A solution for fixture configuration using projective geometry

by

Shankaran Matrubhutam

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE

Department : Industrial and Manufacturing Systems Engineering
Major : Industrial Engineering

Iowa State University
Ames, Iowa

1992

TABLE OF CONTENTS

Page

LIST OF FIGURES iv

NOMENCLATURE vi

ABSTRACT viii

1. INTRODUCTION 1

1.1 Fixturing Fundamentals 1

1.2 Modular Fixtures 5

1.3 Research Objectives 8

2. LITERATURE REVIEW 10

3. WORKPIECE PROJECTION 13

4. DESCRIPTION OF THE ALGORITHM 15

4.1 Determination of Candidate Fixturing Points 15

4.2 Vertical Location and Vertical Clamping 20

4.3 Horizontal Location 23

4.4 Horizontal Clamping 29

4.5 Height Determination for Horizontal Location and Clamping 33

5. SOFTWARE IMPLEMENTATION 36

6. EXAMPLE 42

6.1 Determination of Candidate Fixturing Points 42

6.2 Vertical Location and Vertical Clamping 43

6.3 Horizontal Location 44

6.4 Horizontal Clamping 45

6.5 Height Determination for Horizontal Location and Clamping 45

7. CONCLUSION 49

REFERENCES 50

ACKNOWLEDGEMENT 52

APPENDIX A: Fixture Configuration for Sample Workpiece 1 53

APPENDIX B: Fixture Configuration for Sample Workpiece 2 56

APPENDIX C: NURB Representation 59

LIST OF FIGURES

Page

Figure 1. Plane locating on specific points 3

Figure 2. Plane locating on flat planes 4

Figure 3. Combining point and plane locations 4

Figure 4. Determination procedure for candidate points 16

Figure 5. Determination procedure for candidate points 17

Figure 6. Determination procedure for candidate points 18

Figure 7. Projected workpiece with candidate fixturing points and the notations r, t, pe_i, and N_{pe_i} marked on it 20

Figure 8. Determination procedure for vertical location and clamping 21

Figure 9. Workpiece shown with projected vertical fixturing points 22

Figure 10. Determination procedure for horizontal location 24

Figure 11. Determination procedure for horizontal location 26

Figure 12. Workpiece shown with projected horizontal locating points 28

Figure 13. Determination procedure for horizontal clamping 30

Figure 14. Horizontal clmaping points for a projected workpiece 31

Figure 15. Determination procedure for location and clamping heights 32

Figure 16. 2-pt fixturing height for a workpiece 33

Figure 17. 1-pt fixturing height for a workpiece 34

Figure 18. Structure for representing a NURB surface 37

Figure 19. Structure for representing the polynomial form of a surface 37

Figure 20. Structure for representing an original curve 38

Figure 21. Structure for representing a NURB curve 38

Figure 22. Structure for representing the polynomial form of a curve 38

Figure 23. An isometric view of the workpiece with locators in blue and clamps in magenta 47

Figure 24. An isometric view of the workpiece with locators in blue and clamps in magenta 48

Figure 25. An isometric view of the workpiece with locators in blue and clamps in magenta 54

Figure 26. An isometric view of the workpiece with locators in blue and clamps in magenta 55

Figure 27. An isometric view of the workpiece with locators in blue and clamps in magenta 57

Figure 28. An isometric view of the workpiece with locators in blue and clamps in magenta 58

NOMENCLATURE
(Bold face symbols denote sets, vectors or matrices)

$\mathbf{PE} = \{ pe_i \}$	$i = 1, .., n_{PE}$	candidate projected outer edges of the workpiece (edges which do not have any unmachined face or whose unmachined faces have heights beyond the range of the fixture elements are removed).
$\mathbf{F}_{pe_i} = \{ f_j \}$	$j = 1, .., n_{F_{pe_i}}$	set of faces belonging to the edge pe_i that do not require machining or which are not beyond the range of the fixture elements.
$\mathbf{PE}_{d1}$		projected edges of f_{d1}.
$\mathbf{P}_{vlc}$		set of candidate points for vertical fixturing.
$\mathbf{PP}_j$	$j = d1, d2$	set of candidate fixturing points on the projected edge of f_j.
$\mathbf{F}_j$		jth cutting force ordered in decreasing magnitude.
$\mathbf{S}_i$		set of coordinates of points on edge i and is a subset of S.
$\mathbf{F}_{pe_i}$	$i = l2, l1, c2, c1$	set of faces whose projected edge is pe_i where l2 refers to two-point location, l1 to single point location, c2 to clamping against the two-point locators and c1 to clamping against the single-point locator.
pe_i	$i = l2, l1, c2, c1$	the projected edge which has been chosen for i th fixturing purpose.
$\overline{\mathbf{N}}_i$		Average inner normal to the projected edge, i, directed towards and not away from the workpiece.
$\mathbf{N}_i(P)$		Normal to the projected edge, i at the point P.
f_{d1}		primary datum face, if specified.

f_{d2}		secondary datum face, if specified.
f_{d3}		tertiary datum face, if specified.
t		increment along each projected edge specified by the user.
r		increment along the normal to each projected edge specified by the user.
h_i	$i = l2, l1, c2, c1$	maximum of the heights of all faces whose projected edge is pe_i.
FSETS(S)		a function which returns the number of subsets in the set **S** belonging to the same face.
$n_{\mathbf{PE}_{d1}}$		number of edges in $\mathbf{PE}_{d1}$.
$n_{\mathbf{PE}}$		number of edges in **PE**.
U_i	$i = x, y$	i value of **U**.
sign (a, b)		= 't' if a and b have identical signs = 'f' otherwise.
SIGN (**U**, **V**)		= (sign (U_x, V_x), sign (U_y, V_y)).
l_{d2}		= 1 if f_{d2} has been specified = 2 otherwise.

ABSTRACT

Fixtures play an active role in many manufacturing operations such as machining, assembly, inspection and welding. This wide application of fixtures and the increasing use of automation in design and manufacturing has aroused considerable interest in Automatic Fixture Design (AFD). Although a good amount of literature is available on this subject, most of the work done in this area has been restricted to prismatic parts. In this research, a set of algorithms is proposed to determine the fixturing locations of a workpiece whose fixturing faces are either parallel or perpendicular to the baseplate. The algorithms discussed here, employ heuristic search techniques on the projected envelope of the workpiece to determine the locating and the clamping points. The application of projective geometry reduces the complexity of the fixture configuration problem since search operations then degenerate from 3-D to 2-D. The search for the fixturing points is performed in five major steps--determination of candidate fixturing points on the outer edges of the projected envelope, determination of the configuration for vertical location and clamping, determination of the horizontal locating points on the projected edges, determination of the horizontal clamping points corresponding to the horizontal locating points, and finally, determination of the height for the horizontal locating and the clamping points. The inputs for the algorithms include the boundary representation (B-rep) of the workpiece, the machining forces, and the workpiece orientation. The algorithms have been implemented in C and interfaced with I-DEAS, a solid modeler, to obtain the B-rep information.

1. INTRODUCTION

Workholding has been an integral part of manufacturing ever since the first product was conceived and made. Workholding devices, commonly referred to as **Jigs** and **Fixtures,** have not only been used in machining but also in other areas of manufacturing like inspection, welding and assembly, to name a few. Although the cost of manufacturing these workholding devices is very high, they have been treated as necessary hardware by manufacturing firms. New developments in manufacturing and design have reduced the lead time enormously and have also lead to a more cost-effective and efficient production. This has generated the need to look for better ways of designing and manufacturing workholding devices, in terms of both time and efficiency. One of the outcomes of this need is the growing interest in Automatic Fixture Design (AFD). This is the concept of designing and fabricating fixtures directly from the CAD drawing of the workpiece, thereby reducing the lead time considerably and achieving an integrated setup.

1.1. Fixturing Fundamentals

Workholding devices are commonly classified as Jigs and Fixtures. Although a jig and a fixture serve the same basic purpose, i.e., workholding, a jig, in addition, often provides guidance for the cutting tool while a fixture lacks this feature. Since a jig provides tool guidance, it is mostly used in machining whereas a fixture is used in a wide range of applications like assembly, inspection, and welding. A jig is more difficult to design and fabricate since tool guidance must also be considered. Hence, automating the jig design process is more difficult than automating the fixture design process.

Any fixturing task is composed of two essential elements. These are:

1. Locating and supporting the workpiece.
2. Clamping the workpiece.

Locating and supporting the workpiece

A proper location and support of the workpiece is necessary to ensure accuracy and repeatability. Accuracy is a measure of how close the position of a feature is with respect to its intended position. Repeatability is a measure of the deviation in position of a feature among workpieces produced over a period of time. Accuracy and repeatability are two most important characteristics a fixture must possess. Location and support are both part positioning operations. While support refers to locating the workpiece along the vertical axis by using locators underneath the workpiece, location is generally used to refer to positioning along the horizontal axes. According to the **3-2-1 fixturing principle**, which is the one of the most commonly used locating schemes for prismatic parts (Hoffman, 1985), location is achieved by using locators on three outermost planes of the workpiece. The first plane, known as the **primary plane**, which usually has the largest area, is located by using three locating points. The surface with the next largest area, generally establishes the **secondary plane** and is located by two locating points. The final locator is placed on the **tertiary plane** which generally has the next largest area, to complete the location of the part. In order to enhance repeatability, the three planes must be mutually perpendicular to each other. The locators are positioned as far apart as possible in order to improve the stability of the workpiece and to reduce the location error. These points may be six actual locating points, as shown in Figure 1, or, in the case of machined surfaces contacting flat planes, individual high points on each surface as shown in Figure

2. The other alternative is to combine point-location and plane-location to satisfy 3-2-1 fixturing principle as shown in Figure 3.

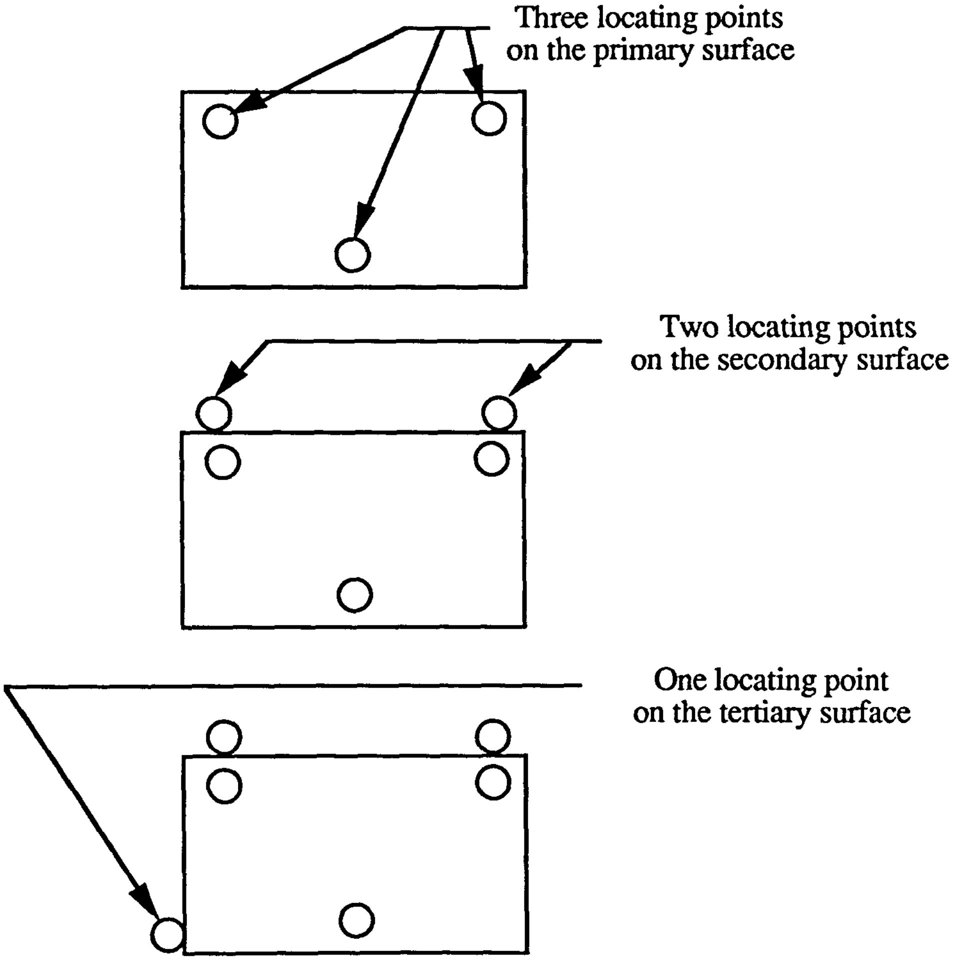

Figure 1. Plane locating on specific points

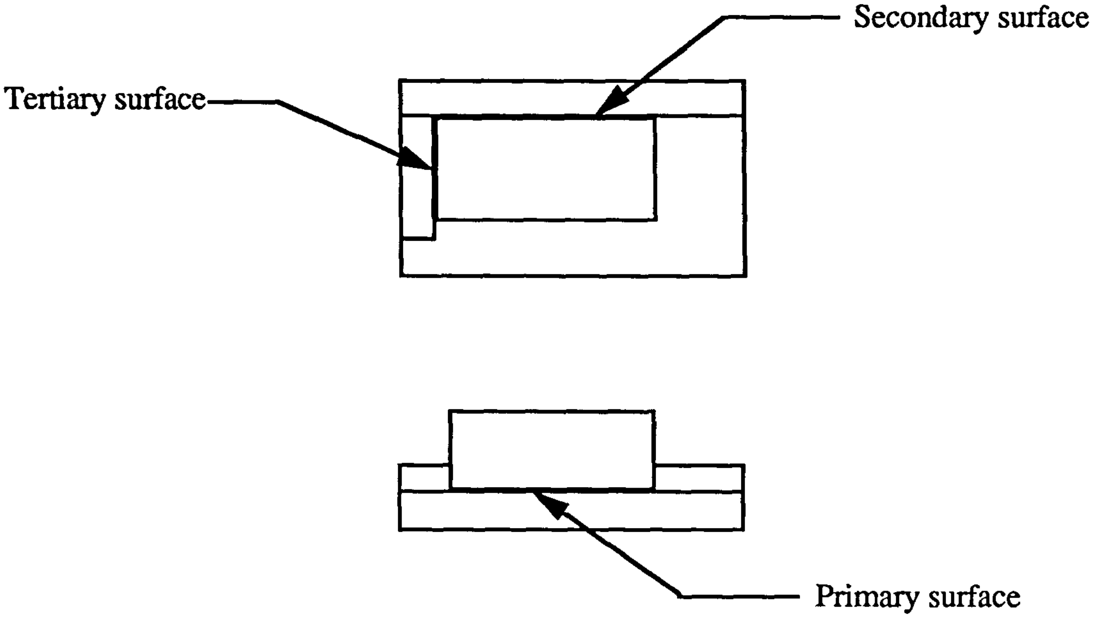

Figure 2. Plane locating on flat planes

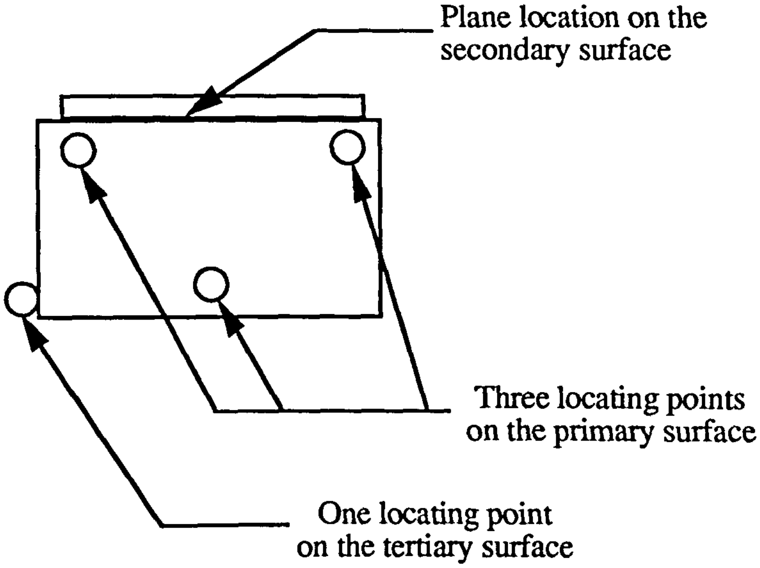

Figure 3. Combining point and plane locations

Clamping the workpiece

The principal function of clamps in a fixture is to hold the workpiece firmly against the locators and the supports, and prevent it from shifting under the action of external forces such as the cutting forces during machining, and the insertion forces during assembly. Generally, the clamps are not designed to resist these external forces. Hence, the clamps must be positioned away from the external forces and instead, the locators must be positioned properly to resist these forces. On many occasions, the external force itself could be used to hold the part against the locators (as in face milling), thus eliminating the need for a clamp. Another important point to consider when fixturing a part is the clamping forces. The forces exerted by the clamps must be directed towards the locators and not away from it. Clamping the workpiece in an unlocated area or in a direction away from the locators can only lead to instability of the workpiece. Excessive clamping forces should also be avoided to prevent workpiece distortion.

