A Thesis report on

GENERALIZED TOOL PATH PLANNING APPROACH FOR FINISH MACHINING FOR 3-AXIS VERTICAL MILLING

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Submitted by

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CERTIFICATE

This is certify that the thesis titles, "**GENERALIZED TOOL PATH PLANNING APPROACH FOR FINISH MACHINING FOR 3-AXIS VERTICAL MILLING**" being submitted by "**Mr. GAURAV KUMAR, REGISTRATION NO.801081009**", in partial fulfillment of the requirements for the award of degree of MASTER OF ENGINEERING in CAD/CAM & ROBOTICS ENGINEERING at THAPAR UNIVERSITY, PATIALA is a bonafide work carried out by him under my guidance and supervision and that no part of this thesis has been submitted before for the award of any degree.

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ABSTRACT

The generalized tool path planning approach for finish machining has been presented in the present thesis work. The aim of present work is development of generalized tool path planning for finish machining / pencil cutting for 3-axis vertical milling. The CAD modeller provides the information about the part geometry, which has been taken as STL file (Stereo Lithography). The STL data has been used as input to the tool path generation algorithm, which calculates the cutter location (CL) points for a pre-decided density of CL positions in X-Y plane. With the help of CL data as input for pencil cut tracing algorithm, the CL data pints for continuous contoured pencil cutting operation has been extracted.

Tool path generation strategies for pencil cutting have been discussed in detail. Also the literature about the side feed, forward feed and triangular mesh have been discussed. Various checks have been applied in the algorithm to find the best suitable point at particular tool position for finding the best CL data net and Pencil cutting data.

The main features of the proposed approach are the extraction of pencil-cut points from the CL-surface, which has been scanned in X and Y directions by continuously comparing the Z level values of respective CL points. The relationship for estimation of the scallop height for ball end mill has been used to find the best CL data density for finding the appropriate pencil cutting positions. It is well known fact that the scallop height can be reduced with the help of reducing the side step value between two adjacent tool paths. The process of generating pencil-cut path is clear to understand, robust, and efficient, and the quality of the resulting path is high. The main techniques used for the tool path planning, positioning and pencil cutting tool path have been discussed and the results have been presented in a logical way. The verification and testing of the accuracy of the pencil cutting algorithm has been done using a graphical simulator for 3-axis NC machining.

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CHAPTER: 1

INTRODUCTION

Numerically controlled (NC) automated machine tools, such as milling, drills and lathes, that operates from instructions in a program. First-generation machines were hardwired to perform specific tasks or programmed in a very low-level machine language. Today, they are controlled by microprocessors and are programmed in high-level languages, such as APT and COMPACT II, which automatically generate the tool path (physical motions required to perform the operation).machining is used widely in the aerospace, automotive and many other industries. NC has a significant role in the daily life. NC is essential to the operation of modern industrial robots. A category of

The two basic types of NC systems are point-to-point, in which a device is programmed to perform a series of motions with fixed starting and stopping points, and continuous-path, in which a point-to-point programmed device has sufficient memory to be “aware” of its former actions and their results and to act in accordance with this information.

A number of commercial CAD/CAM systems including UG, CATIA, are capable of generating clean-up tool paths, but very few methods have been openly published [33]. The operations of CNC machines requires modeling a part in the Computer Aided Design (CAD) package, and subsequently planning the tool path by processing the CAD data into a part program with the Computer Aided Manufacturing (CAM) package. CAM systems can only automatically generate tool-path, the cutting parameters are usually designed by the programmer [34].

Pencil-cutting in 3-axis machining has recently attracted much attention in both research and industry. After the finishing process, the clean-up machining removes the remaining material left at the sharp corners or edges, which are identified as the ‘clean-up regions’ [31]. Clean-up machining can be classified into two major types: pencil-cut and fillet-cut. The major benefit of pencil-cutting includes better surface finish and shorter total machining.

1.1 BASIC COMPONENTS OF CNC SYSTEM

The CNC system consists of basic components. These basic components are discussed below in detail.

1.1.1 Program of instruction: The program of instructions is the detailed step by step instructions to the machine tool to do. The most common method for the input is 1-in-wide punched tape. By the time the other mediums also come in the existence like punched card, magnetic tape, and even 35-mm motion picture film [36]. One can also input the instructions directly into the control unit manually, this method is called manual data input (MDI), which is used for very simple jobs. These machine instructions command the tool movements and control all the devices on the CNC machines during the machining process. The program online contains the tool movement information and has no access or information to the part geometry. \

Part programs are generally generated manually or with Computer Aided Manufacturing (CAM) software packages by using the cutting parameters and the part's Computer Aided Design (CAD) model data. Commands that will instruct a specific machine to follow the tool paths that were created during the CAD/CAM phase of design. This is generally a two step process. The first step converts the tool paths to machine independent commands that are stored in a file using the Automatic Programmed Tools (APT) format. This file is then read by a post-processor that converts the APT commands to machine control data for a specific controller. The commercial CAM packages use inbuilt tool positioning strategies to generate tool path plans in the ISO G & M-code programming language or some machine specific proprietary languages. Up to 3-axis machining, the algorithms for tool path planning are simplified, but one cannot work without CAM packages or automatic tool path programming for tool path generation for multi-axis milling center like turning mills, 4-axis or 5-axis machine tools.

1.1.2 NC Controller unit or machine control unit (MCU)

The controller unit is most important parts part of the NC and CNC machines. The controller unit is made of the electronics components. It reads and interprets the program of instructions and converts them in the mechanical actions of the machine tool. Thus the controller unit forms an important link between the program and the machine tool. The control unit operates the machines as per the set of instructions given to it.

The control unit comprises of tape reader, a data buffer, signal output channels to the machine tools, feedback channel from the machine tool, and the sequence control to coordinate the overall machining operation. Initially, the set of instructions from the punched tape are read by the tape reader, which is sort of the electromechanical devise. The data from the tape is stored into the data buffer in form of logical blocks of instructions with each block resulting in certain sequence of operations. The controller sends the instructions to the machine tool via signal output channels that are connected to the servomotors and other controls of the machines. The feedback channels ensure that the instructions have been executed by the machine correctly. The sequence control part of the controller unit ensures that all the operations are executed in the proper sequence.

A power converter, usually referred to as the "power supply unit (PSU)," is often used to change the form of the supplied power from alternating current (AC) to direct current (DC) that is more easily used by the machine's drive motors. The circuitry protection system contains a breakout board to isolate signals from the computer, distribute the signals to the desired drivers, and also allows easy hook up of peripherals such as limit switches that feed information back to the computer. Fuses are also part of the circuitry protection system. Fuses could save the equipment in case of electrical spikes, shorts, or faulty wiring.

1.1.3 Machine tool: A machine tool is a machine for shaping or machining metal or other rigid materials using conventional metal removal processes like cutting, boring, grinding, shearing or other forms of deformation like press working and using non-conventional machining processes like electric discharge machining or laser cutting. All machine tools have some means of constraining the work piece and provide a guided movement of the parts of the machine. Thus the relative movement between the work piece and the cutting tool which is called the tool path is controlled or constrained by the mechanical mechanism of machine tool. The common NC system are designed to perform machining operation, wherein the machine tool consist of the worktable and spindle as well as the motors and control systems required to drive them. Its also includes the cutting tools, work fixture, and auxiliary equipment needed in the machining operation. Such NC machining systems are called machining centers, which have several timesaving features into a single of automatic production equipment. A machining centre is capable of performing a variety of different operation like drilling, tapping, reaming, milling, and boring. The best part of the machining centers is the capacity to change tools automatically.

Another unique capability of the NC machining centre is work piece positioning. The machine table can orient the job so that it can be machined on several surfaces, as required. Finally, a fourth feature possessed by some machining centers is the presence of two table or pallets for work piece holding. When machining is being performed on one work part, the operator can unload the previously completed piece, and loading the next one.

1.2 NC MACHINING STRATEGY

In NC machining, milling processes are generally classified as roughing, finishing and clean-up machining [20] as shown in figure1.1. The rough cutting process constitutes a major portion of the machining operation by an NC milling machine in terms of the machining volume that must be removed by the process. In particular, a fair amount of the machining time may be spent in this process when a large portion of the raw material has to be removed. The semi finishing process has some portion. After the strategy is executed finishing with the smallest finishing ball cutters. For each cutter, the current stock model is compared with the final surface model, to define an area of operation for that cutter. Operations are then scheduled for that cutter to remove all the material it can access within the area of operation, and leave the stock model with a reasonable finish ready for the next cutter.

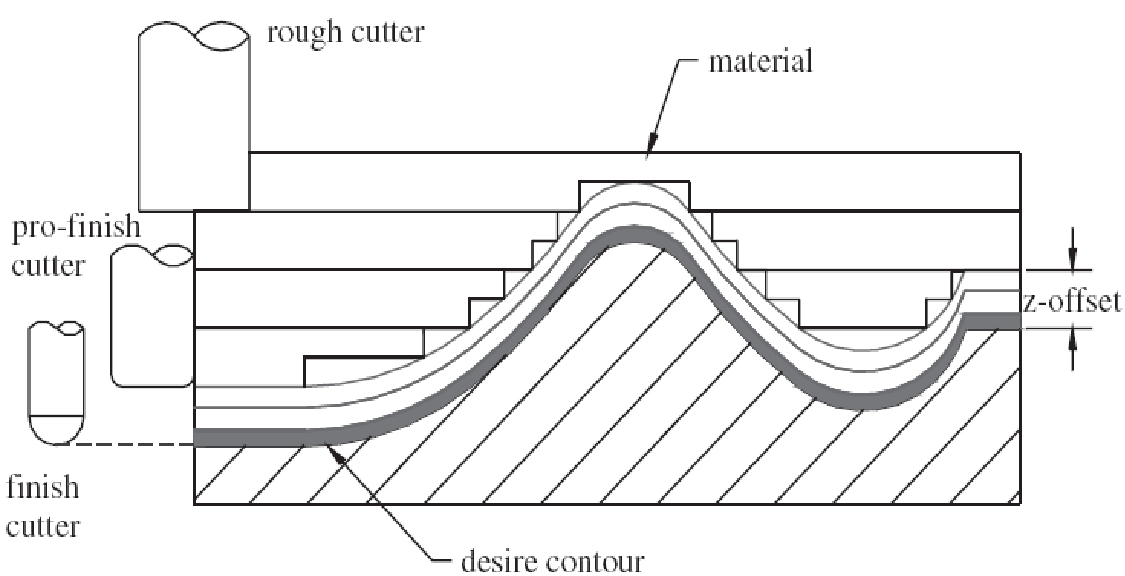


Figure1.1: Different Machining Process

The rough machining step takes 8-16%, finish machining takes 27-39% and polishing takes 13-23%, of the overall manufacturing time. Machining parameters are of great concern in manufacturing environments, where economy of machining operation plays a key role in competitiveness in the market. Due to high capital and machining costs of Numerical Control (NC) machines, there is an economic need to operate NC machines as efficiently as possible in order to obtain the required pay back. Since the finish machining on NC machines is sensitive to the machining parameters, optimal values have to be determined before a part is put into production. Recently different methods have been reported in the literature to finish machining parameters of pencil cutting milling operations. The pencil cutting tool path cannot be achieved without considering the objective function and constraint equations. In multi-tool milling operation, the optimum values of finish conditions are searched for pencil cutting tool and each pass. Each pass for pencil cutting tool is optimized individually. In the present work, a work piece machined by NC vertical milling machine is evaluated according to the pencil cutting tool path.

1.3 STRATERGIES USED FOR PENCIL CUTTING

During the last 5–6 years, an increasing trend has been developing in Computer-Graphics, as well as in the CAD community, towards surface models based on discrete elements like polygons, triangles and, very recently, points. Regarding polygons and triangles, these have long been the standard ‘basic element’ in graphics, and recently their importance has also been increasing in CAD/CAE/CAM. The trajectory of the ball-center point of a ball-end mill slid along a concave-edge region on a part surface becomes a pencil curve, and the ball-end milling along the pencil curve is called pencil curve machining [28].

Pencil-cutting in 3-axis machining has recently attracted much attention in both research and industry. Clean-up machining removes the uncut volumes left at the sharp concave fillets that a larger cutter cannot machine during the finishing process [28]. In the proposed method, to find the ‘pencil points’ of the pencil-cut path from scanning tool path are generated using the ‘curve-based approach’ developed by [29]. Methods of computing pencil curves can be classified into two categories according to the pencil curve generation surface: the cutter-contact (CC) surface approach and the cutter location (CL) surface approach. The tool path plays an important role in the machine. The present thesis work points toward the tool path algorithm for generalized pencil cutting for 3-axes vertical milling. This algorithm is particularly made for the ball nose cutter with varying radius. A tool path is generated along which the different points of contact are decided. The input is taken from .STL file which can be generated from any CAD software. Model with vertical wall of the STL (Stereo-lithography) form as part surfaces since geometric processing with the model is very robust and the models are very popular in CAD/CAM applications [25].

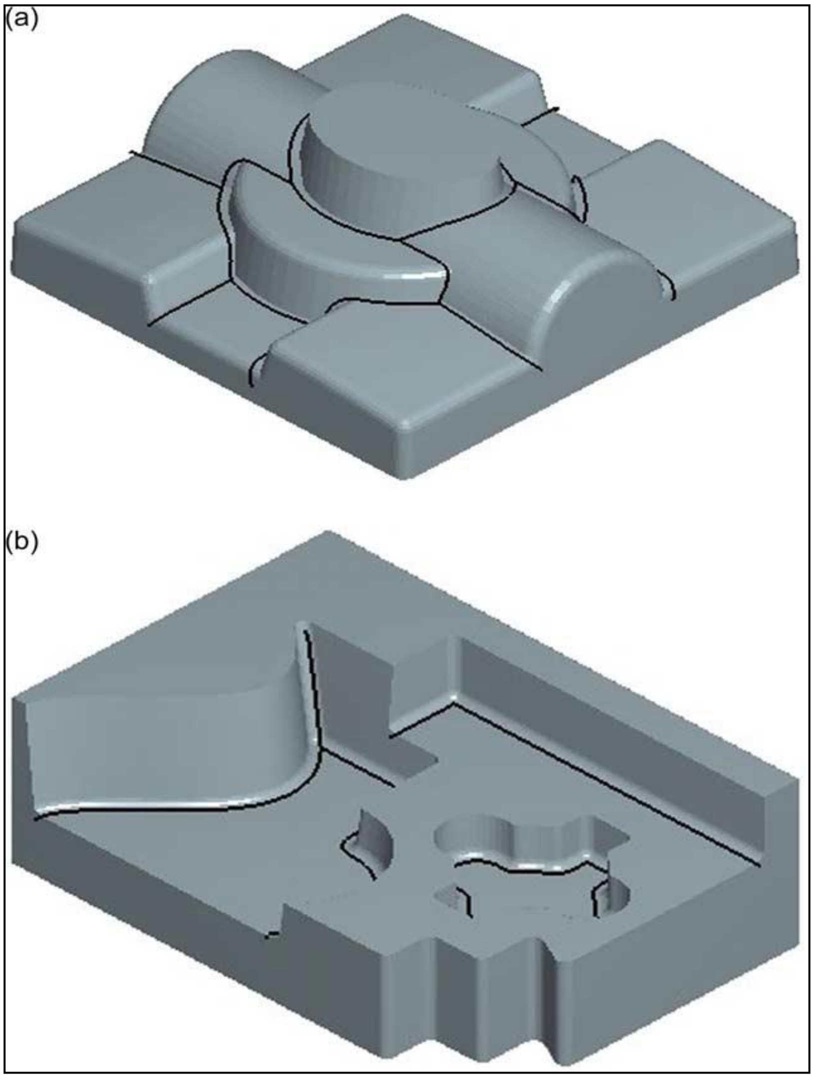


Figure1.2: Pencil cutting regions in the contoured part geometry [25]

Pencil-cut curves usually exist at the sharp concave edges (with G1 discontinuity) on a CL-surface (cutter-location). It is not a trivial task to compute the CL-surface for generalized cutters. Estimation and approximation have to be applied to construct the pencil-cut curves from a Z-map. It also suffers difficulty in tracing and correctly linking the pencil-cut curves of a model due to the error-prone connectivity issue of the very close adjacent pencil-cut curves.

