

**A**  
**THESIS REPORT**  
**REAL TIME GRAPHICAL DISPLAY AND ERROR**  
**REPORTING OF FEEDBACK ON A 3-AXIS LATHE**  
**MILL**

**Submitted in partial fulfilment of the requirement for the award of degree of**

**MASTER OF ENGINEERING**  
**IN**  
**CAD/CAM & ROBOTICS**

**Submitted by**

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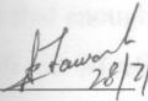
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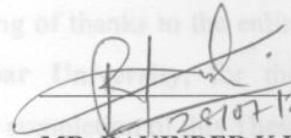
## ACKNOWLEDGEMENT

This is to certify that the Thesis titled, “**REAL TIME GRAPHICAL DISPLAY AND ERROR REPORTING OF FEEDBACK ON A 3-AXIS LATHE MILL**” being submitted by **Mr. PUNEET SHARMA**, in partial fulfilment of the requirements for the award of degree of MASTER OF ENGINEERING in CAD CAM & ROBOTICS 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 seminar has been submitted before for the award of any degree.

  
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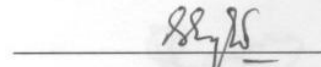


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# CHAPTER-1

## INTRODUCTION

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At the present time, there is a great need for identification and elimination of all sources of error in machine tools. A significant amount of work, over recent years, has been done into this area. As a result, modern day machine tools are able to achieve accuracies in the range of 0.005 mm due to improved design techniques and advanced materials technology.

The major types of error are geometric, thermal and cutting-force induced errors. Geometric errors make up the major part of the inaccuracy of a machine tool, the error caused by cutting forces depends on the type of tool and workpiece and the cutting conditions adopted.

The problem of erroneous movement, however, is very difficult to eliminate completely by any amount of improvement in this area. No matter how well a machine is designed, there is a limit to the accuracy that is actually achieved. Errors like thermal deformation, cutting force induced deformation etc., cannot be completely removed by the design. The use of materials such as ceramics and concrete for producing machine tool beds is quickly gaining popularity amongst machine tool building companies, but these methods are still incapable of taking into account the changes that take place in the shop floor environment on a day to day basis. Moreover, the manufacturing costs involved in such an effort are also considerably large.

One option that is gaining notable success nowadays for easy implementation and cost-reduction is the technique of error compensation. This technique enables one to manufacture more accurate machine tools as well as produce high precision components even when using a relatively less accurate machine tool. With the help of this technique, traditional barriers on accuracy of machine tools are being overcome. This system monitors the condition of the machine continuously and any error that may be generated is compensated for accordingly.

The basic philosophy behind this concept is that it is very difficult to construct a perfect machine tool because despite thorough design, the accuracy of the machine changes when subjected to thermal loads and excessive cutting forces. So, errors cannot be avoided but can be predicted efficiently so that there is an effective machining.

Apart from this we are in an urgent need of a system which is flexible and easy to understand not only by a professional but also by the laymen who is working on the machine. Larger production houses heavily rely on CNC operators for better production and a quick error correction which in some cases is not achieved due to improper error assessment or negligence by the operators. Error assessment and understanding of the error which is generated by the machine is very important.

Errors can be classified into two categories namely

1. Quasi-static errors
2. Dynamic errors

Quasi-static errors are those between the tool and the workpiece that are slowly varying with time and related to the structure of the machine tool itself. These sources include the geometric/kinematic errors, errors due to dead weight of the machine's components and those due to thermally induced strains in the machine tool structure.

Dynamic errors on the other hand are caused by sources such as spindle error motion, vibrations of the machine structure, controller errors etc. These are more dependent on the particular operating conditions of the machine. Quasi-static errors account for about 70 percent of the total error of the machine tool and as such, are a major focus of error compensation research.

Error prediction and its assessment carry a great influence and potential in terms of the research carried out in the field of machining. There is a great need of a system which is easy to understand, easy to predict and use. We need to shift to a system more user friendly such as a **graphical system or Computer assisted simulation** for error prediction can be an effective alternative which can show a machining process but also compare the machined geometry with the original CAD geometry so that errors can be classified and corrected in real time during actual machining. A computer assisted simulation system can prove to be a grate aid to the machining process and error assessment and its correction.

## CHAPTER-2

### LITRATURE SURVEY

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The literature survey has been conducted to focus on the following areas.

#### 2.1 ERRORS IN CNC

##### 2.1.1 GEOMETRIC ERRORS

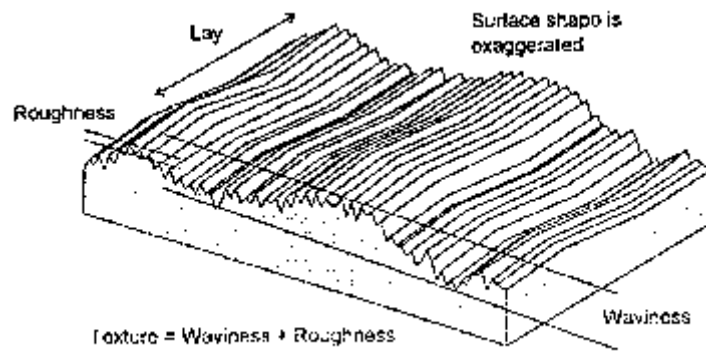
Geometric errors are those errors that are extant in a machine on account of its basic design, the inaccuracies built-in during assembly and as a result of the components used on the machine. As such, they form one of the biggest sources of inaccuracy. These errors are concerned with the quasi-static accuracy of surfaces moving relative to one another. Geometric errors can be smooth and continuous or they could exhibit hysteresis or random behavior.

These errors are affected by factors like surface straightness, surface roughness, bearing pre-loads etc. Geometric errors have various components like linear displacement error (positioning accuracy), straightness and flatness of movement of the axis, spindle inclination angle, squareness error, backlash error etc.

Kinematic errors are concerned with the relative motion errors of several moving machine components that need to move in accordance with precise functional requirements.

These errors are particularly significant during the combined motion of different axes as in the case of gear hobbing or profile machining where co-ordination of rotary with respect to linear axes or linear with respect to linear axes is of prime importance. Such errors occur during the execution of linear, circular or other types of interpolation algorithms and are more pronounced during actual machining.

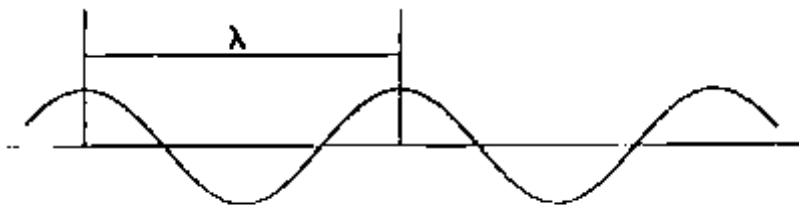
The three form of this error are given below in [Figure 2.1.1.1] [Figure 2.1.1.2][Figure 2.1.1.3]



**Figure 2.1.1.1 WAVINESS**



**Figure 2.1.1.2 SURFACE ROUGHNESS**



**Figure 2.1.1.3 FLATNESS**

The Previous work done is listed below

**M. Sharif Uddin, Soichi Ibaraki, Atsushi Matsubara and Tetsuya Matsushita [1]** Kinematic errors due to geometric inaccuracies in five-axis machining centers cause deviations in tool positions and orientation from commanded values, which consequently affect geometric accuracy of the machined surface. Using an error model of the machining center with identified kinematic errors and considering location and geometry of the workpiece, machining geometric error with respect to the nominal geometry of the workpiece is predicted and evaluated. In an aim to improve geometric accuracy of the machined surface

**Minyang Yang and Jaejong Lee [2]** this paper proposes a method of measuring the geometric and thermal errors that occur with a temperature change of a CNC machining center by means of on-machine measurement using two spherical balls and a touch probe unit. A neural-network model is used to predict the thermal errors of machine tools whilst machining workpiece.

**Ramesh, M.A. Mannan and A.N. Poo [3]** The dynamic response of a machine tool is a complex interaction of several factors that includes the basic design of the machine as well as the capability and performance of the corresponding axis servo system. In terms of the performance of the servo system, tracking and contour errors are two important aspects that significantly affect the machine tool.

**Jingxia Yuan and Jun Ni [4]** one of the important trends in precision machining is the development of real-time error compensation technique. The technique has been applied to more than 10 different kinds of machines including: turning centers and machining centers; small, medium and large machines; new products and retrofitted machines. The accuracy improvement is in the range of 3–10 times. The error sources being compensated for include machine geometric and thermal errors, cutting force-induced errors, and workpiece thermal errors.

**Durmus Karayel [5]** In this study, a neural network approach is presented for the prediction and control of surface roughness in a computer numerically controlled (CNC) lathe. Experiments have been performed on the CNC lathe to obtain the data used for the training and testing of a neural network. The parameters used in the experiment were reduced to three cutting parameters which consisted of depth of cutting, cutting speed, and feed rate.

\P. G. Benardos and G. -C. Vosniakos [6] the general manufacturing problem can be described as the achievement of a predefined product quality with given equipment, cost and time constraints. Unfortunately, for some quality characteristics of a product such as surface roughness it is hard to ensure that these requirements will be met. The resulting benefits allow for the manufacturing process to become more productive and competitive and at the same time to reduce any re-processing of the machined workpiece so as to satisfy the technical specifications.

### 2.1.2 VOLUMETRIC ERRORS

Volumetric errors/accuracy represents the overall errors/accuracy of the machine too. Therefore, it has become one of the important indices to represent the quality of such machines. For a 3-axis machine, there are 6 errors per axis or a total of 18 errors plus 3 squareness errors. These 21 rigid body errors can be expressed as the following.

