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DEVELOPMENT OF A POSTPROCESSOR FOR A MULTI-AXIS CNC MILLING
CENTER

by

MIHIR SATISH ADIVAREKAR

A THESIS

Presented to the Faculty of the Graduate School of the
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY
In Partial Fulfillment of the Requirements for the Degree
MASTER OF SCIENCE IN MANUFACTURING ENGINEERING

2013

Approved by

Dr. Frank Liou, Advisor
Dr. Elizabeth Cudney
Dr. Ashok Midha

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PUBLICATION THESIS OPTION

This thesis is composed of one journal paper which was reformatted in the style used by the university. The paper presented in pages 1-43 titled “DEVELOPING A GENERAL POSTPROCESSOR FOR MULTI-AXIS CNC MILLING CENTERS” is submitted to Special Issue of INTERNATIONAL JOURNAL OF COMPUTER-AIDED DESIGN AND APPLICATIONS (ISSN 1686- 4360).

ABSTRACT

Most of the current college design and manufacturing curricula are primarily focused on computer aided design (CAD), while less emphasis is given to computer aided manufacturing (CAM). A great opportunity has been missed as the benefits of CAD/CAM cannot then be fully learned. Postprocessor plays a vital role in integration of CAD//CAM with computer numerically controlled (CNC) machines. Hence, postprocessor must be developed accurately.

This thesis is composed of one paper. Paper I proposes a novel methodology to determine compensation vectors for the post processor of multi-axis milling center. The new approach that has been implemented in Paper I involves derivation of the analytical equations of NC code with compensation vectors for five-axis spindle-tilting type CNC milling machine and experimental procedure to acquire the compensation vectors. This ensures that part would be machined as per the CAD drawing and accuracy within the limits of CNC machine.

Furthermore, implementation of this procedure for the development of a post processor would streamline the process of integrating CAM systems for multi-axis CNC milling centers. The integrated system is being used to support research and education projects to accurately and quickly produce parts.

ACKNOWLEDGMENT

This research work is a result of some phenomenal help and support extended to me by many individuals at Missouri S&T. Foremost; I would like to express my sincere gratitude towards my advisor Dr. Frank Liou and Mr. Todd Sparks for their continued guidance, encouragement and co-operation throughout my research work. It has been a pleasure working with them over the past two years and without their help this work would not have been possible. The research assistantship extended to me by Dr. Liou through the Manufacturing Engineering program is also greatly acknowledged.

I would also like to thank my committee members Dr. Ashok Midha and Dr. Elizabeth Cudney for their time and advice granted to me during the research. I would like to express my sincere thanks to Sujit, Nandakumar, Raghvendra and Ashish for helping me during the experiments and providing me with valuable suggestions which have been very critical in completing my research work. I would also like to thank my roommates at Rolla who have made the past two years memorable.

Last but not the least , I would like to express my gratitude towards my parents, Mr. Satish Adivarekar, Mrs. Swati Adivarekar , my sister Mrs. Mugdha Akut and brother in law Mr. Ajay Akut for their unconditional love and support and God Almighty for guiding me throughout the various stages of my life.

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1. INTRODUCTION

Multi-axis machining constitutes three translational axes and some rotational axes. The manufacturing process of complex parts has been revolutionized by capabilities of multi-axis machining. Conventional machining processes are slow, inflexible and limited in their capabilities in comparison with multi-axis machining. Hence, by overcoming the constraints of traditional machining, it can provide the advantage of machining complex parts with increased accuracy and higher surface finish with reduced setup time. Consequently, enhancing machine accuracy has been one of the main focuses of research on five-axis machine tools in the past. The complexity of mathematical model has made the application of related techniques difficult and cumbersome. [1, 2]

In design and manufacturing industry, NC concept refers to the automation of machine tools that are operated by abstractly programmed commands encoded on storage medium,. The first NC machines were built in based on existing tools that were modified with motors that moved the controls to follow points fed into the system on paper tape. The early servomechanisms were rapidly improved with analog as well as digital computers, creating the modern computed numerically controlled (CNC) machine tools. A CNC machine includes several types: 2-axis CNC machine, 3-axis CNC machine, 4-axis CNC machine, 5-axis machine, etc. The number of the axis of a CNC machine implies capability of the controller of the machine to interpolate simultaneously. If the axis number increases, the machining efficiency, effectiveness and accuracy will

increase; however, it requires more complex techniques in tool path generation and process of programming. Five-axis milling CNC machine has been proven to be the most efficient tool for fabricating products of complex geometry which may include abundant freeform surfaces. Integration of five axis CNC systems with CAD-CAM systems has revolutionized the industrial automation. The products are widely used in several high technology industries such as the aerospace industry, the automotive industry, the shipbuilding industry, etc. [3].

Many people use different methods to research on a postprocessor for five-axis machine tools. R.S. Lee and C.H. Lee presented an analytical methodology to develop a post processor for three typical five-axis machine tools. According to the distribution of the rotational movement units, the five-axis machine tool can be classified into three basic types- 1. Table tilting with rotations on the table, 2. Spindle-tilting with rotations on the spindle and 3. Table/spindle-tilting with one rotation each on the table and spindle [4].

To measure the error of the machining center, Double Ball Bar (DBB) and laser scanners are widely used in the industries. DBB is a quick measuring system to find out the accuracy of machine tools. The DBB measuring is good for single error origin or error origins having high amplitude. . Hence, offset error in the rotation axes error and misalignment in the spindle is very difficult to measure by the DBB method [5]. The error modeling technique is very useful in predicting the volumetric errors of CNC machine tools.

Until now the implementation of this technique in five axis machine tools faced great challenges. Although the majority of motional errors in the error model are measurable with modern measurement devices, still it consists of some linkage errors which are immeasurable. Taking the information flow of five-axis machining into consideration, one direct way to improve the accuracy of five-axis machining without upgrading the CNC controller's functionality is to apply the error model in the post-processor of CAD/CAM systems[6]. Even though these methods provide highly accurate and precise data, investment and operational cost associated with these methods is high.

The alternative method has been proposed for the same function of DBB and laser scanner. The paper aims to derive the analytical equations of NC code with compensation vectors for five-axis, spindle-tilting type CNC milling machine. Experiments will be carried out to obtain the compensation vectors on the five axis CNC milling Fryer 5X-45 with A and C rotational axes. The methodology discussed in this paper would enable Logical and simple approach of the method would be helpful for post processor developers and machine operators.

2. DEVELOPMENT OF A POSTPROCESSOR

Post processor is an interface that links the CAM system and NC machines and converts CL data to machine code [6]. Basically it's a translator that reads, interprets the manufacturing instructions given by CAM system and converts them into appropriate NC code depending on the combination of machine and controller configuration. For the development of post processor, following three key elements are essential;

- Kinematic Model of Machining center
- Format of Cutter Location (CL) data
- Post processing strategy

2.1. KINEMATIC MODEL

Extensive research has been carried out on developing a kinematic model multi-axis machining center with different approaches. The key point for developing a post processor is the configuration of machine tools. Therefore, it is critical to set up standard machine tools configuration file. All parameters that are needed in building kinematic model are defined in the configuration file [3]. The validity and effectiveness of the post processor depends on these parameters of the kinematic model.

Hence, exact information of these parameters and their accurate values are crucial.

2.2. CUTTER LOCATION (CL) DATA

The model of a part to be machined is designed in CAD/CAM software as surfaces and the cutter location (CL) points in machining trajectories are generated by

discretizing these surfaces within allowable tolerance. To increase the generality of part model, CL data are generated without considering the structure of multi-axis machine tools. The part is assumed to be fixed, and all motions are completed by the cutters. Different structures of multi-axis machines have the same CL data [9]. The cutter location data consists of the cutter position and orientation of the cutter with respect to the work-piece co-ordinate system. In ISO format, the CL data is represented by (x, y, z, i, j, k) where (x, y, z) is co-ordinates of cutter location and (i, j, k) is the direction cosine of the tool axis orientation respectively. Cutter position is defined as the cutter centre tip and not the cutter contact (CC) point. Hence, the CL point is a given point on the cutter [4,5]. Figure 2.1 shows CL data information

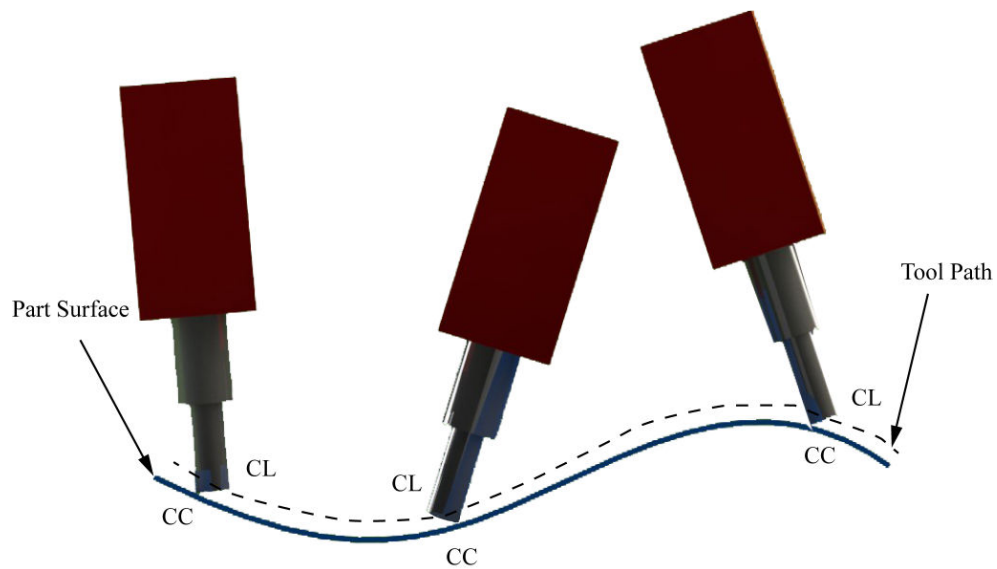


Figure 2.1 The representation of cutter contact (CC) points and cutter location (CL) points on part surface