In the 3-2-1 fixturing scheme, clamps are positioned against each of the primary locators on the plane directly opposite to the primary plane. A single clamp positioned on a plane opposite to the secondary plane is used to hold the workpiece against the secondary locators and finally, the workpiece is clamped on a plane opposite to the tertiary plane.

1.2. Modular Fixtures

Fixtures can be broadly divided into two major categories--**general purpose fixtures** and **special purpose fixtures**. General purpose fixtures are those which incorporate standard workholding devices into the design of the fixture. These devices include vises, chucks, collets, angle plates and other similar standard parts. These fixtures can be used for a wide range of manufacturing situations. Special purpose fixtures are those which are designed and fabricated for a particular application without using any of the standard workholding devices mentioned above. General purpose fixtures are usually cheaper than special purpose fixtures since they are fabricated using standard parts and are reusable. A **modular fixture** is basically a general purpose fixture used to locate and clamp even workpieces with no reference surfaces.

A modular fixturing system is typically composed of a baseplate, locators, clamps and raisers. The baseplate is a flat plate mounted on the machine table on which the fixture is built. Locators and clamps are positioned appropriately on the baseplate and are used to locate and clamp the workpiece, respectively. Raisers are used to increase the heights of the available locators and the clamps. After performing an operation, the locators and clamps can be dismantled and built in a different configuration for another application, thus making the fixture completely reusable. Generally, modular fixturing systems are designed and built to meet the following workholding requirements (Hoffman, 1985):

1. Increase capabilities by fixturing more than one part.
2. Reduce the costs of designing and building workholders, and
3. Reduce overhead costs by eliminating storage and maintenance expense and the cost of obsolete workholders.

Modular fixturing systems are broadly divided into three major categories (Hoffman, 1985). These are:

1. Subplate fixturing system.
2. T-slot fixturing system.
3. Dowel-pin fixturing system.

Subplate fixturing system

Subplate systems are the least expensive and are the most basic form of modular fixtures. These systems are comprised of a baseplate or subplate to which all other components are attached. In its simplest form, a subplate is a flat plate that is either drilled and tapped to accept threaded fasteners or machined with T-slots to accept nuts and bolts. A variation of this tooling system is the vertical subplate system. In this system, the subplate is mounted vertically rather than horizontally. The main difference between the subplate system and the other systems is their scope of application. Although a subplate system is flexible enough to accommodate both holes and T-slots, the number of accessories or attachments is limited compared to the other fixturing systems.

T-slot fixturing system

This is the oldest type of modular fixturing system. T-slot systems use baseplates which have numerous T-slots machined at right angles across their faces. Regardless of the shape of the baseplate which may be rectangular or round, these T-slots are machined exactly parallel and perpendicular to each other and are uniformly spaced. This ensures precise alignment of the fixturing elements. The relative positions of the slots depends on the type of system used. The accuracy of fixturing decreases as the spacing between the slots increases since the fixturing elements can then be positioned only approximately close to their desired positions on the baseplate.

Dowel-pin fixturing system

This is the newest and the most common fixturing system in use today (Hoffman, 1985). Dowel-pin systems consist of a baseplate which is rectangular or round in shape with a series of dowel-pin holes and tapped holes drilled on its face. The space between the holes varies depending on the size of the baseplate and the type of system used. The dowel-pin holes are used to precisely locate the various fixturing elements on the baseplate while the tapped holes are used to secure these elements firmly on the baseplate.

1.3. Research Objectives

Automatic Fixture Design (AFD) has been the topic of research interest for many years now. Two approaches to AFD have been widely used--using a set of rules to derive fixturing configurations through a systematic search and using the laws of statics and dynamics to directly obtain the fixturing positions. The researches have, for the most part, been restricted to prismatic workpieces. This has been mainly due to the difficulty in representing complex workpieces mathematically and the difficulty in extending the general fixturing rules (Hoffman, 1985) to complex geometries. Thus, much of the progress in the area of fixture design has so far been restricted to the domain of prismatic workpieces whose representation is much easier to achieve and whose fixturing heuristic is easier to develop. A brief overview of the past researches in this area is done in Chapter 2 and a detailed review can be found in (Trappey and Liu, 1990a).

In this research, a strategy for fixturing a workpiece which is not necessarily prismatic is evolved. This approach is applicable to all workparts with arbitrarily shaped edges. However, only the faces corresponding to the projected boundary edges which are perpendicular or parallel to the baseplate are considered as candidate fixturing faces. This is, however, not a serious constraint since fixturing elements are generally not placed on inclined surfaces of a workpiece due to the tendency of the elements to slip and due to the difficulty in positioning those elements at odd angles. In this method, the search operations are performed only on the projected edges of the workpiece, i.e., in 2-D. Since the assembly of fixture elements on the baseplate can be considered a 2-D operation, the search operations are simplified enormously if they are carried out on the projected envelope of the workpiece (Trappey and Liu, 1990b). This is feasible because the fixturing faces of the workpiece are assumed to be only parallel or perpendicular to the baseplate. Hence, a 2-D representation will suffice to determine the fixturing configuration on the projected plane. The coordinates of the fixturing points in the projection direction, i.e., z values, can then be determined separately. The proposed method utilizes the boundary representation (B-rep) of the workpiece to determine the fixturing points. The B-rep is obtained from I-DEAS, a solid modeler. It is assumed that the orientation of the workpiece as well as the magnitude and direction of the cutting forces are known. The heuristic algorithms, discussed here, are implemented using C language on a Unix workstation.

2. LITERATURE REVIEW

Automatic Fixture Design is a fairly nascent field though many researchers are currently working in this area. One of the earliest contributions to AFD is by Markus, Markusz, Farkas and Filemen (1984) who developed an expert system which uses PROLOG to design fixtures. This system does not determine the fixturing locations and is designed to select the appropriate fixture elements given the fixturing locations. Asada and By (1985) proposed a fixture design method which uses stability and accessibility of the fixture elements and the workpiece as the criteria for designing the fixture. A number of analytical tools are developed to ensure that the workpiece is stable and accessible. This method considers the workpiece and the fixture elements as rigid bodies and is applicable only to prismatic workparts. Ferriera, Kochar, Liu, and Chandru (1985) proposed a system called AIFIX which uses expert rules to determine the fixturing configuration for a workpiece on a milling center. The workpiece orientation is determined first and then the fixture elements are configured. This system works well for simple workparts with flat surfaces. It is, however, difficult to extend these rules to design fixtures for complex workpieces. Mani and Wilson (1988) evolve a fixture design strategy whose main objective is to fully constrain the workpiece. Rules constructed based on machining practice and workpiece geometry are employed to develop a fixturing plan. This approach to fixture design considers the fixture elements and the workpiece as rigid bodies and also sacrifices accessibility for stability. An automatic fixture planning system proposed by Cutkosky and Lee (1989) uses rules, numerical procedures and symbolic reasoning to determine the fixture layout. This system considers friction as one of the major factors in designing the fixture. Limit surfaces are constructed to analyze friction. These limit surfaces are generated by plotting the slipping forces and moments in the force/moment space. They enclose a volume of safe forces and moments that can be applied without slipping. The construction of limit surfaces, however, becomes complicated for complex fixturing arrangements. In such cases, there is a need for a trade-off between accuracy and computational efficiency.

A method to determine the fixture configuration based on the machining forces was developed by Chou (1990). An envelope of the cutting force field which is an upper bound estimate for the effect of the cutting forces is constructed and a suitable fixture layout is then designed to neutralize it. This method does not consider factors like accessibility of the workpiece and workpiece deformation. Menassa and Devries (1990) propose a fixture design method which configures the fixture elements so as to prevent the workpiece from shifting or rotating under the action of the cutting forces and also to minimize the elastic deformation of the workpiece and the fixture elements. In an earlier related work in 1989, a fixture design method for prismatic workparts was proposed by them. This method uses the 3-2-1 fixturing configuration and employs six rules to determine the locating datum surfaces. The locating and clamping points are then determined by applying kinematic rules with accessibility as the main criterion. Both the methods are strictly restricted to prismatic parts.

Trappey and Liu (1990b) use a technique called Projective Spatial Occupancy Enumeration (PSOE) to determine the fixturing locations. In this technique, the workpiece is projected onto the grid plate of the fixture and decomposed into a number of cells. A heuristic search based on empirical rules is then performed to determine the fixturing locations. Though this research is the first to employ PSOE in the fixture design of non-prismatic workpieces, the proposed heuristic involves extensive computation for complex workpieces which may have a large number of projected cells.

Research in AFD is mostly restricted to prismatic parts with or without simple non-prismatic features like cylindrical holes, whose representation is easier to achieve than those of non-prismatic parts. But, the rapid development of CAD/CAM systems and the widespread use of versatile CNC machines has increased the need to plan and control the manufacture of non-prismatic parts automatically. Hence, there is a growing need for developing fixture design methods which can integrate with existing CAD/CAM systems and be applied to a wider range of workparts. This research is focussed on developing algorithms which can be used to determine the fixturing locations for a more general domain of workpiece geometry.

3. WORKPIECE PROJECTION

Boundary representation (B-rep) is one of the many ways in which a workpiece can be represented. Here, the workpiece is represented in the form of its boundary entities like faces, edges, and vertices. In this work, this 3-D representation is first transformed into its equivalent 2-D form by using an operation known as projection.

In the projection operation, the workpiece is projected onto what is called a projection plane which can be any desired plane in the 3-D space. In fixture design, this plane is the baseplate, which is generally designated as the XY plane. In order to project the workpiece onto the XY plane, the projection axis should be opposite in direction to the baseplate normal which is the positive Z axis. The projection of the workpiece onto the XY plane requires the transformation of the boundary entities of the object into the projection entities. This is done by using a transformation matrix which converts the coordinates in the object space to the projection plane coordinates. The transformation matrix, M, is obtained as the product of a translational matrix, T, and a rotational matrix, R, where

$$T=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -x_o & -y_o & -z_o & 1 \end{bmatrix}$$

$$R=\begin{bmatrix} | & | & | & 0 \\ X_p & Y_p & Z_p & 0 \\ | & | & | & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(x_o, y_o, z_o) and (X_p, Y_p, Z_p) refer to the origin and the direction of the projection plane axes respectively with respect to the original object coordinate system. Any point (x, y, z) in the object space can then be transformed to (x', y') in the projection plane by using the transformation

$$(x', y', z', 1) = (x, y, z, 1) \cdot M$$

z' is then made zero to complete the projection of the 3-D object onto the 2-D projection plane.

4. DESCRIPTION OF THE ALGORITHM

The algorithm for determining the fixturing locations is divided into five parts. It starts with the determination of candidate fixturing points and proceeds on to the determination of the vertical locating and clamping points, the determination of the horizontal locating points, the determination of horizontal clamping points, and finally, the determination of heights for the horizontal fixturing points. The subsequent sub-sections describe the various steps of the algorithm in detail. This algorithm has been implemented in C in the form of five major functions, each representing one of the following subsections, in the same sequence as outlined below.

4.1. Determination of Candidate Fixturing Points

The first step of the algorithm involves the determination of those points on the workpiece which can be used for fixturing purposes. The boundary faces of the workpiece which are perpendicular to the baseplate are projected onto the baseplate to form a set of projected edges. The projected edges that form a part of the outer boundary envelope of the projected workpiece are grouped into a set, **PE**. Further, all those projected edges in **PE** which either do not have a non-machined face or whose non-machined faces are beyond the range of the dimensions of the available fixture elements are eliminated. A flow chart outlining the steps described below is shown in Figures 4, 5 and 6.

If the primary datum face, f_{d1}, is specified, then the candidate vertical locating and clamping points are determined on the projected edges of f_{d1} obtained by projecting f_{d1} onto

