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A unified rough and finish cut algorithm for NC machining of free form pockets using a grid based approach

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A unified rough and finish cut algorithm for NC machining of free form pockets using a grid based approach

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Yong-hoon Choi

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy *dedicated to*

my father who is watching me in heaven and mother who always advises me positively

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ABSTRACT

Determination of tool cutter path in an efficient manner is very important to generate final NC codes for machining. This is particularly true for machining general pockets with sculptured surfaces on a three-axis CNC milling machine. A machined surface is judged by the surface roughness, accuracy of machined features and by the total machining time.

Many CAD/CAM systems use linear interpolation to generate numerical control tool paths for a curved surface. However, this needs to be modified to improve the smoothness of the machined surface and to reduce machining time. This is because linear interpolation has limitations such as larger values of surface roughness and accuracy, more machining time because of repeated 'stop & go' motions and large cutter location data files.

Curved machining can be a solution to reduce these problems. In this thesis, an analytical procedure for generating a final NC program based on linear interpolation and a combination of linear and curvilinear interpolation is presented. The algorithm for tool path determination allows for motion along a line, circular arcs and Bezier curves.

The tool path is planned using a navigation algorithm on a surface discretized using an appropriate grid size. The navigation strategy is to move the tool from one grid point to the next in an efficient manner so that a valid coverage of the bottom surface of the pocket is produced. X and Y zigzag motion commands are additionally added to minimize the surface roughness. The entire tool path consists of interior navigation amidst the grid points; machining along the wall periphery and zigzag motion commands. Deep pockets are handled

by extending the algorithms with a layered machining approach. Rough machining is performed in several layers and the last layer is the finish cut.

The algorithm works for any general pocket with arbitrary wall geometry and freeform bottom surface. The bottom surface can be represented by any analytical or parametric surface or can be grid data from reverse engineering. The grid-based approach allows the application of suitable curvilinear interpolation algorithms for high fidelity machining. The algorithm is validated by graphical simulations in OpenGL as well as by machining experiments.

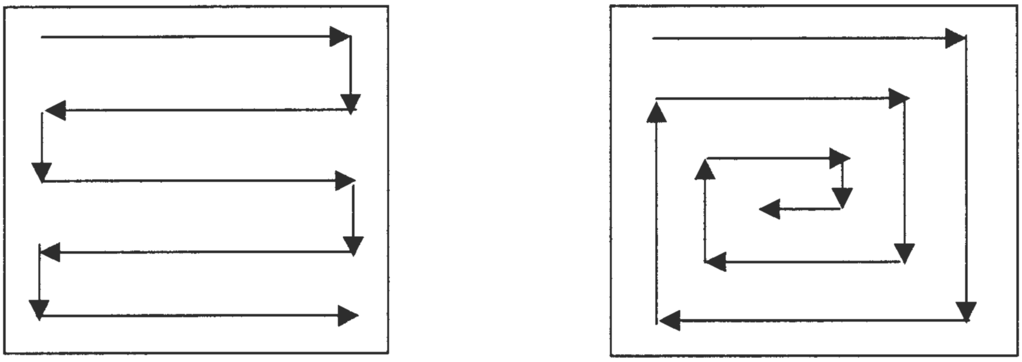
CHAPTER 1. INTRODUCTION

With increased demand for complicated form and functional surface shape in many industrial products, there is a distinct need for efficient CNC (computer numerical controlled) machining of compound-curved and intricate surfaces. One of the most important features in determining CNC machining efficiency and productivity is cutter path motion. This cutter motion on compound-curvature surfaces determines the machining time and the surface roughness. Surface roughness always exists because of the lack of geometry matching between cutter and the surface to be machined. The major problem in generating automatic ball end milling cutter paths is the difficulty of determining the cutter path for general polygons with compound-curvature surfaces.

Generally two strategies have been used, namely, *Staircase* and *Window-frame*. In the staircase pattern the tool is moved along parallel line segments in a chosen direction. In the window-frame technique the cutter path is a spiral obtained by offset from the wall boundary. Figure 1 shows both the staircase and window-frame techniques. These techniques are easy to implement for convex polygons with flat bottoms, but are quite difficult when the polygons are non-convex and have sculptured bottoms.

Most CAD/CAM systems machine curved surfaces by an approximation using linear interpolation. This method creates many short linear move commands with sudden changes in direction. Further, a lot of data points are needed to specify the tool size and this can result in prohibitively large cutter location file sizes. Moreover, machining with linear segments contributes to significantly larger values of surface roughness because of interpolation approximation errors and considerably longer machining times due to repeated 'stop and go' tool motion.

Curved bottom machining algorithms with real curvilinear interpolation strategies are needed for efficient pocket machining. Cutter location file sizes also need to be reduced, so that complex-curved surfaces can be efficiently machined. This is becoming increasingly more relevant today with the common practice or desire for distributed design and manufacture. With curvilinear machining algorithms the cutter location file size can be significantly reduced because for machining the same amount of volume, curved data only needs starting and ending points and arc center or intermediate control points while linear movements need all data points to show the tool path.



a) Staircase Procedure b) Window-frame Procedure

Figure 1. Staircase and Window-Frame Procedures

In view of the deficiencies mentioned above, the primary objective of this thesis is to develop an algorithm for machining freeform pockets with arbitrary wall geometry using a combination of linear and curvilinear interpolation strategies. The window-frame technique augmented with a grid-based navigation technique is used. The freeform pocket surface is discretized into set of 3D XYZ data points. The number of points obtained is dependent on the grid size, which in turn is related to the diameter of the end mill. The navigation algorithm plans tool motion from the center of each grid element to the next one. The motion starts from one of the edges of the polygon and continues in a counter-clockwise direction whenever it reaches a pocket wall. The navigation algorithm is a search procedure that ensures valid coverage of the pocket. The searching process stops somewhere near the center of the polygon. This essentially makes up the tool path for the interior of the pocket. To this, extra X and Y zigzag motion commands are added to improve the surface roughness. This is particularly important here because of the freeform bottom pocket surface. The periphery of the pocket wall is then subsequently obtained by connecting a set of corner points that are determined as an offset from the vertices of the polygon defining the pocket. The interior cutter motion is actually reversed for physical machining of the pocket as this procedure reduces the tool moving time for subsequent wall machining.

The motion along the grid center points can then be post processed for implementing curvilinear machining algorithms. A circular arc-machining algorithm is implemented to improve the surface roughness, reduce machining time, and cutter location file size. To remove the same amount of volume compared to line movements, arc-machining only requires specifying the start point, end point, and arc radius. A series of data points are approximated by an arc which passes through the start point, the end point and the middle point. The user can specify a suitable tolerance value for the error between the arc and the grid data points. If the error is within the tolerance, then this arc is accepted and the next data points are considered. If not, the data point set is reduced by one and the process is repeated.

Bezier curve path is another approach. This method requires the specification of start and end points as well as intermediate control points. Since the first and last control points are the same as start and end points, only intermediate control points need to be found with given information. To define a cubic Bezier curve at least four known points on the curve are needed. These are the start and end points and two intermediate points. If the number of data points is less than four, then linear interpolation is used. Depending on the polygon shape, this approach might be useful.

To handle the machining of deep pockets, a layer based machining strategy is used. Material is removed layer by layer. The navigation algorithm is essentially the same but is used repeatedly in layers. For this search, the algorithm is termed as a "unified rough and finish cut" algorithm. The algorithm allows the user to choose unit depth step at each layer. If curvature at a certain layer is steep relatively to the other layer, the unit depth of that layer can be modified flexibly.

The algorithm can be extended to machine pockets that are reverse-engineered. This is particularly simple because the algorithm is based on a grid-based approach and the points that are measured are essentially the grid points.

The entire pocket-machining algorithm is illustrated schematically in Figure 2 and can be stated as follows:

1) The bottom surface and polygon shape of pocket are defined.
2) Main interior, wall machining, X zigzag, and Y zigzag tool paths are determined in navigation stage
3) Tool path motion is obtained in terms of line, arc + line, and Bezier curve + line movements as desired.

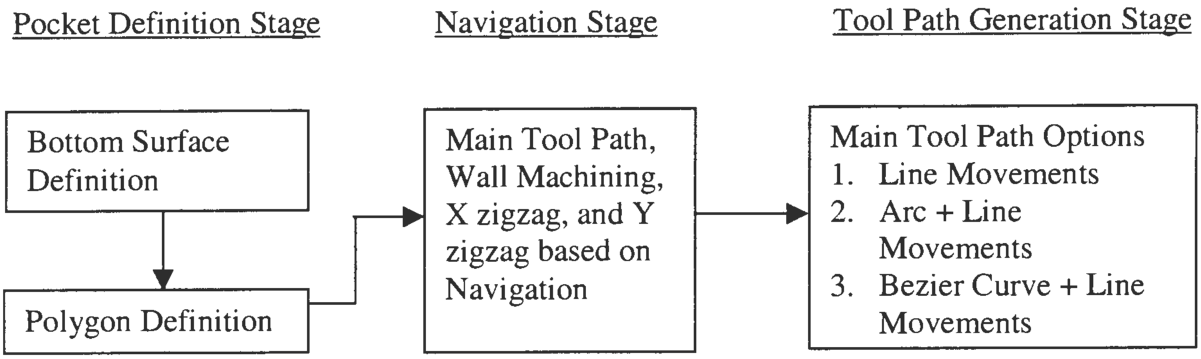


Figure 2. NC Pocket Machining Algorithm

The rest of the thesis is organized as follows. Relevant literature is introduced in Chapter 2. Chapter 3 describes the definition of the pocket in terms of the bottom surface of the pocket using grids and the polygon defining the walls. The grids are specified by the user in relation to the tool diameter. The navigation strategies with all possible cases are also described in Chapter 3. Machining path determination and NC code generation which may comprise of line, arc + line, and Bezier curve + line movements are shown in the first half of Chapter 4. Rough and finish cut and reverse engineering methods are introduced in the second half of Chapter 4. Case studies are clearly shown by simulations and machining experiments in Chapter 5. Finally, conclusions are presented in Chapter 6.

CHAPTER 2. RELEVANT LITERATURE

CAPP (computer aided process planning) is considered as one of the most important steps in converting a design concept into a manufactured product. The introduction of CAPP has certainly made the planning function more efficient. According to Houtzeel (1995), there are three general basic principles for CAPP. These are *variant*, *generative*, and *automatic* process planning.

The variant approach to process planning is to create a new plan for a new part by recalling, identifying and retrieving an existing plan for a similar part. A set of standard process plans is established for all the part families identified through GT (group technology). When a new plan is required, the most closely matching standard plan is retrieved and edited to suit the specific requirements of the new part. Variant process planning systems are relatively easy to build and complicated activities and decisions require less time and labor. This approach is still popular even though experienced process planners are required to adjust the standard plan.

The generative approach to process planning is to generate a new plan automatically by means of decision rules, algorithms and geometry based data to perform uniquely many processing decisions from converting a part from raw material to a finished part. An attempt is made to synthesize each individual part using appropriate algorithms that define the various technological decisions that must be made in the course of manufacturing. In a truly generative system, unlike the variant approach, the sequence of operations as well as all the process parameters would be established automatically, without reference to prior plans.

Automatic process planning can generate a complete process plan directly from an engineering design model. The major goal of the automatic approach is to have the ability to generate a process plan for manufacturing parts automatically using no human input except the computer databases that contain the required information. The major difference between an automatic approach and other approaches is the CAD interface to extract for manufacturing.

Lee and Chang (1995) proposed to apply computational geometry techniques in process planning and optimizing the machining of complex surfaces. Polygon decomposition techniques and convex hulls were used to interrogate the surface and facilitate automatic process planning for machining complex surfaces. The concept of Group Technology (GT) was adopted to classify surfaces into different categories to assist in selecting machining operations. An operation plan was generated based on the geometric information extracted from the surface description arising from surface interrogation. Techniques have been proposed in this paper to optimize tool selection and cutter path generation of 2.5D surface pocketing to improve machining productivity.

Different types of tool path planning strategies have been developed to generate a free form surface. These include iso-parametric machining, adaptive iso-curve machining, and pocketing with window frame or staircase style.

By using iso-parametric curves as tool paths, costly surface-surface intersection computations can be avoided. Iso-curvature machining was proposed due to the advantages it offers in terms of local placement and orientation of the tool. However the spacing between iso-parametric lines, in general, will be non-uniform causing overmachining or under-machining. And also the difficulties associated with the computation of lines of curvature are the disadvantages of this approach (Sarma and Dutta 1997). Another problem with iso-parametric curves is that tool paths do not provide an optimal coverage of the surface. Some areas may be overmachined because of redundancy. Elber and Cohen (1994) developed an adaptive sub-isocurve extraction approach that provided more optimal and valid coverage of the surface by adaptively introducing partial sub-isocurves.

Yang and Kong (1994) performed a comparative study of linear interpolators and parametric interpolators used for command generation for CNC machining. They found that the linear interpolator has the advantage of simplicity, and requires less computation while the parametric interpolator is superior in terms of its memory-size requirement, speed, accuracy, and so forth.

The ultimate goal of pocket machining is the automated generation of correct and optimal tool paths. Held (1994) classifies pocket-machining algorithms broadly into two categories. These are contour-parallel machining and direction-parallel machining. Contour-parallel machining uses offset segments of the boundary elements of the pocket as tool path segments (window frame approach). Thus the pocket is machined spirally by the tool(s) being driven along the boundary offset that is at constant distances from the pocket's boundary. So this strategy is also known as offset machining. In directional-parallel machining (staircase style), the tool(s) is moved along line segments, which is parallel to a reference line selected initially. On the basis of this strategy, a connected tool path is obtained by linking these parallel segments such that they are either all traversed from right to left (or from left to right), or alternatively from left to right and from right to left. Held proposed an approach to the efficient generation of tool paths for pocketing based on 'proximity maps' and is basically contour-parallel machining.

Wang *et al.* (1988) proposed an approach to optimize NC tool path planning for flat face milling. A mathematical model was formulated and a solution procedure for calculating an optimal length of cut for a triangle was made for a convex shaped polygon.

Recently, Voronoi diagrams have been used in pocketing machining. Jeong and Kim (1998) developed a Voronoi diagram of a pocket to partitions regions inside the pocket. In this scheme, each region, called a Voronoi polygon, contains the set of points that are closer to the associated curve segment than to the others in the pocket boundary.

Sarma and Dutta's (1997) tool path generation method requires the surface data and tool radius as input. Their premise was that geometry and spacing of the tool paths impact scallop height and manufacturing time respectively. So they worked towards controlling the scallop height of the manufactured surface by modifying the tool path. They used offsets of the design surface to generate the tool path with the objective of obtaining a constant scallop height. According to Maeng, Ly, and Vickers (1996), the best geometry match between cutter and surface is obtained when the cutter is moved along the lines of the steepest surface slope.

Lynch (1996) states that more and more companies are finding it necessary to machine complex three-dimensional shapes. With the increasing availability of excellent and relatively easy-to-use computer-aided manufacturing (CAM) systems, this trend toward machining complex shapes on CNC machining centers will continue well into the foreseeable future. Based on the shape to be machined, the CAM system will generate a series of very tiny movements, usually straight-line G01 movement, which will form the shape being machined. In essence, the CAM system will do its best to interpolate the shape being machined based on an interpolation resolution. This resolution determines how accurately the workpiece will be machined, and how long the CNC program will be. The tighter this resolution, the better the work-piece accuracy, but the longer the CNC program.

Beard (1997) states that the linear interpolation paradigm has come to be a limiting factor on the contour machining process since it is not accurate, forcing the machinist to work from an approximation of the true work-piece surface geometry rather than the real three-dimensional surface. Therefore, the resultant machined surface is not smooth and the file size is also enormous. As the tool path is defined by shorter line-segments, it will generate a more accurate definition of the part surface definition, but results in enormous amounts of data (Herrin 1995).

For machining of curved surfaces, a milling cutter suitably oriented to the surface normal is usually directed from point to point on a surface mesh with linearly interpolated motion. For many applications this can result in thousands of small linearly interpolated and repeated 'stop and go' moves across the surface. To solve these problems, Vickers (1992) developed a recursive curve-fitting algorithm. The approach is to fit a circular arc, within a prescribed error tolerance, through given specific surface data points. Unnecessary surface points are eliminated to produce a concise tool path program. Circular interpolation provides an excellent way to define a very accurate circle or circular segment with a very little amount of data.

Hu *et al.* (1998) proposed a layered shape rough machining technique to overcome the tool depth limitations. This means that an object that has a large depth or height will not be machined in just one pass, but will need a 2nd or 3rd machining layer. This strategy is needed for deep pocket machining because they are usually produced from a billet by 2.5D roughing and 3D and 5D finishing.

Joo and Cho (1999) developed a feature-based technique for NC pocketing. Bulky pocket features were decomposed into compact features organized in several thin layers. The efficiency in machining the bulky feature is largely dependent on the cutter specification and cutting parameters. Consequently, the factors affecting machining efficiency should be considered in extracting pocket features.

Suh and Shin (1996) modeled pocket machining as a TSP (Traveling Salesman Problem) optimization problem. They used a neural network formulation to solve the optimization problem.