The CLS (Cutter Location Source) File is converted from the operations of CAM in UG software, which belongs to a ASCII file comprising mainly of the coordinates of geometry and other auxiliary codes to operate machine tool, to explain the operation information [7]. The keywords of CL data are shown in Table 2.1

Table 2.1 Keywords of CL data in UG system

Key words in CLSF	Interpretation
TOOL PATH	Tool path operation in CAM
TLDATA	Tool cutter information
MSYS	Machining coordinate system in CAM
GOTO/X,Y,Z,I,J,K	Linear interpolation , X, Y, Z is the reference point of cutting tool, I, J, K is the spindle vector of the cutting tool
SPINDL	Spindle revolution
FEDRAT	Feed rate
RAPID	Move with the max. speed
\$\$	Comment statement
CIRCLE	Circle interpolation

2.3. POST PROCESSING

The main functions of a post processor are, (i) Understanding and interpreting the CL data generated by CAM software and (ii) Transformation of machine independent CL data (x, y, z, i, j, k) into machine dependent NC commands such as (X,Y,Z,A,B) , (X,Y,Z,A,C) or (X,Y,Z,B,C) [4]. Most of the commercial CAM software provides CL data file in ISO format. This CL data file is saved as Cutter Location Source File (CLSF). Y.Y. Hsu, S.S. Wang has discussed the post processing method of UG/POST system in detail in [1].

Post Builder provides two post processing methods. In the first method, CAM tool path data including tool tip position and tool axial direction are used to produce the CLSF. This is followed by applying a specific machine post processor to produce NC code corresponding to the positions of machine axes according to different machine structure and controller. In the second method, a postprocessor directly reads the cutting path data and then translates them into the NC code required. This study adopted the second method to develop a postprocessor with the function of compensation. The flowchart for establishing the compensation mechanism is shown in Figure 2.2 the postprocessor employed in UG/POST is of a semi-open structure and the development program language is Tool Command Language (TCL). UG/POST uses manufacturing output manager (MOM) as a driving tool for events, whose functions include reading tool path data, conducting kinematic translation, and loading event handler and definition file. An event is an action that the machine is ordered to perform during tool path, such as linear motion, rapid motion, and tool change. The event handler then conducts the

required pre-process, and depending on different definitions of controller, outputs an NC file to produce NC code. MOM is a closed system, but its event handler and definition file are open systems. Therefore, the present study installed the compensation model in the event handler, obtained the tool pose vector (position and orientation), V_s , describing the tool path of CAM system through MOM, and translated the tool pose vector to the position vector, U_s , in the machine axes coordinates with the inverse kinematic translation.[1]

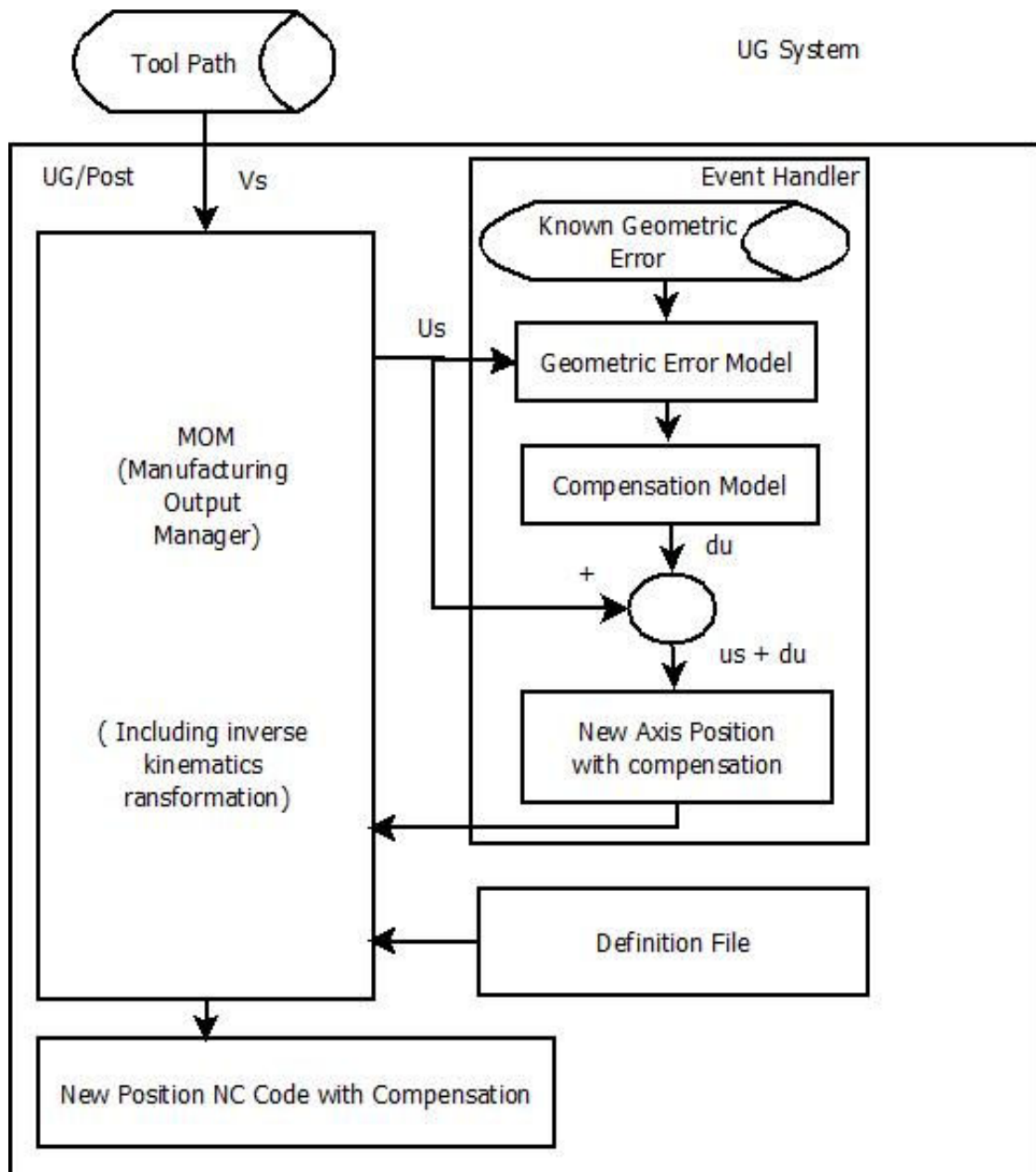


Figure 2.2 The error compensation mechanism in UG Post Processor [1]

3. INVERSE KINEMATICS TRANSFORMATION

R.-S. Lee and C.-H. She have developed the analytical equations for NC data for three typical five-axis machine tool configurations.[6] Based on their work for spindle-tilting/ universal rotary head type configuration, the inverse kinematics transformation equation have been developed. The position vector is written as $[Q_x \ Q_y \ Q_z \ 1]^T$ and the tool axis vector is of form $[K_x \ K_y \ K_z \ 0]^T$. The superscript “T” denoted the transposed matrix. Figure 3.1 shows the geometric definition of CL data.

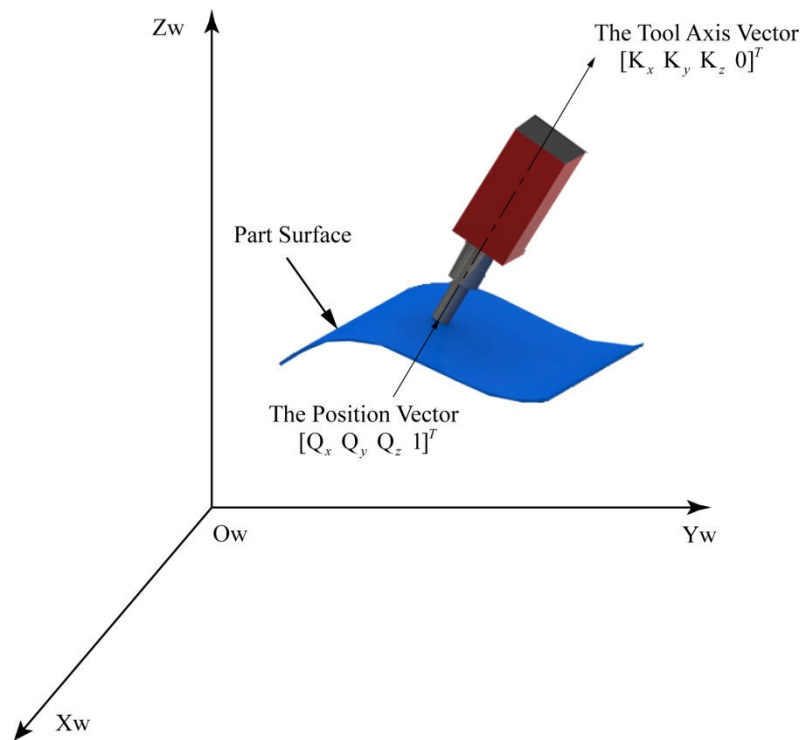


Figure 3.1 Geometric definition of Cutter Location (CL) data in work-piece coordinate system, The position vector is $[Q_x \ Q_y \ Q_z \ 1]^T$ and the tool axis vector is $[K_x \ K_y \ K_z \ 0]^T$ are also shown part surface.