Linear displacement errors:  $D_x(x)$  ,  $D_y(y)$  ,  $D_z(z)$

Vertical straightness errors:  $D_y(x)$  ,  $D_x(y)$  ,  $D_x(z)$

Horizontal straightness errors:  $D_z(x)$  ,  $D_z(y)$  ,  $D_y(z)$

Roll angular errors:  $A_x(x)$  ,  $A_y(y)$  ,  $A_z(z)$

Pitch angular errors:  $A_y(x)$  ,  $A_x(y)$  ,  $A_x(z)$

where, D is the linear error, subscript is the error direction and the position coordinate is inside the parenthesis, A is the angular error, subscript is the axis of rotation and the position coordinate is inside the parenthesis.

The Previous work done is listed below

**Kyoung Gee Ahn' and Dong Woo Cho [7]** a automatic sampling technique for fast checking of volumetric errors of CNC machine tools. With the proposed automatic sampling technique, the verification work is carried out automatically and reliably. Furthermore, the analyzed result

obtained via the traditional least-squares method is not the minimum zone solution, and may overestimate the volumetric error. Thus, genetic algorithms (GAs) are employed to obtain the minimum zone solution in this paper. Experimental test results show that the proposed method is superior to the least-squares method.

**Ji-Hun Jung, Jin-Phil Choi and Sang-Jo Lee [8]** this paper uses a parameterized error model to analyze machine tool errors within the workspace and the methodology of on-machine measurement for improving the machining accuracy. Based on the rigid body kinematics, positioning errors derived using the homogeneous transformation matrices are parameterized by approximating error components with polynomial functions. Only fourteen measurement points are required to determine the model parameters and obtained from four diagonal measurements.

### **2.1.3 THERMAL ERRORS**

Another principal cause for inaccurate work pieces is error due to improper tool positioning on account of thermal deformation. It is well understood that errors due to thermal factors account for 40–70% of the total dimensional and shape errors of a work piece in precision engineering. Six sources of thermal influence are identified:

- (i) Heat from the cutting process.
- (ii) Heat generated during machining
- (iii) Temperature corrosion.
- (iv) Heat generated in motor of machine
- (v) Thermal errors due to machined component
- (vi)

Critical among these sources is heat generated by the machine. Continuous running of the machine causes heat to be generated at the moving elements as a result of frictional resistance, at the motors, in pumps etc . This heat causes relative expansion of the various elements of the machine tool leading to inaccurate positioning of the cutting tool tip.

Consequently errors due to spindle growth, thermal expansion of the ball screws and thermal distortion of the column are generated at the tool tip. As heat generation at contact points is unavoidable, this source of error is one of the most difficult to eliminate completely. In the

manufacture of precision components error due to thermal deformation of the machine elements plays a vital role in limiting the accuracy of the part produced. Comprehensive analysis of one source of thermal error in CNC turning lathes was done which shows how to improve the working accuracy of the lathe by predicting and compensating the thermal expansion of the tool and tool holder during machining. The amount of thermal expansion could be accurately calculated by a predictive equation, in which the amount of heat generation is represented as a function of the cutting conditions.

**Minyang Yang and Jaejong Lee [9]** This paper proposes a method of measuring the geometric and thermal errors that occur with a temperature change of a CNC machining center by means of on-machine measurement using two spherical balls and a touch probe unit. A neural-network model is used to predict the thermal errors of machine tools whilst machining workpiece.

**Yiding Wang, Guoxiong Zhang, Kee S. Moon and John W. Sutherland [10]** This paper presents a systematic methodology for the thermal-error correction of a machine tool. The generalized geometric error model of a multi-axis machine is derived to describe the error motion between the cutting tool and the workpiece using the homogeneous transformation matrix. The thermal deformation is modeled using grey system theory so that a dynamic model can be obtained. An off-line method and an on-line method are proposed to use the grey system model to predict and compensate for the thermal error. This method can significantly reduce the number of sensors used in temperature monitoring during the compensation process.

#### **2.1.4 CUTTING FORCE INDUCED ERRORS**

The dynamic stiffness of the components of the machine tool (namely the bed, column etc. that are within the force–flux flow of the machine is responsible for errors caused as a result of the cutting action . This is one of the major sources of error in metal-cutting machines as the force involved in the cutting action is considerable. As a result of the forces, the position of the tool tip with respect to the work piece varies on account of the distortion of the various elements of the machine. Depending on the stiffness of the structure under the particular cutting conditions, the accuracy of the machine tool would vary. Thus, for a machine with a given stiffness a heavy cut would generally produce more inaccurate components than a light cut.

Previous work has been listed below

**S. Hinduja, D. Mladenov and M. Burdekin [11]** this paper describes a procedure to evaluate the force-induced errors occurring in cylindrical turned components. This procedure is based on a model which represents the real-time stiffness of the spindle-bearing system and the rotational clamping stiffness of the component held in a chuck. The stiffness values are determined from a single cutting test in which the deflection of a test bar is measured. The model also takes into account the stiffness of the component and toolpost. The model is validated by comparing the predicted error in the cylindricity of a machined bar with the measured value.

**S. Yang, J. Yuan and J. NI [12]** A real-time error compensation system has been developed to reduce the cutting force induced planar error of a two-axis turning center by using sensing, metrology, modeling, and computer control techniques. Ten error components are formulated as a two-dimensional error field. A piezoelectric force sensor mounted in the pocket under the tool turret is used to characterize the cutting forces. A compensation controller based on an IBM/PC has been linked with the existing computer numerical controller (CNC) to correct machine errors in real time. Three different types of cutting tests were performed and the results showed that the maximum diameter error in the workpiece was reduced by 67–85% using this compensation system.

**Eyüp Sabri Topa and Can Çoğun [13]** the aim of this study is to compensate the cutting force induced dimensional workpiece errors in CNC turning operations. In realizing this, a strain gauge based cutting force dynamometer is designed and constructed. Cutting forces are measured and recorded by a computer for standard specimens under various machining conditions. Empirical equations between the diameter errors and cutting forces are established experimentally. A compensation method based on computer-aided generation of an alternative tool path, which is symmetrically inversed to error characteristics, is developed.

### 2.1.5 TOOL WEAR ERROR

Error occurs due to the change in the profile of the tool is known as the Tool wear error .As the machining is carried out, within the machining zone a lot of heat is generated and due to this heat their occurs the distortion of the tool profile and hence ultimately the workpiece roughness.Thus it,s effect during machining should also be taken into account .The general profile of Tool wear error

**Tamas Szecsi [14]** This paper addresses the problem of automatically defining cutting-tool wear on CNC lathes. The problem is solved by analysing the axial force during the pressing of the cutting edge of an insert into the workpiece while the cutting process is stopped. During machining the feed movement is interrupted and the position of the cutting tool at this moment becomes a reference point. With no feed movement the rotation of the workpiece continues for a few revolutions, the cutting edge being moved off the transient surface in the axial direction, after which the rotation stops. With slow axial movement the cutting edge is pressed into the surface of the workpiece and at the same time the pressing depth relative to the reference point and the axial force are measured. Analysis of the results shows a close relationship between the axial force, measured at a fixed pressing depth and the flank wear of the cutting tool. The paper also presents some results on cutting-tool condition monitoring using artificial neural networks.

**N. Ghosh , Y.B. Ravi , A. Patra , S. Mukhopadhyay, S. Paul, A.R. Mohanty and A.B. Chattopadhyay [15]** Cutting tool wear degrades the product quality in manufacturing processes. Monitoring tool wear value online is therefore needed to prevent degradation in machining quality. Unfortunately there is no direct way of measuring the tool wear online. Therefore one has to adopt an indirect method wherein the tool wear is estimated from several sensors measuring related process variables. In this work, a neural network-based sensor fusion model has been developed for tool condition monitoring (TCM). Features extracted from a number of machining zone signals, namely cutting forces, spindle vibration, spindle current, and sound pressure level have been fused to estimate the *average flank wear of the main cutting edge*. Novel strategies such as, signal level segmentation for temporal registration, feature space filtering, outlier removal, and estimation space filtering have been proposed. The proposed approach has been validated by both laboratory and industrial implementations.

## 2.1.6 FIXTURING AND DEFLECTION ERRORS

Other errors like tool wear and fixturing errors add to the overall inaccuracy of the machined component. Errors in fixturing are caused by fixture set-up and geometric inaccuracies of the locating elements and by fixture flexure. In cases where the work piece is restrained by a small area of contact with the fixture, the errors due to deformation or liftoff of the work piece could cause significant errors. Work piece displacement is dependent on several factors like position of the fixturing elements, clamping sequence, clamping intensity, type of contact surface etc. Thus work piece displacement could be a significant source of machine error. In the end milling process with a rigid cutter the passing tooth leaves its imprint in the form of a cycloid on the machined part. In the case of a compliant cutter the shape of the imprint depends on the deflection of the tool. To characterize the effect of tool deflection on the machining error, one may define the error to be the difference in the  $Y$  direction between the imprints generated by a rigid cutter and a deflected cutter.

The Previous work done is listed below

**S. Y. Liang' and L. Zheng[16]**, Tool deflection resulting from cutting forces places a constraint on the achievable precision and productivity in machining. This paper presents an analytical model of machining error, in terms of part form deviation in end milling due to the elastic compliance of cutting tool. Based on the relationship of local cutting forces and chip thickness, the shear loading and bending moment on the tool cross section are presented in terms of cutter angular position. The tool deflection resulting from the bending moment is then established from the principle of virtual work. The resulting deflection of workpiece and machine tool structure is also considered through shear loading analysis. The expression for machining error is derived as a closed-form function of the machining parameters, cutting configuration, material characteristics, and machine receptance. End milling experiments were conducted to verify the analytical model under various cutting conditions. Error maps are presented to illustrate the effects of process conditions on the achievable part accuracy.

