CNC Machining of Reverse Engineered Pseudo-symmetric Sculptured Surface Models

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Abstract

Replicating the complex sculptured surfaces with fair degree of precision cannot be accomplished without the use of reverse engineering technologies. The modern Computer Aided Design (CAD) systems offer variety of tools to manipulate 3D data of the reverse engineered parts/surface features so that these can be manufactured using multi-axis machining systems. Objectives: In the present work an attempt has been made to use the 3D scanning, CAD and Computer Numeric Control (CNC) technologies together for the machining of pseudo-symmetrical sculptured models. The 3D scanned models have been first converted to a triangulated/STereoLithography (STL) data model of suitable accuracy. Methods/Statistical Analysis: The developed STL models are further manipulated in the Pro-E CAD environment for making machinable STL model suitable for a custom developed CNC tool path planning software code. The CNC tool path code takes the modified STL model as input to generate the roughing and finishing tool path data required for actual machining. The validity of the developed CNC tool path data files is verified using a 3D graphical CNC simulator before machining. Findings: The design details of the complex sculptured parts can be captured from initial handmade / crafted models using 3D scanning technologies. The scanned data can be used to generate the 3D CAD model of the scanned part using the general purpose CAD modelling software. Finally the sculptured artistic models are machined on a 3-axis CNC milling lathe. The machined sculptured surface models closely matched the design intend of the scanned parts, which proves the validity of the procedure followed for the machining of complex pseudo-symmetric surface models. Application/Improvements: To machine the complex sculptured surfaces. Five axis CNC milling can be use to machine the Bezier and Non-Uniform Rational B-Spline (NURBS) surfaces instead of STL.

Keywords: Computer Numeric Control (CNC), Pseudo-symmetric, Reverse Engineering, Sculptured Surface Models, STereoLithography (STL)

1. Introduction

Throughout the history and around the world, humans have been using various crafted or artistic or ornamental parts to embellish their buildings, tools, belongings, and themselves these artistic features give the world perspective and personality at human scale. The design of the artistic feature involves various aspects such as analysis, creativity, and development. The designers or the craftsmen have to deal with several aspects in order to balance the beauty and functions of the artistic/ornamental products. Moreover, creativity of design typically depends on knowledge, experiences, and perceptions of the designers. Meanwhile, they have to consider their creative designs in term of possibility in production.
The craft work cannot be completed without the manual operations because such workmanship is the outcome of the some special skills owned by the artisans/craftsman. The initial canvas or the base parts required for craftwork are produced using some simple hand tools or manual machine tools as in case of wooden handicraft. As a result it takes considerable amount of time to carve the required base geometry of the part on which finally hand carving is done to generate the final product. The final outcome of the craft work is some specialized item and the number of finished pieces is generally very less, may be only one in some cases. Because of this reason most of the craftsmen prepare the rough canvas for their work themselves rather than going in for some kind of automation solution, as the cost of capital invested may not be distributed over the larger number of units. The stringent demand on product quality and shorter times to market has imposed few more constraints which need to be addressed. Thus a need has been identified for the development of new cost effective machining automation strategies for the production of artistic parts so as to reproduce the identical finished artistic products in smaller time duration.

The most intricate crafted parts are the pseudo-symmetric sculptured parts which need special techniques for their automatic machining using Computer Numeric Control (CNC) systems. The manual traditional machining methods are not sufficient for efficient machining of complex sculptured surfaces. The CNC technology can help in a great way to achieve the desired accuracy and repeatability for the machined sculptured parts. The CNC machining systems need the accurate tool path data and the appropriate machine configuration to cut the desired part shapes. Not all CNC machines can cut the sculptured shapes and particularly for machining of the pseudo-symmetric part shapes one need 3-axis milling lathe configuration.

The tool path data required for CNC machining is generated using Computer Aided Manufacturing (CAM) packages, which need the accurate geometry of 3D part model as the main input. In addition the CAM systems need the geometric shape and size of the cutting tool, the physical configuration of CNC machining system, the tool path footprint pattern, the feed forward and side step discretization of tool path pattern to generate the tool path data. Tool path planning involves the determination of the Cutter Location (CL) data corresponding to the required cutter contact locations to avoid the possible gouging and to minimize the scallop formation for the given tool shape and size. The most common tool shape used for sculptured surface machining is the ball end milling cutter which offers the best machined surface in case of complex sculptured surfaces.

