

Teaching Multi-axis Complex Surface Machining via Simulation and Projects

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Abstract

Multi-axis Computerized Numerical Control (CNC) machines have become the application of choice for complex sculptured surface machining. Simulation of tool paths and machine operations is desirable for cost and time savings. These advanced technologies are being integrated into a senior Manufacturing Engineering Technology (MNET) curriculum at the South Dakota State University (SDSU).

Seven projects or exercises were assigned to students. A 4-axis HAAS machining center with Direct Numerical Control (DNC) capability was setup by students. 3D complex sculptured surface models were created from 2D drawings at different Z levels for turbine blades. CNC programs were generated for free-form surfaces and 4-axis parts via computer aided manufacturing (CAM) software. Feed-rates were optimized for more efficient machining and improved finish quality. Models of 3 and 4-axis machines in the manufacturing lab were created for simulation. CNC programs were verified by Vericut software prior to actual machining in the lab.

Goals of these projects include: extend students' knowledge in CNC machines, programming, simulation, verification and optimization; teach students how to model and machine the complex free-form surface; and foster students' independent learning. This paper will describe the curricular module used in the course in detail and provide simulation demonstrations. Results of simulation and the production lab machining are shared.

1. Introduction

Multi-axis computerized numerical control (CNC) machines have become the application of choice for complex surface machining. These machine tools are widely used in the aerospace, automotive, tool and die making and other industries requiring complex shapes. Collision-avoidance and geometric-error detection are critical issues for multi-axis CNC machining [1]. Simulation of tool paths and machine operations is desirable for cost and time savings. Vericut is a powerful CNC verification software, which detects errors and inefficient motions in CNC programs [2]. Vericut can also perform realistic 3D simulation of entire CNC machines, just like they behave in the shop.

These cutting edge technologies are being integrated into a senior Manufacturing Engineering Technology (MNET) curriculum at the South Dakota State University (SDSU). Projects shown below provide a curricular module for students in the manufacturing engineering program to really understand the complex surface modeling and multi-axis machining. These projects also extended students' knowledge in CNC machines, CNC controls, CNC programming, CNC verification and optimization.

2. Projects

2.1 Initial project 1: set up the 4-axis CNC machine

Problems/objectives

The maximum memory for NC codes is only 170K with the machining center in the department of Engineering Technology and Management (ETM). That is not enough for complex sculptured surface machining. With the direct numerical control (DNC), there is no limit to the size of one CNC program. The HAAS vertical machining center (VMC) has four directly controlled axes. The 4th axis rotary table needs to be set up properly.

Actions

- Students were divided into three teams.
- One team set up the DNC.
- One team set up the 4-axis with the existing rotary table HRT160 and learned how to operate the machine with the HAAS manual.
- The third team learned the simulation software Vericut and evaluated it.
- The deadline for the initial project was 3 weeks after the day assigned. Final reports and presentations were required for each team. The report should include team members, objectives, methods/steps for objectives, and knowledge and skills gained from this assignment.



Figure 1: 4-axis HAAS VMC setup

Outcomes

The first team of four students located and installed HRT160 rotary table on the table as shown in Figure 1. All students gained a great experience on how to mount the fourth axis and use an indicator to locate the HRT160 at one proper position. They also learned how to operate the CNC machine.

The second team of three students installed and used commercial DNC software. This group learned the importance of reading manuals carefully. Their proficiency with the machine has been increased and they felt comfortable working with the control.

In the third team, three students studied the simulation software Vericut. They showed the class how to modify models in Vericut during their presentation and gave a general instruction on how to use Vericut. Students were able to obtain a version of the HAAS VF-3 model implemented into the software. The HAAS VF-3 is a larger scale version of the VF-1 model used in the manufacturing lab of the department. Students' comments about the software were: this software will be beneficial in machining with the HAAS machining center; this software will help simulate the machining of parts and help operators and designers see mistakes before they happen; and this software eliminates crashes and also improves process efficiency.