## **2.1.7 OTHER SOURCES OF ERRORS LIKE SERVO ERRORS OF THE MACHINE AND INTERPOLATION ALGORITHM ERROR**

These errors are also called Blind errors because they are caused due to the mistakes of the programmer or machine user and hence non required machining is done and effects the surface finish of the work piece .Sometimes the programming errors in algorithms also contribute to these type of errors.

The Previous work done is listed below

**B.S. So , D.H. Park , Y. Cho , T.J. Kim , T.S. Song , T.J. Ko[17]** It is known that the Numerical Control (NC) data obtained from the inverse kinematic transformation can generate singular positions, which have incoherent movements on the rotary axes. Such movements cause unexpected errors and abrupt operations, resulting in scoring on the machined surface. To resolve this problem, previous methods have calculated several tool positions during a singular operation, using inverse kinematic equations to predict tool trajectory and approximate the maximum error.

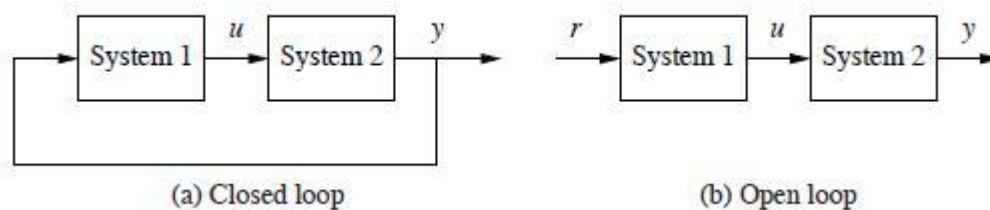
**Yizhen Lin, Yin-Lin Shen [18]**, Sculptured surface machining is a time-consuming and costly process. It requires simultaneously controlled motion of the machine axes. However, positioning inaccuracies or errors exist in machine tools. The combination of error motions of the machine axes will result in a complicated pattern of part geometry errors. In order to quantitatively predict these part geometry errors, a new application framework ‘enhanced virtual machining’ is developed. It integrates machine tool error models into NC machining simulation.

## **2.2 ERROR ASSESMENT AND FEEDBACK ON CNC MACHINES**

### **2.2.1 FEEDBACK**

Feedback is a central feature of life. The process of feedback governs how we grow, respond to stress and challenge, and regulate factors such as body temperature, blood pressure, and cholesterol level. The mechanisms operate at every level, from the interaction of proteins in cells to the interaction of organisms in complex ecologies.

A dynamical system is a system whose behavior changes over time, often in response to external stimulation or forcing. The term feedback refers to a situation in which two (or more) dynamical systems are connected together such that each system influences the other and their dynamics are thus strongly coupled. Simple causal reasoning about a feedback system is difficult because the first system influences the second and the second system influences the first, leading to a circular argument. This makes reasoning based on cause and effect tricky, and it is necessary to analyze the system as a whole. A consequence of this is that the behavior of feedback systems is often counterintuitive, and it is therefore necessary to resort to formal methods to understand them. [Figure-2.2.1.1] illustrates in block diagram the types of feedback.



**Figure-2.2.1.1**

Feedback has many interesting and useful properties. It makes it possible to design precise systems from imprecise components and to make relevant quantities in a system change in a prescribed fashion. An unstable system can be stabilized using feedback, and the effects of external disturbances can be reduced. Feedback also offers new degrees of freedom to a designer by exploiting sensing, actuation and computation. In this section we survey some of the important applications and trends for feedback in the world around us. The proliferation of control in engineered systems occurred primarily in the latter half of the 20th century. There are some important exceptions, such as the centrifugal governor described earlier and the thermostat, designed at the turn of the century to regulate the temperature of buildings.

The thermostat, in particular, is a simple example of feedback control that everyone is familiar with. The device measures the temperature in a building, compares that temperature to a desired set point and uses the feedback error between the two to operate the heating plant, e.g., to turn heat on when the temperature is too low and to turn it off when the temperature is too high.

This explanation captures the essence of feedback, but it is a bit too simple even for a basic device such as the thermostat. Because lags and delays exist in the heating plant and sensor, a good thermostat does a bit of anticipation, turning the heater off before the error actually changes sign. This avoids excessive temperature swings and cycling of the heating plant. This interplay between the dynamics of the process and the operation of the controller is a key element in modern control systems design

Feedback is a powerful idea which, as we have seen, is used extensively in natural and technological systems. The principle of feedback is simple: base correcting actions on the difference between desired and actual performance. In engineering, feedback has been rediscovered and patented many times in many different contexts. The use of feedback has often resulted in vast improvements in system capability, and these improvements have sometimes been revolutionary, as discussed above. The reason for this is that feedback has some truly remarkable properties. In this section we will discuss some of the properties of feedback that can be understood intuitively.

The Previous work for errors in CNC is listed below

**Chi-Ho Yeung, Yusuf Altintas' and Kaan Erkorkmaz [19]** The paper presents a comprehensive virtual simulation model of a realistic and modular CNC system. The Virtual CNC architecture represents an actual CNC but with modular feed drives, sensors, motors, and amplifiers. The CNC software library includes a variety of trajectory interpolation and axis control laws. Constant, trapezoidal and cubic acceleration profiles can be selected as a trajectory generation module.

**A Sata [20]** has done work for error measurement using ball geometry cutter .To improve the accuracy of machined parts, it is necessary to increase the accuracy of the machine tool. Machine tool accuracy depends on a number of errors including the geometric error of the body structure, backlash and the distortion due to temperature changes, humidity, servo-control error and error in motion of spindle axis rotation. It is very difficult to avoid error completely during manufacturing while measurement and calibrating of error is best way. Therefore, it Is required to measure these errors and calibrated regularly for their error i.e. 3-dimensional positioning

error, for high precision machining. This paper includes study of measurement techniques and calibration techniques of five axis CNC machine using total ball bar device taking industrial case study.

**M. Rahou, A. Cheikh, and F. Sebaa [21]**, Manufacturing tolerancing is intended to determine the intermediate geometrical and dimensional states of the part during its manufacturing process. These manufacturing dimensions also serve to satisfy not only the functional requirements given in the definition drawing, but also the manufacturing constraints This study was carried out on three stages .The first stage allows machining without elimination of dispersions (random, systematic) so the tolerances of manufacture according to total dispersions. In the second stage, the results of the first stage are filtered in such way to obtain the tolerances according to random dispersions. Finally, from the two previous stages, the systematic dispersions are generated.

**M.F.F. Ab. Rashid and M.R. Abdul Lani [22]**, In CNC milling process, proper setting of cutting parameter is important to obtain better surface roughness. Unfortunately, conventional try and error method is time consuming as well as high cost. The purpose for this research is to develop mathematical model using multiple regressions and artificial neural network model for artificial intelligent method. Spindle speed, feed rate, and depth of cut have been chosen as predictors in order to predict surface roughness. 27 samples were run by using FANUC CNC Milling  $\alpha$ -T14E. The experiment is executed by using full factorial design. Analysis of variances shows that the most significant parameter is feed rate followed by spindle speed and lastly depth of cut. After the predicted surface roughness has been obtained by using both methods, average percentage error is calculated.

**M. Wan, W.H. Zhang, G.H. Qin, and Z.P. Wang [23]** this paper aims at developing efficient strategies for controlling the force-induced surface dimensional errors in peripheral milling of thin-walled structures. Emphasis is put on how to select the feed per tooth and depth of cut simultaneously for tolerance specification and maximization of the feed per tooth simultaneously. Three methods are presented. Mechanistic model for cutting force estimation, cantilever beam model for cutter deflection estimation and finite element method for workpiece deflection estimation are used in all three methods. Besides, improvements on the calculation

scheme of the surface dimensional error have been made and both numerical and experimental results are adopted for verification.

**Ondrej Svoboda and Pavel Bach [24].** There are many possible definitions, such as the root mean square of the 3 axes displacement errors, the root mean square of the total errors in the 3-axis directions, the maximum 4 body diagonal displacement errors without squareness and the maximum 4 body diagonal displacement errors with squareness errors. Reported here are some definitions of 3D volumetric positioning errors and their correlations. We have measured the positioning errors of 10 CNC machine tools, representing a selection of modern mid-size CNC machining centers. Based on these measurement results, the 3D volumetric errors using various definitions can be calculated. It is concluded that the 4 body diagonal displacement errors with squareness errors correlate with the true 3D volumetric errors very well. It may be used as a quick check of 3D volumetric accuracy of CNC machine tools.

**Seng Khim, Tan and Chin Keong, Lim [25].** A study of developing the error modeling on an industrial five-axis CNC machine tool will enable the understanding of the accuracy performance of machine and therefore to minimize the error by mechanical adjustment or error compensation methods. A mathematical modeling to determine the volumetric error can be developed from the kinematic error models accounting for the unique structural configuration of a CNC machine tool. Since there were discussions on the modeling of three-axis CNC machine tool done by previous research publications [1-3] hence, the rotary table modeling of five-axis CNC machine tool and the combination of both will be the main subject in this paper.