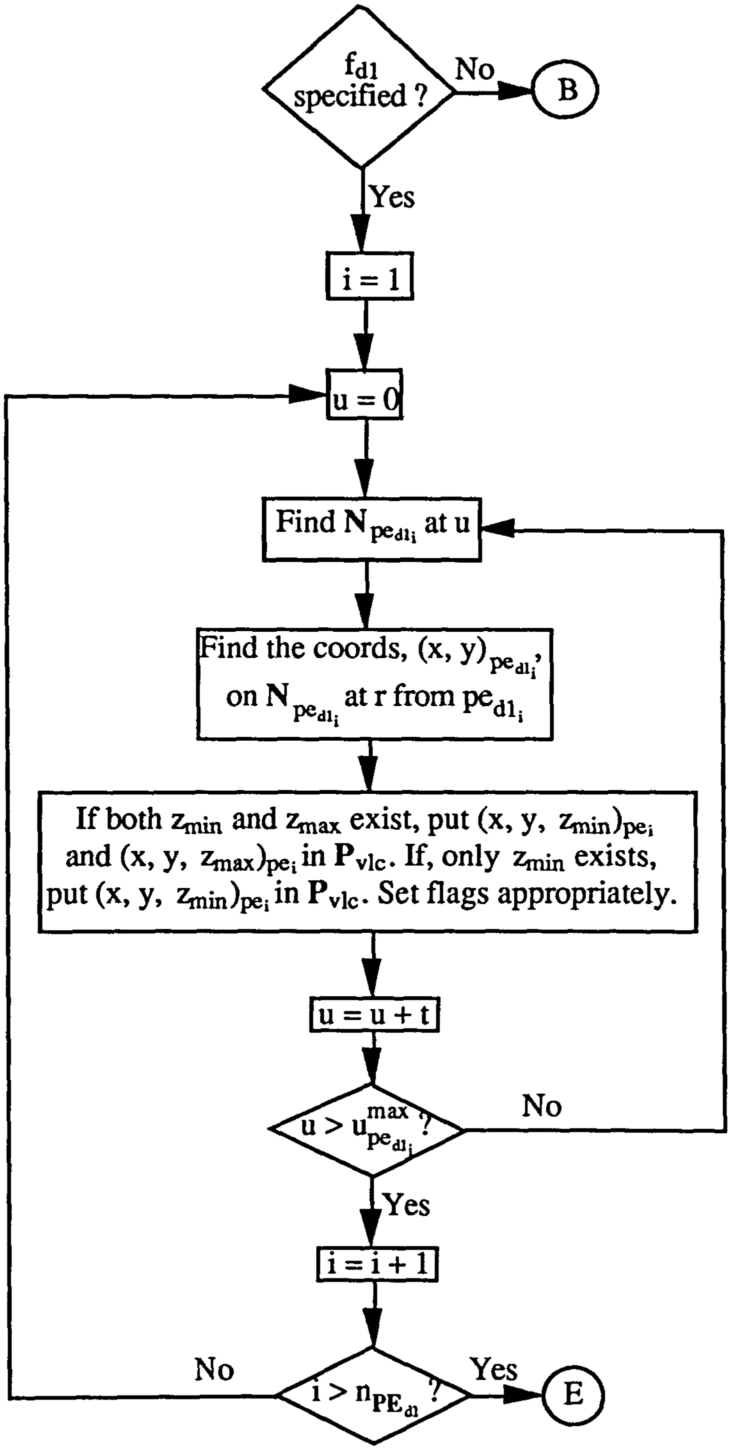

Figure 4. Determination procedure for candidate points

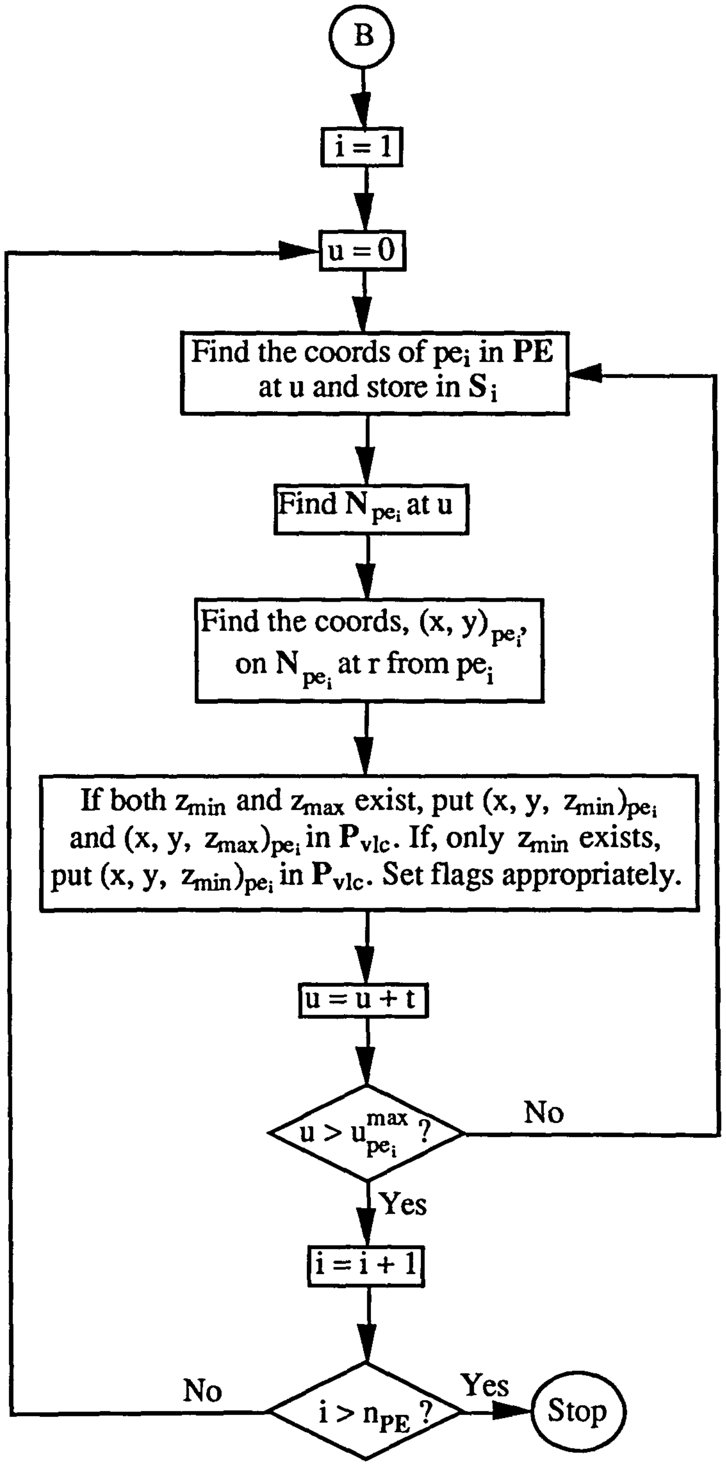

Figure 5. Determination procedure for candidate points

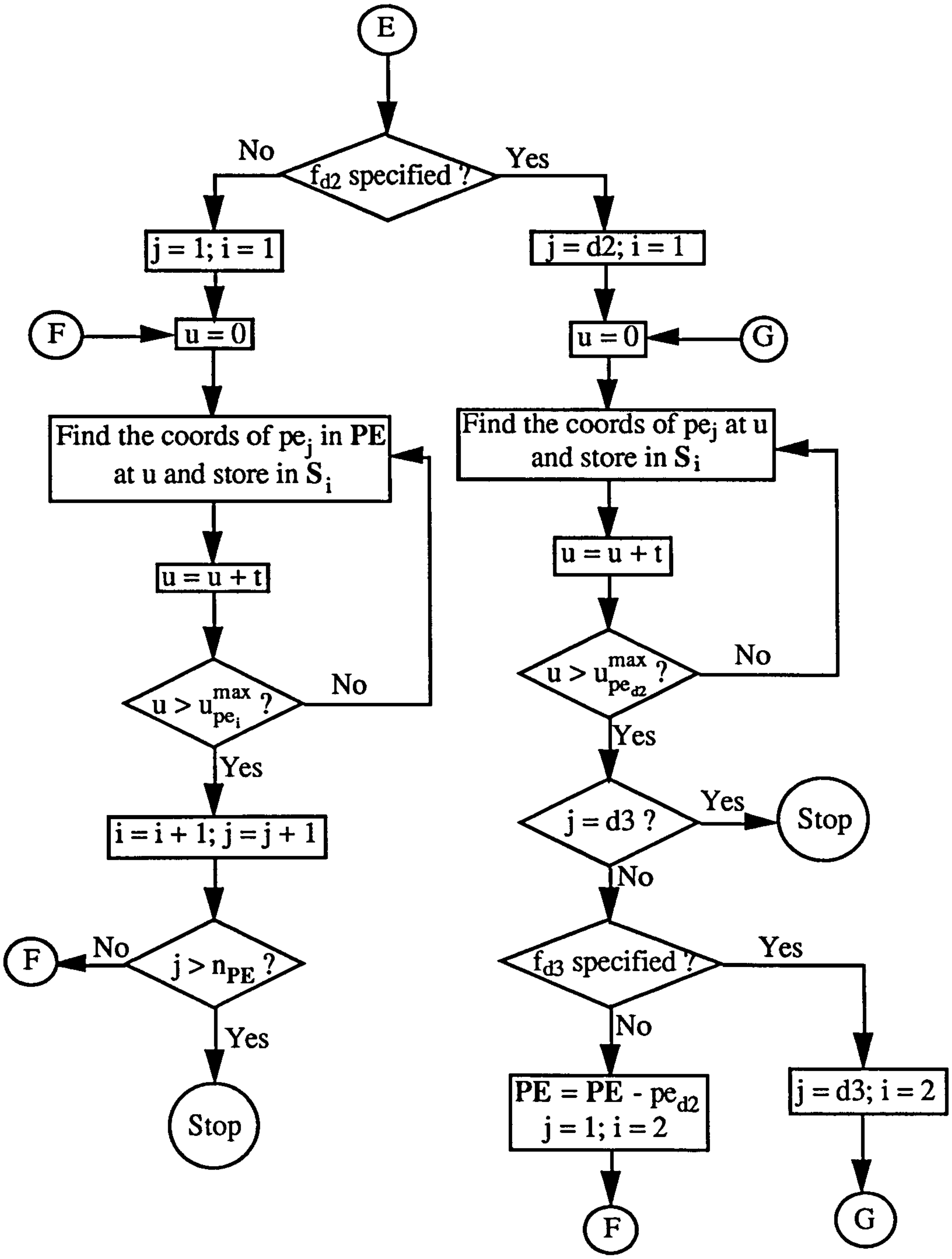

Figure 6. Determination procedure for candidate points

the baseplate. These projected edges constitute the set, $\mathbf{PE}_{d1}$. At fixed intervals, t, along each of these edges, inner normals, $\mathbf{N}_{pe_{d1_i}}$, which point towards the workpiece, are determined. Along each of these normals, coordinates $(x, y)_{pe_{d1_i}}$ at a fixed distance, r, from the edge are determined. The values z_{min} and z_{max} are obtained by finding the minimum and maximum z values, respectively, among the points of intersection of the line, $(x, y) = (x, y)_{pe_{d1_i}}$ with the boundary faces of the workpiece. If the topmost face at this point is to be machined, then z_{min} alone exists at this point and hence $(x, y, z_{min})_{pe_{d1_i}}$ is placed in the set, $\mathbf{P}_{vlc}$, with an appropriate *flag* set to indicate that this point allows only vertical location and no vertical clamping. If both z_{min} and z_{max} exist and the topmost face does not require machining, then $(x, y, z_{min})_{pe_{d1_i}}$ and $(x, y, z_{max})_{pe_{d1_i}}$ are placed in the set, $\mathbf{P}_{vlc}$ with a *flag* appropriately set to indicate that both vertical and clamping are possible at this point. The above sequence of steps is repeated with all the edges in $\mathbf{PE}_{d1}$.

The next step is to determine the feasible horizontal fixturing points. If the secondary datum face, f_{d2}, and the tertiary datum face, f_{d3}, are specified, then, only the edges of these two faces are considered for horizontal fixturing. At fixed intervals, t, along each of these edges, coordinates are determined. If f_{d2} or f_{d3} has not been specified, then all the edges in **PE** are considered for horizontal fixturing. At fixed intervals along each of the edges, pe_i in **PE**, the coordinates are determined and placed in the set, $\mathbf{S}_i$. The $\mathbf{S}_i$ form subsets of the set **S**.

If f_{d1} had not been specified in the first place, then f_{d2} and f_{d3} would not have been specified too. Hence, both the candidate vertical fixturing points and the candidate horizontal fixturing points are determined simultaneously on each of the edges in **PE** using the same procedure as explained above.

Figure 7 shows the projected envelope of a workpiece with the candidate fixturing points marked on it. For this workpiece, none of the datum faces were specified.

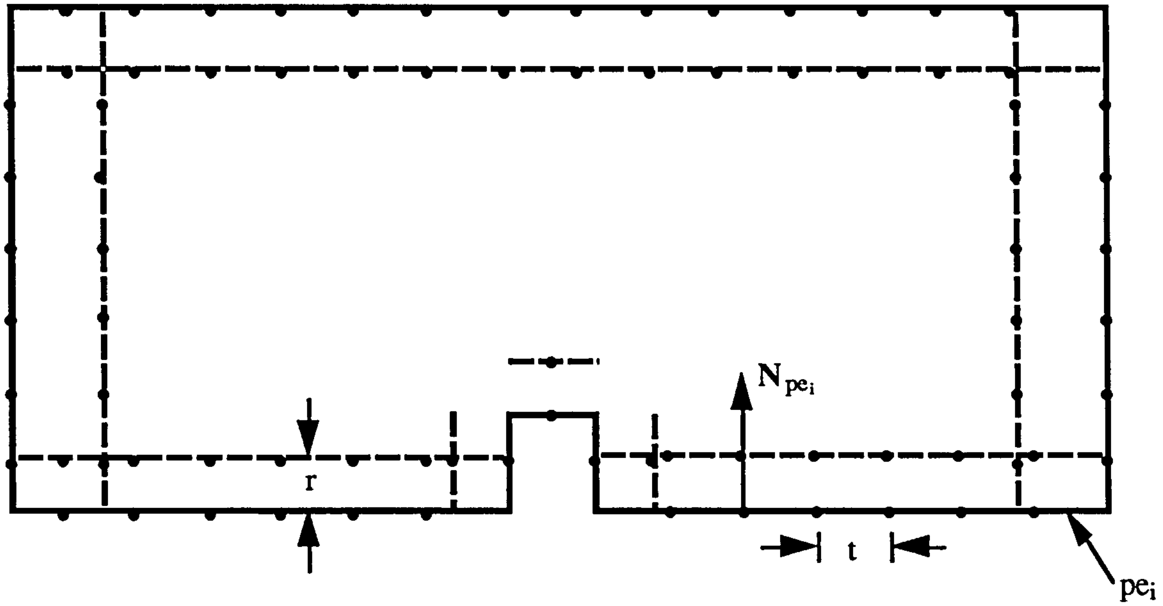

Figure 7. Projected workpiece with candidate fixturing points and the notations r, t, pe_i, and N_{pe_i} marked on it

4.2. Vertical Location and Vertical Clamping

The workpiece is located in the vertical direction by using fixture elements at three points (or four points for large workpieces) which are at their lowest positions (z_{min}) on the workpiece. To determine the vertical fixturing points, the set P_{vlc} is analyzed with respect to various criteria discussed here. A flow chart outlining the steps detailed below is shown in Figure 8.

If the set P_{vlc} exists, then the points in the set are projected onto the baseplate and the projected points are used as vertices to form all possible triangles. All those triangles which do not enclose the projected center of mass (CM) or whose sides are too close to the CM, i.e., within a certain tolerance, are eliminated. This enables the selection of a

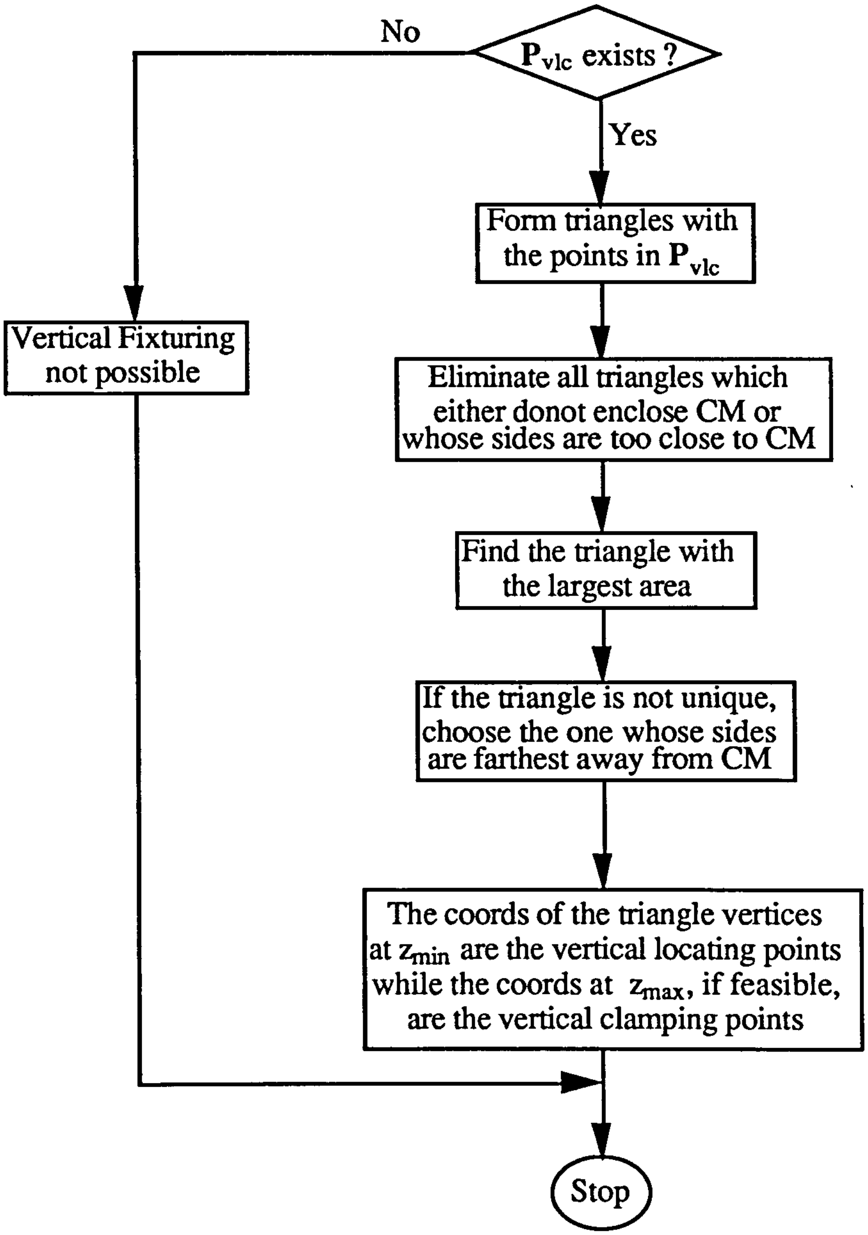

Figure 8. Determination procedure for vertical location and clamping

configuration which provides maximum workpiece stability. Among the remaining triangles, the triangle with the largest area is chosen as the best vertical fixturing configuration. If this triangle is not unique, i.e., more than one triangle has the same largest area, then the triangle whose sides are farthest away from the CM is selected. The vertices of this triangle form the vertical fixturing points. At each fixturing point, (x, y), vertical location is done at (x, y, z_{min}) while vertical clamping, if possible, is done at (x, y, z_{max}).