In summary, the tool path planning algorithms determine the tool path motion in an optimal fashion ensuring adequate coverage of the pocket. The surface roughness is minimized and a compact representation for the tool path is desired. Further, the machining time needs to be as small as possible.

CHAPTER 3. POCKET DEFINITION AND NAVIGATION

3.1 Surface Definition

The bottom surface defined in this study is a Bezier surface. Bezier surface formulation uses a control net of points. Points on the Bezier surface are given by

$$P(u,v) = \sum_{i=0}^{m}\sum_{j=0}^{n} B_{i,m}(u)B_{j,n}(v)P_{ij} \qquad u,v \in [0,1]$$

where P_{ij} are the vertices of the control polygon and $B_{i,m}$ and $B_{j,n}$ are the Bernstein blending functions. In matrix form, we may describe the Bezier surface patch by the equation.

$$P = P(u,v) = \begin{bmatrix}1 & u & u^2 & u^3\end{bmatrix} MBM^T \begin{bmatrix}1 & v & v^2 & v^3\end{bmatrix}^T$$

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -3 & 3 & 0 & 0 \\ 3 & -6 & 3 & 0 \\ -1 & 3 & -3 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} p_{00} & p_{01} & p_{02} & p_{03} \\ p_{10} & p_{11} & p_{12} & p_{13} \\ p_{20} & p_{21} & p_{22} & p_{23} \\ p_{30} & p_{31} & p_{32} & p_{33} \end{bmatrix}$$

The control points control the shape of the Bezier surface. Bezier surfaces pass through the corner control points and have edge curves that are tangential to the edges. They also have variation diminishing, and convex hull properties. Figure 3 shows a representative Bezier surface.

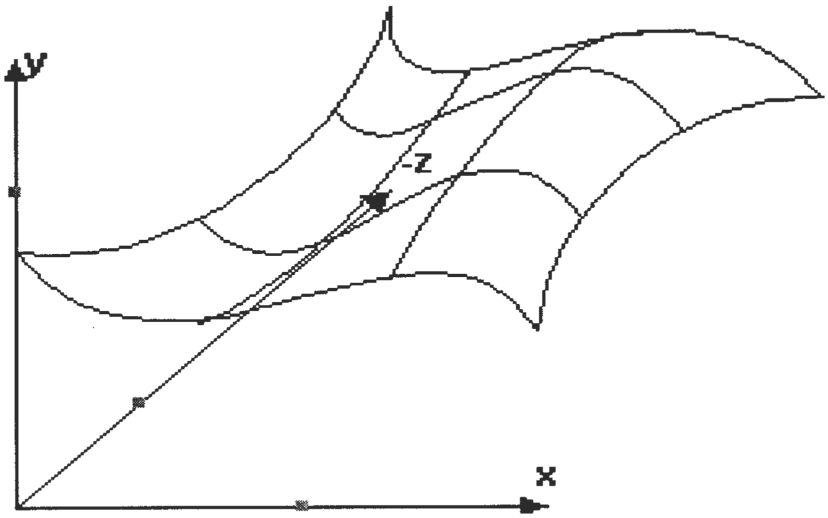


Figure 3. A Representative Bezier Surface

3.2 Grid Definition

The notion for grid based navigation stems from the guidance of autonomous guidance vehicles in unknown terrain and in the absence of vision feedback. First, the machined region is, assumed to be divided into a grid with size equal to or less than $D/\sqrt{2}$ where D is the diameter of the tool as shown in Figure 4. The reason for this is that when the centers of grid and tool are coincidental, the area covered by the tool should enclose the entire area of the grid. This would ensure that that no uncut material is left by the tool path. If the grid sizes are bigger than $D/\sqrt{2}$, there would be some uncut material at certain locations. From Figure 4, the following assumption can be made and then questioned.

"Whenever a cutter passes through the center point of each grid, this grid is completely removed because cutter will cover entire area of each grid."

This assumption will be true only when the pocket's bottom is planar. When the pocket has an arbitrarily shaped bottom surface, the cut portion is clean only in XY view (top view). Uncut material may remain in XZ and YZ views. This is because the tool did not pass through all adjacent grid points. This situation will occur, whenever there are any regions that the tool center does not pass through all 4 directions in X or Y.

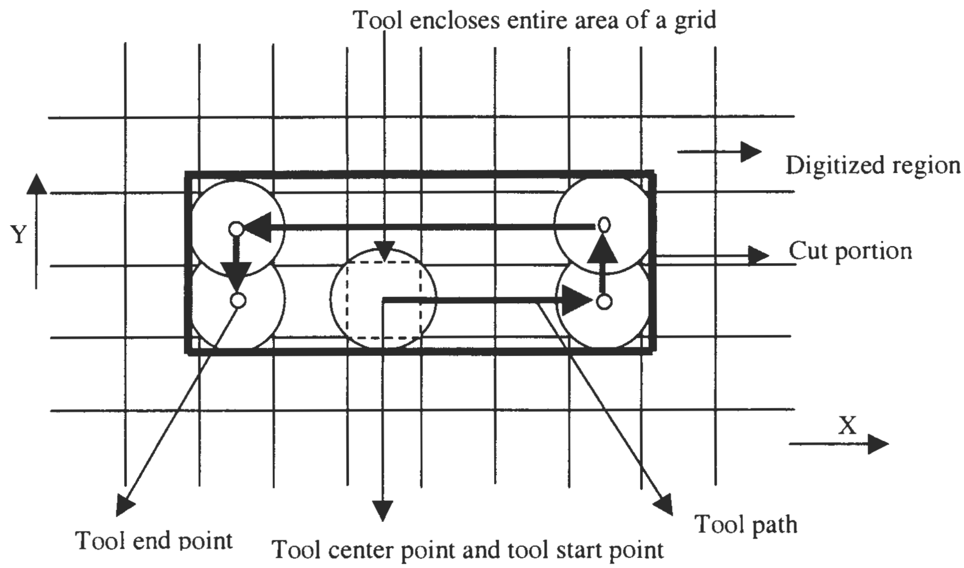


Figure 4. Digitization of Bottom and Tool Path Motion in XY View

With Figure 5, a comprehensive explanation of the uncut material can be made. Regardless of tool path type, like window-frame or staircase, let's assume that the tool path goes through all points (A, B, C, D, and E) and bottom surface is sculptured surface. If there are direct motions only from grid E to grid D and from grid E to grid B, there would be uncut material between grid E and grid A and between grid E and grid C. This contributes to the scallop height and it depends on tool diameter and grid size. The side view of the cutting situation is illustrated in Figure 6.

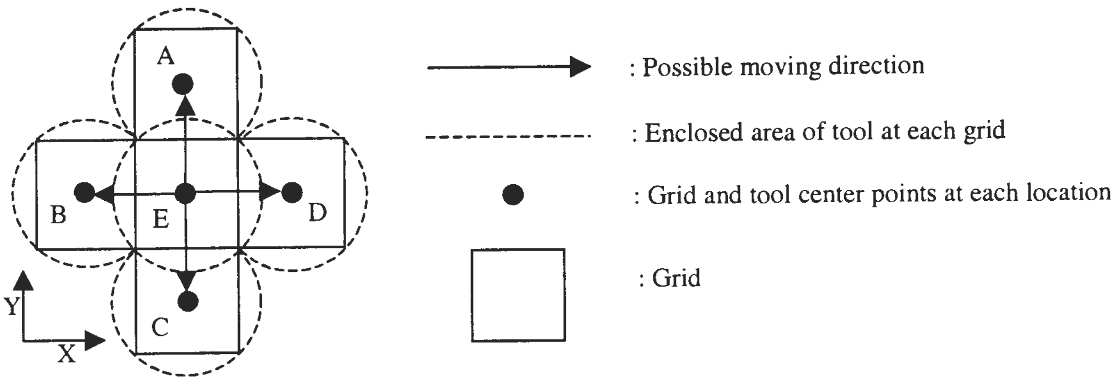


Figure 5. Possible Tool Moving Directions at Current Location

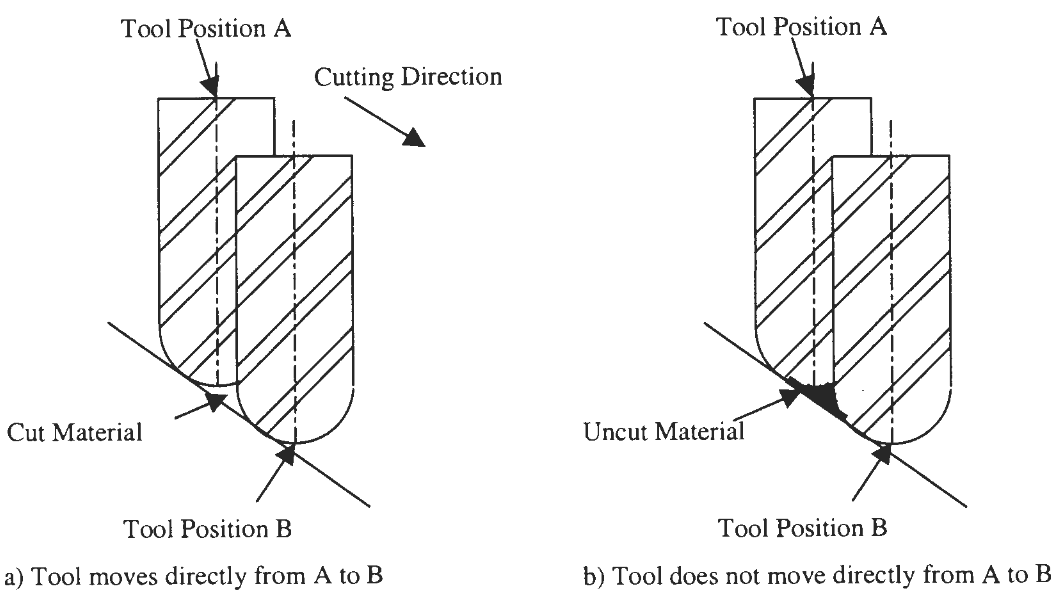


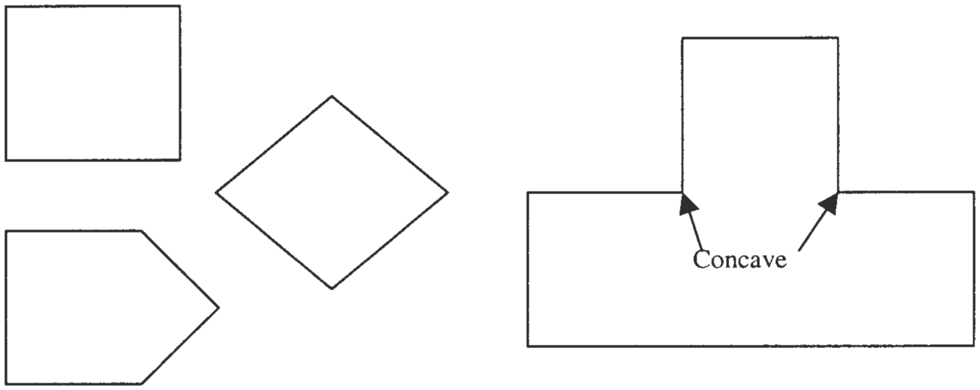
Figure 6. Side View Corresponding to the Tool Path

To solve this problem, the final NC tool path needs to be generated such that all uncut material is removed. Therefore, extraneous X zigzag and Y zigzag motions are needed for later execution to produce a smooth surface. However, these may be required only when better surface is necessary since more machining time is required for these additional operations.

3.3 Definition of Polygon

A general polygon can include both convex and concave shapes. A pocket with arbitrary wall geometry should therefore be a general polygon. Examples of convex and concave polygons are presented in Figure 7.

Vertex points are input to define a polygon. If the input polygon is rectangular or diagonal, it is required to input four vertices. As the polygon shape is more complex, it may



a) 3 Polygons having only convex shape b) Polygon has both convex and concave shape

Figure 7. General Polygons with Convex and Concave Shape

require more number of vertices. Input vertex points (polygon points) are required to be at the intersection of the grids. It is to be noted that the tool center points should not be the same as grid center points because of problems with possible over-cutting for pocket boundary machining in XY view (see Figure 8).

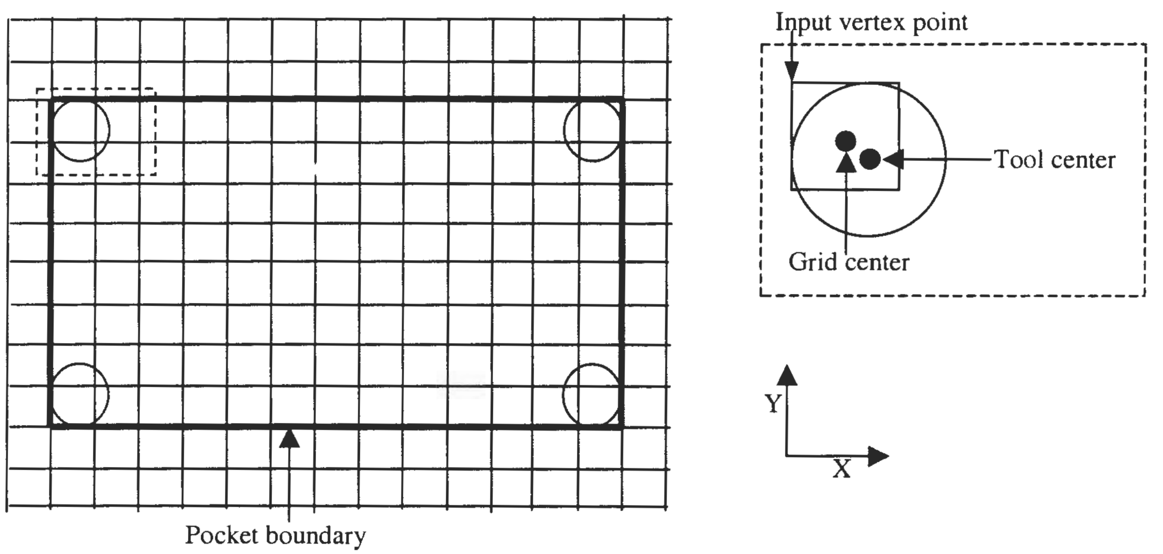


Figure 8. An Example of a Defined Polygon

As can be seen from the Figure 8, the tool centers are not at the same locations as grid centers. If these are the same, it will cause over-cut. So the amount of gap should be calculated when wall (boundary) machining is being done to prevent over-cut.

3.4 Navigation Strategies

Before the details of the proposed methodology are given, two important aspects are discussed first: selection of mapping grid size and navigation strategies. The mapping grid size is selected as a function of the cutter diameter. As shown earlier in Figure 4, if the grid size is taken as equal to $1/\sqrt{2}$ of cutter diameter then the tool overlap between two consecutive and parallel grids will be equal to the difference between cutter diameter and mapped gird size. This amount of overlap is sufficient to clean away any residual material left between the two passes, especially when flat end milling tools are used for flat bottom surface.

The navigation strategy uses a priority such that the first permissible direction is in a counterclockwise sequence. After finding the nearest legitimate grid first, the tool moves there so that milling can go on until the pocket is completely traversed. The overall procedure showing detail information about navigation strategy can now be specified as shown in Figures 9, 10, 11, and 12. These figures show all possible directions of tool path from the current tool positions depending on the direction of previous position to current position.

