A thesis report on

GENERALIZED TOOL PATH GENERATION ALGORITHM FOR SCULPTURED PSEUDO SYMMETRIC SURFACE MACHINING

Submitted

In partial fulfilment of the requirement for

The award of degree of

MASTER OF ENGINEERING

IN

CAD/CAM & ROBOTICS ENGINEERING

Submitted by

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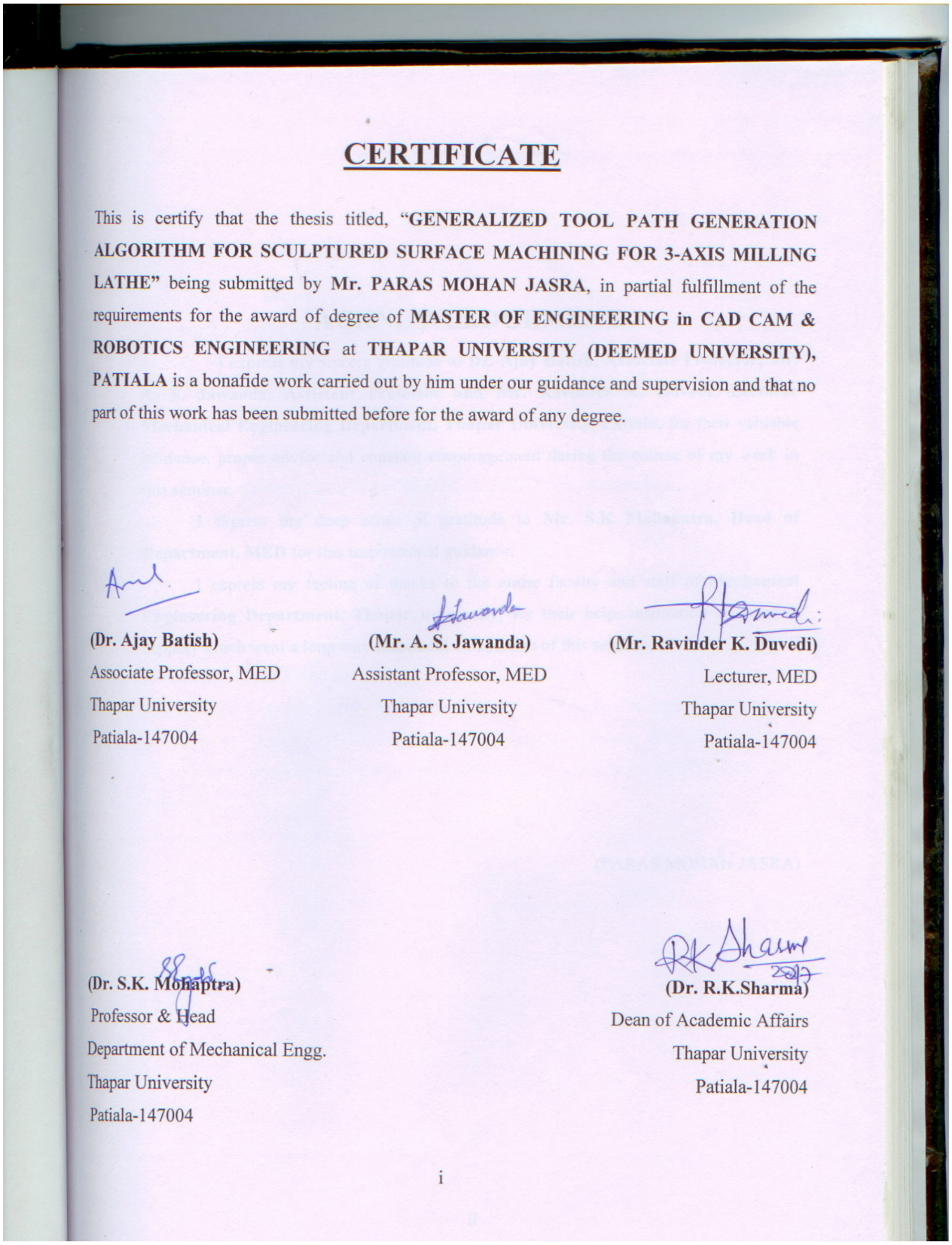
JULY, 2009



CERTIFICATE

This is certify that the thesis titled, **"GENERALIZED TOOL PATH GENERATION ALGORITHM FOR SCULPTURED SURFACE MACHINING FOR 3-AXIS MILLING LATHE"** being submitted by **Mr. PARAS MOHAN JASRA**, in partial fulfillment of the requirements for the award of degree of **MASTER OF ENGINEERING in CAD CAM & ROBOTICS ENGINEERING** at **THAPAR UNIVERSITY (DEEMED UNIVERSITY), PATIALA** is a bonafide work carried out by him under our guidance and supervision and that no part of this work has been submitted before for the award of any degree.

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ACKNOWLEDGEMENT

I express my sincere gratitude to **Dr. Ajay Batish, Associate Professor, Mr. A. S. Jawanda**, **Assistant Professor and Mr. Ravinder K. Duvedi**, **Lecturer Mechanical Engineering Department, Thapar University**, **Patiala,** for their valuable guidance, proper advice and constant encouragement during the course of my work in this seminar.

I express my deep sense of gratitude to **Mr. S.K Mohapatra, Head of Department, MED** for this inspirational guidance.

I express my feeling of thanks to the entire faculty and staff of **Mechanical Engineering Department**, **Thapar university**, for their help, inspiration And moral support which went a long way successful completion of this seminar.

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ABSTRACT

The generalized tool path generation algorithm has been made in the presented thesis work. The aim for the development of tool path algorithm is to machine the pseudo symmetric patterns. The CAD modeler provides the information about the part geometry is taken as STL file, which will be used as input to the tool path generation algorithm. With the help of STL as input, and depth of cut for roughing pass is entered by the user, the algorithm calculates the cutter location (CL) points. Also the extreme dimensions of the part to be made are extracted so as to decide the initial stock size.

Tool path generation strategies are also discussed. Also the literature about the side feed and forward feed has been discussed in the present thesis report. The overall literature is divided into three parts.

Various checks have been applied in the algorithm to find the best suitable point at particular tool position. The tool path follows the spiral path to machine the surface, with cutter profile as ball nose end mill with varying radius for roughing and finishing passes, which can be changed by the user.

The tool path is verified on the PBG2048 CNC lathe mill by machining the various work pieces on wood pieces. Machining time is optimized by adjusting the roughing passes. Those results are compared with the tool path made particularly for the PBG2048 CNC lathe mill.

ABBRIVATIONS

MCU:	Machine Control Unit
NC:	Numeric Controlled
CNC:	Computer Numeric Controlled
CAD:	Computer Aided Design
CAM:	Computer Aided Manufacturing
APT:	Automatic Programmed Tools
CL:	Cutter Location
CC:	Cutter Contact
DMAC:	Direct Machining And Controlling
STEP:	Standard for the Exchange of Product Model Data
IGES:	Initial Graphics Exchange Specification
STL:	Stereo Lithography
NURBS:	Non-Uniform Rational B-Splines
B-Rep:	Boundary Representation

NOMENCLATURE

u : Parameter between initial tool position and final tool position

s : Parameter between one edge of the vertex(triangle)

t : Parameter between other edge of the vertex(triangle)

T_1 : Initial tool position

T_2 : Final tool position

P_1, P_2, P_3 :Vertices of tringle(facets)

N :Normal vextor

R :radius of tool

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CHAPTER 1

INTRODUCTION

In the era of technology, there is a significant role of NC machines in the daily life, as the most of the daily useable thing are being automated with the help of NC machines. The tool path plays an important role in the manufacturing of work pieces, as it decides the time to machine the piece and hence the productivity of the machine. The present thesis work points toward the tool path algorithm for generalized 3-axes lathe. This algorithm is particularly made for the ball nose cutter with varying radius. A helical 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.

1.1 NC MACHINING SYSTEM

The operation of conventional NC control system consists of following basic components:

Program of instructions

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.

Controller unit

The control unit, also called machine control unit (MCU), commonly called as the machine controlled unit consists of the electronics hardware and software to interpret the commands written on the input medium to direct the tool.

Machine tool or other controlled process

The machine tool is the part which performs the useful work and executes the command written on the input medium with the help of the controller.

The manufacturing process for CNC machines involves many stages and any simplification or automation of these stages is appreciated by the manufactures as it results in reduced operating cost. Computer Numerical Controlled (CNC) machines are a fundamental tool used to automate the manufacturing production processes. CNC machines can provide reliable, robust repetitive production in a mass production environment. Thus the development of fully automated CNC machines to produce better quality products and reduce production time has become the focus of machine designers and researchers.

Computer Numerical Controlled (CNC) machine specifically refers to machine tools that are computer controlled to machine complex parts. The first CNC machine was a continuous path numerically-controlled milling machine developed by the MIT Servomechanisms Laboratory in the early 1950s. The machine setup, work piece positioning, and part machining were all performed manually in the earlier times of CNC machines. The introduction of CNC machines have assisted in reducing the human operational errors from fatiguing repetitive manual tasks. Thus, there exists an increasing demand for using CNC machines to automate and improve the manufacturing processes in the modern manufacturing industry.

The overall design of CNC machines has changed little since its inception. The architecture of CNC machines is generally divided into three layers, namely the user interface, the machine controller, and the machine interface, Figure 1.1. The user interface of CNC machines is front-end of the system on the CNC controller console that allows the operators to interact with the machines. The user interface displays the current machine status and the part program. It also allows the operators to edit and verify part programs prior to actual machining to prevent any errors in the tool path. 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. This part program contains the machine movement instructions usually in a standard machine tool language, such as ISO G&M codes. The initial machine setup, such as entering the tool compensation and the work piece origin, are done through the user interface. Simulations of the machining process could also be displayed on the user interface of some modern CNC machines.

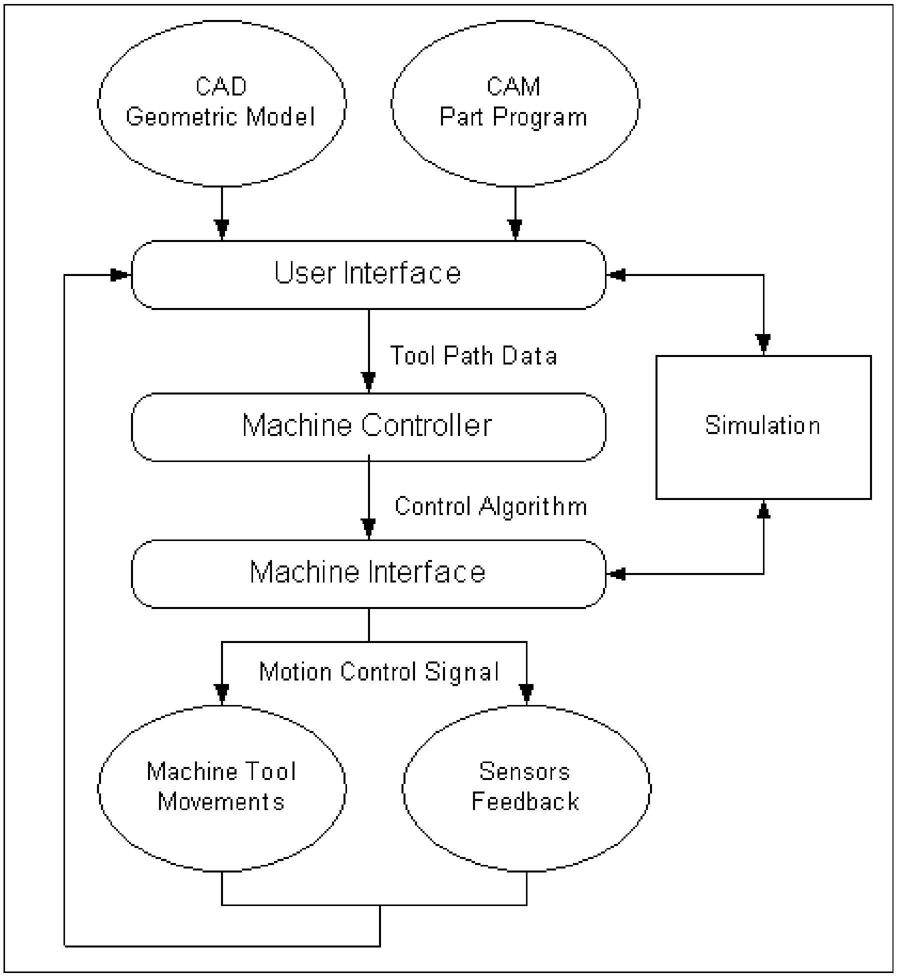

Figure 1.1: The Architecture of Conventional CNC Machines

The machine controller on CNC machines is the kernel of the system. The machine controller is aware of the in process machine status and the part coordinate systems to determine the current tool and part locations. It is also a motion control system that interprets the part program and commands the motions of the hardware devices during production.

