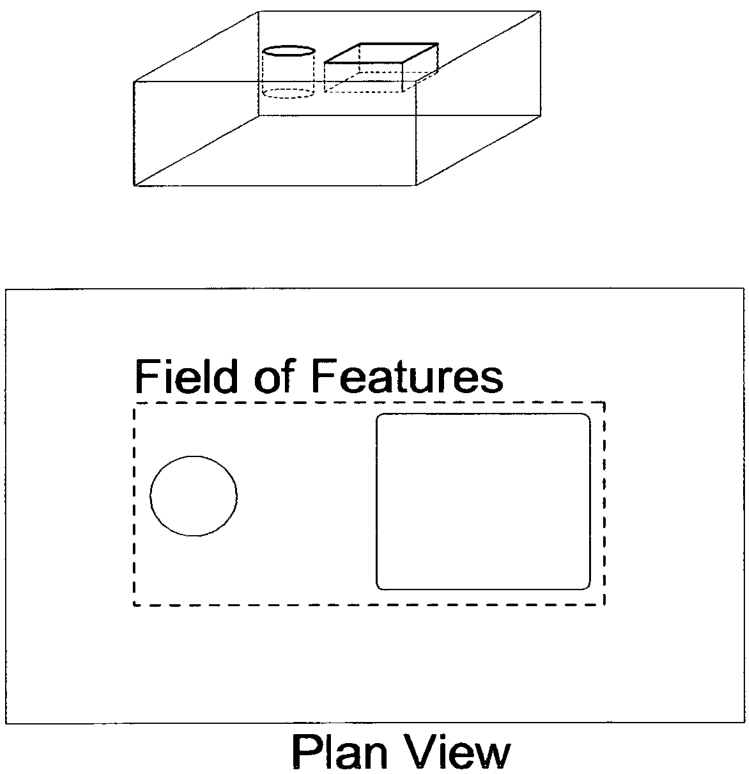


Figure 4-20 Field of features of a set-up.

4.4.1 Selection of locating points

The laws of kinematics state that in order to maximise the rotational stable region, the locators must be positioned as far apart from each other as possible. Since the extreme positions of the field are known, it is sufficient to locate the position of the locators so that it forms a boundary that will enclose the entire field, thus providing a stable region. As shown in Figure 4-21, the locating points form a region that encloses the field which provides stability to the component during machining when incorporated with clamps.

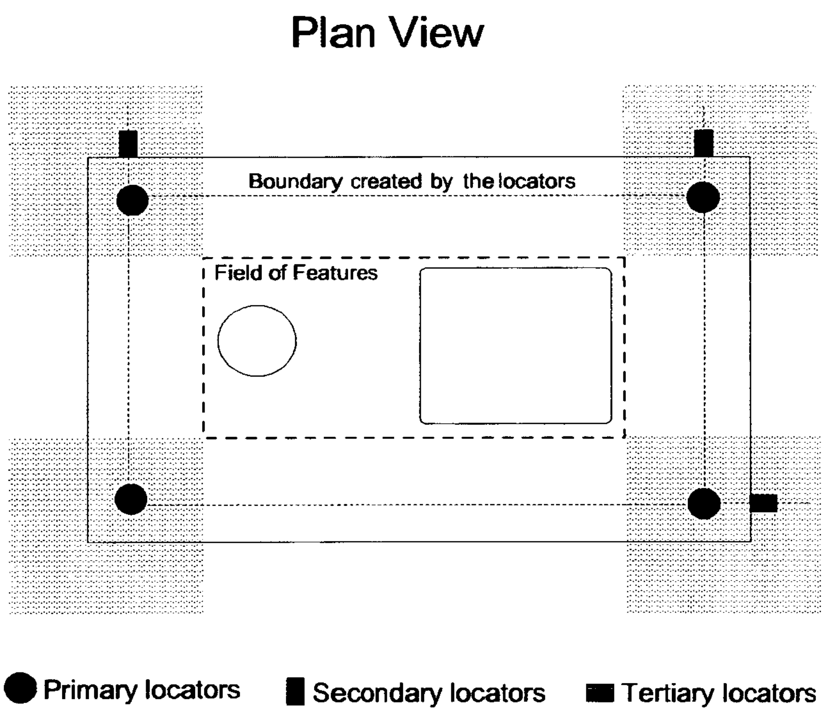


Figure 4-21 Selection of locating points using field of features.

The need for primary locating tools depends on the type of features that exist in the set-up. In Figure 4-21, if the two features in this example are not a through hole and a pocket, then the need for primary locators will be rendered obsolete. The component can simply be placed on the base plate which could equally perform the task of the locators. However if the features were a through hole and a pocket, then locators and probably supports would be needed to locate the component as well as to provide a clearance between the component and the base plate for the cutting tool such as a drill or an end mill. From the above example, it can be seen that geometric reasoning plays an important role in the selection of locating points. It provides the planner with all the necessary information to configure the field of features so as to generate the sets of points for locating.

The procedure for the selection of the secondary and tertiary locating points is similar to that of the primary locating points. The search for suitable points is carried out on the secondary and tertiary datum respectively. To ensure that the boundary created by the locators encloses the field of features, the locating points have to be selected from the shaded region in Figure 4-21. This of course applies to all the locating points, namely the primary, secondary and tertiary locating points. However this method of selecting locating points does not always work. In the next example, compromises have to be make on the above mentioned method in order to generate the correct sets of point.

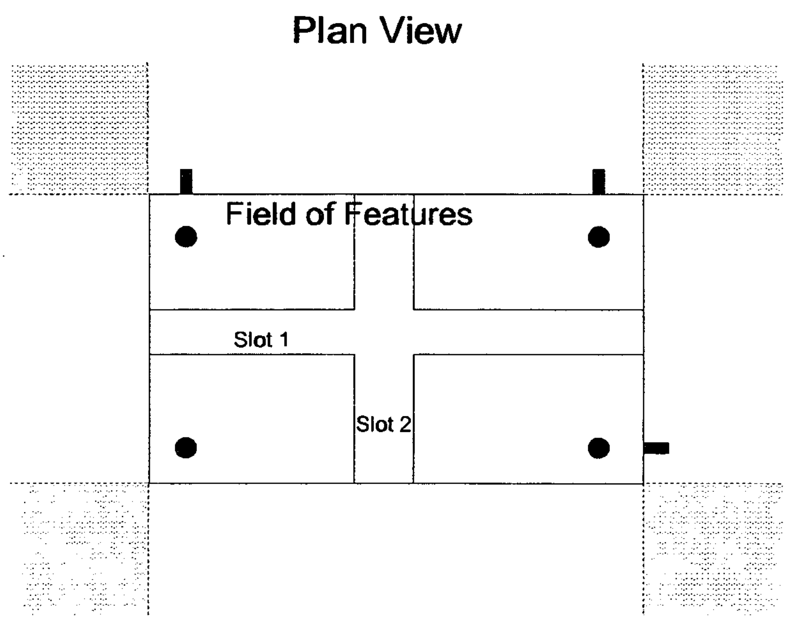


Figure 4-22 Compromises in the selection of locating points.

In Figure 4-22, the field of features of the set-up encloses the entire component which means that the method discussed previously no longer holds, thus compromises have to be made. In this circumstance the shaded regions are no longer valid. Instead of having the locating points outside the field boundary, the points are moved inwards just enough so that locators can be placed, forming an enclosure that covers the majority of the field area.

4.4.2 Selection of support points

In most cases, the locators also double as a support for the component. However in some circumstances, additional supports are required to maintain the stability of the component during the machining process. An example of where additional supports are needed was highlighted in section 4.3.2. The procedure for the selection of supporting points is similar to that described in the previous two sections. The selection of supporting points is not restricted by the size and shape of the field of features. Points are instead added to locations where supports are needed.

Deflection and distortion of the component under machining forces or its own weight is a common occurrence in manufacturing processes. This will result in tolerance errors which must be prevented. Additional supports will have to be added to eliminate the deflection and distortion of the component. Finite Element Analysis is one of the best methods for identifying deflection and distortion of components under various types of forces. Once the problems have been identified, supports will be added to the appropriate positions to either eliminate or minimise deflection or distortion.

4.4.3 Selection of clamping points

Clamps are needed to secure components in every single machining operation. Too many clamps might result in over design and possibly obstructing the loading and unloading of the component, too few clamps may result in the deflection of the component. Logically, for every locating point there should be a clamp to counter it.

However in doing so, a situation will arise whereby the component will be over restrained. Figure 4-23a is an example of over constraining the component with clamps, it has clamping point for every locating point on the datum faces.

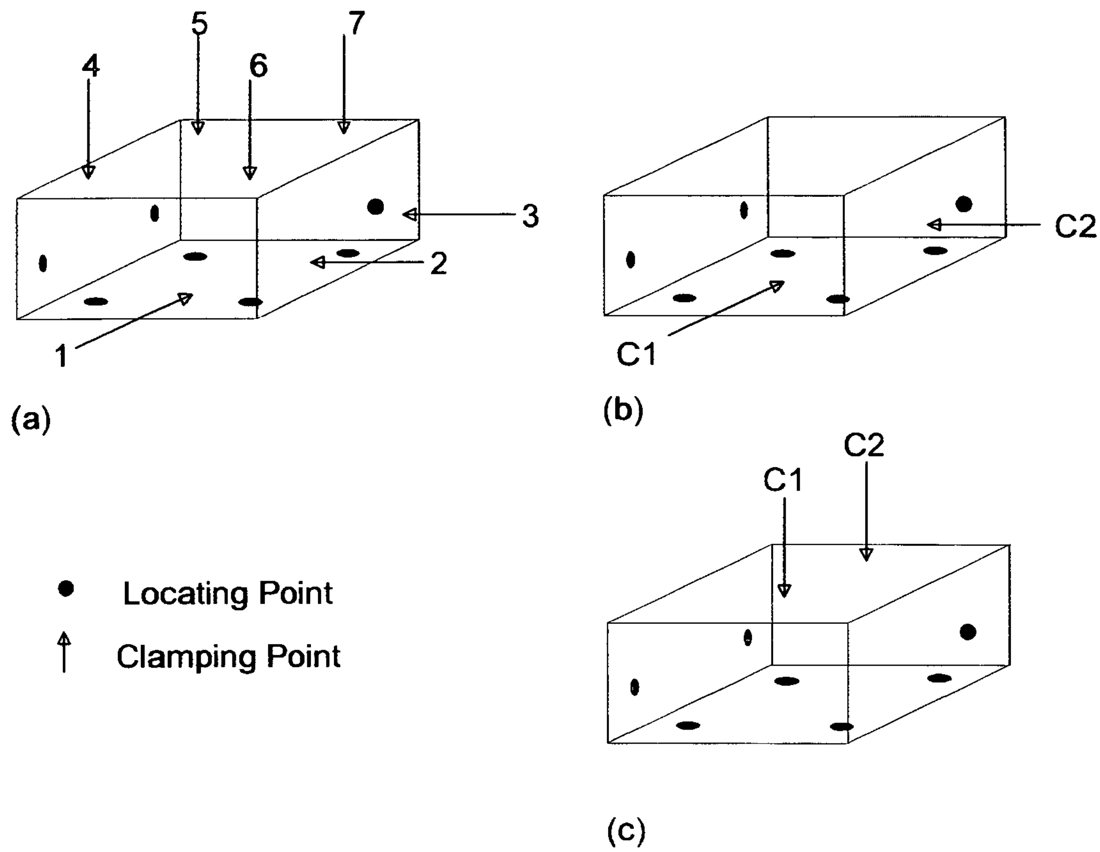


Figure 4-23 Selection of clamping points.

As mentioned earlier, the two methods of clamping are vertical and horizontal. The method of clamping selected will determine the position of the clamping points. It is important that there is enough space around the selected clamping point so that the clamp will not intersect with the machining envelope thus causing obstruction to the tool. The number of clamps needed is also influenced by the size and shape of the component and the position of the locators. Similar to selection of locating and supporting points, geometric reasoning is heavily utilised to interrogate the component to obtain information for clamping as well as selecting the clamping points itself. Figure 4-23a and Figure 4-23b show examples of horizontal and vertical clamping respectively.

4.5 Selection of Fixture Elements

For every locating, supporting and clamping point generated, suitable fixture elements will be selected from a modular fixture set which must in turn satisfy the various criteria and factors affecting it.

The type of locator is influenced by:

- the accuracy of workpiece blank
- the amount of free space around the point
- the surface topology
- the magnitude of the machining forces.

The type of support is influenced by:

- the accuracy of the workpiece blank
- the strength and stiffness of the workpiece
- the surface topology
- the magnitude of the clamping and machining forces.

The type of clamp is influenced by:

- the shape and size of the workpiece
- the surface topology
- the size and position of the machining envelope

- the desired clamping force
- the method of clamping.

Geometric reasoning is once again used to analyse the workpiece so as to retrieve the necessary information required for the selection of various fixture elements. With this information, suitable fixture elements such as a locators for each point, can be selected from a data base containing all the available fixture elements. Each element in the data base is defined by its size and function.

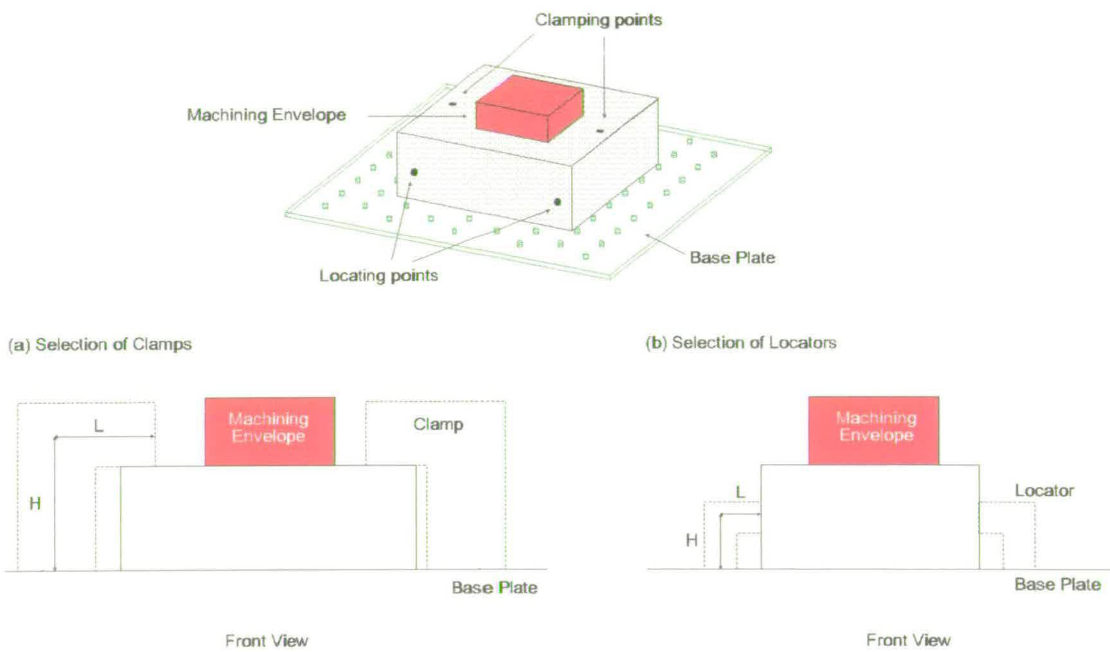


Figure 4-24 Selection of fixture elements.

As can be seen from Figure 4-24, for each point the geometric reasoning algorithm must find the respective holes on the base plate for the positioning of the fixture elements. For example in Figure 4-24a, with the hole and clamping point identified it is possible for the algorithm to calculate required height and length of the elements. These parameters together with the factors stated above are used to retrieve the most suitable element from the data base. If there is any intersection between elements or machining envelope, it should be detected and replaced by another element that will not cause any such problem. The same procedure is applied to the example shown in Figure 4-24b, where the locators and supports are selected.

4.6 Summary

In this chapter, the structure of FixPlan was highlighted. An outline of how each module within FixPlan should function was also provided. The importance and advantage of applying geometric reasoning to fixture planning was also made apparent in this chapter. From this chapter, it can be concluded that geometric reasoning can greatly enhance the fixture planning processes. In the next chapter, the implementation of FixPlan is discussed, how each modules within FixPlan work and relate to each other.

CHAPTER V

5. Implementation of FixPlan

In Chapter I, a brief description of FixPlan was outlined. FixPlan uses a 3D solid modeller, geometric reasoning and heuristic rules to determine the fixture configuration of a prismatic part. FixPlan uses the ACIS 3D Toolkit solid modeller for the designing of the workpiece. The workpieces in FixPlan are described using the Component Description Language (CODL) [Salmon94] while the interfacing mechanism between the various modules was developed using Scheme. Visual Basic is then used to enhance the user interface with the system. The system is build on a Windows platform, and therefore can be run in either Windows95 or Windows NT. The system could also be run in UNIX, however a new user interface would be required as the present system does not work under UNIX. The interface for UNIX could be build using Motif as it is based on the X-Window system which has become a standard windowing system for UNIX platforms. FixPlan consists of the following three modules: Feature Based Design, Geometric Reasoning and Fixture Planning. In this chapter, the implementation of the three modules will be examined.

5.1 Scheme Language

Scheme [Martin94, Springer93] is a language, similar to LISP, that uses an interpreter to run commands. Scheme benefits from having been deliberately designed to be clear and simple with very few syntactic rules. This makes it one of the easiest computer languages to learn. Scheme looks very different when compared to other programming languages such as BASIC, FORTRAN, C or C++. These procedural programming languages usually contain a long lists of instructions that are performed one after the other. Scheme however tends to be very much shorter in length than the corresponding program in other languages and is a declarative language.

The Scheme interface is a collection of functions that allow a Scheme based application to use the Application Procedural Interface (API) functions, Direct Interface (DI) functions, class functions and ACIS data. As Figure 5-1 illustrates, the Scheme application, in this case FixPlan, is built on top of ACIS, interfacing to the modeller via the Scheme Interpreter Husk, which then interfaces to the rest of ACIS using C++ calls.