For the spindle tilting type configuration with rotational axes A & C, the pivot point is selected to be the intersection of these two axes. In case of this type of machines, pivot point is point where rotary head tilts. $P_x P_y P_z$ are the relative translation distances in X, Y and Z respectively. The effective tool length, L_t , is distance between pivot point R to cutter tip center O_t . It can be calculated by,

$$L_t = L_{HO} + L_{LO} \quad (1)$$

Where LHO and LLO is tool holder offset and tool length offset respectively. In more general terms, tool holder offset is pivot distance and tool length offset is gage length. Figure 3.2 shows coordinate system of spindle-tilting AC type configuration.

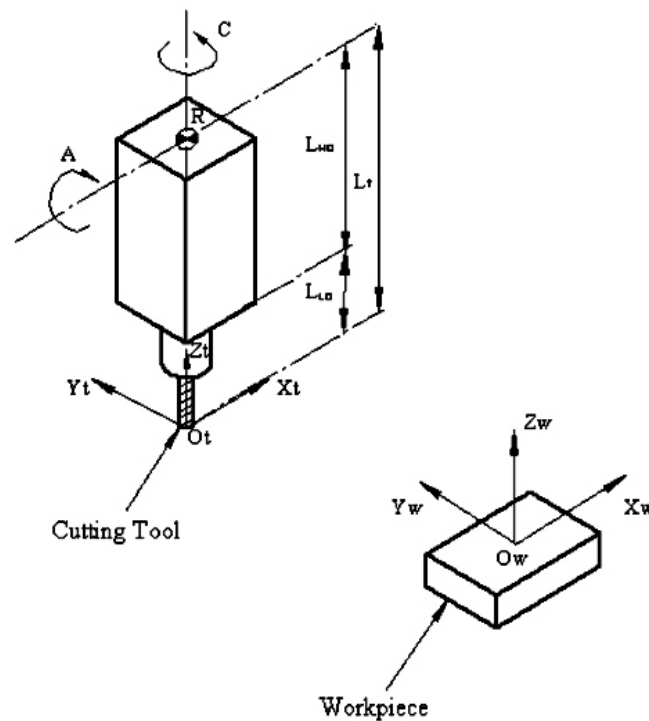


Figure 3.2 Coordinate system of spindle-tilting AC type configuration

The inverse kinematics transformations are given by,

$$[K_x K_y K_z 0]^T = T(P)R_z(\theta_C)R_x(\theta_A)[00 \ 1 \ 0]^T \quad (2)$$

$$[Q_x Q_y Q_z 1]^T = T(P)R_z(\theta_C)R_x(\theta_A)[00 \ -L_t 0]^T \quad (3)$$

$$[X \ Y \ Z \ 1]^T = [P_x \ P_y \ P_z - L_t \ 1] \quad (4)$$

Where,

$$T(P) = \begin{bmatrix} 1 & 0 & 0 & P_x \\ 0 & 1 & 0 & P_y \\ 0 & 0 & 1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_z(\theta_C) = \begin{bmatrix} \cos\theta_C & -\sin\theta_C & 0 & 0 \\ \sin\theta_C & \cos\theta_C & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_x(\theta_A) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_A & -\sin\theta_A & 0 \\ 0 & \sin\theta_A & \cos\theta_A & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Solving Equations (2) - (4) gives,

$$A = \theta_A = \cos^{-1}(K_z) \quad (5)$$

$$C = \theta_C = -\tan^{-1}(K_x/K_y) \quad (6)$$

$$X = P_x = Q_x + L_t \sin \theta_A \sin \theta_C \quad (7)$$

$$Y = P_y = Q_x - L_t \sin \theta_A \cos \theta_C \quad (8)$$

$$Z = P_z - L_t = Q_z + L_t \cos \theta_A - L_t \quad (9)$$

Equations (5)-(9) give the theoretical machine dependent coordinates. The actual coordinates vary on because of the tool length compensation vector for each axis. Tool length compensation for Z axis has been already taken care.

Tool length compensation for X and Y axis must be calculated for accurate NC program. If the rotational axes are not perpendicular to each other, then there exists rotation around an arbitrary axis in the space; the dot product of orthogonal axis is not zero. $\hat{a} \cdot \hat{c} = 0$ is assumed. Hence, angular compensation of rotary axis is negligible. The following derivations give the actual machine dependent coordinates.

Equations (2)-(4) can be written as,

$$[K_x K_y K_z 0]^T = T(P)R_z(\theta_C) T(J)R_x(\theta_A)T(t)[0 0 1 0]^T \quad (10)$$

$$[Q_x Q_y Q_z 1]^T = T(P)R_z(\theta_C) T(J)R_x(\theta_A)T(t)[0 0 -L_t 0]^T \quad (11)$$

$$[X Y Z 1]^T = [P_x P_y P_z -L_t 1] \quad (12)$$

Where,

Tool axis compensation vector is $[t]^T = [t_x t_y t_z 1]^T$

Rotation center compensation vector is $[J]^T = [J_x J_y J_z 1]^T$

Equations (10)-(12) gives,

$$A = \theta_A = \cos^{-1}(K_z) \quad (13)$$

$$C = \theta_C = -\tan^{-1}(K_x/K_y) \quad (14)$$

$$X = P_x = Q_x - \cos\theta_C(t_x + J_x) + \sin\theta_C[J_y + t_y\cos\theta_A - \sin\theta_A(t_z - L_t)] \quad (15)$$

$$Y = P_y = Q_x - \sin\theta_C(t_x + J_x) - \cos\theta_C[J_y + t_y\cos\theta_A - \sin\theta_A(t_z - L_t)] \quad (16)$$

$$Z = P_z - L_t = Q_z + J_z - t_y\sin\theta_A - \cos\theta_A(t_z - L_t) - L_t \quad (17)$$

Comparing Equations (15)-(17) with (7)-(9), offset in X, Y and Z respectively will be,

$$X_{offset} = -\cos\theta_C(t_x + J_x) + \sin\theta_C[J_y + t_y\cos\theta_A - t_z\sin\theta_A] \quad (18)$$

$$Y_{offset} = -\sin\theta_C(t_x + J_x) - \cos\theta_C[J_y + t_y\cos\theta_A - t_z\sin\theta_A] \quad (19)$$

$$Z_{offset} = J_z - t_y\sin\theta_A - t_z\cos\theta_A \quad (20)$$

Now for a machine under consideration, as \hat{a} and \hat{c} are assumed it to be orthogonal, $\hat{a} \times \hat{c}$ will have component in Y axis.

Hence, rotational compensation vector will have only J_y component. i.e. J_x and J_z will be zero. Machine controller does not take account these compensation vectors while machining. Also, machine controller itself calculates tool compensation in Z direction. Hence t_z will be zero.

4. EXPERIMENTAL IMPLEMENTATION

4.1. 5-AXIS MACHINING USING NX-CAM

The first step in the experiment is to actually cut the part by following the post-processing procedure discussed in Section 2.1. Figure 4.1 shows some screen shots of the procedure. Figure 4.2 shows the machining of a semi-sphere. The parts are pretty accurate, but this paper would explore more accurate procedure as discussed in the following section.

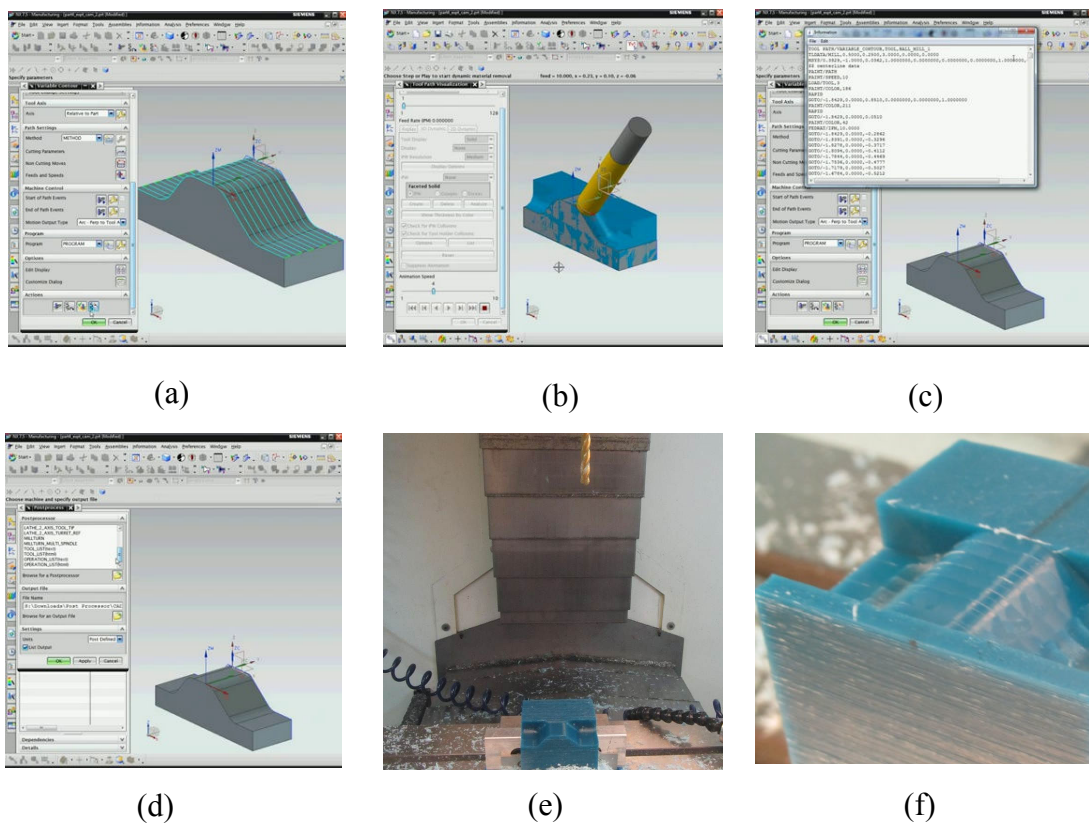


Figure 4.1 Using NX Post processor to output CNC code to drive Fryer 5X machining center: (a) Tool path planned on the CAD model; (b) Validation by simulation of tool path; (c) CLSF file generated; (d) Post-processing for Fryer 5X; (e) Machining using Fryer 5X; (f) Close-up of the Wax part.