The machine interface layer is considered as the execution level of the CNC machines. The machine interface consists of the machine motion fixtures and the communication protocol for handling the interactions between the machine and the control system. The operation of the machines is executed by transferring motion control data from the control system via the machine interface. The data transmitted includes the motion (tool positions and velocity) and machine parameters (the motors and drivers parameters).

The conventional CNC machines consist of the mechanical, electrical, and controlling components as illustrated in Figure 1.2. The mechanical components comprise of the fixture table that holds the part, the spindle assembly that carries the cutting tool, and the mechanical driving mechanisms that carry out the machine movements. The electronics comprises of sensory systems, limit switches, and actuating motors, provide the driving power and motion feedback to the CNC controller for controlling the machine movements. The CNC controller interprets and commands a series of machine motions in sequential order to machine a part according to the part program. The part program is a list of machine commands usually written in G-code format. The capability of using part programs with CNC controller offers the flexibility of machining different designed parts with minimal mechanical or electrical modifications on the CNC machines.

Figure 1.2: CNC Machine Design

CNC machines have a high capital cost and long operational life. This leads the manufacturers to keep the machines in production until the machine is obsolete. Since the machine life is long, industry is interested in multi-purpose CNC machines that are capable of machining a variety of parts on one machine. The structure of the machine is difficult to modify once the machine is designed and built. However, the

CNC controllers the heart of a CNC machine that drives and controls the entire machine movements is flexible to perform different machining operations. Thus, the development of customizable and upgradeable CNC controllers is considered to be economical efficient.

In the present NC machining system, the CAD modeller is used to make the parts. Then the process planning is done. Tool path is made on the CAM package and then G & M codes are generated in post processor. Simulation is done to verify the tool path generated in the post processor. Then machining is done after setting the jigs and fixtures and at last, the machining is done on the machine to get the final part. The complete NC machining system is shown in figure 1.3 given below.

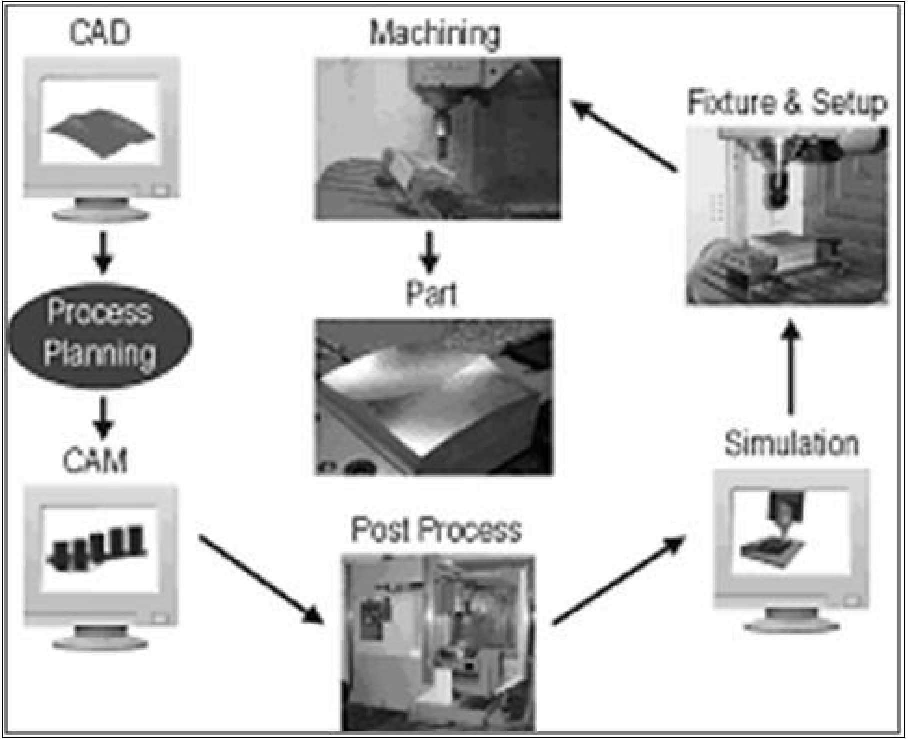

Figure 1.3: Existing NC machining system

Also, with present NC machines, the artistic features like Rangoli, Phulkari etc given in the figure 1.4 are difficult to engrave on any feature, or, to machine these features, 5-axis machines or specialized machines are required which in turn increase the cost, which may not be affordable for artisans or hobbyists. Thus there is a need of a general purpose NC machine, which, other than machining simple turning or milling features, also able to machine these types of artistic features also.

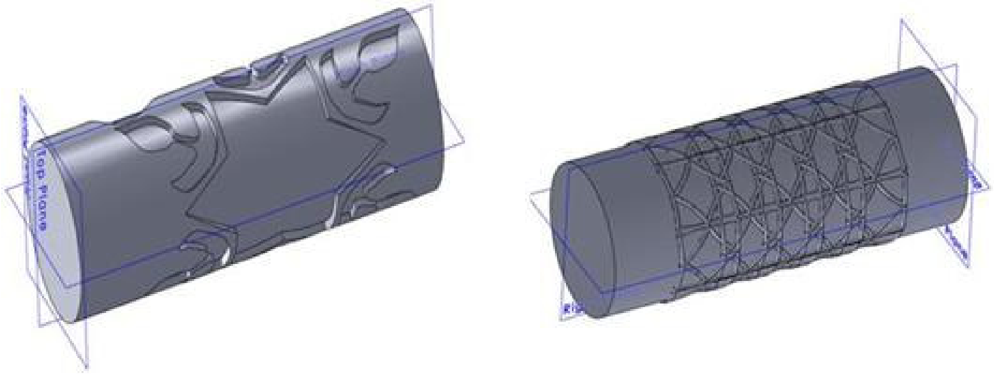

Figure 1.4: Some artistic features

Although, CNC machines have proven to have an effective quality assurance property when integrated into the manufacturing industry, there are some drawbacks on the operations of the CNC machines.

CNC machines are blind in the way that they would indisputably follow the input of the part program disregarding whether the program would lead to inappropriate machine movements.

Simulations are performed on the part program prior to the machining process to check for errors that could occur. Simulators could verify the tool path but it could not detect any current parameter mismatches for individual machines because various software packages are used at different data processing stages.

In addition, CNC machines are constructed with high speed and large cutting force moving components, which could cause catastrophic damages to the machine or the work piece when there is any error in the machining process. Thus, specialized operators are required at each stage of the CNC manufacturing process to administrate each task.

Well experienced specialized operators require a lot of training, and including specialized operators at each task in the manufacturing process would increase the manufacturer's operating costs and decrease the operational efficiency. The remedy of constructing CNC machines to automate the machining processes with minimal human intervention allows the manufacturer to effectively allocate operators to perform other tasks better and with efficiency.

1.2 NEED FOR A COST EFFECTIVE NC MACHINING SYSTEM

The applications of the computer aided design (CAD) and computer aided manufacturing (CAM) technologies is very wide. The applications of advanced CAD and CAM systems extends from manufacturing of the basic process equipment components to the intricate surface machining applications in crafted parts. But the use of such technologies for productivity enhancement is still a dream for a great portion of the population across the world, especially for those who are small scale entrepreneurs and the artisans/ craftsman, as the cost of owning such technologies is still very high. This is one of the main reasons, why most of the artisans/ craftsman do not use the automation for their customized manufacturing facility. As a result many artisans/ craftsman find it difficult to meet the requirement of production levels to break even. Another aspect is the reproducibility of the art work, as manufacturing without automated facilities/ systems these people cannot produce the identical finished artefacts or artistic goods in bulk.

The idea behind reducing the cost of production per unit in batch production system paved the path for the development of numeric controlled (NC) machine tools. The higher investment in such systems was justified only for the mass or batch production systems where at least a few thousand components of each variety are produced. Also application of NC technology is better suited for manufacturing of components/ parts where the time required for actual machining constitute a significant part of the total production time per unit. During the early days of the invention of the NC technology, it was very expensive and unless the cost of capital invested in the NC machine tools got spread over a large number of units to be produced on these machine tools, the investment in such technology was not commercially viable. The NC technology got improved over a period of time and with the reduction in the cost of the computer technology it has become further cheaper. As a result NC technology has become affordable to the batch and job shop production systems which are producing considerably small number of units of each part variety.

Even though there is drastic reduction in the cost of owning the NC technology, still it seems to be expensive for the small scale artisans/ craftsmen. This is because of the reason that the number of parts they produce are of very intricate shape which can only be produced in specially designed NC systems. Another reason is the number of units of each variety they produce are also very less.

The craft work cannot be completed without the manual operations because such workmanship is the outcome of the some special skills owned by the artisans/ craftsman. The initial canvas or the base parts required for craftwork are produced using some simple hand tools or manual machine tools as in case of wooden handicraft. As a result it takes considerable amount of time to carve the required base geometry of the part on which finally hand carving is done to generate the final product. The final outcome of the craft work is some specialized items and the number of finished pieces is generally very less. Because of this reason most of the craftsmen prepare the rough canvas for their work themselves than going in for some kind of automation solution, as the cost of capital invested may not be distributed over the larger number of units.

The challenges such as shorter product life cycles, frequent design revisions, stringent demands on product quality and shorter times to market has imposed few more constraints before we start to think of designing new automation strategies for small scale manufacturing systems. Moreover the manufacturing activities have become customer centric rather than manufacturer driven. Globalization has added further challenges for the artisans and craftsman across the world as they are now being forced to produce the better quality product in shorter time span and sell their products at reasonable prices.

Thus there is an urgent need for cost effective automated system for the handicraft workers/ artisans, so that these people would be able to reproduce the identical finished products in smaller time duration and may be able to get righteously compensated for their skills.

1.3 DMAC (Direct machining and controlling)

After the work piece is designed in the CAD package, and then the tool path is simulated on the CAM package, the tool path is to be converted into G&M codes for the machining on the machines. There is a significant loss of data while conversion. Also the curves are not exact while conversion and are interpolated to be exact. That curves may not suitable for requirement. Thus there should be any alternate for G&M

codes, so that this loss can be eliminated and there should be proper interpolation of exact model.

For this purpose the concept of direct machining and controlling was introduced [41]. Direct machining and control (DMAC) has provided a unique solution to the shortcomings of typical machine tool controllers described above. The DMAC controller is software-based and very flexible.

1.4 PC BASED NC MACHINING SYSTEM

Gray et al. [1] proposed a new paradigm, in which the machine operates from simple PC. The work done by Bedi et. al.[37] is an elaboration of such paradigm, and implements the paradigm that can be used to produce parts directly from the model. In order to make a part directly from the model, the information of CAD model is taken as STL (Steriolithography) file and tool path is directly generated from STL file, thus eliminating the need of postprocessor, in which is used to generate the G & M codes. Now the tool path is directly made without the conversion of part program into G & M codes. The present thesis work also explores the tremendous capabilities of computer for the development of CAD-CAM integrated system.