2.2 Project 2: learn solid surface modeling and machining

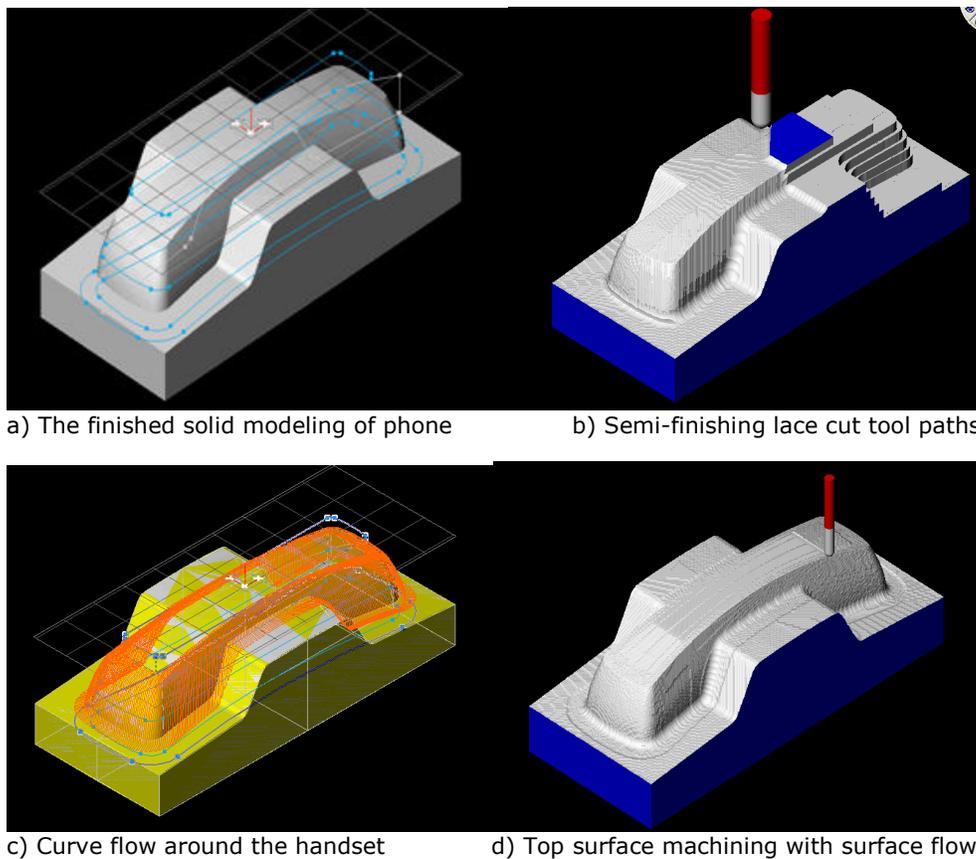


Figure 2: Solid machining example: Phone

In this phase, students learned the solid modeling at first. The phone solid was created from the geometry by using solid loft, solid extrusions, solid Boolean operations (intersection, subtraction) and corner filleting in the GibbsCAM [3]. Three segments slightly shown in Figure 2.a were used to generate the phone model. Figure 2.a also shows the finished solid modeling.

Figure 2.b, 2.c and 2.d show steps to machine the phone from the 240mm X 100mm X 75mm stock. Figure 2.b shows semi-finishing lace cut tool paths after rough process which removes most material from starting stock. The lace cutting is designed to machine surfaces at a specified angle and width. The curve flow creates the tool path that moves along or between two pieces of geometry. The operation shown in Figure 2.c is a two curve flow cutting around the handset. The surface flow cutting is used to machine the entire area of a selected single face. It works best for machining simple chamfers and fillets. The top of the handset is machined with the surface flow cutting in Figure 2.d. The final operation which is not shown in Figure 2 is to clean up intersections between the handset and the phone base with smaller ball-nose end-mill. CNC codes are generated for a 3-axis vertical machining center (VMC) and will be used for CNC verification via Vericut.

In this project, students learned complex solid surface molding and machining step by step. They learned how to choose cut width, cut angle, cut direction, step over, and start points in complex surface machining from this example.