In the proposed method, to find the 'pencil points' of the pencil-cut tool path with the help of scanning tool paths are generated using the 'CL data-based approach'.

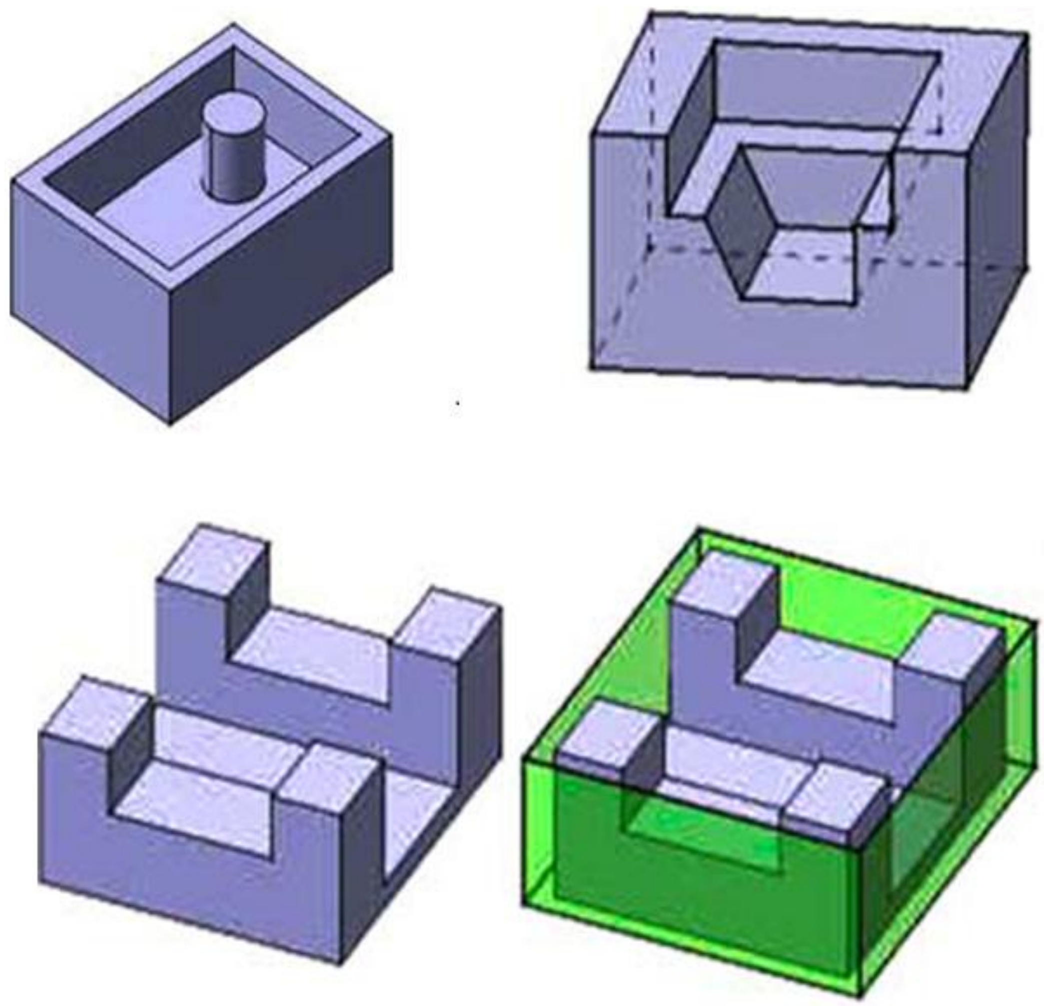


Figure1.3: Different Types of Vertical Wall Surfaces [38]

Pencil cutting tool can be used for concave edges of different type of surfaces as discussed below;

(i) Pencil cutting along vertical surfaces: The different surfaces have concave path with vertical wall as shown in figure1.3. Angle between horizontal and vertical wall is equal to right angle. The die or mould is made from the stock material in three steps, 1. Finish machining, 2.In the roughing, 3.Polishing. In woods, the remaining material at the concave surface removes with the help of pencil cutting tool and a tool path generates for pencil cutting along this path.

(ii) Pencil cutting along inclined surfaces: The different surfaces have concave path with incline wall as shown in figure1.4. Pencil cutting tool moves along the concave edge in inclined surfaces and produced better surface finishing.

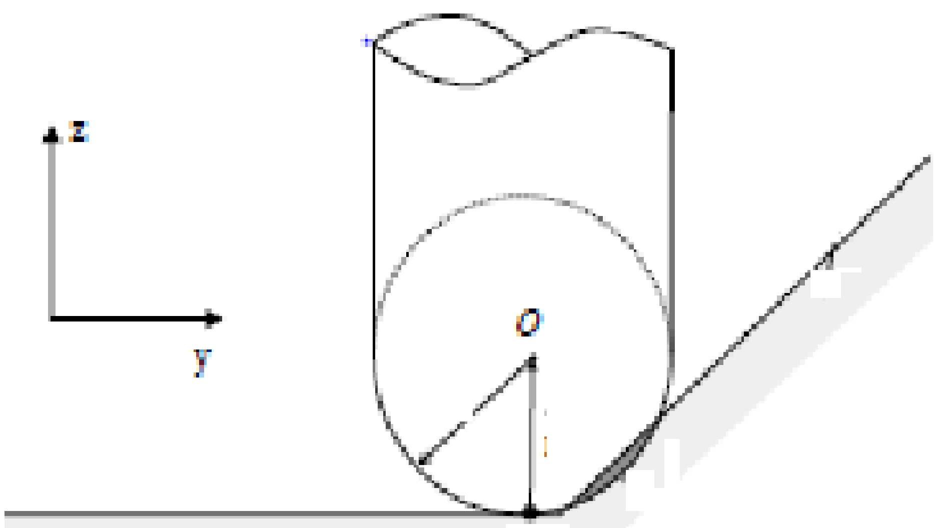


Figure1.4: Tool Moves Along inclined Surface [20]

(iii) Pencil cutting along Sculptured surface: Any of the surface patches introduced thus far is seldom enough by itself to model complex surface typically encountered in designed and manufacturing applications they complex surfaces are known as sculptured or free form surfaces. They arise extensively in automotive die and mold making, aerospace, glass, and appliance industries. A sculptured surface is defined as a collections or sum of interconnected and bounded parametric patch together with blending and interpolation formulas' as shown in the figure 1.5 and figure 1.6, and tool moves along this path for better surface finishing.

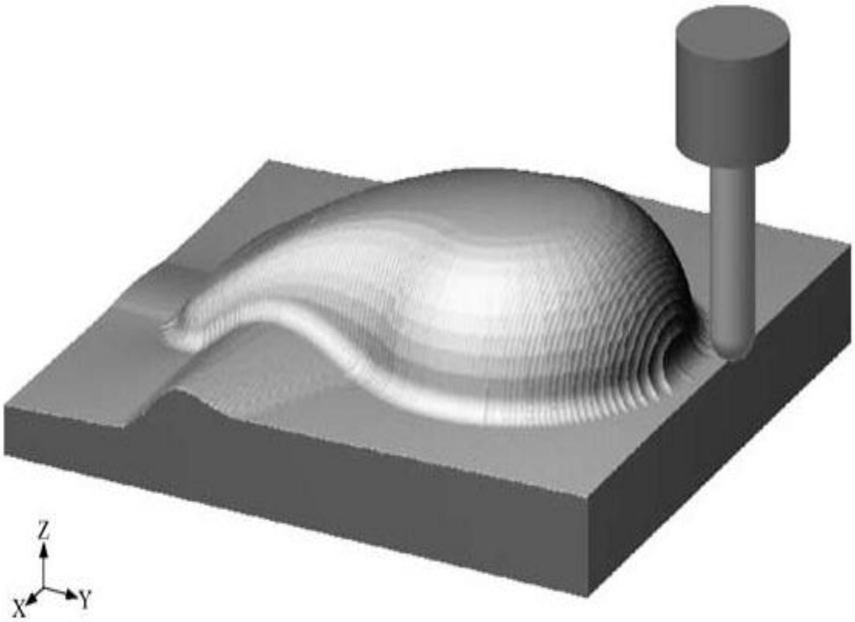


Figure1.5: Tool Moves Along Sculpture Surface [20]

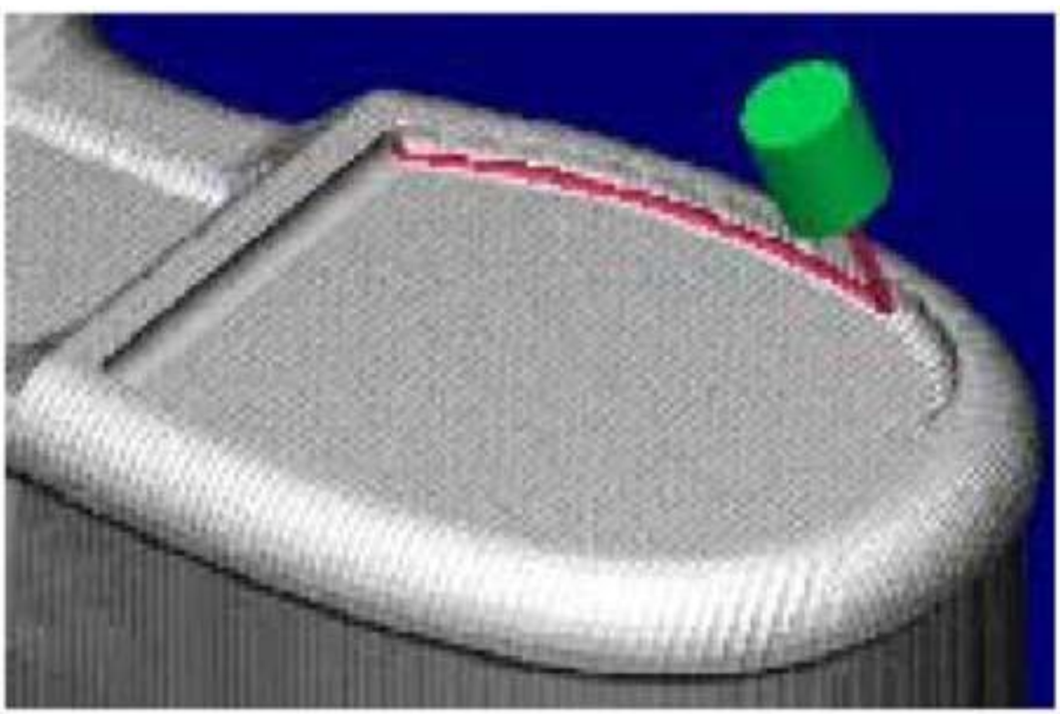


Figure1.6: Pencil Cutting Tool [19]

1.4 PRESENT WORK

The general NC machining strategies includes the tool path for roughing, semi-finishing, finishing and pencil machining. After roughing and finishing operations have been carried out on the work piece, sometimes some concave uncut material is left in the sharp corner regions of the work piece. To avoid the uncut material in sharp regions one possible solution could be to develop the finishing tool path using very small forward and side steps. But this strategy will take a lot of machining time to finish the part. Other possible approach can be to detect the continuous tool path along the sharp corners of the work piece to remove uncut materials with very precise forward step distances between adjacent tool positions. This pencil cut tool path generated for smaller diameter tools will move only along the contour boundaries rather than cutting through the whole of the work piece, which will save a lot of machining time.

Thus under the present thesis work a generalized tool path generation algorithm for three-axes vertical milling machine for pencil cutting tool path extraction has been developed in JAVA. SOLIDWORKS has been used to generate the STL (Stereo Lithography) file of the work piece. The 3D part data in STL file format has been used as input for the tool path planning algorithm for creation of CL data net. Further a pencil cutting algorithm developed in JAVA modular has been used to extract pencil cutting tool path information from the input CL data net file. CL data file has all the information about the work piece and then pencil cutting algorithm rearranges the cutter location (CL) points for pencil cutting regions in a text file. The pencil cutting algorithm is capable of generating tool path sequences for all types of artistic features and complex parts (flat parts) which can be machined on a 3-axes vertical milling centers.

CHAPTER: 2

LITERATURE REVIEW

In this chapter the various techniques used for finish tool path planning for numeric control machining has been discussed with an objective of exploring the possibility for development of an improved and simplified approach for pencil cut tool path planning.

The literature related to NC tool path planning for various type of surface definition including STL format has been studied and presented in a logical way as given below:

2.1 TOOL PATH PLANNING METHODS FOR NC MACHINING

Yau [11] and Lee [23] have presented tool path planning method, which have two types of tool paths, first one parametric and other non-parametric tool paths. The tool path is defined by two or three parameters which represents the complete surface. The computer representation of the designed surface is usually of parametric form. These parametric form are Bezier, B-helical, and Non-uniform rational B-helical (NURB) surfaces. Tool path planning has been shown in figure2.1.

Chen and Shi [32] proposed a polyhedral machining method, which has regained attention from NC programming software developers. The polyhedral model is becoming popular as a data exchange medium between different CAD/CAM systems.

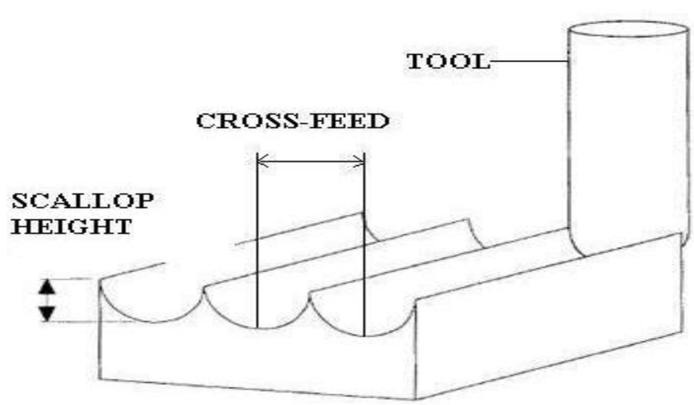


Figure 2.1: Cross Feed and Scallop Height Definition [36]

A new method for tool path generation based on the algorithms: The free-form surfaces are approximated by triangular meshes. The vertices of triangular meshes are offsetted along surface normal. All offset vertices are then connected to form offset triangular meshes on which are sliced by a group of planes to obtain tool paths. The proposed method has been used to improve and automate three-axis free-form surfaces machining for CAD/CAM systems.

2.2 TOOL POSITIONING METHODS

Jensen and Anderson [9] have proposed a method for calculating an optimal tool angle based on the local curvature of the cutter contact point. A flat end mill is placed on the surface such that the feed direction lines up with the direction of minimum curvature on the surface. The tool is inclined such that the effective radius of the tool at the cutter location equals the minimum radius of curvature of the surface. The profile of a torus is a 4th order curve while the profile of a fiat end mill is only a 2nd order curve. A better match between the surface and a toroidal end mill should be possible. Rao[12] has been developed a similar technique that they called the Principal Axis Method, PAM, and successfully used it to machine a surface patch. Jensen et al.[9] extended this work to the toroidal end mill and developed a numerical procedure for calculating cross feeds.