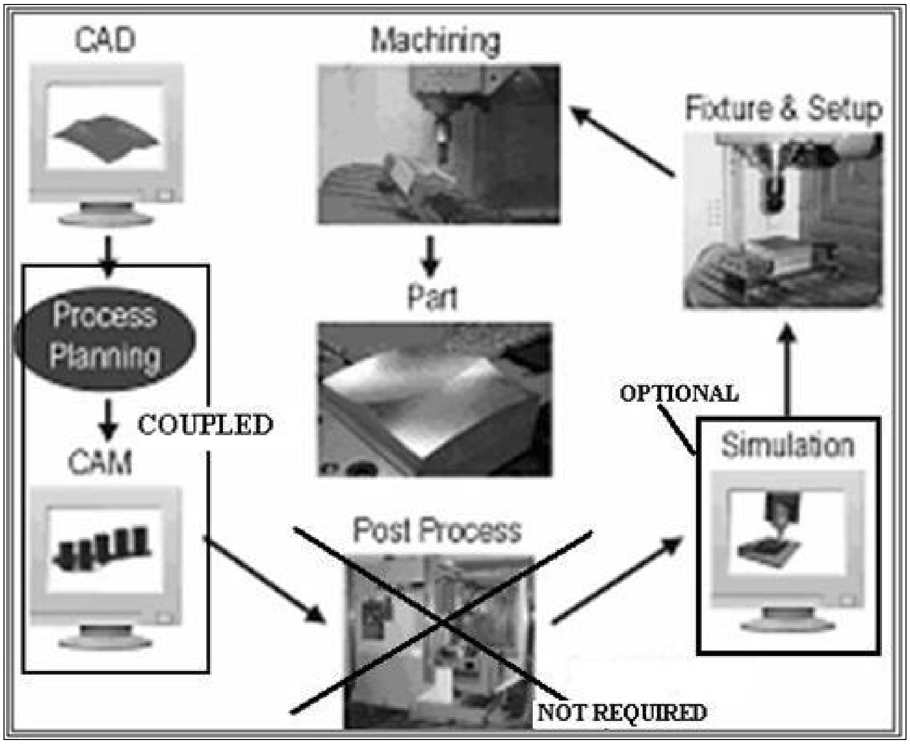

Figure 1.5: New CNC Manufacturing Paradigms

As shown above, the process planning and CAM module are clubbed in new CNC manufacturing module. Also there is no need of post processor as now G & M codes are not being generated and the tool path is generated directly in CAM package. The simulation is kept optional for the time being.

1.5 SINGLE CONTROLLED AXIS LATHE MILL

Manos et. al. [37] has developed the machine called Single controlled axis lathe mill (SCALM) presents a method for machining complex three-dimensional surfaces using only one axis of controlled motion for positioning a cutting tool on a specially designed numerically controlled (NC) machine. This single controlled axis lathe is configured like a lathe, but is used to produce complex sculptured surfaces out of wood. This is accomplished by mechanically linking two axes of motion to produce a fixed helical footprint of a tool path with constant step-over distance. As the linked axes are rotated, their location is measured by an encoder and passed directly to a personal computer (PC). Software running on the PC determines the depth of the computer controlled axis. The depth information is used to control the depth axis. Several test pieces have been machined out of cedar for evaluating the method.

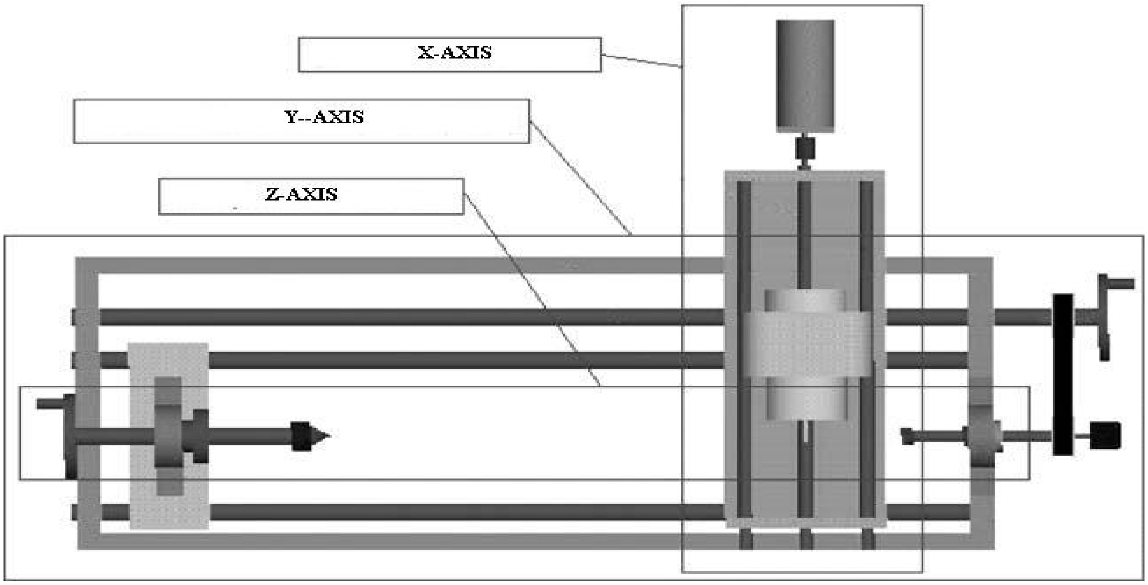

Figure1.6: CAD drawing of the single controlled axis lathe mill (SCALM) with axes highlighted

CHAPTER 2

LITERATURE REVIEW

A lot of research has been done in the field of tool path optimization. The literature has been divided into following parts:

2.1 TOOL PATH PLANNING METHODS

Works has been done in parametric and non-parametric tool paths. A brief history has been discussed by Dragomat et.al.[21]. The tool path is defined by two or three parameters which represents the complete surface. Catania[26] gives the estimation of the cutting depth. The computer representation of the designed surface is usually of parametric form; common forms include Bezier, B-helical, and Non-uniform rational B-helical (NURB) surfaces [34, 35, 36].The die or mould is made from the stock material in three steps, namely, rough, finish machining and polishing. In the roughing, the stock material is machined rapidly into an approximated shape. Finish machining is performed on the remained stock to bring it to within a specified surface tolerance of the die or mould. Scallop height is used to specify surface tolerance, and it is related to the cross-feed (Figure 2.1). By reducing the cross-feed will decrease scallop height, but simultaneously it will increase the machining time. In the finishing/polishing step, the scallops are removed by grinding or polishing operations. The length of this step is dependent on the scallop height, and thus a longer finishing step leads to a shorter polishing step and vice versa.

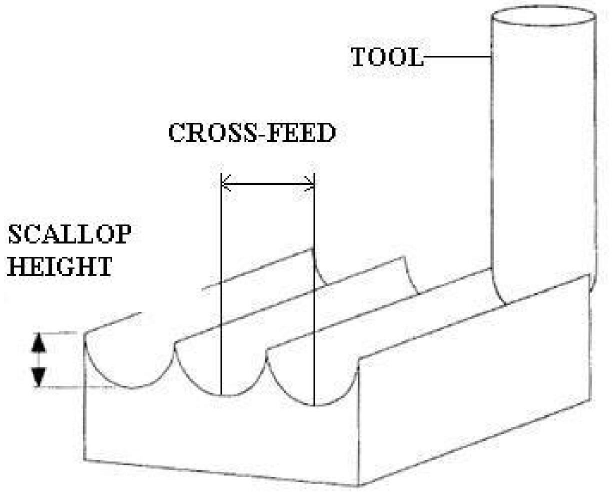

Figure 2.1: Scallop Height and Cross Feed Definition

2.2 MACHINING METHODS

Altan et al. [23] reported from a survey of mould manufacturers that the rough machining step takes 8-16%, finish machining takes 27-39% and polishing takes 13-23%, of the overall manufacturing time. Clearly, the last two steps consume the majority of the total manufacturing time. In order, to reduce cost and time for mould and die production, the finish machining and polishing steps should be improved. In industry 3-axis CNC machines are used for both the rough and finish machining steps. Commonly, 3-axis machining methods for machining complex surfaces use a ball-end mill cutter. An inherent problem in using ball-end mills is a zero cutting speed at the bottom of the ball. This problem can be overcome either by using other cutter geometries, such as radiused-end or fiat-end mills, or by using 4/5-axis CNC machines to avoid cutting with the bottom of the ball.

The first approach has difficulty in machining the bottom of cavities and the crests of convex shapes; in addition, a non uniform scallop height is left over the entire surface. The second approach uses expensive machines and achieves little gain in production time. To overcome the above problem, 5-axis machines have been used to machine dies and moulds with flat-end mills. Choi et al. [17] used a 5-axis CNC machine to mill sculptured surfaces using a method called Sturz milling. Vickers et al. [24] used a similar method to machine compound curvature surfaces. In this method, a flat-end mill is inclined in the direction of feed by a fixed angle, defined between the tool axis and the surface normal. Vickers et al.[25] show how the inclination of a fiat-end mill changes the effective cutting radius. In Sturz milling the inclination angle is chosen somewhat arbitrarily and remains constant throughout machining. Furthermore, because machining is done with the edge of the cutter, material is left in the wake of the tool.

Cho et al.[18] showed this problem to be a concern as it created surface roughness in the direction of feed. To address the fixed inclination angle Jensen and Anderson [27] used the effective cutting radius of a flat-end mill to vary curvature of the cutter's swept silhouette curve to match surface curvature. This technique adapts the fixed Sturz angle to best fit the local surface topology. The curvature matching was done by projecting a 3D cutting edge onto the osculating plane at the point of contact, and matching it with the surface curvature. To realise the projection requires the cutter to move linearly along a perpendicular to the osculating plane. 5-axis machines in general cannot perform linear interpolation with 5-axis simultaneous motion, thus the projection method is approximate.

The significant work has been done by Choi [18] and Saitho [19]. Saito presented the surface machining with G-Buffer method. other work has also been done by Choi [10][12]. Roth et.al [22] has presented sculptured surface machining with toroidal cutter for 5-axis. Chung [13] has presented the machining form scanned data to machine the sculptured surfaces. Other paper by Chung is [6].In recent work, Jensen et al. [27] and, in independent work, Bedi et al. [28] developed techniques using radiused end mills to match curvatures of the tool and the part surface. The basic idea for this method is that the cutting edge sweeps atoms as it rotates about the tool axis. The toroidal cutting surface offers a large range of radius of curvatures which can be realised in the cutting plane without any projection. Although this method has been simulated, it remains unimplemented.

2.3 TOOL POSITIONING METHODS

Jensen and Anderson [27] 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. This procedure matches the local geometry of the tool with that of the surface as closely as possible without gouging the surface in the neighbourhood of the cutter contact point. The authors also noted that the profile of a torus is a 4th order curve while the profile of a fiat end mill is only a 2nd order curve. Therefore, a better match between the surface and a toroidal end mill should be possible. Jensen et al. [27] extended this work to the toroidal end mill and developed a numerical procedure for calculating cross feeds.

Rao [29] developed a similar technique that they called the Principal Axis Method, PAM, and successfully used it to machine a surface patch. Using simulation and cutting tests, Rao [29] investigated the principal limitation of this technique which is the difficulty in lining up the feed direction with the direction of minimum curvature. Unless this condition is met, scallops are larger than expected and gouging may occur. Kruth and Klewais [30] used curvature matching as a first approximation for their tool inclination calculation. The authors recognized the importance of the work piece global geometry and not just the local curvature at a point. Even with curvature matching, gouging may still occur when the surface curvature is changing radically. They checked to see if any portion of the cutting tool was penetrating the desired surface by numerically approximating the distance between the tool and the surface. The tool inclination angle was altered based on the location and depth of gouging.