## CHAPTER-3

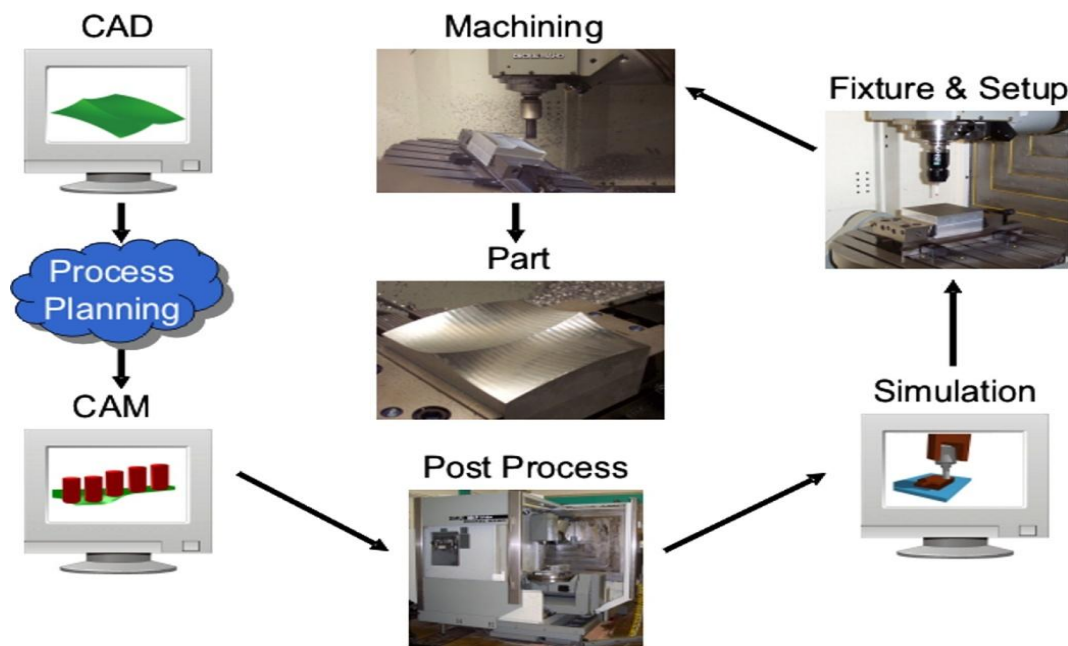
### PROBLEM DEFINITION

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Errors in CNC machining can be catastrophic in nature due to the large forces, high velocities and the high cost of the machines, tools and workpiece stock material. Simulation process is designed to assist in error prevention; it can not only detect tool path errors but can also be helpful in displaying the real machining process with assistance of the feedback which can be simulated in real time to show the actual process of machining.

It is clear that today's CNC machine is blind in that the only object it knows exists in its workspace is the cutting tool. It has no information about the stock material, fixturing and clamping, or of the part it is supposed to make except for the relative coordinate frame of the part with respect to the machine coordinate frame. It blindly follows the commands given to it even if it is commanded to destroy itself.

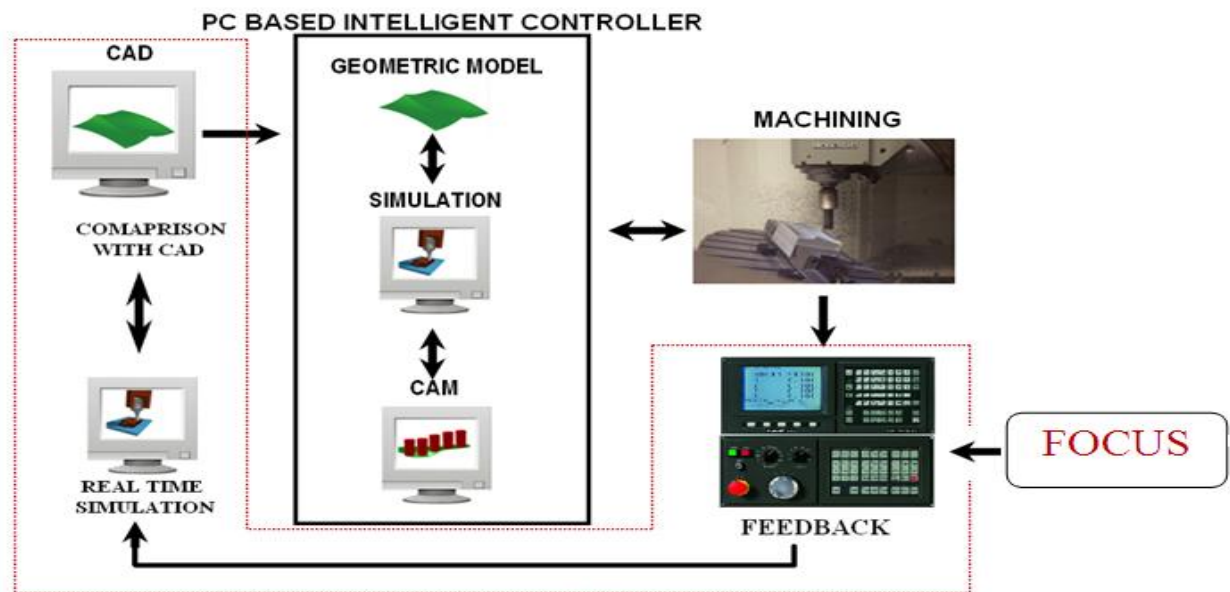
The CNC machining paradigm [Figure 3.1] has not changed since its inception. The machine motions are dictated by the part program that contains the tool path. Tool path generation is done prior to the machining process and the tool path is usually generated offline with a commercial CAM package.



**Figure 3.1 CNC machining paradigm**

Today's machining processes are focused upon errors which are prior to machining process. Most of the errors and its correction are focused on pre-machining but in actual most of the errors are contributed during machining process and are realized post-machining. The feedback generated by the machine is not utilized to its potential due to which the Production houses face some serious problems. The current structure definitely carries some drawbacks such as

1. In present state there is no utilization of feedback in real time the error is corrected only after machining is over.
2. Data available during feedback (Alpha-numeric) is difficult to interpret by the operator.
3. Real time error correction cannot implement.
4. There is no comparison of the machined component with the original CAD/STL data for error prediction.

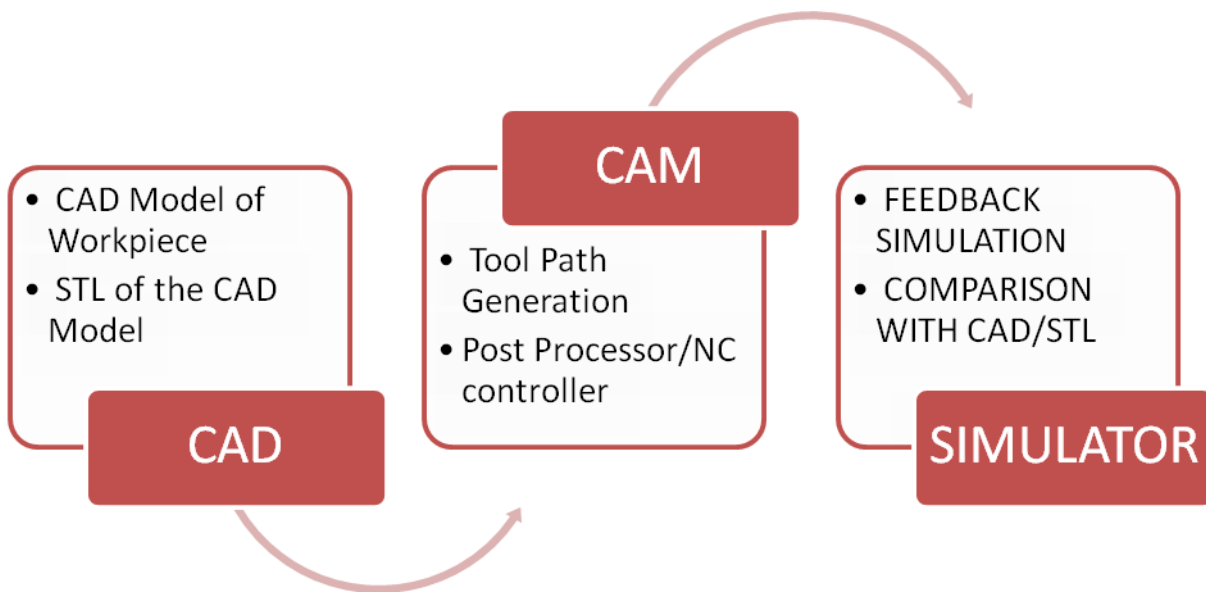


**Figure 3.2 PROPOSED WORK**

Proposed work will show in real time the machining process which will be simulated with the help of feedback which is generated during machining. Paradigm of proposed work is shown in [figure 3.2].

### 3.1ALGORITHM

The simulator is designed to cover the all aspects of the requirement to simulate the feedback and compare it with the CAD/STL during the machining process in Real time. Proposed simulator shown in [Figure 3.2.1]will cover the process involved during machining process which includes use of feedback for simulation and comparison with original CAD/STL.



**Figure 3.2.1Algorithm**

The machining process includes three process listed below:

#### **CAD PROCESS**

In CAD we create the workpiece which is needed to be produced using CAD software. A 3-D model is generated which is converted and saved into the STL data. This STL data is further used for comparison with the simulated geometry.

## **CAM PROCESS**

The tool path generation is done with the help of the module of manufacturing in the CAD software. Tool path is the co-ordinate data for the machining process. This tool path is fed to the machine interface for the machining process. The machining process is controlled by the controller which converts the toolpath data into machine language. The machining process is post processor part of the machining processor.

## **SIMULATOR**

For the simulation process we require the machine feedback which is stored in text file which contains the co-ordinate data by modifying the machine interface. After achieving this feedback stored is made input to the simulator which simulates the machining process in real time. The simulation is overlapped over the STL.

The algorithm is arranged to following steps

1. STL file reading and display on simulator.
2. Initiate controller and start the machining process.
3. Read the feedback and store it.
4. Calibration of feedback using the input TP file.
5. Display of feedback overlapped on the STL.
6. Mark any deviation on the screen.