Figure 4.2 Using NX Post processor to drive Fryer 5X machining center to make a wax part

4.2. EXPERIMENTAL PLAN FOR COMPENSATION VECTORS

Based on the analysis in Section 2.2 and 2.3, experiments for error compensation were designed and carried out. The objective of experiments is to determine the numerical value of rotational compensation vector and tool axis compensation vector for spindle-tilting five-axis CNC milling machine Fryer-5X 45. The objective is to use simple cutting operations to decouple and find the variables in the compensation vectors. For illustration purpose, \hat{a} and \hat{c} are assumed it to be orthogonal and machine controller itself calculates tool compensation in Z direction, thus t_z , J_x and J_z will be zero. This assumption is that the mounting of two rotational axes is according to the specifications. The experiment designs consist of simple machining of wax block with different combinations of A and C axis along both X and Y axis. Wax was chosen so that we can assume that there is no tool wear during experiment to concentrate on the machine axis errors. The sequence of the cutting operation is shown in Table 4.1 and Table 4.2 along with corresponding expressions for X_{offset} and Y_{offset} derived in the above section.

Table 4.1 Expressions for X_{offset} and Y_{offset} when $\theta_A=0$

θ_C	0°	90°	180°	-90°	-180°
X_{offset}	$-t_x$	(J_y+t_y)	t_x	$-(J_y+t_y)$	t_x
Y_{offset}	$-(J_y+t_y)$	$-t_x$	(J_y+t_y)	t_x	(J_y+t_y)

Table 4.2 Expressions for X_{offset} and Y_{offset} when $\theta_C=0$

θ_A	0°	90°	-90°
Xoffset	$-t_x$	$-t_x$	$-t_x$
Yoffset	(J_y+t_y)	$-J_y$	$-J_y$

Figure 4.3 shows the deviation associated with the reference cut $\theta_C=0^\circ$ $\theta_A=0^\circ$ and measured machining of wax block. It is designed so that we can use two simple cuts to find the offsets and necessarily compensation factors of the CNC machine. The deviations can be easily measured through the dimension of L as shown in Figure 4.3:

$$L = D - 2r + (\delta_2 - \delta_1) \quad (21)$$

Where,

L= Thickness of uncut portion;

r= Radius of tool

δ_1 = deviation with reference cut $\theta_C=0^\circ$ $\theta_A=0^\circ$

δ_2 = deviation with following cut with different combinations of θ_C and θ_A

During the experiment center to center distance between two respective cuts is kept constant. Center to center distance is indicated by “D” in Figure 4.3. To simplify the calculations, D is taken as twice the diameter of the tool

$$D = 2 * (2r) \quad (22)$$

Hence, Equation (21) becomes,

$$L = 2r + (\delta_2 - \delta_1) \quad (23)$$

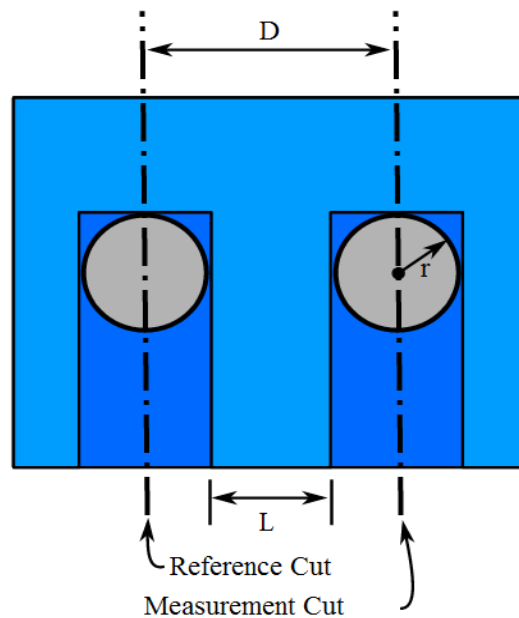


Figure 4.3 Deviation associated with the reference cut $\theta_C=0^\circ$ $\theta_A=0^\circ$ and measured cut

In other words, by measuring L at various points, the deviations in x and y directions, δx and δy , can be obtained. Similarly, with different combinations of θ_C and θ_A , the Table 4.3 gives the deviations in X and Y axis.

Table 4.3 Deviation in X and Y axis for different θ_C and θ_A

Combination of θ_A & θ_C	Deviation along X axis	Deviation along Y axis
$\theta_C=0^\circ$ $\theta_A=0^\circ$	δx	δy
$\theta_C=90^\circ$ $\theta_A=0^\circ$	$(-)\delta y$	δx
$\theta_C=180^\circ$ $\theta_A=0^\circ$	$(-)\delta x$	$(-)\delta y$
$\theta_C=(-)90^\circ$ $\theta_A=0^\circ$	δy	$(-)\delta x$
$\theta_C=(-)180^\circ$ $\theta_A=0^\circ$	$(-)\delta x$	$(-)\delta y$

4.3. EXPERIMENTAL SETUP

Experiments were carried out on the spindle-tilting 5-axis CNC milling center - Fryer 5X-45 with A and C as rotational axis. The following are the specifications of machine:

X Travel = 45"

Y Travel = 25"

Z Travel = 25"

Rotational axis limits: A = +/- 150°; C= +/- 213°

The part was machined along both X and Y directions. Experiments were conducted with the following machining parameters:

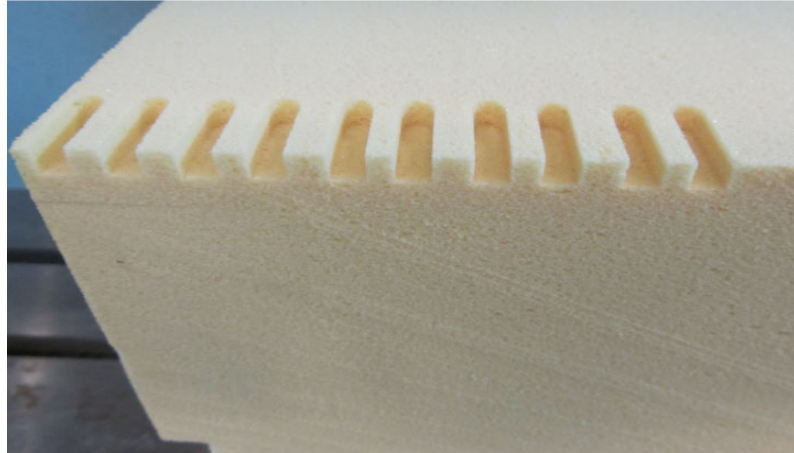
Work-piece Material: Wax and high density foam

Tool: 0.25" diameter Flat end mill

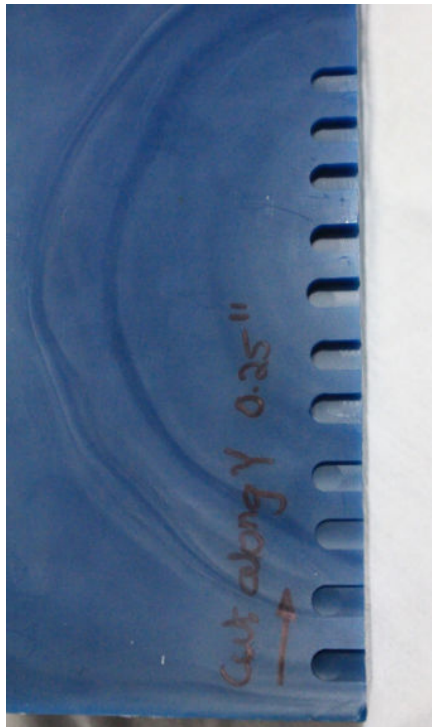
Spindle speed: 1000 rpm

Feed rate: 60 IPM

The CAD drawing of the machining experiment was drawn in NX. 3 axis machining tool path was generated in NX CAM. NC program for machining on Fryer-5X was formed using developed post processor. Before the start of experiment, top surface, front surface and left side surface was milled. X-Y-Z was set on the left front top corner of the milled block. As per the previous section, during the experiment D is kept constant. $D = 0.5''$. Radius of tool is $0.125''$ and $(\delta_2 - \delta_1)$ gives total deviation from original value of L along the measured direction. Figure 4.4 shows machined slots along both (a) X axis and (b) Y axis direction with the above machining parameters.



(a)



(b)

Figure 4.4 Machined slots with 0.25" diameter flat end mill with spindle speed of 1000 RPM and feed rate of 60 IPM- (a) along X axis, raw material: high density foam block
(b) along Y axis, raw material: wax block

4.4. MEASUREMENT, DATA RECORDING AND ITS PROCESSING:

To get accurate values of compensation vector components, it was essential to carry out measurement procedure correctly using high fidelity measurement device. Hence, laser displacement sensor was used for measurement of the widths of the machined slots. The machined slots were measured using high-speed, high-accuracy Keyence LK G-5000 Series laser displacement sensor. The sensor has repeatability of $0.005\mu\text{m}$, accuracy of 0.02%. Measurement system includes laser displacement sensor, controller and software to collect sampling data. Figure 4.5 shows the setup for the measurement system.