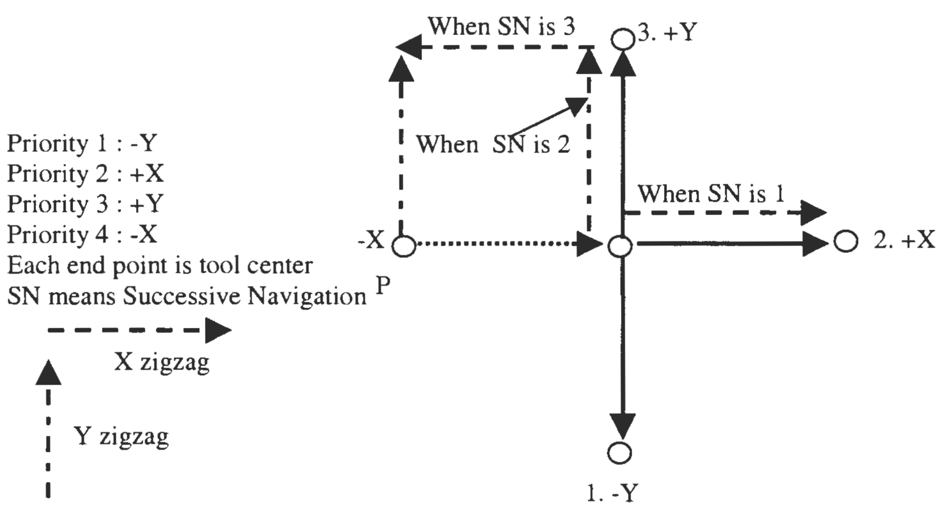


Figure 9. Checking Navigation Condition When Precedent Navigation was +X Direction

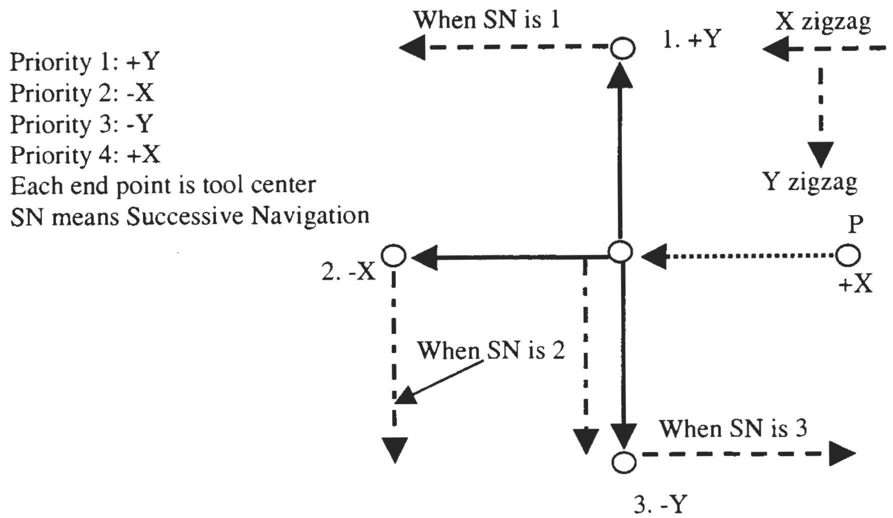


Figure 10. Checking Navigation Condition When Precedent Navigation was –X Direction

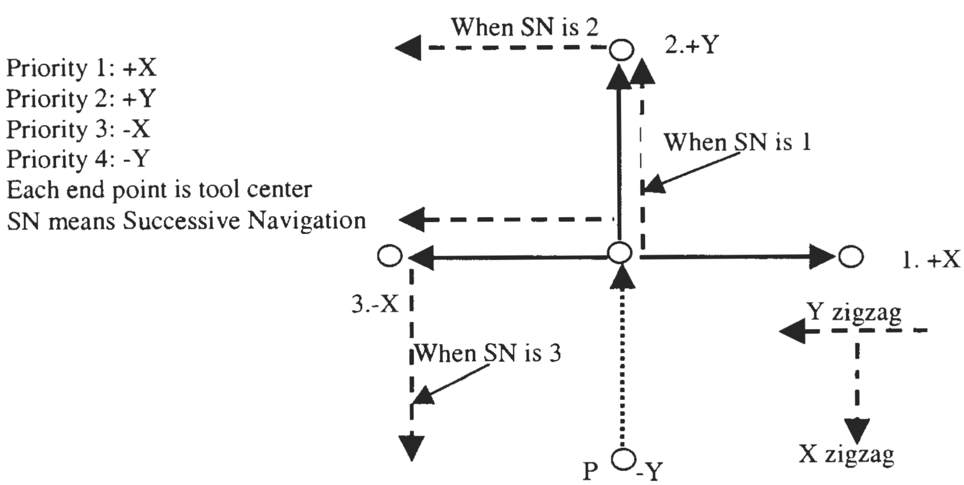


Figure 11. Checking Navigation Condition When Precedent Navigation was +Y Direction

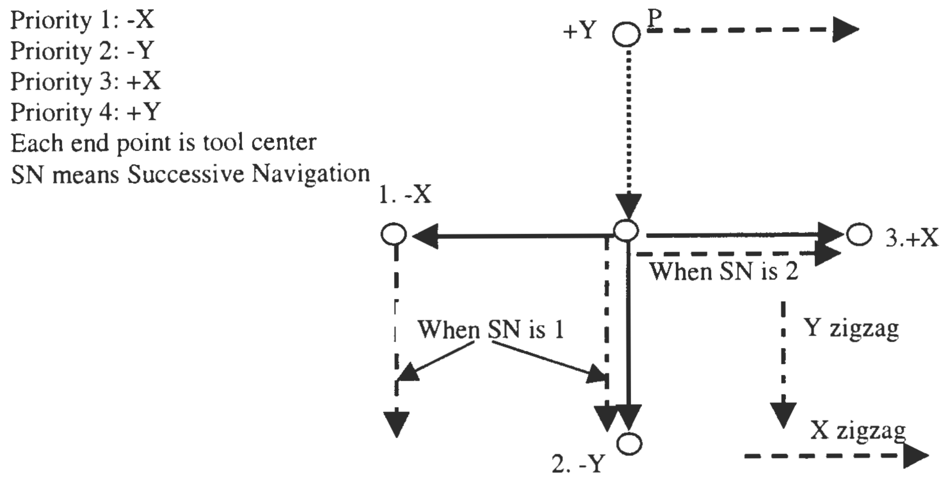


Figure 12. Checking Navigation Condition When Precedent Navigation was -Y Direction

P on each figure means precedent position. As P approaches to the current position, the direction is expressed as a dotted line. At each current position (at each center point of figures), there are 4 priorities. If there is no obstruction or no previous cut, the tool moves to the direction of priority 1. If not it will be checked for priority 2 whether there is any obstruction or previous cut. If there is no obstruction for priority 2, the tool will move to that direction. Priority 3 and 4 are tested in a similar fashion if there are obstructions for both priority 1 and 2 directions. X and Y zigzag motions are shown as dashed lines. These motions are made depending on the successive number that results in a priority number. Depending on the precedent navigation's direction, all 4 cases are shown. The following definitions are useful in defining the algorithm.

Definitions

Precedent Navigation (P): Direction from previous to current point (each center point of the figures)

Successive Navigation (SN): Direction from current point to next point

Priority Number: Direction that has a priority on precedent navigation

3.5 Pocket Machining Algorithm

Input values are: a. Vertex points of a polygon

b. Tool diameter

c. Grid size in X direction

d. Grid size in Y direction

a) Interior navigation for main tool path

1. Model the sculptured bottom Bezier surface with Z direction's control points.
2. Digitize the 2D shape in XY as a function of tool diameter and grid size in X and Y directions.
3. Depending on the number of digitized grids in XY plane, determine the unit parameter value (u and v) in X and Y directions from Bezier surface in step 1.
4. Match each X and Y value from step 2 with Z values from step 3 based on an ordered specification. Call this set K. Finally all surface coordinates are determined in relation to the tool diameter, X and Y grid size.
5. Find a set of edge cutter extreme points (tool center point) at every vertex (polygon point) defined by user. Call this set C.
6. Make a new polygon based on C.
7. Determine the set of all grid centers inside the new polygon found in step 5. Call this new set S.

8. Find the navigation path from the point that has the left-most minimum Y value by using proposed navigation procedure. Call this set U. And keep the path made by X zigzag and Y zigzag algorithm separately and find Z values by using set K. Call this set N (Zigzag motions).
9. Reverse the navigation path(U) and find Z values by using set K. Call this set P (Main tool path)

b) Finding a path for wall machining, and combine with main, X zigzag, and Y zigzag tool paths.

1. Find the nearest neighborhood point within set C to begin wall machining.
2. Calculate tool centers between every two vertex in set C. Call this set F.
3. Sort the counterclockwise order of set C and set F, then find Z values by using set K. Call this new set W (Pocket wall path).
4. Make a final navigation path such that $T=\{P \cup W \cup N\}$.
5. Determine the main tool path machining or simulation method among line movements, arc + line movements, and Bezier curve + line movements.

This NC pocketing algorithm can be summarized as shown in Figure 13. The polygon defined in the case study has the shape as shown in Figure 14 in XY view. Outer thick lines denote the pocket boundary. Inside the pocket boundary, there are thin lines connecting each cutter edge extreme point. Inner thick lines are the boundary of main tool path grids that are located inside of thin lines. Inside the inner thick line boundary, the tool path consists of the

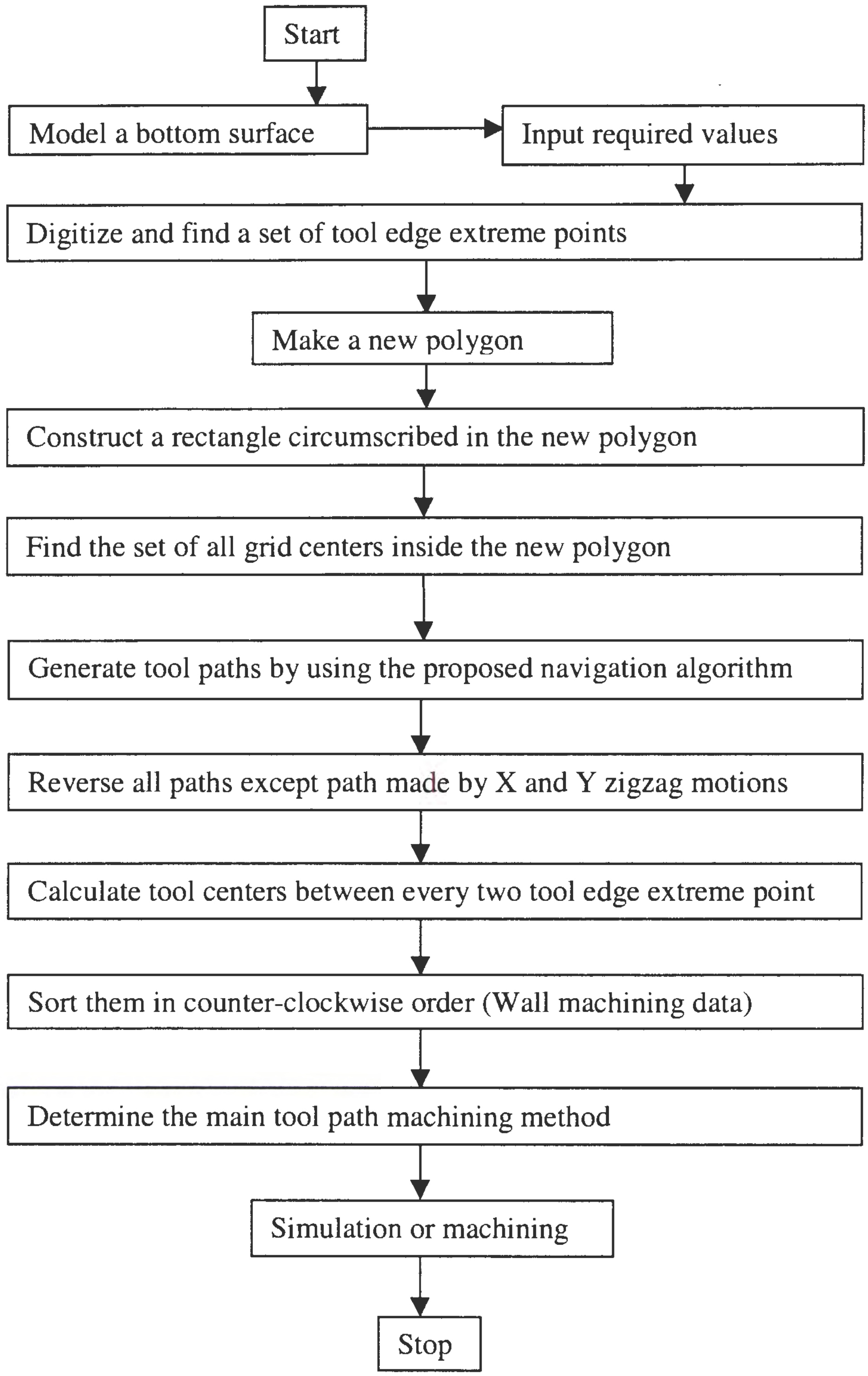


Figure 13. Flowchart for NC Pocketing

main tool path, X zigzag, and Y zigzag machining. Wall machining is performed on the outside of inner thick lines.

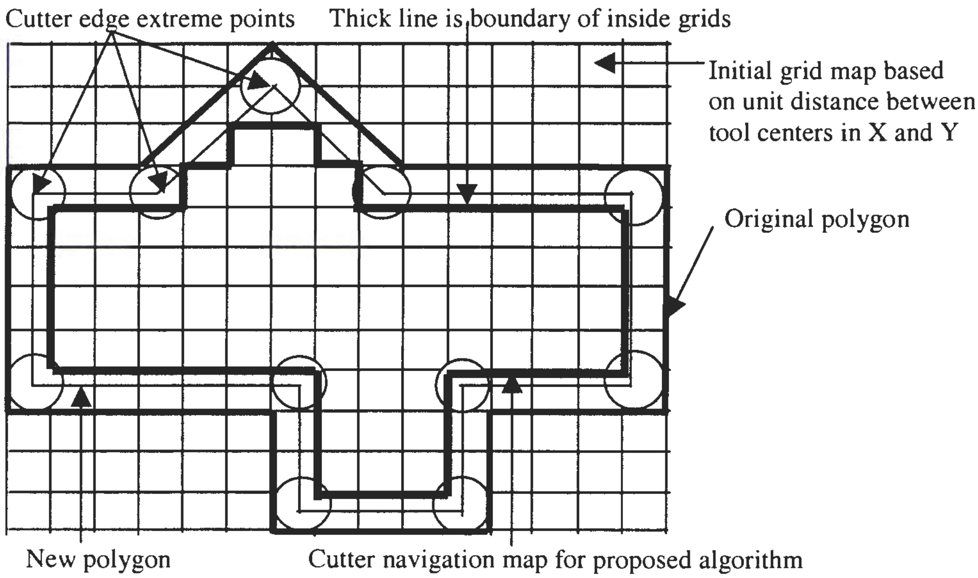


Figure 14. Initial Preprocessing Procedure

CHAPTER 4. MACHINING PATH AND NC CODE GENERATION

There are 3 methods used in this study for generating machining path categorized by tool movements. These are line movements, arc + line movements, and Bezier curve + line movements.

4.1 Line Movements

Line movements are done by linear interpolation. Linear moves can be made by one or any combination of all the active axes (X,Y,Z). An example is shown in Figure 15.

As it can be seen in Figure 15, there are consecutive linear motions to generate a mountain + valley shape curve. In this case, the advantage is that there is no need of changing active axis plane, just next destination coordinate (X, Y, and Z) needs to be specified after one movement. However, the disadvantages are that there are a lot of 'stop and go' motions that cause machining time delay and large file sizes.

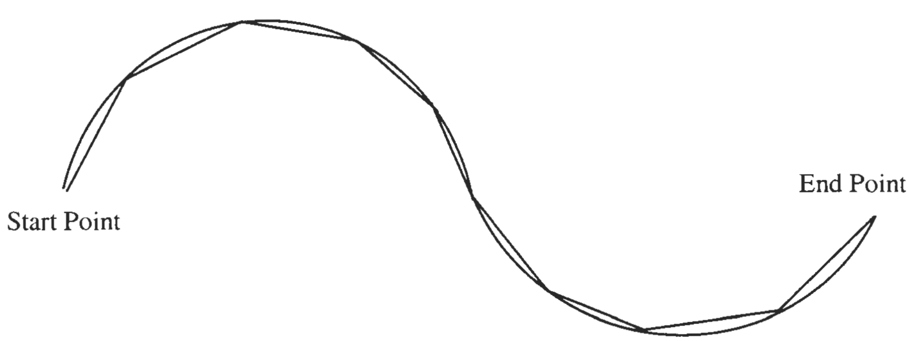


Figure 15. Linear Movements to Generate Curve

4.2 Arc + Line Movements

The algorithm presented in this study is similar to that used by Vickers and Bradley (1992) which is a recursive approach to fit circular arcs, within a prescribed error tolerance, through surface data points. Unnecessary surface points are eliminated and linear interpolation segments are used only where necessary to produce a concise tool path program. The segmentation algorithm in case of XZ plane proceeds as follows.

1. Start with a set of cross-sectional points (X_i, Z_i), i=1,….,N. If N=2, linear interpolation is formed.
2. Calculate the data set mid-point.
3. Calculate the arc center through the first, mid, and last points.
4. Calculate and test the error between the arc and the intermediate surface points. The error is given as

   $$Error = |r - d|$$
   $$\left| r - \left[(X_i - X_c)^2 + (Z_i - Z_c)^2 \right]^{1/2} \right|$$

   where d is the distance to the data point (X_i, Z_i) from the arc center (X_c, Z_c) and r is the arc radius.
5. If the test fails(exceeding the specified maximum error tolerance), the span of the arc is decreased from {i=1,….,N} to {i=1,…,N-1}

6. If the test passes, the radius of the arc is checked to see if it is larger than specified (whether the radius goes to unlimited value). If so, a linear command is formed from start to end point.
7. If the radius of the arc is not larger than specified, the appropriate circular interpolation command is generated, otherwise (N=2) a linear interpolation command is generated.
8. The process is stopped if the last point is reached, otherwise a new arc center for the current location and the old end point is calculated.
9. The same algorithm is repeated for the next YZ plane and then it would finally stop at the end of the data point.

The decomposition of a curve into a set of lines and arcs is shown in Figure 16 and the entire algorithm is schematically shown in Figure 17. A circle of radius *r* and center (*h*, *k*) in XZ plane is expressed in implicit form to determine the center and radius of a circular arc passing through three data points. The form in YZ plane is the same as XZ plane.