For automatic tool path generation we need the 3D CAD model of the part. Various CAM algorithms use different CAD data formats which can be parametric or faceted/tessellated/STL format. The computation of gouge free tool positioning from the parametric CAD models is a computationally expensive approach. Lasemi et al., Lauwers et al., Yau et al., Manos et al. and Patel et al. have indicated that the computation of tool path data is relatively simple and efficient using triangulated or STL representation of sculptured part model. Another important factor to be considered during computation of tool path data is the cusp height or the scallop height, which is directly related to the feed forward and side feed discretization of tool path footprint.

The reverse engineering is a tool for generation of CAD data for the physical model which are otherwise difficult to model in CAD environment, like sculptured surfaces or dies or moulds for casting or press working for manufacturing of intricate surfaces. The 3D scanning technology need to be integrated to the CNC machining to increase the productivity of overall operation from design to manufacturing. The reverse engineering application for manufacturing of sculptured surfaces relies mainly on rapid prototyping technology, which is quite costly process. Through the use of custom tool path planning software and custom designed CNC machine tools the manufacturing process can be simplified and cost of production of complex sculptured parts can be significantly reduced. The 3D design details of complex sculptured parts can be best captured using 3D scanning technologies. The 3D scanned data can be modified or manipulated and presented in a desired format for the purpose of tool path planning and hence for CNC machining applications. The present study has considered the above stated facts and tried to establish the process of...
machining of complex pseudo-symmetric parts for which 3D scanned data is available or can be captured.

The work presented in this paper shows the use of reverse engineering, CAD and CNC manufacturing technologies for the manufacturing of pseudo-symmetric sculptured surfaces. The process followed for CNC machining of three different 3D scanned sculptured models have been presented in this paper. The 3D scanned data has been used in the STL format for CNC tool path generation. The tool path data thus developed for roughing and finishing operations has been used on a 3-axis CNC milling lathe to actually machine the sculptured models.

2. Methodology Developed for Machining of Pseudo-Symmetric Sculptured Models

In the work presented in this article the methodology used to develop the machinable triangulated 3D model of the pseudo-symmetric parts and the steps used to machine such part shapes on a 3-axis CNC milling lathe is explained. The 3D scanned data of the pseudo-symmetric sculptured part model to be machined is required as the primary input for the proposed methodology. The 3D scanned data then need to be converted to a valid 3D CAD representation which can then be used for automatic CNC tool path generation. The accuracy of the machined part using a CNC system depends on the accuracy of the 3D data used to represent its original shape as well as the precision of tool path generation algorithm. The following steps have been used in the proposed methodology for machining of the sculptured parts:

- Capture the accurate 3D scanned data for the sculptured part to be machined in a valid format recognized by standard CAD packages.
- Development of a valid 3D CAD model from the scanned data suitable for automatic CNC tool path generation algorithm.
- Development of CNC tool path data using CAM package for required cutting tool geometry and tool path strategy for machining the particular part design.
- Machining of the sculptured surfaces on suitable multi-axis CNC machining system.

The detailed procedure followed in the present work to machine the desired sculptured surface models has been explained in the following sections.

3. Development of 3D CAD Model of a Pseudo-Symmetric Sculptured Part

The development of 3D CAD model of a Pseudo-symmetric sculptured part is mainly done using two methods. The first method is through the use of commercial CAD software while another method is through using reverse engineering techniques. In the first method, the CAD software like Pro-E and SolidWorks™ can be used to develop the 3D sculptured part models directly using the interactive CAD environment, but this process is very complicated and tedious especially when 3D part shapes with sculptured surfaces need to be modeled. It takes a lot of time in development of accurate sculptured features in these CAD systems. Moreover, in most cases the sculptured features created using freeform surface modelling tools may not closely match the actual detailing available in the original 3D physical part.