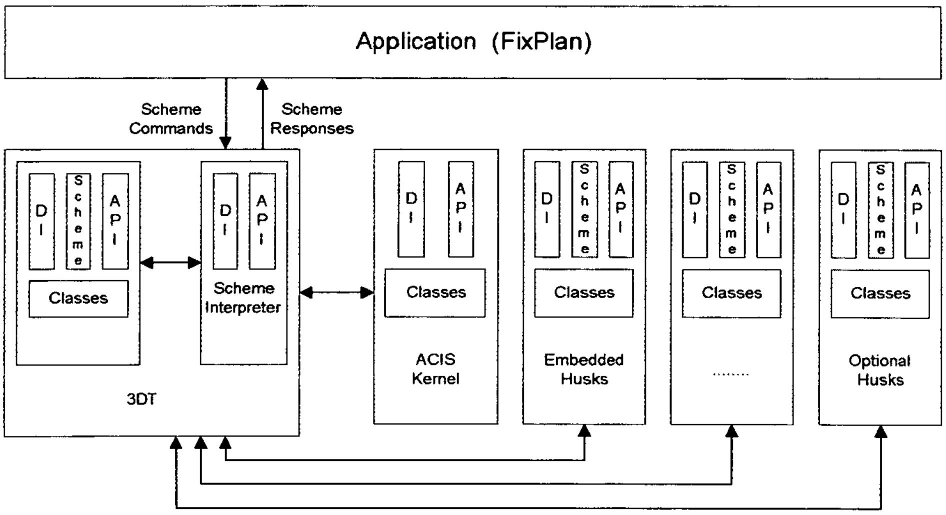


Figure 5-1 Scheme application (FixPlan) interface to ACIS.

5.2 ACIS 3D Toolkit

The ACIS 3D Toolkit is a collection of functions and commands that are fully integrated with the ACIS Geometric Modeller [ACIS96]. Its design accelerates prototyping and development of 3D modelling applications and provides applications with the ability to interact easily with ACIS through the use of the Scheme language. ACIS is an object oriented geometric modelling toolkit from Spatial Technology Inc. (STI) [ACIS94a, ACIS94b] and is a boundary representation geometric modeller that integrates wireframe, surface and solid modelling by allowing these alternative representations to coexist naturally in its data structure. The ACIS kernel which forms the core of the solid modeller is a geometry engine that provides the functionality common to many modelling applications. Wireframe, surface, and solid models are represented in the same data structure within the kernel. The architecture of the kernel is shown in Figure 5-2.

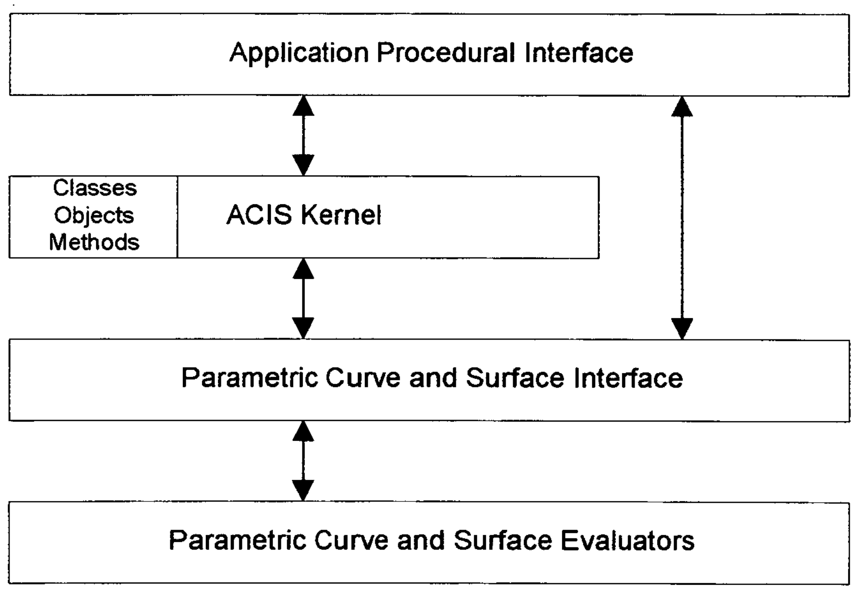


Figure 5-2 ACIS kernel architecture.

In ACIS, the hierarchical decomposition of an entity consists of a BODY which is the highest level of the topological entity, which in turn is composed of a LUMP. A LUMP is a topological entity that represents a connected 3D or 2D region. It is bounded by a SHELL. A SHELL consists of a set of connected FACES. The SHELL can represent a sheet region, or bound a solid region, or both. The FACE can be connected along either edges or vertexes. A FACE is a surface bounded by a LOOP. A LOOP is a list of COEDGES containing EDGES that are attached to a FACE. An EDGE is a curve bounded by two object types VERTEX.

Figure 5-3 shows the topology of a typical entity. Topology refers to the spatial relationships between the various levels of boundary representation.

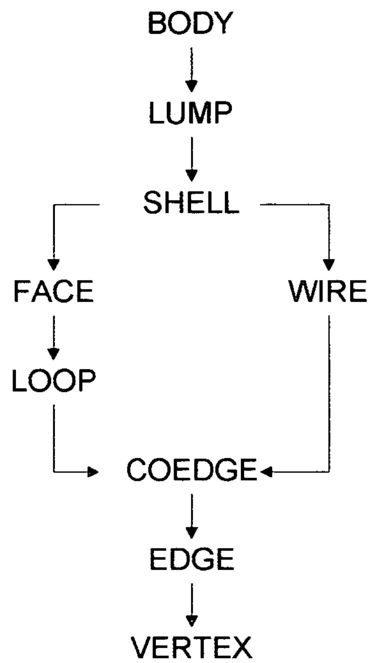


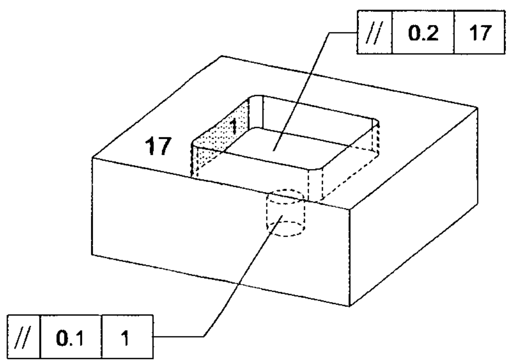
Figure 5-3 Topology of an ACIS entity.

An ENTITY is the most basic ACIS object. It is the top level object from which all other objects representing permanent objects in ACIS, such as geometric, topological, attributes, and transform objects, are derived. Attributes are then used to attach data to entities. It is a general purpose data entity that can be attached to other entities to record user or other information. Each entity may have any number of attributes.

ACIS is designed as a foundation technology for virtually any 3D application. FixPlan was therefore built on top of ACIS due to its ability to provide common modelling functionality as well as flexibility for adaptation and extension.

5.3 Component Description Language (CODL)

CODL was first developed by Salmon [Salmon94] in the Manufacturing Planning Group of The University of Edinburgh. It is concise and human readable with a C++ like structure. The sole purpose of CODL was to provide the interface between the Feature Oriented Design System (FODS) and Computer Aided Process Planner (HAPPI) developed by the group [Mill94]. The need to communicate between the various modules of FixPlan, as well as possible future integration with other process planning systems, has prompted the use of CODL as its interfacing agent. However due to incompatibility (CODL is in the syntax of the C language) only the concept of CODL was used.



;name	type	X	Y	Z	Roll	Pitch	Yaw	Handle	Level	L	W	D		
"B1"	"blank"	"-40.0	-40	0	0	0	0	0	0	80	80	30	"	
;name	type	X	Y	Z	Roll	Pitch	Yaw	Handle	Level	L	W	D	crad	
"P1"	"rect_pocket"	"-20.0	-20	0	0	0	0	0	0	40	40	10	3	"
;name	type	X	Y	Z	Roll	Pitch	Yaw	Handle	Level	rad	d	end_type		
"h1"	"hole"	"0.0	0	-30	0	0	0	0	0	5	-10	1	"	
;name	type	FO-x	FO-y	FO-z	Type	VAL	LX	LY	LZ	RXe-3	RYe-3	RZe-3	TFe-4	
"Th1-10-01"	"Tolerance"	"0	0	1	1	0.1	0	0	10	10	0	0	100	"
;name	type	FO-x	FO-y	FO-z	Type	VAL	LX	LY	LZ	RXe-3	RYe-3	RZe-3	TFe-4	
"TP1-09-17"	"Tolerance"	"0	0	-1	1	0.2	60	60	0	3.3	3.3	0	24	"

Figure 5-4 CODL used in FixPlan.

Figure 5-4 shows the version of CODL used in FixPlan. As can be seen from the example instead of having a C++ like structure this version of CODL is simply a text formatted file that contain all the necessary information to describe a prismatic component. Therefore throughout this thesis whenever CODL is mentioned, it refers to the version that was modified for FixPlan.

A CODL file can be thought of as a list of features where each feature is represented as a string of text. The CODL description of a component can be split into three types. These are the description of the blank, the description of the features to be removed from the blank and the description of the relationship between the different features and/or the blank. The following shows an example of a CODL description of a feature extracted (pocket) from Figure 5-4:

;name	type	X	Y	Z	Roll	Pitch	Yaw	Handle	Level	L	W	D	crad	
"P1"	"rect_pocket"	"-20.0	-20	0	0	0	0	0	0	40	40	10	3	"

name - the name of the feature

type - indicates the type of feature, which in this case is a rectangular pocket

x, y and z - indicates the position of the feature

Roll, Pitch & Yaw - defines the angles of rotation of the feature

Handle and level - allows features to be positioned with respect to a particular surface or edge

L, W and D - defines the dimensions of the feature (Length, Width, Depth).

crad - defines the corner radius of the pocket

It should be noted that for different features, the number of arguments within the string will be different. For example, the CODL description of a BLANK will not have corner radius (CRAD), whereas the CODL description of a HOLE will have radius (RAD), depth (D) and end type (end_type) instead of L, W, D.

5.3.1 Position and orientation of features

The X, Y and Z parameters in CODL define the position of the feature relative to the global co-ordinate system. The rotation of the feature is defined by the roll, pitch and yaw parameters. Roll, pitch and yaw are rotation about the x, y, and z axes respectively. To achieve the correct feature orientation in space, the order in which the rotations are performed is very critical.

5.3.2 Handles and levels

Some feature based design systems allow the user to specify a feature with an offset local co-ordinate. This convenience allows the features to be positioned in a way that is more convenient to the designer, allowing the designer to position it with respect to a particular surface or edge. CODL supports such function in the form of handles and levels. Handles and levels are pre-defined local co-ordinate offsets. Figure 5-5 shows the handles and levels of a slot. The handle is an integer that refers to one of the location in the X-Y plane, and the level is one of TOP, MIDDLE and BOTTOM, and refers to the position of the handle in the local Z plane relative to the feature.

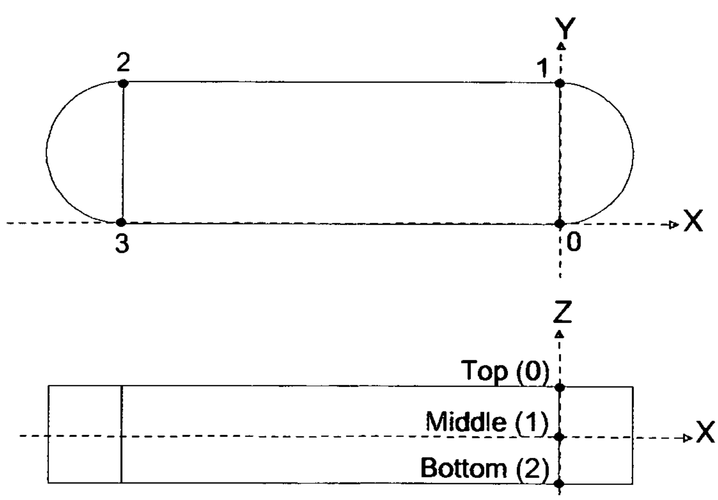


Figure 5-5 Handles and levels of a slot.

5.3.3 CODL description of virtual features

Virtual features are features that have no physical presence in the component, but are used to specify the relationships between each machining feature. Geometric tolerances in FixPlan are defined as a virtual feature, the following example shows a CODL representation extracted from Figure 5-4,

;name	type	FO-x	FO-y	FO-z	Type	VAL	LX	LY	LZ	RXe-3	RYe-3	RZe-3	TFe-4	
"Th1-10-01"	"Tolerance"	"0	0	1	1	0.1	0	0	10	10	0	0	100	"

name - the name of the feature or in this case tolerance

type - indicates the types of feature, which in this case is a virtual feature representing geometric tolerance

FO-x, FO-y, FO-z - indicates the pre-defined tool access direction of the feature

Type - indicates the type of tolerance, e.g. Parallelism, Positional, Concentricity, etc.

VAL - defines the tolerance value

LX, LY, LZ - indicates the value of the relevant lengths of the feature

RX, RY, RZ - indicates the admissible rotation values of the tolerance feature with the respect to its reference feature around respectively the X, Y, Z-axis

TF - indicates the Tolerance factor which is the combine admissible rotation around one or two axes depending on the Type of tolerance.

The 'name' in this instance indicates more then just the name of the tolerance. It holds information regarding the features that are involved in the tolerance. As can be seen from the above CODL representation, the name of the tolerance is shown in Figure 5-6.

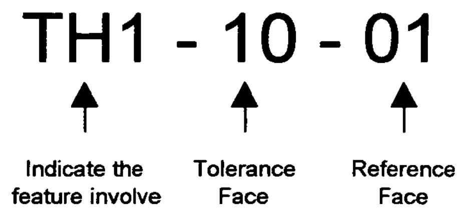


Figure 5-6 Name of the tolerance.

The first part of the name *Th1* indicates that the tolerance belongs to the feature H1, which in this example is a hole. *10-01* indicates that Face 10 is the tolerance face that takes reference from Face 1. Using the face-feature relationships algorithm, it is recognised that Face 10 is owned by the hole feature H1 and Face 1 belong to the pocket P1. As attributes on the faces are transferred to the features, it implies that hole H1 takes reference from pocket P1, which means that P1 must be machined before H1. Virtual features are therefore used extensively for the configuring and sequencing of fixture set-ups.

The three main types of geometric tolerances covered in FixPlan are Parallelism, Perpendicularity and Positional tolerances. Concentricity and Angularity are not implemented but could be added to the system by extending the program.

As CODL is a simple human readable text formatted file, it can easily be edited by any text editor. The ease of interpreting CODL implies that FixPlan can be integrated with any system that can read and output data in CODL.

5.4 FixPlan User Interface

The FixPlan user interface is created using Visual Basic. This helps the user by eliminating the need to key in commands in the command window of ACIS 3DT. It is also simple to use as the user does not have to remember all the commands needed to execute the various tasks within the system. The interface is just like any other Windows application with a tool bar on the top where the user can execute a command by simply clicking the desired task on the tool bar. Figure 5-7 shows the user interface of the system.

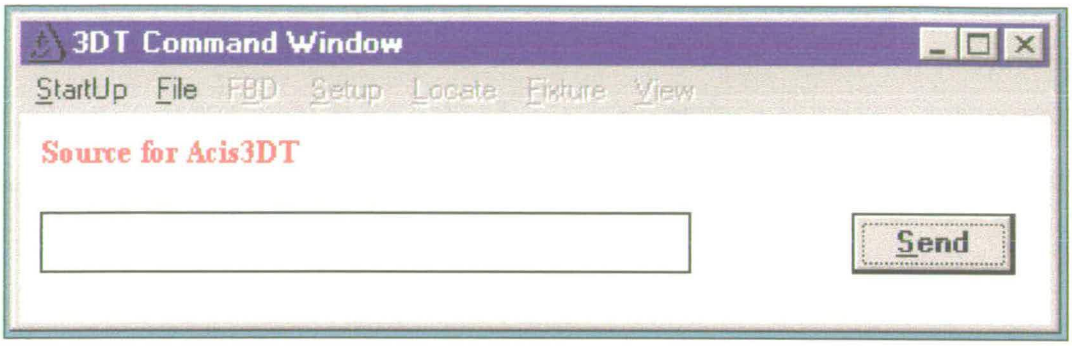


Figure 5-7 User Interface (Source Window) of FixPlan.

Dynamic Data Exchange (DDE) based programs are used by Visual Basic to provide the capabilities of exchanging data between programs. In DDE programs, data flows from one DDE program to another DDE program. The program that supplies the data is called the source application, and the program that receives the data is called the destination application.

In FixPlan, the destination application is therefore the command window of the ACIS 3D Toolkit. The user interface created is known as the source window. Figure 5-8 shows an example of the usage of the source window. To create a blank instead of typing in a string of commands that the user might not know or remember, all the user has to do is select the task "Blank" on the tool bar. Once selected a window will pop out to allow user to specify the various parameters of the blank. Upon completion all the user has to do is hit the return key or click the "OK" button to create the blank.

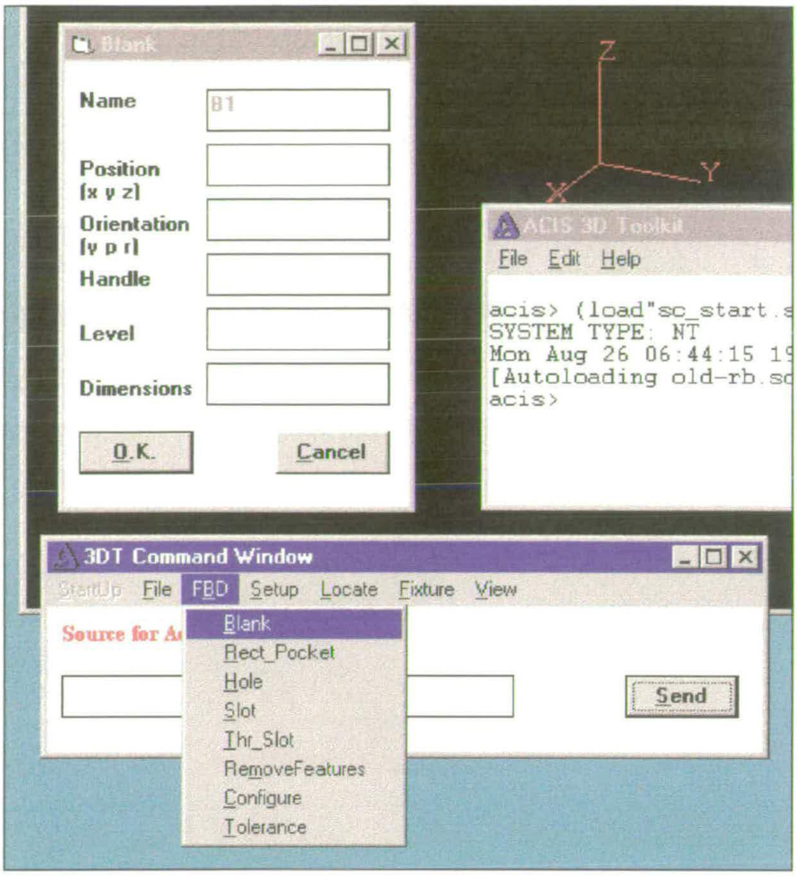


Figure 5-8 Example of the usage of the source windows.