The entire above 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. Bedi et al. [31]proposed a tool positioning strategy called multi-point 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 authors were able to machine spherical surfaces with virtually 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. In the present paper a general technique for finding multi-point contact at a tool position is developed. The tool-surface interface is modelled 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, namely, a spherical cavity and 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. In recent developments the another Hosseinkhani et al.[32] proposed a method for machining of sculptured surfaces. Other developments in this field have also been done [2] [33][34][35]

Though there is a vast history of the methods of tool path, yet there is need of better method to save the time, money and to compete in the industrial environment to get the better results.

2.4 TOOL PATH GENERATION METHODS

The conventional tool path generation method used in the industry is to specify the cutter contact point on the part surface and then offset that point to yield the cutter location. The cutter contact point (CC) is the location where the tool touches the part surface. The cutter location (CL) is the location of the centre of the tool. There exist a number of tool path generation methods that are popular in industry. Some of the common ones are:

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 isoparameteric 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 [40].

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 [39].

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 [38]. 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 [11] has generated helical tool path for offset surface with constant scallop height. Tang [9] has also give the surface offset method.

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. [16] 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.

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 [20]. . Yau et.al.[14] 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 [8] has described the inverse offset method for tool path generation.

2.5 CONCLUSION OF LITERATURE SURVEY

The literature related to NC tool path planning strategies and tool positioning strategies have been discussed elaborately discussed in the previous sections. As apparent from the literature review, there is no method suitable for machining for sculptured surfaces having pseudo-symmetric shapes. There is a need of suitable NC tool path planner to generate Cartesian space cutter location points, which can be used for machining of sculptured surfaces on specially designed 3-axis NC milling lathe. The tool path planner can be developed for suitable tool shapes to determine the problem of tool gauging. Moreover actual machining time can be optimized by selecting the suitable value of side stepper revolution, which will also satisfy the criterion of surface finish required. As on the experimental study, the generic ball nose end mill cutter of suitable diameter can be considered for such a tool path planner.

CHAPTER 3

PROBLEM DEFINITION AND MATHEMATICAL MODELLING

3.1 PROBLEM DEFINITION

A generalized tool path generation algorithm for three axes machine with ball nose end mill cutter has been developed in Microsoft Visual C++ 2008, which moves in the helical path with uniform side feed and varying radius of cutter for roughing and finishing passes, to develop a gouge free surface with the help of .STL(Stereo Lithography) file as input of the algorithm which gives all of the information about the work piece. By taking the STL (Steriolithography) file as initial input from the CAD modeller, the computer program generates the cutter location (CL) points in a text file. Tool path generated is capable of generating the all artistic features and complex parts other than making the simple turn parts. The work piece may be made on the any design software as all designing software has capability to save the part as .STL format. The user has freedom to give the radius of the tool for roughing and finishing passes. Also the freedom has been given to the user to give the depth of cut for both roughing and finishing passes.

A brief methodology for the generation of tool path has been described below:

3.2 MODELLING OF TOOL PATH GENERATION ALGORITHM FOR NC MILING LATHE

The generic ball end mill cutter of varying radius for roughing and finishing cycles can be used for generating of sculpture surface. The NC tool path planning strategy for NC milling lathe has been discussed in this section in detail.

3.2.1 INPUTS REQUIRED FOR NC TOOL PATH PLANNING

The various inputs which are used for the machining to be done are:

1 **STL data for CAD model**: The STL file [5][7] is used as first input to the tool path generation algorithm. This STL can be made on any of the CAD model.

Every CAD model has capability to store the CAD model as .STL format. For now the SOLIDWORKS has been used to make the .STL file. This discretizes the CAD model in small number of triangles name facets. The size of facets can be changed from fine to coarse in SOLIDWORKS. Also there are two formats of STL file named BINARY and ASCII. ASCII file is human-readable and can be modified by a text editor if required, thus for this reason we are using the ASCII format, which has structured as:

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***

Where n1 to n3 and v11 to v33 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.

Facet orientation

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 counter-clockwise order when looking at the object from the outside (right-hand rule).

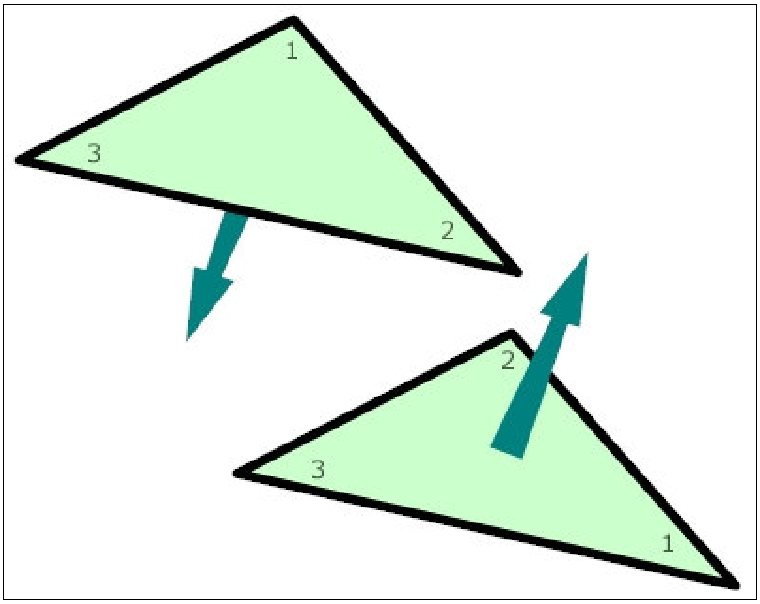

Figure 3.1: Counter clockwise orders of STL facets. The arrows point toward outside of the object.

This ASCII file format of STL is used as input to the program which is written in the **Microsoft visual c++ 2008.** The work piece is extruded in Z direction.

2 Radius of roughing and finishing tool: The next input which is to be input by user is the radius of roughing and finishing tool. This will give user the ability to use the ball end tool for any radius.

3 Depth of cut: The other input is depth of cut for roughing pass. The raw material generally is of much bigger size then the part dimensions to be manufactured. In case if the part dimensions are of much smaller in size, then the user has given independence to cut the raw material in multiple passes by giving depth of cut. First, the difference between maximum and minimum dimensions of work piece is displayed on the execution windows. By seeing the difference, the user can put any depth of cut. A computer algorithm automatically calculates the number of passes for the entered value of depth of cut and it displays the number of passes on the execution window. If the depth of cut is more than the difference between maximum and minimum dimensions, then it cuts the material in one go.

4 **Finishing allowance:** The another value which user inputs in the program is the finishing allowance which the roughing tool should leave for finishing tool. Generally it is kept 2mm but the user may enter the another value if the part is not so complex or the tool used for finishing is of higher radius

5 **Side feed:** The value of side feed is to be entered by the user. This value is kept large for roughing pass and 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 STL file required with ASCII format has been explained in the 4.3.1 section

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 NC TOOL PATH PLANNING

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 milling lathe.

1 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:

$$(1-u)T_1 + uT_2 = P_1 + (P_2 - P_1)t + (P_3 - P_1)s + \tilde{N}r, \tag{1}$$

Where

$$\tilde{N} = \frac{(P_2 - P_1) \times (P_3 - P_1)}{|(P_2 - P_1) \times (P_3 - P_1)|}.$$

t & s parameters are to define the surface of facet and $\tilde{N}$ is the facet normal.

Solving this as:

$$\begin{bmatrix} (T_2 - T_1)_x & (P_1 - P_2)_x & (P_1 - P_3)_x \\ (T_2 - T_1)_y & (P_1 - P_2)_y & (P_1 - P_3)_y \\ (T_2 - T_1)_z & (P_1 - P_2)_z & (P_1 - P_3)_z \end{bmatrix} \begin{bmatrix} u \\ s \\ t \end{bmatrix} = \begin{bmatrix} (P_1)_x + (\tilde{N})_x r + (T_1)_x \\ (P_1)_y + (\tilde{N})_y r + (T_1)_y \\ (P_1)_z + (\tilde{N})_z r + (T_1)_z \end{bmatrix}$$

$$\begin{bmatrix} u \\ s \\ t \end{bmatrix} = \begin{bmatrix} (T_2 - T_1)_x & (P_1 - P_2)_x & (P_1 - P_3)_x \\ (T_2 - T_1)_y & (P_1 - P_2)_y & (P_1 - P_3)_y \\ (T_2 - T_1)_z & (P_1 - P_2)_z & (P_1 - P_3)_z \end{bmatrix}^{-1} \begin{bmatrix} (P_1)_x + (\tilde{N})_x r + (T_1)_x \\ (P_1)_y + (\tilde{N})_y r + (T_1)_y \\ (P_1)_z + (\tilde{N})_z r + (T_1)_z \end{bmatrix}$$

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.

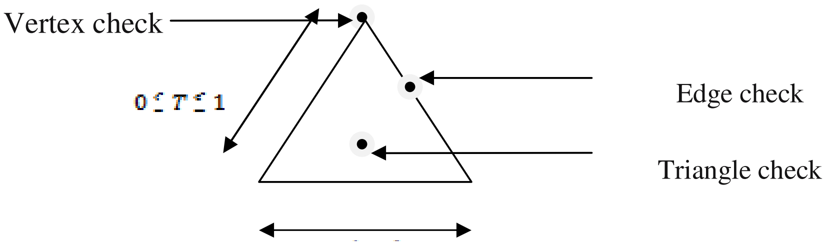

Figure 3.2: STL facet with all checks applied

2 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 $P_1 + (P_2 - P_1)t + \widehat{N}r$ 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 tringle. If the tool touches any edge of the face, it must satisfy the following equation:

$$(1-u)T_1 + uT_2 = P_1 + (P_2 - P_1)t + \widehat{N}r \tag{2}$$

Where

$$\widehat{N} = \frac{(T_2 - T_1) \times (P_2 - P_1)}{|(T - T_1) \times (P_2 - P_1)|}$$

Solving this as:

$$\begin{bmatrix} (T_2 - T_1)_x & (P_1 - P_2)_x \\ (T_2 \quad T_1)_y & (P_1 \quad P_2)_y \\ (T_2 - T_1)_z & (P_1 - P_2)_z \end{bmatrix} \begin{bmatrix} u \\ t \end{bmatrix} = \begin{bmatrix} (P_1)_x + (\widehat{N})_x r + (T_1)_x \\ (P_1)_y + (\widehat{N})_y r + (T_1)_y \\ (P_1)_z + (\widehat{N})_z r + (T_1)_z \end{bmatrix}$$

Let,

$$A = \begin{bmatrix} (T_2 - T_1)_x & (P_1 - P_2)_x \\ (T_2 - T_1)_y & (P_1 - P_2)_y \\ (T_2 - T_1)_z & (P_1 - P_2)_z \end{bmatrix}$$

Then,

$$\begin{bmatrix} u \\ t \end{bmatrix} = A^{-1} \begin{bmatrix} (P_1)_x + (\widehat{N})_x r + (T_1)_x \\ (P_1)_y + (\widehat{N})_y r + (T_1)_y \\ (P_1)_z + (\widehat{N})_z r + (T_1)_z \end{bmatrix}$$

Now the given matrix A is asymmetric. So its inverse will be solved by pseudo-inverse.

$$A^{-1=}(A^t A)^{-1} A$$

Solving this equation gives the contact point P_c and the tool location T_c. If P_c is within the edge, the cutter location is kept, otherwise, it is discarded and the final check is performed.

3 VERTEX CHECK

This check is performed to see if a vertex P_i 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 P_i, it must satisfy the equation:

$$|P_i - [(1-u)T_1 + uT_2]| - r \quad . \tag{3}$$

Solving the above equation for u gives the location of the tool axis as the tool touches the vertex P_i. If there are no real-valued solutions, then the tool will not touch P_i, for any value of u. In general, when the tool can touch P_i, 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_c 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_c are stored in a file to retrieve for the next step.