The second option is the use of the reverse engineering tools which can directly capture the 3D position data in the point cloud format using laser scanners or Computed Tomography (CT). In the 3D scanner a set of images of physical model are captured by the scanning system which is processed to generate the 3D image of the part in the form of 3D point cloud data defined with respect to a predefined coordinate system. The scanned data to be used for construction of the valid 3D CAD model of the required part need to be processed so as to ensure that the unwanted noise or abrupt discontinuities in the scanned data are removed. The 3D point cloud data can be processed to construct the 3D CAD model into various formats including parametric formats like Non-Uniform Rational B-Spline (NURBS), freeform surface or freeform solid models or non-parametric representations like faceted/STL models depending upon the requirement of the downstream application in which the developed 3D CAD model need to be used.

There are a number of commercial software packages available which can be used to process the 3D point
cloud data to create the surface model. The 3D scanning is a relatively easy, cost effective and an efficient approach for modelling of the sculptured parts. In terms of time required to build the 3D digital models for already available physical 3D part shapes the reverse engineering is very fast process as compare to CAD modelling, and hence this method is cost effective. The 3D scanning technologies are very effective in creating the 3D digital CAD models of the sculptured parts because the exact details of sculptured features can be captured with accuracy in the range of a few microns. Thus the accuracy and efficiency of the 3D scan technologies makes them more effective for 3D modelling of sculptured surfaces compared to the modelling such parts in professional CAD packages. Moreover, 3D scanning methods have proved to be of great significance for producing the live sized 3D digital human models which can be categorized as unique class of pseudo-symmetric models.

An accurate and best fitting poly mesh can be created from the point cloud using reverse engineering software. The professional CAD software provides the tool to handle the 3D point cloud data and fit the cleaned-up poly mesh into the NURBS curves, or NURBS surfaces which are exported to CAD packages for further refinement, and analysis. Out of various CAD data formats the faceted/STL data models are preferred because in this case the complex sculptured surfaces are approximated by non-intersecting single degree of freedom planar triangulated facets. The faceted/STL data can be generated as per user defined accuracy/resolution from scanned data and the tool path generation using triangulated data is quite accurate and gauge free. The STL data for the sculptured parts may not be always useful as such for generating the CNC tool path data required for machining. Thus the STL data developed from 3D scanning need to be augmented by attaching certain other 3D features so that actual machining operation can be accomplished properly.

In our work we have obtained the 3D scanned data images from Mesh Lab which are later processed using “Scan to 3D” tool available in Solidworks™. The “Scan to 3D” tools in Solidworks™ can be used for a number of 3D scanned data formats and process the 3D scanned data into surface model or solid models or STL/meshed models as per user requirements. In the present work the “Scan to 3D” tool has been used to create the meshed models from the 3D scanned data available in *.ply format. The meshed models are later modified in Pro-ECAD environment in order to reposition and reorient the STL part model as per requirements of custom the CAM module. The STL model can be scaled according to the required product size. A few additional part features can be added if required and the updated model thus developed can be further saved as STL data file which can be further used for CNC tool path generation using suitable CAM packages. Using the CNC tool path data thus developed for the pseudo-symmetric sculptured part can be machined on a multi-axis CNC machine tool.

4. STL File Format

STereoLithography (STL) data format has been used to store the information about the outer and inner 3D geometric details of a physical part model in the form of interconnected triangulated data sets. The use of STL data format is very commonly used in rapid prototyping and reverse engineering applications. In the medical field the STL data format is used to model the artificial replacement joints and prostheses. Also STL format is being used to model the 3D shapes of the tumors or other abnormalities from the scanned data captured using CAT, MRI, or PET scan technologies for the proper study of such abnormalities before proceeding for the right diagnosis. In manufacturing the triangulated models has been successfully used to model and machine the die and mould parts for sheet metal parts, dental and knee transplants and several other sculptured part shapes which are otherwise difficult to model and machine using CNC technologies8,9,11,12.