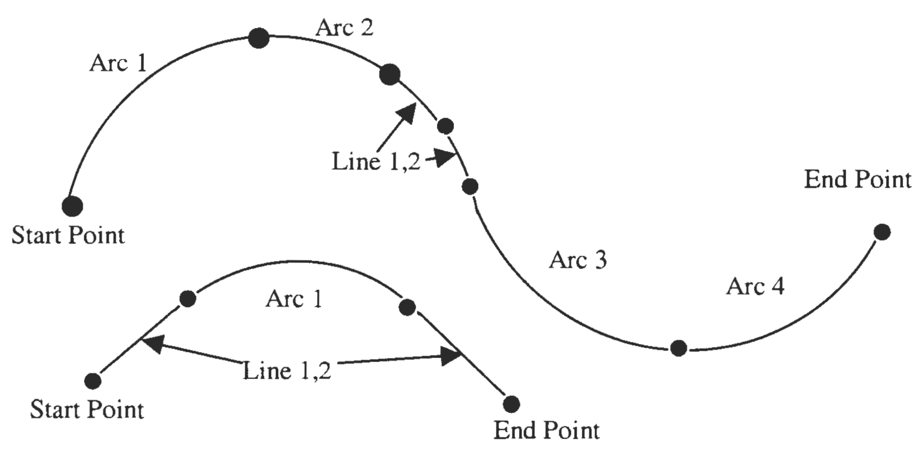


Figure 16. Illustration of Arc + Line Movements

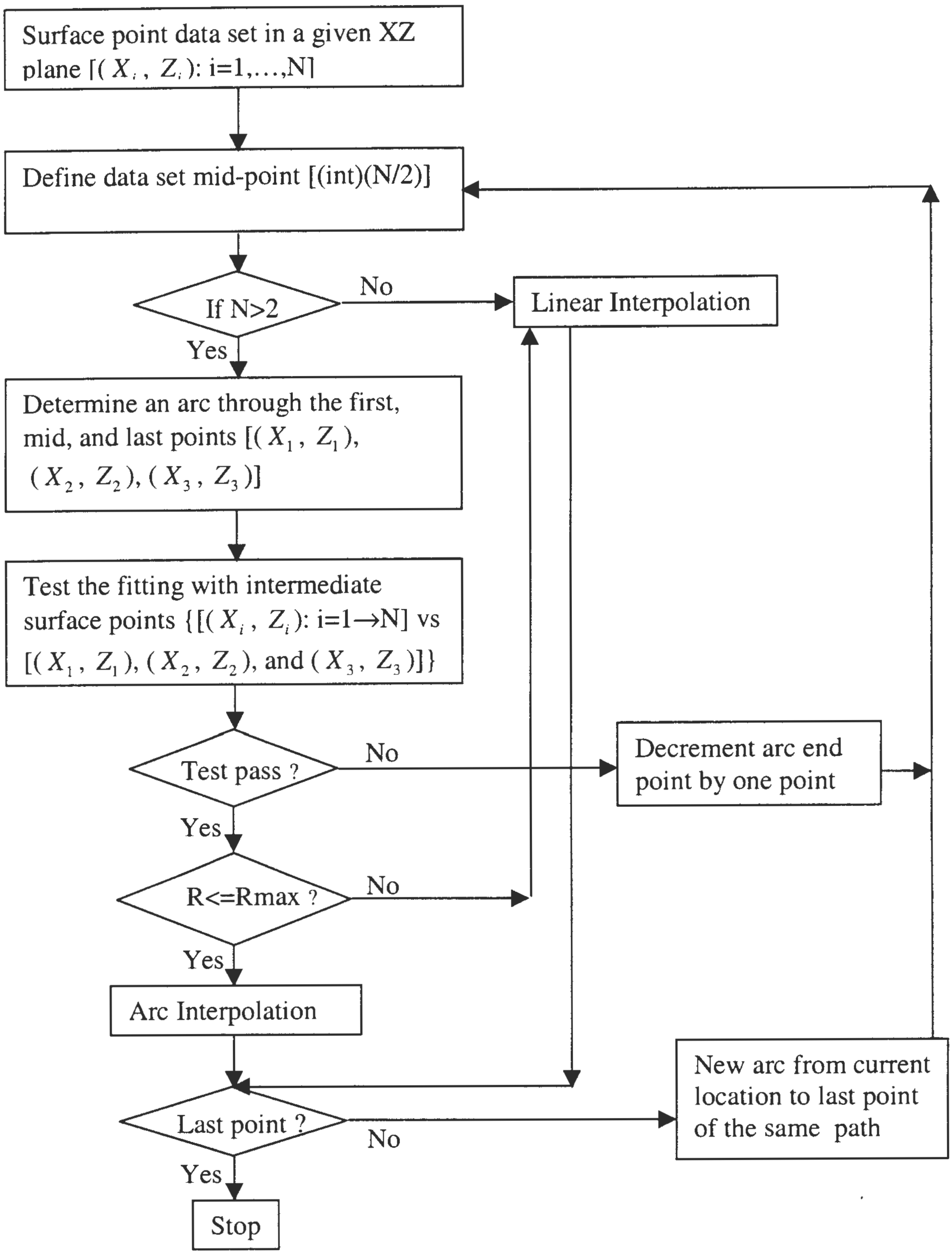


Figure 17. Flowchart of the Arc/Line Segmentation Algorithm in XZ Plane

$$X^2 + Z^2 + aX + bZ + c = 0$$
$$where\ \ a = -2h, \quad b = -2k \quad c = h^2 + k^2 - r^2$$

A system of three equations, in the variables a, b, and c are created for the data points $\{(X_1, Z_1), (X_2, Z_2), (X_3, Z_3)\}$, all of with lie on the arc. The matrix form of three equations is as follows.

$$\begin{bmatrix} X_1 & Z_1 & 1 \\ X_2 & Z_2 & 1 \\ X_3 & Z_3 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} -(X_1^2 + Z_1^2) \\ -(X_2^2 + Z_2^2) \\ -(X_3^2 + Z_3^2) \end{bmatrix}$$

4.3 Bezier Curve + Line Movements

With Bezier curve motion, more efficient tool path is generated. Bezier curve equations can be made using given surface points. First and last control points are start and end points. The problem is how to find 2nd and 3rd control points. With approximation skill, the problem has been solved.

The explicit form of cubic Bezier curve equation is as shown below.

$$P(u) = P_0(1-u)^3 + 3P_1u(1-u)^2 + 3P_2u^2(1-u) + P_3u^3 \quad 0 \le u \le 1$$

u_1 and u_2 can be input to make two equations of two variables, which are

$$u_1 = \frac{1}{(n-1)}, \quad u_2 = 1 - u_1 \text{ where n is the number of points}$$

$$P(u_1) = P_0(1-u_1)^3 + 3P_1u_1(1-u_1)^2 + 3P_2u_1^{\ 2}(1-u_1) + P_3u_1^{\ 3} \qquad 0 \le u_1 \le 1$$

$$P(u_2) = P_0(1-u_2)^3 + 3P_1u_2(1-u_2)^2 + 3P_2u_2^{\ 2}(1-u_2) + P_3u_2^{\ 3} \quad 0 \le u_2 \le 1$$

An assumption made in this approach is that the coordinates of $P(u_1)$ and $P(u_2)$ are equal to the 2nd grid center point and (n-1)th grid center point when a Bezier curve is given n surface points. This is shown in Figure 18.

A Bezier curve shown in Figure 19-(b) is expressed as a straight line. $P(u_i)$ (i=1,…,n) has exactly the same coordinates as grids in this case since the grids size are equal to $P(u_{i+1}) - P(u_i)$ which is a unit Bezier curve. However, as Bezier curve's curvature becomes larger, a unit Bezier curve size is bigger than a grid size (Figure 19-(a)). It causes surface point error in Z direction. As can be seen in Figure 19, those points' error will be larger as curvature of curve is larger. Surface point error can be approximated as follows as shown in Figure 20.

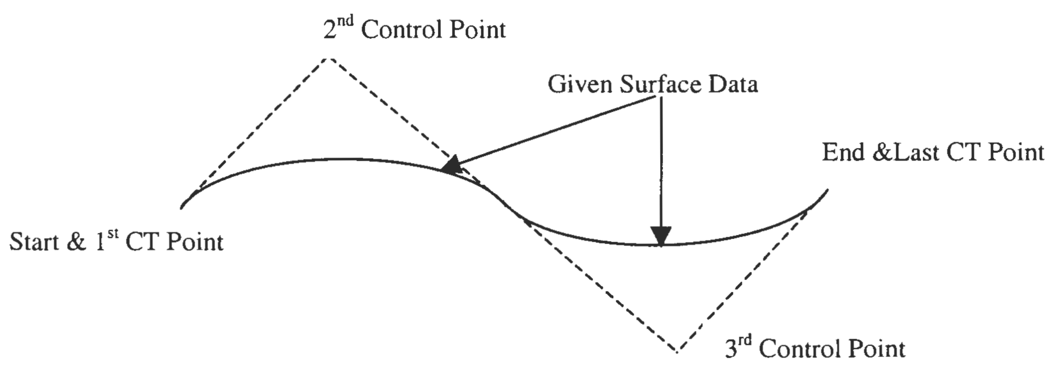


Figure 18. Generation of Bezier Curve Tool Path

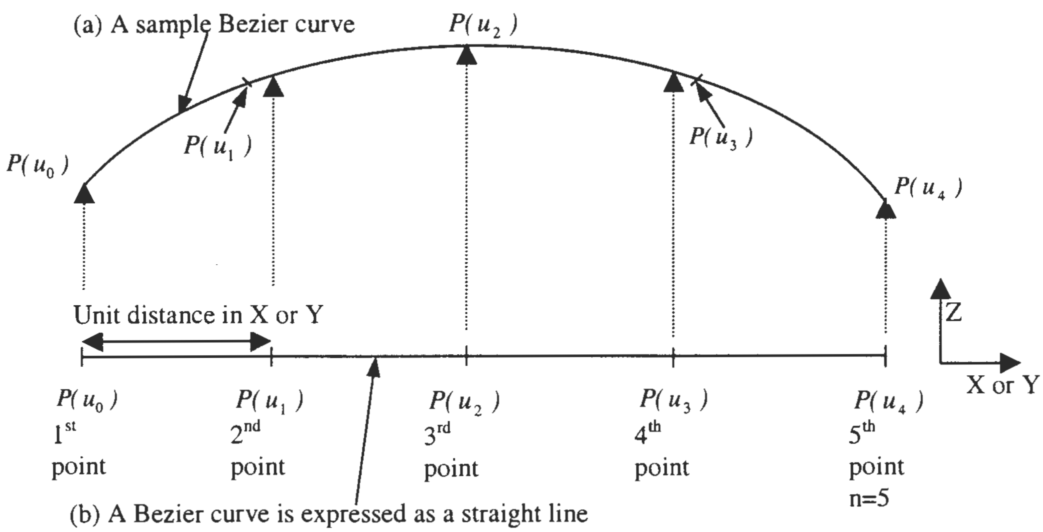


Figure 19. Unit Distance in Bezier Curve

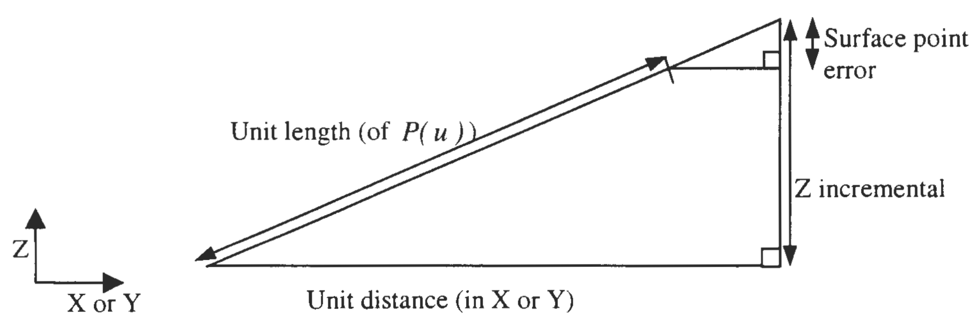


Figure 20. Surface Point Error in Bezier Curve

$$\sqrt{(Unit\ distance)^2 + (Z\ incremental)^2} : Z\ incremental$$

$$\cong \sqrt{(Unit\ distance)^2 + (Z\ incremental)^2} - Unit\ length : Surface\ Point\ Error$$

$$Surface\ Point\ Error \cong \frac{Z\ incremental\left(\sqrt{(Unit\ distance)^2 + (Z\ incremental)^2} - Unit\ length\right)}{\sqrt{(Unit\ distance)^2 + (Z\ incremental)^2}}$$

The algorithm is as follows.

1. Start with a set of cross-sectional points (X_i, Z_i), i=1,….,N.
2. If N>3, calculate $P(u_1)$ and $P(u_2)$ which correspond to the second (X_2) point and (n-1)th (X_{n-1}) point. If not, linear interpolation is formed.
3. Calculate intermediate control points.
4. The same algorithm is repeated for the next YZ plane [(Y_i, Z_i): i=1,…,N] and then it would finally stop at the end of the data point.

The algorithm generating Bezier curve + line movements is also shown in Figure 21.

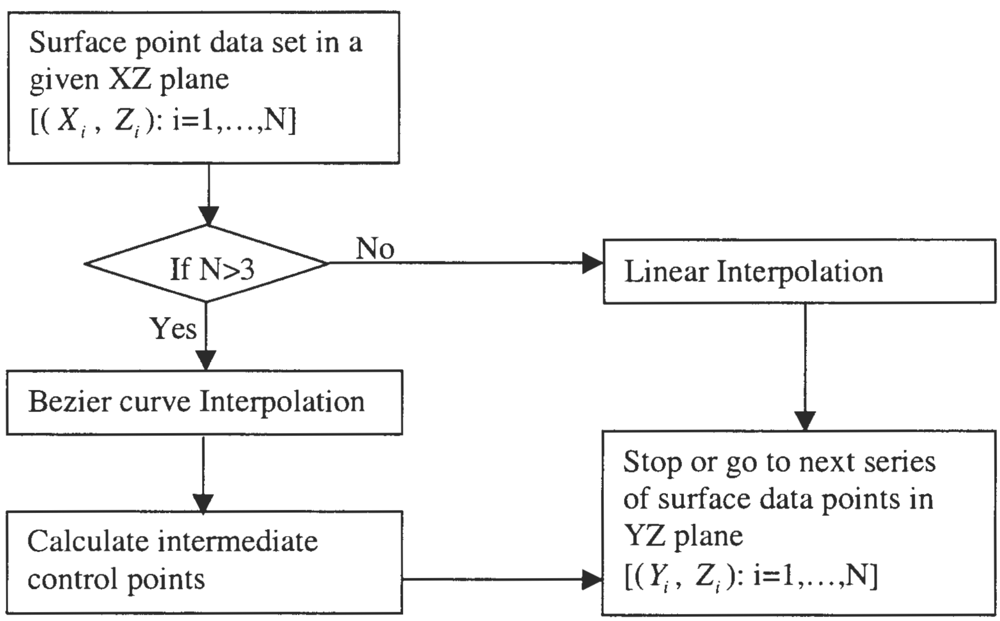


Figure 21. Bezier Curve + Line Movements Algorithm in XZ Plane

4.4 Rough and Finish Cut

In most real machining situations, it is required to separate machining depth into some layers to protect tools from deflection and wear and to overcome the limitation of the tool length. These steps are necessary especially in deep pocket machining. Dividing machining into a number of layers means that there would be a different shape at each layer.

The proposed method in this study is controlling Z coordinates on the bottom surface points. This means that Z coordinates of surface points need to be specified to fit each layer's specification range. A simple 2D example is in Figure 22.

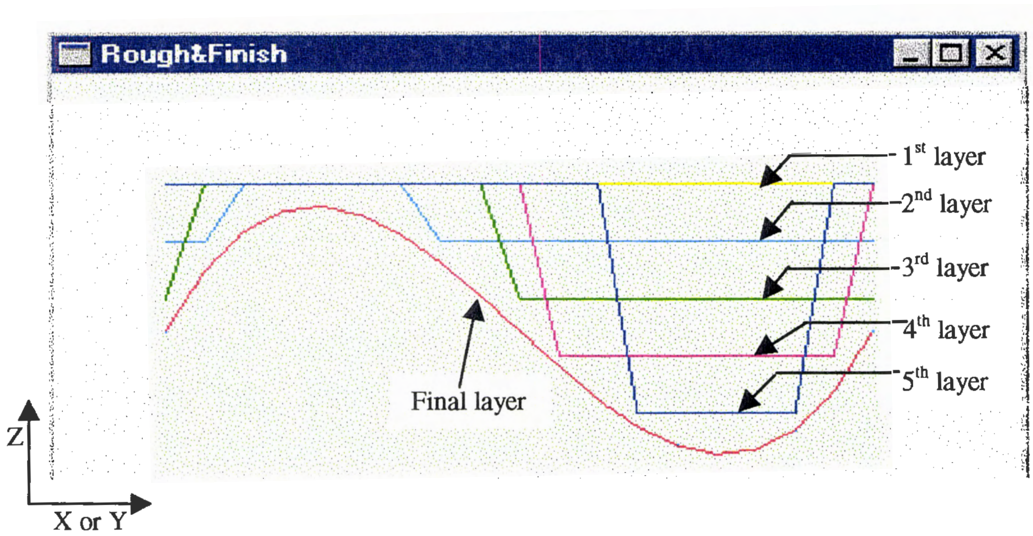


Figure 22. An Example of Rough Cutting Steps in 2 Dimensions

Since machining depth (Z coordinate) is concerned, this approach is selected for the main navigation tool path. From the top view, X and Y grid navigation of tool path is the same for each layer. After final layer's tool path machining followed by 1st to 5th, pocket wall, X zigzag, and Y zigzag machining paths would be followed. If curvature at a certain layer is steep relative to other layers, the unit depth of that layer can be modified flexibly.