3.3 TOOL PATH PLANNING FOR ROUGHING

After predicting the tool path, the depth of pass is entered from the user and then the algorithm automatically calculates the number of passes and makes the file for different passes. The finishing cut depth cut allowance is also entered from user to make it convenient for him to select these parameters.

U_{diff} =Difference between maximum and minimum value of U parameter which is between the tool position and workpiece position.

U_{max}=maximum value of U

U_{min}=Minimum value of U

Now as shown in figure, the first pass is greater than the extreme value of workpiece. Now for the second pass, there will be the comparison between the selected U which is calculated for particular depth given by the user ($U_{selected}$) and the value of U which is for the tool path for particular radius of cutterU_{file}. Thus if ($U_{selected} \geq U_{file}$), then keep the value of $U_{selected}$ and move to next position else keep U_{file} and then move to next position. This will be done for all points and then tool is moved forward as according to the depth of cut and then repeat this whole process for that depth also.

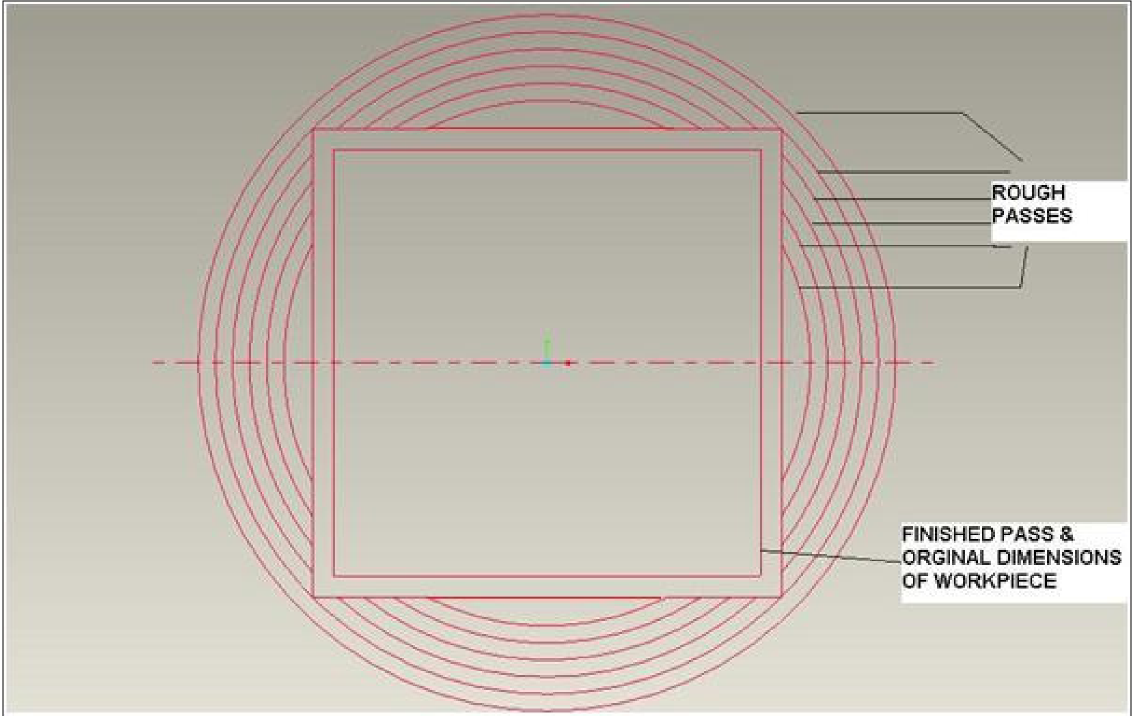

Figure 3.3: Roughing and Finishing Pass Shown

3.4 TOOL PATH PLANNING FOR FINISHING

In the roughing pass, the maximum cut is kept away as the user input the allowance from the actual dimensions of work piece; this distance is kept for roughing pass. As shown in fig. 3.3, the finishing pass is applied up to the actual dimensions of the work piece, thus making the dimensions of the work piece to its actual dimensions.

After applying all of the checks, the tool is rotated in the helical way and then the above given checks are applied again for that position.

3.5 SOLUTION PROCEDUTE

A computer program in Microsoft Visual C++ has been developed for the mathematical procedure defined from sections 3.2 to 3.4 above. The solution procedure for NC tool path generation for 3 axis NC milling lathe has been discussed stepwise below:

1 The STL file is generated in any CAD modeling software.
2 The STL file is attached with the program and then the program is run on the PC.
3 The input STL data for the 3D model of the part is used to extract the required dimensions of the part for the algorithm. Unnecessary facets are removed and others are saved during the program execution.
4 The other inputs which are required during the program are also asked from the used like, depth of cut for roughing pass, finishing allowance. After these inputs, the program starts running.
5 The maximum size of the work piece is calculated to get the stock size.
6 The program runs for the whole of the work piece. It checks the extreme tool position where the value of u is least at every point and after storing that value, it moves to next position.
7 Now the program applies the roughing passes. The number of passes are calculated from the depth of cut given by the user.
8 After applying the roughing passes the tool goes for finishing pass. The allowance for this is given earlier by the user.
9 All Cutter Location (CL) points are saved in auto generated text files with different names for roughing passes and finishing pass.

The flow chart for methodology is shown below:

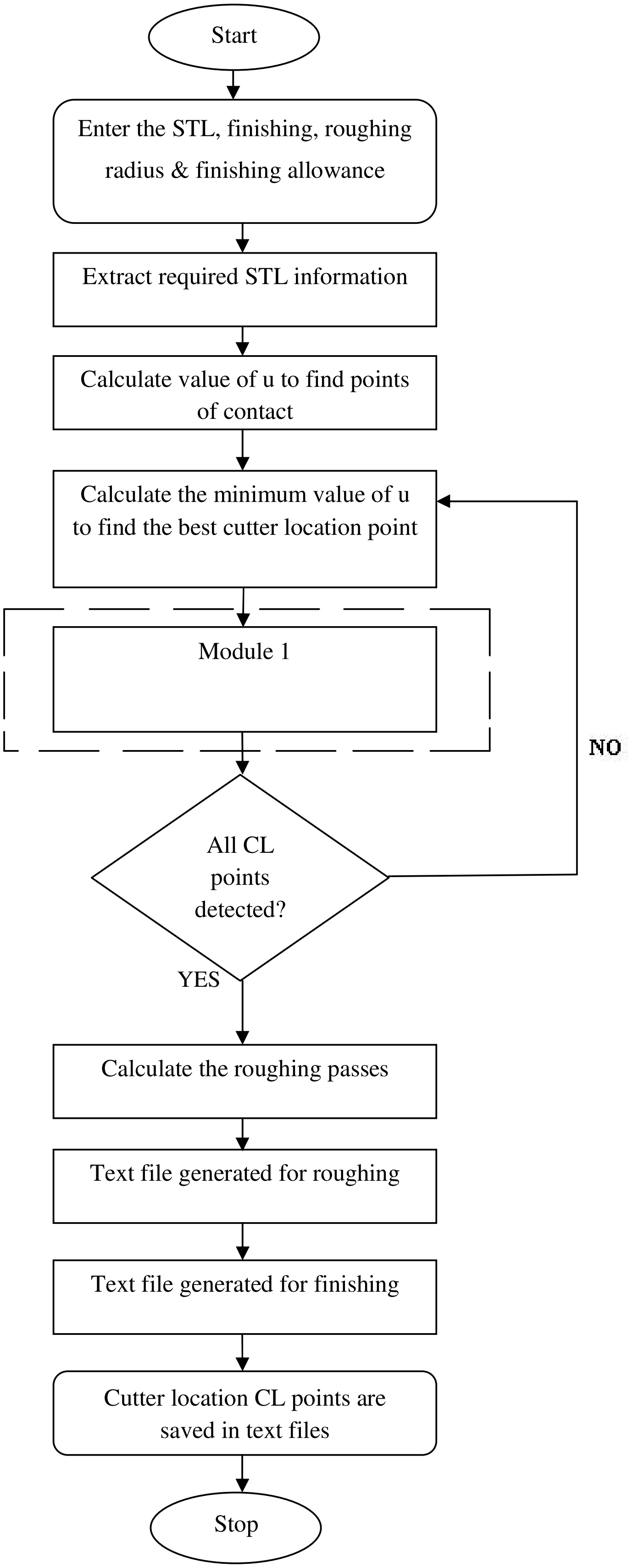

Figure 3.4: Overall flow chart

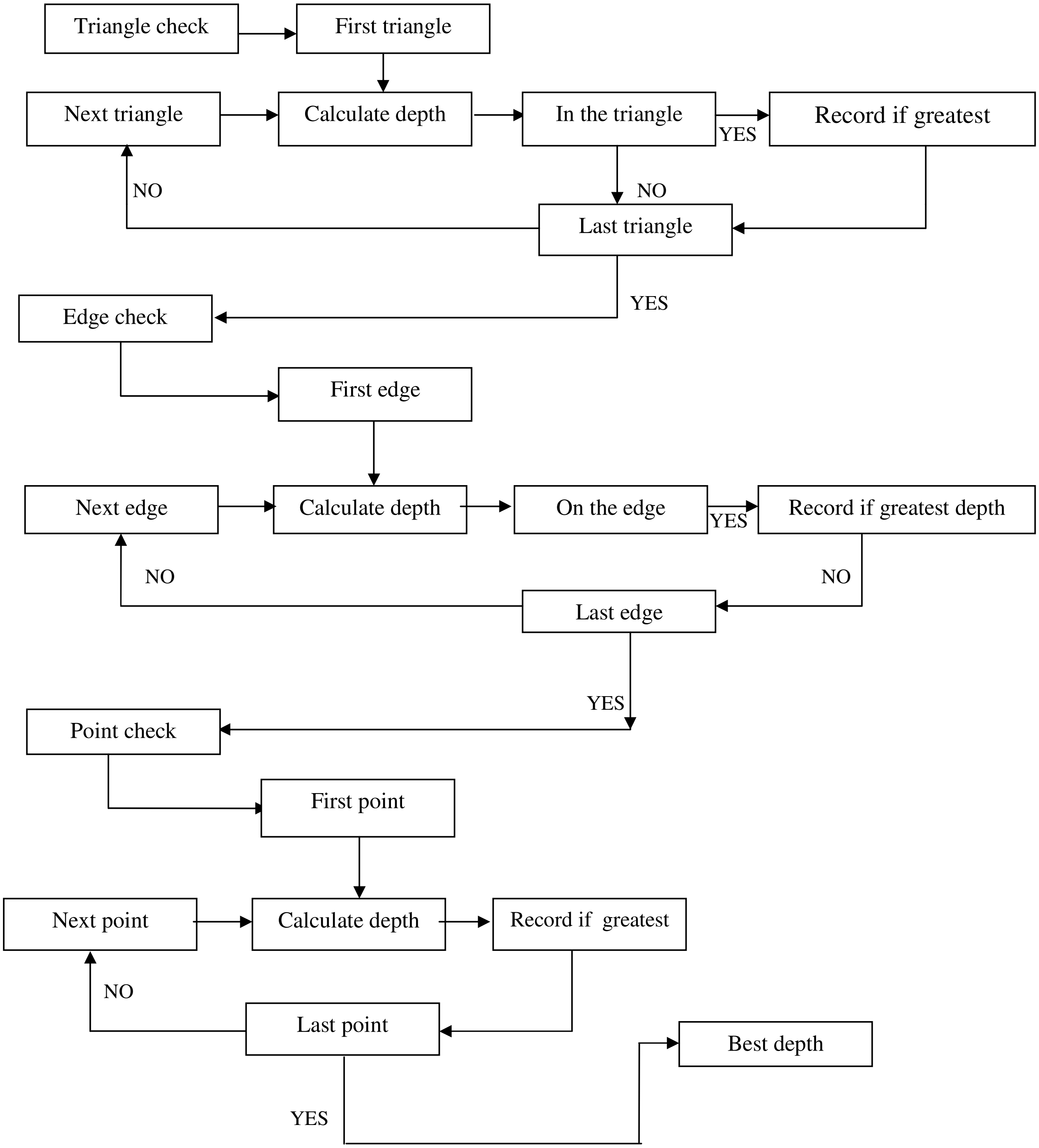

Figure3.5: Module 1

CHAPTER 4

RESULTS AND DISCUSSIONS

The experimentation is done on PBG2048 CNC lathe (figure 4.1). It has the controller resolution of 1/2000 in a single turn and the treaded rod has pitch of 20, which translates the Y 1.27 mm per rotation. The stepper motor has resolution of 2000 steps per revolution, thus making the minimum linear movement of 0.000635 mm. The cutter rotates at 28000 rpm under no load conditions. The machine operates with the PC. Also the cutter only translates along the Y. The work piece rotates along the Z and cutter moves back and fro along X. The software installed is Pewin32PRO2 and PBG_EMC. Pewin32PRO2 software has been for the controller and other one is for simulating the tool path on the PC monitor. Various parts were tested on the machine to validate the tool path generation algorithm. Then the path is compared with the tool path generated by Bedi et.al. [37], which have also generated the tool path for pseudo symmetric surfaces, which can be downloaded from the web site given in reference [15]. The different tool paths for roughing and finishing cycles are made by submitting the STL file on the website.