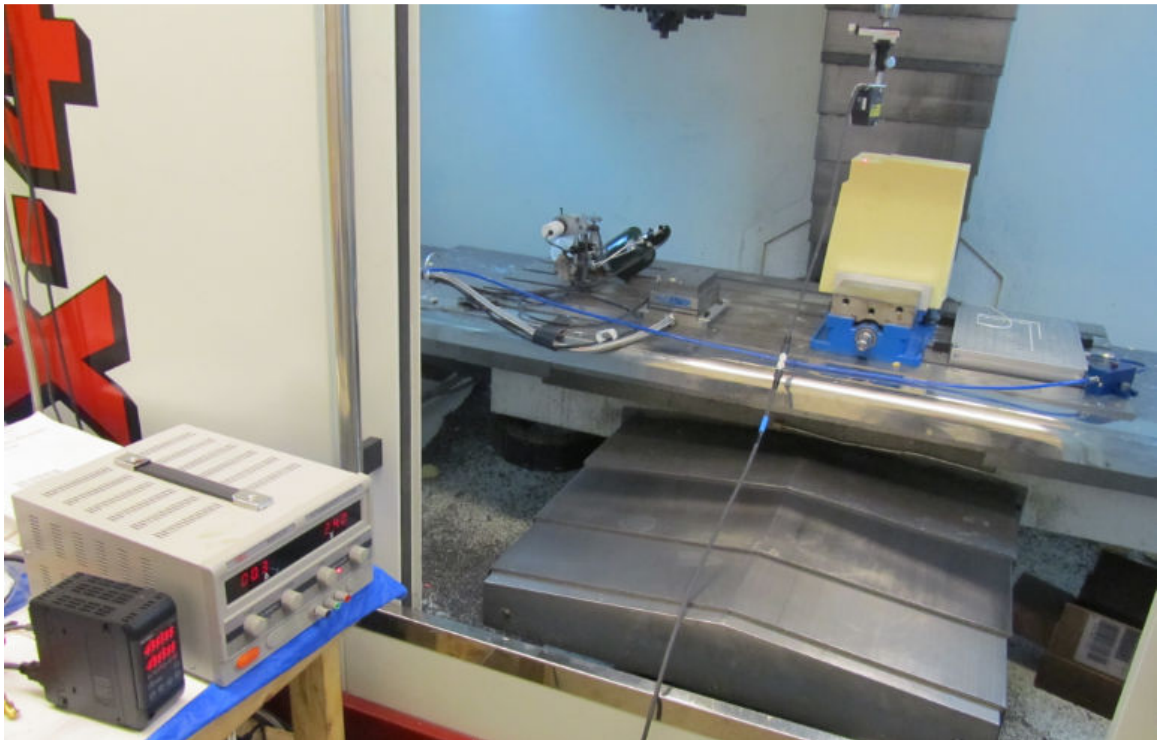


Figure 4.5 Setup for measurement system

Following procedure has been used for data recording of displacement measurement. Software and controller used:

1. Keyence sensor was secured to the mounting plate and whole assembly was attached to the spindle. During the displacement measurement of a machined slot, the sensor head was mounted in such a way that the emitted and reflected lights were not blocked by the vertical surface of the slot [12]. Figure 4.6-(a) and (b) illustrates correct and wrong mounting of sensor head respectively.

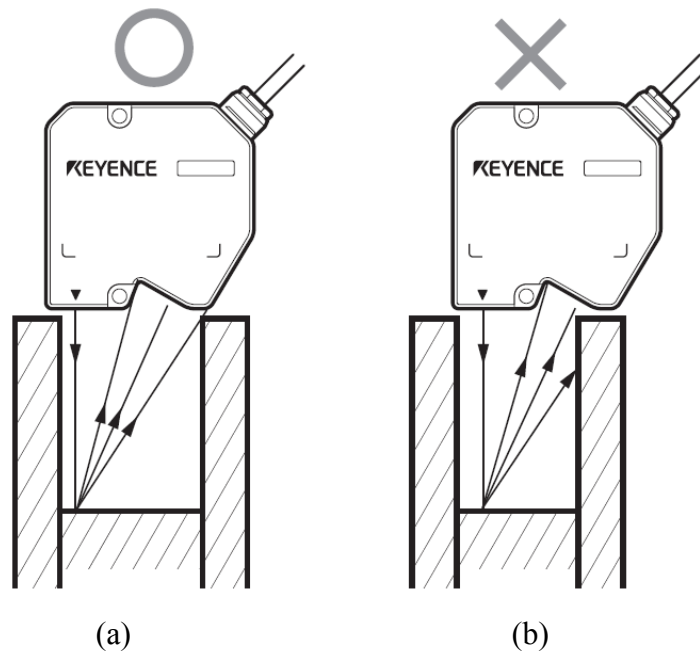
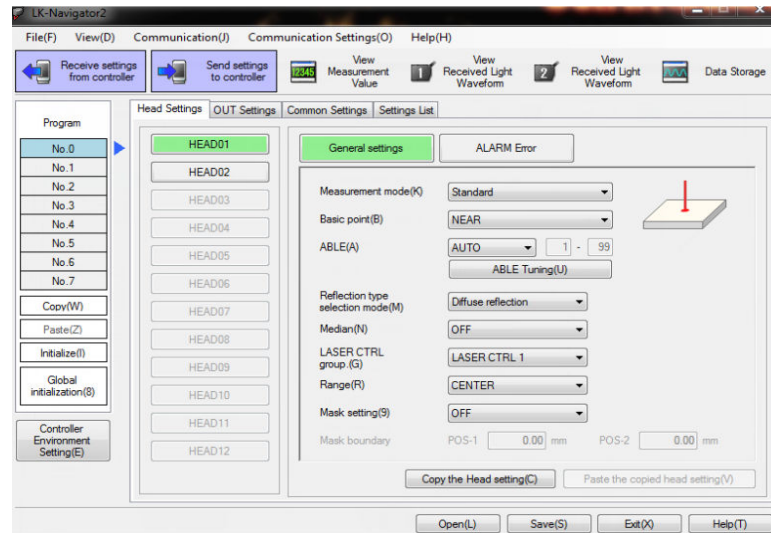
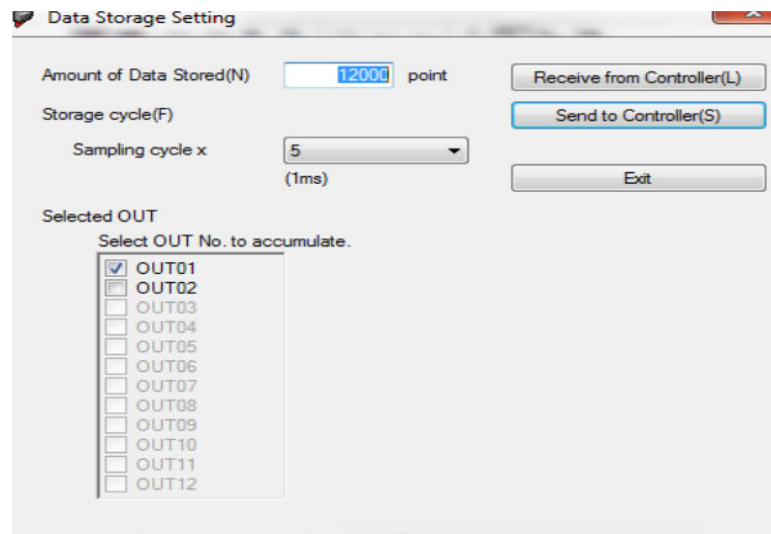


Figure 4.6 (a) Correct mounting of sensor head for taking measurements of slot (Reflected light rays received by receiver) (b) Wrong mounting of sensor head (Reflected rays are intercepted by edge of slot)

2. The connector of head-to-controller cable was connected to the head connector 1 on the terminal panel of the controller. 24 VDC power supply was then connected to the terminals 1 and 2 of a 12-pin terminal block. LK-Navigator 2 software was used to operate the sensor from computer. It displays the measured value and the data of measured values can be stored.
3. Control knobs on the sensor head were adjusted in such a way that laser beam will remain steady during the motion. This ensures that the beam is focused during data recording.
4. Measurement and data storage settings have been selected as shown in Figure 4.7–(a) and (b) respectively.



(a)



(b)

Figure 4.7 (a) and (b) Snapshots of the Measurement and data storage settings on LK-Navigator 2 software respectively

5. These settings were sent to controller prior to starting data collection.
6. The spindle was moved, first along X axis with a feed rate of 60 IPM and then along the Y axis. At the same time data recording was started using LK-Navigator

2. Figure 4.8 shows the measurement carried out along X axis using laser displacement sensor- Keyence LKG-5000. The same procedure was carried out for measurements along Y axis.



Figure 4.8 Measurement carried out along X axis using laser displacement sensor- Keyence LKG-5000.