It is to be noted here that vertical clamping may not be possible at three points although vertical location may be possible at three points. For large workpieces, it may be desirable to use clamps on the positions given by the algorithm, even when the number is less than three, since this would enhance the stability of the workpiece while machining.

Figure 9 shows the largest triangle determined for the projected envelope of a workpiece. The vertices of this triangle are the vertical fixturing points.

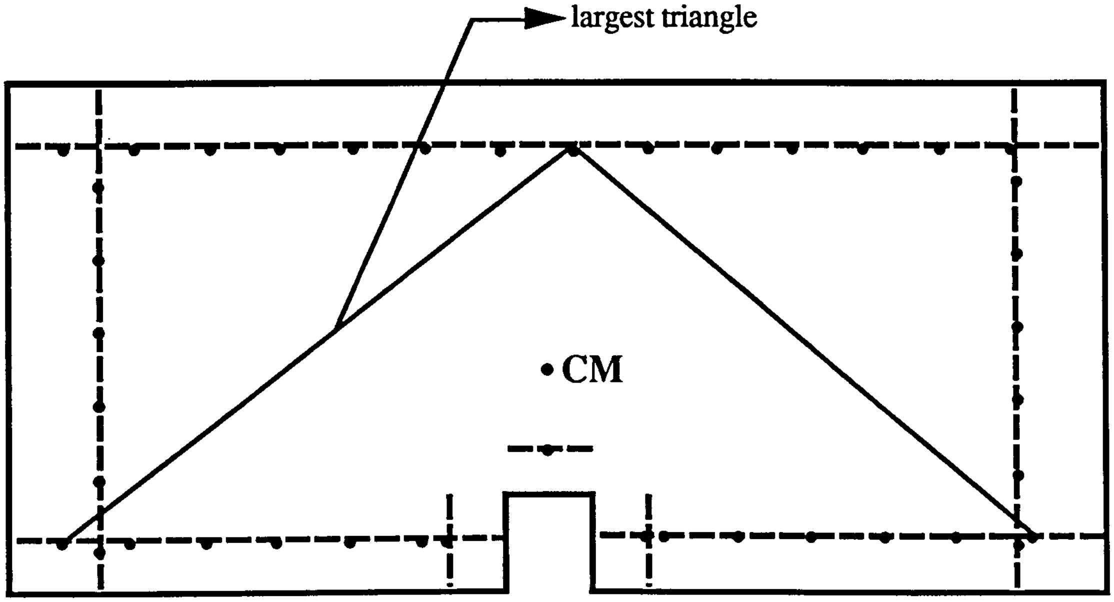

Figure 9. Workpiece shown with projected vertical fixturing points

4.3. Horizontal Location

The horizontal location of the workpiece is achieved by using three locators--two on a face that is perpendicular to the baseplate and the third on one of the remaining faces that is also perpendicular to the baseplate. This section describes only the determination of the position of these points on the baseplate (i.e., the x and y coordinates). The heights of the locators (i.e., the z coordinate) are determined in Section 4.5 along with the heights of the clamps so that they can be considered simultaneously. The search for the (x, y) positions of the horizontal locators is carried out using the candidate fixturing point set **S** determined in Section 4.1. A flow chart for horizontal location is shown in Figures 10 and 11.

There are three different cases to be considered here.

<u>Case 1</u> f_{d2} and f_{d3} are specified.

$$\mathbf{PP}_{d2} = \{ \mathbf{S}_{pe_{d2}} \}$$

$$\mathbf{PP}_{d3} = \{ \mathbf{S}_{pe_{d3}} \}$$

$$\mathbf{S} = \mathbf{S} - \mathbf{PP}_{d2} - \mathbf{PP}_{d3}$$

The two extreme points, M and N, of $\mathbf{PP}_{d2}$ are determined. Similarly, the two farthest points in $\mathbf{PP}_{d3}$ are determined. Triangles are formed using M, N and each of the two extreme points in $\mathbf{PP}_{d3}$ as vertices. The triangle having the maximum area is then chosen as the best horizontal locating configuration. The vertices, M, N, O, of this triangle are recorded along with the corresponding projected locating edges given by,

$$pe_{l2} = pe_{d2}, \text{ and}$$

$$pe_{l1} = pe_{d3},$$

where pe_{l2} is the projected two-point locating edge containing the points, M and N, and pe_{l1} is the projected single-point locating edge containing the point O.

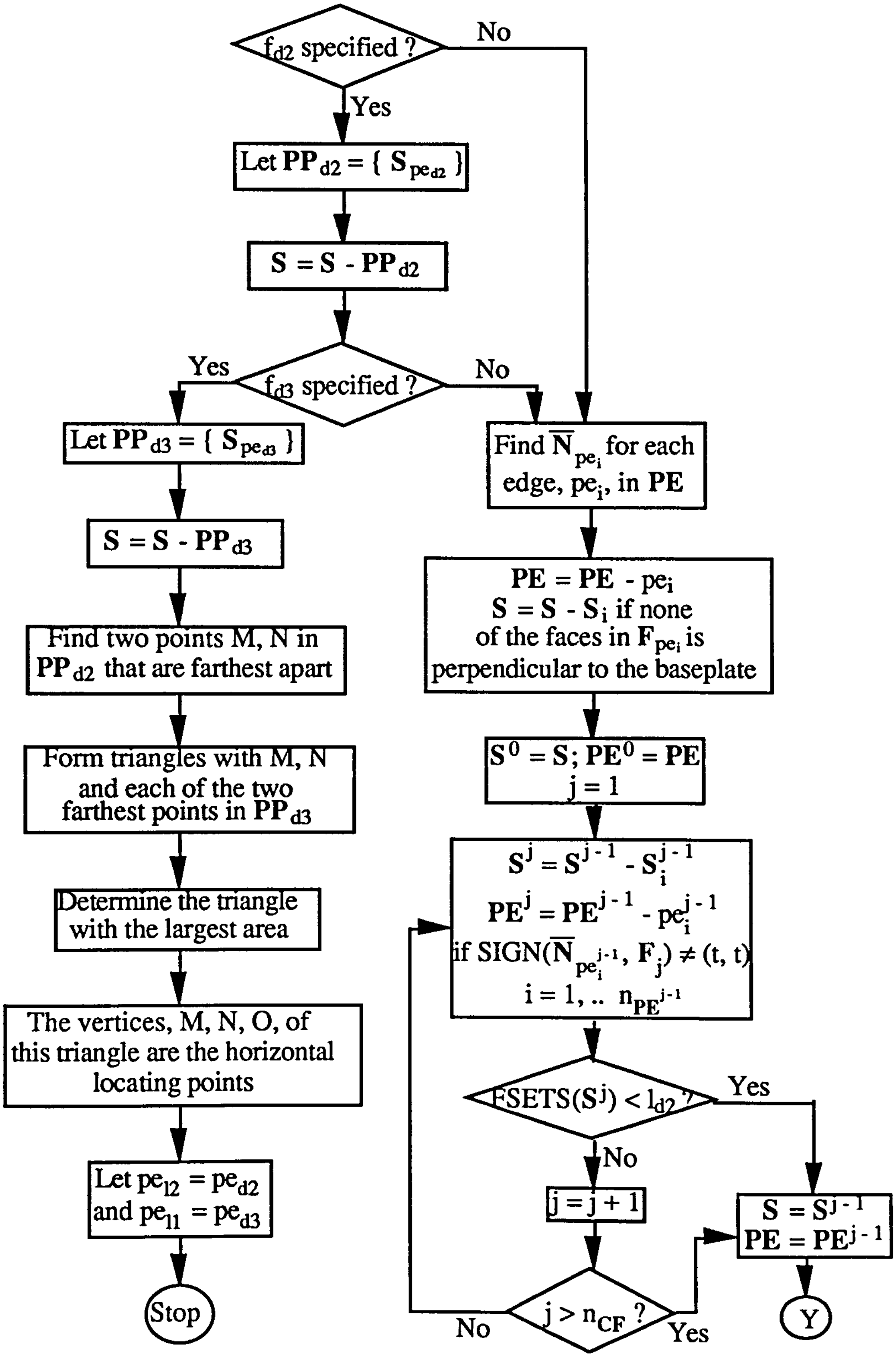

Figure 10. Determination procedure for horizontal location

Case 2 f_{d2} is specified but not f_{d3}.

$$\mathbf{PP}_{d2} = \{ S_{pe_{d2}} \}$$

$$\mathbf{S} = \mathbf{S} - \mathbf{PP}_{d2}$$

$$\mathbf{PE} = \mathbf{PE} - pe_{d2}$$

All those projected edges, pe_i, which are not directed towards any of the major cutting forces are eliminated along with their corresponding candidate fixturing point set, S_i, i.e.,

$$\mathbf{S} = \mathbf{S} - \mathbf{S}_i \text{ and } \mathbf{PE} = \mathbf{PE} - pe_i$$

$$\text{if SIGN } (\overline{N}_{pe_i}, \mathbf{F}_j) \neq (f, f); \;\; j = 1, .. \, n_{CF}$$

If FSETS(**S**) becomes less than 'l_{d2}' (= 1), the **S** obtained at the end of the previous iteration is considered for subsequent operations. The two extreme points, M and N of $\mathbf{PP}_{d2}$ are determined. For each $\mathbf{S}_i$ in **S**, the two extreme points, P^i_1 and P^i_2, in that set are determined such that the normals at each of the two points are not directed towards or away from the normals at M and N, i.e.,

$$\text{SIGN } (N_{pe_{d2}}(M), N_{pe_i}(P^i_k)) = (t, f) \text{ or } (f, t) \text{ and}$$

$$\text{SIGN } (N_{pe_{d2}}(N), N_{pe_i}(P^i_k)) = (t, f) \text{ or } (f, t)$$

$$i = 1, .. \, n_{PE} \; ; \; k = 1 \text{ or } 2$$

Triangles are then formed using M, N and the two feasible extreme points in each S_i as vertices. The largest triangle is selected as the best configuration and its vertices M, N and O are recorded along with the corresponding projected locating edges given by,

$$pe_{l2} = pe_{d2}, \text{ and}$$

$$pe_{l1} = pe_i \;\; \text{such that} \;\; O \in \{ S_i \},$$

where pe_{l2} is the projected two-point locating edge containing M and N, and pe_{l1} is the projected single-point locating edge containing O.

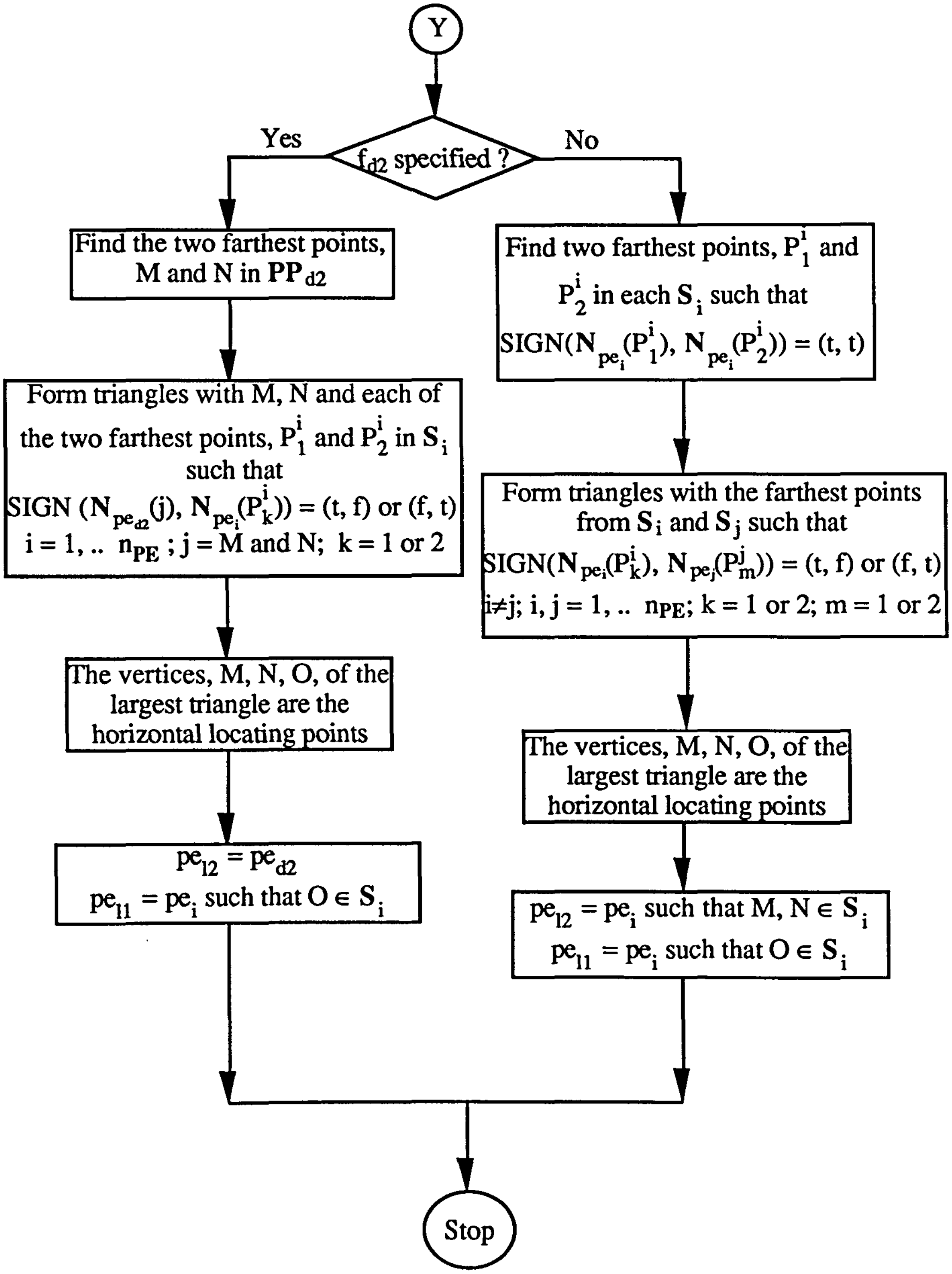

Figure 11. Determination procedure for horizontal location

Case 3 Both f_{d2} and f_{d3} are not specified.

All those projected edges, pe_i, which are not directed towards any of the major cutting forces are eliminated along with their corresponding candidate fixturing point set, S_i, i.e.,

$$\mathbf{S} = \mathbf{S} - S_i \text{ and } \mathbf{PE} = \mathbf{PE} - pe_i$$

$$\text{if SIGN } (\overline{N}_{pe_i}, F_j) \neq (f, f); \; j = 1, .. n_{CF}$$

If FSETS(S) becomes less than 'l_{d2}' (= 2), the S obtained at the end of the previous iteration is considered for subsequent operations. For each S_i in S, the two extreme points, P^i_1 and P^i_2, in that set are determined such that the normals at the two points are not directed towards each other, i.e,.

$$\text{SIGN } (N_{pe_i}(P^i_1), N_{pe_i}(P^i_2)) = (t, t)$$

Triangles are then formed using the extreme points in S_i and S_j such that the normals at the two-point location are not directly pointed towards or away from the normal at the single-point location to facilitate easy loading/unloading of the wokpiece and to avoid two-point location redundancy, i.e.,

$$\text{SIGN } (N_{pe_i}(P^i_1), N_{pe_j}(P^j_m)) = (t, f) \text{ or } (f, t) \text{ and}$$

$$\text{SIGN } (N_{pe_i}(P^i_2), N_{pe_j}(P^j_m)) = (t, f) \text{ or } (f, t)$$

$$i, j = 1, .. n_{PE} \; ; \; m = 1 \text{ or } 2$$

The largest triangle is selected as the best configuration and its vertices M, N and O are recorded along with the corresponding projected locating edges given by,

$$pe_{l2} = pe_i \text{ such that } M, N \in \{ S_i \}, \text{ and}$$

$$pe_{l1} = pe_j \text{ such that } O \in \{ S_j \},$$

where pe_{l2} is the projected two-point locating edge containing M and N and pe_{l1} is the projected single-point locating edge containing O.