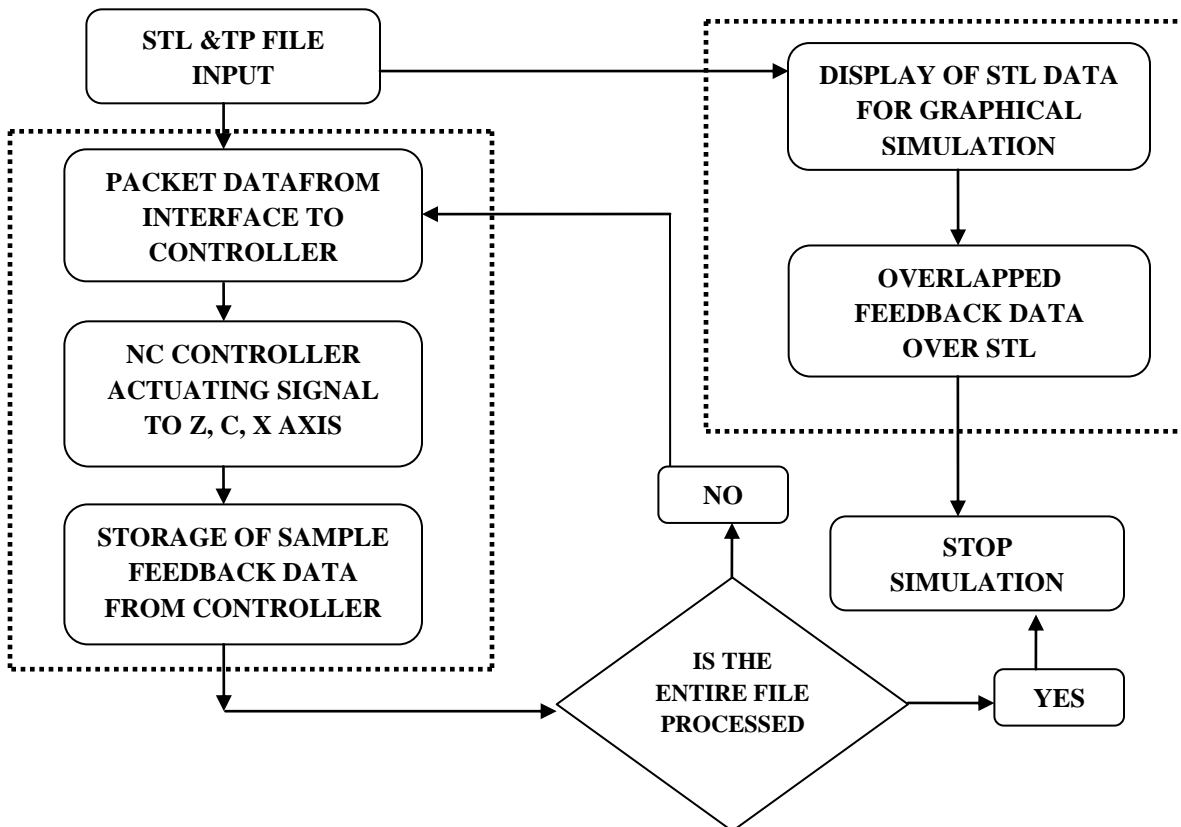
# CHAPTER-4

## SIMULATOR

The simulator is designed to incorporate the use of feedback which is simulated in real time to show the actual process of machining and comparison of the simulated part with the original CAD/STL for error prediction which will be helpful in filling the gap in the machining process and the desired objective is achieved effectively. After designing the simulator its output is verified by doing machining over the trial workpiece which are described in detail in the literature below. The Simulator takes the Feedback during machining which is stored by modifying the old interface and then it is fed to the simulator as an input which generates the machined surface in real-time. The errors are evaluated by comparison of specific intervals on the machined surface with the CAD/STL file. The algorithm used, simulator working, experimental testing and its verification is detailed below.

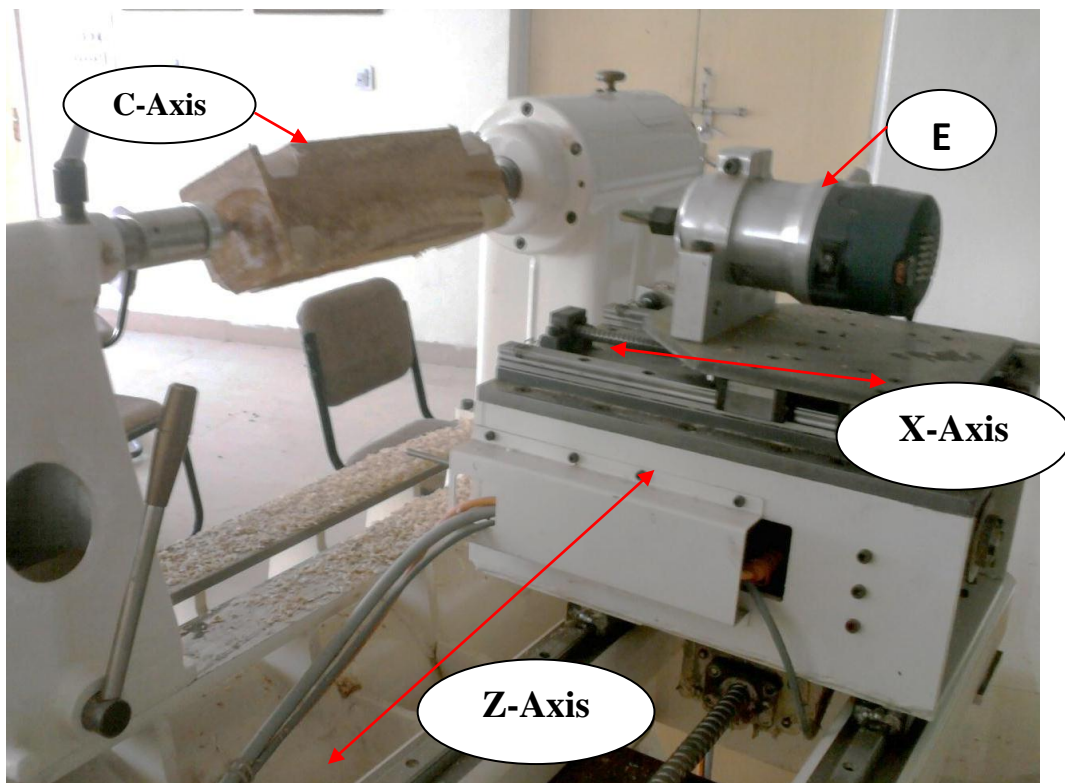
### 4.1 SIMULATOR WORKING

Simulator working is shown in the following paradigm



## 4.2 EXPERIMENTAL SETUP

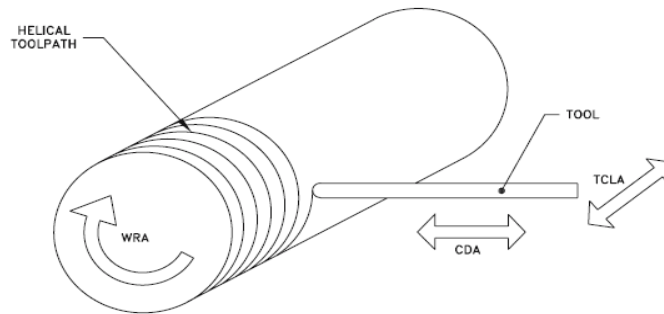
The machine which will be incorporated for this work is 3-Axis Lathe Mill. This is a simple machine originally constructed with the intention of providing woodworking hobbyists an inexpensive approach to CNC machining of complex ornamental wood pieces [Figure 4.2.1] shows the 3-Axis Lathe Mill.



**Figure 4.2.2 EXPERIMENTAL SETUP**

A router tool (*E*) serves as the machine spindle whose motion is controlled by a stepper motor, perpendicular to the cylindrical workpiece's longitudinal axis and this defines the depth of cut for a given tool position. The router axis is mounted on a platform (*C*) that moves longitudinally along the workpiece's rotary axis. This axis is mechanically linked to the motor shown (*B*) which is linked to the rotation of the workpiece. Thus, the tool path simplifies to a helical path around the part. As shown in [Figure 4.2.2]

The control of the machine is handled by a P-MAC controller device. The input and output commands are communicated via the parallel port. As the workpiece is rotated the CDA controls the depth of the cutter on the helical path.

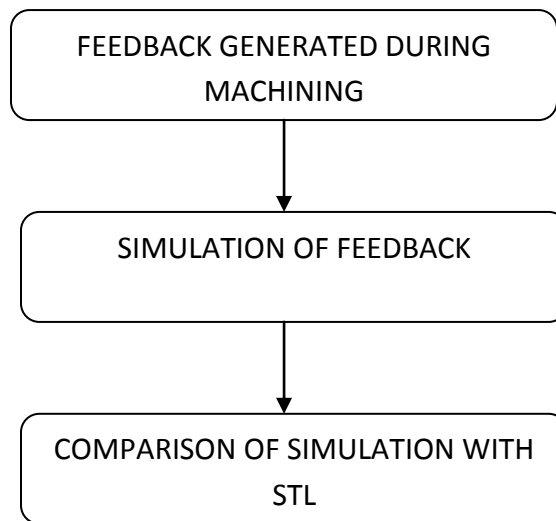


**Figure 4.2.2**

3-Axis Lathe mill is unique in its configuration in that there are three axes of motion, X (CDA), Z (TCLA), and C (WRA). The workpiece rotation axis (WRA) is responsible for rotating the workpiece. The cutting tool moves in two directions; along the length of the workpiece with the transverse cutter location axis (TCLA) and towards and away from the workpiece with the cutter depth axis (CDA).

