

2006-721: MANUFACTURING LABORATORY LEARNING MODULES ON CAD/CAM/CMM AND ROBOTICS

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Manufacturing Laboratory Learning Modules on CAD/CAM/CMM and Robotics

Abstract

Students' achievement in design and hands-on laboratory experience are important part of engineering education. To meet this requirement, the department of mechanical and industrial engineering offers design and manufacturing courses to engineering students at Mercer University School of Engineering (MUSE). In this paper, how the manufacturing laboratory facilities, and design/automation hardware and software available are effectively integrated to teach Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), CAD/CAM integration, dimensioning and tolerancing, and measurement and inspection with appropriate hands-on experiences to engineering students are presented and discussed. A Design (CAD), Fabrication (CAM), and Measurement (CMM) module, a Design and Fabrication of Spline (DFS module) using the rotary axis of a CNC machining center, and a laboratory experiment in robotics along with results obtained from student team projects are presented, analyzed, and discussed.

Introduction

The advancement in technology, computers, and automation demands continuous improvement in the quality of education, both in theory in the classroom, as well as hands-on practice in design, computer simulation, and manufacturing laboratories. There is a growing need for preparing the students both in theory and practice so that they are well prepared to meet the challenges in the job market, especially in the manufacturing industries of the 21st century. A strong multi-disciplinary background is required from engineers due to increased automation in the shop floor and the globalization of industries. Assessment of student achievement in engineering design is an important part of engineering education and vital to engineering program accreditation. Systematic assessment of design is challenging yet necessary for program improvement.

Several educators, design researchers, and designers from industry have studied and addressed the importance of goals for design engineering education³, engineering design process^{4, 6, 7}, design considerations and constraints in the design course sequence⁹, visualization skills¹², freshman engineering design^{1, 2}, senior capstone design^{10, 11, 13}, and multi-university design project⁸.

The objectives of manufacturing engineering education and possible ways of introducing the subject into an undergraduate curriculum¹⁴ and the urgency for improving it in the educational system that supply industry with engineers¹⁵ have been discussed. A reverse engineering model and team projects for the freshman design^{1, 2}, and computer-based teaching⁵ in engineering education have also been studied.

At MUSE, the mechanical and industrial engineering students are prepared for careers in manufacturing industries. The students are trained from the freshman through senior year in design, materials, manufacturing, and measurement related areas as explained below.

The design and manufacturing facilities at MUSE include the following:

- CAD lab with software packages AutoCAD and Pro/Engineer;
- Conventional machine shop with lathes, milling, drilling, and grinding machines;
- Welding shop with resistance and arc welding equipment;
- CAM and robotics lab with a 3-axis CNC machining center capable for 4th axis machining, CNC machines and equipment, two five-axis robot arms, vision system, and a Coordinate Measuring Machine (CMM) with *PC-DMIS v 3.2* software.

In the engineering graphics and visualization course students are trained in hands-on construction activities, paper and pencil drafting, 2-D computer aided design, and 3-D solid modeling. This course is a prerequisite for the subsequent CAD/CAM courses. The topics and activities of graphics and visualization are arranged in a logical order for the development of 3-D spatial skills. The course outline includes: visualization skills in engineering and science; oblique and isometric sketching; orthographic projection views; pattern development; 2-D working drawings of components; sectional views; translation; scaling; tolerances, assembly drawings; 3-D solid modeling. The software packages used in this course include AutoCAD and Pro/Engineer.

In the manufacturing processes course, students design 2-D and 3-D parts and use the CNC machining center to make these parts. Typical design and fabrication of parts made by the students include: ashtray, star, heart, waffle, spider web, smiley/sad face, yin-yang, Star of David, Mickey Mouse, Christmas tree, etc. The students learn to program, using G-code, linear, circular, elliptical, and parabolic motions of tool path on the CNC machining center. They also use rectangular/circular pocket commands for machining 3-D parts.

In the computer assisted manufacturing course, the students learn to program the robot, using programming languages and interface the robot with numerically controlled devices and conveyor systems. They are trained in CNC 4th axis machining (programming and fabrication of parts), as well as robot vision system. The coordinate measuring machine is used to demonstrate the measurement aspects of manufactured parts as well as reverse engineering concepts.