5.5 Feature Based Design Module

The main function of the feature based design module is to provide the designer with a tool that can design components with ease. As mentioned in the last chapter, this module should not be consider as part of FixPlan, but due to the fact that FixPlan needs some kind of feature based design system as an input, it was therefore necessary to develop this module and incorporate it into FixPlan. The components designed are defined in term of features, such as blank, slot and holes. These "machining features" are then subtracted from the blank to form the component, thus they are known as negative features. Each feature is defined by one or more Scheme procedures/functions. A Scheme procedure, a collection of one or more Scheme commands grouped with parentheses, is created in a file using the Scheme text editor. Once loaded into ACIS 3DT this can then be run as many times as needed with the appropriate parameters. Figure 5-9 shows the architecture of the feature based design module which consists of numerous sets of procedures/programs, which are written in Scheme, that define the various functions within the module.

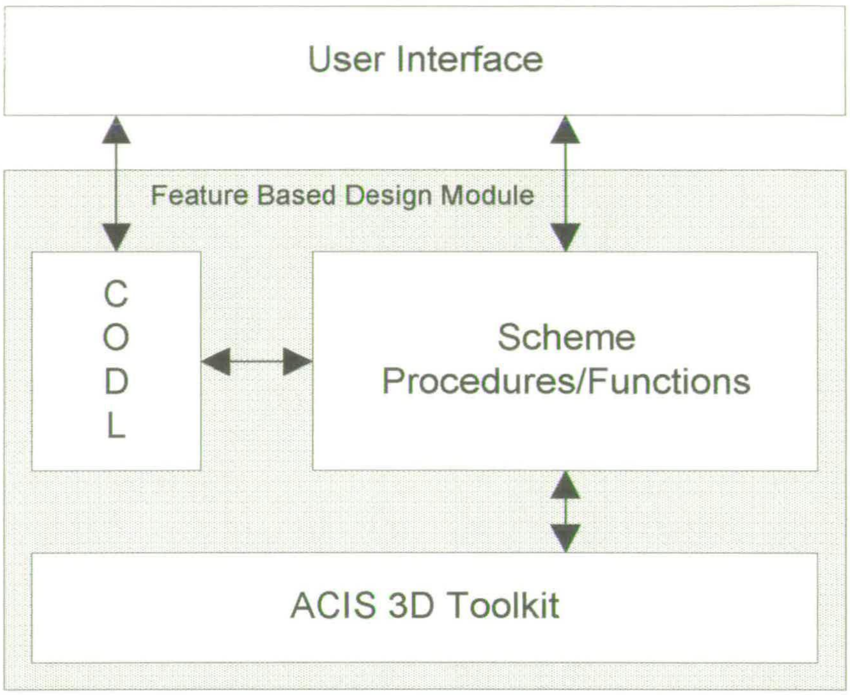


Figure 5-9 Architecture of the feature based design module.

The module only addresses four types of negative features. These are holes, rectangular pockets, slots and through-slots. Though simple, these features can be combined to form relatively complex machining features, thus allowing the design of complex components. The features can be created by running their respective procedure with the appropriate parameters. All the parameters will be automatically converted by the module into a CODL file, which is then utilised in the various modules of FixPlan to assist the planning process. The module is also capable of reading in a CODL file to reconstruct a model that was designed earlier. An example of a Scheme procedure for the feature "Hole" is illustrated in Figure 5-10.

As can be seen from the example, eight parameters have to be provided for this feature to be created.

```
(define hole
  (lambda (str pos orientation handle level radius depth end_type)
    (begin
        :
)))
```

Figure 5-10 Example of scheme procedure.

The eight parameters needed by the "hole" procedure are:

str	- the name of the Hole
pos	- the position of the hole in the global co-ordinate
orientation	- the roll, pitch and yaw of the hole
handle	- the position of the handle
level	- the position of the level
radius	- the radius of the hole
depth	- the depth of the hole
end_type	- the end type of the hole

Geometric tolerances which are crucial to the set-up planning process are added to the solid model in this stage/module of the system. Geometric tolerances are added to the model by running the appropriate procedure in FixPlan. Once executed, the procedure prompts the designer to pick the tolerance face and reference face respectively from the model using the cursor. With both faces selected, the procedure asks the designer for the tolerance value and the tolerance type. When all the necessary information is collected, the module will automatically configure the CODL representation of the geometric tolerances which are added to the CODL file that describes the component. This is achieved by using various procedures in the geometric reasoning module as well as the procedure for calculating the various rotation misalignments. For example, the face-feature algorithm in the geometric reasoning module is used to identify the face number of the selected faces as well as the owner of the toleranced face, this information is then put together to form the tolerance feature's name.

It is important to note that tolerance features can only be added to a completed model. Adding tolerance features during the design stage is not recommended as the model is undergoing constant change. In other words, a tolerance or reference face that is present now might not be present in the later stage of the design due to the addition of another feature. Kripac [Kripac94] devised a topological identification (ID) system that could be used as a possible solution to the problem. The topological ID system is a mechanism for naming topological entities in history based solid models. When the parameter of a model is changed, the model is re-evaluated automatically so that the topological ID of old versions can be mapped onto the corresponding topological entities in the new version of the model.

5.6 Geometric Reasoning Module

Geometric reasoning is the most important module in the whole system, as the other two modules, namely feature based design and fixture planning, are unable to function without it. The main task of this module is to provide whatever information, for example attributes of features, as well as geometrical data of the features that is required by the other two modules. It is used to analyse and interrogate the feature model of the components through a list of Scheme procedures. Each procedure can be called by both the feature based design and fixture planning modules. An illustration of the architecture of the geometric reasoning module can be seen in Figure 5-11.

When a call is made by another module, for example the feature based design module, the appropriate Scheme procedure will be selected and executed accordingly. The procedure will then acquire the necessary information from the feature based model and CODL through ACIS 3DT.

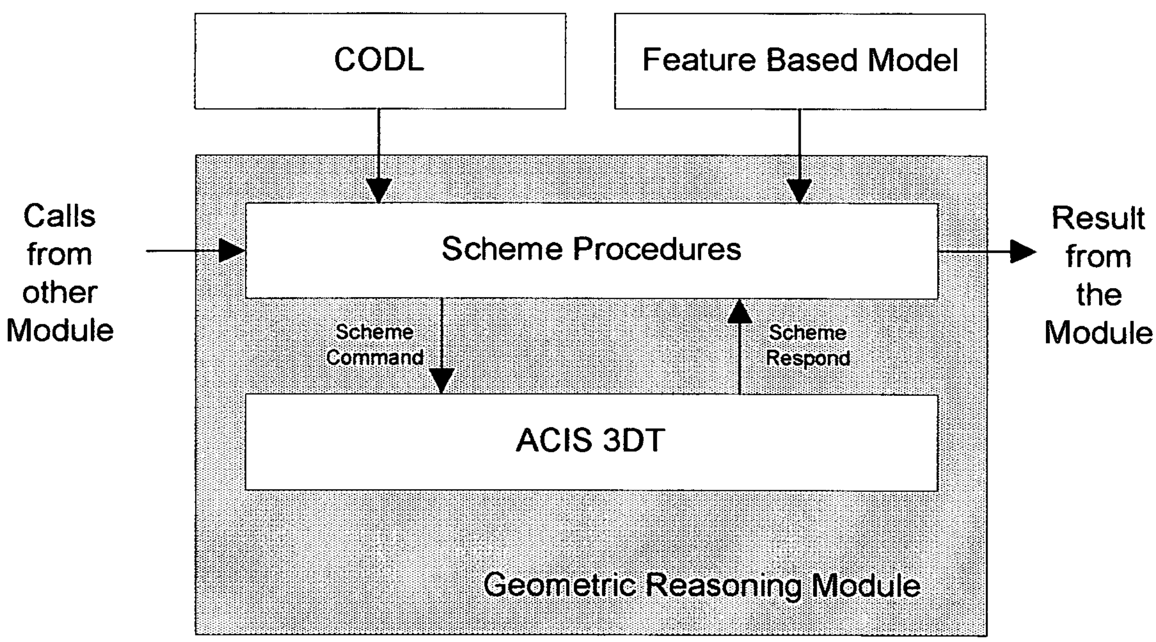


Figure 5-11 Architecture of geometric reasoning module.

There are many procedures in the module, here are the procedures that are crucial to the system,

- Face Feature Relation
- Compound Face Detection
- Split Face Detection
- Alternate Tool Access Direction
- Checks for Tools Interference
- Configuring the Field of Features
- Generation of Locating and Supporting Points
- Generation of Clamping Points

The methodology for all the above were discussed in Chapter IV. In this section the main consideration is on the implementation of the procedures.

5.6.1 Face-feature relation procedure

The BODY of the feature model is decomposed to a list of FACE entities using ACIS 3DT. For each FACE entity, an intersection process is carried out between it and all the features that are within the model. When an intersection occurs it indicates that the FACE belongs to that feature. Attributes are then added to represent this relation. The number of features present in the model can be easily determined by interpreting the CODL file that represents it. Therefore the procedure simply reads in the CODL file to obtain the number of features present. An example of the attributes are,

```
((face number 1)(F_OWNER 1))
((face number 2)(F_OWNER blank))
        .
        .
        .
((face number n)(F_OWNER m)
```

where F_OWNER indicates the feature that it belongs to. In this case Face 1 belongs to Feature 1 and Face 2 belongs to the BLANK.

5.6.2 Compound face detection procedure

This procedure is very similar to the Face-Feature Relation Procedure. The only difference is in the attribute. As the FACE in this case will intersect with more than one feature, the attribute added to the FACE has to reflect this fact. An example of the attribute is shown below,

((face number 1)(COMPOUND (f1, f2, f3....)))

where COMPOUND indicates that it is a compound face and it belongs to Feature f1, f2, f3 ....etc. Figure 5-12 shows the result of compound face detection of FixPlan, the compound face is highlighted in red.

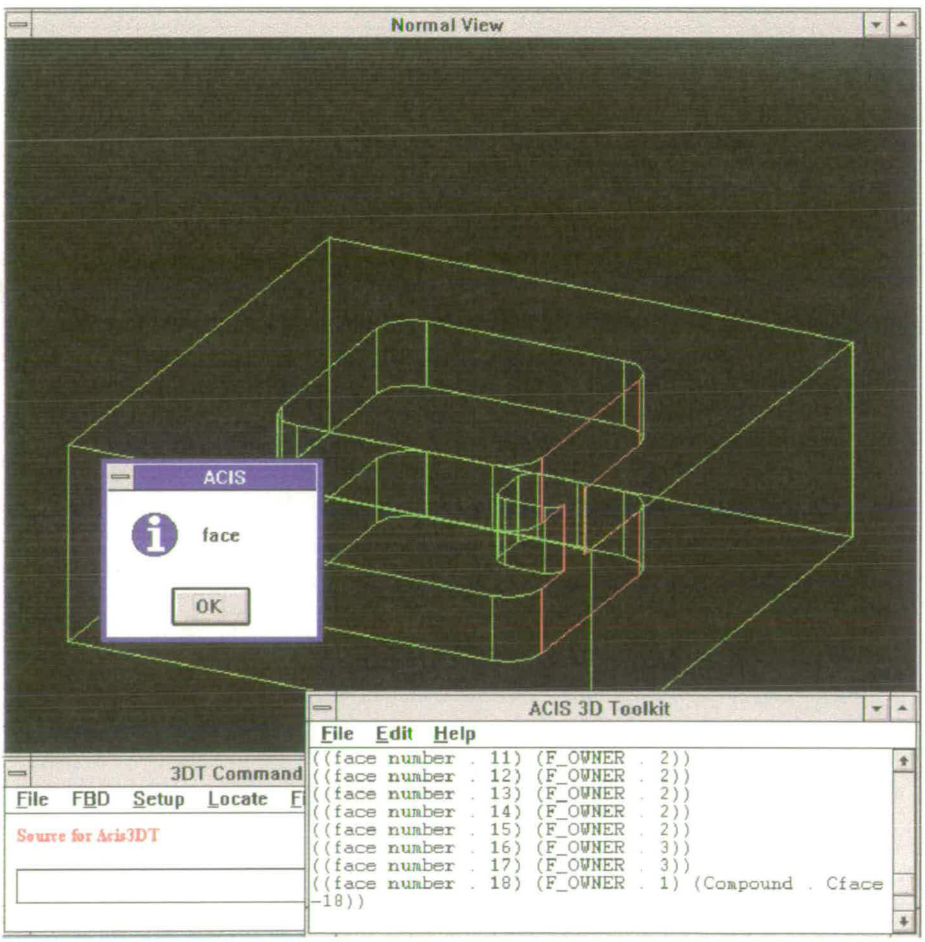


Figure 5-12 Detection of compound face.

5.6.3 Split face detection procedure

This procedure takes one parameter, FACE, and returns a list of related split faces. An equation representing the plane of the FACE is formed. This equation is then used to check all the faces in the model. Any face that satisfies the equation is classified as a possible split face. In order to confirm the relationship, the 'owner' feature of each face must be the same. Once confirmed, the procedure returns a list of faces, which includes FACE as well as all related split faces. Figure 5-14 shows the result of the split face detection algorithm.

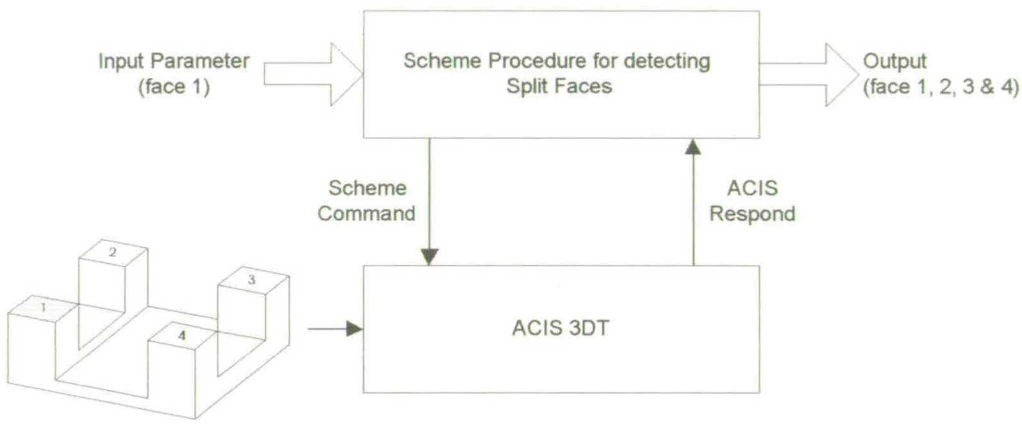


Figure 5-13 Procedure for detection of split faces.

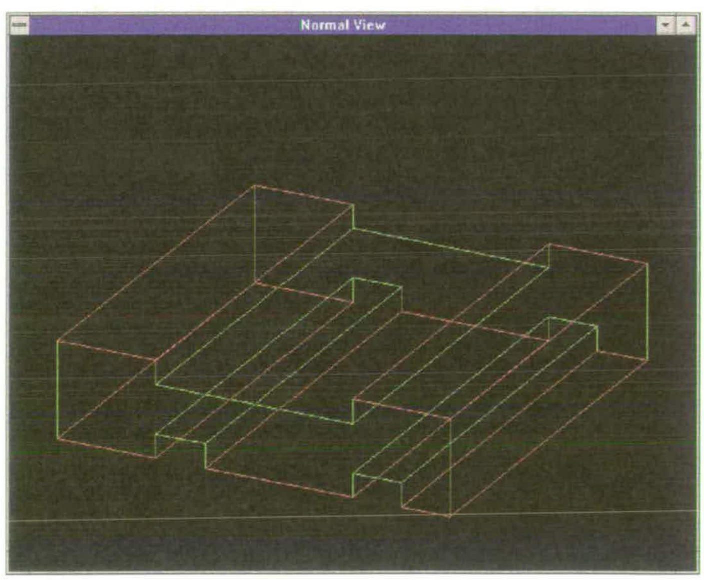


Figure 5-14 The result of split face detection.

5.6.4 Alternate Tool Access Direction procedure

Tool Access Directions are derived directly from the CODL file of the model. It is assumed that the tool access direction is the pre-defined sweep direction of the feature, so geometric reasoning is not needed to determine the tool access direction of a feature. However geometric reasoning is needed to determine the alternate tool access direction of features.

To determine the alternate tool access direction, the procedure converts the BODY of the feature involved into a list of FACE entities. For each FACE entity, an INTERSECT procedure is used to check for intersection between the FACE entity and the model. If an intersection occurs, it implies that the face is present in the model. However if no intersection is found, it implies that the face is not present in the model and machining can be carried out from the inverse normal of that face. The inverse of that face normal is termed the Alternate Tool Access Direction (ATAD).

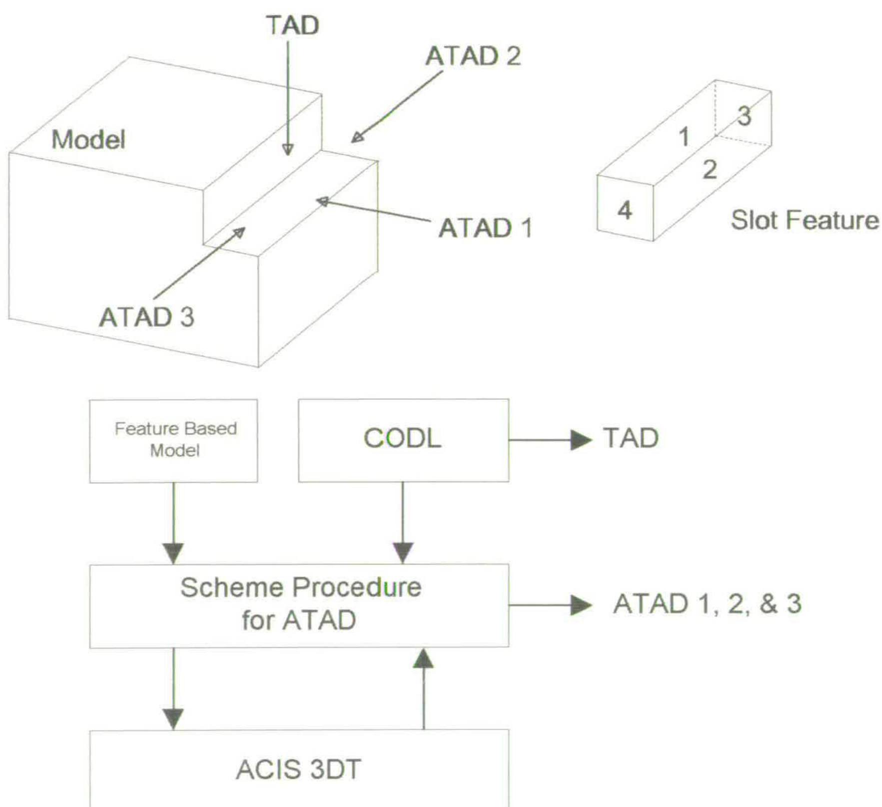


Figure 5-15 Alternate Tool Access Direction (ATAD) procedure.