At each layer, there is a range of Z values, such as -0.1in< Z < 0 (top surface), -0.2in < Z < -0.1in, and -0.3in < Z <-0.2 in etc. If Z values of the bottom surface belong to each layer's Z value zone at each layer machining time, those Z values would be changed into the highest layer's Z value bigger than the maximum Z value of the bottom surface to prevent unwanted cut which includes over-cut.

Another advantage of this approach is controlling machining speed. For rough machining, quality is not an important factor. So it allows increasing machining speed for roughing, then final layer is machined with proper speed.

The final layer can be machined by 3 choices (line, arc + line, Bezier curve + line) introduced in previous sections.

4.5 Proposed Algorithm for Reverse Engineering

Since the bottom surface is defined with coordinates of (X, Y, Z), it can be applied to reverse engineering. For instance, there is an object that someone wants to machine and there is no existing CAD model. If the object can be reverse engineered or, in other words, those coordinates can be measured by devices like CMM (Coordinate Measurement Machine), then the surface can be machined using the pocketing algorithm described here regardless of the type of the surface. This is an advantage of the surface generation method used in this study. The reverse engineering procedure is shown in Figure 23.

Surface data is defined by coordinate points, depending upon the tool diameter in XY view. These data are then matched with Z data points determined by control points. It means that as long as the measuring device traverses the data points with this unified grid method in XY view and measures the depth in Z direction, the surface would be generated with no

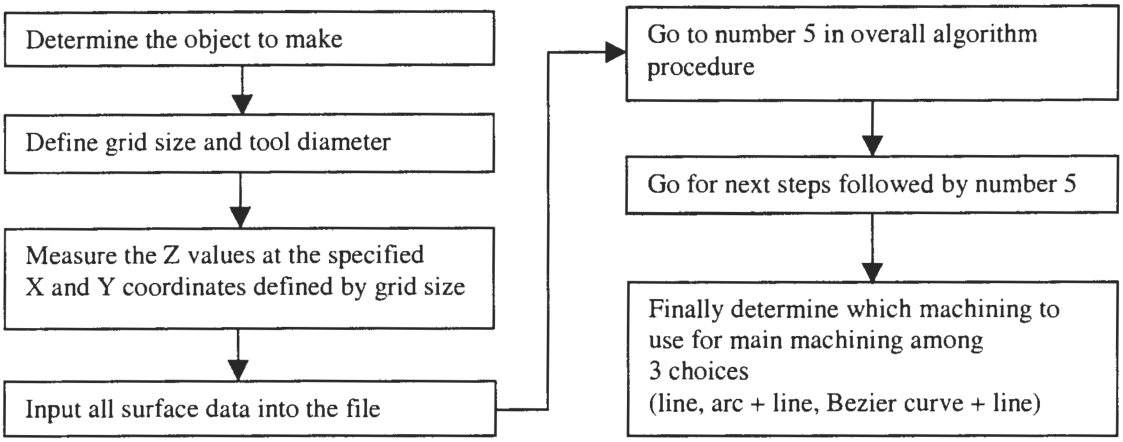
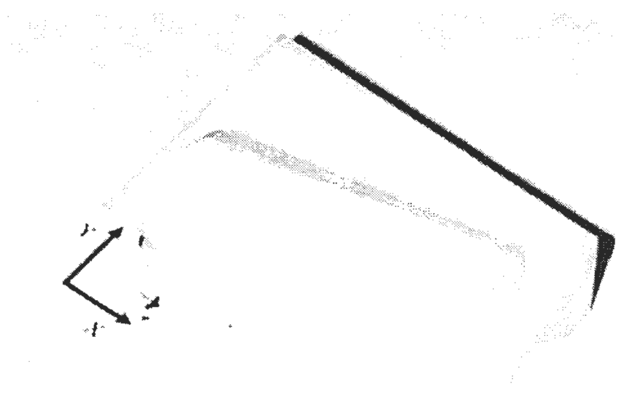


Figure 23. Proposed Reverse Engineering Algorithm



Measured points are
(0.0, 0.0, 0.0), (0.0, 0.3, 0.0), (0.0, 0.6, 0.5744), (0.0, 0.9, 0.6553), ·······, (0.9, 0.0, 0.0), (0.9, 0.3, 0.5284), (0.9, 0.6, 0.7655), (0.9, 0.9, 0.6795), ········, (2.4, 0.9, 0.6816), (2.4, 1.2, 0.7390), (2.4, 1.5, 0.8459), (2.4, 1.8, 0.4924)

Figure 24. An Example of Bottom Surface for Reverse Engineering

problem. As grids' size is made smaller, more accurate surface would be made. However, it would take more time to machine.

A sample object that has a bottom surface as in Figure 24 is measured to show this algorithm with CMM. Each unit grid size in X and Y is 0.3 inch.

CHAPTER 5. CASE STUDY

Two case studies have been made in this study. These are to show general polygon and to show rough and finish cut. The actual machining G&M code for the case study is shown in the Appendix.

Different colors are used in these case studies. Main tool path is expressed with red color. Wall machining is shown with green color. Blue and dark green colors are used for X zigzag and Y zigzag each. Machining samples are illustrated to show how navigation strategies work for general polygon case with line movements.

To show arc + line and Bezier curve + line machining, red color of main machining is replaced by blue (thick) for arc and Bezier curve machining and yellow (light) for line movements. The algorithm for NC pocketing is implemented in Visual C++ and OpenGL.

1. Input
    a. Vertex points of a polygon
    b. Tool diameter: 0.25 in
    c. Grid size in X direction: 0.125 in
    d. Grid size in Y direction: 0.0625in
2. Output
    a. Output is a set of cutter paths to remove the inside area of a general polygon with an arbitrarily shaped bottom surface.
    b. Drawing of the sculptured bottom surface with the defined polygon.

5.1 General Polygon

5.1.1 Line movements

The sequence of machining shown in this study is main tool path first (Figure 25), wall machining next (Figure 26). Then X zigzag (Figure 27) and Y zigzag (Figure 28) machining are subsequently done. Finally, there is no left over area without direct movement between grid center points. In other words, all grids are connected to each other. Real machining samples are shown in Figure 29 and the final simulation result is displayed in Figure 30.

5.1.2 Arc + line movements

Substituting linear main tool path to arc + line tool path is shown in Figure 31. Light (yellow) lines show linear movements between point to point and thick (blue) lines show arc movements for more than at least 3 points.

5.1.3 Bezier curve + line movements

These two figures for arc + line movements and Bezier curve + line movements in Figure 31 and 32 show how these two methods are efficient in terms of saving a number of commands. With line movements only, all grid center points are connected by each unit line segments with red color. However, it shows clearly how these methods work. Of course, the total number of arc segments varies depending on the arc tolerance for arc + line movements. As tolerance is tighter, more arc segments or more line movements would be needed.

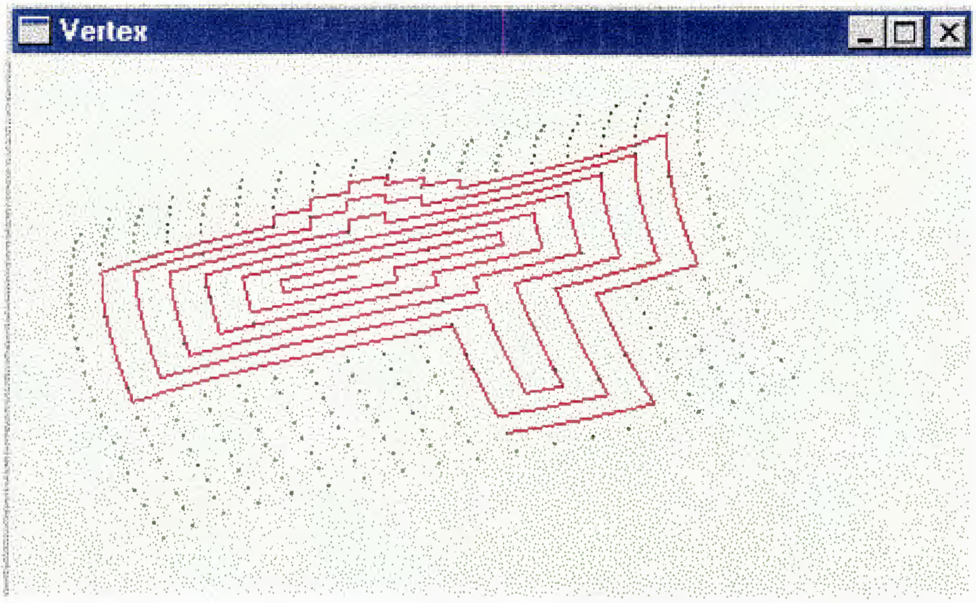
5.2 Rough and Finish Cut with Rectangle Pocket Shape

To avoid confusion due to many layers in the same shape of pocketing process, the total of 6 layers were divided into 2 figures (each 3 layers) as in Figure 33 and Figure 34. The final layer is the main tool path. After final layer machining, pocket wall machining, X and Y zigzag machining is performed. The algorithms for these are the same as the previous case study.

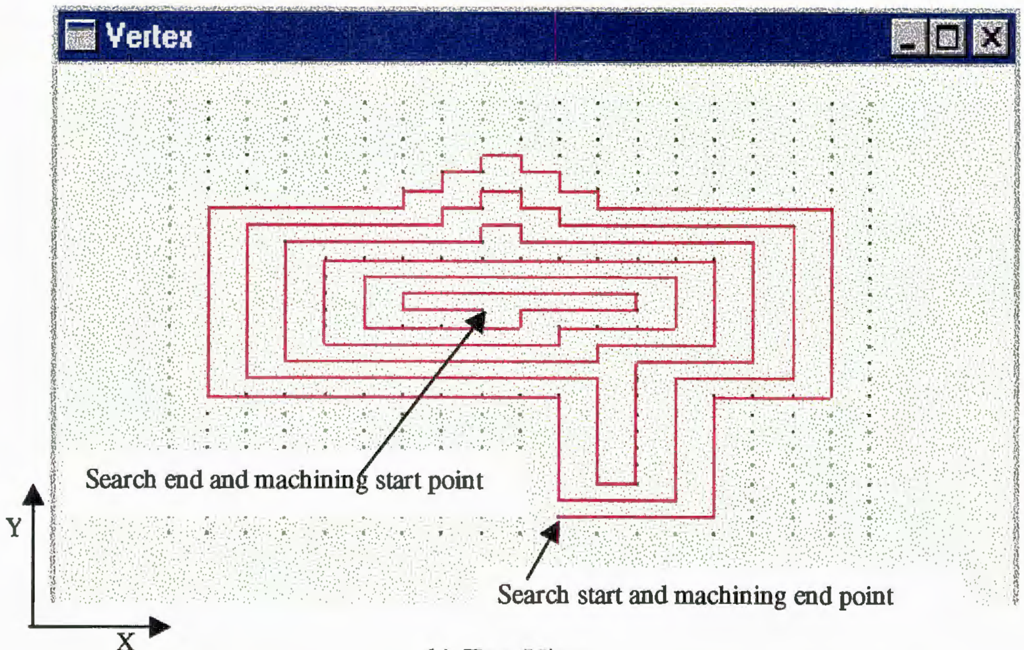
5.3 Comments on Surface Error/Roughness/CL/CC

As shown in Figure 15, arc + line movements will have less surface error for a given tool path than line movements in terms of surface generation. In a given tolerance zone, arc + line algorithm generated arc tool path and line tool path was generated when necessary. Simply, arc movements would follow real surface points more accurately while line movements make an approximation. Surface roughness (Scallop height) is proportional to the relation between tool diameter and grid size as shown in Figure 35. As tool diameter become larger on a given grid size, surface roughness would be reduced. The case of arc + line movements would have smaller value of roughness because of the same reason as surface error.

The point that needs to be considered is the relation between CL (Cutter Location) and CC (Cutter Contact) of the tool. Tools move along the center points of the grids except for pocket wall machining. It means that tools go to and from center points (CL). If the bottom surface is smooth, CL and CC would be almost same. However, if the bottom surface is steep, tt would be different. The magnitude of the difference between CL and CC points is also proportional to tool diameter and grid size. So when complex and more accurate surface need to be designed, this point should be considered.