Using simulation and cutting tests, Rao [12] investigated the principal limitation of this technique which is the difficulty in lining up the feed direction with the direction of minimum curvature. The tool inclination angle has altered based on the location and depth of gouging. The tool positioning strategies attempts to maximize the metal removal by considering the local geometry of a single point on the design surface and a single point on the tool. A tool positioning strategy called multipoint machining, MPM, which matches the geometry of the tool to the geometry of the surface by positioning the tool in a manner that maximizes the number of contact, points between the surface and the tool. The machine spherical surfaces have able to no scallops in a fraction of the time required by conventional machining techniques. They fully exploited the special features of the spherical surfaces. But they did not demonstrate the technique on a general surface. The tool-surface interface is modeled as an intersection problem between two surfaces. The nature of multi-point contact is examined by considering the contact between a tool and two surfaces, 1.a spherical cavity, 2.a more general quadratic concave parametric surface. These surfaces have been machined to verify the numerical formulations and as such to demonstrate the potential of the multi-point machining concept. Finally, MPM is used to machine a cubic Bezier surface as a further confirmation of the applicability of the method. This method has been saved the time, money and to compete in the industrial environment to get the better results.

2.3 TOOL PATH GENERATION METHODS

Tool-path generation (TPG) for clean-up is one of the most challenging problems in sculptured surface machining. The TPG method is to specify the cutter contact point on the part surface and then offset that point to yield the cutter location. The cutter location (CL) is the location of the centre of the tool. The cutter contact point (CC) is the location where the tool touches the part surface.

2.3.1 The Isoparametric Method: The isoparametric method is one of the simplest tool path generation algorithms in which the cutter contact points are specified along isoparametric lines on the part surface. Isoparametric lines are curves of constant parameter value on parametric surfaces. The isoparametric curves are approximated by linear segments. However, if the linear segments are large, it may results in under-cuts on the sculptured surfaces of the model [3].

2.3.2 The Cartesian Method: In contrast to determining the tool movements based on the part surface's parameters, the Cartesian method allow the operators to generate tool paths with respect to the global X-Y-Z Cartesian coordinates. The tool path generator takes the X-Y coordinate of the cutter location as its input and computes the Z-value of the cutter location. The instantaneous tool location is also checked for gouging. This method is more difficult to implement for parametric curved surfaces when compared to isoparametric method. This is due to the complexity of the computational relationship between the cutter contact points in the global X-Y-Z coordinates and the part surface coordinate [2].

2.3.3 The Offset Surface Method: The offset surface method is conceptually similar to the Cartesian method. The offset method generates the tool path by offsetting the part surfaces by the tool radius. The center of the cutter tool travels along the offset surface to machine the part, and the tool path is calculated by identifying tool passes on the offset surface. However, self-intersections tool path that leads to over-cut or cavities of under-cut must be detected and corrected while performing the offset surface algorithm [4]. An advantage of this method is one can find a tool trajectory parallel to X-axis in which the tool moves only along the Y- and Z-axis. Lee [16] has generated helical tool path for offset surface with constant scallop height. Tang [6, 10] has also give the surface offset method.

2.3.4 Feed Forward Method: Feed forward is also important in tool path generation as the machine movements is discretized into finite piecewise motions. Huang et. al.[8] discussed parameterizing the surface to determine the step size while maintain the machining errors within a desired tolerance. The linear feed-forward tool motion between two tool positions is used to determine the deviation between the actual straight line tool paths and the desired surface.

2.3.5 Side Step Method: The step-over increments, which are the distance between the adjacent tool paths in the side-step direction, are used to determine the height of cusps that remain after the machining process. Thus, the tool path is basically recognized as a set of tool positions for the tool to traverse and interpolate into a smooth path movement. Hence, the method of determining the tool positions is a factor that can affect the finish quality of the machined parts. There are many significant developments done [13]. Yau et.al.[18] has presented the generalized cutter, in which the tool path algorithm is made for generalized cutter. The cutter profile varies with the variation of parameters of generalized cutter. Kishinami[5] has described the inverse offset method for tool path generation.

2.4 PENCIL-CUT MACHINING

Lee et al [26] proposed a new Material-Side-Tracing method and a pencil-cut curve refinement technique are proposed for 3-axis pencil-cut path generation. Pencil-cut machining has been used to remove remaining material at highly corners or curved regions after the finishing process. Procedures of evaluating and extracting valid pencil-cut points are developed by taking practical cases into account. The tracing process, smooth and clean pencil-cut curves has been generated even if the actual adjacent pencil cut curves has very close, with the help of the strategy of using material-side information. The limitation due to the discrete CL-net intervals and the smooth pencil-cut paths has made complete at sharp corners for a technique of pencil-cut curve refinement.

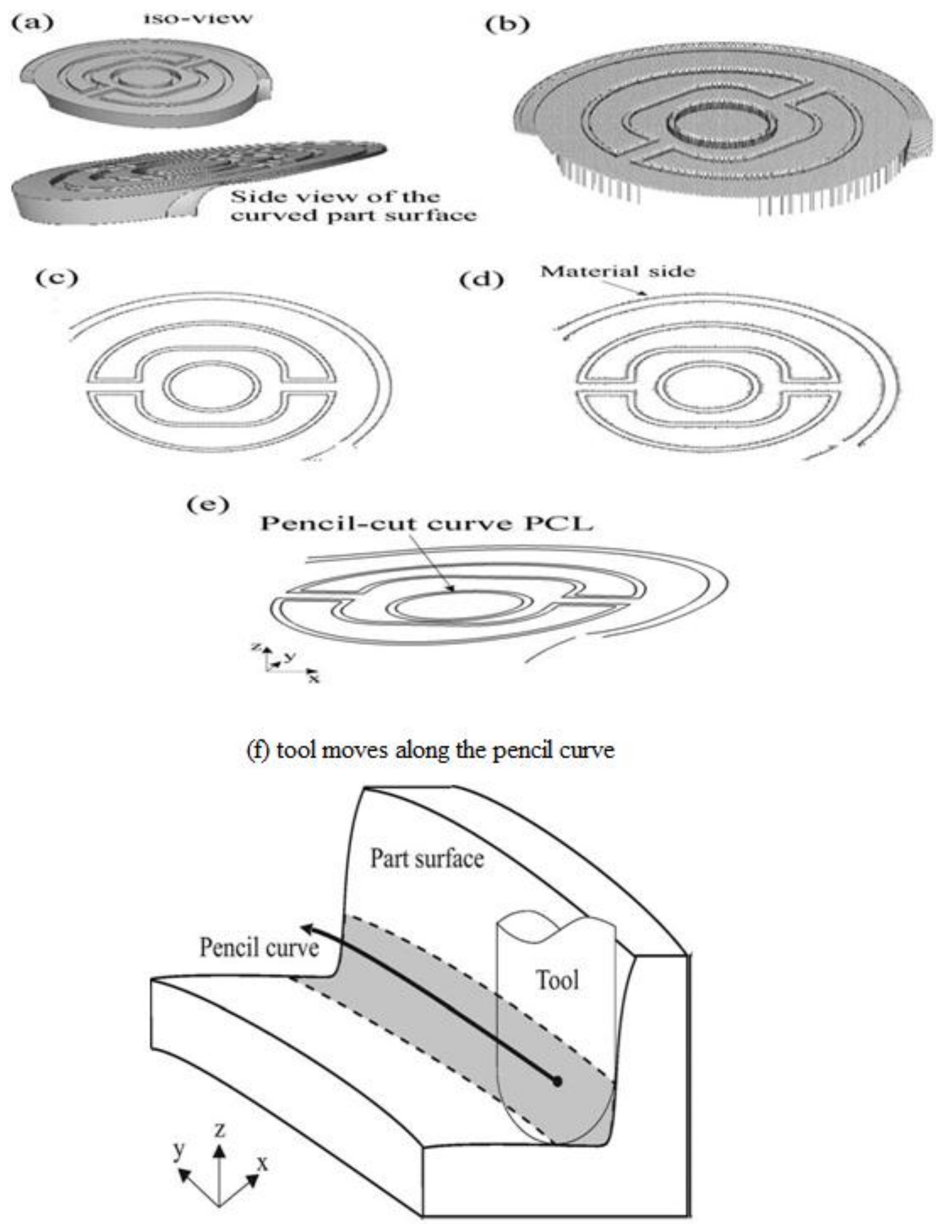


Figure2.2:.Pencil Cut Curve [26]

2.5 OPTIMAL TOOL SHAPE SELECTION BASED ON SURFACE GEOMETRY

Patel et al [37] have represented the 3D models of personalized custom products. It have a unique, and to machine each model, a unique tool path. The manual generation of the tool paths has not economically viable for the mass production of these products; a viable option has to generate the tool path automatically. The tool paths depend on the tool shape, and an essential part of optimal machining of sculptured surfaces is the selection of the cutter shape. Ball nose and radius end milling cutters are positioned at a given point along a defined tool path footprint. These tool positions are compared to determine which cutter achieves maximum material removal or surface roughness, that is, scallop height. The scallops and the material removed are calculated for the cutter at all points along the tool path and are processed in order to determine the best tool or tools for machining the surface. The surface geometry has a great impact on the type of tool required to machine a surface.

Manos et al [17] has been developed the "ball drop" cutter location method. A surface definition is required in order to generate a tool path. For this research, the surfaces on the wooden signs are discretized as triangular meshes that can be generated by all computer-aided design software. Furthermore, when a very fine triangular mesh is used it can accurately define complex surfaces.

2.6 TRIANGULAR MESH SLICING

Park et al [21] have been presented the procedure computes tool paths by slicing a CL-surface (Cutter Location surface), which is a triangular, mesh containing invalid triangles. Tool path generation have two steps: first, it obtains a set of line segments by slicing the triangular mesh with two-dimensional geometric elements (slicing elements), and secondly, it extracts a valid tool path from the line segments by removing invalid portions. Two algorithms based on the slicing elements are presented: a 'line projection' algorithm based on the plane sweeping paradigm, which works efficiently by using the characteristics of a monotone chain; and a 'curve projection' algorithm for the projection of curves, which transforms the curve projection problem into a line projection problem by mapping the XYZ-space of the cylinder surface to the TZ-plane of the unfolded cylinder. The proposed procedure has been implemented and applied to tool path generation in regional milling. Performance tests show the efficiency of the proposed procedure.

2.7 SURFACE OFFSET METHODS

Singh et al [37] have been developed, a surface offset method for STL file format which have to save easily from most of the CAD modeling software such as SOLIWORK, PRO-E, CATIA, and SOIDWORK. The data has a definite order and easy extraction as compared to other neutral format like STEP, IGES. STL (stereo lithography) format has rather conceptually simple and sufficiently accessible as it repetitively describes every normal and vertex of triangular facets built for object approximation. Facet data has saved in computers in two types of data format: text (ASCII) format and binary format. The text STL format is a set of facet descriptions in the form of ASCII containing its unit normal vector and 3D coordinates of three vertices. An STL file in text format is obviously redundant for computer storage as it records every character and digit of items. The content of a text STL file size is so large that it is generally used as a testing tool. The structure of text STL format is as follows, (Nx, Ny, Nz) is a normal vector, and $(X1, Y1, Z1)$, $(X2, Y2, Z2)$ and $(X3, Y3, Z3)$ are coordinates of vertices.

2.8 CUTTING AREA DETECTION

Park and Choi [38] have represented the cutting area detection of sculptured surface. The sculpture surface machining has many machining operations require for cutting areas to be expressed in terms of a boundary representation. To extract cutting areas from a sculptured surface, employs a regular grid model (Z-map model) and presents a procedure extracting areas from a Z-map model. The extracted areas have corresponded to various machining features, depending on what the Z-map stores, such as curvature (uncut area), slope (wall) and Z-values (contour). The core of the procedure has a `boundary extraction algorithm' extracting boundaries and identifying the inclusion relationships among the boundaries from a binary image. In terms of its time complexity and simplicity, the proposed algorithm has advantages over the prior ones. Empirical tests show the performance of the proposed algorithm.

2.8 MOLD MACHINING

Lee et al [38] have represented a new method to detect interference regions in 3-axis mold machining. In this method, the surface geometry is first analyzed and local interference is detected in the concave and saddle surfaces. Algorithms on interference detection have developed and implemented in a CAD system. Most molds are machined with 3-axis CNC machines, and ball end-mills are used in finish machining of sculptured surfaces. Larger cutting tools have higher machining efficiency, but cannot ensure to machine all parts of the mold surfaces. To select a set of proper cutting tools, the regions that cannot be machined by a specific cutter (i.e. the interference regions) must be detected first. This research has proposed a new NC tool path interference detection method. Local interference is then detected by comparing the extreme curvature values of concave and saddle surfaces with that of the cutter. Global interference features are analyzed, and the global interference can be detected starting from surface boundaries. This researcher has shown that the algorithms can detect interference regions without tool path generation or surface offset, and it is applicable to most surface types commonly appearing in a CAD model.

2.9 CONCLUSION OF LITERATURE SURVEY

The literature related to NC tool path planning strategies and tool positioning strategies have been discussed elaborately in the previous sections. As apparent from the literature review, there is no method universally suitable for machining for surfaces having different shapes with vertical walls. Thus there is a need of suitable NC tool path to generate Cartesian space pencil cutting tool/cutter location points, which can be used for machining of surfaces on a 3-axis NC milling center. The tool path can be developed for pencil tool shapes to determine the problem of different scallop's height.

CHAPTER: 3

MATHEMATICAL MODELLING FOR PENCIL CUTTING TOOL PATH PLANNING

According to the pencil curve generation surface, the methods of computing pencil curves can be classified into two categories:

1. Cutter-contact (CC) surface approach and

2. Cutter location (CL) surface approach.

Cutter contact (CC) and cutter location (CL) have been shown in figure 3.1. The radius of the concave-edge region is smaller than the radius of the ball-end mill. The pencil curve tracing problem may be regarded as an edge-blending problem in the CC-surface approach and pencil curves may be obtained by employing the 'rolling-ball' or 'ball position sampling' methods.

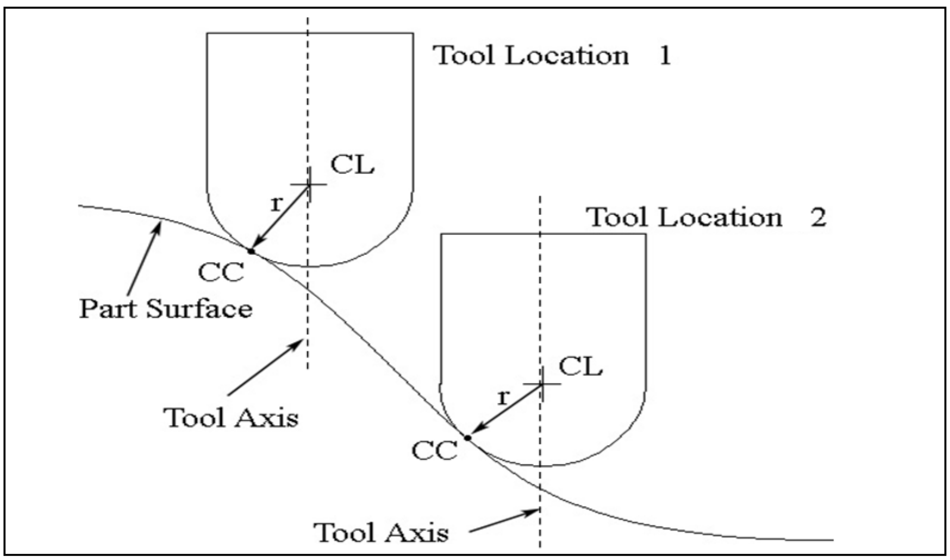


Figure3.1: Cutter Contact CC and Cutter Location CL Points

Tool path determines a sequence of path that guide the cutter to generate the desired part surface. Two tool path patterns commonly used in two-dimensional end milling operations are direction parallel tool paths and contour parallel tool paths, also known as boundary parallel tool paths.