In Figure 5-15, it can be seen that faces 1, 2, 3 and 4 of the slot feature do not intersect with the model, which implies that machining can be carried out from the inverse normal of these faces. It should be noted that since face 1 is used as the tool access direction, it is not checked by the procedure. Since faces 2, 3 and 4 have no intersection, their inverse face normals are converted into ATAD 1, 2 and 3 respectively.

5.6.5 Checks for tool interference

The main function of this procedure is to check for access problems of the features that might arise during machining. A "tool access body" is generated for each of the features present in the model. Intersection between the tool access body and the model is checked by the procedure. If an intersection is encountered, it implies that the tool path of that particular feature is obstructed. The procedure will prompt the designer to remove the feature that is causing the problem and replace it with one that does not. Figure 5-17 shows the tool access body generated by FixPlan.

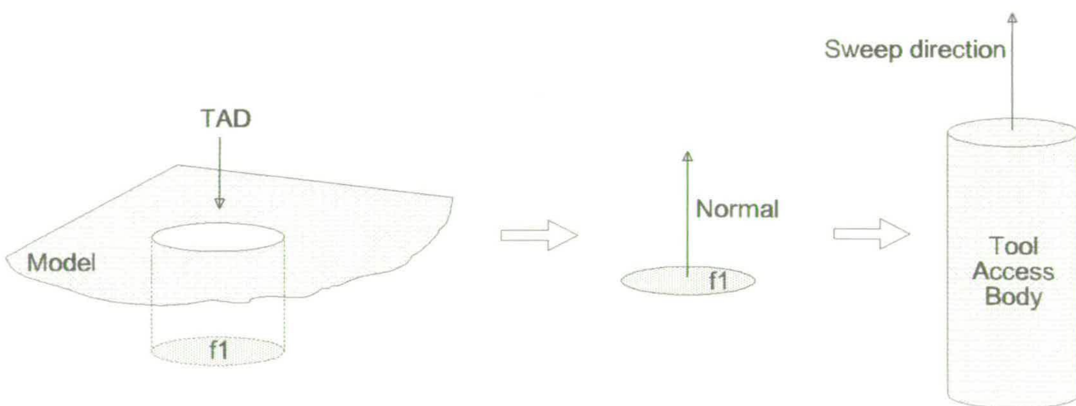


Figure 5-16 Generation of tool access body.

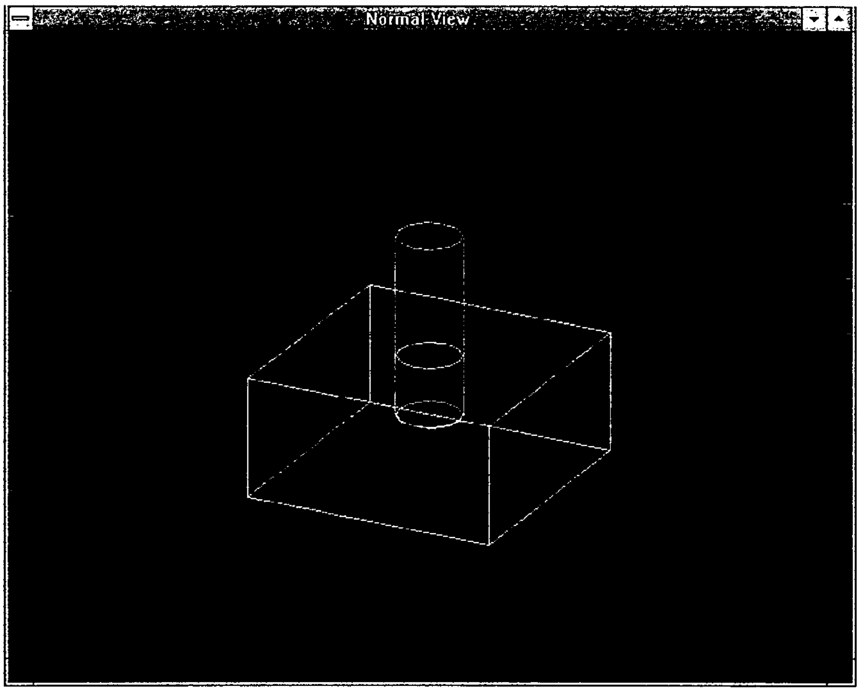


Figure 5-17 Tool access body generated by FixPlan.

To generate the tool access body, the access direction of the feature in the model must first be determined (see Figure 5-16). This is achieved by using the procedure described in section 5.6.4. Once the access direction has been identified, the next phase is to extract the appropriate faces from the feature. An appropriate face is one that has a face normal anti-parallel to the access direction. The tool access body is then generated by sweeping the selected face along its face normal for a given distance. Only a simple tool access body has been implemented in FixPlan which has difficulties identifying certain access problems that have been highlighted in Chapter IV, section 4.1.4. However, the procedure could be modified to generate the expanded tool access body outlined in section 4.1.4, which would eliminate the problem.

5.6.6 Field of features procedure

The field of features can be defined as an envelope that encloses all the features present in the model (see Figure 5-18). To generate the field, the procedure must first determine the number of features that are present within the model. With the list of features, the procedure will proceed to initiate the BOX function of ACIS 3DT.

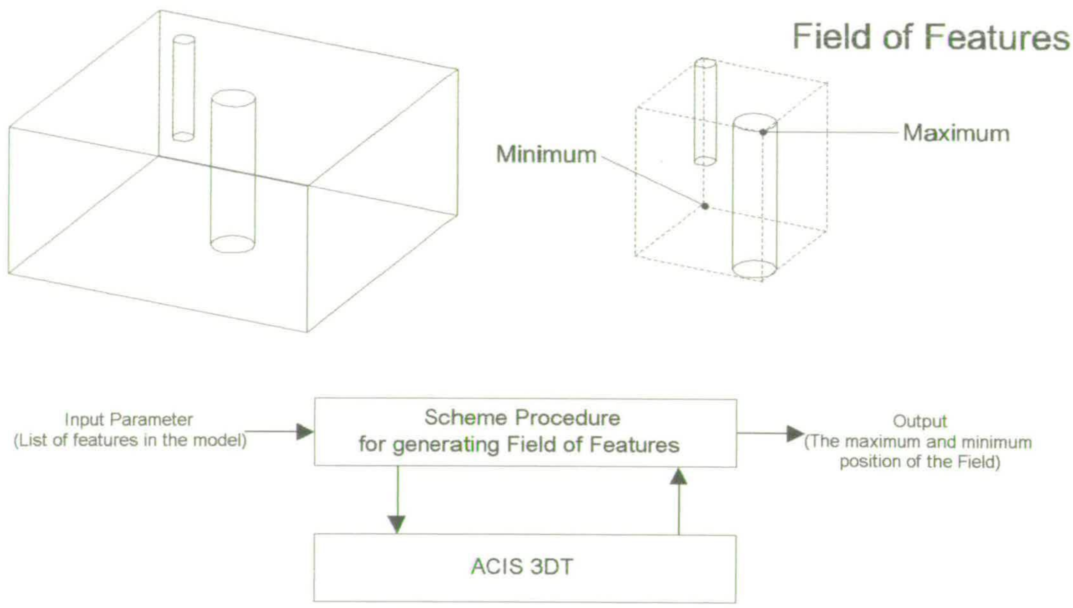


Figure 5-18 Field of feature procedure.

The BOX function of ACIS will calculate the maximum and minimum position of each feature. The resultant of these positions will be return as the maximum and minimum position of the box that encloses all the features. This box is thus known in FixPlan as the Field of Features and is the smallest axis aligned box that contains all the features.

5.6.7 Locating and supporting points procedure

The generation of locating and supporting points can only be performed after the selection of the three datum faces. For each datum face, a set of locating points will be generated. The number of points in each set depends on the type of datum it is on. As the 4:2:1 locating principle is applied in FixPlan, four points are needed on the primary datum face, two points for the secondary datum face and one point on the tertiary datum face. Support points are selected only when locators fail to provide stability of the component.

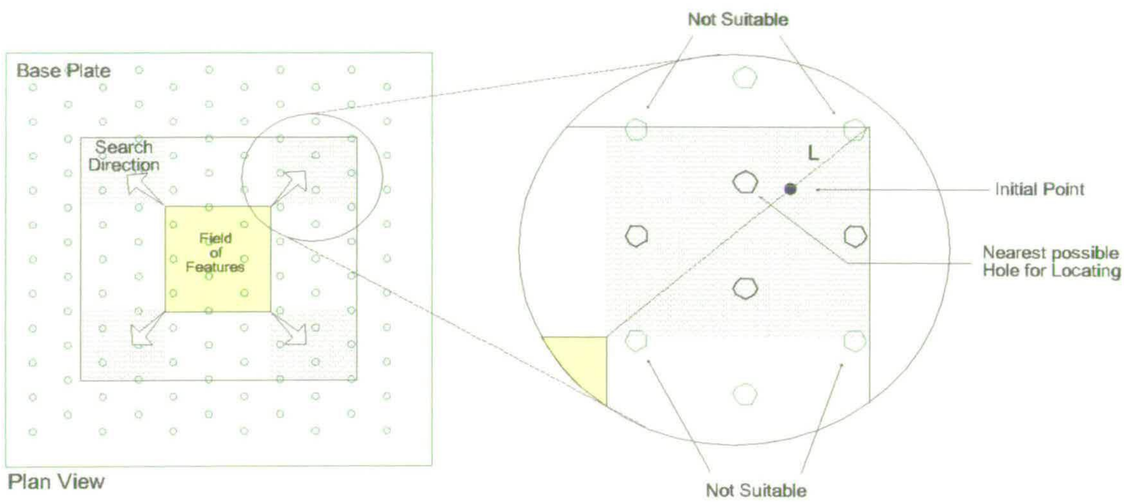


Figure 5-19 Generation of locating points on the primary datum face.

An example of generating locating points is illustrated in Figure 5-19. In order to maintain the static equilibrium of the component, all the locating points have to be well within the shaded regions. The search begins by selecting an initial point along the dotted line. The point should be as far away as possible from the field of features. However, it must be some distance, L, away from the edge of the component. This is to ensure that the locators are well within the datum faces. Once the initial point has been obtained, the hole on the base plate that is nearest to it will be selected as the new locating point. Therefore the locating point will be shifted to that position.

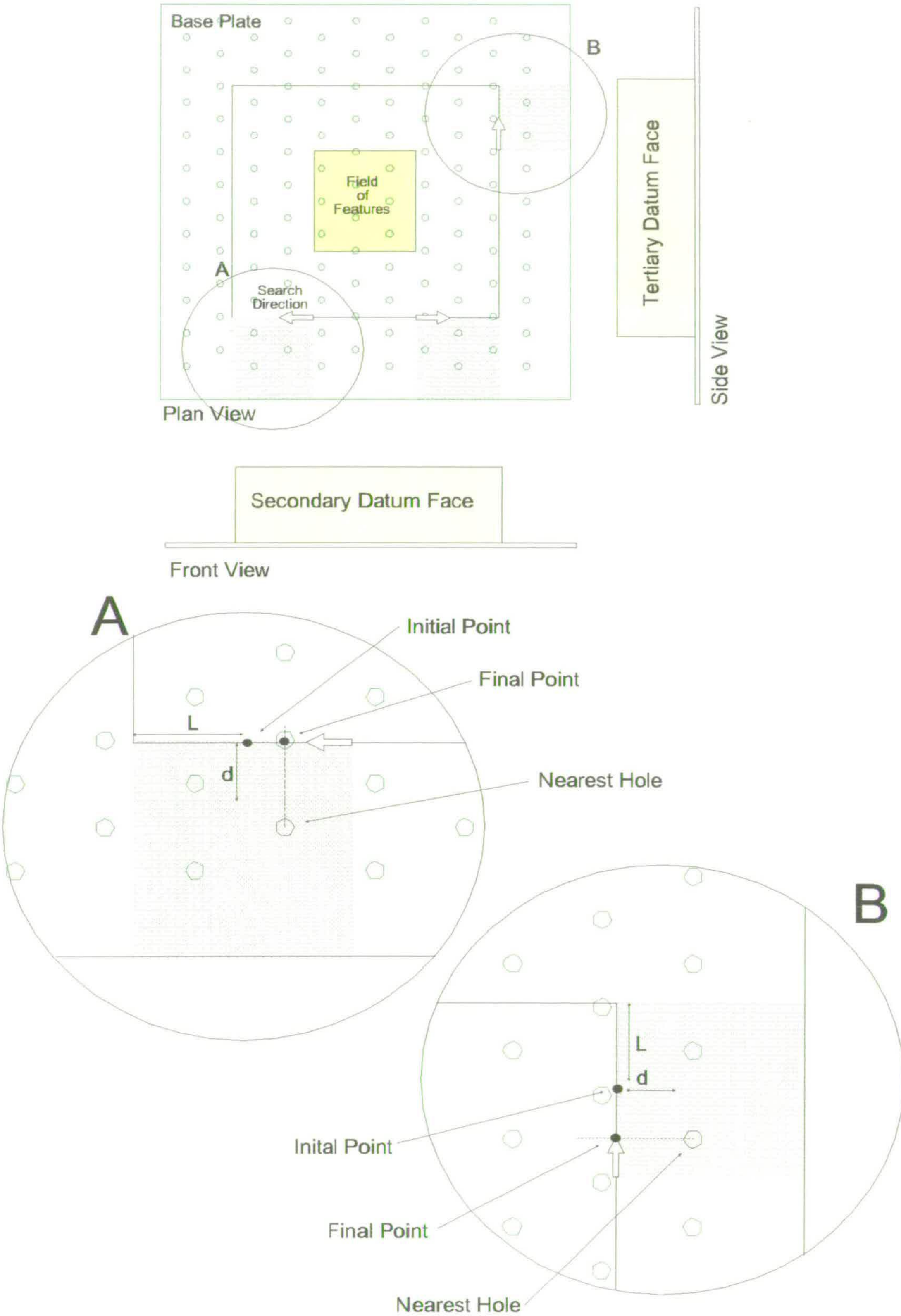


Figure 5-20 Generation of secondary and tertiary locating points.

Figure 5-20 shows an example of generating secondary and tertiary locating points. In Figure 5-20A, the generation of the secondary locating point is shown. Similar to the previous example, an initial locating point is selected. Once determined, the hole that is nearest to it will be selected. The hole must however be a distance, d, away from the datum face to allow the positioning of the locator. The distances L and d are determined by the size of the locator, for example the diameter or length of the locator. The position of the hole is then projected onto the datum face to form the new locating point.

In Figure 5-20B, the generation of the tertiary locating point is shown. The procedure used to determine the locating point is the same as those used for the secondary locating points.

The supporting points are generated by a similar procedure. Instead of selecting an initial point as in the previous two examples, a point must be supplied to the procedure in order to determine the final supporting point based on the hole position on the based plate.

5.6.8 Clamping points procedure

Ideally for every locating point there should be one clamping point, however this might result in over restraining the component. Therefore whenever possible, the number of clamps should always be reduced to a minimum. The procedure starts by assigning an initial clamping point to each of the corresponding locators. Each point is located so that it is directly opposite the locator. Figure 5-21 illustrates the generation of horizontal clamping points, C1, C2 and C3, the initial clamping points. All selected holes have to be some distance, L, away from the clamping face due to the length of the clamps. The distance, L, between the hole and the face must be at least equal to the length of the shortest clamp.

The hole that is closest to C1 is H5. However when the position of the hole is projected onto the clamping face, it is too close to the edge which implies that it is not suitable to place a clamp there. With H5 rejected the next hole to consider is H1.

When the position of H1 is projected onto the clamping face, the point is well within the face which implies that both the hole, H1, and the point could be use for clamping.

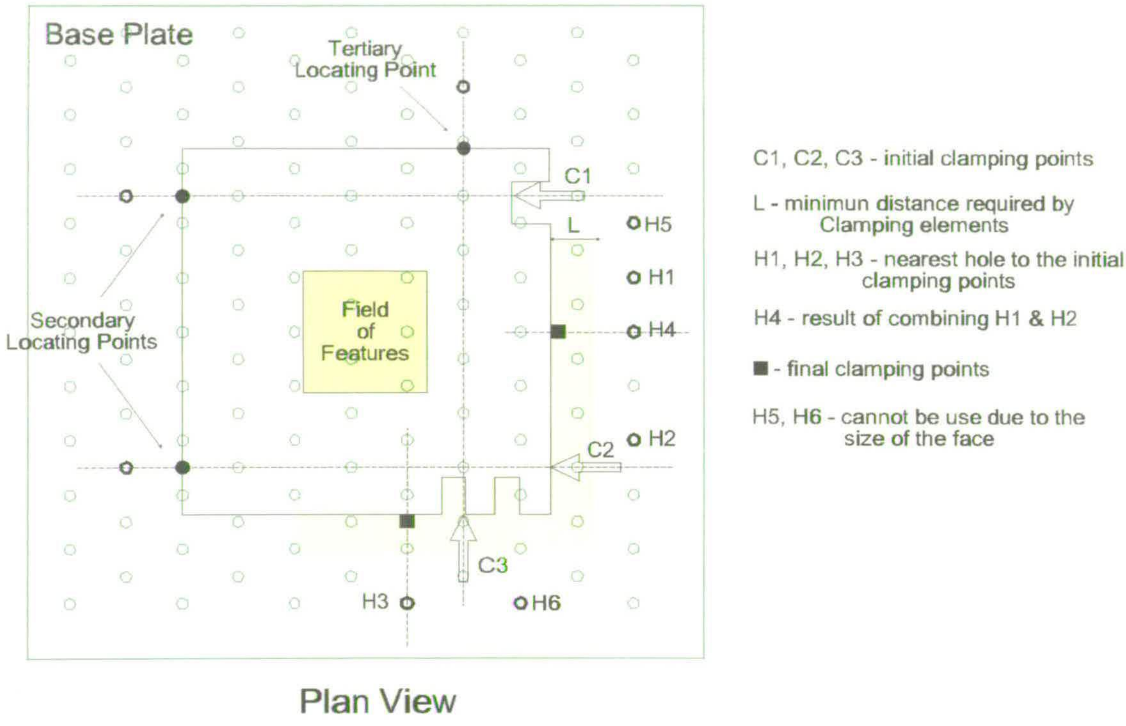


Figure 5-21 Generation of horizontal clamping points.