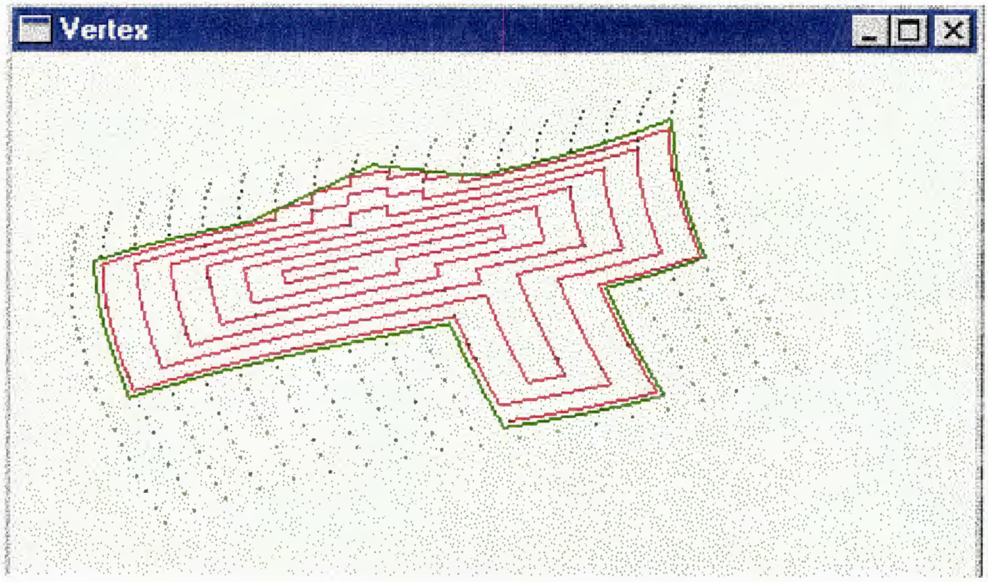


a) Isometric View

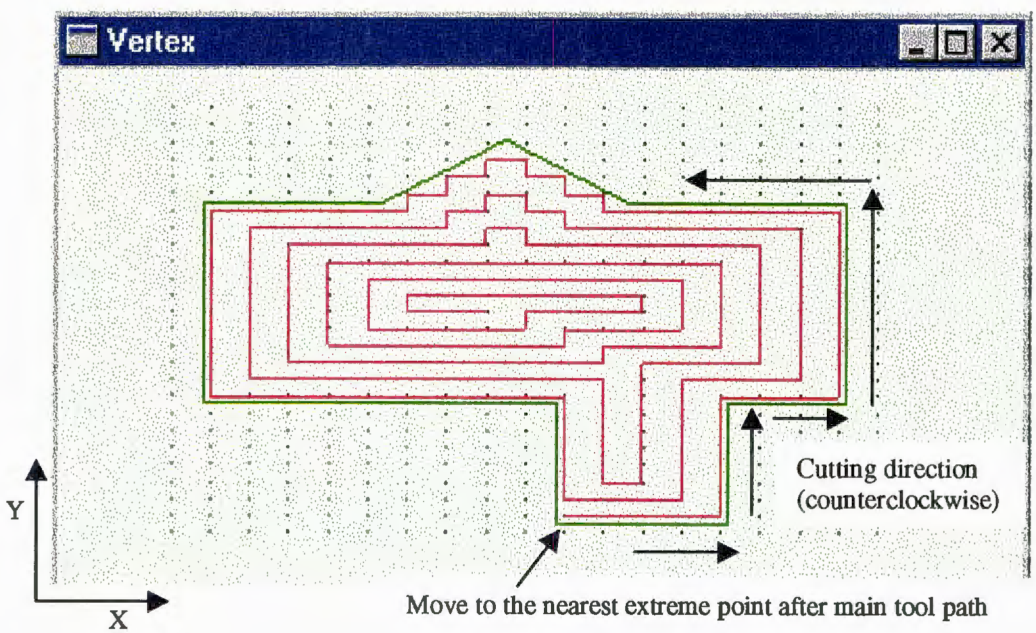


b) Top View

Figure 25. Isometric and Top Views of the Main Tool Path

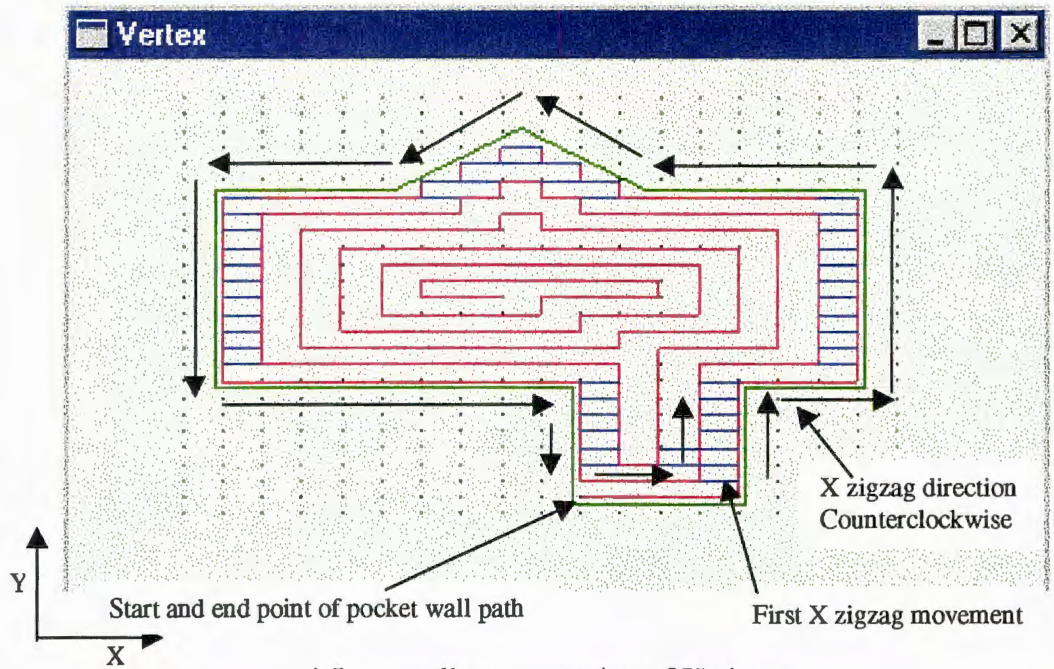


a) Isometric View

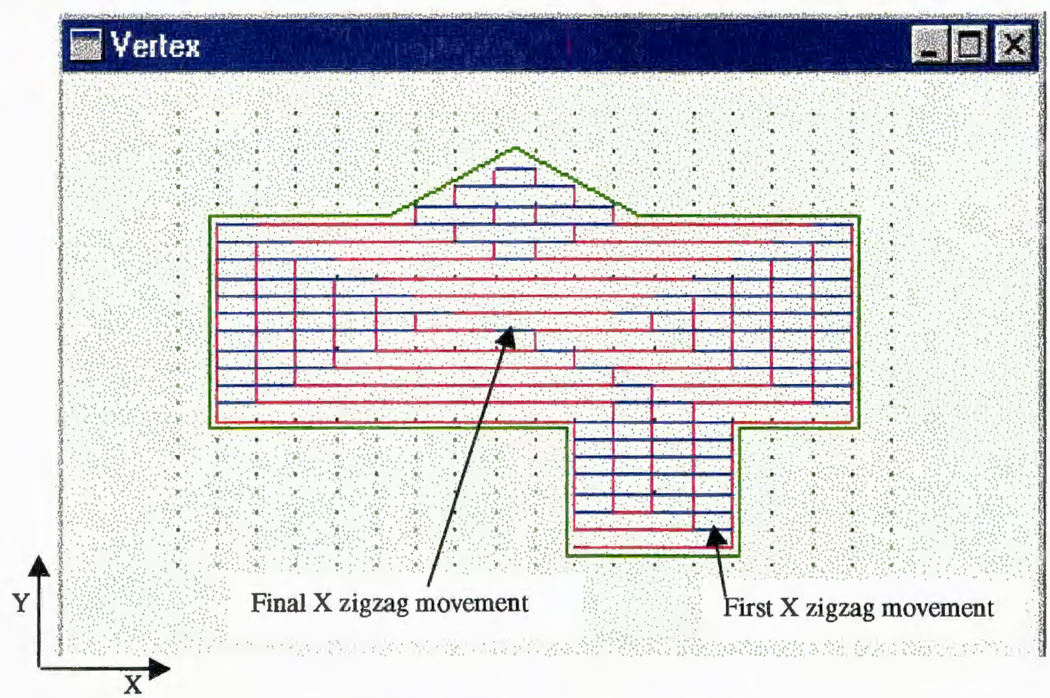


b) Top View

Figure 26. Isometric and Top Views of the Pocket Wall Tool Path

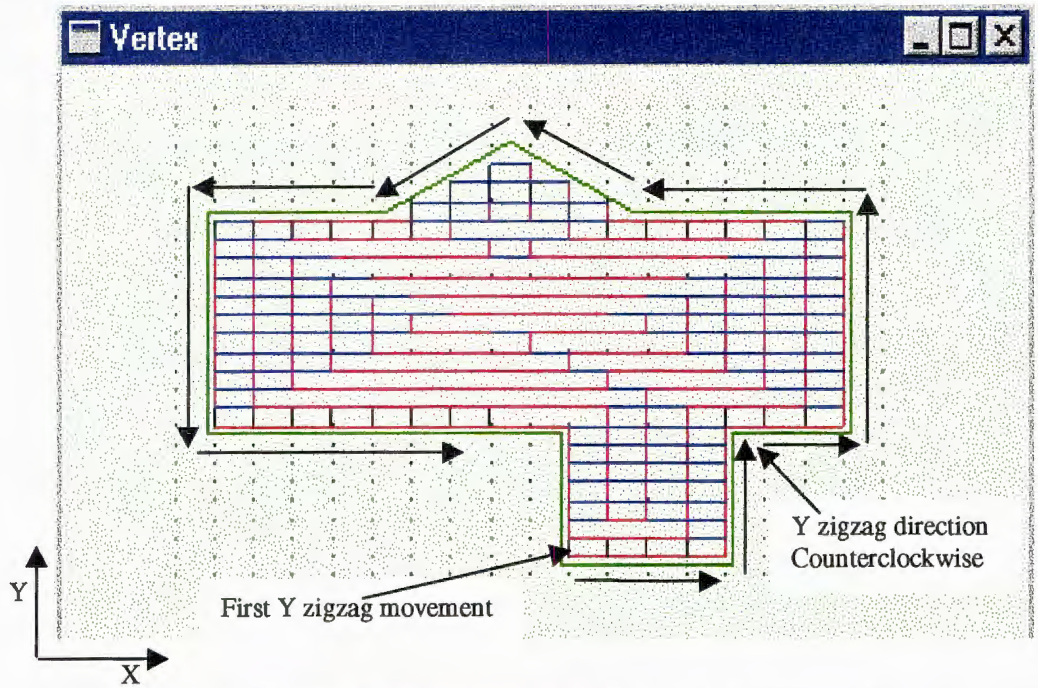


a) Intermediate processing of X zigzag

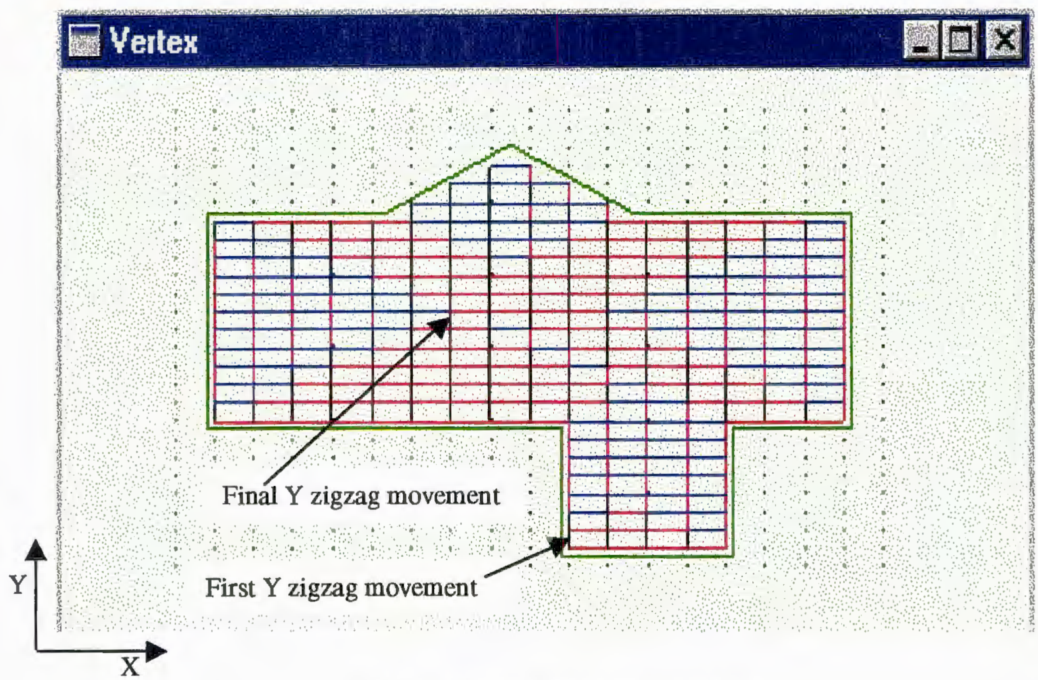


b) After all X zigzag movements

Figure 27. Intermediate and Full Processing of X zigzag Tool Path

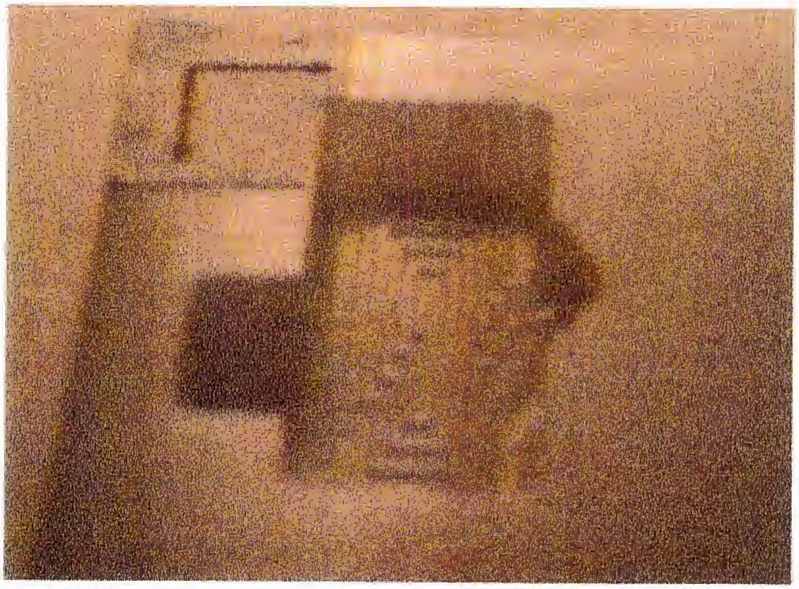


a) Intermediate processing of Y zigzag movements

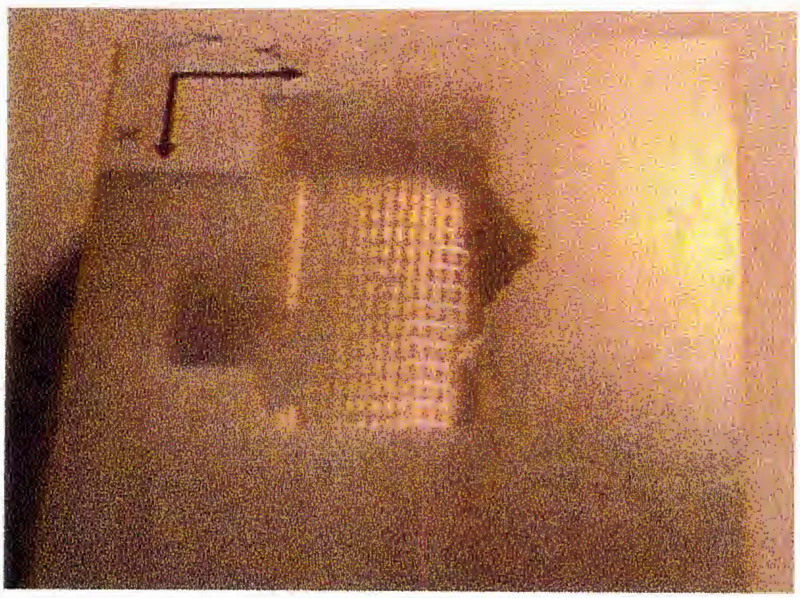


b) After all Y zigzag movements

Figure 28. Intermediate and Full Processing of Y zigzag Tool Path

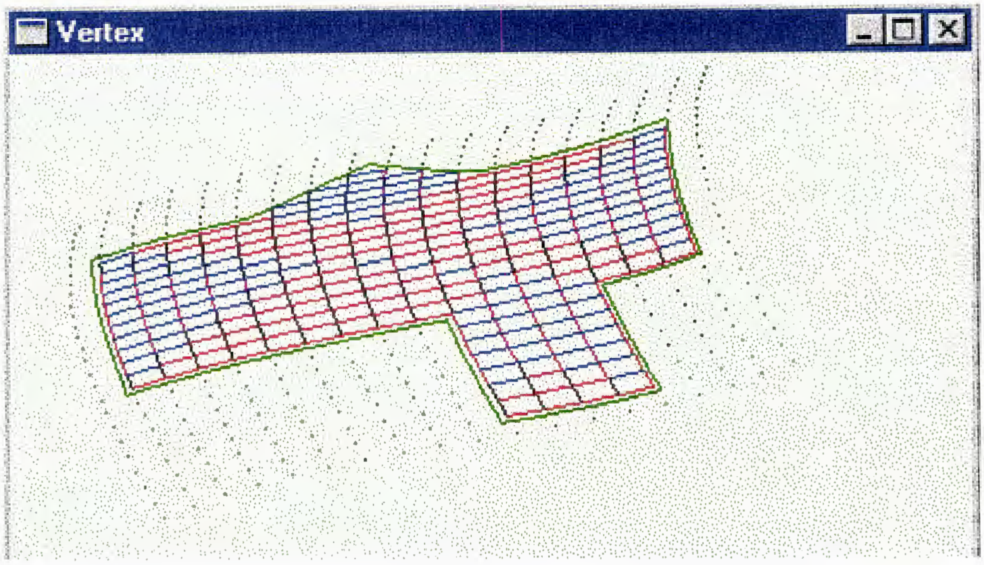


a) After main and wall tool paths

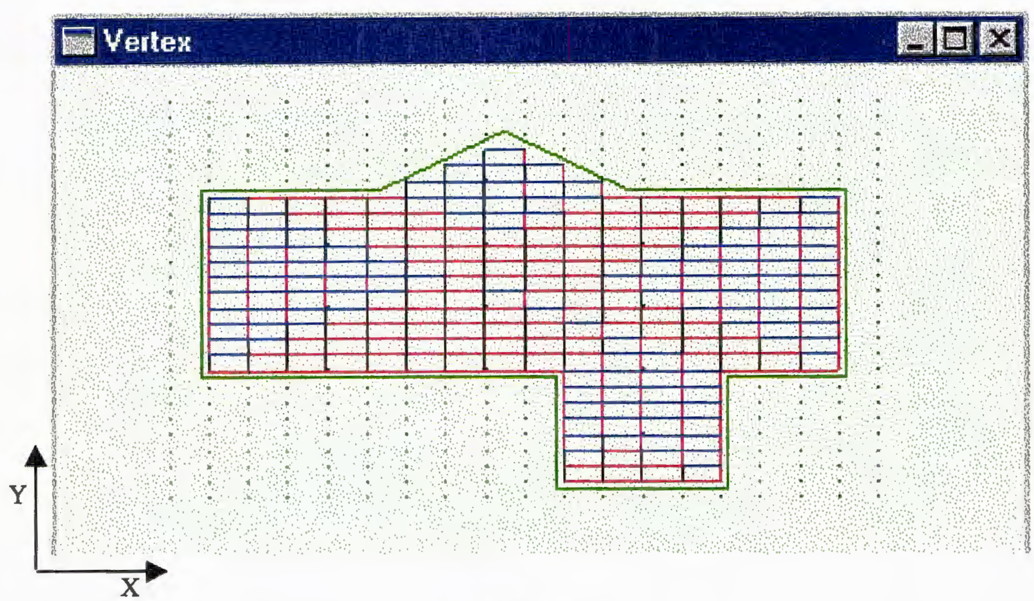


b) After all machining tool paths including zigzag movements

Figure 29. Real Machining Samples



a) Isometric View



b) Top View

Figure 30. Isometric and Top Views of Final Result after Main, Wall, X and Y zigzag Tool Path