2.3 Project 3: learn 4-axis index machining via a simple example

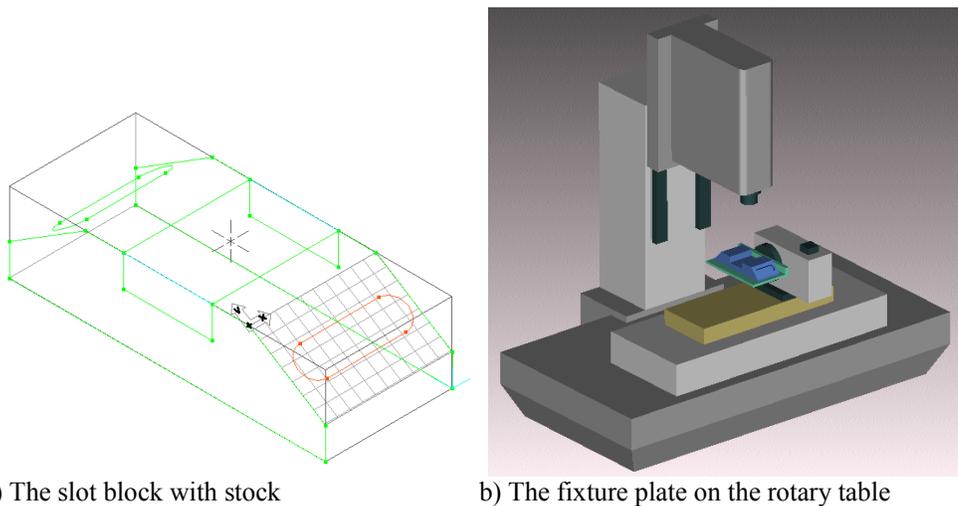


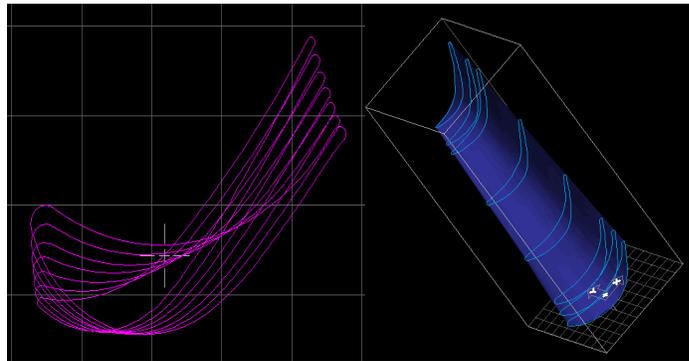
Figure 3: 4-axis machining exercise: slot block

In this exercise, a 4-axis part named slot block in Figure 3 was created [4]. The center of the part is pocketed and both angle planes are face milled and pocketed with angle changes of the rotary axis A. The part is mounted to the rotary table on a fixture plate as illustrated in Figure 3.b.

2.4 Project 4: use loft to make a free-form surface from 2-D drawings

Figure 4.a shows 2-D drawings of one Turbo blade from industry. Those profiles were moved to the same center (0, 0) and different Z levels in 3-D CAD or CAM software such as Pro/Engineering, SolidWorks or Gibbs CAM. Z values for those eight shapes are based on original values $Z=0, 0.125, .25, 0.694, 1.25, 1.764, 1.861, 2.035$ inch. Students changed Z-levels at random within ± 0.050 range to make their Turbo blades different from others.

These eight closed shapes at different Z-levels were blended into a solid with free-form surface in Figure 4.b. These selected shapes define cross sections of the resulting blade. These points on each section act as alignment or synchronization points [3]. The software breaks up shapes between those points into segments and generates a surface by matching each segment. These alignment points on each shape match up in the finished lofted solid.



a) Shapes in 2-D view

b) The lofted surface

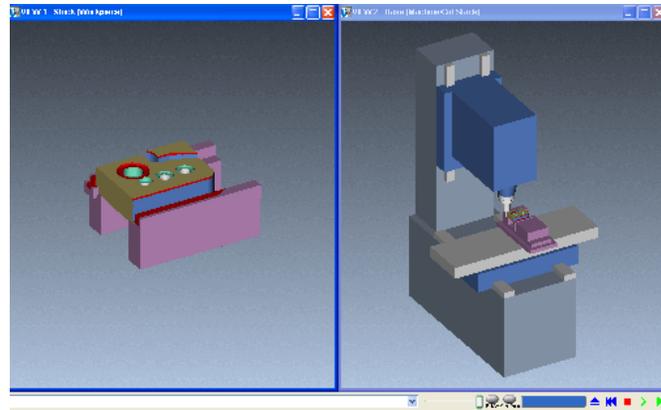
Figure 4: Use loft function to generate a free-form surface

From this project, students learned how to generate a free-form surface from 2-D profiles at different Z-levels. These solid models of Turbo blades would be used for future 4-axis simultaneous machining projects.

2.5 Project 5: learn Vericut via training sessions

In three classes, students finished 15 basic Vericut training sessions [2] with the instructor's help. With these training sessions, they understood basic requirements of the CNC simulation, definition and positioning parametric models, creating a Vericut tool library, controlling tool path simulation, using X-caliper to virtually inspect a machined part in simulation, comparing the design model with the machined part via Autodiff, optimizing CNC codes via Optipath, building kinematics models of 3-5 axis CNC machines, and customizing CNC control.

In one training session, students learned how to start with a generic "shapeless" 3-axis machine and added 3D models to represent a Bridgeport-type vertical mill, which is shown in Figure 5. Figure 5.a shows the fixture and the part to be machined. Figure 5.b is the modeling of the machine and the part.



a) The finished part and fixture b) Machine & part
Figure 5: Bridgeport 3-axis vertical mill

Students configured a Vericut machine file that describes the kinematics of a 4-axis horizontal mill with a "B" rotary table. Students also defined a Cincinnati T30 5-axis milling machine using CAD generated Stereolithography (STL) model files to represent component shapes. The Figure 6 shows components of the milling machine tool defined.