The hole that is closest to C2 is H2. Since the point projected by the position of the hole is well within the clamping face, both the hole H2 and its point are also selected. The final clamping point is that of C3. There are two holes, H3 and H6, that are an equal distance away from it. Since the projected point of H6 is on the edge of the clamping face it is rejected. As the projected point of H3 is within the clamping face, both H3 and its point are selected.

In this example, the three clamping points are therefore the projected points of H1, H2 and H3. However, it is possible to combine the points of H1 and H2 into one single point so as to minimise the number of clamps used. Therefore hole H4 is selected as it in between H1 and H2 as well as being approximately midway between C1 and C2. As a result of the combination, only two clamping points are used to clamp the component.

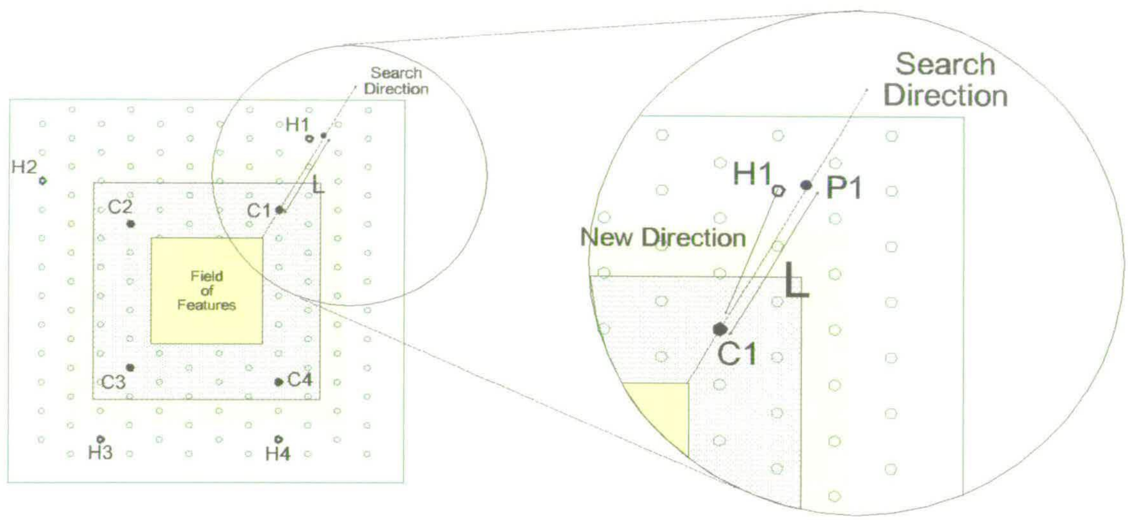


Figure 5-22 Generation of vertical clamping points.

Figure 5-22 shows the generation of vertical clamping points. The procedure is very different from the horizontal clamping. The four clamping points, C1, C2, C3 and C4, are directly above the four locating points. The search for the corresponding holes on the base plate begin by moving a point, P1, a distance, L, away from C1 along the search direction (where L is the minimum distance required to allow a clamp to be properly positioned and the search direction is then in the direction of the corner of the field of features towards the clamping point). The point, P1, is then used to locate the nearest hole on the base plate. In this example the nearest hole is H1 which will be used for locating a clamp. The direction of the clamp towards the clamping point, C1, is therefore the new direction between the hole H1 and C1. The same procedure is used to locate the hole on the base plate as well as the new direction for the other three clamping points.

Referring to Figure 5-26, Set-up 1 consists of TH1-15-19 and TH1-15-12. Since the feature H1 takes its reference from Faces 19 and 12 in this set-up, both faces are used as the secondary and tertiary datum face. Since both features have the same tolerance factor, it does not make a difference as to which face is chosen as the secondary face. However, it must be noted that the reference face of the feature that has the lowest tolerance factor will be selected as the secondary datum face. Figure 5-27 shows the result of the selection procedure for Set-up 1, the selected datum faces are highlighted in yellow.

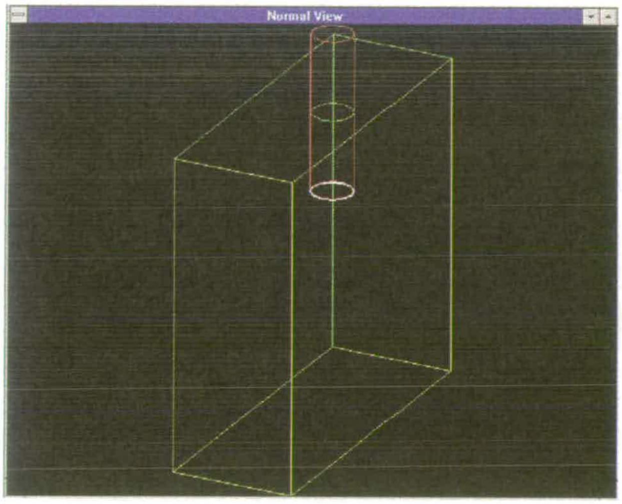


Figure 5-27 Selected datum faces for Set-up 1.

Referring to the same example, Set-up 2 consists of TS1-11-15 and TP1-09-10. The first feature S1 takes its reference from Face 15 which belongs to hole H1. However as locating using internal locators is not considered in FixPlan, Face 15 is rejected as a datum face. The second feature P1 takes its reference from Face 10 which belongs to S1 of the same set-up, therefore Face 10 is also rejected as a datum face. In a situation like this, the datum faces will be selected from faces that have normal perpendicular to the tool access direction. The secondary face will be the face with the largest surface area, and the tertiary datum face will be the next largest face that subsequently sequencing them. The datum face planning sub-module is used to determine the datum faces for each set-up. The data generated by this module is then transferred to the geometric reasoning module where locating, supporting and clamping points are generated. These points together with the datum faces are used by the fixture element sub-module to retrieve the appropriate fixture element from the fixture data base for each of the corresponding points.

5.7.1 Set-up configuration procedures

Set-up configuration is carried out by extracting relevant information from the CODL file through a series of heuristic rules written in Scheme. Information such as tolerance factors, relationships between features and the tool access direction of each feature is used for the configuration of set-ups. Figure 5-24 shows a component that is described by the CODL file shown in Figure 5-25. It should be noted that only the tolerance features are considered as they contain all the information needed for the configuration of set-ups.

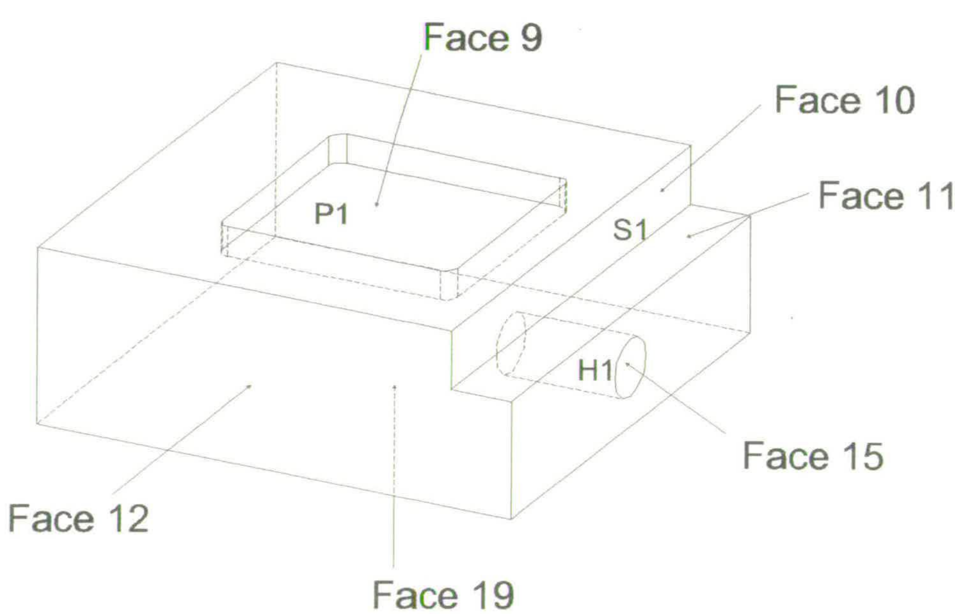


Figure 5-24 Sample component for set-up configuration.

;name	type	X	Y	Z	Roll	Pitch	Yaw	Handle	Level	L	W	D		
"B1"	"blank"	"-40.0	-40	0	0	0	0	0	0	80	80	30		"
;name	type	X	Y	Z	Roll	Pitch	Yaw	Handle	Level	L	W	D	crad	
"P1"	"rect_pocket"	"-20.0	-20	0	0	0	0	0	0	40	40	5	2	"
;name	type	X	Y	Z	Roll	Pitch	Yaw	Handle	Level	L	W	D		
"S1"	"thr_slot"	"-40.0	30	0	0	0	0	0	0	80	10	10		"
;name	type	X	Y	Z	Roll	Pitch	Yaw	Handle	Level	rad	d	end_type		
"H1"	"hole"	"0.0	40	-20	-90	0	0	0	0	5	20	1		"
;name	type	FO-x	FO-y	FO-z	Type	VAL	LX	LY	LZ	RXe-3	RYe-3	RZe-3	TFe-4	
"TS1-11-15"	"Tolerance"	"0.0	0	-1	1	0.1	80.1	10	0	10	1.2	0	12	"
;name	type	FO-x	FO-y	FO-z	Type	VAL	LX	LY	LZ	RXe-3	RYe-3	RZe-3	TFe-4	
"TH1-15-12"	"Tolerance"	"0.0	-1	0	3	0.01	0	20	0	0	0	0.5	5	"
;name	type	FO-x	FO-y	FO-z	Type	VAL	LX	LY	LZ	RXe-3	RYe-3	RZe-3	TFe-4	
"TH1-15-19"	"Tolerance"	"0.0	-1	0	3	0.01	0	20	0	0.5	0	0	5	"
;name	type	FO-x	FO-y	FO-z	Type	VAL	LX	LY	LZ	RXe-3	RYe-3	RZe-3	TFe-4	
"TP1-09-10"	"Tolerance"	"0.0	0	-1	2	0.5	40	40	0	12.5	0	0	88	"

Figure 5-25 CODL file for set-up configuration.

The tolerance features with the smallest tolerance factor are TH1-15-12 and TH1-15-19 as they are the position tolerances for hole H1. Therefore hole H1 is used to form Set-up 1. The next feature to be added should be one that is related to H1. However since none of the other features in the file have any relation to H1, the procedure proceeds to identify features that have the same tool access direction. As can be seen from the figure, none of the features in the file have a tool access direction similar to H1, which implies that the configuration of Set-up 1 is completed.

The procedure now proceeds to configure Set-up 2. The next smallest tolerance factor is provided by TS1-11-15, As the virtual feature belongs to S1, it is added to Set-up 2. Since none of the features remaining have any relationship with S1, the procedure proceeds to identify features with the same tool access direction. As virtual feature TP1-09-10 has the same tool access direction, P1 is then added to Set-up 2. This concludes the first part of the set-ups configuration module, Figure 5-26 shows the result.

```
SETUP-1
;name        type         FO-x FO-y FO-z Type VAL  LX   LY LZ RXe-3 RYe-3 RZe-3 TFe-4
"TH1-15-19" "Tolerance" "0.0  -1    0    3    0.01 0    20 0  0.5   0     0     5    "

;name        type         FO-x FO-y FO-z Type VAL  LX   LY LZ RXe-3 RYe-3 RZe-3 TFe-4
"TH1-15-12" "Tolerance" "0.0  -1    0    3    0.01 0    20 0  0     0     0.5   5    "


SETUP-2
;name        type         FO-x FO-y FO-z Type VAL  LX   LY LZ RXe-3 RYe-3 RZe-3 TFe-4
"TS1-11-15" "Tolerance" "0.0  0     -1   1    0.1  80.1 10 0  10    1.2   0     12   "

;name        type         FO-x FO-y FO-z Type VAL  LX   LY LZ RXe-3 RYe-3 RZe-3 TFe-4
"TP1-09-10" "Tolerance" "0.0  0     -1   2    0.5  40   40 0  12.5  0     0     88   "
```

Figure 5-26 Result of set-up configuration.

The second part of the module is used to determine if the various set-ups can be grouped together thus reducing the number of set-ups required. Since both set-ups in Figure 5-26 do not have the same tool access direction, they cannot be group together. However, if set-up 1, that is hole H1, had an alternate tool access direction equivalent to the tool access direction of set-up 2, then the two set-ups could be combined thus reducing the number of set-ups to one. However if a multi-axis machine was made available to the system, then it would be possible to combine the two set-ups into one thus reducing the number of set-ups required. Since FixPlan only considers a three-axis machine during set-up planning, it is not possible to combine the two set-ups together in this example. The output from the set-up planning module is therefore the two set-ups shown in Figure 5-26.

5.7.2 Set-up sequencing procedure

The sequence of the set-ups depends on the relationships between the various set-ups. Sequencing begins by selecting the set-up that has the feature with the smallest tolerance factor. Depending on the relationship between the selected set-up and the remaining set-ups, their respective priorities are determined. Once this has been established, the next set-up with the smallest tolerance factor will be considered. This process continues until all the set-up relationships have been established.

Looking at Figure 5-26, the set-up with the smallest tolerance factor is Set-up 1. Therefore Set-up 1 is considered first. The virtual features in Set-up 1 are TH1-15-19 and TH1-15-12, which implies that H1 takes its reference from Face 19 and 12. Through geometric reasoning, it is established that Face 19 and 12 do not belong to any features, thus implying that the two virtual features have no relation with any other features except the blank from which the component is made.

The next set-up to be considered is Set-up 2. There are two virtual features in Set-up 2, these are TS1-11-15 and TP1-09-10. TS1-11-15 implies that feature S1, which is the step on the component, takes its reference from Face 15. Geometric reasoning identifies that Face 15 belongs to the hole H1, which means that S1 takes its reference from H1. The next virtual feature is TP1-09-10, which implies that the pocket P1 takes its reference from Face 10 which belongs to the step S1. This means that P1 takes its reference from S1.

Since S1 of Set-up 2 takes its reference from H1 of Set-up 1 and P1 of Set-up 2 takes its reference from S1 of the same set-up, this implies that H1 must be machined before S1and S1 before P1. Therefore Set-up 1 must be processed before Set-up 2.

5.7.3 Datum face selection procedure.

The selection of the primary datum face is very straight forward, it is the face that has a normal in the same direction as the tool access direction of that particular set-up. The selection of the secondary and tertiary datum faces depends on the reference of the various features within the set-up. The selection of these datum faces is therefore carried out by extracting the reference face of the various features within the set-ups. This is achieved by interpreting the names of the various virtual features.

will form a wedge effect with the secondary datum face. These datum faces are then used by the geometric reasoning module for the generation of locating and clamping points. Figure 5-28 shows the selected datum faces for Set-up 2.

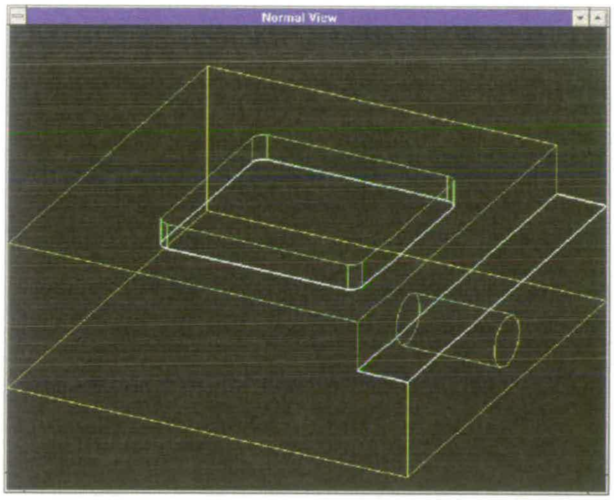


Figure 5-28 Selected datum faces for set-up2.

5.7.4 Fixture element retrieving procedure.

With the datum faces selected as well as the locating and clamping points generated, the final phase of the fixture planning module is the selection of fixture elements for each of the corresponding locating and clamping points.

The selection of the primary locators is straight forward. The height of the locator is calculated by measuring the vertical distance between the locating point and the hole on the base plate. Once this distance has been obtained, an appropriate locator will be selected from the fixture element data base. The locator selected must satisfy the height required as well as the diameter of the hole on the base plate.

Figure 5-29 shows the selection of the locating and clamping points. The procedure for the selection of the secondary locating points, tertiary locating points and horizontal clamping points are the same. As can be seen from the Figure 5-29, the length of the elements should be equal to the horizontal distance (l_1) between the point and the hole. The length, l_1, is calculated by projecting the point along the normal of the face until it is above the position of the hole. The height of the elements is the vertical (h_1) distance between the point and the hole. The height, h_1, s calculated by projecting the position of the hole along the normal of the face of the base plate until it reaches the same level as the point. With l_1 and h_1 calculated, an appropriate fixture element is then selected from the data base.