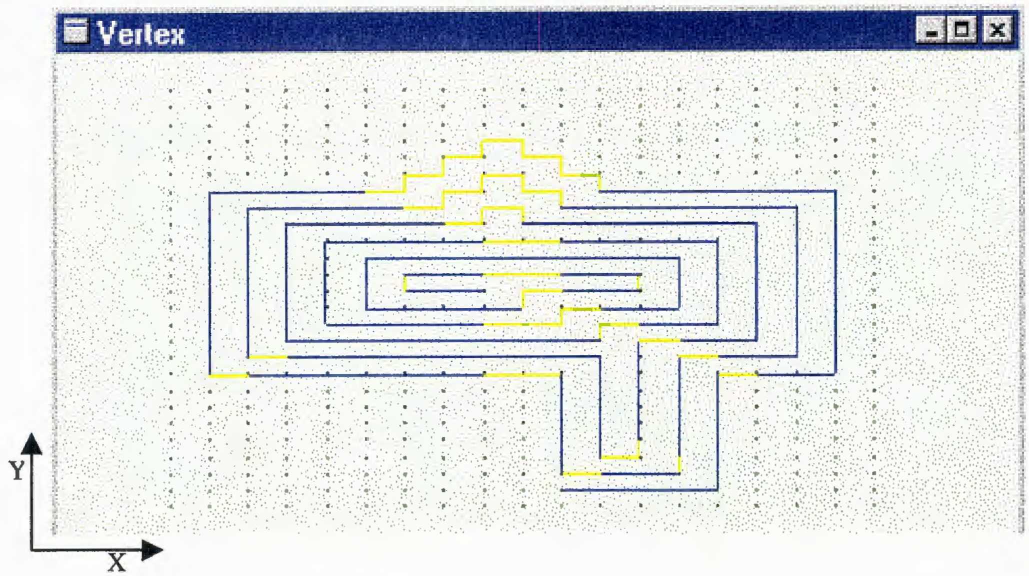


Figure 31. Arc + Line Movements on the Same Polygon

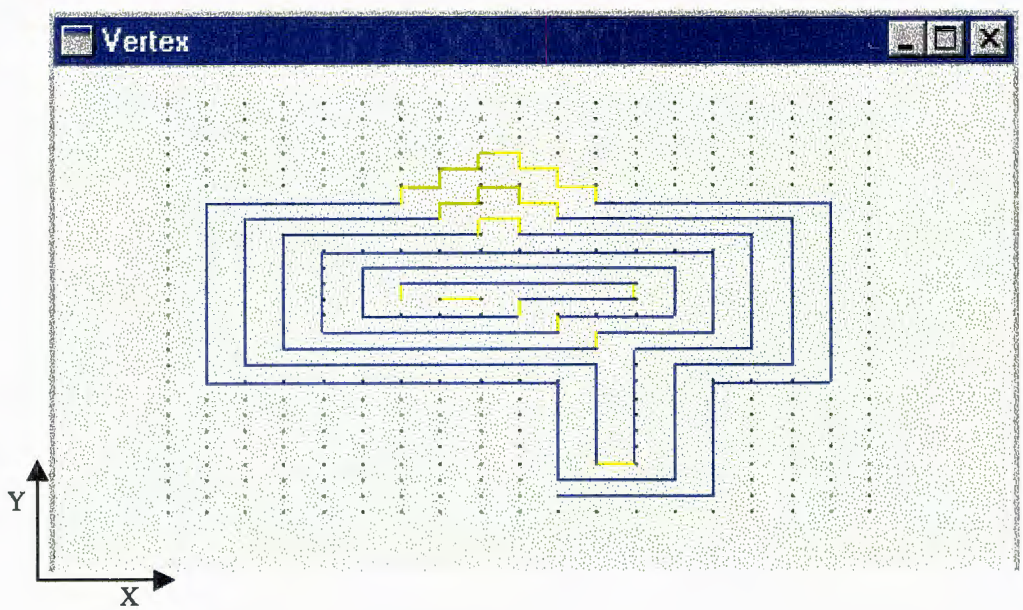


Figure 32. Bezier Curve + Line Movements on the Same Polygon

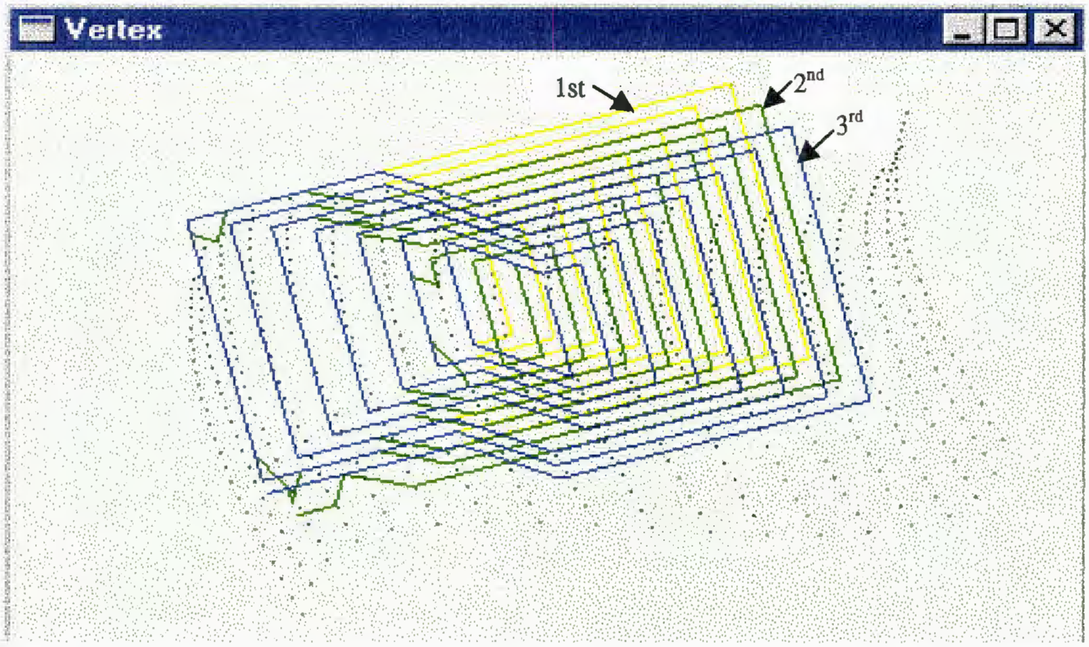


Figure 33. 1st, 2nd, and 3rd layers of Rough & Finish Cut

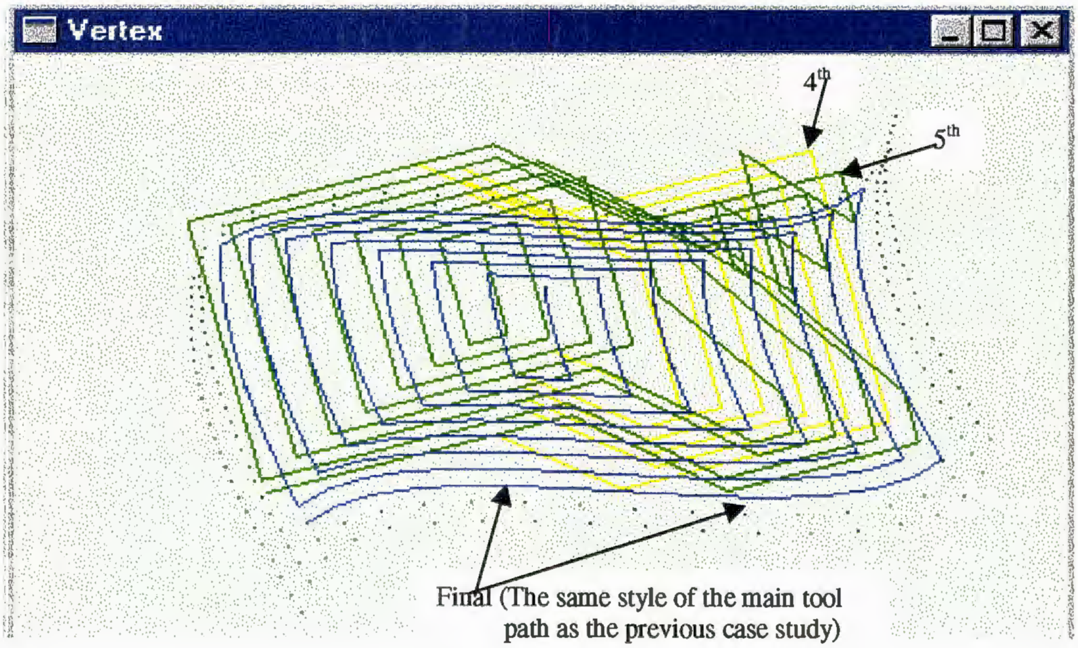
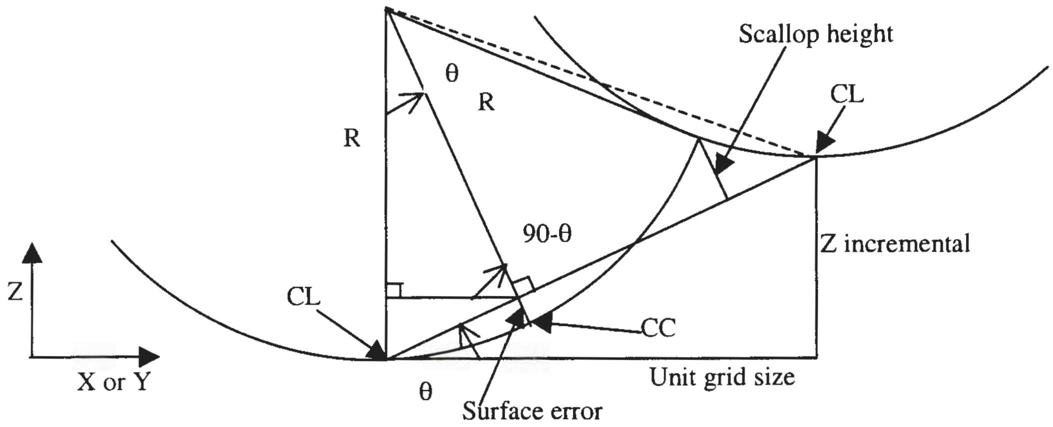


Figure 34. 4th, 5th, and Final Layers of Rough & Finish Cut



$$\theta = \tan^{-1}(Z\,incremental\,/\,unit\ grid\ size)$$
$$R\cos\theta \cong R - Surface\ Error$$
$$Surface\ Error \cong R(1-\cos\theta)$$

$$\sqrt{unit\ grid\ size^2 + (R - Zincremental)^2} : R\cos\theta$$
$$\cong \sqrt{unit\ grid\ size^2 + (R - Zincremental)^2} - R : Scallop\ Height$$
$$Scallop\ Height \cong \frac{R\cos\theta(\sqrt{unit\ grid\ size^2 + (R - Zincremental)^2} - R)}{\sqrt{unit\ grid\ size^2 + (R - Zincremental)^2}}$$

Figure 35. Relation of CL, CC, and Surface Error

CHAPTER 6. CONCLUSIONS

An algorithm to generate final NC codes for machining the general polygon with a sculptured bottom surface was presented. It is an improvement on the classical window-frame approach with an added component that the cutting direction is either in X or in Y axis making the cutting particularly simple to implement on a 3-axis CNC machine. The methodology can be applied to all convex and concave shaped polygons, and even though the polygon has more complicated bottom surfaces, this algorithm works.

A grid based navigation strategy is used in planning the tool motion. The cutter path consists of the interior main tool path, machining along the periphery (wall machining), and X and Y zigzag motion. The X and Y zigzag motion commands are added to reduce the surface roughness. The wall machining is performed to improve the surface finish and accuracy along the walls of the pocket. A unified rough and finish cut algorithm is incorporated to machine deep pockets. This is necessary because the machining depth is limited by the length and rigidity of the cutting tool.

The grid based navigation strategy lays a foundation for the implementation of curvilinear interpolation algorithms. Three strategies, namely, line, arc + line, and Bezier curve + line movements were implemented for NC tool path generation in this study. All the methods were graphically simulated. The graphical simulations show that arc + line and Bezier curve +line methods can remove the excessive data points, and thus reduce the size of NC program compared to line movement. And we know by appeal to analytical proof that this algorithm should improve the smoothness of the final bottom surface and machining time since it has less data points and greatly reduced 'stop and go' motions. The amount of saved data files and machining time will vary depending on how the pocket polygon is defined.

The navigation algorithm was experimentally validated for linear machining on a 3 axis CNC machine. Experimental verification of curvilinear interpolation techniques are part of planned future research work. We expect these experimental results to match with those predicted by the simulations. Future work also is planned in the development of general-purpose curvilinear interpolation controllers for CNC machine tools. There has been significant work in the development of open architecture controllers to serve this purpose, however they are still not "open" enough and we expect to further work on the hardware control infrastructure to support the implementation of general purpose curvilinear interpolation algorithms.