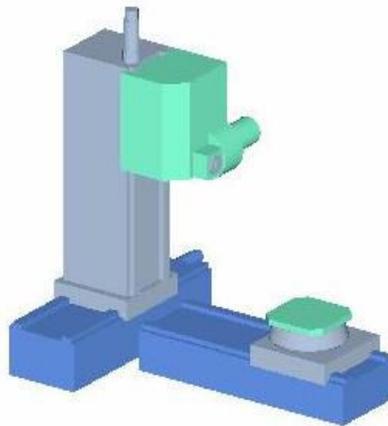


Figure 6: Cincinnati T30 5-axis milling machine

Poor feed-rates contribute to more machining time, bad finishes, increased tool wear and tool failure [5]. Vericut Optipath can generate an optimized tool path by recalculating feed-rates and spindle speeds. Vericut Optipath analyzes the NC program (G codes or native CAM output), then divides the motion into smaller segments to determine ideal feeds and speeds for current cutting conditions, and inserts new feed-rates to create a more efficient new tool path.

In one class, students learned how to use the Optipath Manager function to define the Optipath records required for optimizing cutting in H13 tool steel. Then they configured Vericut for optimizing a G-code tool path file by adding references of Optipath records to tools stored in the tool library file. Figure 7 shows the machining time saved in the sample

optimized NC codes. From this session, students understood further the importance of appropriate feed-rates in different cutting conditions.

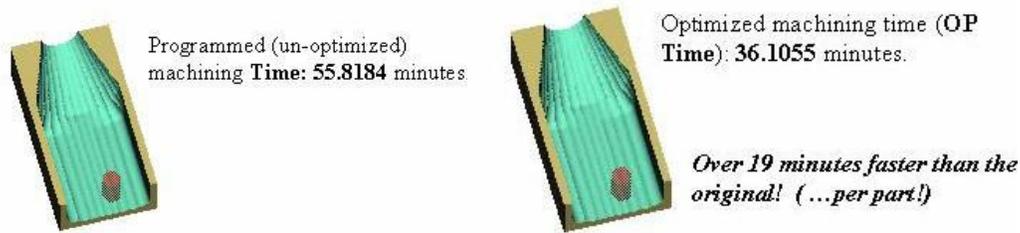


Figure 7: Sample for CNC optimization via Optipath

2.6 Project 6: use Vericut to verify phone & slot block machining

With these Vericut training sessions, students obtained the ability to model real machines in the department: 3-axis Bridgeport Vertical Machining Center (VMC), 2-axis turning machines, and 4-axis HAAS VMC. The modeling of the 4-axis HAAS VMC with slot block mounted on the fixture plate has been shown in Figure 3.b. The phone program for the 3-axis Bridgeport VMC generated in project 2 was also being verified by Vericut.

2.7 Project 7: machine Turbo blades via Vericut and 4-axis HAAS VMC

In this project, the 4-axis HAAS CNC machine center in the production lab will be used to machine Turbo blades with verified CNC programs, but current CAM software used does not have the 4-axis simultaneous machining capability. The tool path and G-codes can not be generated for the Turbo blades with current Gibbs CAM. Another CAM package IBM CATIA V5 with simultaneous 4 or 5-axis programming capability will be available soon in the department. Students will finish the following based on results described above:

1. Create tool paths and NC programs for Turbo blades. The X, Y, Z and A axis will be controlled simultaneously to machine Turbo blades.
2. Verify NC codes to avoid collisions, inspect the machined part virtually and optimize the NC codes with Vericut.
3. Machine the part by the 4-axis HAAS machining center in the shop with fixture and setup shown in Figure 1.
4. Measure the finished part via CMM in the department.

3. Conclusions

Vericut enabled the instructor to demonstrate simple to complex tool paths and CNC machines without using expendable materials. It is a very desirable teaching and learning tool for the Manufacturing Engineering program.

The instructor could teach students in using Vericut for CNC programming verification & optimization. Students used Vericut for 4-axis complex surface machining projects. CNC programs were tested without using machines. It brought more hands-on experience and

increased safety for students in the CNC machining lab. It also cut the machining expenses and instructional time because of machine crashes. Students also got more experience in various virtual 3-axis to 5-axis CNC machines.

Projects shown above provide a curricular module for students in the manufacturing engineering program to really understand the complex surface modeling and multi-axis machining. Experience in 4-axis complex surface machining will be very helpful for students' career in industry. These projects also foster students' independent learning. Students can correct their mistakes in CNC programs by themselves with Vericut.

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Qian, Li received his Ph.D. in Industrial Engineering from the Kansas State University in 2003, M.S. in Mechanical Engineering from Harbin Institute of Technology, China in 1996, and B.S. in Mechanical Engineering from Wuhan Institute of Technology, China in 1993. He has been working as a project manager in industry for two years before he became an assistant professor in the South Dakota State University at Fall 2004.