The direction parallel tool paths are linear tool paths that can further be classified as: one-way or zig tool path, zig-zag tool path and smooth zig-zag.

Figures 3.2, 3.3, and 3.4 show the three different types of direction parallel tool path patterns.

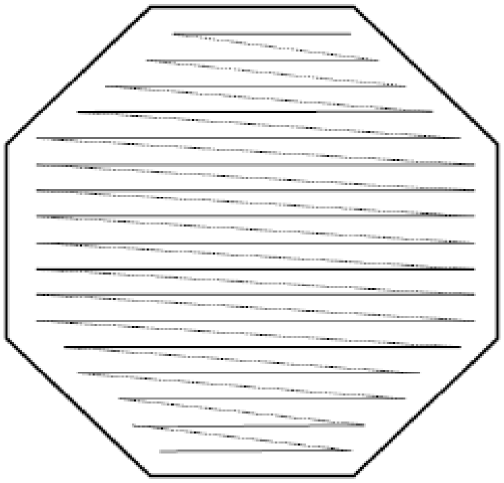


Figure 3.2: one way or zig Tool Path Pattern

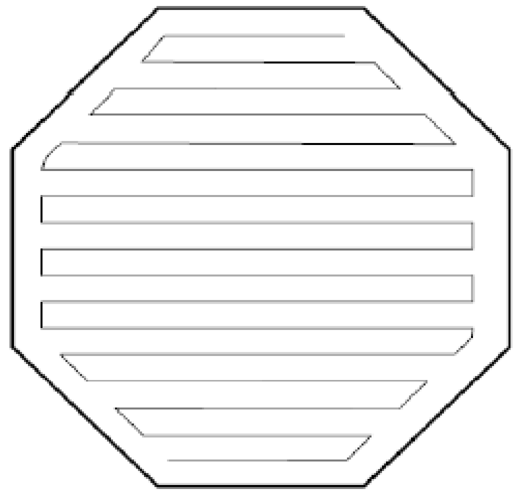


Figure 3.3: Contou Tool Pattern

Figure 3.5 shows the contour parallel tool path pattern for machining a pocket. A series of offset contours of the work piece (for example a pocket) boundary are first generated in contour parallel tool path patterns,. The tool travels along these offsets one by one, until the entire pocket is machined. Contour parallel tool path is derived from the boundary of the concerned machining region has been shown in figure 3.5. It is a coherent tool in the sense that the cutter is kept in contact with the cutting material most of the time. So it incurs less idle times such as those spent in lifting, positioning and plunging the cutter. At the same time it can also maintain the consistent use of either up-cut or down-cut method throughout the cutting process.

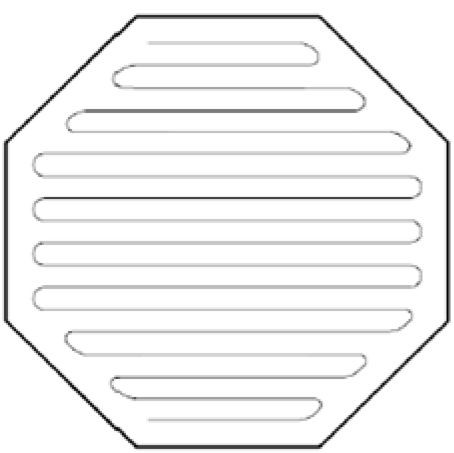


Figure 3.4: Smooth Zig-Zag Tool Path Pattern

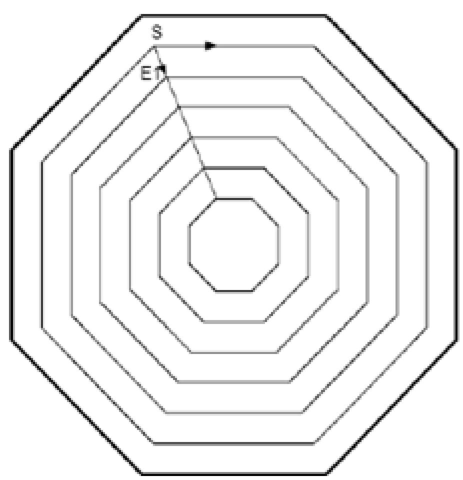


Figure 3.5: Contour Parallel Tool Pattern

3.1 TOOL PATH PLANNING FOR VERTICALSURFACE FOR 3 AXIS NC VERTICAL MILLING MACHINE

Tool path planning for vertical surface for 3 axis NC vertical milling machine are based on raster milling. Specification and parameter of raster milling has been discussed below.

3.1.1 Specification of 3-Axis NC milling machine: The tool planning is done for 3 Axis NC Raster Milling machine is having all three translational motions, tool penetrate the work piece along Z axis, the tool traverse along Y axis till it reaches to maximum position of it with forward feed and then jump back to X axis with some user defined side feed till the end of part. The part geometry should be made from (0, 0, 0) position in Cartesian coordinates and all X, Y, Z Axis should be in positive direction as shown in figure 3.6.

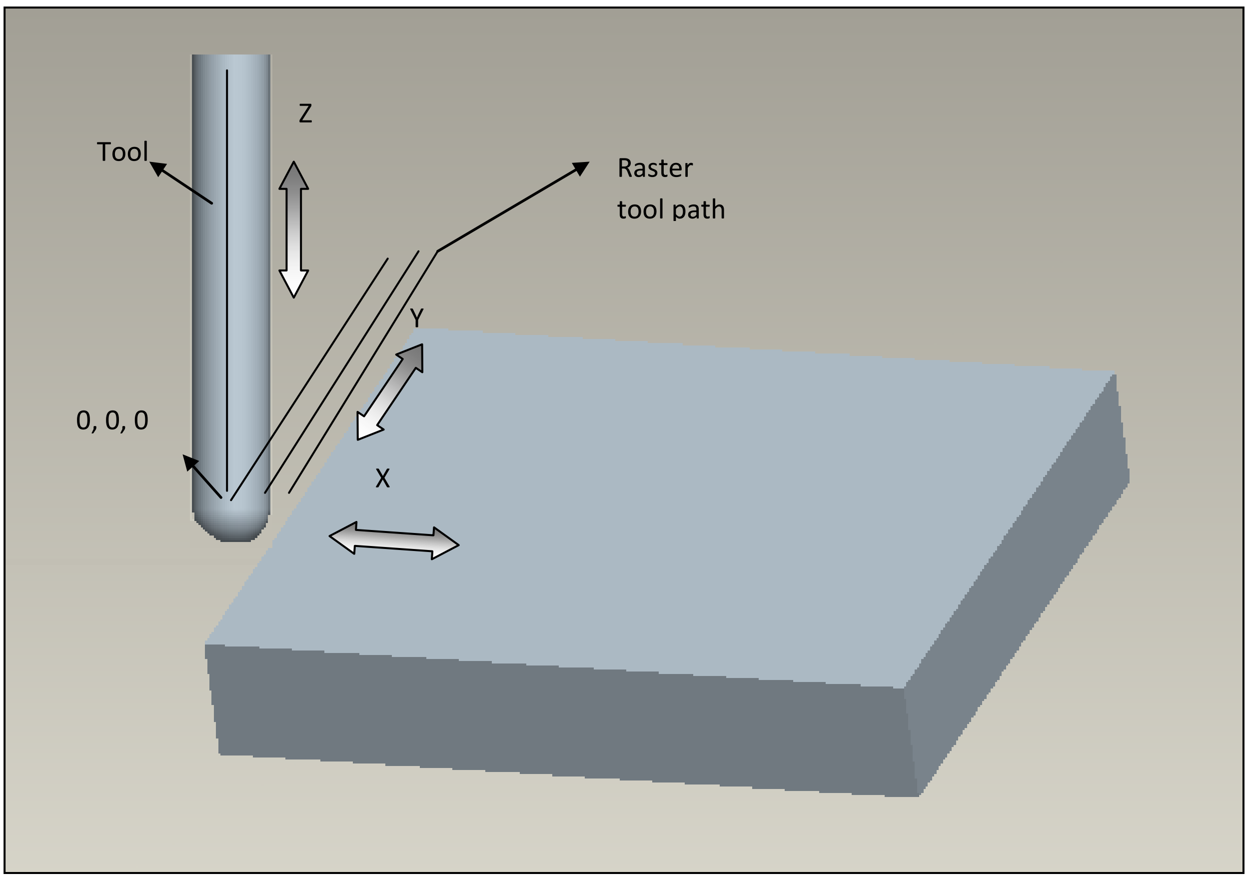


Figure 3.6: 3-axis NC raster milling[35]

Any sculptured surface which is not a revolving or round body can be machined by this machine. This methodology is only used by ball nosed milling tool. The tool path of this machine is raster tool path for milling machine as shown in figure 3.6.

3.1.2 Parameter required for raster milling: Some parameters required for tool path planning for sculptured surface, which is user dependent, are as follows:

1. Diameter for finishing pass of ball nosed end cutter
2. Forward feed in Y Axis
3. Side step in X Axis

3.2 MODELLING OF TOOL PATH GENERATION ALGORITHM FOR NC VERTICAL MILING

The generic ball end mill cutter of varying radius for finishing and pencil cutting tool cycles can be used for generating of protrusion and cavity modals. The NC tool path planning strategy for NC vertical milling machine has been discussed in this section in detail. The CL data net of predefined side step and forward step can be used for extraction of pencil cutting tool path.

3.2.1 Inputs required for NC tool path planning: The various inputs which are used for the machining to be done are:

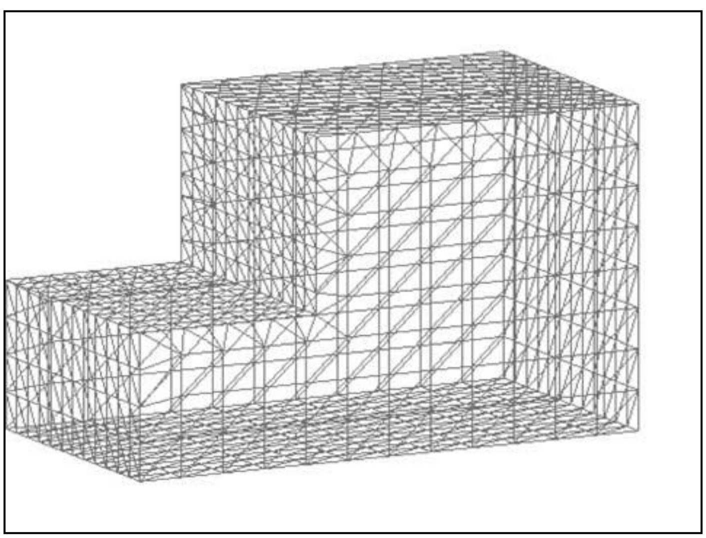


Figure3.7: Triangular Mesh [21]

(i) STL data for CAD model: The STL file [5][19] is used as first input to the tool path generation algorithm for finish machining. This STL(Stereo-lithography) can be made on any of the every CAD model has capability to store the CAD model as .The input CAD modals are triangulated surface modals .STL format. For now the SOLIDWORK has been used to make the .STL file. STL file of a CAD modal have triangular mesh and surface triangles as shown in figure 3.7 and figure 3.8.

solid*name*

facet normal *n1 n2 n3*

outer loop

vertex*v11 v12 v13*

vertex*v21 v22 v23*

vertex*v31 v32 v33*

endloop

endfacet

endsolid*name*

Figure3.8: STL File Format

The STL data representation of model has two formats, namely:

(i) BINARY format, and

(ii) ASCII format.

ASCII file is human-readable and can be modified by a text editor if required, thus for this reason ASCII format is used in the first algorithm for CL data net generation. In ASCII format of

STL file n_1 to n_3 and v_{11} to v_{33} are floating point numbers .White space (spaces, tabs, newlines) may be used anywhere in the file except within numbers or words. The spaces between 'facet' and 'normal' and between 'outer' and 'loop' are required.

The facets define the surface of a 3-dimensional object. As such, each facet is part of the boundary between the interior and the exterior of the object. The orientation of the facets (which way is "out" and which way is "in") is specified redundantly in two ways which should be consistent. First, the direction of the normal is outward. Second, which is most commonly used now-a-day, list the facet vertexes in counterclockwise order when looking at the object from the outside (right-hand rule).

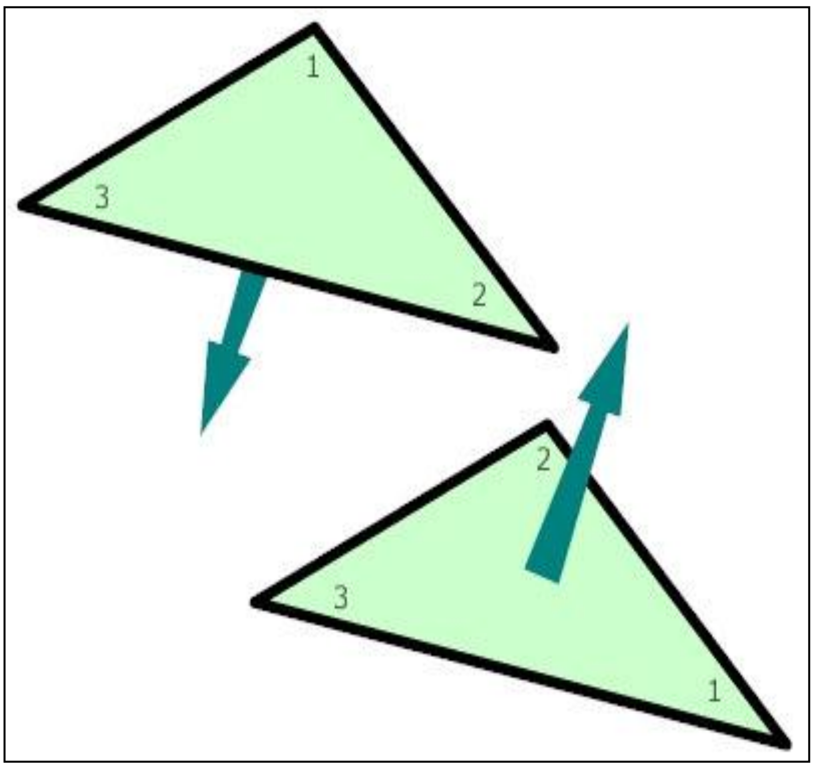


Figure3.9: Counter clockwise orders of STL vertices. The arrows point toward outside of the surface model of object [36]

This ASCII file format of STL is used as input to the program which is written in the Microsoft visual studio C++ 2010. The work piece is extruded in Z direction, so that the features to be machined are on the top surface parallel to X-Y plane along positive Z-axis.

(ii) Radius of finish/ pencil cutting tool: The next input which is to be input by user is the radius of finish machining (pencil cutting) tool. This will give user the ability to use the ball end tool for any radius.

(iii) Side feed: The value of side feed is to be entered by the user. This value is kept small for finished passes. The STL file which is used as the input for the tool path algorithm contains numerals, strings which are not required. Thus there is a need to refine the STL file. A computer algorithm is used for this purpose. It automatically ignores the unnecessary data and strings which are not desired in the coming program. The STL file contains the vector normal and coordinates vertices of all facets. The major dimensions of the work piece are extracted from the STL file as it may help to make the initial stock so that it may help to optimize the stock dimensions.