### **4.3ALGORITHM**

The simulator is designed to cover all the aspects required to measure the errors in real-time. Proposed simulator and its process flow is shown below.



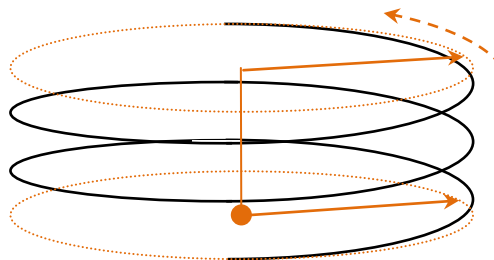
**Feedback generation:** feedback is generated during the machining process the first task was to start the feedback which was not working due to the errors in the Interface/Code on the machine so the first task was to correct and start the feedback process followed by generating and implementing the Code for feedback storing in the old interface. The stored feedback is used as an input for the simulator which simulates the feedback.

The P-Mac device is basically a controller which controllers the machining process. The P-Mac is interfaced with a computer controlled interface. The machining process is done through this interface. The TP file is uploaded on this interface, offset value, tool radius, feedback modules are integrated to this interface.

The feedback which is generated during the machining process is saved into a file and made as an input to the simulator. The simulator simulates the machining process in real time enabling a real time monitoring of the machining process.

#### 4.3.1 ALORITHM FOR GENERATING A HELICAL TOOLPATH

Helix for a constant diameter cylinder can be created from a parametric equation with a single parameter  $t$ , a radius  $r$ , a height of  $h$ , and a center point  $C$ .  $t$ , is used to drive the rotation of the spiral as well as its vertical distance.



$$\begin{aligned}x &= x_c + r \cdot \cos(2\pi N \cdot t) \\y &= y_c + r \cdot \sin(2\pi N \cdot t) \\z &= z_c + h \cdot t\end{aligned}$$

The quantity  $N$  represents the number of turns the spiral will make throughout the distance  $h$ . The pitch  $p$  of the helix can therefore be calculated by:

$$P = d \div N$$

By using the algorithm we generate toolpath for a constant diameter cylinder which in this case is 45mm and the length of the part is 140mm then we machine the part using this diameter. The input TP file has been shown in the **Table-1** below.

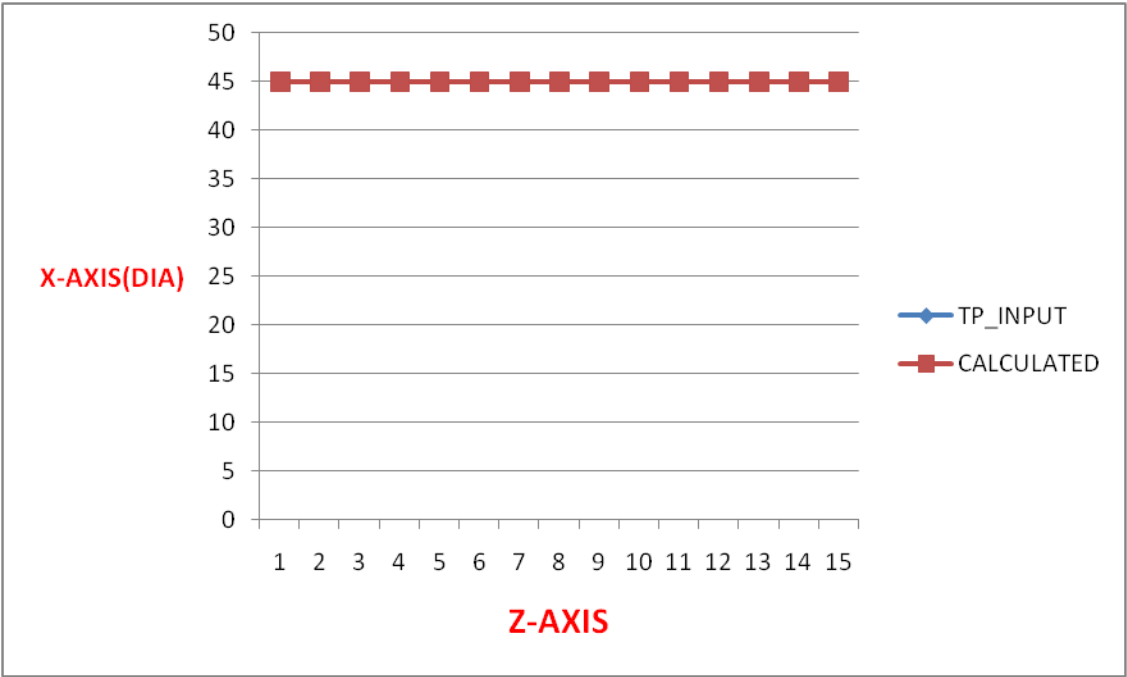
**TABLE-1: INPUT TP FILE**

| <b>X-Axis(mm)</b> | <b>Z-Axis(mm)</b> | <b>C-Axis(rad)</b> |
|-------------------|-------------------|--------------------|
| 45.00             | 0                 | 0                  |
| 45.00             | 0.0126            | 1.44               |
| 45.00             | 0.0253            | 2.88               |
| 45.00             | 0.0380            | 4.32               |
| 45.00             | 0.050             | 5.76               |
| 45.00             | 0.0634            | 7.19               |
| 45.00             | 0.0761            | 8.64               |
| 45.00             | 0.0889            | 10.08              |
| 45.00             | 0.1015            | 11.52              |
| 45.00             | 0.1142            | 12.96              |
| 45.00             | 0.1269            | 14.39              |
| 45.00             | 0.1379            | 15.84              |
| 45.00             | 0.1523            | 17.28              |
| 45.00             | 0.1650            | 18.72              |
| 45.00             | 0.1778            | 20.16              |
| 45.00             | 0.1904            | 21.59              |
| 45.00             | 0.2031            | 23.04              |

|       |        |       |
|-------|--------|-------|
| 45.00 | 0.2159 | 24.48 |
| 45.00 | 0.2285 | 25.92 |
| 45.00 | 0.2413 | 27.36 |
| 45.00 | 0.2539 | 28.79 |

The z -value goes from 0-140mm the total length which we want to make for the part. The C is the rotation of the workpiece. X-value is the constant diameter of the part which we want to machine in this case it is a constant diameter cylinder.

To validate our calculated diameter with the input diameter we plot the graph for the calculated diameter using algorithm with the input TP which is shown in **Figure 4.3.1.2**



**Figure 4.3.1.2 TP and Calculated Diameter Comparison**

From the plot it is very clear that the calculated value and the generated value of TP is same so the generated part has the exact dimension which we want to have so that there is not variation in the feedback data.

Now we machine the part for cylinder and store the desired feedback into a text file which is shown in the table below with that we see that weather there is any variation in the feedback so that the error value can be calculated. The machine requires certain parameters apart from the TP file which are the offset value, the tool radius which are fed to the machine by manually calculating the value of offset and physically input it into the machine interface. The offset value entered in this case was 101.15mm which was reduced in the simulator code to generate the exact overlapped simulation of the feedback. The diameter value which is in the TP is compensated with the tool radius which in this case was ½” ball nose cutter. The feedback then generated is shown in the **TABLE-2**.

**TABLE-2: FEEDBACK FROM MACHINE CONTROLLER**

| <b>X<sub>m</sub> –Axis(mm)</b><br><b>Feedback</b> | <b>Z-Axis(mm)</b> | <b>C-Axis(rad)</b> |
|---|-------------------|--------------------|
| 45.00   | 0.406             | -47.904            |
| 45.00   | 0.427             | -50.057            |
| 45.00   | 0.449             | -53.009            |
| 45.00   | 0.48              | -55.961            |
| 45.00   | 0.505             | -59.231            |
| 45.00   | 0.533             | -62.502            |
| 45.00   | 0.566             | -65.852            |
| 45.00   | 0.591             | -69.123            |
| 45.00   | 0.619             | -72.394            |
| 45.00   | 0.653             | -75.664            |
| 45.00   | 0.678             | -78.935            |

|       |       |            |
|-------|-------|------------|
| 45.00 | 0.712 | -82.206    |
| 45.00 | 0.739 | -85.476    |
| 45.00 | 0.764 | -88.747    |
| 45.00 | 0.798 | -92.098    |
| 45.00 | 0.826 | -95.368    |
| 45.00 | 0.857 | -98.639    |
| 45.00 | 0.882 | -101.91    |
| 45.00 | 0.913 | -105.5     |
| 45.00 | 0.943 | -108.45.00 |
| 45.00 | 0.968 | -111.72    |

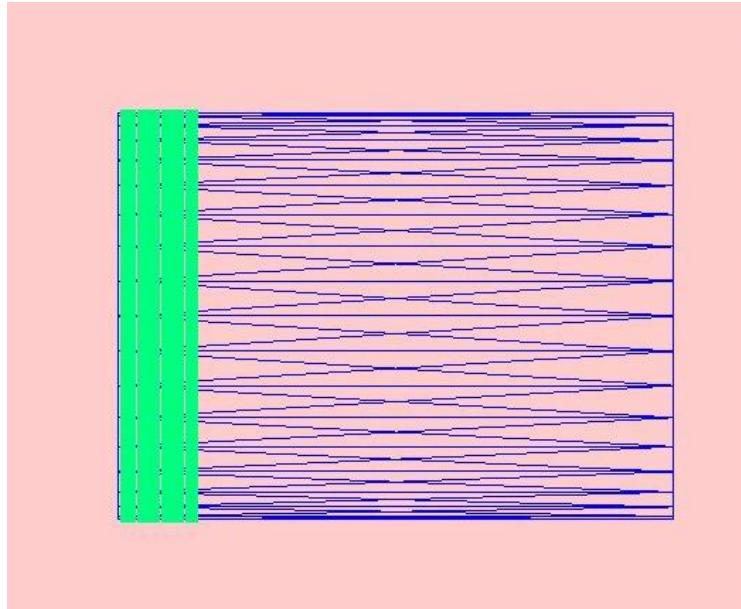
Using the following data of feedback we find that the feedback value for the diameter is 146.15. By subtracting the offset of 101.15 values we find that the diameter generated in feedback is 45 mm. this shows that our machining process is accurate and the feedback which is obtained from the controller is accurate.