The objective of this paper is to present some of the laboratory modules developed and taught in the design and manufacturing courses that are expected to meet the following ABET's EC-2000 "a" through "k" requirements such as: b) ability to design and conduct experiments as well as to analyze and interpret data; c) ability to design a system, component, or process to meet desired needs; d) ability to function on multidisciplinary teams; and g) ability to communicate effectively, as well as the Mercer University's learning objectives such as: critical thinking, application of technology, knowledge integration, knowledge application, and written and oral communication. Selected results from student team projects are also presented, analyzed, and discussed.

CAD/CAM/CMM Module

The objective of this module is to train the students to design, fabricate, and measure a simple part using the knowledge they gained in the manufacturing processes course (ISE 370). This course is offered in the Fall Semester of the junior year.

The design sub-module consists of: 1. Brainstorm ideas of possible parts to design and make. 2. Determine the part which would be challenging yet attainable to complete. 3. Draw the part drawing using correct dimensions on engineering paper. 4. Provide appropriate tolerances, if necessary, to certain dimensions in the drawing. 5. Draw the part drawing in Pro-Engineer/AutoCAD. Label all end points and points of interest to tool path. 6. Decide whether to use absolute or incremental dimensioning. The design of the part should also contain linear and circular paths for the cutter to machine the part. 7. Write the CNC program either in absolute and/or incremental dimensioning method(s) using G-code. 8. Confirm the program in G-code is correct with the instructor.

The fabrication sub-module consists of: 1. Load the program in the CNC machining center. Debug the program and verify whether the program is correct for the intended part. 2. Learn how to operate the CNC machining center by going through the step-by-step operator training manual. 3. Load the part on the vise and go through the operating sequence and run the machine to make the part. 4. Once the part is successfully made, take the part to CMM machine.

The measurement sub-module consists of: 1. Learn how to operate the CMM machine for making simple measurements using manual/DCC mode that are explained in the step-by-step CMM training manual. 2. Measure the part dimensions using the CMM. 3. Print a measurement report and verify whether the measured dimensions are within the design dimensions and tolerances. 4. Make an error analysis on the part dimensions.

The student teams then write a lab report covering all aspects of design, fabrication, and measurement and submit it to the instructor. The project evaluation is carried out considering the following: 1. Team effort and team interaction. 2. Design skills that include - Creativity in design; Part design and part specifications; Use of design software packages. 3. G-code programming skill – manual or use of a software package. 4. Machining skills that include - Selection of proper material, tools, fixture, and machining conditions; Accuracy of machining. 5. Measurement skills that include - Use of manual/DCC mode for measurement; Comparison of design specifications with the measurements made. 6. Learning experience indicating the difficulties encountered in design, fabrication, and measurement phases.

The methods of assessment are based on: 1. Grading of the lab report submitted at the end of the completion of the module. 2. Verification of the design for creativity, dimensioning, and tolerancing. 3. Verification of the part made on the CNC machining center for dimensional accuracy and surface finish. 4. Verification of the CMM report on whether the part made by the team meets the design specifications and tolerances.

This module also helps to assess the ABET requirements such as ability to design and conduct experiments as well as to analyze and interpret data, ability to design a component to meet



Fig. 3: Mickey Mouse (Part Made)



Fig. 4: Coordinate Measuring Machine

The measurements made using the CMM for the three diameters left, center, and right circles in inches are compared with the nominal diameters and found to be within the tolerance range of $\pm 0.05''$. The results are presented in Table 1.