Figure 12 shows a workpiece wtih the projected horizontal locating points determined according to the steps of the algorithm described above.

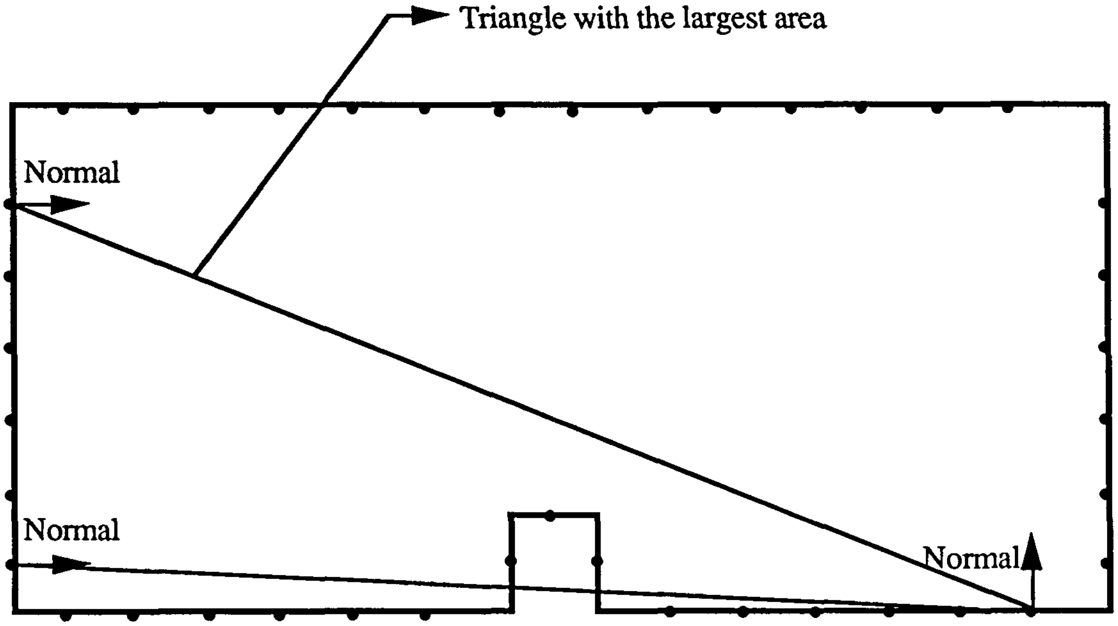

Figure 12. Workpiece shown with projected horizontal locating points

4.4. Horizontal Clamping

The horizontal clamping of the workpiece is achieved by using two horizontal clamps--one against the two-point locators and the other against the single-point locator. This section describes only the determination of the x and y coordinates of the clamping positions (on the baseplate). The z coordinate i.e., the height of the clamps is determined in Section 4.5. A flow chart for this section is shown in Figure 13.

The clamping position for the two-point locators is first determined. The midpoint P2, of the 2 locating points M and N, and the vector V, which is the average of the normals at M and N, are determined.

$$P2 = (M + N) / 2$$

$$V = (N_{pel2}(M) + N_{pel1}(N)) / 2$$

The projected locating edges, pe_{l2} and pe_{l1} are removed from the set of projected edges, **PE**, i.e.,

$$\mathbf{PE} = \mathbf{PE} - pe_{l2} - pe_{l1}$$

The intersecting points of **V** with each of the edges in **PE** are determined. If there are no intersections, then two-point clamping is not possible. Otherwise, the intersecting point C2 on the edge pe_{c2}, which is farthest from P2 among all the intersecting points and whose normal is directed towards the average normal of the two-point location, i.e.,

$$\text{SIGN}\ (\mathbf{V}, N_{pe_{c2}}(C2)) = (f, f),$$

is chosen as the horizontal clamping position.

The next phase involves the determination of the clamping position corresponding to the single-point locator. The normal $N_{pe_{l1}}(O)$ is determined.

The projected two-point clamping edge, pe_{c2}, is removed from the set of projected edges, **PE**, i.e.,

$$\mathbf{PE} = \mathbf{PE} - pe_{c2}$$

The intersecting points of the normal with each of the edges in **PE** are determined. If there are no intersections, then single-point clamping is not possible. Otherwise, the intersecting point C1 on the edge pe_{c1}, farthest from O among all the intersecting points and whose normal is directed towards the normal at the single-point location, i.e.,

$$\text{SIGN}\ (N_{pe_{l1}}(O), N_{pe_{c1}}(C1)) = (f, f),$$

is chosen as the single-point clamping position.

The projected horizontal clamping points for a projected workpiece determined using the steps outlined above, is illustrated in Figure 14.

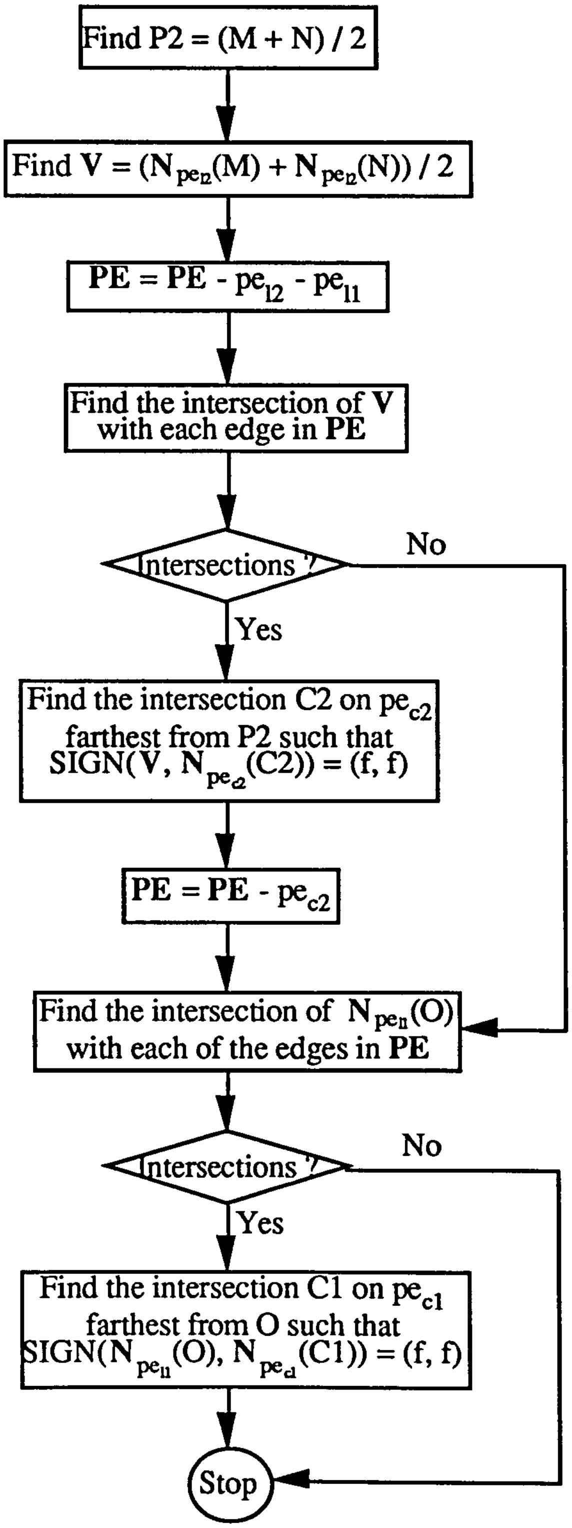

Figure 13. Determination procedure for horizontal clamping

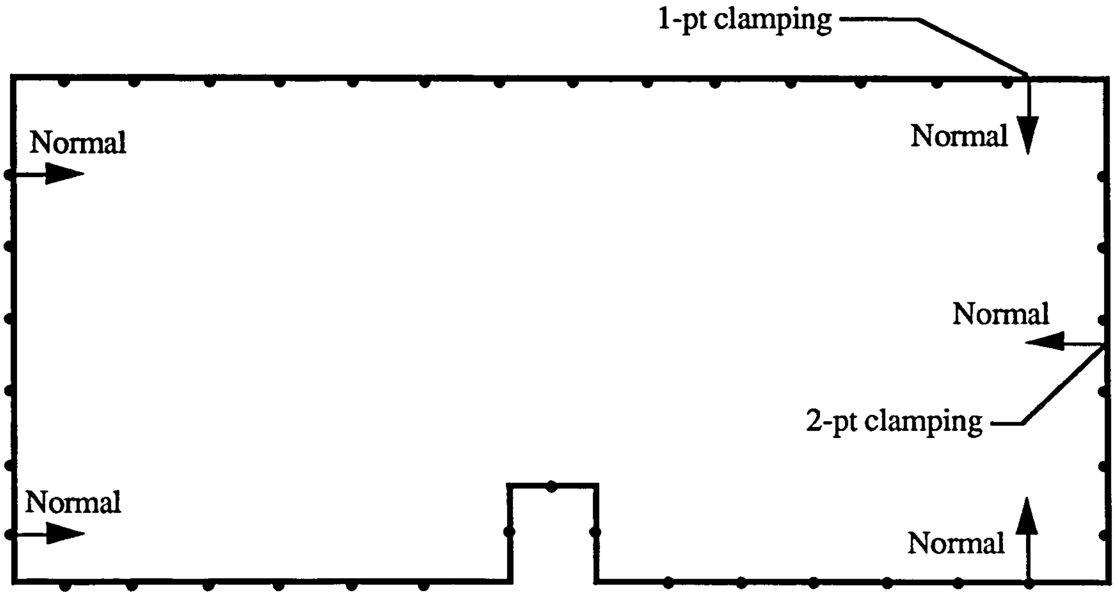

Figure 14. Horizontal clamping points for a projected workpiece

4.5. Height Determination for Horizontal Location and Clamping

The final phase involves the determination of the z coordinate i.e., the height for the horizontal locating and clamping positions determined in the previous sections. A flow chart for this section is shown in Figure 15.

The set of faces, F_{pe_i}, i = 12, 11, c2, c1, whose projection is the edge pe_i, are determined. In each set, all those faces which are not perpendicular to the baseplate are eliminated, i.e.,

$$F_{pe_i} = F_{pe_i} - f_j,$$
$$i = 12, 11, c2, c1; \; j = 1, .. n_{F_{pe_i}},$$
$$\text{if } N_{f_j} . (0\ 0\ 1) \neq 0.$$

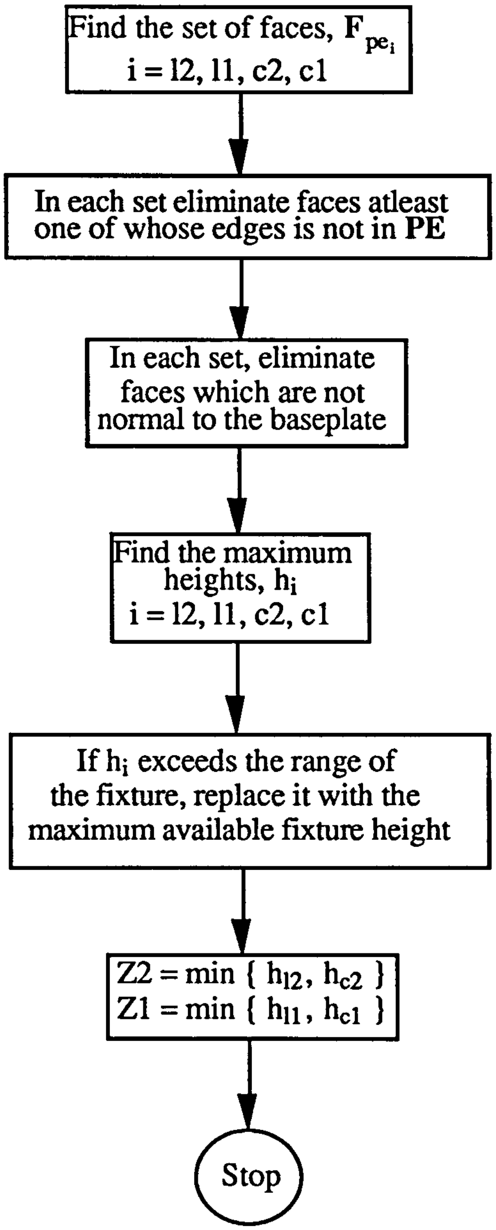

Figure 15. Determination procedure for location and clamping heights

The maximum heights h_i, i = l2, l1, c2, c1, are obtained by finding the maximum z value of the faces in F_{pe_i}. If any of these heights exceed the range of the available fixture elements, then it is replaced with the maximum height of the available fixture element. Z2, which is the height for the two-point clamping and locating positions, M, N, and C2 respectively, and Z1, which is the height for the single-point locating and clamping positions, O and C1 respectively, are then given by,

$$Z2 = \min \{ h_{l2}, h_{c2} \}, \text{ and}$$

$$Z1 = \min \{ h_{l1}, h_{c1} \}.$$

Figure 16 shows the heights determmined for 2-pt fixturing for a workpiece while Figure 17 shows the 1-pt fixturing height determined using the steps outlined above.