#### 4.4 SIMULATOR TESTING

The test is done on a simple cylinder to be able to visualize the machining process as the dimensions of the cylinder are known. We machine a cylinder and store the feedback the feedback is made input to the simulator and the simulation in real time is done over the STL.

The simulator will show in real time the machining process by simulating the feedback in real time. For this purpose the simulator will show the STL file simulated and then the machining process over the simulated STL. We can see the process of machining in overlap with the STL geometry. The simulation of TP cycles are shown in **Figure 4.4.1, Figure 4.4.2, Figure 4.4.3 and Figure 4.4.4** the Blue portion shows the STL plotting while the Green portion shows the

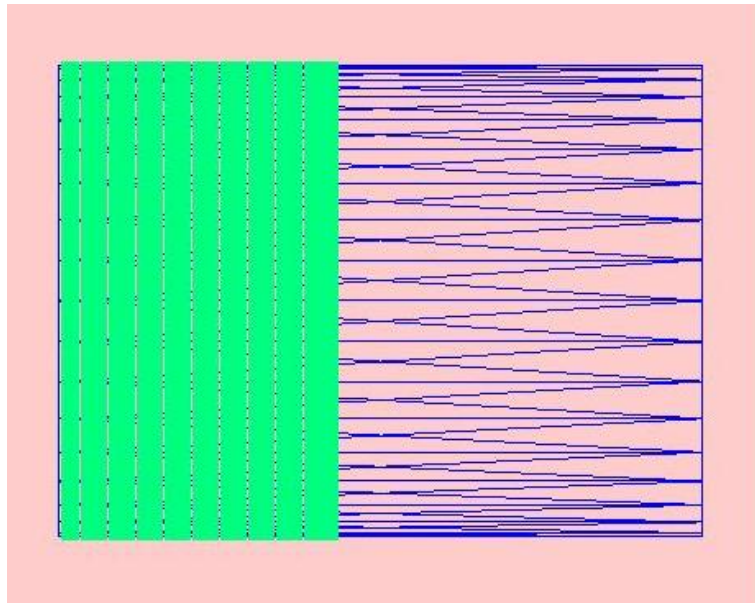
machining of the roughing-1 file which is being simulated in real time over the STL geometry. Figures below shows machining process for Roughing-1 file which is a cylinder.

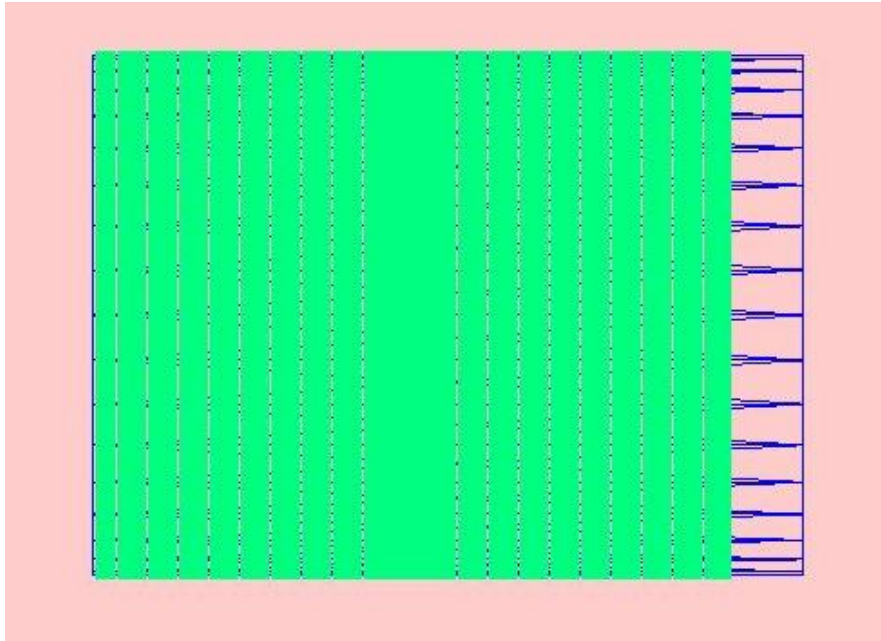


**Figure 4.4.1 Simulation in Process**

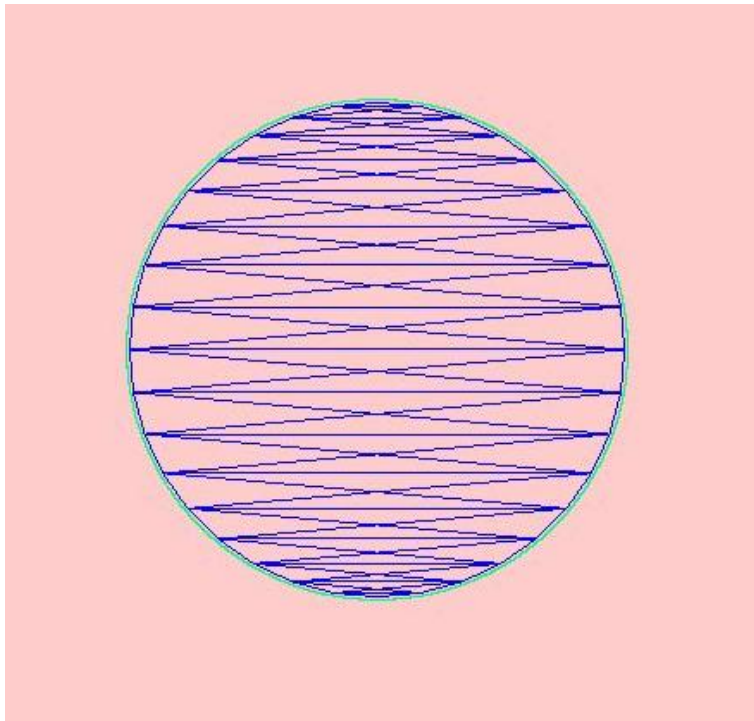
In Figure-4.4.1 we can see a STL being plotted in blue color and the simulated machining process in green color. Furthermore views are shown to clearly visualize the process of Machining.

**Figure 4.4.2 Simulation in Process**





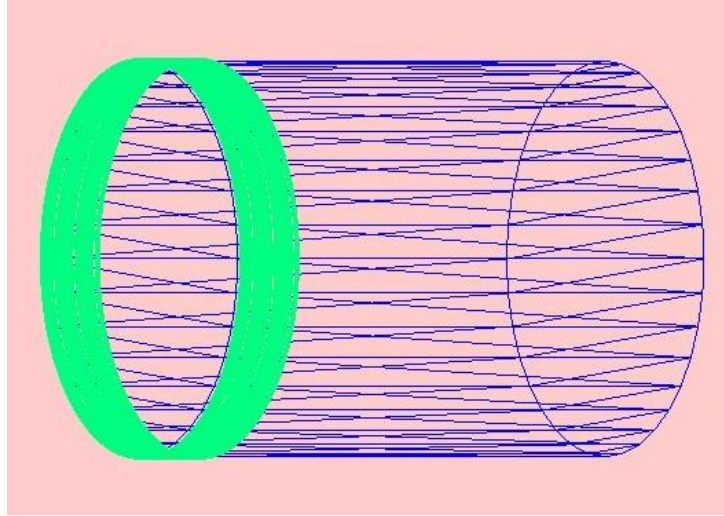
**Figure 4.4.3 Simulation in Process**



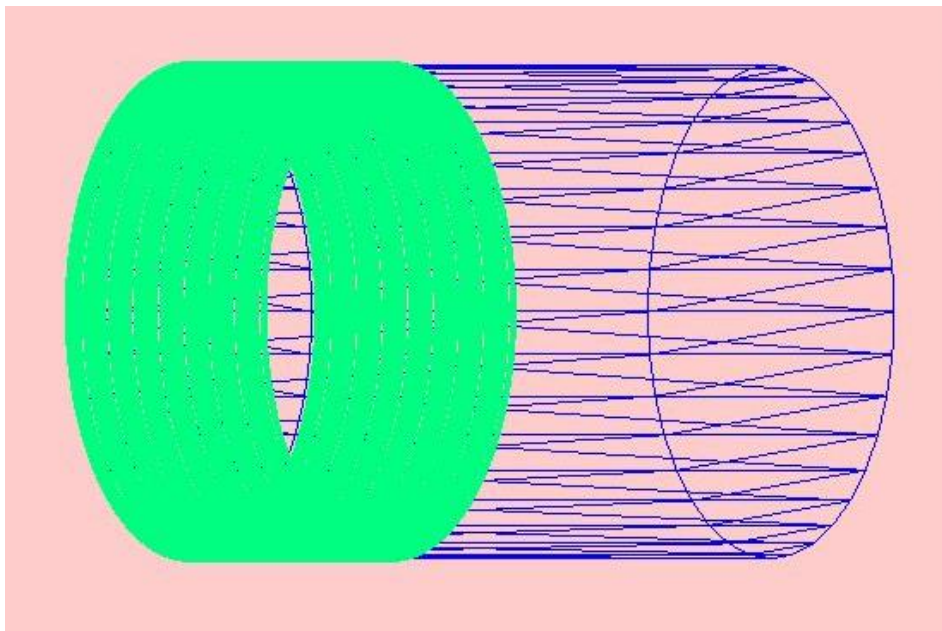
**Figure 4.4.4 Axial view of Simulation**

The above figure shows an axial view showing the blue lines as the triangles of the STL and the green ring depicts the simulation of the machining process.