Table 1: Measurements using CMM

Diameter	Measurement	Nominal	Tolerance	Deviation	Out of Control
Left, D_1	2.2485''	2.2500''	$\pm 0.0500''$	- 0.0015''	0.0000
Center, D_2	3.9967''	4.0000''	$\pm 0.0500''$	- 0.0033''	0.0000
Right, D_3	2.2489''	2.2500''	$\pm 0.0500''$	- 0.0011''	0.0000

Design and Fabrication of Spline (DFS Module)

This CAM module is designed and taught to the students in the Computer Assisted Manufacturing Systems (ISE 424) course during the Spring Semester of the junior year. The objective of this module is to provide the students: 1. The basic understanding of designing a

complex shape such as spline; 2. The use of G-codes, XZ-plane and “A” axis to program the part designed; 3. Make the part with the help of rotary axis and the CNC machining center; 4. Measure certain part dimensions using dial gage/caliper; and 5. Verify whether the measured dimensions are within the specifications and tolerance limits of the part designed through error analysis.

The DFS module is open-ended and the students are provided with the following instructions:

- Material given: Use cylindrical piece of blue wax with a diameter of 2 inches.
- The spline portion of the part should be from 2.5 to 3 inches in length.
- The final part should have grooves of properly defined depth and width (from 1/4” to 1/2”).
- The number of grooves in the spline can be 6, 8, or 12.
- The milling cutters to cut the grooves should be chosen based on the number of grooves in the spline (from 1/4” to 1/2” diameter).
- The front end of the spline should be tapered to a length of 1/8” at a 45 degree angle, while the back end of the grooves should taper up to the original diameter of the wax part.

The steps involved in making the spline include:

- Create a design that satisfies all of the criteria mentioned above.
- Design the part using Pro-Engineer/AutoCAD software. Label all the critical points in the drawing that are of interest to tool path. Provide appropriate tolerances to different dimensions of the spline. Decide whether to use absolute or incremental dimensioning.
- Write the CNC Program in G-Code using XZ-plane and “A” axis that would accurately represent the drawing. Confirm the program in G-code is correct with the instructor.
- Load the program into the CNC machine and debug the program for errors.
- Install the rotary axis on the machine table. Load the part in the chuck of the rotary axis and run the program to make the spline.
- Use the dial gage/caliper to make measurements such as: spline length and diameter; length, width, and depth of the groove; and chamfer angle. Compare the measured values with the design specifications.
- Calculate the percentage error for each dimension and make the error analysis.
- Draw appropriate conclusions on the spline made.
- Write a lab report covering all aspects of creativity in design, fabrication using rotary axis, measurement using dial gage/caliper, and error analysis and submit to the instructor.

The project evaluation is carried out considering the following: 1. Team effort and team interaction. 2. Design skills that include - creativity in design; part design and part specifications; and use of software packages such as AutoCAD or Pro-Engineer. 3. Programming skill - G-code programming – manual or use of software package; use of “A” axis and XZ- plane in G-code programming. 4. Machining skills that include - selection of proper material, tools, fixture, and machining conditions; use of rotary axis (4th axis) for machining; and accuracy of machining. 5. Measurement and analysis skills that include - use of dial gages/calipers for making measurement; comparison of design specifications with the measurements made.

6. Learning experience indicating the difficulties encountered in design, fabrication, measurement, and analysis phases.

The methods of assessment are based on: 1. Grading of the DFS module lab report submitted by the student teams. 2. Verification of the design for creativity, dimensioning, and tolerancing. 3. Verification of the part made on CNC machining center using the rotary axis for dimensional accuracy. 4. Verification of the error analysis for determining whether the part made by the team meets the design specifications and tolerances.

This module also helps to assess the ABET requirements such as ability to design and conduct experiments as well as to analyze and interpret data, ability to design a component to meet desired needs, ability to function as a team, and ability to communicate effectively, as well as the Mercer University's learning objectives such as creativity and critical thinking, application of technology, knowledge integration, knowledge application, and written communication.

Example:

The design of a typical spline with 12 grooves made by a team consisting of three students is shown in Fig. 5. The part made is shown in Fig. 6. The desired and the average of 5 actual measurements in inches as well as the absolute percentage error obtained for certain dimensions of the spline designed and fabricated are given in Table 2.

The Absolute Percentage Error (APE) is calculated using the relation:

$$APE = |(Desired - Actual)/Desired| * 100 \tag{1}$$

The average APEs for all measured dimensions are found to be less than 2%.