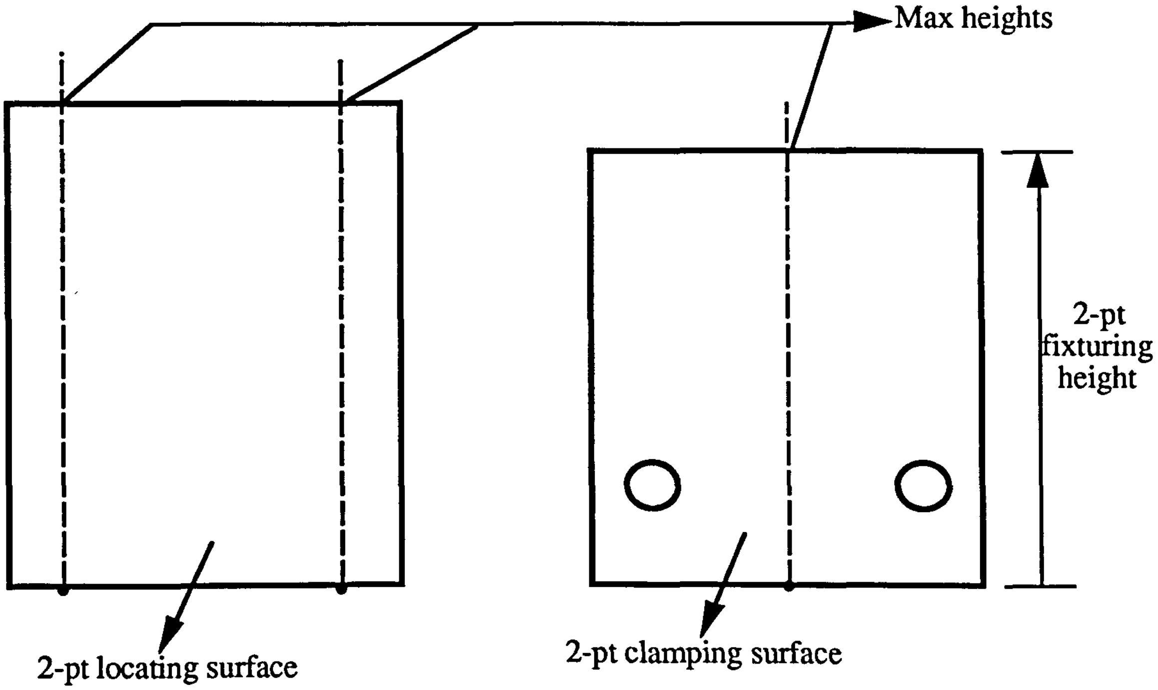

Figure 16. 2-pt fixturing height for a workpiece

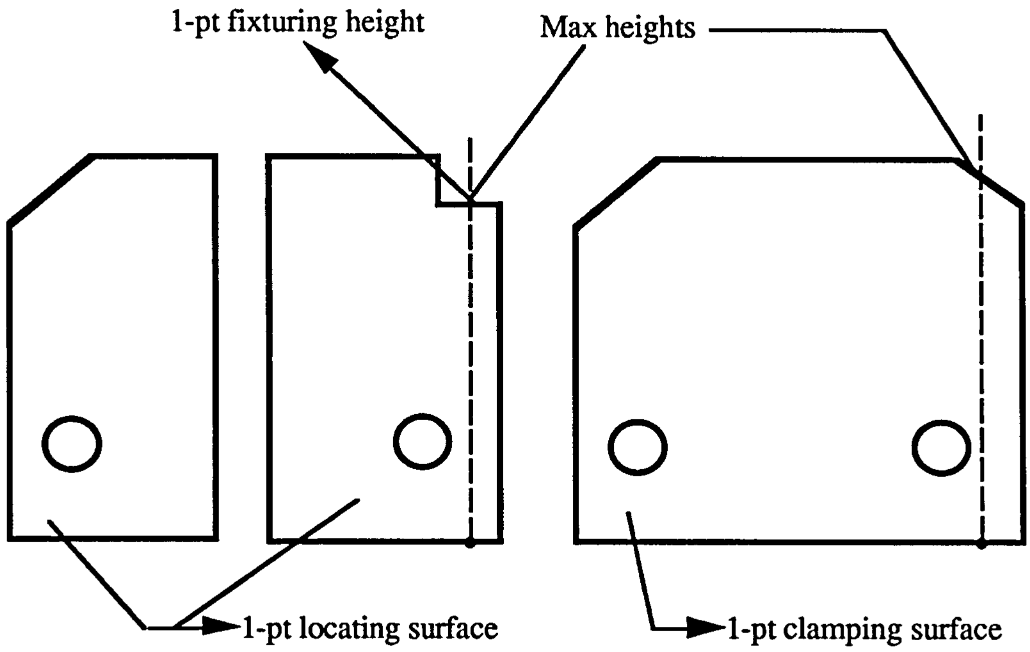

Figure 17. 1-pt fixturing height for a workpiece

5. SOFTWARE IMPLEMENTATION

The algorithms discussed in the previous chapter have been implemented in C language on a **Unix** workstation. A module based approach is used to achieve the implementation. The various stages of the algorithm are implemented as individual modules to enable easy development and debugging. The software obtains the required B-rep information of the workpiece from the **PEARL** database of **I-DEAS**, a solid modeler.

The main program reads the necessary inputs from a file whose name is specified by the user. The inputs read from the file are :

1. B-rep information of the final workpiece--the surfaces and the edges of the workpiece including the relationship between the surfaces and the edges.
2. A list of the surfaces being machined,
3. The cutting forces represented as vectors,
4. The Center of Mass (CM) of the workpiece,
5. The IDs of the datum surfaces, and
6. The stepping length along the edge as well as along the normal from the edge.

The B-rep information obtained from the PEARL database is in the Non-Uniform Rational B-spline (NURB) format. All surfaces are represented in the form of non-periodic NURB of upto order four. The NURB represntation is discussed in Appendix C. Since this algorithm assumes that all the feasible boundary surfaces for fixturing are either parallel or perpendicular to the baseplate, there is no necessity to store the surfaces which are neither perpendicular nor parallel to the baseplate. Thus, the surfaces are read one at a time, converted into their corresponding polynomial form and stored only if they are parallel or perpendicular to the baseplate. In order to check the perpendicularity of a surface, the normal to the surface at each of the breakpoints is verified against the baseplate normal. Each surface has an ID attached to it.

The surfaces of the workpiece are represented in the form of non-periodic Non-Uniform Rational B-splines. In this format, each surface has a set of control points which define a polygon that encloses the surface, a set of knot points along the u and the v directions which determine the range of the parameters in each patch, and a set of weights assigned to each control point (Choi, 1991). The surface is divided into a series of patches and the shape of each patch is controlled only by a subset of the control points, the size of which is determined by the order of the surface along the u and the v directions. The knot points then determine the range of the parameters in each of these patches. The weights are used to pull the surface towards the control points. The larger the weight assigned to a control point, the closer the surface is to it. The data structure used to represent the NURB surface is shown in Figure 18. The data structure contains a pointer to the set of control points, a pointer to the array of knots along u, a pointer to the array of knots along v, the number of control points along u, the number of control points along v, the order of u, the order of v, and the ID of the surface. The NURB surface is converted to the polynomial form using a recursive function and the data structure used to store this polynomial form is shown in Figure 19. This data structure contains a pointer to the array of coefficients of the polynomials, a pointer to the array of breakpoints along u, a pointer to the array of breakpoints along v, the number of patches along u, the number of patches along v, a flag to indicate if the surface is parallel to the xy plane, and the ID of the surface.

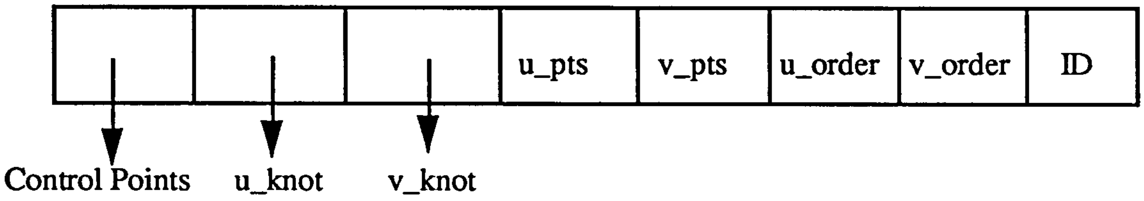

Figure 18. Structure for representing a NURB surface

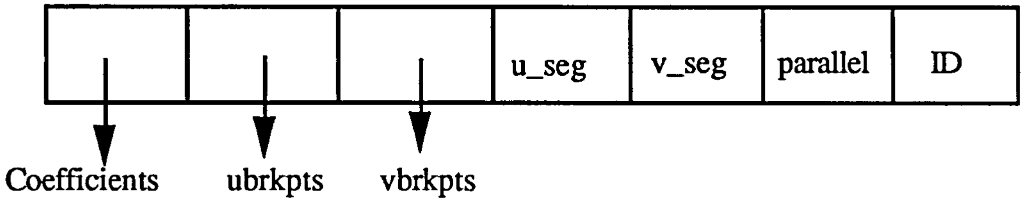

Figure 19. Structure for representing the polynomial form of a surface

The edges of the workpiece are represented in the form of NURB curves. The PEARL database contains two different types of curves--original and computed. An original boundary curve is an iso-parametric curve on a surface and is obtained by setting one of the parameters of the surface to a constant value. Thus, an original curve need not have a separate NURB representation. It can be obtained from the surface to which it belongs, once the constant parameter and its value are known. On the other hand, a computed curve is a curve which requires a separate NURB representation in the form of control points, knot points, and weights. This is not an iso-parametric curve of the underlying surface. An original boundary curve is stored with the constant parameter ID (constant **u** or constant v), the constant parameter value, the surface ID, the curve ID, and the start and end points of the varying parameter. The polynomial form of this curve is obtained from the polynomial form of the underlying surface, whenever needed. This reduces the amount of memory used to store the B-rep information. The data structure used to store a curve of this type is shown in Figure 20.

const_flag	const_value	init_value	final_value	surf_id	cur_id

Figure 20. Structure for representing an original curve

The computed curves are in the NURB format similar to that of a surface but with a single parameter. Each of these curves have a series of control points, a set of knot points, and a set of weights similar to that of a surface described above. The data structure used to store this curve is shown in Figure 21. Each of the computed curves is converted into its polynomial form using a recursive function called the blending function and stored along with its ID and its underlying surface ID in a structure shown in Figure 22. Curves belonging to only the perpendicular and the parallel surfaces are stored since only those surfaces form candidate fixturing surfaces.

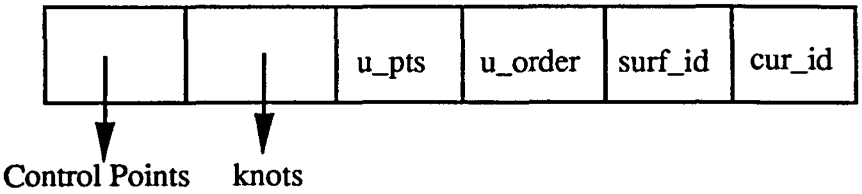

Figure 21. Structure for representing a NURB curve

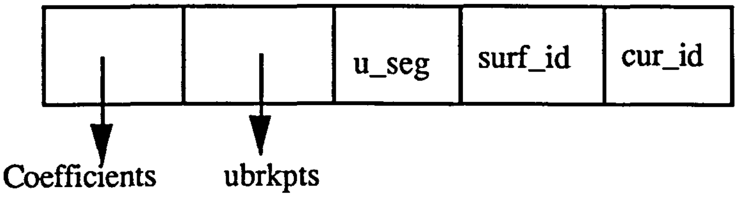

Figure 22. Structure for representing the polynomial form of a curve

The method followed to determine the fixturing points depends on the number of datum faces specified.

Case 1 All three datum faces are specified.

The candidate fixturing points need to be determined only on the projected edges of the three surfaces. The projection of each surface is determined by comparing the z values of the constituting edges. The projection of a surface may compose of a series of original boundary curves and a series of computed boundary curves. The z values of the edges of a surface are compared at three points on each of the edges and the edges with the maximum values at each of these points are retained as the projection of the surface after setting their z coordinates to zero. Once the projected edges are known, the candidate fixturing points are determined as explained in Chapter 4. The maximum and minimum z coordinates at each of the candidate vertical fixturing points are determined and stored in a structure along with the corresponding x, y coordinates. The points on the secondary datum face are stored in a structure different from that of the tertiary datum face. Each of these structures also contains the curve id corresponding to each point.

The vertical locating (and clamping, if feasible) points and the horizontal locating and clamping points are determined by applying the optimality criteria discussed in the previous chapter. The heights for horizontal fixturing are determined using an iterative procedure. At each of the horizontal fixturing points, the z coordinates of all the edges of the underlying surface are determined by intersecting the normal to the baseplate drawn through this point with each of the edges. The list of heights are compared and the maximum height for which both location and clamping are feasible is selected as the horizontal fixturing height. Thus, both location and clamping are at the same height, if they are feasible.

Case 2 Only two datum faces are specified.

The candidate fixturing points need to be determined on the projected edges of the primary surface, the secondary surface as well as on all the outermost projected edges. The projected edges are determined as explained before. In order to determine the outermost projected edges, a tehnique similar to the one used to determine the projections is applied. At three points on each of the projected edges, lines parallel to x-axis and the y-axis are drawn in turn. The maximum and the minimum intersecting edges at each of these points then members of the set of outermost projected edges. The candidate fixturing points are stored in structures the same way as explained under Case 1.

The vertical locating (and clamping) points and the projected horizontal locating and clamping points are determined using the optimality criteria discussed in Chapter 4. The heights for horizontal fixturing points are determined using the same subroutines as the ones used for Case 1.

Case 3 Only the primary datum face is specified.

The candidate fixturing points need to be determined on the projected edges of the primary datum face and on all the outermost projected edges. The candidate points for horizontal fixturing are stored in a single structure since only the primary datum face is specified. The vertical locating (and clamping) points and the projected horizontal locating and clamping points are determined using the optimality criteria discussed in Chapter 4. The heights for horizontal fixturing points are determined using the same subroutines as the ones used for Case 1.

Case 4 None of the datum faces are specified.

The candidate fixturing points for both vertical fixturing and horizontal fixturing need to be determined on all the outermost projected edges and are handled concurrently. The rest of the computations are handled the same way as in Case 3.

The working of the software is demonstrated using a sample workpiece. The program was run for two different setups of the workpiece and the results are shown in Appendices A and B in the form of figures with the positions of the locators and clamps displayed on the workpiece.

6. EXAMPLE

To demonstrate the working of the algorithm, the workpiece shown in Figure 6 is used as the example. For this workpiece, the primary datum face f_{d1} is specified while f_{d2} and f_{d3} are not specified. The machining operation to be done is the milling of the deep pocket on the top face of the workpiece. The subsequent sections describe the steps following the sequence of the algorithms discussed in Chapter 4.

6.1. Determination of Candidate Fixturing Points

The first step involves the determination of candidate points for horizontal and vertical fixturing. The boundary representation of f_{d1} obtained from the database of a solid modeler, I-DEAS, is shown in Table 1.

Table 1. Boundary representation of f_{d1}

FACE_ID	EDGE_ID	START VERTEX	END VERTEX	NORMAL
f_{d1}	e_{d1_1}	1	2	(0, 1, 0)
f_{d1}	e_{d1_2}	2	3	(-1, 0, 0)
f_{d1}	e_{d1_3}	3	4	(0, -1, 0)
f_{d1}	e_{d1_4}	4	1	(1, 0, 0)

The negative z axis forms the projection axis. Hence, the projected edges of f_{d1} are obtained by setting the z coordinate of each of the edges of f_{d1} to zero. Thus, the set $\mathbf{PE}_{d1}$ becomes

$$\mathbf{PE}_{d1} = \{ pe_{d1_i} \}, i = 1, .. 4.$$

Taking the values of r and t as 10 and 0.1 respectively, the set of candidate fixturing points, for all the edges in $\mathbf{PE}_{d1}$ are determined. In order to avoid points at the corners, the corner points are removed from the set of candidate fixturing points. Since a major portion of the top face undergoes machining, vertical clamping is not possible and hence all these points are placed in the set $\mathbf{P}_{vl}$. $\mathbf{P}_{vl}$ appears as follows :

$$\mathbf{P}_{vl} = \{ (x_j, y_j, z_{min})_{pe_{d1_i}} \},$$

$$i = 1, .. 4 \text{ and } j = 1, .. n_i.$$

Since f_{d2} and f_{d3} are not specified, the coordinates of candidate horizontal fixturing points should be determined on each of the edges in **PE**. The set **PE** is composed of the edges of the outer boundary envelope of the projected workpiece. In order to obtain the projected envelope, the faces of the workpiece are projected onto the xy plane and the outermost edges are identified using the ray-casting technique. **PE** altogether has four edges. By taking the value of t as 0.1, the sets $\mathbf{S}_1$ through $\mathbf{S}_4$ which are the feasible projected fixturing points on the edges pe_1 through pe_4 are determined. The set **S** is then formed using these subsets.

$$\mathbf{S} = \{ \mathbf{S}_j \}, j = 1, .. 4.$$

6.2. Vertical Location and Clamping

For this workpiece $\mathbf{P}_{vl}$ exists and clamping is not possible at any of the candidate vertical fixturing points. The points in $\mathbf{P}_{vl}$ are used as vertices to form triangles that enclose the projected center of mass which is at (70, 46). The largest among these triangles satisfying the conditions imposed in Section 4.2 is found to be the one with vertices at (130, 9.2, 0), (130, 82.8, 0) and (10, 46, 0). Hence, the vertical locating points are (130, 9.2, 0), (130, 82.8, 0) and (10, 46, 0).

6.3. Horizontal Location

The machining operation considered in this example is the milling of the pocket on the top face. From Chou (1990), the forces at each of the four segments of the pocket are dominated by the forces at the end points of those segments. In addition, the tangential force is the most significant force. Since this force is approximately uniform on all segments, there are eight forces with equal magnitude which point along the normal to the corresponding edges. As all the forces are equally significant, it is not possible to eliminate any of the edges based on the criteria described in Case 3 in Section 4.3.

The two most extreme points in each subset of **S** are determined such that their normals are not directed towards each other, i.e.,

{ (0, 6), (0, 86) }, { (14, -4), (126, -4) },

{ (140, 6), (140, 86) }, and { (126, 96), (14, 96) }.

By forming triangles with these points such that the normals of two-point location are not directed towards or away from the normal of the single-point location, the largest triangle is determined to be the one with the vertices (14, -4), (126, -4) and (140, 86). Thus, the three projected horizontal locating points are :

M = (14, -4),
N = (126, -4), and
O = (140, 86)

where M and N are the two-point locations and O is the single-point location.