3.2.2 Mathematical model used for generating CL data net for ball end mill: The entire surface to be machined is represented mathematically by the vertices of triangle known as facets and surface normal called facet normal. The tool path planning algorithm has been designed to check for the shadow of the tool in a given position that the generic ball end milling cutter is touching with the part of the triangulated surface. The parameter u is set for the extreme position of the tool, and it keeps on decreasing as goes from centre to the outer of the work piece. The tool surface may touch the triangle on edge, on vertex or inside the triangle. The tool positioning strategy must stops the tool forward motion at the first contact of the tool with either of edge, triangle surface or vertex for which following checks have been applied to extract the information about tool position along X-axis direction of the 3- axis NC vertical milling.

(i) Triangle check: This check is performed to identify if a tool of radius r moving along a tool axis $(1-u)T_1-uT_2$will contact a triangle within the bounds of its vertices, P_1, P_2 and P_3 where u is the parameter from $T_1$to T_2. As the centre of the tool lies along the tool axis and the tool contacts the plane of the triangle tangentially, we get the following equations:

$$(1 - u).T_1 – u.T_2 = P_1 + N.r$$

Where

$$\text{N} = \frac{((\text{P2} - \text{P1}) + (\text{P3} - \text{P1}))}{|\,(\text{P2} - \text{P1}) + (\text{P3} - \text{P1})\,|}$$

Parameters are to define the surface of facet and *N* is the facet normal.

Solving this as:

$$\begin{bmatrix} (\text{T}_2 - \text{T}_1)_x & (\text{P}_1 - \text{P}_2)_x & (\text{P}_1 - \text{P}_3)_x \\ (\text{T}_2 - \text{T}_1)_y & (\text{P}_1 - \text{P}_2)_y & (\text{P}_1 - \text{P}_3)_y \\ (\text{T}_2 - \text{T}_1)_z & (\text{P}_1 - \text{P}_2)_z & (\text{P}_1 - \text{P}_3)_z \end{bmatrix} \begin{bmatrix} u \\ s \\ t \end{bmatrix} = \begin{bmatrix} (\text{P}_1)_x + \text{Nr} + (\text{T}_1)_x \\ (\text{P}_1)_y + \text{Nr} + (\text{T}_1)_y \\ (\text{P}_1)_z + \text{Nr} + (\text{T}_1)_z \end{bmatrix}$$

$$\begin{bmatrix} u \\ s \\ t \end{bmatrix} = \begin{bmatrix} (\text{T}_2 - \text{T}_1)_x & (\text{P}_1 - \text{P}_2)_x & (\text{P}_1 - \text{P}_3)_x \\ (\text{T}_2 - \text{T}_1)_y & (\text{P}_1 - \text{P}_2)_y & (\text{P}_1 - \text{P}_3)_y \\ (\text{T}_2 - \text{T}_1)_z & (\text{P}_1 - \text{P}_2)_z & (\text{P}_1 - \text{P}_3)_z \end{bmatrix}^{-1} \begin{bmatrix} (\text{P}_1)_x + \text{Nr} + (\text{T}_1)_x \\ (\text{P}_1)_y + \text{Nr} + (\text{T}_1)_y \\ (\text{P}_1)_z + \text{Nr} + (\text{T}_1)_z \end{bmatrix}$$

Where r is the radius of the tool, and s and t are the point of contact between the triangle and the tool. Solving the above equation tells us the contact point P_c in the plane of the triangle and the location of the tool T_c along the tool axis. Then the check is performed to check that the point $P_c$tool T_c is within the boundaries or not.

(ii) Edge check: This check is performed to see if the tool moving along the line (1-u)T_1-uT_2 will touch the edge P1+(P_2-P_1)t+Nr tangentially within the end vertices $P_1$and P_2 (i.e. with t [0, 1]). This check is performed for all three edges of a single triangle. If the tool touches any edge of the face, it must satisfy the following equation:

$$(1\text{-}u)T_1\text{-}uT_2 = P1+(P_2\text{-}P_1)t+ N.r$$

Where

$$\text{N} = \frac{((\text{T2} - \text{T1}) + (\text{P2} - \text{P1}))}{|\,(\text{T} - \text{T1}) + (\text{P2} - \text{P1})\,|}$$

Solving this as:

$$\begin{bmatrix}(\mathrm{T}_2-\mathrm{T}_1)_x & (\mathrm{P}_1-\mathrm{P}_2)_x\\(\mathrm{T}_2-\mathrm{T}_1)_y & (\mathrm{P}_1-\mathrm{P}_2)_y\\(\mathrm{T}_2-\mathrm{T}_1)_z & (\mathrm{P}_1-\mathrm{P}_2)_z\end{bmatrix}\begin{bmatrix}u\\t\end{bmatrix}=\begin{bmatrix}(\mathrm{P}_1)_x+\mathrm{Nr}+(\mathrm{T}_1)_x\\(\mathrm{P}_1)_y+\mathrm{Nr}+(\mathrm{T}_1)_y\\(\mathrm{P}_1)_z+\mathrm{Nr}+(\mathrm{T}_1)_z\end{bmatrix}$$

Let,

$$\mathrm{A}=\begin{bmatrix}(\mathrm{T}_2-\mathrm{T}_1)_x & (\mathrm{P}_1-\mathrm{P}_2)_x\\(\mathrm{T}_2-\mathrm{T}_1)_y & (\mathrm{P}_1-\mathrm{P}_2)_y\\(\mathrm{T}_2-\mathrm{T}_1)_z & (\mathrm{P}_1-\mathrm{P}_2)_z\end{bmatrix}$$

Then,

$$\begin{bmatrix}u\\t\end{bmatrix}=\mathrm{s}\ \mathrm{A}^{-1}\begin{bmatrix}(\mathrm{P}_1)_x+\mathrm{Nr}+(\mathrm{T}_1)_x\\(\mathrm{P}_1)_y+\mathrm{Nr}+(\mathrm{T}_1)_y\\(\mathrm{P}_1)_z+\mathrm{Nr}+(\mathrm{T}_1)_z\end{bmatrix}$$

Now the given matrix A is asymmetric. So its inverse will be solved by pseudo-inverse. Solving this equation gives the contact point and the tool location. If is within the edge, the cutter location is kept, otherwise, it is discarded and the final check is performed.

(iii) Vertex check: This check is performed to see if a vertex P_t will touch the tool as it moves along the line tool axis $(1 - u)T_1 - uT_2$. The check is performed for all three vertices of the triangle. As the tool contacts the vertex Pt, it must satisfy the equation:

$$\left| P_t - [(1\text{-}u)T_1 + uT_2] \right| = r$$

Solving the above equation for u gives the location of the tool axis as the tool touches the vertex P_t. If there are no real-valued solutions, then the tool will not touch P_t, for any value of u. In general, when the tool can touch P_t, there will be two solutions; we choose the solution furthest away from the work piece axis.

After applying all these checks, the value of P_t is checked whether it is in the triangle or not and the appropriate value is stored and then tool is moved to another location. These values of P_t are stored in a file to retrieve for the next step.

3.3 CL-SURFACE AND THE CL-NET DATA

A CL-net is used to store the CL information of a given top view of work piece. To construct a CL-net, a series of CL-curves (curves sliced from CL-surface by parallel guide planes) are first generated along both the X and Y directions with an interval d, respectively. Each CL-curve consists of a set of consecutive CL-points, and they can be generated by a projection algorithm. The CL-curves in X and Y directions interlace together and form a CL-net. Pencil-cut points are usually those ‘sharp’ points with abrupt change of surface normal (with G1 discontinuity) in the concave regions of a CL surface. Although each pencil-cut point is on either an X–CL-curve (CL-curve along the X-axis direction) or a Y–CL-curve, it is not necessarily on the cross-section locations of X and Y grid lines.

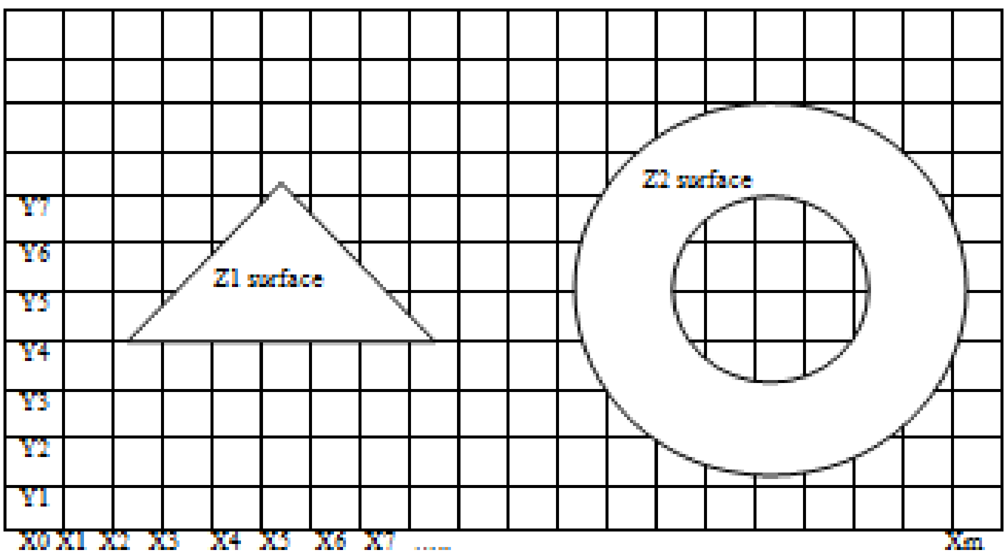


Figure3.10: 2D Graph with Top View

Compared to the approaches based on the Z-map, where pencil-cut points are usually evaluated from the grid points of a Z-map, more accurate pencil-cut points can be extracted from the proposed CL-net structure.

A CL data consists many inside triangles. Value of Umax has been recorded with the help of different checks as triangle check, edge check and vertex check. Where, Umax is the maximum value of every CL point. Z- Direction of a CL points depend upon the Umax value and getting Z value from the equation as shown blow.

$$Z = T_1 + u\,(T_1 - T_2)$$

Where $u = U_{max}$ and T_1 is the lowest position of the tool and T_2 is the highest position of the tool. Graph plot xyz in 2D has been shown in figure3.10.

3.4 DETECTING PENCIL-POINTS

CL data net has x, y and z coordinates for all points in top view. In this paper, scanning of CL data net has been two types first in x direction and second in y direction. In this method, find the points, have larger change in z coordinate and get the values of minimum z. In x direction, data net has scanned x minimum to x maximum and in y direction, y minimum to y maximum. All pencil cutting path points have been shown in figure 3.11.

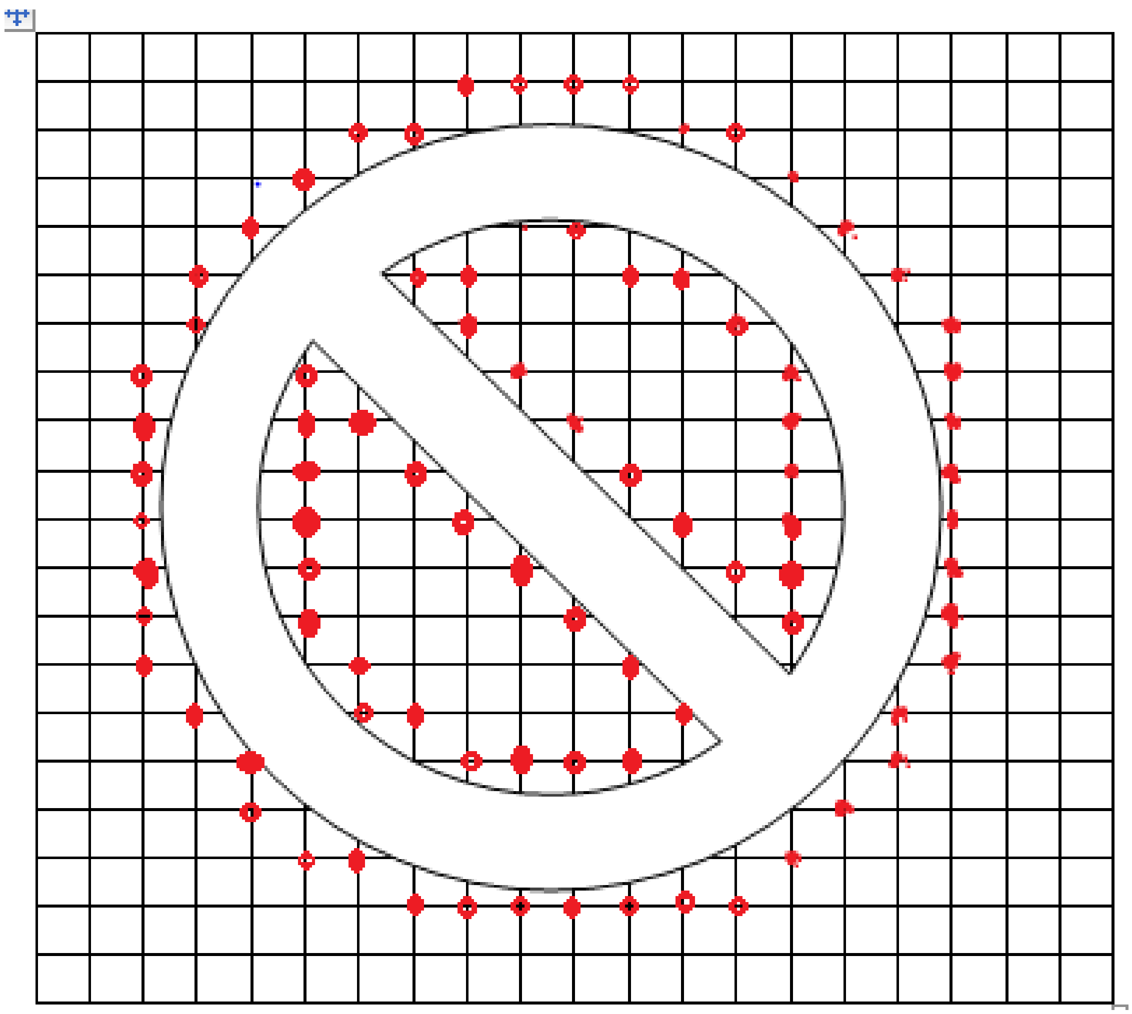


Figure3.11: Tool Path Points for Pencil Cutting

3.5 TRACING A PENCIL-CUT PATH

Path specification of pencil cutting point has different points as discussed below:

1. First select the X minimum point.
2. Check the minimum value of Y for X minimum.
3. Select the first point Xmin and Ymin.
4. Tool moves along clockwise direction with different way a shown in figure3.12.