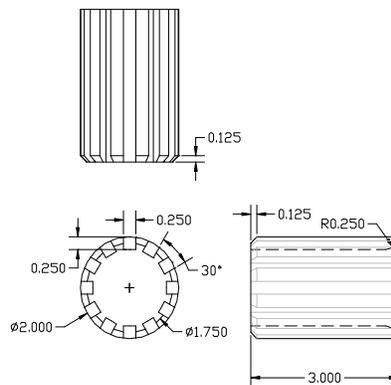


Fig. 5: A Typical Spline with 12 Grooves



Fig. 6: Spline with 12 Grooves (Part Made)

Table 2: Absolute Percentage Error (APE)

Measurement	Desired	Actual	APE
Groove length	2.50 in	2.538 in	1.52
Groove width	0.25 in	0.253 in	1.20
Groove depth	0.25 in	0.254 in	1.60
Chamfer angle	41°	41°	0.00
Spline length	4.0 in	4.02 in	0.50
Spline diameter	2.0 in	2.0332 in	1.66

A Laboratory Experiment in Robotics (Robotics Module)

Robotics (ISE 429) course is offered in the senior year as an elective course. A student team in this course programmed the CRS A255 robot arm to simulate a kindergarten student painting the first letter of four students' first names, spelling "KATE". The CRS A255 robot arm has 5 rotational joints and a gripper, utilizes a windows-based software package called *Robocomm3*, and can be manipulated manually using a teach pendant. The operating system used by the *Robocomm3* package is called CROS-500. The language used to program the robot is RAPL-3, which stands for Robot Automation Programming Language. *Robocomm3* allows the users to create and edit robot programs, transfer files between the computer and the controller, and communicate interactively with the controller using the terminal window.

The student team first designed and created a fixture to house the paint containers. The design requirements for the fixture were to effectively house four icing containers for storing paints and water, and to be stable so that there was no risk of spillage. The container height and the opening diameter were measured. Using these measurements, a model of the fixture was created using Pro/Engineer as shown in Fig. 7. The top of the fixture was fabricated in the machine shop out of wood using a drill press with a hole-cutter attachment to create four holes. Then, four legs

were cut using a miter saw and attached to the top board using a hammer and six nails. Finally, two sponges stacked on top of one another were nailed to the top board using two nails. Three of the containers were filled with yellow, red, and blue paint, and the fourth container was filled with water. The four containers were then placed into the wooden fixture. The fixture setup along with the robot is shown in Fig. 8.

Once the fixture was constructed, the student team began developing the program to manipulate the robot's motions to complete the painting. The painting process begins with placing the paintbrush into the robot's gripper. Next the paintbrush is dipped into the yellow paint and the first part of the letter "K" is painted. Then the robot must return to the yellow paint and re-dip the paintbrush and complete the remaining portions of the letter. Once the letter "K" is completed, the robot dips the paintbrush into the water and then moves it back and forth twice to remove the remaining paint from the brush. The brush is then dabbed on the sponge to remove excess paint/water from the brush. The robot then continues to the red paint container and dips the brush. From here, the robot returns to the drawing area and draws the letter "A". Again the robot moves to the water container and removes excess paint/water. This process is continued using blue paint for the letter "T" and red paint again to create the color purple to use for the letter "E". Once all the letters have been completed, the robot places the paintbrush into the water container and releases it and continues back to its home position.