APPENDIX

Generated G&M Codes for General Polygon Case with Line Movements

```
/* Start main tool path machining */

N0G5M3
N1G90G0Z0.5F3
N2X1.275000Y1.212500G01
N3Z-0.295210
N4X1.150000Y1.212500Z-0.289395
N5X1.025000Y1.212500Z-0.284524
N6X1.025000Y1.275000Z-0.286268
N7X1.150000Y1.275000Z-0.291204
N8X1.275000Y1.275000Z-0.297095
N9X1.400000Y1.275000Z-0.303464
N10X1.525000Y1.275000Z-0.309833
N11X1.650000Y1.275000Z-0.315724
N12X1.775000Y1.275000Z-0.320661
N13X1.775000Y1.212500Z-0.318469
N14X1.650000Y1.212500Z-0.313597
N15X1.525000Y1.212500Z-0.307782
N16X1.400000Y1.212500Z-0.301496
N17X1.400000Y1.150000Z-0.301496
N18X1.275000Y1.150000Z-0.295210
N19X1.150000Y1.150000Z-0.289395
N20X1.025000Y1.150000Z-0.284524
N21X0.900000Y1.150000Z-0.281066
N22X0.900000Y1.212500Z-0.281066
N23X0.900000Y1.275000Z-0.282765
N24X0.900000Y1.337500Z-0.286161
N25X1.025000Y1.337500Z-0.289756
N26X1.150000Y1.337500Z-0.294820
N27X1.275000Y1.337500Z-0.300865
N28X1.400000Y1.337500Z-0.307400
N29X1.525000Y1.337500Z-0.313935
N30X1.650000Y1.337500Z-0.319980
N31X1.775000Y1.337500Z-0.325045
N32X1.900000Y1.337500Z-0.328639
N33X1.900000Y1.275000Z-0.324164
N34X1.900000Y1.212500Z-0.321926
N35X1.900000Y1.150000Z-0.321926
N36X1.775000Y1.150000Z-0.318468
N37X1.650000Y1.150000Z-0.313597
N38X1.525000Y1.150000Z-0.307782
N39X1.525000Y1.087500Z-0.309833
N40X1.400000Y1.087500Z-0.303464
N41X1.275000Y1.087500Z-0.297095
N42X1.150000Y1.087500Z-0.291204
N43X1.025000Y1.087500Z-0.286268
N44X0.900000Y1.087500Z-0.282765
N45X0.775000Y1.087500Z-0.281172
N46X0.775000Y1.150000Z-0.279495
N47X0.775000Y1.212500Z-0.279495
N48X0.775000Y1.275000Z-0.281172
N49X0.775000Y1.337500Z-0.284528
N50X0.775000Y1.400000Z-0.289560
N51X0.900000Y1.400000Z-0.291256
N52X1.025000Y1.400000Z-0.294988
N53X1.150000Y1.400000Z-0.300245
N54X1.275000Y1.400000Z-0.306520
N55X1.400000Y1.400000Z-0.313304
N56X1.525000Y1.400000Z-0.320088
N57X1.650000Y1.400000Z-0.326363
N58X1.775000Y1.400000Z-0.331621
N59X1.900000Y1.400000Z-0.335352
N60X2.025000Y1.400000Z-0.337048
N61X2.025000Y1.337500Z-0.330273
N62X2.025000Y1.275000Z-0.325756
N63X2.025000Y1.212500Z-0.323497
N64X2.025000Y1.150000Z-0.323497
N65X2.025000Y1.087500Z-0.325756
N66X1.900000Y1.087500Z-0.324164
N67X1.775000Y1.087500Z-0.320661
N68X1.650000Y1.087500Z-0.315724
N69X1.650000Y1.025000Z-0.319980
N70X1.525000Y1.025000Z-0.313935
N71X1.400000Y1.025000Z-0.307400
N72X1.275000Y1.025000Z-0.300865
N73X1.150000Y1.025000Z-0.294820
N74X1.025000Y1.025000Z-0.289756
N75X0.900000Y1.025000Z-0.286161
N76X0.775000Y1.025000Z-0.284528
N77X0.650000Y1.025000Z-0.285344
N78X0.650000Y1.087500Z-0.281968
N79X0.650000Y1.150000Z-0.280280
N80X0.650000Y1.212500Z-0.280280
N81X0.650000Y1.275000Z-0.281968
N82X0.650000Y1.337500Z-0.285344
N83X0.650000Y1.400000Z-0.290408
N84X0.650000Y1.462500Z-0.297160
N85X0.775000Y1.462500Z-0.296271
N86X0.900000Y1.462500Z-0.298050
N87X1.025000Y1.462500Z-0.301964
N88X1.150000Y1.462500Z-0.307478
N89X1.275000Y1.462500Z-0.314060
N90X1.275000Y1.525000Z-0.323486
N91X1.400000Y1.525000Z-0.331016
N92X1.400000Y1.462500Z-0.321176
N93X1.525000Y1.462500Z-0.328292
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N94X1.650000Y1.462500Z-0.334874
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N96X1.900000Y1.462500Z-0.344302
N97X2.025000Y1.462500Z-0.346081
N98X2.150000Y1.462500Z-0.345192
N99X2.150000Y1.400000Z-0.336200
N100X2.150000Y1.337500Z-0.329456
N101X2.150000Y1.275000Z-0.324960
N102X2.150000Y1.212500Z-0.322712
N103X2.150000Y1.150000Z-0.322712
N104X2.150000Y1.087500Z-0.324960
N105X2.150000Y1.025000Z-0.329456
N106X2.025000Y1.025000Z-0.330272
N107X1.900000Y1.025000Z-0.328639
N108X1.775000Y1.025000Z-0.325044
N109X1.775000Y0.962500Z-0.331620
N110X1.775000Y0.900000Z-0.340388
N111X1.775000Y0.837500Z-0.351348
N112X1.775000Y0.775000Z-0.364500
N113X1.775000Y0.712500Z-0.379844
N114X1.775000Y0.650000Z-0.397380
N115X1.775000Y0.587500Z-0.417108
N116X1.650000Y0.587500Z-0.409343
N117X1.650000Y0.650000Z-0.390194
N118X1.650000Y0.712500Z-0.373172
N119X1.650000Y0.775000Z-0.358279
N120X1.650000Y0.837500Z-0.345512
N121X1.650000Y0.900000Z-0.334874
N122X1.650000Y0.962500Z-0.326363
N123X1.525000Y0.962500Z-0.320088
N124X1.400000Y0.962500Z-0.313304
N125X1.275000Y0.962500Z-0.306520
N126X1.150000Y0.962500Z-0.300245
N127X1.025000Y0.962500Z-0.294988
N128X0.900000Y0.962500Z-0.291256
N129X0.775000Y0.962500Z-0.289560
N130X0.650000Y0.962500Z-0.290408
N131X0.525000Y0.962500Z-0.294309
N132X0.525000Y1.025000Z-0.289102
N133X0.525000Y1.087500Z-0.285631
N134X0.525000Y1.150000Z-0.283895
N135X0.525000Y1.212500Z-0.283895
N136X0.525000Y1.275000Z-0.285631
N137X0.525000Y1.337500Z-0.289102
N138X0.525000Y1.400000Z-0.294309
N139X0.525000Y1.462500Z-0.301252
N140X0.525000Y1.525000Z-0.309931
N141X0.650000Y1.525000Z-0.305600
N142X0.775000Y1.525000Z-0.304659
N143X0.900000Y1.525000Z-0.306542
N144X1.025000Y1.525000Z-0.310684
N145X1.150000Y1.525000Z-0.316520
N146X1.150000Y1.587500Z-0.327370
N147X1.275000Y1.587500Z-0.334796
N148X1.275000Y1.650000Z-0.347991
N149X1.400000Y1.650000Z-0.356600
N150X1.400000Y1.587500Z-0.342824
N151X1.525000Y1.587500Z-0.350852
N152X1.525000Y1.525000Z-0.338547
N153X1.650000Y1.525000Z-0.345512
N154X1.775000Y1.525000Z-0.351349
N155X1.900000Y1.525000Z-0.355490
N156X2.025000Y1.525000Z-0.357373
N157X2.150000Y1.525000Z-0.356432
N158X2.275000Y1.525000Z-0.352102
N159X2.275000Y1.462500Z-0.341100
N160X2.275000Y1.400000Z-0.332299
N161X2.275000Y1.337500Z-0.325698
N162X2.275000Y1.275000Z-0.321297
N163X2.275000Y1.212500Z-0.319097
N164X2.275000Y1.150000Z-0.319097
N165X2.275000Y1.087500Z-0.321297
N166X2.275000Y1.025000Z-0.325698
N167X2.275000Y0.962500Z-0.332299
N168X2.150000Y0.962500Z-0.336200
N169X2.025000Y0.962500Z-0.337048
N170X1.900000Y0.962500Z-0.335352
N171X1.900000Y0.900000Z-0.344302
N172X1.900000Y0.837500Z-0.355490
N173X1.900000Y0.775000Z-0.368916
N174X1.900000Y0.712500Z-0.384580
N175X1.900000Y0.650000Z-0.402481
N176X1.900000Y0.587500Z-0.422619
N177X1.900000Y0.525000Z-0.444996
N178X1.775000Y0.525000Z-0.439028
N179X1.650000Y0.525000Z-0.430620
N180X1.525000Y0.525000Z-0.420585
N181X1.525000Y0.587500Z-0.400075
N182X1.525000Y0.650000Z-0.381617
N183X1.525000Y0.712500Z-0.365209
N184X1.525000Y0.775000Z-0.350852
N185X1.525000Y0.837500Z-0.338547
N186X1.525000Y0.900000Z-0.328292
N187X1.400000Y0.900000Z-0.321176
N188X1.275000Y0.900000Z-0.314060
N189X1.150000Y0.900000Z-0.307478
N190X1.025000Y0.900000Z-0.301964
N191X0.900000Y0.900000Z-0.298050
N192X0.775000Y0.900000Z-0.296271
N193X0.650000Y0.900000Z-0.297160
N194X0.525000Y0.900000Z-0.301252
N195X0.400000Y0.900000Z-0.309079
N196X0.400000Y0.962500Z-0.301771
N197X0.400000Y1.025000Z-0.296291
N198X0.400000Y1.087500Z-0.292637
N199X0.400000Y1.150000Z-0.290810
N200X0.400000Y1.212500Z-0.290810
N201X0.400000Y1.275000Z-0.292637
N202X0.400000Y1.337500Z-0.296291
N203X0.400000Y1.400000Z-0.301771
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N204X0.400000Y1.462500Z-0.309079
N205X0.400000Y1.525000Z-0.318214
N206X0.400000Y1.587500Z-0.329176
N207X0.525000Y1.587500Z-0.320345
N208X0.650000Y1.587500Z-0.315728
N209X0.775000Y1.587500Z-0.314725
N210X0.900000Y1.587500Z-0.316732
N211X1.025000Y1.587500Z-0.321148
N212X1.025000Y1.650000Z-0.333356
N213X1.150000Y1.650000Z-0.340028
N214X1.150000Y1.712500Z-0.354494
N215X1.275000Y1.712500Z-0.363071
N216X1.275000Y1.775000Z-0.380037
N217X1.400000Y1.775000Z-0.390056
N218X1.400000Y1.712500Z-0.372344
N219X1.525000Y1.712500Z-0.381617
N220X1.525000Y1.650000Z-0.365209
N221X1.650000Y1.650000Z-0.373173
N222X1.650000Y1.587500Z-0.358279
N223X1.775000Y1.587500Z-0.364501
N224X1.900000Y1.587500Z-0.368916
N225X2.025000Y1.587500Z-0.370923
N226X2.150000Y1.587500Z-0.369920
N227X2.275000Y1.587500Z-0.365303
N228X2.400000Y1.587500Z-0.356472
N229X2.400000Y1.525000Z-0.343818
N230X2.400000Y1.462500Z-0.333273
N231X2.400000Y1.400000Z-0.324837
N232X2.400000Y1.337500Z-0.318510
N233X2.400000Y1.275000Z-0.314292
N234X2.400000Y1.212500Z-0.312182
N235X2.400000Y1.150000Z-0.312182
N236X2.400000Y1.087500Z-0.314292
N237X2.400000Y1.025000Z-0.318510
N238X2.400000Y0.962500Z-0.324837
N239X2.400000Y0.900000Z-0.333273
N240X2.275000Y0.900000Z-0.341100
N241X2.150000Y0.900000Z-0.345192
N242X2.025000Y0.900000Z-0.346081
N243X2.025000Y0.837500Z-0.357373
N244X2.025000Y0.775000Z-0.370923
N245X2.025000Y0.712500Z-0.386732
N246X2.025000Y0.650000Z-0.404799
N247X2.025000Y0.587500Z-0.425124
N248X2.025000Y0.525000Z-0.447708
N249X2.025000Y0.462500Z-0.472550
N250X1.900000Y0.462500Z-0.469609
N251X1.775000Y0.462500Z-0.463140
N252X1.650000Y0.462500Z-0.454025
N253X1.525000Y0.462500Z-0.443146
/* Start wall machining */
N254G0Z0.3
N255G1X1.501405Y0.434972F2
N256G0Z-0.443146
N257X1.626405Y0.434972Z-0.454025
N258X1.751405Y0.434972Z-0.463140
N259X1.876405Y0.434972Z-0.469609
N260X2.048596Y0.434972Z-0.471080
N261X2.048596Y0.497472Z-0.446352
N262X2.048596Y0.559972Z-0.423872
N263X2.048596Y0.622472Z-0.403640
N264X2.048596Y0.684972Z-0.385656
N265X2.048596Y0.747472Z-0.369920
N266X2.048596Y0.809972Z-0.356432
N267X2.048596Y0.872472Z-0.345192
N268X2.173596Y0.872472Z-0.341100
N269X2.298596Y0.872472Z-0.333273
N270X2.423596Y0.872472Z-0.321176
N271X2.423596Y0.934972Z-0.313304
N272X2.423596Y0.997472Z-0.307400
N273X2.423596Y1.059972Z-0.303464
N274X2.423596Y1.122472Z-0.301496
N275X2.423596Y1.184972Z-0.301496
N276X2.423596Y1.247472Z-0.303464
N277X2.423596Y1.309972Z-0.307400
N278X2.423596Y1.372472Z-0.313304
N279X2.423596Y1.434972Z-0.321176
N280X2.423596Y1.497472Z-0.331016
N281X2.423596Y1.615028Z-0.342824
N282X2.298596Y1.615028Z-0.356472
N283X2.173596Y1.615028Z-0.365303
N284X2.048596Y1.615028Z-0.369920
N285X1.923596Y1.615028Z-0.370923
N286X1.732296Y1.615028Z-0.364501
N287X1.607296Y1.688267Z-0.390194
N288X1.482296Y1.761506Z-0.400075
N289X1.337500Y1.846344Z-0.409736
N290X1.212500Y1.773105Z-0.380037
N291X1.087500Y1.699866Z-0.354494
N292X0.942704Y1.615028Z-0.321148
N293X0.817704Y1.615028Z-0.316732
N294X0.692704Y1.615028Z-0.314725
N295X0.567704Y1.615028Z-0.315728
N296X0.376404Y1.615028Z-0.329176
N297X0.376404Y1.552528Z-0.318214
N298X0.376404Y1.490028Z-0.309079
N299X0.376404Y1.427528Z-0.301771
N300X0.376404Y1.365028Z-0.296291
N301X0.376404Y1.302528Z-0.292637
N302X0.376404Y1.240028Z-0.290810
N303X0.376404Y1.177528Z-0.290810
N304X0.376404Y1.115028Z-0.292637
N305X0.376404Y1.052528Z-0.296291
N306X0.376404Y0.990028Z-0.301771
N307X0.376404Y0.872472Z-0.309079
N308X0.501404Y0.872472Z-0.301252
N309X0.626404Y0.872472Z-0.297160
N310X0.751404Y0.872472Z-0.296271
N311X0.876404Y0.872472Z-0.298050
N312X1.001404Y0.872472Z-0.301964
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N313X1.126404Y0.872472Z-0.307478
N314X1.251404Y0.872472Z-0.314060
N315X1.376404Y0.872472Z-0.321176
N316X1.501405Y0.872472Z-0.328292
N317X1.501405Y0.809972Z-0.338547
N318X1.501405Y0.747472Z-0.350852
N319X1.501405Y0.684972Z-0.365209
N320X1.501405Y0.622472Z-0.381617
N321X1.501405Y0.559972Z-0.400075
N322X1.501405Y0.497472Z-0.420585
N323X1.501405Y0.434972Z-0.443146

/* Start Y zigzag machining */
N324G0Z-0.1
N325G1X1.525000Y0.462500Z-0.1
N326G0Z-0.443146
N327G1X1.525000Y0.525000Z-0.420585
N328G0Z-0.1
N329G1X1.650000Y0.462500Z-0.1
N330G0Z-0.454025
N331G1X1.650000Y0.525000Z-0.430620
N332G0Z-0.1
N333G1X1.775000Y0.462500Z-0.1
N334G0Z-0.463140
N335G1X1.775000Y0.525000Z-0.439028
N336G0Z-0.1
N337G1X1.900000Y0.462500Z-0.1
N338G0Z-0.469609
N339G1X1.900000Y0.525000Z-0.444996
N340G0Z-0.1
N341G1X2.025000Y0.900000Z-0.1
N342G0Z-0.346081
N343G1X2.025000Y0.962500Z-0.337048
N344G0Z-0.1
N345G1X2.150000Y0.900000Z-0.1
N346G0Z-0.345192
N347G1X2.150000Y0.962500Z-0.336200
N348G0Z-0.1
N349G1X2.275000Y0.900000Z-0.1
N350G0Z-0.341100
N351G1X2.275000Y0.962500Z-0.332299
N352G0Z-0.1
N353G1X2.275000Y1.587500Z-0.1
N354G0Z-0.365303
N355G1X2.275000Y1.525000Z-0.352102
N356G0Z-0.1
N357G1X2.150000Y1.587500Z-0.1
N358G0Z-0.369920
N359G1X2.150000Y1.525000Z-0.356432
N360G0Z-0.1
N361G1X2.025000Y1.587500Z-0.1
N362G0Z-0.370923
N363G1X2.025000Y1.525000Z-0.357373
N364G0Z-0.1
N365G1X1.900000Y1.587500Z-0.1
N366G0Z-0.368916
N367G1X1.900000Y1.525000Z-0.355490
N368G0Z-0.1
N369G1X1.775000Y1.587500Z-0.1
N370G0Z-0.364501
N371G1X1.775000Y1.525000Z-0.351349
N372G0Z-0.1
N373G1X1.650000Y1.587500Z-0.1
N374G0Z-0.358279
N375G1X1.650000Y1.525000Z-0.345512
N376G0Z-0.1
N377G1X1.525000Y1.650000Z-0.1
N378G0Z-0.365209
N379G1X1.525000Y1.587500Z-0.350852
N380G0Z-0.1
N381G1X1.400000Y1.712500Z-0.1
N382G0Z-0.372344
N383G1X1.400000Y1.650000Z-0.356600
N384G0Z-0.1
N385G1X1.275000Y1.775000Z-0.1
N386G0Z-0.380037
N387G1X1.275000Y1.712500Z-0.363071
N388G0Z-0.1
N389G1X1.275000Y1.712500Z-0.1
N390G0Z-0.363071
N391G1X1.275000Y1.650000Z-0.347991
N392G0Z-0.1
N393G1X1.150000Y1.712500Z-0.1
N394G0Z-0.354494
N395G1X1.150000Y1.650000Z-0.340028
N396G0Z-0.1
N397G1X1.150000Y1.650000Z-0.1
N398G0Z-0.340028
N399G1X1.150000Y1.587500Z-0.327370
N400G0Z-0.1
N401G1X1.025000Y1.650000Z-0.1
N402G0Z-0.333356
N403G1X1.025000Y1.587500Z-0.321148
N404G0Z-0.1
N405G1X1.025000Y1.587500Z-0.1
N406G0Z-0.321148
N407G1X1.025000Y1.525000Z-0.310684
N408G0Z-0.1
N409G1X0.900000Y1.587500Z-0.1
N410G0Z-0.316732
N411G1X0.900000Y1.525000Z-0.306542
N412G0Z-0.1
N413G1X0.775000Y1.587500Z-0.1
N414G0Z-0.314725
N415G1X0.775000Y1.525000Z-0.304659
N416G0Z-0.1
N417G1X0.650000Y1.587500Z-0.1
N418G0Z-0.315728
N419G1X0.650000Y1.525000Z-0.305600
N420G0Z-0.1
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N421G1X0.525000Y1.587500Z-0.1
N422G0Z-0.320345
N423G1X0.525000Y1.525000Z-0.309931
N424G0Z-0.1
N425G1X0.400000Y1.587500Z-0.1
N426G0Z-0.329176
N427G1X0.400000Y1.525000Z-0.318214
N428G0Z-0.1
N429G1X0.400000Y0.900000Z-0.1
N430G0Z-0.309079
N431G1X0.400000Y0.962500Z-0.301771
N432G0Z-0.1
N433G1X0.525000Y0.900000Z-0.1
N434G0Z-0.301252
N435G1X0.525000Y0.962500Z-0.294309
N436G0Z-0.1
N437G1X0.650000Y0.900000Z-0.1
N438G0Z-0.297160
N439G1X0.650000Y0.962500Z-0.290408
N440G0Z-0.1
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N1404G0Z0.5F3
N1405G1X0.0Y0.0
N1406M05
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