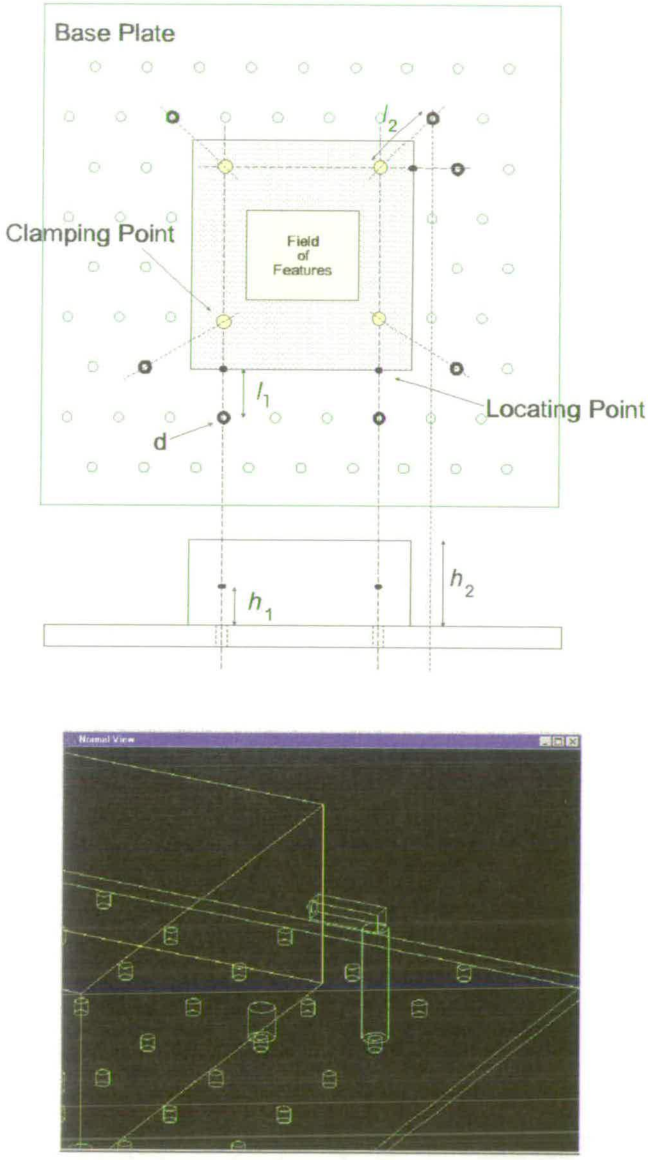


Figure 5-29 Selection of locating and clamping elements.

length of the elements should be equal to the horizontal distance (l_1) between the point and the hole. The length, l_1, is calculated by projecting the point along the normal of the face until it is above the position of the hole. The height of the elements is the vertical (h_1) distance between the point and the hole. The height, h_1, s calculated by projecting the position of the hole along the normal of the face of the base plate until it reaches the same level as the point. With l_1 and h_1 calculated, an appropriate fixture element is then selected from the data base.

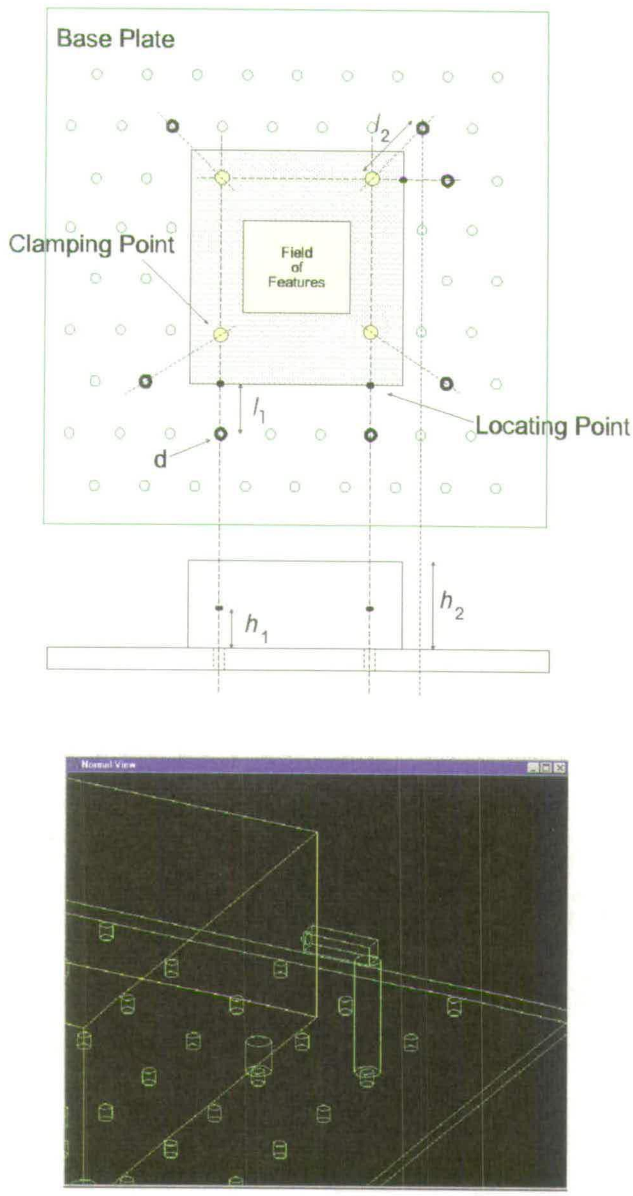


Figure 5-29 Selection of locating and clamping elements.

The selection of the vertical clamping elements is quite similar to the previously mentioned methods, except for the direction of the projection used for the calculation of the horizontal distance. Instead of using the face normal, the projection direction for calculating the horizontal distant (l_2) is the direction of the point towards the hole. Similarly once the length and height of the elements have been determined, the appropriate elements will be selected from the data base.

For every element selected, an interference test is carried out by the geometric reasoning module, to check for obstruction. If obstruction is detected, the element will be rejected and a new point will be selected.

Figure 5-30 and Figure 5-31 respectively show the fixture plan generated by FixPlan for set-ups 1 and 2.

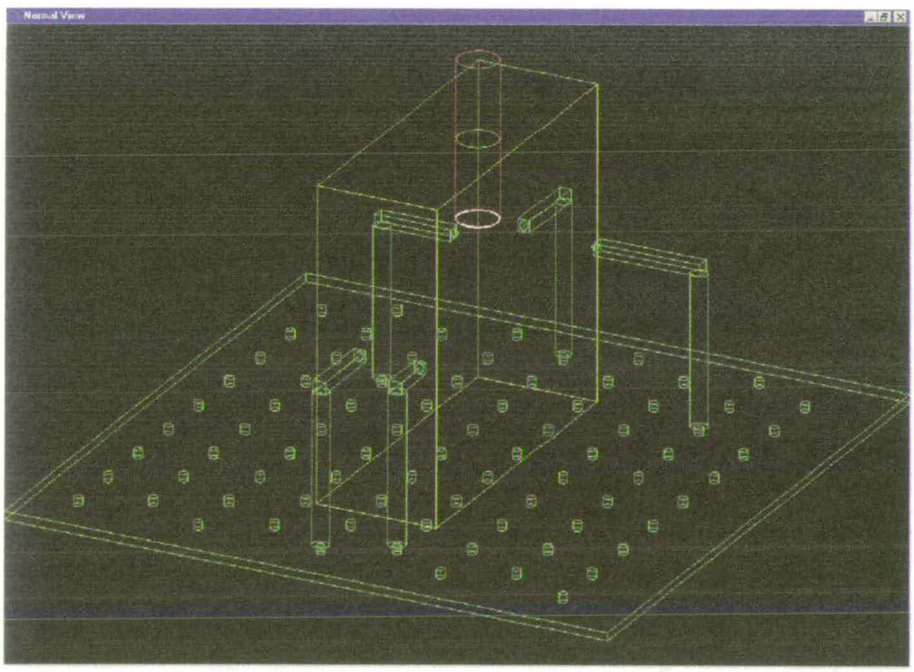


Figure 5-30 Fixture Plan for Set-up 1.

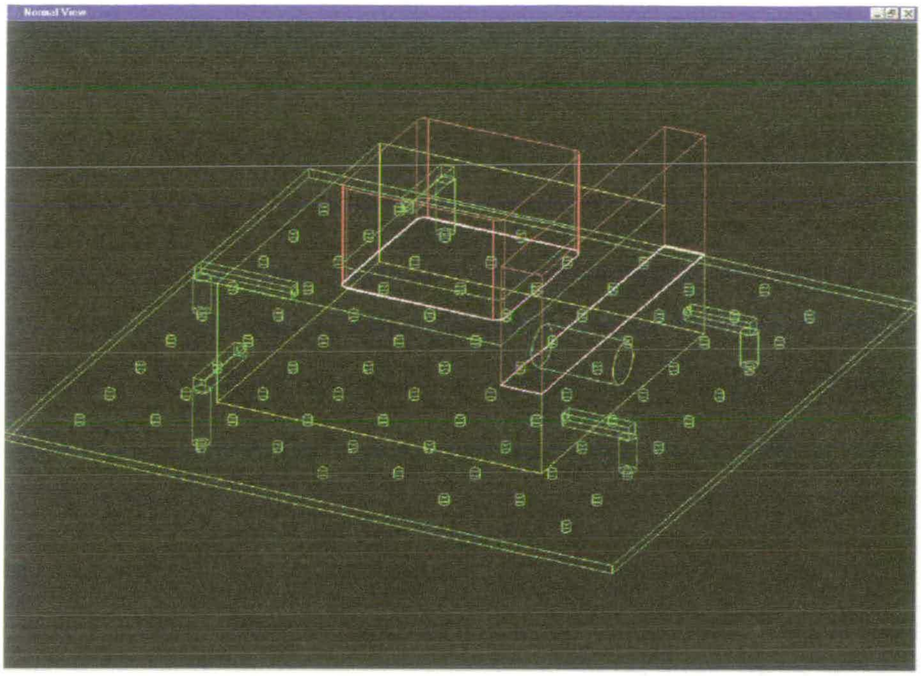


Figure 5-31 Fixture Plan for Set-up 2.

5.8 Summary

FixPlan has been successfully implemented, it allows the user to design a prismatic solid model with features provided by the system. Through geometric reasoning, the system is able to determine the number of set-ups required, and for each set-up, a set of locating faces and points are generated which allows the system to automatically select the corresponding fixture elements from the database. Another example of the whole fixture planning process is provided in the appendix. It show the intermediate stages of the planning process within FixPlan.

CHAPTER VI

6. Conclusions

Most fixture designs are still being carried out manually due to the lack of an automated fixture planning system that is capable of performing the task with a satisfactory result. At most a computer aided fixture planning system is used to reduce the time and amount of drawing needed. The fixturing process can be time consuming and forms a major part of the cost incurred in most manufacturing environments. Improper fixturing of components during the machining process can result in costly errors. To improve the process of fixture planning has therefore prompted many researchers to carry out much research into fixturing and the development of a computerised fixture planning/design system. However a comprehensive and complete fixture design system that incorporates all the micro activities of fixturing has yet to be developed. This has prompted the development and implementation of FixPlan.

The main objectives of the research were:

- to establish the functionality of a geometric reasoning system for fixture planning.
- to define the relationship between fixture planning and geometric reasoning.
- to explore the success of geometric reasoning function in supporting fixture planning.
- to build and establish a fixture planning system.

The implementation of geometric reasoning has proved to be very essential to fixture planning as it simplify many of the fixturing procedures that might otherwise be very complex to implement. The advantage of geometric reasoning is in its ability to detect the relationships between the faces and features, compound faces, split faces, tool access directions, and alternative tool access directions which are used for the design of fixtures. Geometric reasoning thus forms the core to the entire research and it is the main module within FixPlan. Other modules within FixPlan obtain necessary information and data for each respective stage of the fixture planning process from the geometric module.

The implementation of geometric tolerances allows relationships to be formed between features which in turn are used for the selection and generation of set-ups. The same information is also used for the selection of datum faces. The ability of the system to recognise and retrieve information regarding the faces and features through geometric reasoning enables the planning module to select the necessary positioning, support and clamping faces and points. This again increases the importance of geometric reasoning within the system.

The successful development and implementation of FixPlan has demonstrated the difficulties and problems of automating fixture design in a feature based environment. The system is unique in its utilisation of geometric reasoning and a fully embedded 3D solid modelling representation of parts to enabled spatial reasoning in enhancing fixture planning. Although the system seems at times over simplified, it does however provide the foundation for further improvement and development as it contains rules and algorithms which could be easily changed and altered. The next section will deal with the recommendations for further work that is required to improve the system further thus making it more robust.

6.1 Recommendations for Future Developments

It is necessary to reduce the number of assumptions as well as considering details that were previously excluded to further develop and improve the system. The position of the locators, supports and clamps as well as the forces that are acting on the respective points greatly affect the stability of the component being restrained. Therefore it is necessary to ensure that the points generated by the system are able to restrain the component without compromising its stability. At present FixPlan does not provide any means of analysing and checking the validity of the positioning, supporting and clamping points generated. Further improvement can therefore be made by the introduction of kinematic analysis to the system, which will solve this validity problem. It is also necessary to consider the type of component material and surface finishes required as it will also affect, as well as limit, the magnitude of the forces that can be applied to it.

The accuracy of the component can be greatly affected by both the cutting and clamping forces. At present FixPlan assumes that both forces applied are well within the limits and will not in anyway cause any deflection or distortion that could affect the accuracy of the component. In reality it is therefore necessary to consider deflection and distortion of the component under such forces to ensure the accuracy of the component. Finite Element Analysis (FEA) could be used to detect the location of such deflection and distortion so that remedies, for example adding additional supports, could be introduced to minimise them thus ensuring the accuracy of the component.

At present, the system is able to check for tool interference through the use of the tool access body. This however does not take into account the direction of these forces. As discussed in Chapter IV section 4.3.1, the direction of the cutting forces forms one of the major factors that affect the decision for the selection of the secondary and tertiary datum faces. It is therefore necessary for the system to take into account the direction of the cutting force. Introduction of the cutting force direction will therefore further enhance the system by ensuring that the selected datums are capable of maintaining the component's positional accuracy thus reducing any tolerance errors. It is also necessary to improve the system so that it could handle models with higher complexity as well as considering the usage of machine with more then 3 axis, for example a five axis machine. At present, it is assumed that a pre-machined blank is used as the base of the solid model, it would further improve the system if it could actually handle raw material, such as a billet, as the blank. Finally it is necessary to change the present fixture element data base to one that is based on a commercially available modular tool set.

Most of the present research is concentrated on the development of systems that deal with machining fixtures. However this will be extended in the future to cover the fixturing of others manufacturing processes, such as assembly, inspection and welding, as well as the automatic assembly of the fixture.

REFERENCES

ACIS94a ACIS 3D Toolkit Version 1.2, 1994: Programmers Manual, Spatial Technology Inc., USA.

ACIS94b ACIS 3D Toolkit Version 1.2, 1994: Application Guide, Spatial Technology Inc., USA.

ACIS96 ACIS Geometric Modeler, 1996: Application Guide. Spatial Technology Inc., USA.

Alting89 Alting, L., and Zhang, H.C., 1989, Computer Aided Process Planning: the state of the art survey. International Journal of Production Research, 27(4), 553-585.

Asada85 Asada, H. and By, A.B., 1985, Kinematic Analysis of Workpart Fixturing for Flexible Assembly with Automatically Reconfigurable Fixture. IEEE Journal of Robotics and Automation, 1(2), 86-94.

Bidanda90 Bidanda, B. and Cohen, P.H., 1990, Development of a Computer Aided Fixture Selection System for Concentric, Rotational Parts. ASME Annual Winter Meeting, PED-47, ASME Publication No. G00569, 151-162.

Boerma88 Boerma, J.R., 1988, FIXES, A System for Automatic Selection of Set-up and Design of Fixtures. Annals of the CIRP, 37/1 443-446.

Boerma89 Boerma, J.R., 1989, Fixture Design with FIXES: the Automatic Selection of Positioning, Clamping and Supporting Features for Prismatic Parts. Annals of the CIRP, 38/1, 399-402.

Boerma90 Boerma, J.R., 1990, The Design of Fixtures for Prismatic Parts. Ph.D. Thesis, University of Twente.

Bronsvoort93 Bronsvoort, W.F., and Frederik, W.J., 1993, Feature Modelling and Conversion - Key Concepts to Concurrent Engineering. Computer in Industry, 21, 61-86.

Case91 Case, K., and Gao, J., 1991, Feature Technology - An Overview. Symposium: Feature-Based Approaches to Design and Process Planning, Loughborough University of Technology, 24 & 25 September.

Chou86 Chou, Y.C. and Barash, M., 1986, Computerised Fixture Design from Solid Models of Workpieces. Proceedings of the Symposium on Integrated Intelligent Manufacturing Systems, ASME Winter Annual Meeting, Purdue University, USA (New York: American Society of Mechanical Engineers) 133-141.

Chou89 Chou, Y.C., Chandru, V., and Barash, M., 1989, A Mathematical Approach to Automatic Configuration of Machining Fixtures: Analysis and Synthesis. Journal of Engineering for Industry, 111, 299-306

Chou90 Chou, Y.C., 1990, A Methodology for Automatic Layout of Fixture Elements Based on Machining Forces Considerations. Symposium on Advances in Integrated Product Design and Manufacturing, ASME Winter Annual Meeting, Dallas, TX, 181-189

Corney91 Corney, J. and Clark, D.E.R., 1991, Face Based Feature Recognition: Generalising Special Cases. Symposium Feature-Based Approaches to Design and Process Planning.

Corney91b Corney, J. and Clark, D.E.R., 1991, June 5, A Feature Recognition Algorithm for Multiply Connected Depressions and Protrusions in $2\frac{1}{2}$D objects, Proceedings of Symposium on Solid Modelling Foundations and CAD/CAM Applications, 171-183.

Darvishi88 Darvishi, A.R. and Gill, K.F., 1988, Knowledge Representation Database for the Development of a Fixture Design Expert System. Proceedings of the Institute of Mechanical Engineers, London, 202(B1), 37-49.

Delbressine93 Delbressine, F.L.M., de Groot, R. and van der Wolf, A.C.H., 1993, On the Automatic Generation of Set-ups given a Feature Based Design Representation. Annals of the CIRP, 42(1), 527-530.

Dong91 Dong, X., DeVries, W.R. and Wozny, M.J., 1991, Feature Based Reasoning in Fixture Design. Annals of the CIRP, 40/1, 111-114.

Ferreira85 Ferreira, P.M., 1985, AIFIX, An Expert System Approach to Fixture Design. ASME Computer Aided/Intelligent Process Planning, PED-19, 73-82.

Gandhi86 Gandhi, M.V. and Thompson, B.S., 1986, Automated Design of Modular Fixtures for Flexible Manufacturing Systems. Journal of Manufacturing Systems, 5(4), 243-252.

Gu95 Gu, Z., Zhang, Y.F. and Nee, A.Y.C., 1995, Generic Form Feature Recognition and Operation Selection using Connectionist Modelling. Journal of Intelligent Manufacturing, 6, 263-273.

Hargrove94 Hargrove, S.K. and Kusiak, A., 1994, Computer Aided Fixture Design: A Review. International Journal of Production Research, 32(4), 733-753.

Hazen90 Hazen, F.B. and Wright, P.K., 1990, Workholding Automation: Innovations in Analysis, Design, and Planning. Manufacturing Review, 3(4), 224-237.