7. LK-Navigator 2 shows the data as shown in Figure 4.9. The data is stored in the CSV file format.

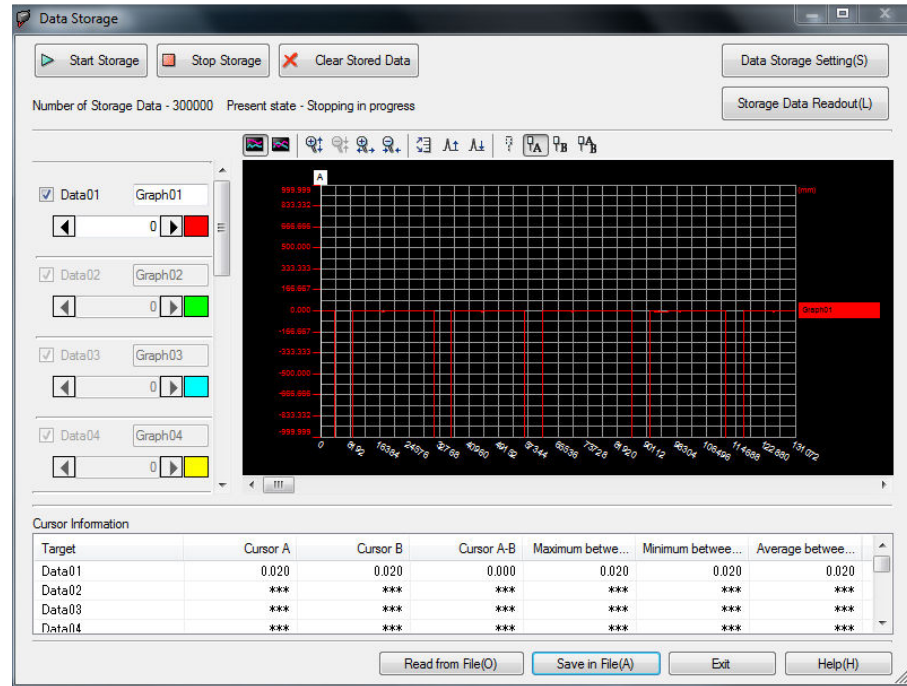


Figure 4.9 Snapshot of the recorded data in on LK-Navigator 2 software

8. Now, this recorded data is the displacement in vertical direction and our focus is to measure the dimensions along X and Y directions/axes. Computational code processes the recorded data and converts in to required dimensions along X and Y directions respective to the movement of laser sensor. Matlab[®] was used to calculate the distances of desired slots. Following algorithm, represented in Figure 4.10, was used for code:

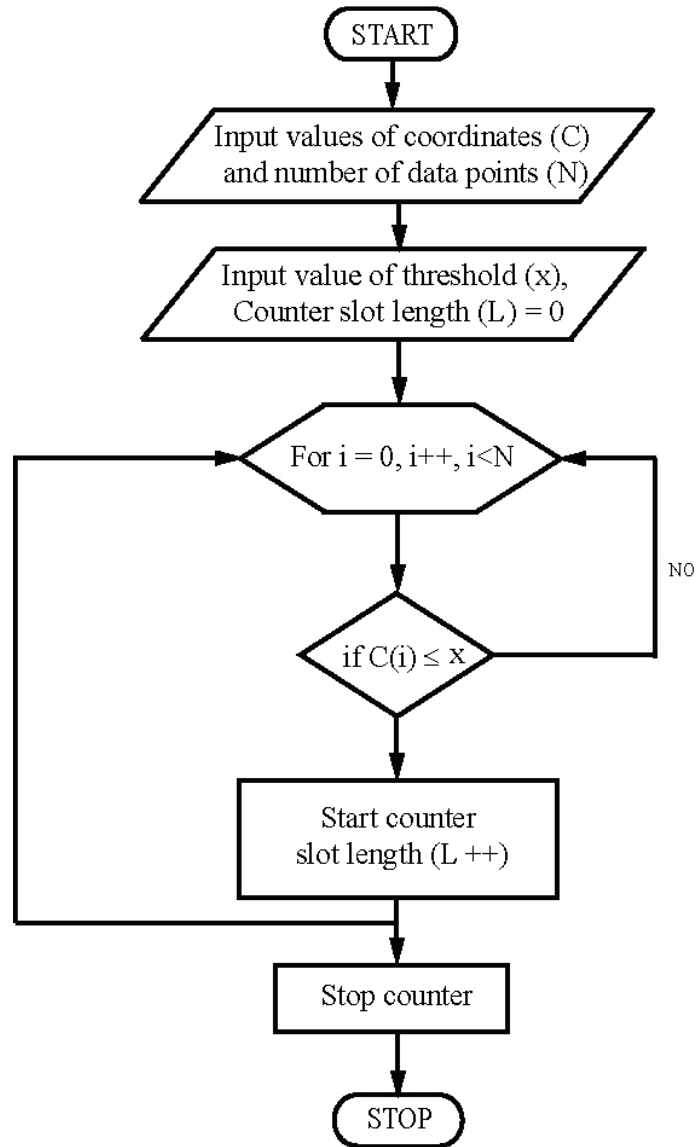


Figure 4.10 Algorithm for the calculating slot length from the data collected using laser displacement sensor

5. RESULTS AND VALIDATION

Using the expressions discussed in the previous section and measurements taken, calculations were carried out and values of t_x , t_y and J_y were found.

For tool axis compensation vector, Table 5.1 shows its individual values.

Table 5.1 Tool axis compensation vector values

Parameter	Value (inches)
t_x	0.002
t_y	0.001
t_z	0

For rotation center axis compensation, Table 5.2 shows its individual values.

Table 5.2 Rotation center axis compensation vector values

Parameter	Value (inches)
J_x	0
J_y	0.0005
J_z	0

Hence,

Tool axis compensation vector is $[t]^T = [0.002 \ 0.001 \ 0 \ 1]^T$

Rotation center compensation vector is $[J]^T = [J_x \ J_y \ J_z \ 1]^T$

Now, these two vectors have been included in the post processor. In UG-Post Builder, these vectors are added to the offset values to machine 4th axis center to 5th axis center. Snapshot of the offset input to postprocessor is shown in Figure 5.1.

4th Axis Center To 5th Axis Center	
X Offset	0.002
Y Offset	0.0015
Z Offset	0.0

Figure 5.1 Offset Input to Post Processor: NX Post Builder

Validation procedure of these offset values is discussed below:

1. CAD drawing of rectangular pockets on different planes, namely – XY and YZ plane was drawn in NX 7.5. The size of the pocket is 1 X 0.75 X 0.2 inches. Size of the raw block is 5.5 X 4 X 4.5 inches. Figure 5.2 shows the CAD drawing of the rectangular pockets on XY and YZ plane.

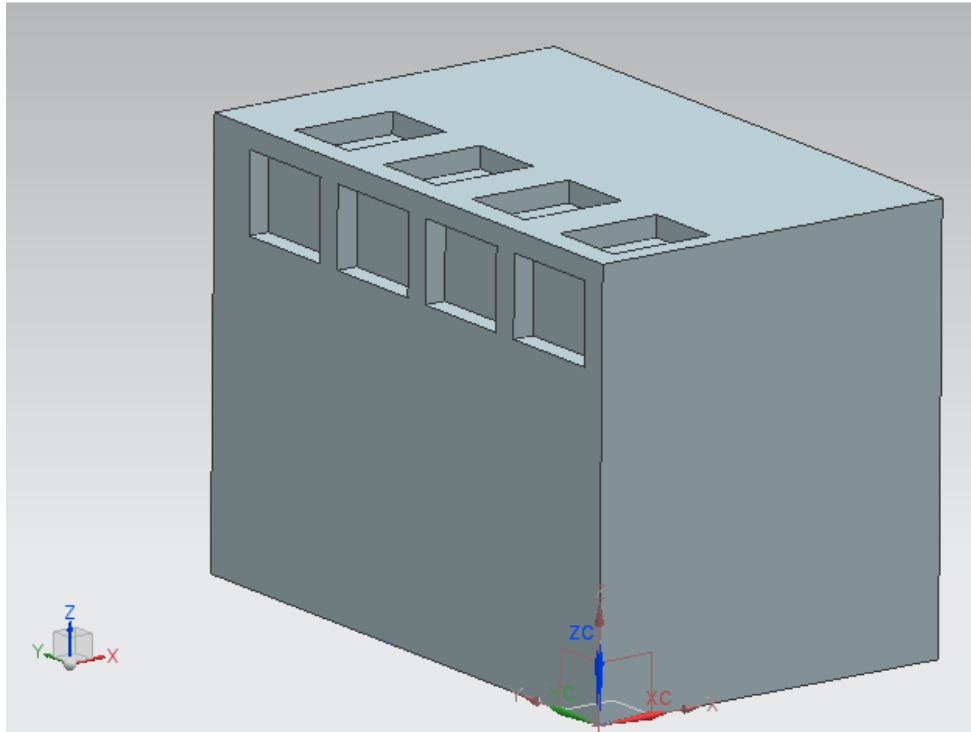
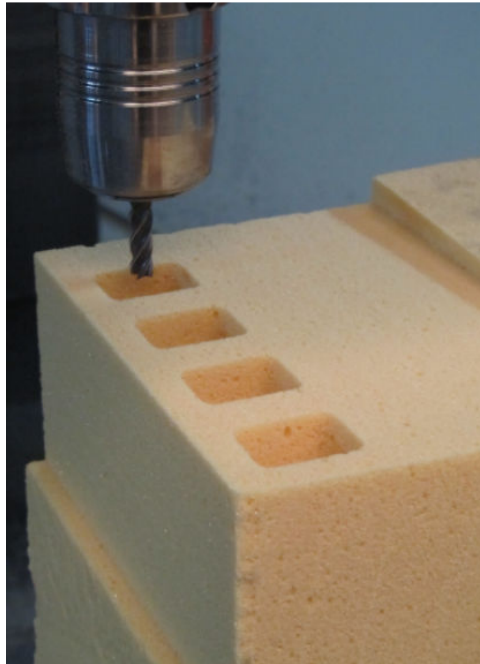
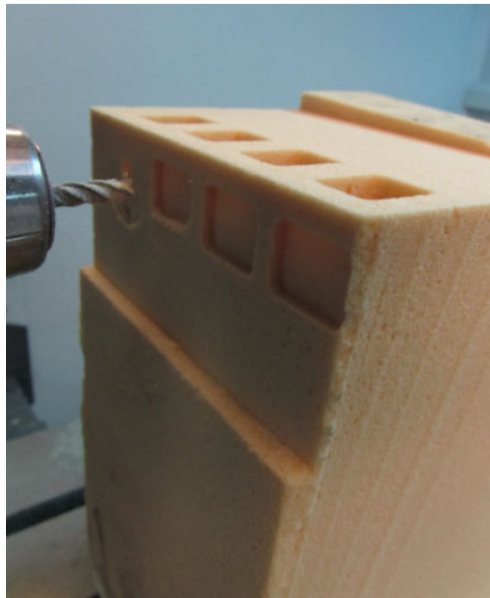


Figure 5.2 CAD drawing showing rectangular pockets of size 1 X 0.75 X 0.2 inches on XY and YZ plane of rectangular block of size 5.5 X 4 X 4.5 inches

2. Machining tool path was generated using NX CAM and Cutter Location file CLS file was created. The CLSF was processed by using developed post processor and NC program was obtained.
3. Rectangular pockets were machined on planes XY and YZ as shown in Figure 5.3–(a) and (b).