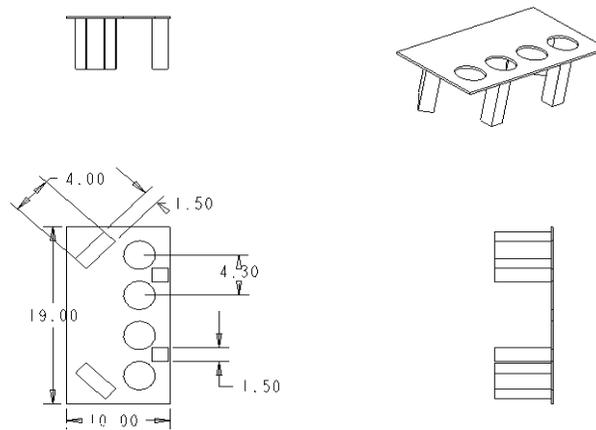


Fig. 7: AutoCAD Drawing of the Fixture



Fig. 8: Robot and Fixture Setup

The major movements the robot utilizes to create “KATE” are listed in Table 3. The process flow diagram of writing “KATE” is shown in Fig. 9. To create these letters, the points were stored and the program sequence was written using these points. The robot arm, with the paintbrush in its gripper, was moved to each point that needed to be stored and saved. After storing all positions, the program was written to guide the robot through each of the designated positions. After the program was completed and then perfected through subsequent trials, the final process was videotaped. The video was then edited using the software iMovie.

Table 3: Letter Configurations

Letter	Robot Motion
K	Dips brush into yellow paint Paints the " " of the "K" Dips brush into yellow paint Paints the "<" of the "K" Clean paintbrush in water Dabs paintbrush onto sponge to remove excess paint/water
A	Dips brush into red paint Paints the "/" of the "A" Dips brush into red paint Paints the "\" and "-" of the "A" Clean paintbrush in water Dabs paintbrush onto sponge to remove excess paint/water
T	Dips brush into blue paint Paints the " " and the "-" of the "T" Clean paintbrush in water Dabs paintbrush onto sponge to remove excess paint/water
E	Dips brush into red paint Paints the "_ " " " "-" and "--" of the "E" Releases the brush into the water cup

Upon completion of the project, the student team recognized the many benefits the robot can offer. Through this process, the team learned how to successfully manipulate the CRS A255 robot arm and create a program to sequence the stored positions. For future users, the program could be modified to make letters that are more advanced than a kindergarten student. This could entail making more refined letters, spelling something different, writing numbers, or drawing a picture. Kindergarten students will be motivated to learn to paint and write by viewing the CRS A255 robot painting “KATE.”

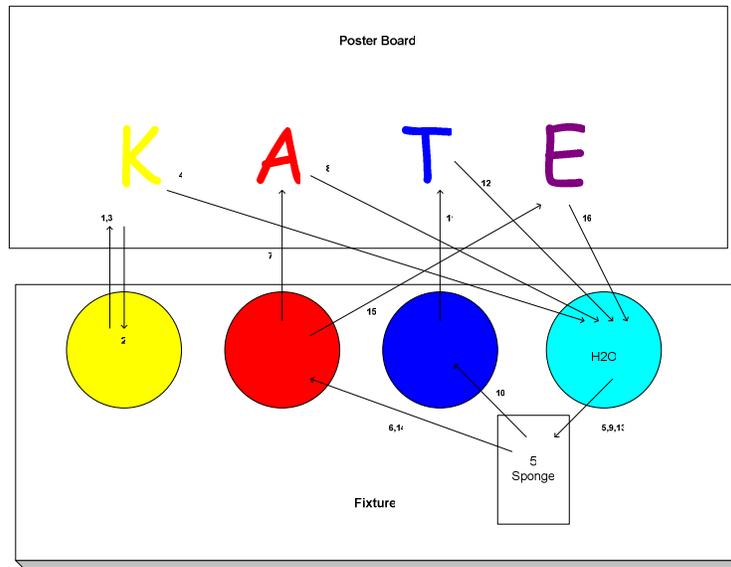


Fig. 9: Process Flow Diagram

This module helps to assess the ABET requirements such as ability to design and conduct experiments, ability to design a process to meet desired needs, ability to function as a team, and ability to communicate effectively, as well as the Mercer University's learning objectives such as creativity and critical thinking, application of technology, knowledge integration, knowledge application, and written communication.

Conclusions

The mechanical and industrial engineering curriculum at MUSE is based on ABET curricular guidelines. It provides the following learning opportunities to the students: theory on design, manufacturing and automation, dimensioning and tolerancing, and measurement and inspection through design and manufacturing courses; hands-on experience in design and manufacturing laboratories, and open-ended design projects from freshman through senior years; real world experience through industry co-op, summer internship, and participation in professional society activities.