Jared89 Jared, G.E.M., 1989, Recognising and Using Geometric Features in Geometric Reasoning. Edited by Woodwark, J., Oxford University Press, Oxford, 168-188.

Joshi88 Joshi, S. and Chang, T.C., 1988, Graph Based Heuristics for Recognition of Machine Features from a 3D Solid Model. Computer Aided Design, 20(2), 58-66.

Joshi90 Joshi, S. and Chang, T.C., 1990, Feature Extraction and Feature Based Design Approaches in the Development of Design Interface for Process Planning. Journal of Intelligent Manufacturing, 1, 1-15.

King93 King, L.S.B. and Flutter, I., 1993, Theoretical Approach for Generating Optimal Fixturing Locations for Prismatic Workparts in Automated Assembly. Journal of Manufacturing Systems, 12(5), 409-416.

Koch89 Koch, D.H., 1989, Undedicated Fixturing: A Solution. Technical Paper, Society of Manufacturing Engineering, TE89-366.

Koh92 Koh, S.P. Chien, C.P. and Wang, S.T., 1992, Integrated CAD/CAE/CAM Prototype System for Complete Modular Fixturing. Japan/USA Symposium on Flexible Automation, ASME, 2, 1655-1662.

Kripac94 Kripac, Jiri, 1991, Topological ID system, A Mechanism for Persistently Naming Topological Entities in History-Based Parametric Solid Models. Ph.D. Thesis, Czech Technical University in Prague.

Kumar92 Kumar, A.S., Nee, A.Y.C. and Prombanpong, S., 1992, Expert Fixture Design System for an Automated Manufacturing Environment. Computer Aided Design, 24(6), 316-326.

Kwasny93 Kwasny, D.M. and Cipra, R.J., 1993, User Interactive Flexible Fixturing System. DE-VOL 65-1 Advances in Design Automation, ASME, 1, 567-576.

Lange89 Lange, N., Gandhi, M.V., Thompson, B.S. and Desai, D.J., 1989, An Experimental Evaluation of the capabilities of a Fluidised Bed Fixturing System. International Journal of Advanced Manufacturing Technology, 4, 192-206.

Lee86 Lee, J.D. and Haynes, L.S., 1986, Finite Element Analysis of Flexible Fixturing System. Japan-U.S.A. Symposium on Flexible Automation, 579-584.

Lee94 Lee, S.K. and Cho, K.K., 1994, Comparison of Limit Surface Approach with other Approaches in Fixture Planning with Friction. Annals of the CIRP, 43(1), 331-335.

Lim91 Lim, B.S., Imao, T., Yoshida, H., Goto, K., Kah, S.L., Lim, D., Chin, L. and Gan, S.C., 1991, Computer Integrated Expert System for Modular Fixture Design, Pricing and Inventory Control. Proceedings of the 11th International Conference of Production Research, Heiei, China (London, Taylor & Francis), 859-862.

Lim92 Lim, B.S., Imao, T., Yoshida, H., Goto, K., Kah, S.L., Lim, D., Chin, L. and Gan, S.C., 1992, Integrated Modular Fixture Design, Pricing and Inventory Control Expert System. International Journal of Production Research, 30(9), 2019-2044.

Liou91 Liou, F.W. and Suen, D.J., 1991, The Development of a Feature Based Fixture Planning System for Flexible Assembly. Journal of Manufacturing Systems, 11(2), 102-113.

Mani88 Mani, M. and Wilson, W., 1988, Automated Design of Workholding Fixtures using Kinematics Constraint Synthesis. Proceedings of the 19th North American Manufacturing Research Conference, 437-444.

Markus84 Markus, A., Markuz, Z., Farkas, J. and Filemon, J., 1984, Fixture Design using Prolog: An Expert System. Robotics and Computer Integrated Manufacturing, 1(2), 167-172.

Martin94 Martin, E.C., 1994, Getting Started with Scheme Using the ACIS 3D Toolkit. Spatial Technology Inc., USA.

McMahon93 McMahon, C., and Browne, J., 1993, CADCAM from Principles to Practice. Addison - Wesley Publishing Company.

Menassa89 Menassa, R.J., and DeVries, W.R., 1989, Locating Point Synthesis in Fixture Design. Annals of the CIRP, 38, 165-169.

Menassa91 Menassa, R.J. and DeVries, W., 1991, Optimisation Methods Applied to Selecting Support Position in Fixture Design. Journal of Engineering for Industry, 113, 412-418.

Mill93 Mill, F.G., Salmon, J.C. and Pedley, A.G., 1993, Representation Problem in Feature Based Approaches to Design and Process Planning. International Journal of Computer Integrated Manufacturing, 6(1&2), 27-33.

Mill94 Mill, F.G., Naish, J.C., and Salmon, J.C., 1994, Design for Machining with a Simultaneous Engineering Workstation. Computer Aided Design, 26(7).

Nee87 Nee, A.Y.C., Bhattacharyya, N. and Poo, A.N., 1987, Applying AI in Jigs and Fixtures Design. Robotics and Computer Integrated Manufacturing, 3(2), 195-201.

Nee91 Nee, A.Y.C. and Poo, A.N., 1991, Expert CAD System for Jigs and Fixtures. Artificial Intelligence in Design, Edited by Pham, D.T. (New York, Springer-Verlag), 343-370.

Nee92 Nee, A.Y.C., Kumar, A.S., Prombanpong, S., Puah, K.Y., 1992, A Feature Based Classification Scheme for Fixtures. Annals of the CIRP, 41(1), 189-192.

Nee95 Nee, A.Y.C., Whybrew, K and Kumar, A.S., 1995, Advance Fixture Design for FMS. Springer-Verlag (Editor Pham, D.T.)

Nnaji90 Nnaji, B.O. and Alladin, S, 1990, E-CAFFS: An Expert Computer-Aided Flexible Fixturing System. Computers ind. Engng, 18(3), 297-311.

Ohwovoriole81 Ohwovoriole, M.S. & Roth, B., 1981, An Extension of Screw Theory. Journal of Mechanical Design, **103**, 725-735.

Ong94 Ong, S.K. and Nee, A.Y.C., 1994, Application of Fuzzy Set Theory to Set-up Planning. Annals of the CIRP, 43(1), 137-144.

Ong95 Ong, S.K. and Nee, A.Y.C., 1995, Process modelling and Formulation for the Development of an Intelligent Set-up Planning System, Proceedings of the Institution of Mechanical Engineers, 209, 455-467.

Pham89 Pham, D.T., Nategh, M.J., and Lazaro, A.D.S., 1989, Jigs and Fixtures Designers Assistant. International Journal of Advanced Manufacturing Technology, 4, 26-45.

Pham90 Pham, D.T., and Lazaro, A.D.S., 1990, AutoFix - An Expert CAD System for Jigs and Fixtures. International Journal of Machine Tools and Manufacturing, 30(3), 403-411.

Sakurai92 Sakurai, H, 1992, Automatic Set-up Planning and Fixture Design Machine. Journal of Manufacturing Systems, 11(1), 30-37.

Salmon94 Salmon, J.C. and Reiken, H., 1994, Component Description Language (CODL) Implementation. Internal Report 18, Manufacturing Planning Group, University of Edinburgh.

Springer93 Springer, G., and Friedman, D.P., 1993, Scheme and the Art of Programming. The MIT Press, Cambridge, Massachusetts London, England.

Tonshoff94 Tonshoff, H.K., and Aurich, J.C., Baum, T, and Hamelmann, S., 1994, A Workpiece Model for CAD/CAPP Applications. Production Engineering - Annals of the German Academic Society of Production Engineering, 1(2).

Trappey90 Trappey, J.C. and Liu, C.R., 1990, A Literature Survey of Fixture Design Automation. International Journal of Advanced Manufacturing Technology, 5, 240-255.

Trappey93 Trappey, J.C. and Liu, C.R., 1993, Automatic Generation of Configuration for on Arbitrary Workpiece using Projective Spatial Occupancy Enumeration Approach. International Journal of Advanced Manufacturing Technology, 8, 297-304.

Wilson62 Wilson, F.W. (Editor), 1962, Handbook of Fixture Design, A Practical Reference Book of Workholding Principles and Design for All Classes of Machining, Assembly, and Inspection. McGraw - Hill Book Company.

Youcef-Toumi89 Youcef-Toumi, K., Bausch, J.J. and Blacker, S.J., 1989, Automated Set-up and Reconfiguration for Modular Fixturing. Robotics and Computer Integrated Manufacturing, 5(4), 357-370.

Young91 Young, R.I.M and Bell, R., 1991, Fixturing Strategies and Geometric Queries in Set-up Planning. International Journal of Production Research, 29(3), 537-550.

Zhang94 Zhang, H.C. and Winkenwerder, C.H., 1994, Design - Decision Support in Concurrent/Simultaneous Engineering. Control and Dynamics Systems, Academic Press, Inc., 62, 171-196.

Zhang95 Zhang, Y.F., Nee, A.Y.C. and Ong, S.K., 1995, A Hybrid Approach for Set-up Planning. International Journal of Advanced Manufacturing Technology, 10, 183-190.

APPENDIX

An Example: Fixture configuration of a workpiece.

The workpiece shown in Figure A-1 will be used to demonstrate FixPlan. Figure A-2 shows the CODL description of the workpiece, it is use by the Feature Based Design Module to reconstruct the workpiece.

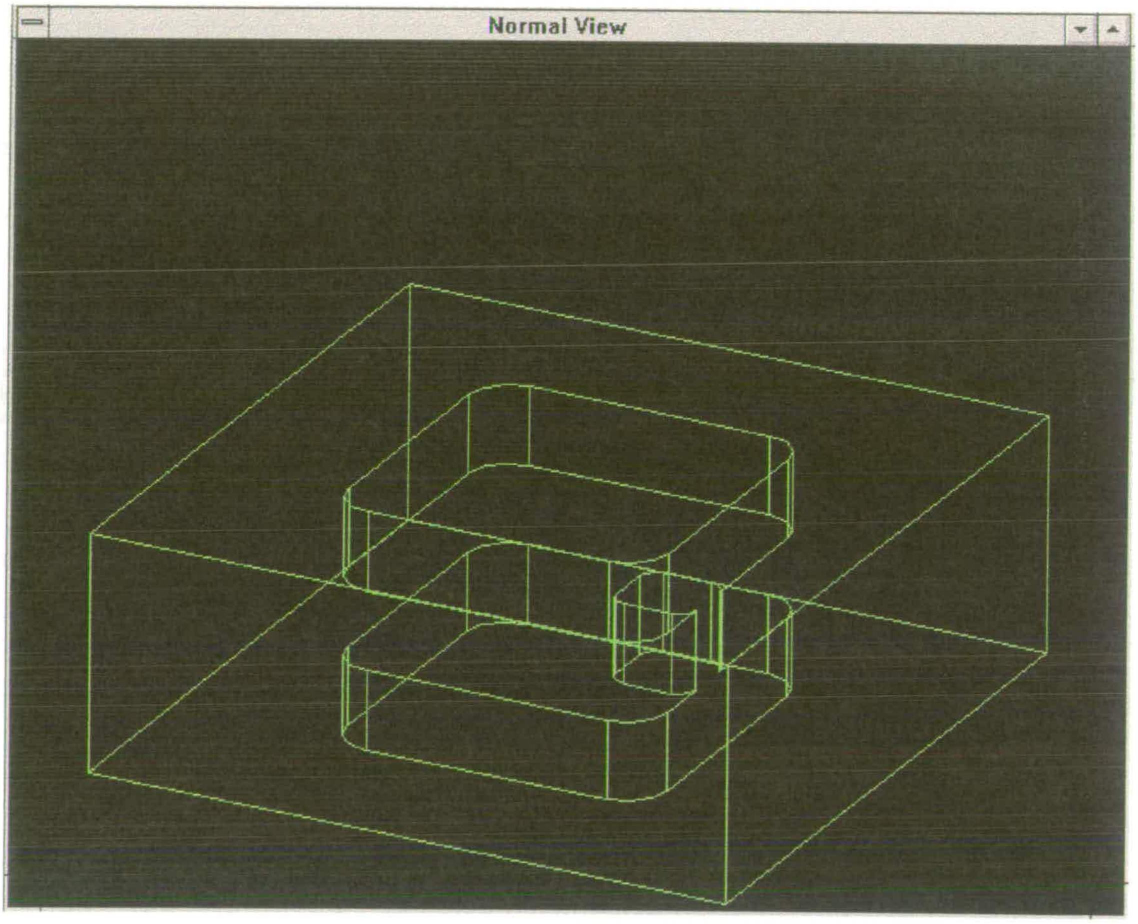


Figure A-1 Sample workpiece.

```
;name         type            X      Y    Z    Roll  Pitch  Yaw  Handle  Level  L    W    D
"B1"          "blank"         "-40.0  -40   0    0     0      0    0       0      80   80   30 "

;name         type            X      Y    Z    Roll  Pitch  Yaw  Handle  Level  L    W    D    crad
"P1"          "rect_pocket"   "-20.0  -20   0    0     0      0    0       0      40   40   10   5 "

;name         type            X      Y    Z    Roll  Pitch  Yaw  Handle  Level  L    W    D    crad
"P2"          "rect_pocket"   "0.0    10    0    0     0      0    0       0      10   10   20   2 "

;name         type            X      Y    Z    Roll  Pitch  Yaw  Handle  Level  L    W    D    crad
"P3"          "rect_pocket"   "-20.0  -20   -30  0     0      0    0       0      40   40   -10  5 "

;name         type            FO-x  FO-y  FO-z  Type  VAL  LX  LY  LZ  RXe-3  RYe-3  RZe-3  TFe-4
"TP1-18-26"   "Tolerance"     "0.0  0     -1    1     0.5  30  0   30  16.7   0      16.7   118 "

;name         type            FO-x  FO-y  FO-z  Type  VAL  LX  LY  LZ  RXe-3  RYe-3  RZe-3  TFe-4
"TP3-18-26"   "Tolerance"     "0.0  0     1     1     0.5  30  0   30  16.7   0      16.7   118 "

;name         type            FO-x  FO-y  FO-z  Type  VAL  LX  LY  LZ  RXe-3  RYe-3  RZe-3  TFe-4
"TP2-18-26"   "Tolerance"     "0.0  0     -1    1     0.5  30  0   30  16.7   0      16.7   118 "

;name         type            FO-x  FO-y  FO-z  Type  VAL  LX  LY  LZ  RXe-3  RYe-3  RZe-3  TFe-4
"TP3-24-01"   "Tolerance"     "0.0  0     1     1     0.5  40  40  0   12.5   12.5   0      88 "
```

Figure A-2 CODL description of sample workpiece.

FixPlan is able to determine that two set-ups are required to produce the desired workpiece. The two set-ups are described in the CODL file shown in Figure A-3. It is also recognised by the system that set-up 2 should be machined before set-up 1. Set-up 2 can be seen in Figure A-4. Figure A-8 shows the fixture configuration of set-up 2. Set-up 1 can be seen in Figure A-9. Figure A-13 shows the fixture configuration of set-up 1.

```
SETUP-1
;name         type            FO-x  FO-y  FO-z  Type  VAL  LX  LY  LZ  RXe-3  RYe-3  RZe-3  TFe-4
"TP3-24-01"   "Tolerance"     "0.0  0     1     1     0.5  40  40  0   12.5   12.5   0      88 "

;name         type            FO-x  FO-y  FO-z  Type  VAL  LX  LY  LZ  RXe-3  RYe-3  RZe-3  TFe-4
"TP2-18-26"   "Tolerance"     "0.0  0     -1    1     0.5  30  0   30  16.7   0      16.7   118 "

;name         type            FO-x  FO-y  FO-z  Type  VAL  LX  LY  LZ  RXe-3  RYe-3  RZe-3  TFe-4
"TP3-18-26"   "Tolerance"     "0.0  0     1     1     0.5  30  0   30  16.7   0      16.7   118 "


SETUP-2
;name         type            FO-x  FO-y  FO-z  Type  VAL  LX  LY  LZ  RXe-3  RYe-3  RZe-3  TFe-4
"TP1-18-26"   "Tolerance"     "0.0  0     -1    1     0.5  30  0   30  16.7   0      16.7   118 "
```

Figure A-3 CODL description of the set-ups required.

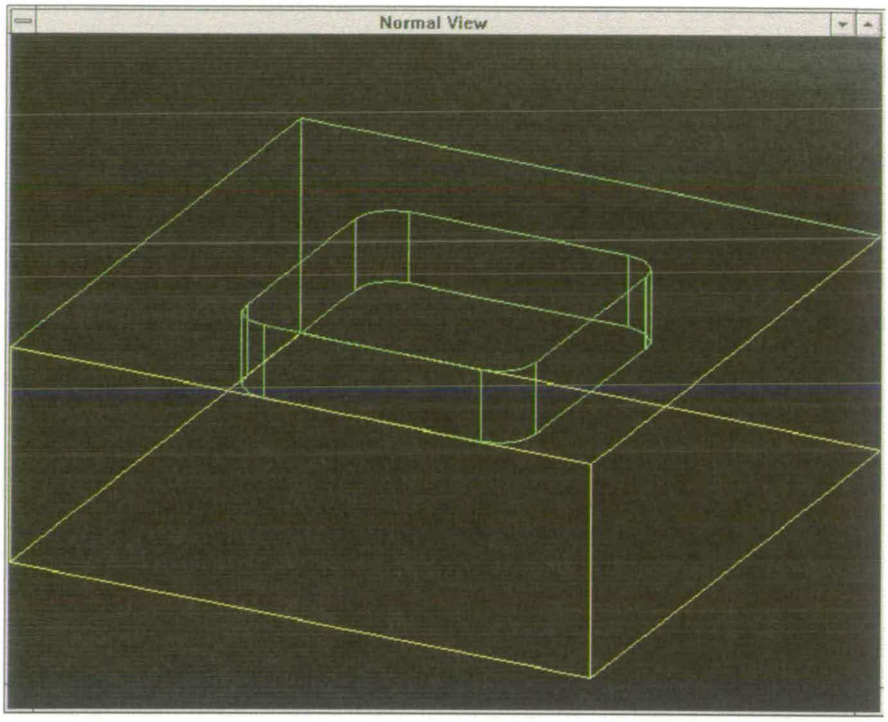


Figure A-4 Set-up 2.