(a)



(b)

Figure 5.3 (a) – (b) Machining of rectangular pocket on XY plane and YZ plane; raw material: high density foam of size 5.5 X 4 X 3.5 inches

4. Same methodology of measurement, discussed in the previous section, was used for the measurement of the dimensions of length, width and depth. The following Table 5.3 and Table 5.4 shows the comparison of the actual measured dimensions of the all four rectangular pocket with the assigned dimensions in the CAD drawing, with and without compensation for case 1: XY plane and case 2: YZ plane respectively.

Case 1: XY plane

Table 5.3 (a) – (b) the comparison of the actual measured dimensions of the rectangular pocket along X and Y axis, with the assigned dimensions in the CAD drawing, with and without compensation for case 1: XY plane

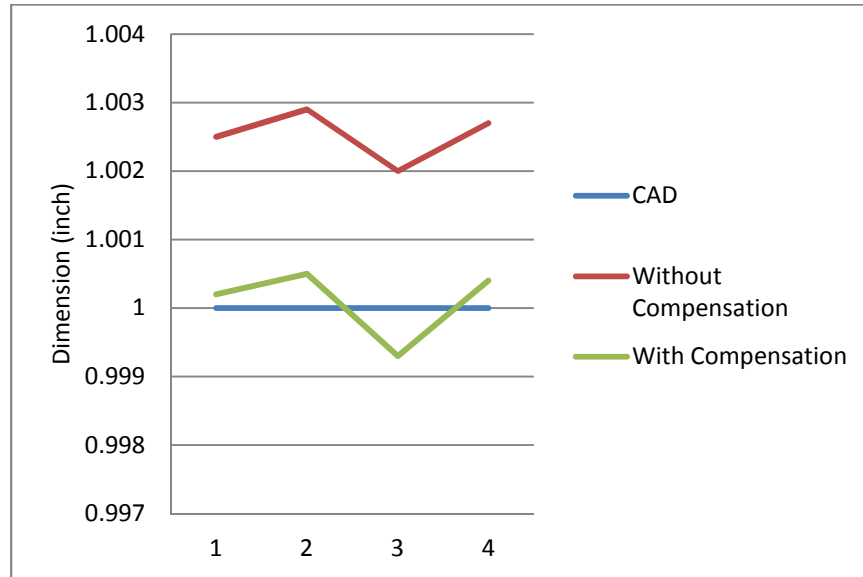
(a) Along X axis

Pocket Number	CAD (inch)	Without Compensation (inch)	With Compensation (inch)
1	1	1.0025	1.0002
2	1	1.0029	1.0005
3	1	1.0020	0.9993
4	1	1.0027	1.0004
Average	1.0000	1.0025	1.0001
Standard deviation	0.0000	0.0004	0.0005

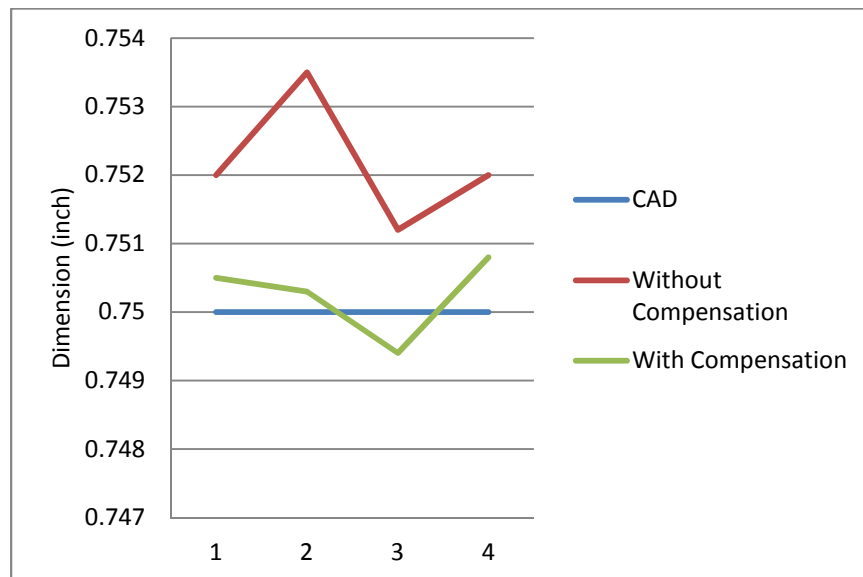
(b) Along Y axis

Pocket Number	CAD (inch)	Without Compensation (inch)	With Compensation (inch)
1	0.75	0.7520	0.7505
2	0.75	0.7535	0.7503
3	0.75	0.7512	0.7494
4	0.75	0.7520	0.7508
Average	0.7500	0.7522	0.7503
Standard deviation	0.0000	0.0010	0.0006

Figure 5.4 (a) and (b) gives the graphical comparison of the dimensions –along X axis and Y axis respectively for Case 1: XY plane



(a)



(b)

Figure 5.4 Graph of the comparison of the dimensions – (a) along X axis for Case 1: XY plane (b) along Y axis for Case 1: XY plane

Case 2: YZ plane

Table 5.4 (a) – (b) the comparison of the actual measured dimensions of the rectangular pocket along X and Y axis, with the assigned dimensions in the CAD drawing, with and without compensation for case 2: YZ plane

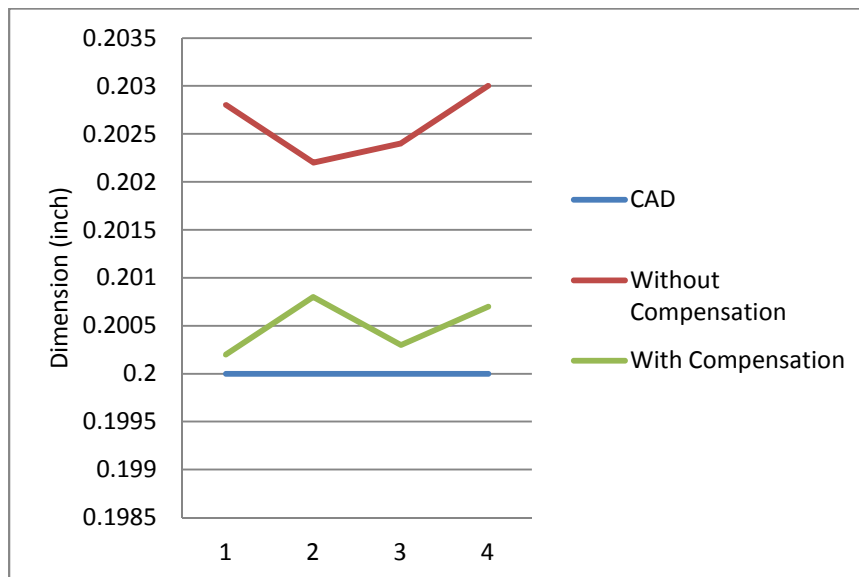
(a) Along X axis

Pocket Number	CAD (inch)	Without Compensation (inch)	With Compensation (inch)
1	0.2	0.2028	0.2002
2	0.2	0.2022	0.2008
3	0.2	0.2024	0.2003
4	0.2	0.2030	0.2007
Average	0.2000	0.2026	2.0005
Standard deviation	0.0000	0.0004	0.0003

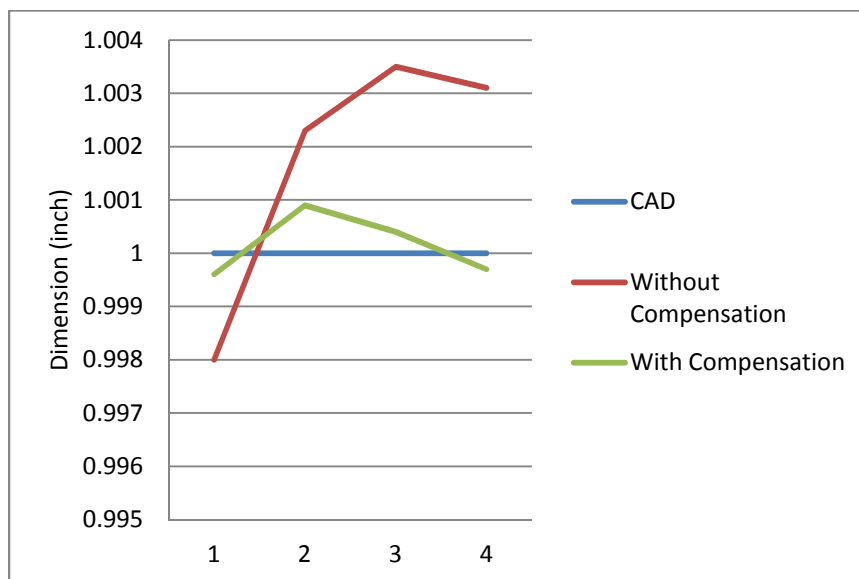
(b) Along Y axis

Pocket Number	CAD (inch)	Without Compensation (inch)	With Compensation (inch)
1	1	0.9980	0.9996
2	1	1.0023	1.0009
3	1	1.0035	1.0004
4	1	1.0031	0.9997
Average	1.0000	1.0017	1.0002
Standard deviation	0.0000	0.0025	0.0006