Every unique interconnected triangular facet in an STL data file contains the information about the three vertices forming the triangular facet as well as the unit surface normal vector. The only issue with the STL data files is the resolution with which the actual part model can be approximated using the triangulated facets. For better approximation the triangulated facets of smaller size are used but it increases the overall number of facets required to approximate the part surfaces and hence the STL data file size increases multifold. On the other hand, if the larger facet sizes are considered then STL data file can have only a coarse representation of actual
part model. Thus one should have a good judgment of the required resolution of the STL part model.

The STL data format is supported by most commercial CAD packages, but most of the time cannot be used as such for generation of rapid prototyping models or for CNC machining. The 3D part models stored as triangulated or STL data models can be manipulated within the CAD packages using reverse engineering tools to support for efficient machining of such parts. This procedure is also critical for accurate machining of the required sculptured surfaces and has been discussed in the next section.

5. Reverse Engineering for 3-Axis Machining of Pseudo-Symmetric Sculptured Models

The first step in reverse engineering is to scan the required part and capture the 3D scanned data for it. The next step is to process the 3D scanned data which is generally available as point cloud data format to the required valid and usable 3D CAD data format for further downstream applications like rapid prototyping or CNC machining. As shown in Figure 1 the 3D scanned data Figure 1(a) can be processed to get the 3D surface model Figure 1(b) or 3D solid part model Figure 1(c) or a meshed/STL model Figure 1(d). All these CAD data formats have their own utility in modern CAD-CAM-CAE systems. The 3D scanned model of a sculptured human portrait shown in Figure 1(a) has been chosen as the first part for the present study which is aimed at establishing a valid procedure to machine such sculptured parts using a 3-axis wood carving CNC milling lathe. The 3D scanned data of various part models in point cloud data (*.ply) format has been used as the first input for this project which have been obtained from Mesh Lab website15.

In this work, the processing of the 3D scanned data for various models is carried out using “Scan to 3D tools” available in Solid Works™ 2008 education version. At the same time Mesh Lab can also be used for this purpose and it is an open source code based on the VCG library developed at the Visual Computing Lab of ISTI - CNR and it can be used for processing and editing of 3D scanned data and also the unstructured 3D faceted models thus generated from the 3D scanned data15. In our work the “Scan To 3D” tools is used to convert the point cloud data (*.ply format) of the scanned model is required to be converted into STL data format similar to one shown in Figure 1(d). In order to machine the 3D STL models, they need to be properly positioned and reoriented in the coordinate system recognized by the 3-axis machining system. Further the reoriented part in required machine coordinate system is required to be scaled to fit the required size of machined part. Moreover, some reference features need to be created for part holding as well as to verify the dimensional accuracy of the part to be machined on the desired CNC machining system. The steps used to convert the scanned STL data to machinable STL model are described below:

Figure 1. Shows (a) the point cloud data, (b) surface model, (c) solid model, and (d) meshed/triangulated/STL surface model.
(i) Placing the STL model in proper orientation and position
The first step involved is the selection of appropriate orientation of reference planes and creation of additional datum planes to appropriately position and orient the scanned graphical data of the scanned part in triangulated format in the CAD environment. In this case the Z-axis in the CAD system is aligned with the required axis for machining of the pseudo-symmetrical part. While machining the part on the 3-axis CNC milling lathe the axis of the part axis is to be made co-axial with the C-axis of the machine. The location and orientation of the rotation axis should be selected such that there is always material on all sides of the axis otherwise the cutting tool will completely cut the part into two halves. The editing operations for repositioning and reorientation of the STL model have been carried out in the Pro-E Creo Elements. The transformed coordinate frames used to reorient and reposition the selected STL geometry is shown in Figure 2(a) and 2(b) respectively.

(ii) Creation of part features to cover the distortions in the selected STL model

Figure 2. (a) Development of coordinate system for pseudo-symmetric part model, (b) placement of STL model on new reference coordinate frame

Figure 3. The distortions in the bottom region of the STL model seen towards the extreme left side of the image along the vertical.
This step is required to cover up the inherent distortions of STL model as well as to create the geometric references for measuring the accuracy of the machined part. The geometric distortions in case of the selected STL model are visible along the vertical line towards left side of the image shown in Figure 3. The additional part features can be easily modeled in the Pro-E CAD environment and can be integrated into the independent STL geometry as shown in Figure 4. In this case the elliptical solid extrusion feature is attached to add to the aesthetic value of the part which is also used for holding the part while machining as well as it is required as the dimensional reference for measuring the accuracy of the machined part.