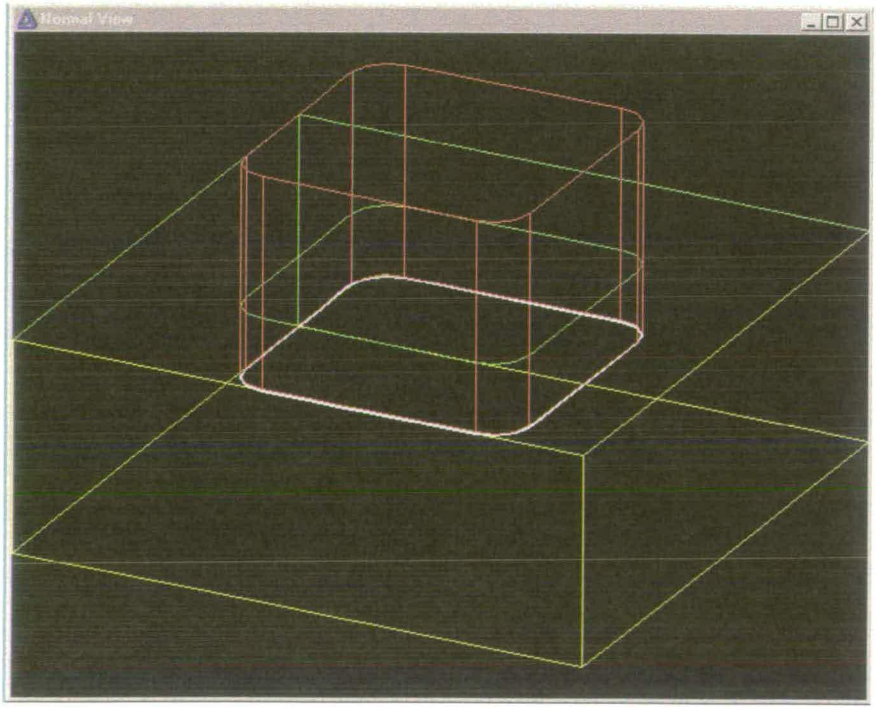


Figure A-5 Tool Access Body of set-up 2.

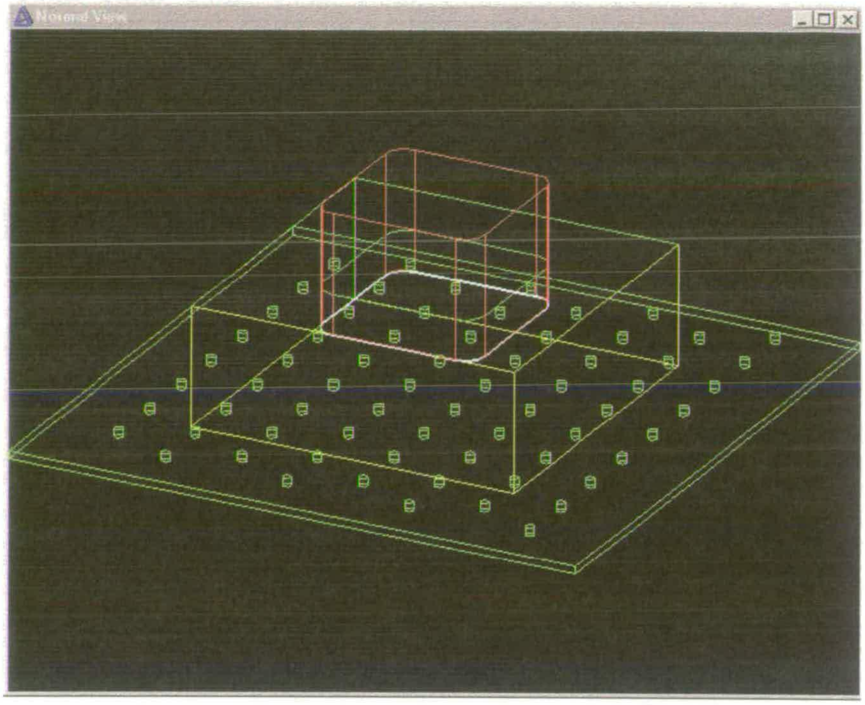


Figure A-6 Selected base plate of set-up 2.

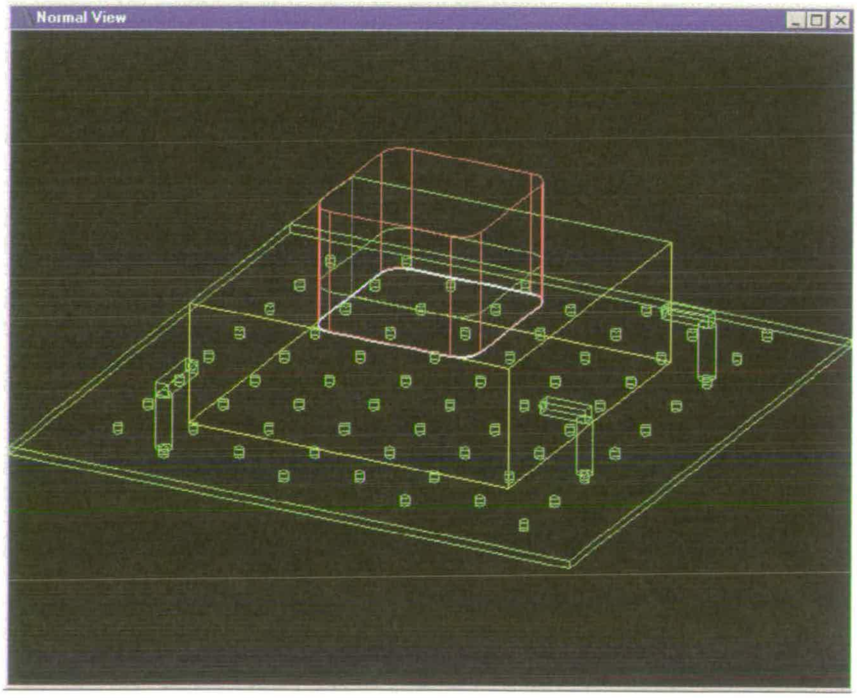


Figure A-7 Selected locators of set-up 2.

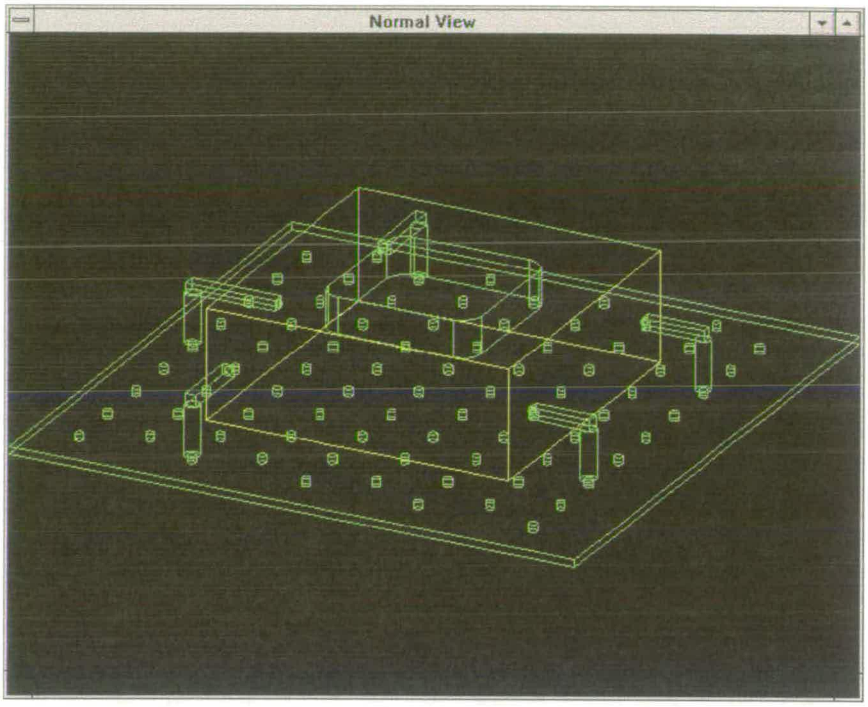


Figure A-8 Fixture configuration of set-up 2.

Figure A-5 shows the Tool Access Body generated by FixPlan. Figure A-6 shows the selected base plate for the set-up. From the tool access body, the field of features is then generated by the planner. With the position of the holes in the base plate together with the dimension of the field of features, the planner is able to generate a set of locators shown in Figure A-7.

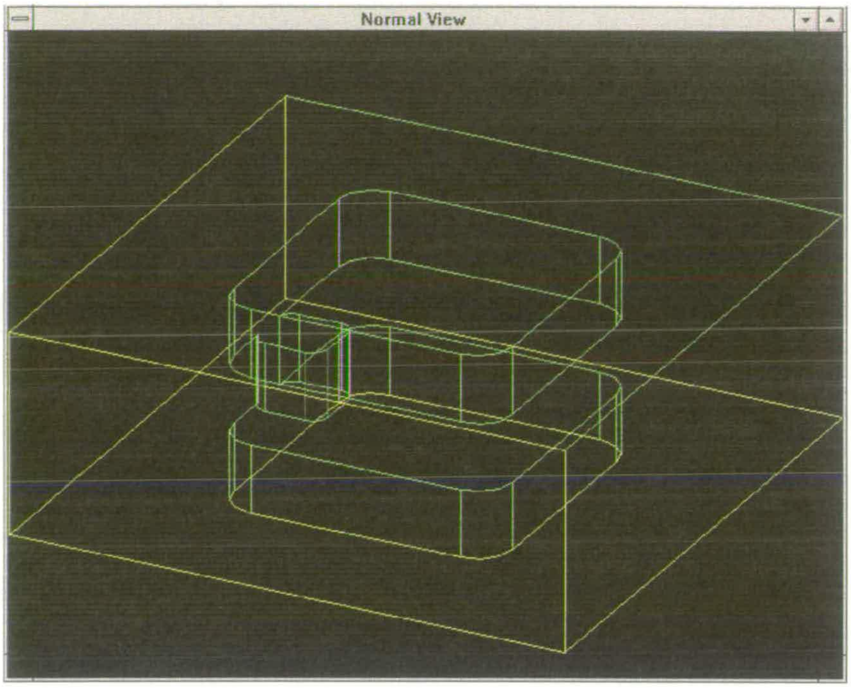


Figure A-9 Set-up 1.

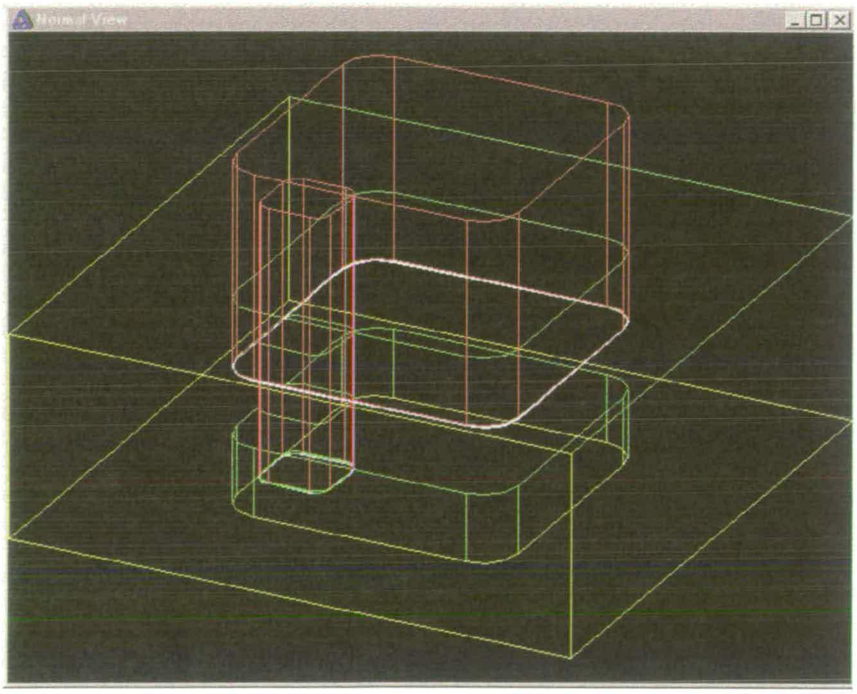


Figure A-10 Tool access body of Set-up 1.

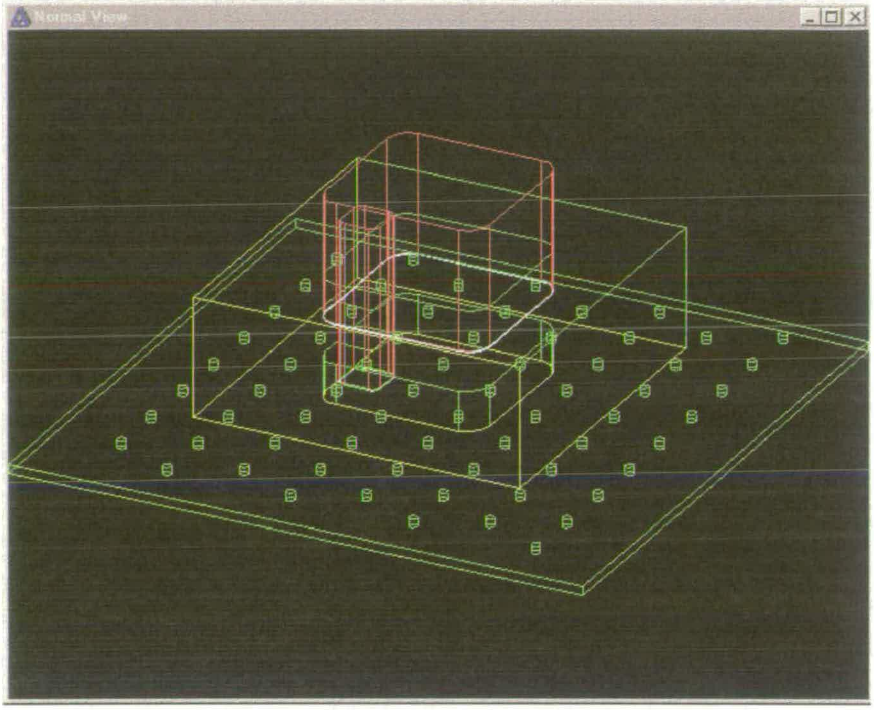


Figure A-11 Selected base plate of set-up 1.

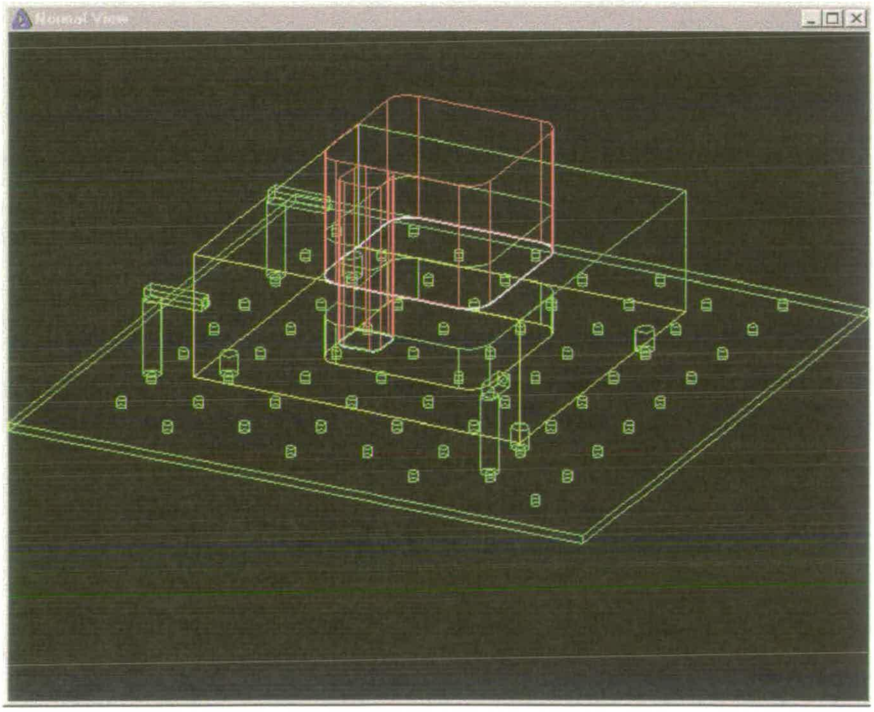


Figure A-12 Selected locators of set-up 1.

Similar to set-up 2, Figure A-10 shows the tool access body generated by the planner. Figure A-11, shows the selected base plate, and Figure A-12 shows the selected locators of set-up 1.

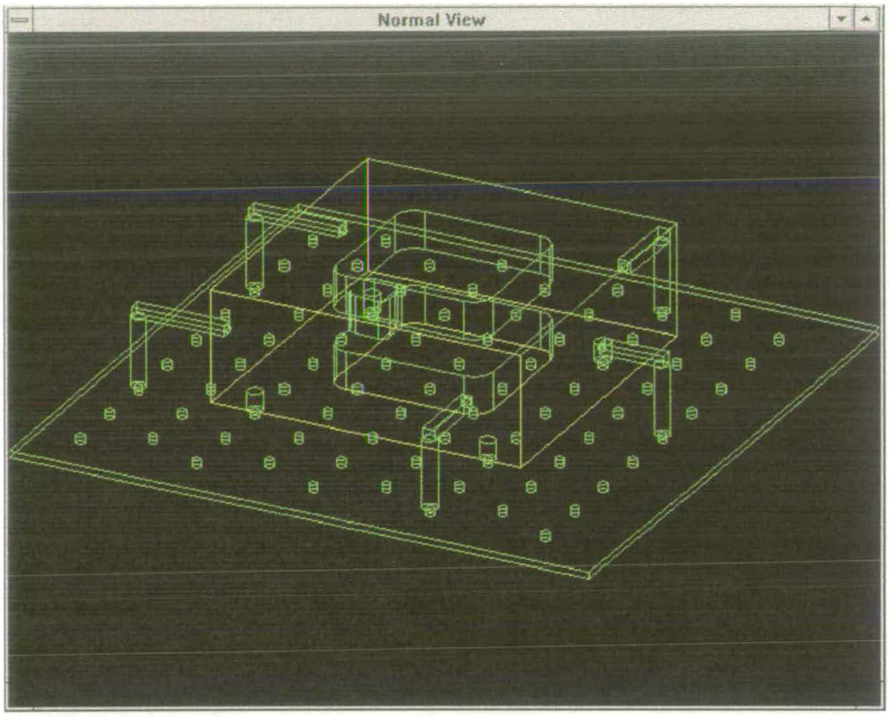


Figure A-13 Fixture configuration for set-up 1.