The projected edges containing these points are pe_1 and pe_2 i.e.,

$$pe_{l2} = pe_1 \text{ and } pe_{l1} = pe_2.$$

6.4. Horizontal Clamping

The midpoint P2 of M and N is (70, -4).

$$\mathbf{V} = (N_{pe_{l2}}(M) + N_{pe_{l2}}(N)) / 2 \equiv (0, 1, 0), \text{ and}$$

$$\mathbf{PE} = \mathbf{PE} - pe_{l2} - pe_{l1} = \{ pe_3, pe_4 \}.$$

V, the average of the normals at the two horizontal locating points, intersects pe_3 at (70, 96). Therefore, the clamping point for two-point location is

C2 = (70, 96) and the corresponding edge containing C2 is $pe_{c2} = pe_3$.

$$\mathbf{PE} = \mathbf{PE} - pe_{c2} = \{ pe_4 \}, \text{ and}$$

$$N_{pe_{l1}}(O) \equiv (-1, 0, 0).$$

$N_{pe_{l1}}(O)$ intersects pe_4 at (0, 86). Therefore, the clamping point for single-point location is C1 = (0, 86) and the corresponding edge containing C1 is the edge pe_4, i.e.,

$$pe_{c1} = pe_4.$$

6.5. Height Determination for Horizontal Location and Clamping

The set of faces whose projected edge is pe_i, $i \in \{ l2, l1, c2, c1 \}$, is determined and the faces which are not perpendicular to the baseplate are eliminated. Thus,

$F_{pel2} = \{ F1 \}$, $F_{pel1} = \{ F2 \}$, $F_{pe_{c2}} = \{ F3 \}$, and $F_{pe_{c1}} = \{ F4 \}$.

It is assumed that the fixture elements require a contact width of 20mm. Using this constraint, the heights h_{l2}, h_{l1}, h_{c2} and h_{c1} are computed as 80, 80, 80 and 80 respectively.

$$Z1 = \min \{ 80, 80 \} = 80$$

$$Z2 = \min \{ 80, 80 \} = 80$$

Therefore, the horizontal locating points are (14, -4, 80), (126, -4, 80), and (140, 86, 80). The horizontal clamping points are (70, 96, 80), and (0, 86, 80).

The positions of the locators and the clamps on the workpiece discussed in this section are shown in Figures 23 and 24. Two different views of the workpiece are shown along with the locators and the clamps at their respective positions as determined by the algorithm.

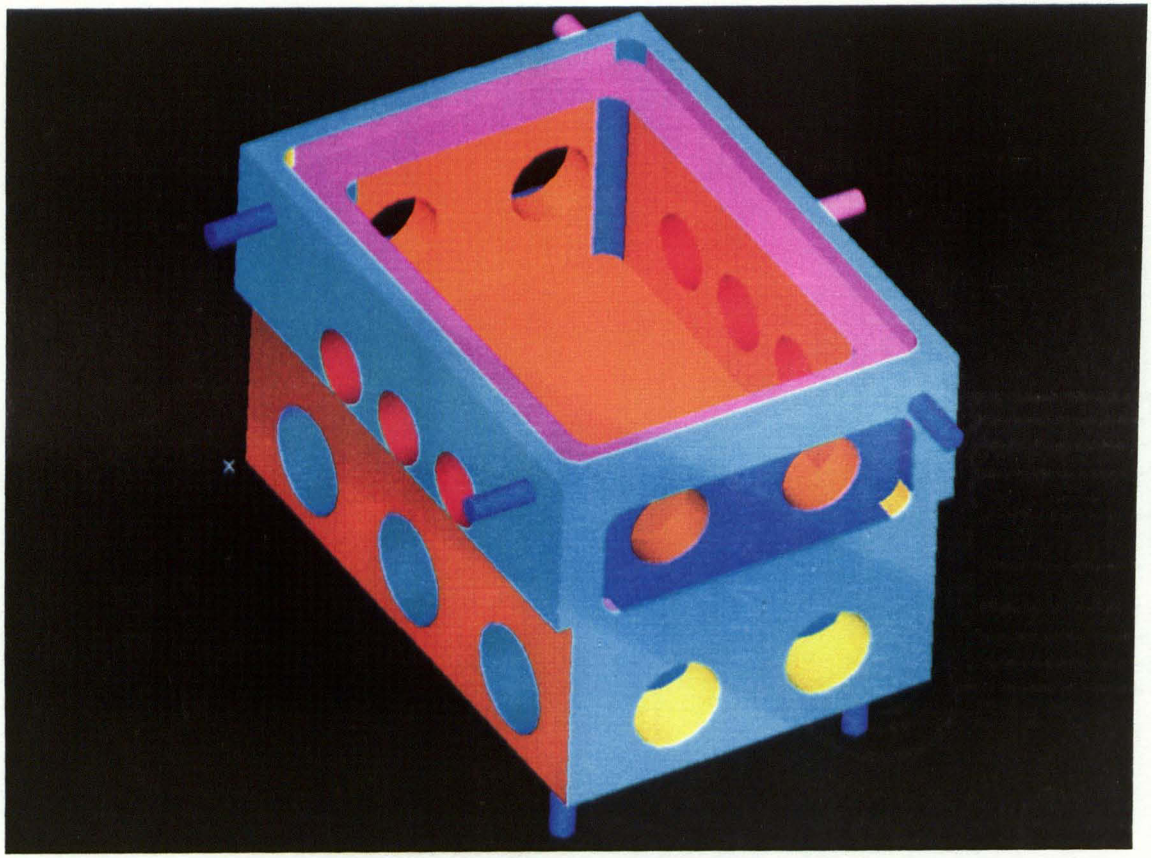

Figure 23. An isometric view of the workpiece with locators in blue and clamps in magenta

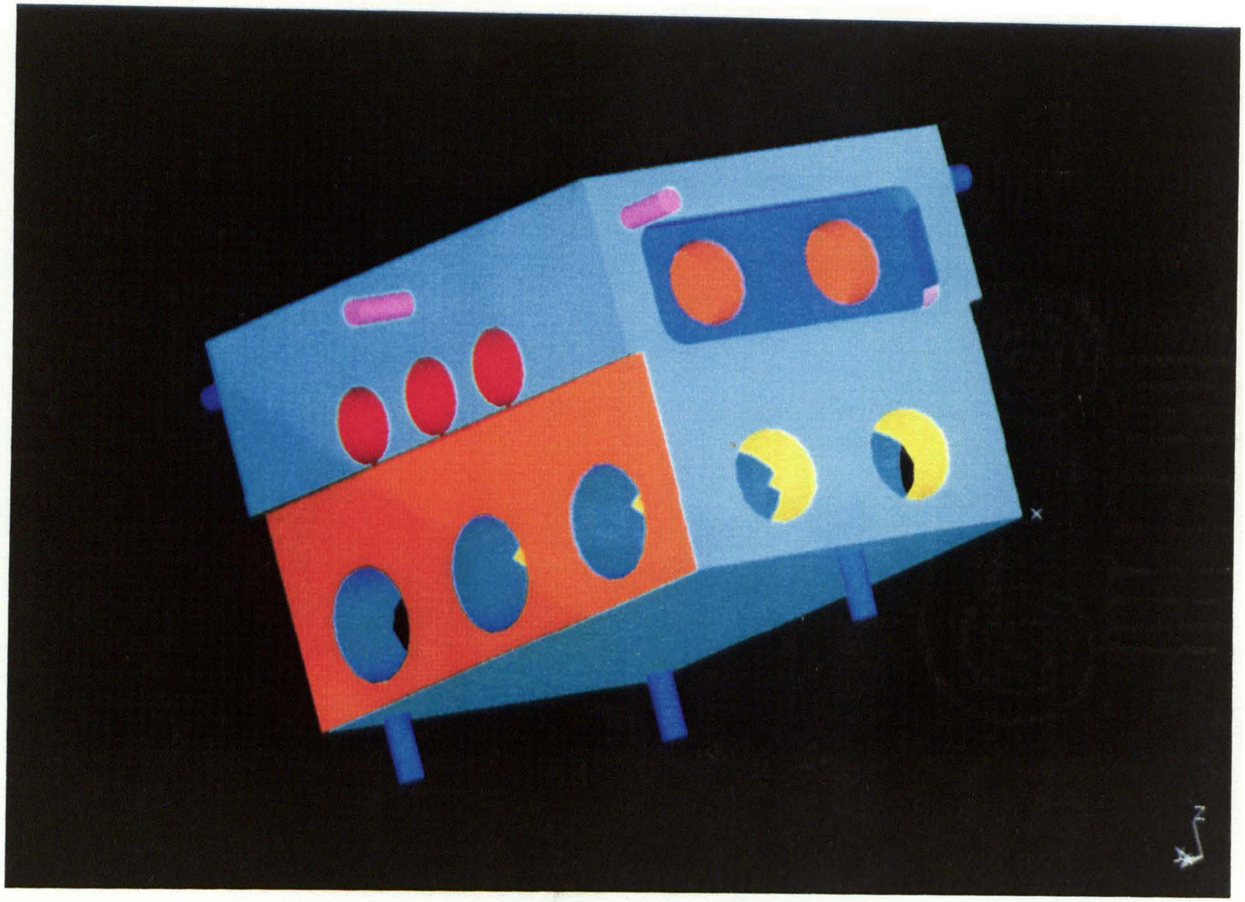

Figure 24. An isometric view of the workpiece with locators in blue and clamps in magenta

7. CONCLUSION

A new approach based on projective geometry and numerical search is used to develop a set of algorithms to determine the fixturing configuration for a workpiece. The heuristic employed in this approach applies to all workpieces with arbitrarily shaped edges. However, only those faces corresponding to the boundary edges of the projected envelope that are either parallel or perpendicular to the baseplate are considered as candidate fixturing faces. The proposed heuristic can be made more rigorous by imposing additional rules for fixture configuration. The fixture design module developed here, can be integrated easily with other modules of computer integrated manufacturing like Computer-Aided Design (CAD) and Computer-Aided Process Planning (CAPP), thus providing an integrated environment for design and manufacturing, and moving a step closer to the realization of CIM and Automated Factory. The working of the algorithms is demonstrated using some sample workpieces with different setups as examples and the results are shown in Appendices A and B.

REFERENCES

Asada, H., and By, A.B., 1985, "Kinematic Analysis of Workpart Fixturing for Flexible Assembly with Automatically Reconfigurable Fixtures," *IEEE Journal of Robotics and Automation*, Vol. RA-1, No. 2, pp. 86-94.

Boerma, J., and Kals, H., 1988, "FIXES, a System for Automatic Selection of Set-Ups and Design of Fixtures," *Annals of the CIRP*, Vol. 37, No. 1, pp. 443-446.

Choi, B.K., Lee, C.S., Hwang, J.S., and Jun, C.S., 1988, "Compound Surface Modeling and Machining," *Computer Aided Design*, Vol. 20, No. 3, pp. 127-136.

Choi, B. K., 1991, *Surface modeling for CAD/CAM*, Elsevier Science Publishers, Amsterdam, Netherlands.

Chou, Y-C., Chandru, V., and Barash, M.M., 1989, "A Mathematical Approach to Automatic Configuration of Machining Fixtures: Analysis and Synthesis," *ASME Transactions, Journal of Engineering for Industry*, Vol. 111, November, pp. 299-306.

Chou, Y-C., 1990, "A Methodology for Automatic Layout of Fixture Elements based on Machining Forces Considerations," *Proceedings, Symposium on Advances in Integrated Product Design and Manufacturing*, ASME Winter Annual Meeting, Dallas, Texas, Nov 1990, pp. 181-189.

Cutkosky, M.R., and Lee, H.S., 1989, "Fixture Planning with Friction for Concurrent Product/Process Design", *Proceedings, NSF Engineering Design Research Conference, Amherst*, Massachusetts, June 1989, pp. 613-628.

Ferreira, P.M., Kochar, B., Liu, C.R., and Chandru, V., 1985, "AIFIX: An Expert System Approach to Fixture Design," *Proceedings, Symposium on Computer-Aided/Intelligent Process Planning*, Winter Annual Meeting, ASME, Miami Beach, FL.

Ferreira, P.M., and Liu, C.R., 1987, "Generation of Workpiece Orientations for Machining Using a Rule Based System," *The International Conf. on the Mfg Science and Tech. of the Future*, MIT, Cambridge, USA, pp. 545-555.

Hoffman, E.G., 1985, *Jig and Fixture Design*, Second Edition, Delmar Publishers Inc., Albany, NY.

Ingrand, F., and Latombe, J.-C., 1984, "Functional Reasoning for Automatic Fixture Design," *Proceedings, CAM-I 13th Annual Meeting & Tech. Conf.*, Clearwater Beach, Florida, Nov. 13-15, pp. 8.53-8.65.

Liu, C.R., and Trappey, J.C., 1989, "A Structured Design Methodology and MetaDesigner: A System Shell Concept for Computer Aided Creative Design," *Bound Volume of Proceedings, ASME Design Automation Conference*, Montreal, Canada, September.

Mani, M., and Wilson, W.R.D., 1988, "Automated Design of Workholding Fixtures Using Kinematic Constraint Synthesis," *Proceedings, 16th North American Mfg. Research Conference*, SME, University of Illinois, Urbana, Illinois, pp. 437-444.

Markus, A., Markusz, Z., Farkas, J., and Filemon, J., 1984, "Fixture Design Using Prolog: An Expert System," *Robotics & Computer-Integrated Manufacturing*, Vol. 1, No. 2, pp. 167-172.

Menassa, R.J., and DeVries, W.R., 1989, "Locating Point Synthesis in Fixture Design," *Annals of the CIRP*, Vol. 38, No. 1, pp. 165-169.

Menassa, R.J., and DeVries, W.R., 1990, "A Design Synthesis and Optimization Method for Fixtures with Compliant Elements", *Proceedings, Symposium on Advances in Integrated Product Design and Manufacturing*, ASME Winter Annual Meeting, Dallas, Texas, Nov 1990, pp. 203-218.

Mortenson, M.E., 1985, *Geometric Modeling*, John Wiley & Sons, New York, USA, 1985.

Trappey, J.C., and Liu, C.R., 1988, "Issues of Automatic Fixture Design in Computer Integrated Manufacturing System," *Proceedings of IASTED International Conf., Robotics & Automation*, Santa Barbara, CA, USA, pp. 149-154.

Trappey, J.C., and Liu, C.R., 1989, "An Automatic Workholding Verification System," *Proceedings, International Conf. on Manufacturing Science & Tech. of the Future (MSTF'89)*, Stockholm, Sweden, June 6-9.

Trappey, J.C., and Liu, C.R., 1990a, "A Literature Survey of Fixture Design Automation," *The International Journal of Advanced Manufacturing Technology*, pp. 240-255.

Trappey, J.C., and Liu, C.R., 1990b, "Automatic Generation Of Configuration For Fixturing An Arbitrary Workpiece Using Projective Spatial Occupancy Enumeration Approach", *Proceedings, Symposium on Advances in Integrated Product Design and Manufacturing*, ASME Winter Annual Meeting, Dallas, Texas, Nov 1990, pp. 191-202.

ACKNOWLEDGEMENT

This research is partially supported by contract # 591-1572 from Society of Manufacturing Engineers' (SME) Manufacturing Engineering Education Foundation and by the University Research Grant and College Of Engineering (ERI) Research Grant at Iowa State University. Their support is greatly acknowledged.