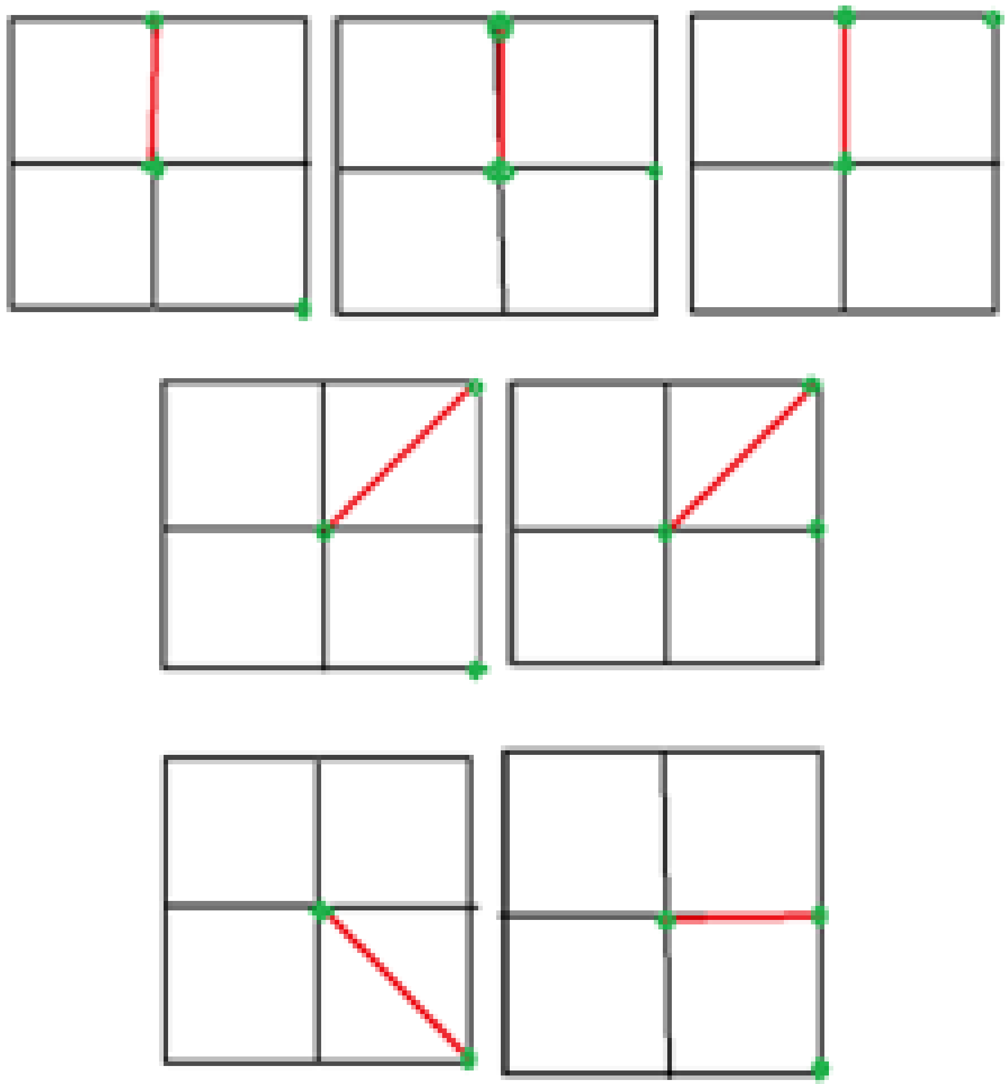


Figure3.12: Tool Moving Direction after First Point selection.

All 8 neighboring points of a center point have shown in the figure3.13. Consider a coordinate as center and check its neighboring coordinates if the boundary coordinate is found then center point sifts previous point and next point takes the center point position. Final tool path file has been stored as shown in figure3.14 with the help of algorithm.

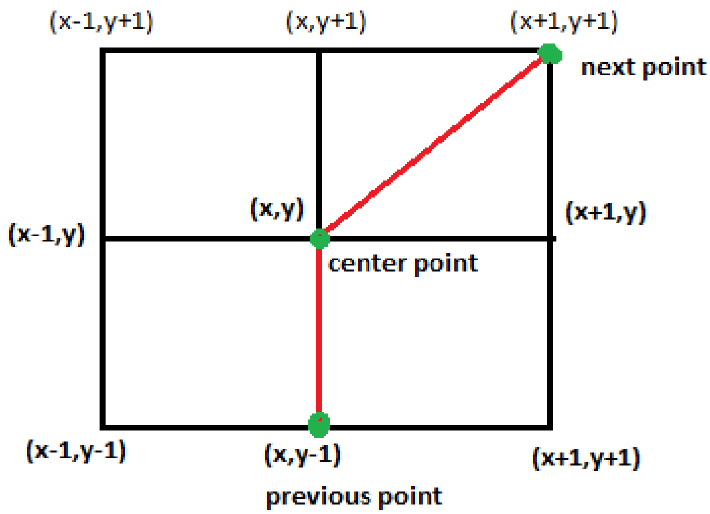


Figure3.13: Tool Moves Along the 8 Points

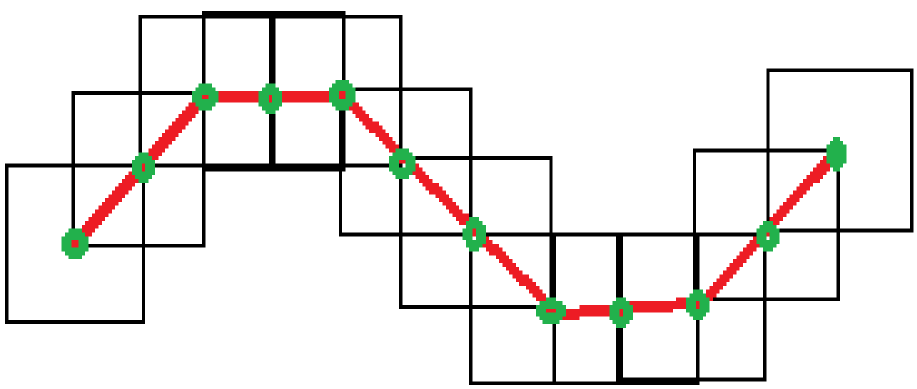
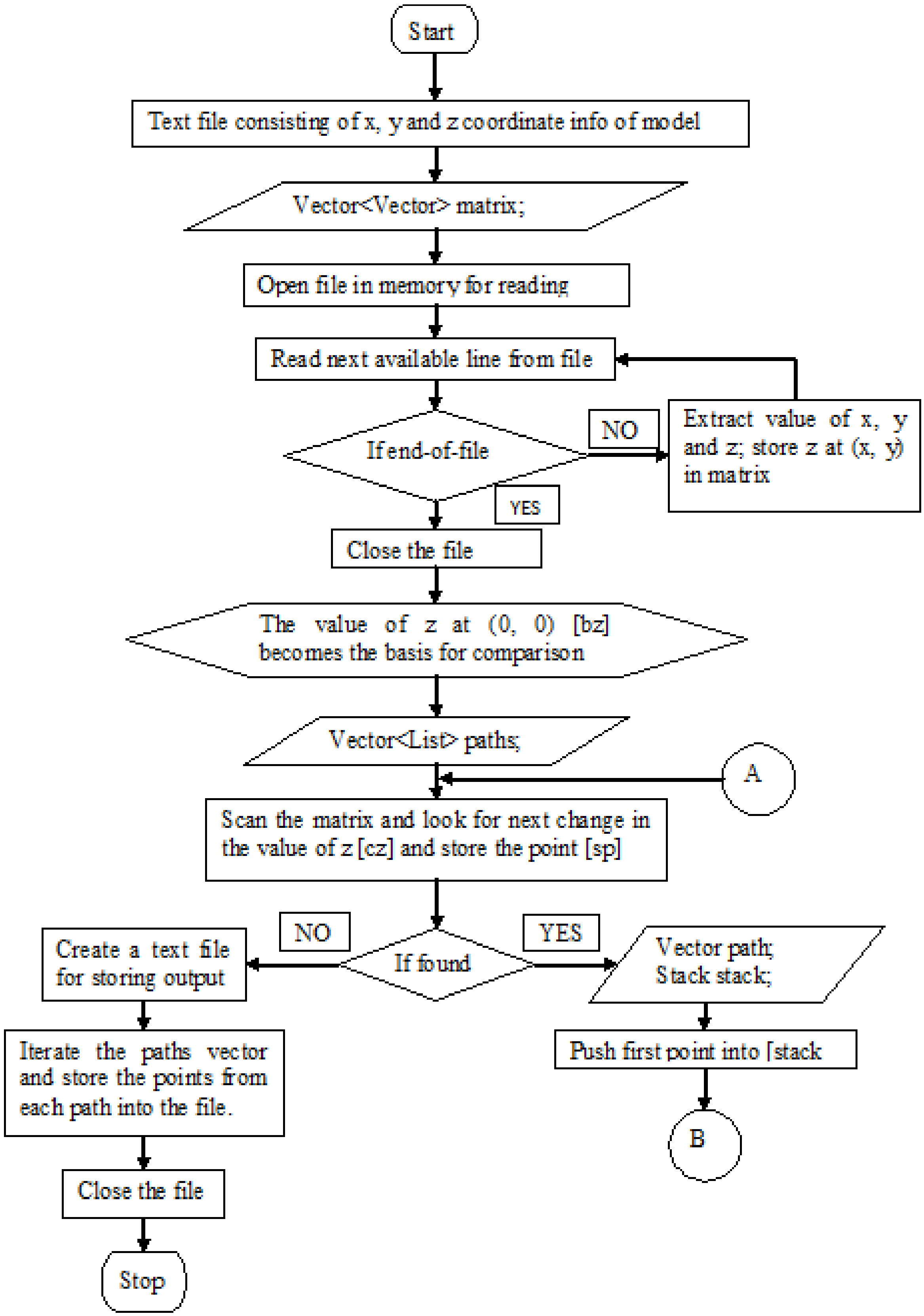


Figure3.14: Tool Path Tracing Sequence of Pencil Cutting Points.

3.6 SOLUTION PROCEDURE FOR PENCIL CUTTING TOOL PATH PLANNING FOR 3-AXIS VERTICAL MILLING

Based on methodology described in previous sections a computer program has been developed in JAVA. The flow chart of an iterative scheme is shown with detailed step taken in figure 3.15.


Start
Text file consisting of x, y and z coordinate info of model
Vector<Vector> matrix;
Open file in memory for reading
Read next available line from file
If end-of-file
NO
Extract value of x, y and z; store z at (x, y) in matrix
YES
Close the file
The value of z at (0, 0) [bz] becomes the basis for comparison
Vector<List> paths;
A
Scan the matrix and look for next change in the value of z [cz] and store the point [sp]
NO
If found
YES
Create a text file for storing output
Vector path;
Stack stack;
Iterate the paths vector and store the points from each path into the file.
Push first point into [stack
B
Close the file
Stop

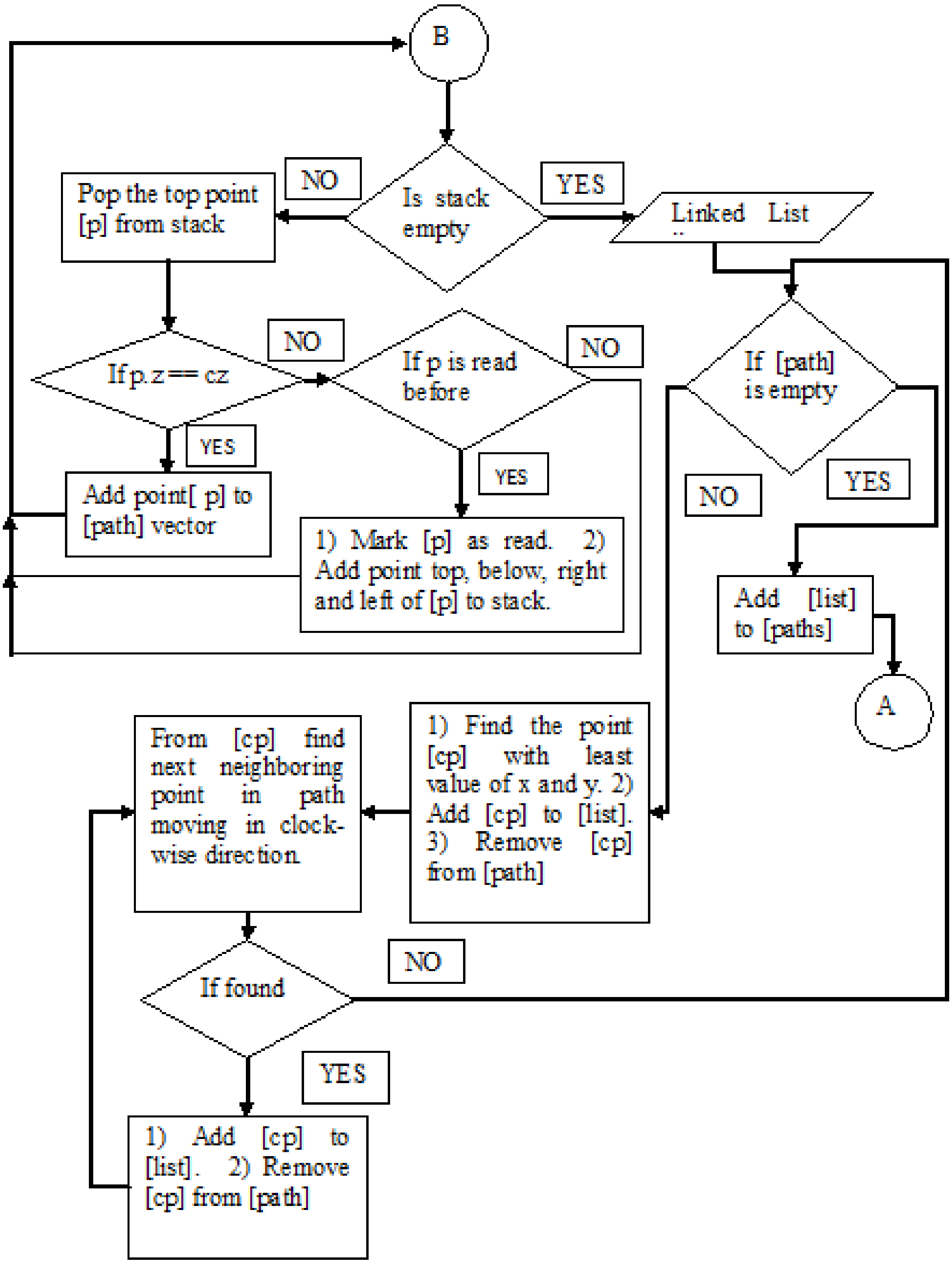


Figure3.15: Flow Chart for overall process

Chapter 4

RESULTS AND DISCUSSION

The tool path generation and planning which has been done in chapter 3 has been validated and actual finishing for flat surface part on 3 Axis vertical milling. The tool path generation and planning for finishing for raster milling is validated on simulator.

4.1 TOOLING USED

The tool used in the algorithm is ball nose end mill cutter. The radius of the tool is 1.5875 mm used, but their radius can be modified and the algorithm works for any tool radius. In the algorithm, the tool is moving in linear and nonlinear way.

CL data points have been calculated for the ball end mill of 1.5875 mm radius. Then using the JAVA algorithm pencil cutting tool path is extracted from CL data net to check the suitability of the above developed algorithm. Three part models have been chooses as described in the validation and discussion part of this chapter.

4.2 RELATION BETWEEN SIDE STEP VALUES AND SCALLOP HEIGHT

Relation between side step and scallops height has been discussed below with the help of figure4.1.

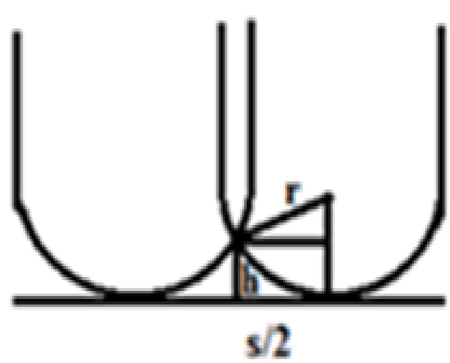


Figure4.1: Scallop Height (h) And Side Step (s)

The scallop height is density proportional to side step value for ball end mill. The mathematical relationship between scallop height (h) and side step value(s) is as written below:

Scallop height formula:

$$h = r - \sqrt{\left(r^2 - s^2/4\right)}$$

Where h= scallops height

r= radius of tool

s= side step

For validation of results from the pencil cutting algorithm the side step values of 0.5, 0.4, 0.3, 0.2 and 0.1mm has been chosen. The maximum scallop height that will be generated in finish milling machining these scallop height has been calculated and shown in table.