(iii) Creation of part features for work piece holding for machining

After the initial setting of the 3D STL model a few additional aesthetic and part holding features can be developed separately and can be assembled to the part model created in the step (ii). Such a manipulation carried out in the model selected for this study is shown in the Figure 5 (a-e).
Figure 5.  (a) Blended feature part created to be added as base for the reverse engineered model, (b) the 3D STL part inserted on blended base, (c) final machinable assembled CAD model, (d) final CAD model assembly in default orientation, (e) the initial 3D scanned STL geometry is seen as if inserted on blended base as visible in the wireframe model
(iv) Saving the final machinable part model as a STL data file

After embedding the 3D scanned STL model into the required coordinate system it need to be saved again in STL file format which is to be used as input for CNC tool path data generation. The Cartesian coordinate system used for positioning the initial 3D scanned STL model is used as reference by the CNC tool path generation software developed for the 3-axis milling lathe. After adding the required geometric references as well as the work holding features to initial 3D scanned model we get the final machinable CAD model of the part. This machinable 3D CAD part model is saved as STL data file in ASCII format in the desired resolution and used further as an input by the custom CNC tool path generation software. The triangulation of the initially borrowed scanned STL file in Pro-E model cannot be changed in this step, while we can only control the resolution for triangulation of 3D part features modelled and added in Pro-E. The machinable STL model for the sculptured part is shown in Figure 5(e).

6. Generation of CNC Tool Path Data for Machining of Pseudo-Symmetric Part Model

Once we have the machinable STL model of the part ready, it can be used to generate the CNC tool path data for machining on a specially designed 3-axis CNC milling lathe. The CNC milling lathe has the capability to produce any pseudo-symmetrical shapes with any amount of detailing of complex crafted features on the part model, given the constraint that the part size to be machined fit into the machinable limits.

For machining of part model from the raw stock one need to have the tool path data for roughing, semi-finishing and finishing operations. The available CNC milling lathe is a wood carving machine with a router spindle of 1.0 kW and rotational speed up to 25000rpm and we have planned the machining operation on a cylindrical wooden work piece. Thus we found that only single roughing and single finishing operation was sufficient for machining the required part. The part is planned to be machined put of Shisham wood sample using ball end mill cutters. The straight fluted ball end mill cutter of ½ inch diameter with two flutes is used for roughing operation while 1/8\textsuperscript{th} inch diameter straight fluted ball end mill cutter with single cutting flute is used for the finish machining. The tool path pattern having helical footprint, as shown in Figure 6, is used for roughing and finishing operations. The axis nomenclature along with concept of helical tool path footprint pattern used in PBG-KW 3-axis CNC milling lathe is shown in Figure 6. For the purpose of tool path planning the side-step value (pitch of helical tool path taken along C-axis of machine) of 6mm per revolution is used for roughing operation while side step value of 0.25mm per revolution is used for finishing operation\textsuperscript{14}.

![Image](image_url)

**Figure 6.** The axis nomenclature and concept of helical tool path footprint pattern used in PBG-KW 3-axis CNC milling lathe.
Custom in-house developed CNC tool path computation software has been used to determine the roughing and finishing tool path data for machining of the sculptured parts. The details of the tool path generation algorithms are based on the work published by\textsuperscript{8,9,11}. The tool path data in terms of Cutter Location (CL) data determined in Cartesian space which refers to the location of center of ball end mill and the CL data for each discretized tool path footprint location on helical tool path is stored in the sequence of desired helical tool motion relative to the work piece. The CL points are determined using the custom software using the well-known ball-drop method\textsuperscript{8,9,11}, where in the first step the cutter Contact Point (CC) is determined such that the dropping tool just touches the desired part surface without gouging. The concept of CL and CC point has been shown in Figure 7. Thus the CC point represents the actual point of contact between the surface of cutting tool and the work piece while the CL point represents the location of the center of the ball end milling cutter corresponding to the required CC point. The CL point is the control point on the tool that machine recognizes and the CC point is the point on the work piece surface where the dropping tool first touch it without gouging.