Figure 5.5 (a) and (b) shows the graphical comparison of the dimensions –along X axis and Y axis respectively for Case 2: YZ plane



(a)

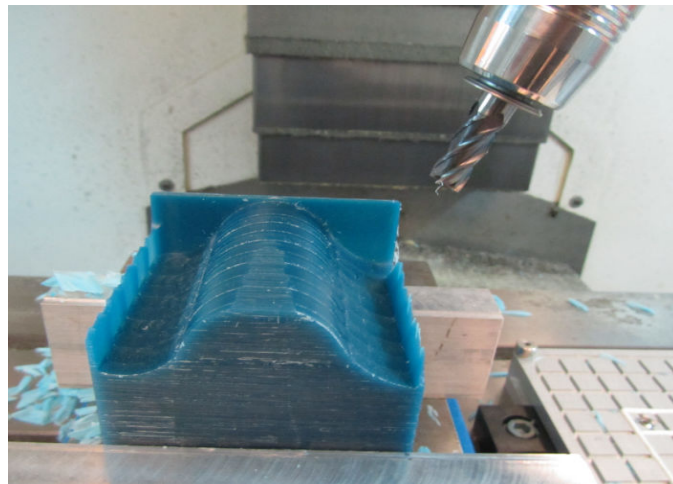


(b)

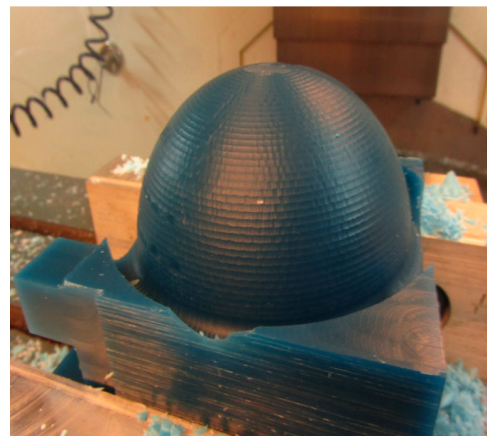
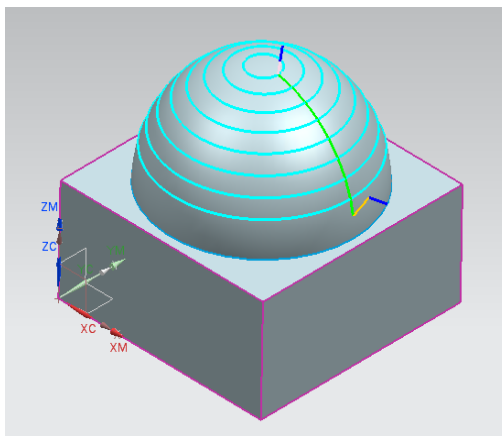
Figure 5.5 Graph of the comparison of the dimensions – (a) along X axis for Case 2: YZ plane (b) along Y axis for Case 2: YZ plane

6. DISCUSSIONS

The validated developed postprocessor has been used to manufacture parts used for academic as well as research projects. NC program for freeform part was generated using the post processor. Figure 6.1 – (a) and (b) illustrates the some 5-axis freeform machined parts along with its CAM model showing toolpath. CAM model of Figure 6.1-(a) has been already shown in Figure 4.2.



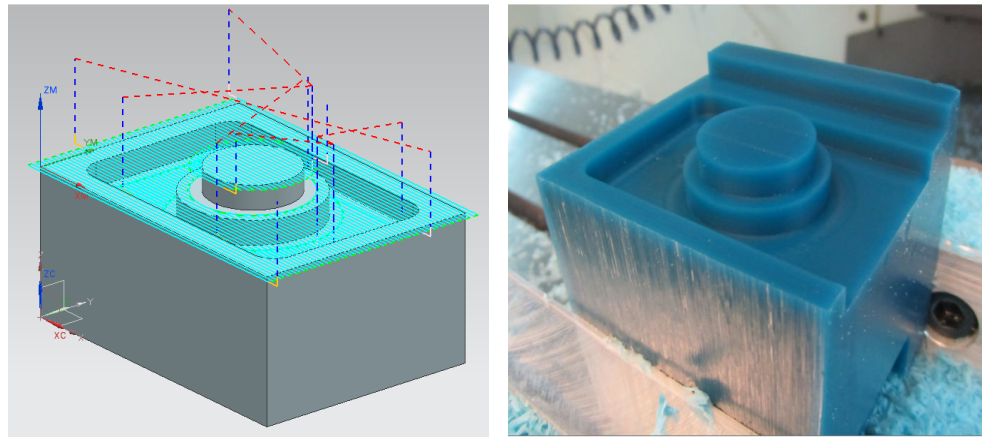
(a)



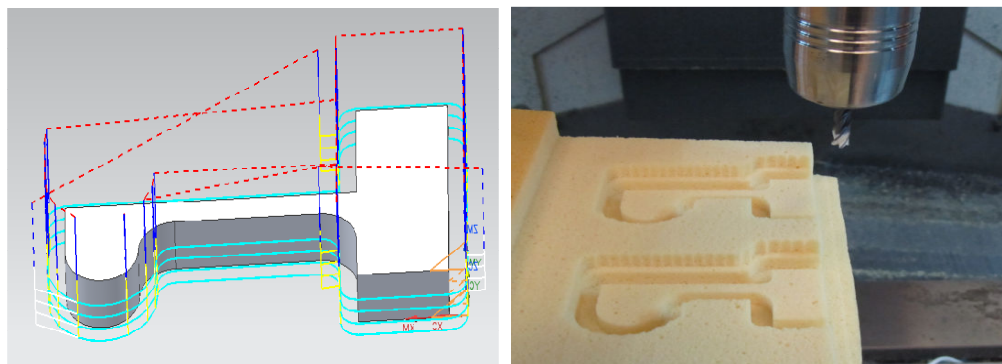
(b)

Figure 6.1 (a) and (b): 5-axis freeform machined parts whose NC program has been generated using post processor

To check the capability of post processor to generate NC program for 3-axis machining, some parts were fabricated. Figure 6.2 – (a) and (b) illustrates the 3-axis parts along with their CAM models showing toolpath:



(a)



(b)

Figure 6.2 (a) and (b): 3-axis parts machined in wax and high density foam along with CAM models

Although the research has successfully reached its aims, there were some limitations in the proposed work. First, developed post processor does not take account tool collision constraints. Simulation of the generated NC program can be integrated into UG system for the verification of tool collision. This will ensure the tool path optimization for the machining of part. Second, real time compensation can also be included as a part of methodology. Due to lack of controller's capability to execute real time compensation, this part was not included the methodology.

A further extension of the research work includes the application of same methodology to other types of five-axis CNC milling centers – table tilting with two rotations on the table type and table/ spindle tilting with one rotation each on the table and spindle type. Moreover, the same technique can be applied to develop a post processor for industrial robots. The compensation vectors can also determined for same robot using principle of inverse kinematic transformation.

7. CONCLUSION

Post processor for 5-axis CNC milling machine -Fryer 5X-45 with FANUC Series18i-MB5 controller has been demonstrated in NX/UG system – Post Builder. Postprocessor reads the tool path data and reformats it for Fryer 5X-45 with FANUC Series18i-MB5 controller. The post processor interpreted the CL data generated by NX CAM software, and then transforms the machine independent CL data into machine dependent NC commands. Actual parts were fabricated using the multi-axis capability of Fryer 5X-45. The paper also presents an alternative method to double ball test, R-Tests and laser scanner for obtaining kinematics parameters of CNC multi-axis machining center. The methodology for determining kinematics parameters of tool compensation vector for post processor has been developed successfully. First of all, the analytical equations of NC code were presented for spindle tilting type of five-axis machining center. Secondly, analytical equations with compensation vectors were obtained and the experiments were carried out obtain these vectors. In addition, the post processor for 5-axis CNC milling machine -Fryer 5X-45 with FANUC Series18i-MB5 controller have been developed in NX/UG system –Post Builder. The same procedure can be used for other CNC machining systems of which the structure, kinematics parameters of machine and controller configuration is the same with Fryer 5X-45.

8. ACKNOWLEDGEMENT

This research is a result of the phenomenal support and guidance extended to me by various individuals at Missouri University of Science & Technology. I would like to express my sincere thanks to my advisor, Dr. Frank Liou who has been a constant source of guidance and encouragement for me.

Secondly, I would like to thank Mr. Todd Sparks for his advice during conceptual work as well as experimentation part of my research. Also, the support from the Missouri S&T Manufacturing Engineering program is greatly appreciated.

Finally, I would like to thank Partners for the Advancement of Collaborative Engineering Education (PACE) and Intelligent Systems Center (ISC) for supporting this research financially.

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VITA

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Mihir received Distinguished Services Award in recognition of outstanding services as a Secretary, Council of Graduate Students at Missouri S&T for the academic year 2011-2012. He received his Master of Science degree in Manufacturing Engineering from Missouri S&T in May 2013.