Pencil tool radius (r) in mm	Side step (s)in mm	scallops height (h) in mm
1.5875	0.5	0.0198087
1.5875	0.4	0.0126488
1.5875	0.3	0.0071025
1.5875	0.2	0.0031528
1.5875	0.1	0.0007876

The validation for the accuracy CL data net and pencil cutting algorithm has been done using a graphical NC simulator developed in Open GL environment available in SIDC LAB of thapar university Patiala. The steps followed for visual validation of algorithm has been presented below:

4.3 VALIDATION AND RESULTS OF PENCIL CUTTING ALGORITHM

The validation of the pencil cutting tool path has been shown in the figure4.3. The side step value for this pencil cut tool path is 0.5mm. the visual inspection as can be seen in the graph for pencil cut in figure 4.3 does not reveal the accuracy level. AB modal without pencil cutting has been shown in figure4.2.

Figure4.2: AB Modal without Pencil Cutting

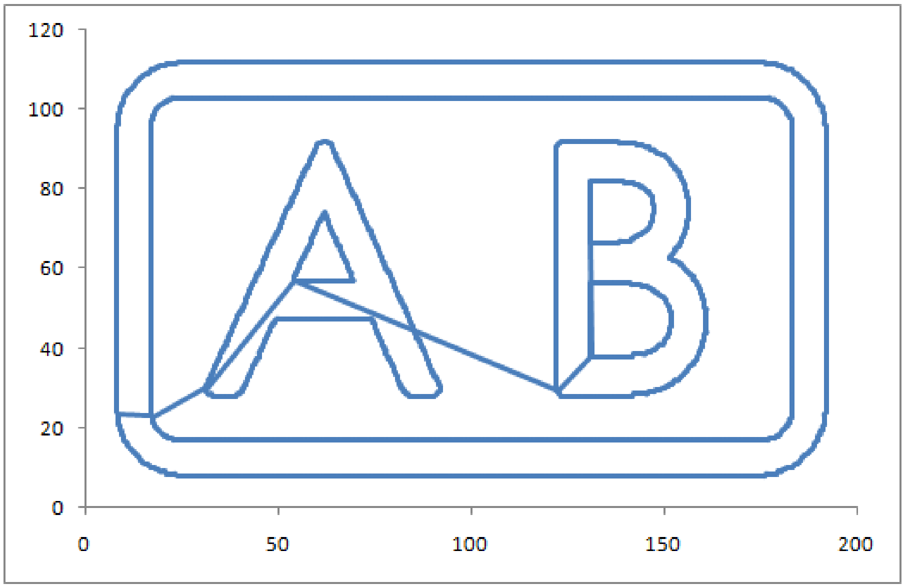


Figure4.3: Pencil Cutting Tool Path for 0.5 Side Step

To compare the accuracy of pencil cut tool paths, the pencil cut tool paths were also developed for 0.4mm, 0.3mm, 0.2mm and 0.1mm side step values and the provides of pencil cut tool path in X-Y plane for smaller section as highlighted in figure 4.4 has been shown for all five side step values. One can compare that the 0.1mm side step tool path is the most precise out of total time pencil path. The figure 4.4 shows the finish cutting operations for AB modal without pencil cut tool. The CL data for AB model for finish machining is developed for raster machining as discussed in section of chapter 3.

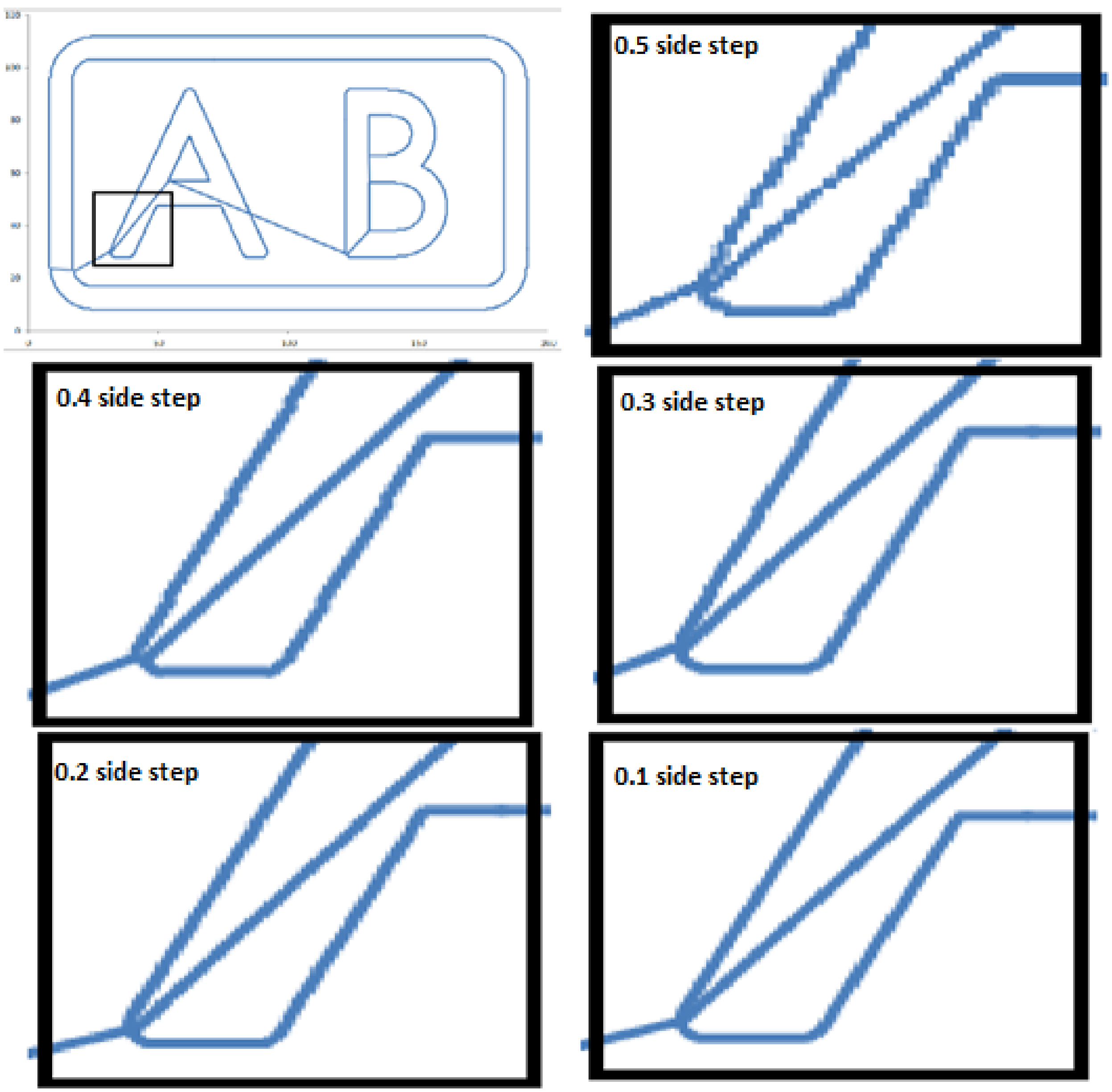


Figure4.4: Pencil Cutting Tool Path for all five Side Step

In the figures 4.5, 4.6 4.7, 4.8 and 4.9 the pencil cut is performed /overlaid on the finishing stock shown in figure4.4 in the specified order and the graphical images shows the level of enhancement of pencil cuts as seen in the figures from 4.5, 4.6, 4.7, 4.8 and 4.9.

Figure4.5: Pencil Cutting for 0.5 Side Step

Figure4.6: Pencil Cutting for 0.4 Side Step

Figure4.7: Pencil Cutting for 0.3 Side Step

Figure4.8: Pencil Cutting for 0.2 Side Step

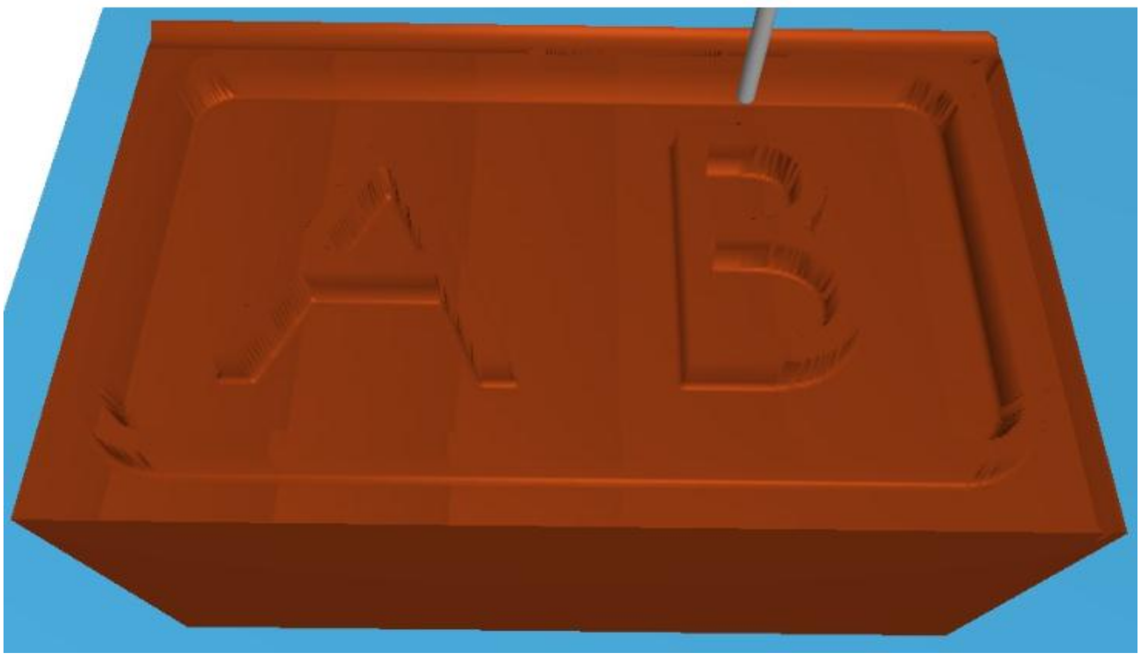


Figure4.9: Pencil Cutting for 0.1 Side Step

Figure 4.9 shows the best pencil cut result. Although it takes a lot of time to developed the CL data net with 0.1mm side step and towards step value, but the extracted pencil cut operation will takes very less time for machining compare to a time machining operation along with such data file having 0.1mm side step and forward step.

Thus one can use 0.5mm or 0.4mm side step or suitable values for side and forward steps for finishing operations on a vertical milling center, where as one can always side step and forward step to generate the pencil cut tool path.

The figure 4.10 and 4.11 shows the 3D shape of other two paths taken to check the accuracy of pencil cut algorithm, manually HEX model, Cavity Protrusion Modal.

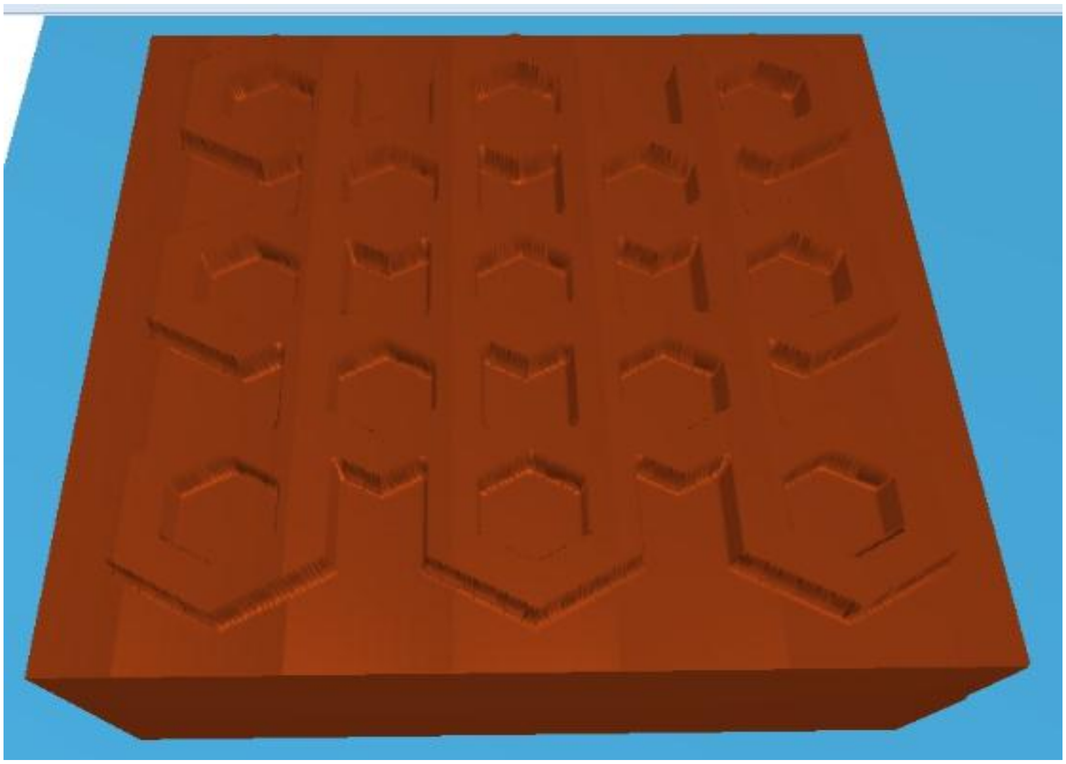


Figure4.10: Hex_Modal without Pencil Cutting

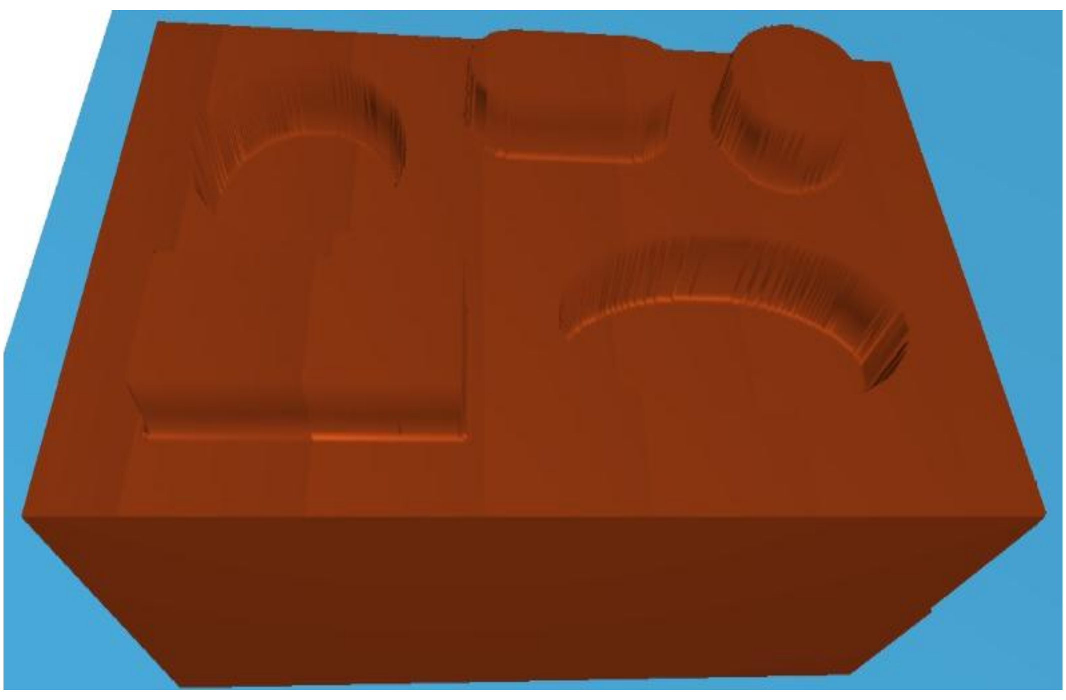


Figure4.11: Cavity_ Protrusion _Modal without Pencil Cutting

As apparent from figure 4.12 and 4.13, the X-Y projection of pencil cut tool path shows the confirmation with the part contours. Hence the work of pencil cut algorithm is as expected.