In case of 3-axis milling lathe, the X-axis component represent the radial distance from axis of the work piece rotating about C-axis to CL point on the cutting tool as shown in Figure 6. The component marked as Y-axis represents the distance which the tool center has to maintain as measured along the axis of the rotating work piece. The Z-axis component shown in Figure 6 represents the rotation angle of the work piece measured from the home reference of the C-axis.

The customized tool path planning software creates NC tool path data files for ¼ inch and 1/8th inch ball nose cutter. The tool path software takes care of the depth of cut in terms of whether the material to be machined need more than one roughing cuts. If so then software generates the tool path files for required number of roughing passes and final finishing pass so that the desired material removal is achieved. The roughing and finishing tool path data files generated from the custom CNC tool path planning software need to be verified before proceeding for actual machining.

7. Tool Path Verification Using Custom CNC Simulator

The roughing and finishing tool path data developed for 3-axis CNC milling lathe in previous step is verified using the custom 3D graphical CNC tool path simulator called ToolSim developed by Mann et al\textsuperscript{13}. The Tool Sim simulator is an OpenGL based 3D graphical simulator capable of simulating 3-axis, 4-axis and 5-axis simultaneous tool

![Figure 7](image-url) The concept of cutter contact (CC) and cutter location (CL) point.
motions and the simulated 3D graphical machining output can also be compared to the original CAD model if required. The output of simulator is exactly the one the 3-axis CNC milling lathe can generate. The output visuals of the simulated roughing and finishing tool path for the 3D human sculptured part selected for the study have been shown in the Figure 8 (a-b) and 8(c-d) respectively.

8. Machining Results

The flow chart shown in Figure 9 enlisted the overall procedure used for CNC machining of pseudo-symmetric sculptured part. Three reverse engineered pseudo-symmetric sculptured parts which are shown in Figure 1(a), 12(a) and 13(a) were selected for machining on a PC based PBG-KW 2048 CNC 3-axis milling lathe which is shown in Figure 10. The PBG KW 2048 CNC 3-axis milling lathe is a PC based CNC system developed for wood carving operations. It uses a multi-axis PC based controller interfaced with PC and three hybrid stepper drives. The three stepper drives control the motion of cutting tool in X, Z, and C axis respectively and their directions are shown in Figure 6. The positional accuracy and repeatability of the CNC milling lathe is 0.005 inch. The PC based machine

Figure 8. Simulator output for (a-b) roughing, and (c-d) finish machining.
controller ensures that the CNC system work within its prescribed limit using two limit switches at the ends of X and Z drives and a proximity switch used to do home referencing for C axis. The roughing and finishing machining operations have been performed at 25000rpm using 1kW router spindle available on the CNC milling lathe. The ball end mill cutters of diameter 1/2” (double flute) and 1/8” (single flute) have been for roughing and finish machining. The feed rate used for roughing operation is taken as 20 rpm while for finish machining is taken as 5rpm. In this machining operation the axial feed rate is a function of the federate of C-axis, while the transverse feed rate is controlled using the control logic such that the rotating ball end milling cutter is always touching the machined surface at a predetermined distance from axis of rotating work piece about C-axis as indicated in commanded tool path. The PC based motion controller available on the CNC milling lathe is responsible for the real time feedback and error correction, if required.

The figure 11 shows the relative comparison of the machined part (figure 11(e)) with the scanned model (figure 11(a)), the edited machinable STL model (figure 11(b)) and the 3D graphical simulation results of roughing and finishing operations in ToolSim graphical simulator. It is clear from the figure 11 that the machining results match quite well with the graphical simulation results as well as the 3D graphical images of the original 3D scan model and the modified STL file used for CNC tool path planning. The height of the initial scanned STL model was scaled to 4 inches and the size of the machined part shown in Figure 11(e) is also 4 inches. The features corresponding to the arms of the scanned model are not machined because the diameter of the raw material used was smaller than the required work piece diameter. The accuracy of the machining operation can be determined from visual comparison of the facial features like the nose as well as the features around head in the scanned and the machined part.