APPENDIX A

Fixture Configuration for Sample Workpiece 1

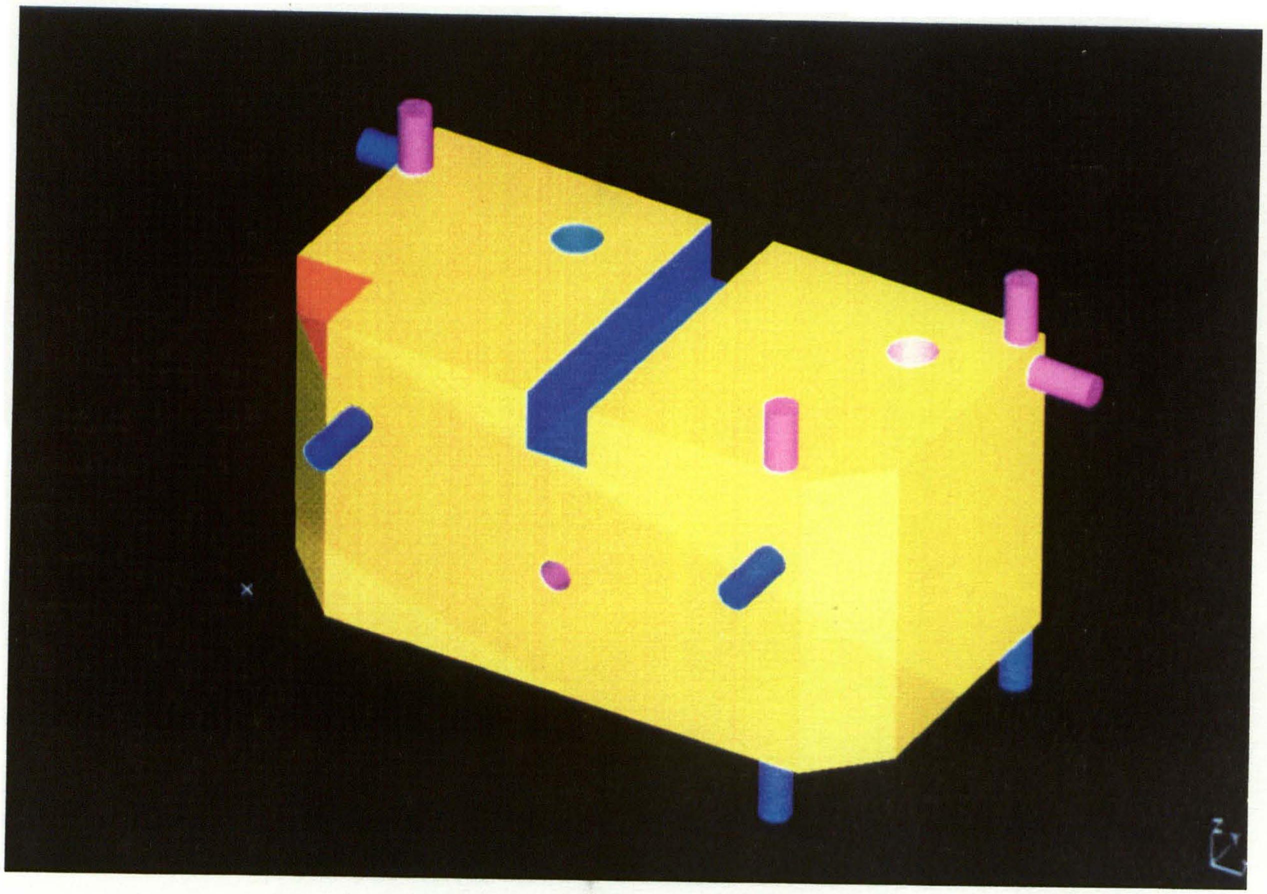

Figure 25. An isometric view of the workpiece with locators in blue and clamps in magenta

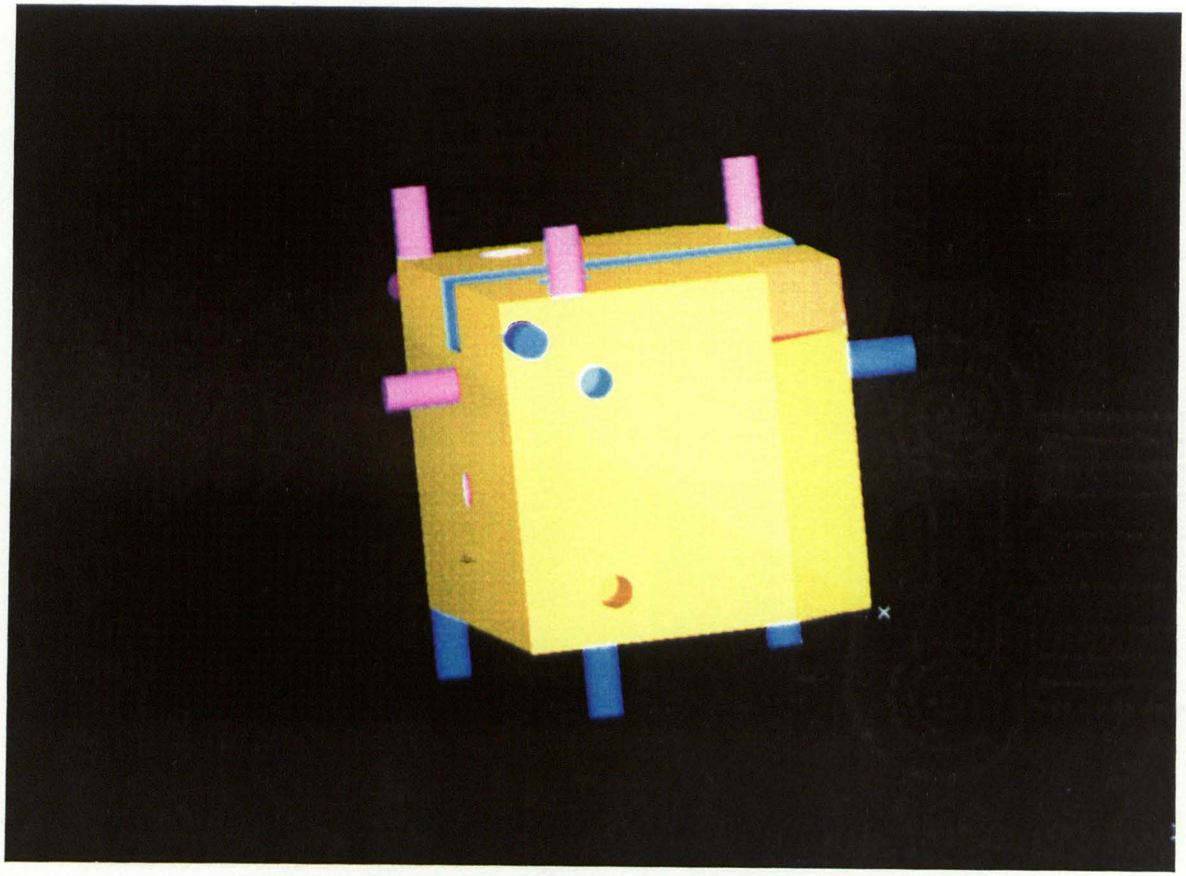

Figure 26. An isometric view of the workpiece with locators in blue and clamps in magenta

APPENDIX B

Fixture Configuration for Sample Workpiece 2

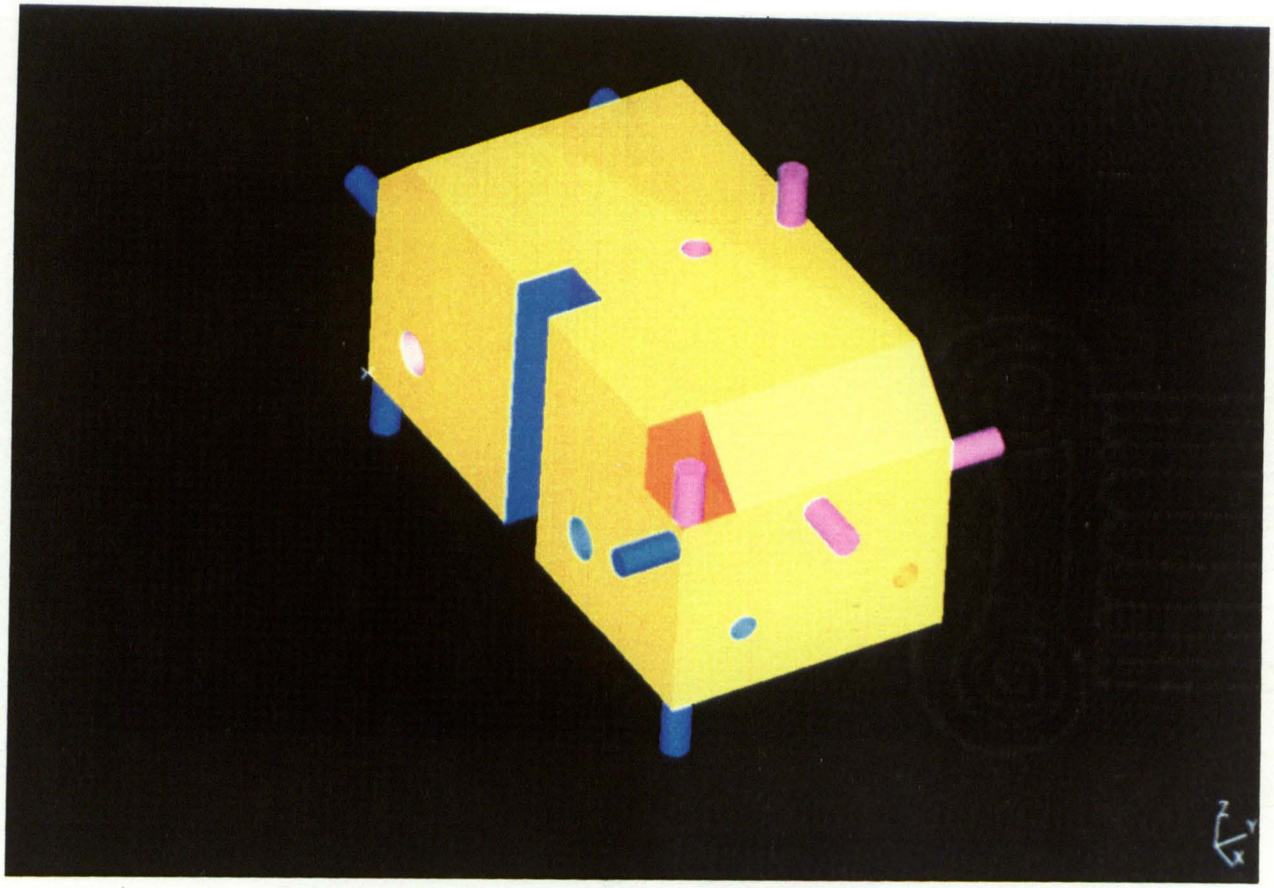

Figure 27. An isometric view of the workpiece with locators in blue and clamps in magenta

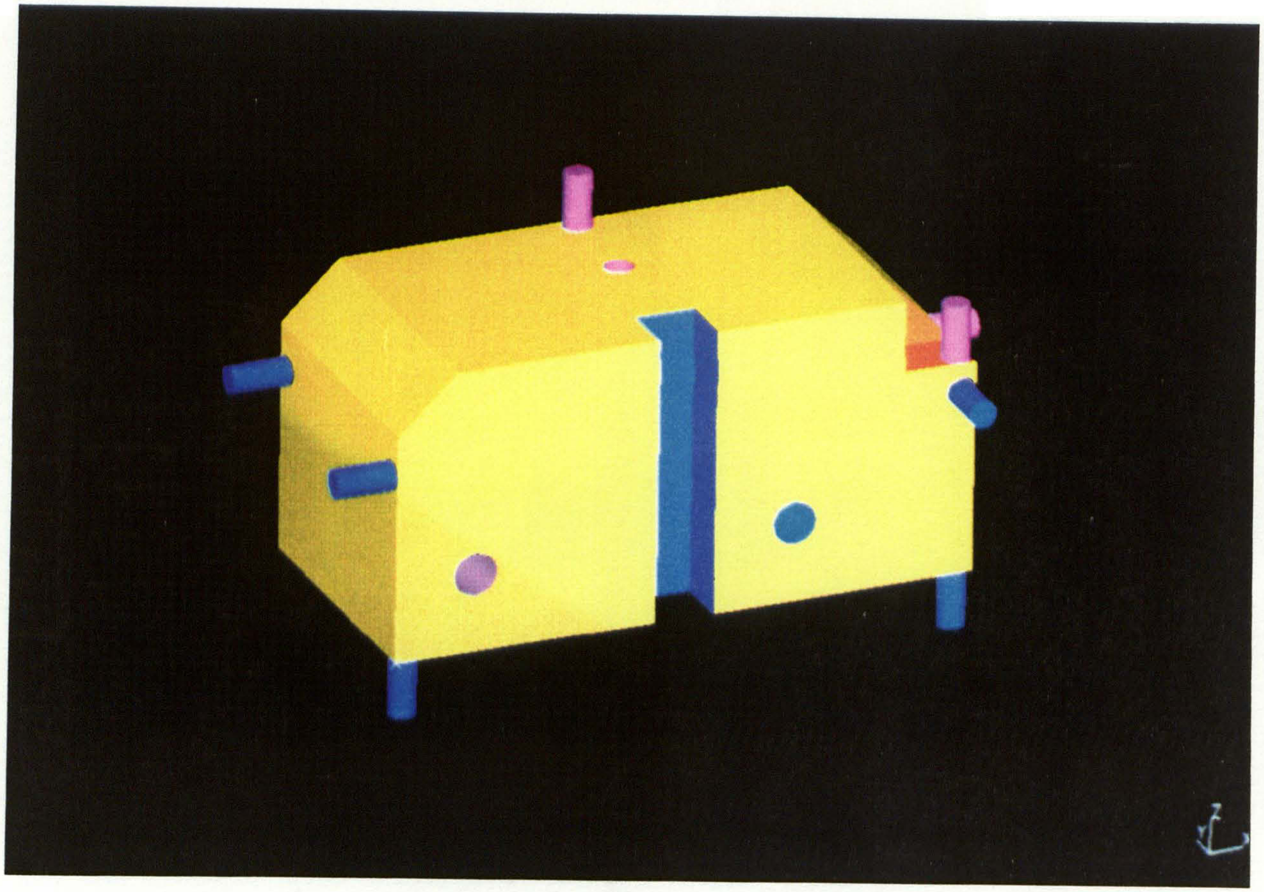

Figure 28. An isometric view of the workpiece with locators in blue and clamps in magenta

APPENDIX C

NURB Representation

A NURB surface is represented using a set of control points, knot points, and weights. The surface is divided into a series of patches, each controlled by a subset of the control points, the size of which is determined by the order of the surface along the u and the v directions. The range of a parameter in a given patch is determined by the knot vector of that parameter. Since the ranges are, in general, non-uniform, the surface is said to be **Non-Uniform.** As weights are assigned to each of the control points, the surface is said to be **Rational.** Any point on a given patch is obtained by blending the control points controlling that patch. The functions used to blend the control points are called the blending functions. The blending function along a particular parameter direction depends only on the knot-vector and the parameter value and is defined recursively (Choi, 1991).

$\{ \mathbf{P}_{ij} \}$: (m+1) x (n+1) control points of the surface.

$\{ W_{ij} \}$: weights for $\mathbf{P}_{ij}$.

$\{ \Delta_i \}$: u-direction knot spans.

$\{ \nabla_j \}$: v-direction knot spans.

$$\mathbf{P}_{ij} = [\quad W_{ij} X_{ij} \quad W_{ij} Y_{ij} \quad W_{ij} Z_{ij} \quad W_{ij} \quad]$$

The polynomial form of the non-periodic surface is obtained by using the following recursive definition for the blending function:

$$N_{i\,1}(u) = 1, \text{ if } \Delta_i \leq u \leq \Delta_{i+1}$$
$$= 0, \text{ otherwise}$$

$$N_{i\,k}(u) = \frac{(u - \Delta_i)\, N_{i\,k-1}(u)}{\Delta_{i+k-1} - \Delta_i} + \frac{(\Delta_{i+k} - u)\, N_{i+1\,k-1}(u)}{\Delta_{i+k} - \Delta_{i+1}}$$

where k is the order of the surface along the u-direction. A similar recursive definition is used for the blending function in the v-direction with Δ, k, and i replaced by ∇, l, and j respectively. The polynomial form for the surface is then given by

$$\mathbf{R}(u, v) = \sum_{i=0}^{m}\sum_{j=0}^{n} \mathbf{P}_{i\,j}\, N_{i\,k}(u)\, N_{j\,l}(v)$$

For a NURB curve, the representation remains the same except that only a single parameter is used instead of two.