The common axis configuration for three axis lathe is shown in figure 4.2. The Z axis is responsible for rotating the work piece. The cutting tool moves in two directions; along the length of the work piece with the transverse cutter location axis which is called Y axis and towards and away from the work piece with the X (Fig. 4.2). The all three axes are independently able to move free (figure 4.2). All three axes are clubbed with the different stepper motors and encoder which gives the exact position of the tool and work piece according to the tool path. The tool is rotating and translates along the length of work piece and work piece is rotating about its own axis. The maximum length of the work piece to be made is 400mm in length. Also the feed rate can be adjusted from 5rev/min to 20rev/min. The machine is connected to the PC which controls the machine.

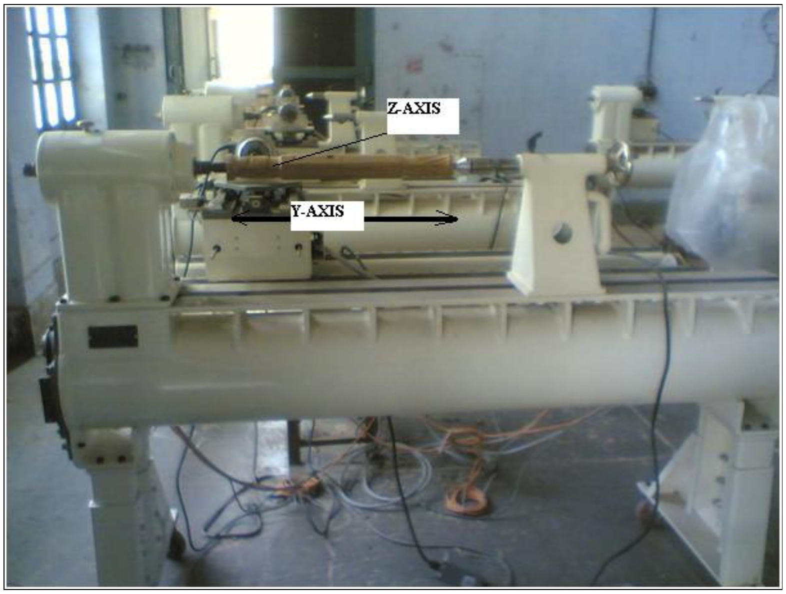

Figure 4.1: PBG2048 CNC Lathe

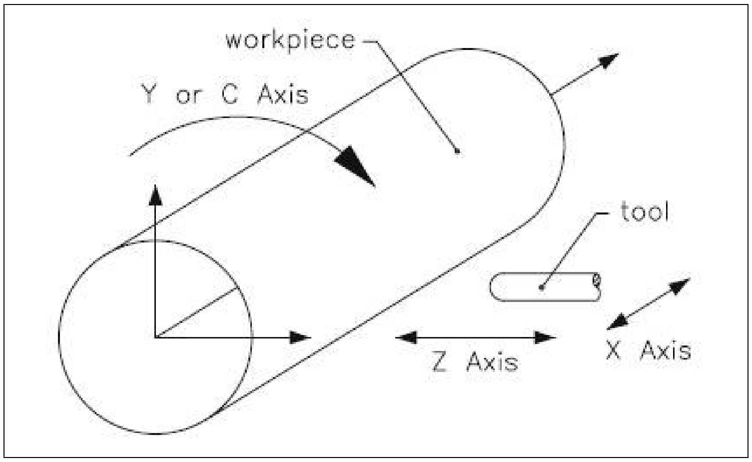

Figure 4.2: Common axis configuration for 3-axis lathe[37]

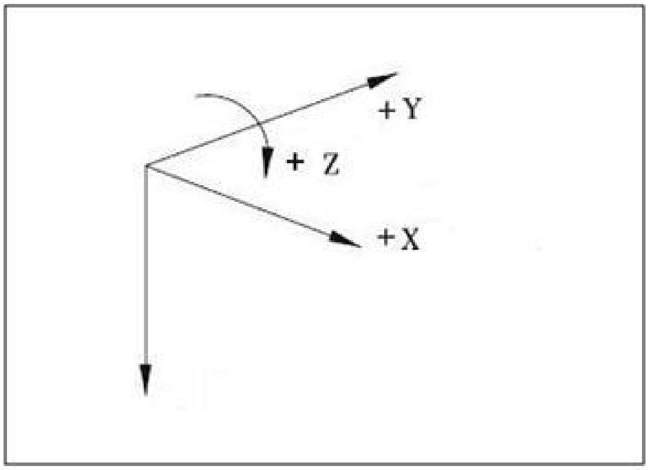

Figure 4.3: Coordinate System [37]

4.1 TOOLING USED

The tool used in the algorithm is ball nose end mill cutter. The two radiuses of the tool are used, but their radius can be modified and the algorithm works for any tool radius. In the algorithm, the tool is moving in helical way.

Then all checks are being applied hare and then thee tool moves to the next position in helical path. It keeps on rotating and finding the suitable points until the length of work piece.

4.2 VALIDATION OF TOOL PATH

The tool path is validated by machining the different work pieces, which are described below:

4.2.1 VALIDATION OF SQUARE PRISM

The tool path is compared with the tool path generated by the University of Waterloo, which is available online and can be downloaded from the website given in the reference [15]. The accuracy of computer algorithm developed for tool pat generation for 3-axis milling lathe has been validated by plotting the 3-D contours of the corresponding Cartesian coordinates of the respective tool location (CL) points in 3-D space which shows the algorithm developed above is accurate in generation of actual cutter location points. This has been demonstrated for a square prism has been shown in graph plotted below.

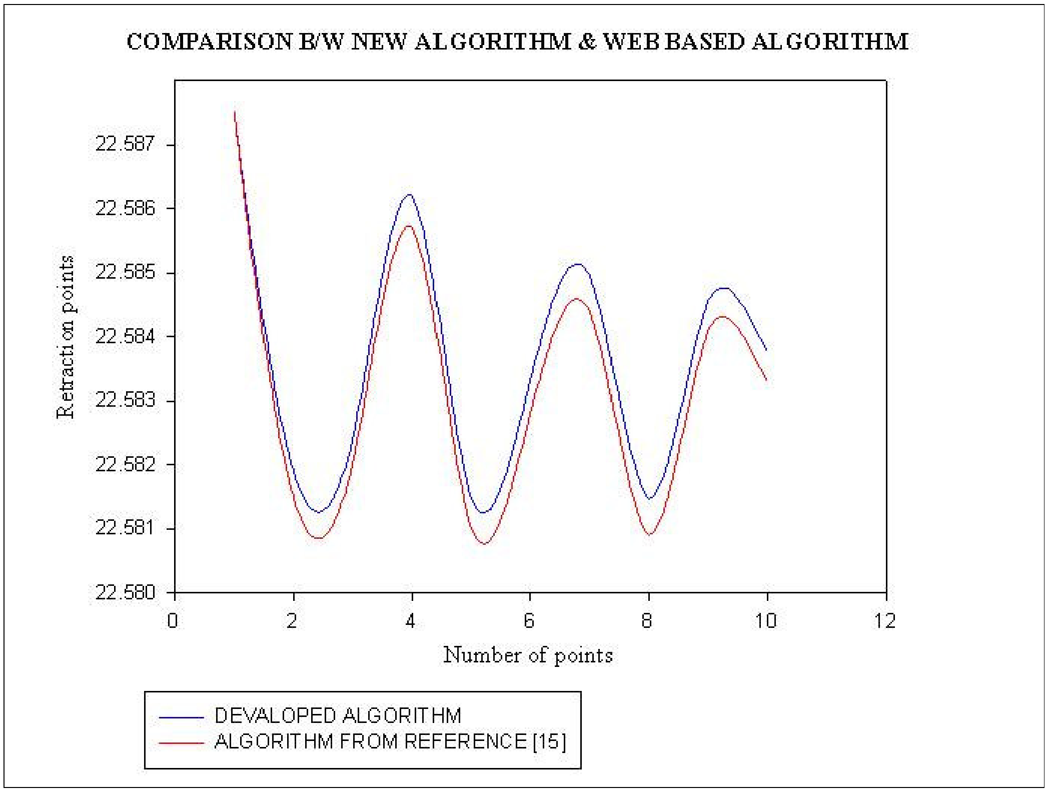

Figure 4.4: Linear graph plotted between the points taken from the web and the newly generated algorithm for a square prism of side 50mm

The total of 20 points is plotted for the work piece. It has been seen that the maximum error between the two values is .0752%, in the complete one rotation which is negligible. The radius of the tool used is 6.35mm.

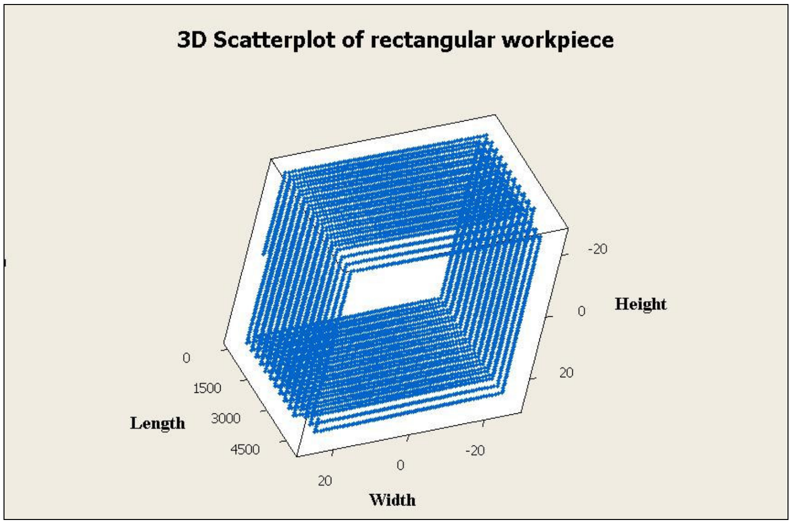

Figure 4.5: Cutter contact and cutter location points for square prism

Above figure shows the cutter contact and cutter location points of square prism of 45mm side. The test has been done on the wooden part of dimensions 45*45*40. Side feed has kept 0.0011025mm and there were 3620 points per rotation. From the test, the part was made successfully with accurate dimensions. The CAD model for square made is shown in figure 4.6.