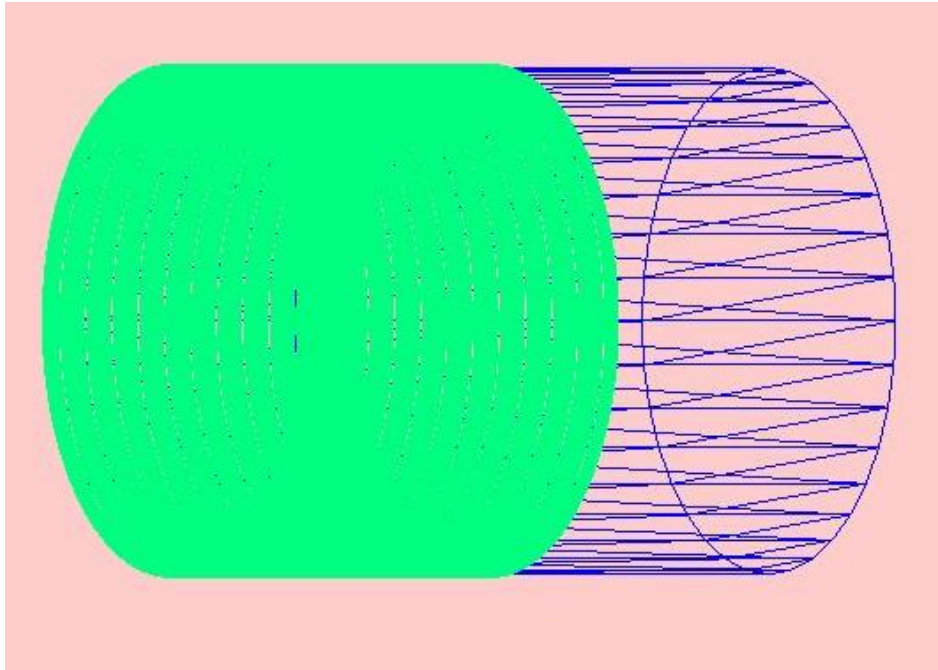
Further following figures are shown for a rotated view



**Figure-4.4.5 Rotated View of Simulation**



**Figure-4.4.6 Simulation Progress**

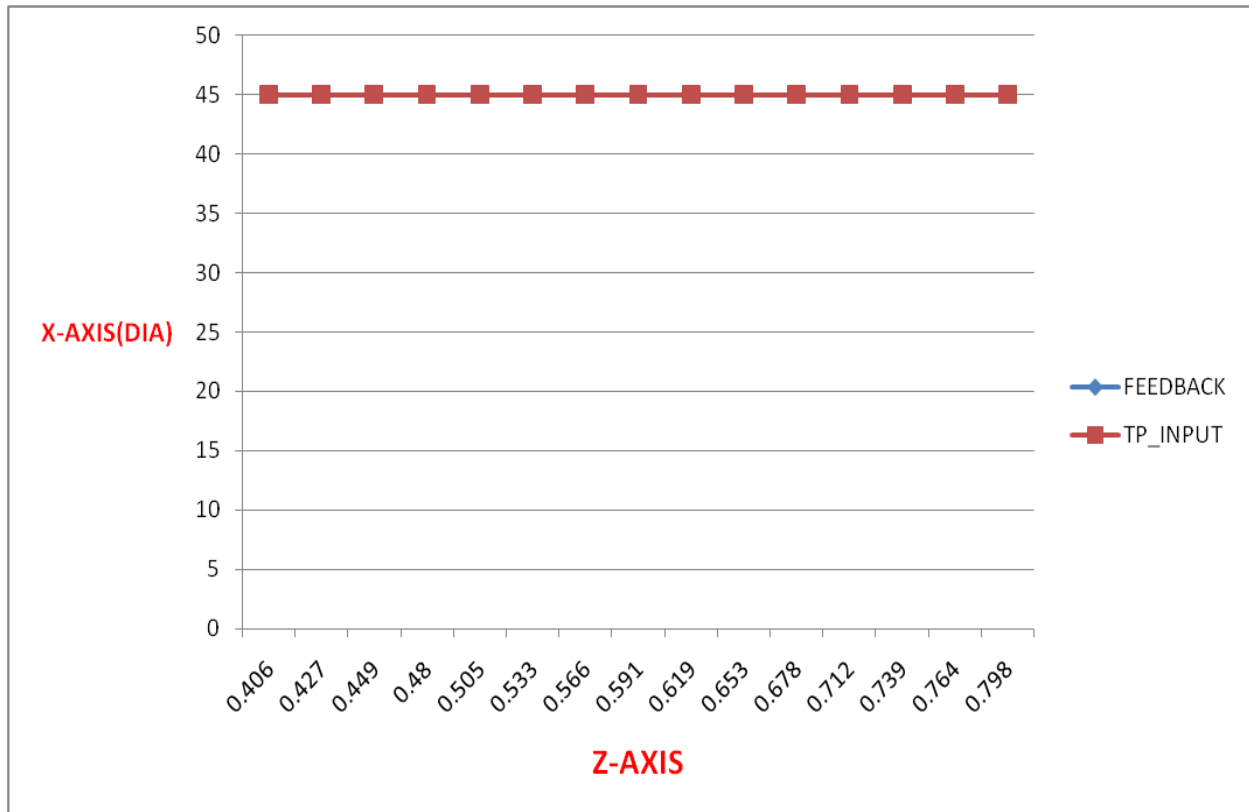


**Figure-4.4.7 Simulated Feedback over STL**

## **4.5 SIMULATOR VERIFICATION**

The data available during the machining process is captured by the hardware. Since the machining process is not having any errors in the hardware. The feedback generated by the TP file is very accurate and the graph shows the value of feedback overlapped on TP file which is the input for the machining process. This very clearly shows that the simulation process is very accurate and there is no error in feedback and its simulation.

This is due to the fact that the hardware used which in this case a P-MAC device basically a controller is having zero mechanical error and the feedback coming is with zero error.



**Figure 4.5.1 Simulator Feedback vs Input TP**

As discussed in the above the sections the live simulator algorithm works as desired. In the live simulator we have first plotted the actual CAD data of the part, taken in STL format for the present algorithm in Visual C++ using OPEN GL environment. The STL file format has been used for tool path planning, and the tool paths created from the tool path planner was saved in TP file format (tool path file) for actual machining operation. The TP file was read by the NC controller of the machine, which commanded the various drives of the machine for actual cutting to be done. The NC controller also keeps the track of the actual commanded position by comparing the feedback at regular intervals from the machine drives and then compensating the errors if found. The feedback values from position of machine drives that have been used by the machine controller were recognized by modifying the original machine interface program code that was in Visual Basic to capture and store that feedback data in a separate text file. The live simulator algorithm used to read the stored information about the feedback from the text file in real time. The live simulator then used to overlay the feedback information over the already displayed part model in precise manner graphically, which is something like the output display

of the cutting operation being controlled by the NC controller of machine. Thus the visual display of the cutting process is also showing the comparison with actual model from where the tool path was generated to machine the component. This concept has been validated by the above discussion and in the next chapter advantages of the live simulator algorithms with the limitations of the algorithm in present form have been discussed.

## **CHAPTER-5**

### **CONCLUSIONS**

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Machining errors cause a great hindrance in the manufacturing process. Quick correction and rectification of errors are a great necessity and it is more effective when we can do it during the machining process or REAL TIME error correction through simulation to achieve desired objective as discussed above. Following were the achievements of the desired simulator.

#### **5.1 STRENGTH OF REAL TIME SIMULATION**

The simulator increased the capabilities by following

1. Real time monitoring of the machining process.
2. Simulation enables easy understanding of machining process.
3. Quick response to error correction.
4. Product rejection is less due to error correction.
5. Product cycle time is reduced.
6. Friendly to Labors.

This simulator enables us to understand and monitor the process of machining without coming into the direct contact of the machine process which is dangerous. This creates a new window for error assessment and its correction with ease and in no time. The simulator only needs the feedback from the machine to simulate the process of machining. This simulator creates a ease to the labor force which are actually working on the machine giving them he edge to predict, manipulate and correct the errors during the machining process.

The simulator can be seen as the future to the machining process which enables each and any kind of operator to work with ease and to judge and rectify the problems which are created during the machining process resulting in an efficient production and effective machining.

## **5.2 LIMITATIONS**

With the pros the simulator also carries its cons they go as under

1. The data comparison with STL may not be accurate as STL itself contains some errors.
2. The feedback and simulation needs to be more refined for better output.
3. Simulation lacks speed in operation so it needs to be modified and upgraded.
4. More precise color coding needs to be incorporated.

## **5.3 SCOPE OF FUTURE WORK**

1. A better hardware or up gradation is needed as there is a data loss in feedback of the machine.
2. Re-setting and re-calibration of the machine is required to achieve better and error free simulation.
3. Proposed simulator can be integrated with other modules and algorithms for predicting the other types of errors than contribute to machining inaccuracies.
4. Advanced software can be implemented in order to increase the speed of the simulation.
5. This simulation can be adopted for various machining centers.

## CHAPTER-6

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