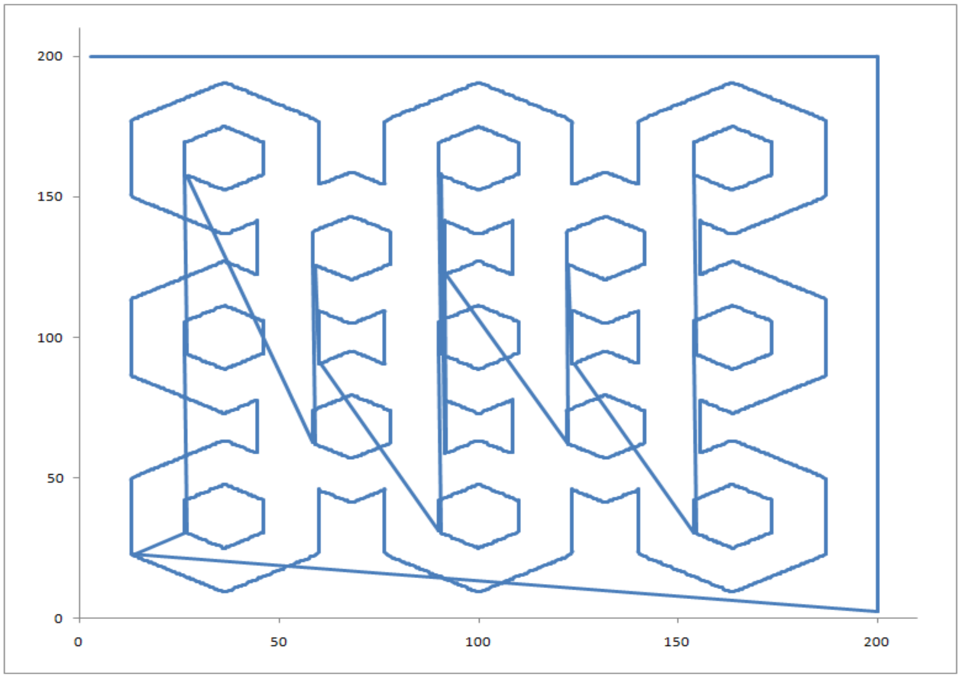


Figure4.12: Pencil Cutting Tool Path for HEX modal

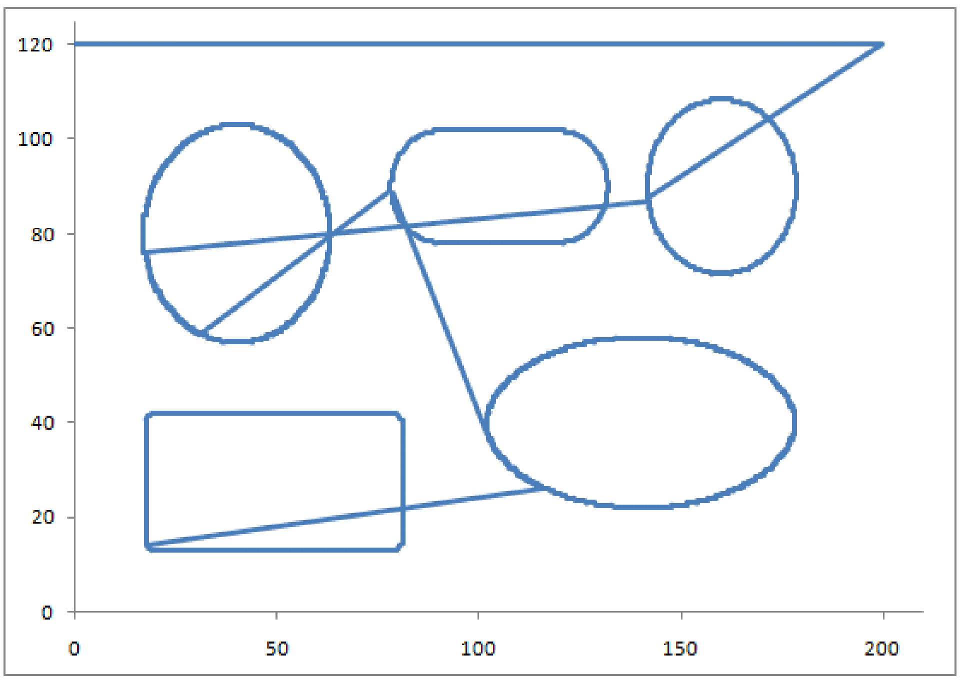


Figure4.13: Pencil Cutting Tool Path for Cavity_Protusion Modal

The figure 4.14 shows the graphical result for HEX modal for pencil cutting operation. Similarly the figure 4.15 shows the graphical results for Cavity_Protusion modal for pencil cutting operations.

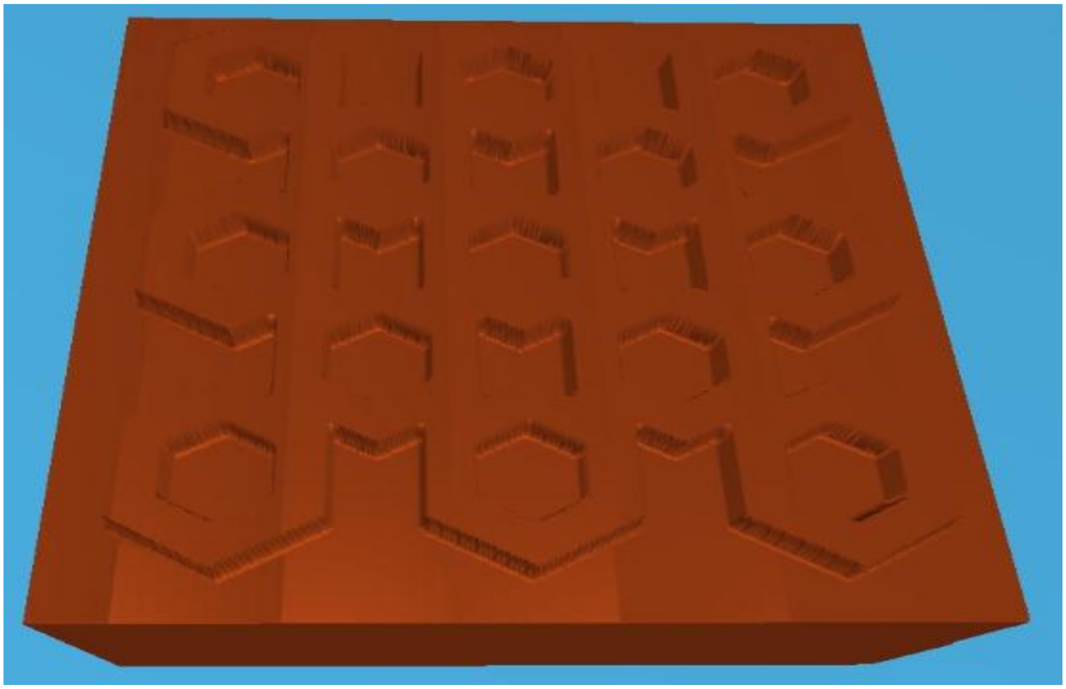


Figure4.14: Pencil Cutting Path for HEX modal

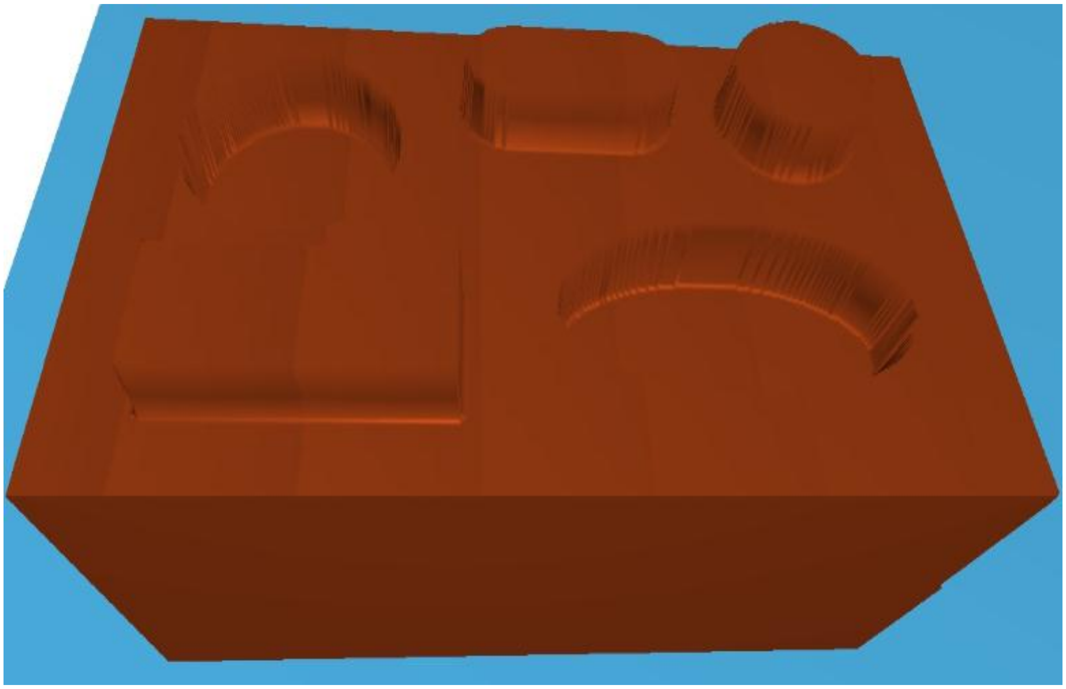


Figure4.15: Pencil Cutting Path for Cavity_Protusion Modal

Although the appearance in the figures 4.10, 4.14 and figure 4.11, 4.15 is similar in the given values, but one can see the highlighted regions for comparison finishing and pencil cutting operations.

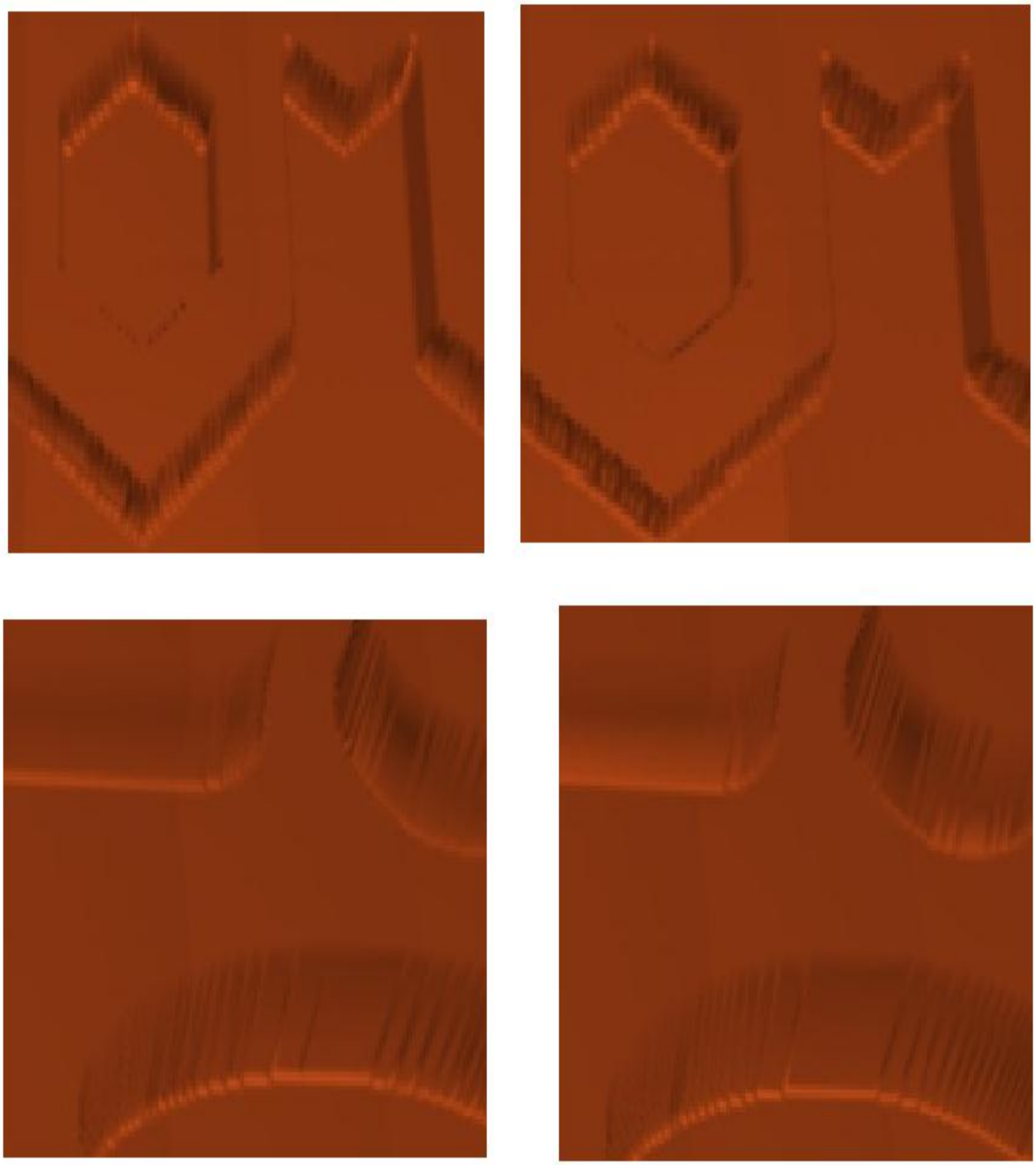


Figure4.16: Highlighted Regions For Finishing And Pencil Cutting Operations.

CHAPTER 5

CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 CONCLUSIONS

The results and validation for working of the pencil cutting algorithm developed in the present thesis work has been explained in detail in chapter 4. As discussed in the section 4.3 of chapter 4.

- It takes a lot of computational time for calculation of CL data net for finish machining at finer side step values, but one can suitably choose comparatively larger side step value for finish machining, and one can take finer side step values for CL data generation for extraction of pencil cutting tool paths. The pencil cut tool path garnered for finer side steps will be far shorter than the corresponding total CL data net.
- The actual machining time for pencil cutting operation is going to be far smaller than finishing operation time even at very fine side step values for finishing.
- The present algorithm is free from additional computations required for offsetting the actual STL surface and other hazels of eliminating the excessive offset data for finding the suitable CL data net for finish and pencil cut operations.
- The present approach gives the best results compared to other pencil cutting approaches reported in literature so far in terms of computational simplicity and accuracy of pencil cutting tool path data as the pencil cut data extracted from CL data net is gouge free.

5.2 SCOPE FOR FUTURE WORK

The following activities can be undertaken for extending the work presented in this thesis work.

(i) The pencil cut tool path can be experimentally verified on commercial vertical NC milling centers, and the precision for surface roughness at the contour boundaries can be accessed in relation to the sidestep values.

(ii) The federate values for pencil cut machining can be estimated and verified experimentally as in pencil cut tool path the path direction changes are very sharp.

(iii) The different types of tool shapes like flat and bull-nosed end mills can be considered.

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