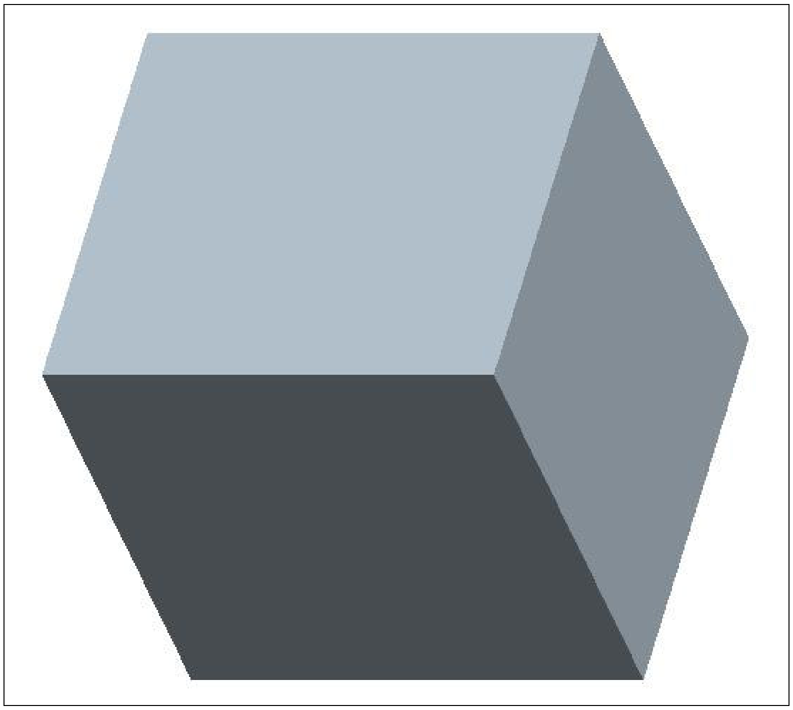

Figure 4.6: CAD model for square prism

4.2.2 VALIDATION OF CYLINDER

The cylinder of diameter 40mm and length 25mm is machined on the PBG CNC wood working lathe mill. The STL is made first on CAD modeller. It has been seen that the error between STL file and the actual diameter of the cylinder is 0.000120757%. The tool path made is compared with web based algorithm mentioned above and graph is also plotted between these two and then the comparison is made with the original dimensions also.

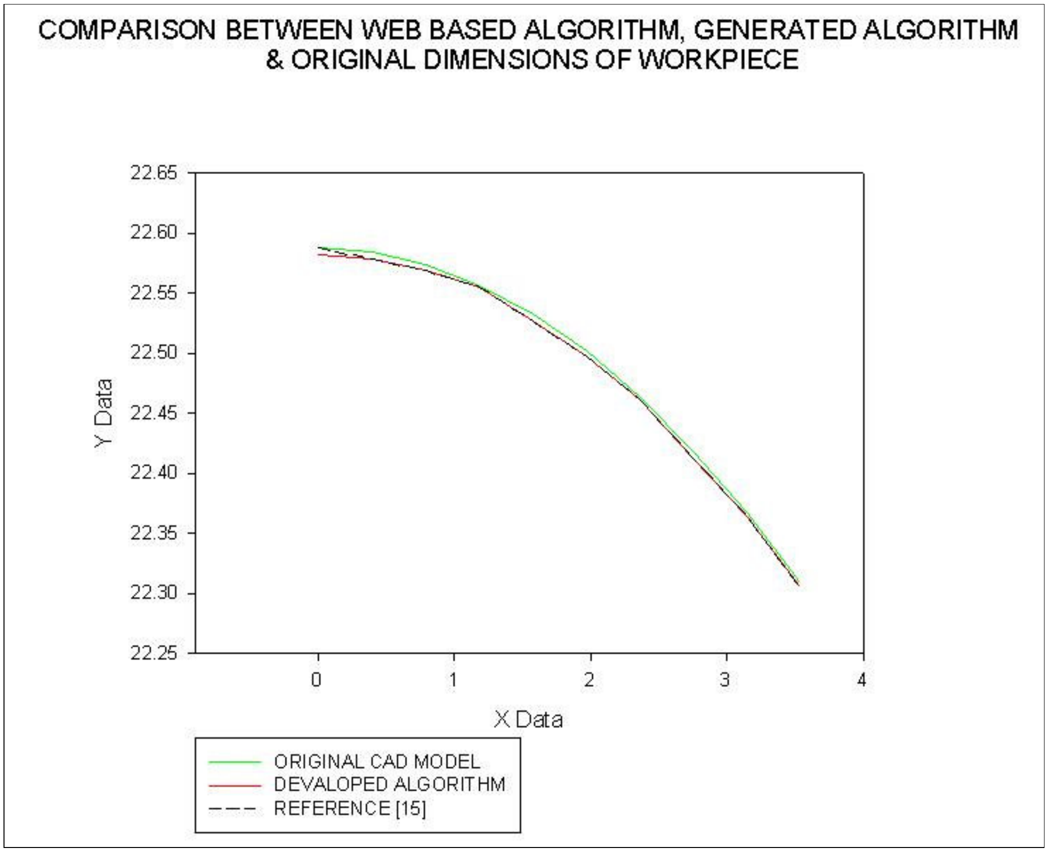

Figure 4.7: Comparison of the cutter location points (CL) of original part, web based CL points and points from newly generated tool path

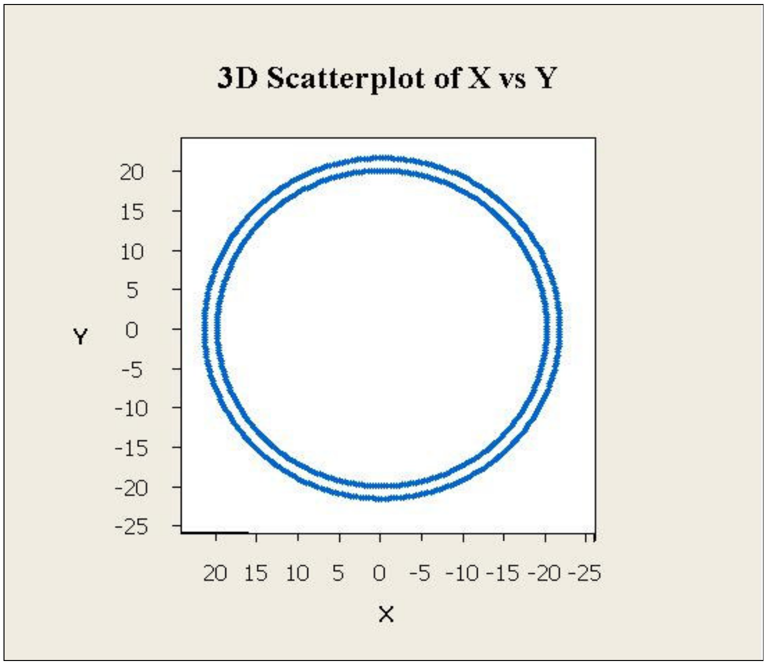

Figure 4.8: 2-D plots for Cutter contact (CC) and Cutter location (CL) points of cylinder with 40mm diameter

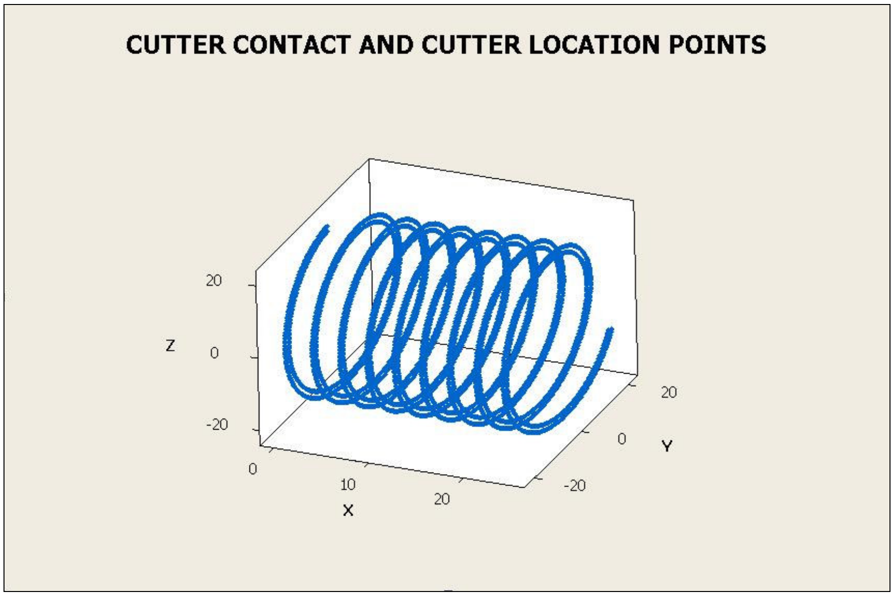

Figure 4.9: 3 D plot of tool path for CL and CC path of cylinder of diameter 20 mm

The maximum error between the web generated tool path and newly generated tool path is 0.007058%, which may be neglected. The tool used is of radius is 1.5875mm. Also the cutter contact and cutter location points are also shown in figure given above.

The comparison has been done between original dimensions of work piece and the dimension which comes with the help of algorithm with radius 0. As shown from the figure given above, the two exactly matches. The %age error between these two is also checked. It has been seen that the maximum %age error between the original dimensions of work piece and the dimensions by algorithm is 0.003398%.

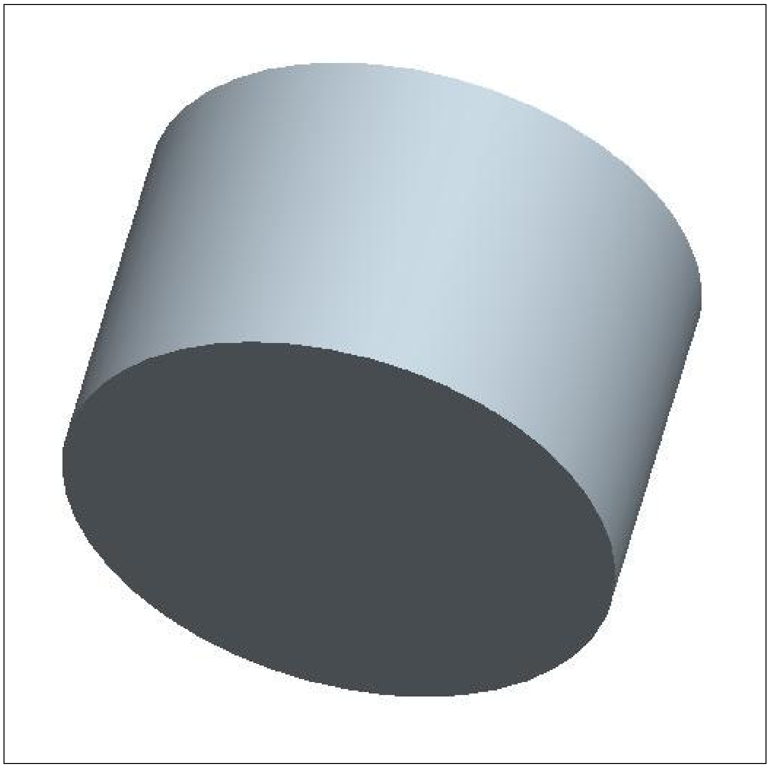

Figure 4.10: CAD model for cylinder with dia. 40mm and length 25mm

The cylinder is machined on the PBG lathe mill and the dimensions comes out is compared with the dimensions of CAD model and the machined is within the tolerances.

4.3 EXPERIMENTAL VERIFICATION

1 SQUARE PRISM

The square prism with side 45mm has been machined. The side feed for the roughing pass has kept 0.008mm and the depth of cut was kept such that the number of passes generated by the algorithm are 2 two. The side feed for roughing pass has kept such that the fast machining of part should be there. Finishing allowance given is 2mm and side feed for finishing pass is 0.002mm. The machined part has been shown in figure 4.11.