Typical laboratory modules on CAD/CAM and CMM, and design and fabrication of a spline, as well as the experiment in robotics developed and taught provides the students the design and fabrication as well as measurement and analysis skills that are needed in the real world industrial environment. In addition, these modules not only met the ABET's EC-2000 requirements such as ability to design and conduct experiments as well as to analyze and interpret data, ability to design component or process to meet desired needs, ability to function on multidisciplinary teams, and ability to communicate effectively, but also the Mercer University's learning objectives such as creativity and critical thinking in the design of components and processes, application of technology, knowledge integration, and knowledge application in making and measuring the parts made, and written and oral communication in writing the lab reports and presenting them in the class. Also, the effective use of theory classes, design and manufacturing lab facilities, and co-op opportunities provide the students the needed expertise and prepare them well to meet the challenges in the industrial workplace.

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Bibliography

1. Barr, R. E., Schmidt, P. S., Krueger, T. J and Twu C-Y. (2000), "An Introduction to Engineering through and Integrated Reverse Engineering and Design Graphics Project", *Journal of Engineering Education*, Vol. 89 (No. 4), pp. 413-418.
2. Burton J. D., and White D. M. (1999), "Selecting a Model for Freshman Engineering Design", *Journal of Engineering Education*, Vol. 88 (No. 3), pp. 327-332.
3. Davis, D. C., Gentili, K. L., Trevisa, M. S., and Calkins, D. E. (2002), "Engineering Design Assessment Processes and Scoring Scales for Program Improvement and Accountability", *Journal of Engineering Education*, Vol. 91 (No. 2), pp. 211-221.
4. Dym, C. L., Sheppard, S. D., and Wesner, J. W. (2001), "A Report on Mudd Design Workshop II: Designing Design Education for the 21st Century", *Journal of Engineering Education*, Vol. 90 (No. 3), pp. 291-294.
5. Hailey C. E., and Hailey, D. E. (2000), "Evaluation of Instructional Design of Computer-Based Teaching Modules for a Manufacturing Processes Laboratory", *Journal of Engineering Education*, Vol. 89 (No. 3), pp. 345-352.
6. Haik, Y. (2003), "Engineering Design Process", Thomson Books/Cole, CA.
7. Hales, C. (2001), "Critical Factors in Design", *Mechanical Engineering Design*, March, pp. 36-38, New York, NY.
8. Kumar, V., Kinzel, G., Wei, S., Bengu, G., and Zhou, J. (2000), "Multi-University Design Project", *Journal of Engineering Education*, Vol. 89 (No. 3), pp. 353-359.
9. Koehn, E. (1999), "Preparing Students for Engineering Design & Practice", *Journal of Engineering Education*, Vol. 88 (No. 2), pp. 163-167.
10. Moor, S. S., and Drake, B. D. (2001), "Addressing Common Problems in Engineering Design Projects: A Project Management Approach", *Journal of Engineering Education*, Vol. 90 (No. 3), pp. 389-395.
11. Sheppard, S. D. (1999), "Design as Cornerstone and Capstone", *Mechanical Engineering Design*, November, pp. 44-47, New York, NY.
12. Sorby, S. A., and Baartmans, B. J. (2001), "The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students", *Journal of Engineering Education*, Vol. 89 (No. 3), pp. 301-307.
13. Stenberg, S. P. K., Johnson, A., Moen, D., and Hoover, J. (2000), "Delivery and Assessment of Senior Capstone Design via Distance Education", *Journal of Engineering Education*, Vol. 89 (No. 2), pp. 115-118.
14. Swearengen, J. C., Barnes, S., Coe, S., Reinhardt, C., and Subramanian, K. (2002), "Globalization and the Undergraduate Manufacturing Curriculum", *Journal of Engineering Education*, Vol. 91 (No. 2), pp. 255-261.
15. Todd, R. H., Red, E.W., Magleby, S. P., and Coe, S. (2001), "Manufacturing: A Strategic Opportunity for Engineering Education", *Journal of Engineering Education*, Vol. 90 (No. 3), pp. 397-405.