Similarly, the Figure 12(a-i) and 13(a-e) shows the comparison of the machining results of a laughing Budha model and a flask model, with the scanned models, the edited STL models, and the machining simulation results. The results shown in Figure 12 and Figure 13 match the sculptured design of the respective models very closely, which is sufficient to show that procedure used to machine the pseudo-symmetric sculptured models using their scanned data is capable of generating the desired results. In this study we have not focused on the measurement of the surface deviations incurred while transferring the data from 3D scanned image to STL and then subsequently during the formation of secondary machinable STL file. The only place where the chances of surface deviations can come is during the formation of primary STL data file which is formed from the scanned point cloud data. This deviation in formation of primary STL data file cannot be avoided completely but can be controlled to a large extent by having the very fine triangular mesh size. The only compromise one has to make in this case will be that the time required to process such STL files for further CAD manipulations, especially the time required for CNC tool path generation will increase significantly.

Figure 9. Process model used for CNC machining of a pseudo-symmetrical sculptured parts.
**Figure 10.** PBG KW 2048 wood carving milling lathe.

**Figure 11.** (a) Point cloud data in ply format. (b) Edited part model in Pro-E CAD. (c) Simulation results for rough machining. (d) Simulation results for finish machining. (e) The details of facial features in finish machined part. The comparison of details of face features of scanned part with the modified STL geometry and the final machined part model.
Figure 12. (a) Point cloud data in ply format for Laughing Budha Model. (b) STL model developed from point cloud data in SolidWorks®. (c) Edited part model in Pro-E CAD. (d) A revolve feature added to the top surface to hold the work piece. (e) Simulation results for rough machining-front view. (f) Simulation results for rough machining-left side view. (g) Simulation results for rough machining-back view. (h) Simulation results for rough machining-right side view. (i) The details of facial features in finish machined part. The steps wise comparison of the surface features of scanned Budha part with the modified STL geometry, the simulation roughing tool path data and the final machined part model.
Figure 13.  (a) Point cloud data in ply format for carved flask model. (b) STL model developed from point cloud data in SolidWorks™. (c) Coordinate frames attached to STL model in Pro-E CAD. (d) A revolve feature added to the front hollow surface to hold the work piece. (e) The machined flask part after finish machining. The comparison of details of carving details of flask part as seen in the scanned part with the modified STL geometry and the final machined part.
The results of the machining process shown in Figure 11 to Figure 13 confirm the required aim that the automatic CNC machining of the pseudo-symmetric sculptured parts can be accomplished quite accurately and the 3D scanned data of such parts can be used for the CNC machining operations in addition to the rapid prototyping processes. This reverse engineering based CNC machining process model presented in this paper is advantageous for mass production of sculptured ornamental parts. In addition this work is a step towards the better integration of reverse engineering, CAD and CAM areas.

9. Conclusion

The 3D scanned data of the sculptured surface models is being used for quite a long time now, but the products manufactured using reverse engineering techniques which use the 3D scanned data are either miniature models or these products are developed only for high value applications. In the present work an application of 3D scanned data for CNC machining of complex unsymmetrical sculptured model has been demonstrated. The 3D scanned models selected for the demonstration of the reverse engineering application for CNC machining include the human sculpture, a laughing Buddha and a carved flask model. These models have been modified for its machinability on a 3-axis milling lathe. The machined parts confirmed the details of the sculptured features of the original 3D scanned model. Thus the procedure outlined in this work for machining of reverse engineered 3D sculptured model can be used for mass production of scaled parts, which can be smaller or larger in size compared to the original 3D scanned model. Thus one can create multiple copies of such complicated parts. This application permits the use of material like wood which are far less expensive and biologically safer option compared to the other materials used in the reverse engineering/ rapid prototyping processes. The use of this methodology can be explored for expansion of for artistic work with the fusion of 3D scanning technologies for various domestic and industrial applications.

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