Figure 4.11: Square prism with roughing and finishing passes shown

2 Cylinder: Other work piece machined is cylinder with diameter of 45mm. Two tools used are of diameter 1.5875mm and 6.35mm. Also, the side feed for roughing and finishing passes and allowance for finishing passes kept same as of square prism. The number of facets in STL file is kept large to decrease the error generated during the STL file. Machined cylindrical part is shown below:

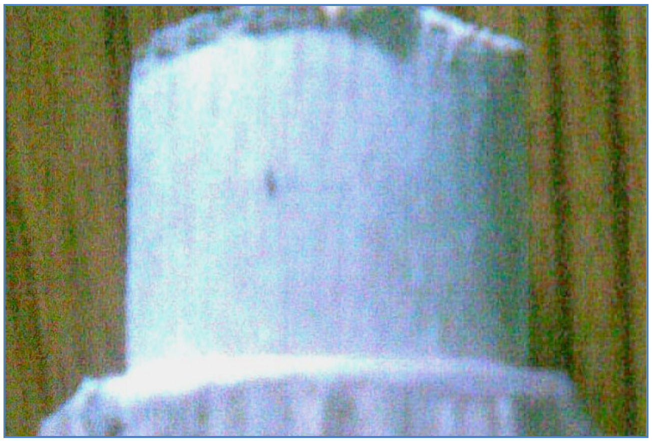

Figure 4.12: Machined cylindrical work piece with 40 mm diameter

3 Twisted prism: The roughing and finishing passes of twisted prism are shown in figure 4.13. The triangular facets can be clearly seen in the rough pass.

Figure 4.13: (a) Twisted prism with rough pass and (b) Twisted prism with finished pass

4 Extruded design: The extrusion is machined on the cylindrical base with the dimension of 1mm per extrusion as shown in Fig. 4.14(a) and 4.14(b). This extrusion is made on SolidWorks^{TM} software with parametric designing.

Figure 4.14: (a) Extruded portion on the cylindrical base (b) Sweep pattern

5 Simple sweep: The other part made was the sweep portion. Now instead of extruding the portions the portions were made sweep along the lines. It has been seen that the algorithm was able to machine the small rounds around the piece also.

CHAPTER 5

CONCLUSION AND SCOPE FOR FURTHER STUDY

In this paper, the tool path generation for 3-axis lathe mill has been developed. Microsoft Visual C++ 2008 is used for programming the algorithm. Various checks have been applied to trace the point of contact of cutter with work piece. Ball nose end mill cutter with any radius of roughing and finishing passes can be used, but for now, tool of radius 6.35 mm has been used for roughing and 1.5875mm for finishing cycles. Tool and work piece moves in such a way that makes the helical tool path for machining. The accuracy of work piece depends upon the STL triangles, radius of tool for finishing and side feed for finishing pass.

Comparing the present tool path with the tool path generated in reference [15], it has been seen that other than the present tool path algorithm can give closest results with the ref [15], the side feed, depth of cut and radius of roughing and finishing passes can also be modified which cannot be done in ref [15]. The present results also give the closest results with the original geometry of work piece.

It has been seen that though the tool path generation algorithm is suitable for the sculptured surfaces and is able to generate the intricate surfaces, machining of work piece greatly depends upon size of triangles created in STL file. Also, the finishing of work pieces take long time as the tool which has been used presently is ball nose end mill cutter, which touches the work piece only at a single point during machining, thus the scallops are formed.

SCOPE FOR FURTHER STUDY

- The tool path can be modified for the various other formats like IGES format [3], STEP format [4] etc. Some work has already been done in this field [10]. The first step of generating the tool path is to convert the CAD model into STL format. During the discretization, significant error comes in the STL file. That error which comes out by converting the CAD model to STL file may be considered for future work.

- The present work can be extended to various tools or a generalized tool from the present ball nose end mill cutter.
- Also the dynamic errors which are not being considered now can be incorporated.
- Yau[36] et.al. has made a generalized tool cutter which may be incorporated, with the help of which the tool path can be generated for various tools, thus giving user the flexibility of changing the tools according to the geometry of the tool to save the time.
- Alike the generalized tool, the different types of contouring can also be considered for different parts to decrease the machining time.

REFERENCES

[1] P.J. Gray, S. Bedi, and S. Mann, “A new paradigm for numerically controlled machines”, Virtual Concept, Biarritz, France, 2003, pp. 128-134.

[2] H. T. Yau, C. M. Chuang, and Y C Lee, “Numerical control machining of triangulated sculptured surfaces in a stereo lithography format with a generalized cutter”, International Journal of Production Research, vol. 42, no. 13, , 2004 pp. 2573–98.

[3] US Product Data Association, “Initial Graphics Exchange Specification”, IGES 5.3, (Charleston, SC: US PDA), 1996.

[4] M. Liang, S. Ahamad and B. Van Den Berg, “A STEP based tool path generation system for rough machining of planar surfaces”, Computers in Industry, vol. 32, 1996, pp. 219-231.

[5] P. F. Jacobs, and D. T. Reid, ”Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography”, McGraw-Hill, New York, 1992.

[6] C. M. Chuang, C. Y Chen, and H. T. Yau, “A reverse engineering approach to generating interference-free tool paths in three-axis machining from scanned data of physical models”, International Journal of Advances in Manufacturing Technology, vol. 19, pp. 23-31 2002.

[7] H. T. Yau, C. M. Chuang, and Y C Lee, “Numerical control machining of triangulated sculptured surfaces in a stereo lithography format with a generalized cutter”, International Journal of Production Research, vol. 42, no. 13, pp. 2573–98, 2004.

[8] T. Kishinami, T. Kondo and K. Saito, “Inverse offset method for cutter path generation”, Proceedings of the 6th International Conference of Production Engineering, Osaka, Japan, 1987, pp. 807–812.

[9] K. Tang, C. C. Cheng, and Y. Dayan, “Offsetting surface boundaries and 3-axis gouge-free surface machining”, Computer-Aided Design, vol. 27, pp. 915–92, 1995.

[10] B. K. Choi, D. H. Kim and R. B. Jerard, “C-space approach to tool-path generation for die and mold machining”, Computer-Aided Design, vol. 29, pp. 657–669, 1997.

[11] E. Lee, “Contour offset approach to helical tool path generation with constant scallop height”, Journal of Computer-Aided Design, Elsevier, vol. 35, pp. 511–518, 2003.

[12] B. K. Choi, and R. B. Jerard, “Sculptured Surface Machining”, Dordrecht: Kluwer, 1998.

[13] C. M. Chuang, C. Y Chen, and H. T. Yau, “A reverse engineering approach to generating interference-free tool paths in three-axis machining from scanned data of physical models”, International Journal of Advances in Manufacturing Technology, vol. 19, pp. 23-31 2002.

[14] H. T. Yau, C. M. Chuang, and Y C Lee, “Numerical control machining of triangulated sculptured surfaces in a stereo lithography format with a generalized cutter”, International Journal of Production Research, vol. 42, no. 13, pp. 2573–98, 2004.

[15] University of Waterloo Web link to download tool path: http://visor.uwaterloo.ca/~krmoule/webcad/ .

[16] Y. Huang and J.H. Oliver, "Non-constant Parameter NC Tool Path Generation on Sculptured Surfaces", ASME Computer in Engineering, Vol. 1,1992, pp 411-419.

[17] B. K. Choi, C. S. Lee, J. S. Hwang and C. S. Jun, “Compound surface modeling and machining”, Computer-Aided Design, vol. 20, 1988, pp. 126–136.

[18] B. K. Choi, “Surface Modeling and Machining”, Advances in Industrial Engineering, Elsevier, New York, vol. 11, 1991.

[19] T. Saito and T. Takahashi, “NC machining with G-buffer method”, Journal of Computer Graphics, vol. 25, 1991, pp. 207–216.

[20] A. C. Lin and H. T. Liu, “Automatic generation of NC cutter path from massive data points”, Computer-Aided Design, vol. 30, 1998, pp. 77–90.

[21] D. Dragomatz and S. Mann, “A Classified Bibliography of Literature on NC Tool Path Generation”, Journal of Computer-Aided Design, vol. 27, pp. 239–247 March 1997.

[22] D. Roth, S. Bedi, and F. Ismail, “Surface Swept by a Toroidal Cutter during 5-Axis Machining of Curved Surfaces”, Computer-Aided Design, vol. 33, no. 1, 2001 pp. 57-63.

[23] T. Altan, B. W. Lilly, J. P. Kruth, W. K6nig, H. K. T6nshoff, C. A. van Luttervelt and A. B. Khairy, "Advanced techniques for die and mold manufacturing", Annals of the CIRP, 42(2), 1993,pp 707-715.

[24] G. W. Vickers, S. Bedi and R. Haw, "The definition and manufacture of compound curvature surfaces using G-surf", Computers in Industry, 6(3) , 1985, pp 173-183.

[25] G. W. Vickers and K. Quan, "Ball-mills versus end-mills for curved surface machining", ASME Journal of Engineering for Industry, (22), February 1989,pp 111.

[26] Catania, G ‘A computer-aided prototype system for NC rough milling of free-form shaped mechanical part-pieces’ Comput. in Indust. Vol 20 No 2 (October 1992) pp 275–93.

[27] C. G. Jensen, S. H. Mullins and D. C. Anderson, "Scallop elimination based on precise 5-axis tool placement, orientation and step-over calculations", ASME Advances in Design Automation, DE 65(2) , 1993, pp 535-544.

[28] .Bedi, S. Gravelle and Y. H. Chen, "Principle curvature K alignment technique for machining complex surfaces", ASME Journal of Engineering for Industry, 2001.

[29] N. Rao, S. Bedi and R. Buchal"Implementation of the Principal-Axis Method for Machining of Complex Surfaces",Int J Adv Manuf Technol (1996) 11, pp249-257.

[30] J.E Kruth, and Klewais, E,” Optimization and dynamic adaptation of cutter inclination during five-axis milling of sculptured surfaces”, Annals of the CIRP 43, 1994,pp 443-448.

[31] A Warkentin, Ismail F, Bedi S (2000)” Multi-point tool positioning strategy for 5-axis machining of sculptured surfaces.” Comput Aided Geom Des 17(1),pp 83–100.

[32] Y. Hosseinkhani, J. Akbari, A. Vafaeesefat” Penetration–elimination method for five-axis CNC machining of sculptured surfaces”, International Journal of Machine Tools & Manufacture vol. 47 (2007),pp 1625–1635.

[33] N. Rao, S. Bedi and R. Buchal"Implementation of the Principal-Axis Method for Machining of Complex Surfaces",Int J Adv Manuf Technol (1996) 11, pp249-257.

[34] Bedi et al. “Implementation of the Principal-Axis Method for Machining of Complex Surfaces” 1996, pp 1-2.

[35] P. Gray, S. Bedi, F. Ismail, “Arc-intersect method for 5-axis tool positioning”, Computer-Aided Design 37 (2005).

[36] H.T.Yau, C.M. Chaung, Y.S. Lee,” 2004)'Numerical control machining of triangulated sculptured surfaces in a stereo lithography format with a generalized cutter”International Journal of Production Research(2004) 42:13,pp2573 – 2598.

[37] Nick P. Manos, Sanjeev Bedi, Dan Miller and Stephen Mann, “Single Controlled Axis Lathe Mill”, International Journal of Advanced Manufacturing Technology, vol. 32, pp. 55-65, August 11, 2005

[38] Y.J. Chen, B. Ravani,” Offset Surface Generation and Contouring in Computer-Aided Design”, ASME, Journal of Mechanisms, Transmissions & Automation in Design, Vol. 109, March 1987, pp132-142.

[39] J.E. Bobrow, “NC machine tool path generation from CSG part representations”, Computer Aided Design, Vol. 17, No. 2, 1985, pp 69-76

[40] P. Broomhead, M. Edkins, “Generation NC data at the machine tool for the manufacture of free-form surfaces”, International Journal of Production Research, Vol. 24, No. 1, 1986, pp 1-14

[41] P.J. Gray, G. Poon, G. Israeli, S. Bedi, S. Mann, D. Miller, “Model to Part: A map for the CNC machine of the future,” 7th International Conf. on Adv. Manuf. Systems and Technology, Udine, Italy, 2005.