Integrated Laboratory Instruction on CAD/CAM and Robotics at MUSE

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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.

Keywords: Design and manufacturing, measurement and inspection, dimensioning and tolerancing, automation and robotics, hands-on experience.

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 education [Davis, 3], engineering design process [Dym, 4; Haik, 6; Hales, 7], design considerations and constraints in the design course sequence [Koehn, 9], visualization skills [Sorby, 12], freshman engineering design [Barr, 1; Burton, 2], senior capstone design [Moor, 10; Sheppard, 11; Stenberg, 13], and multi-university design project [Kumar, 8].

The objectives of manufacturing engineering education and possible ways of introducing the subject into an undergraduate curriculum [Swearengen, 14] and the urgency for improving it in the educational system that supply industry with engineers [Todd, 15] have been discussed. A reverse engineering model and team projects for the freshman design [Barr, 1; Burton, 2], and computer-based teaching [Hailey, 5] 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 freshman through senior year in design, materials, manufacturing, and measurement related areas as explained below.

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The design and manufacturing facilities at MUSE include: CAD lab, conventional machine shop with lathes, milling, drilling, and grinding machines, welding shop, as well as robotics and automation lab with a 3-axis CNC machining center capable for 4th axis machining, two five-axis robot arms, CNC machines and equipment, 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; and 3-D solid modeling. The software packages used in this course include AutoCAD and Pro/Engineer.

In the manufacturing processes course (ISE 370), 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 (ISE 424), 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. Students are also allowed to use the manufacturing lab facilities for designing and fabricating parts for their senior design projects.

This paper presents three laboratory modules developed and taught in the manufacturing and robotics courses at MUSE. Selected results from student team projects are also presented, analyzed, and discussed.

CAD/CAM AND 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 which is offered in the Fall Semester of the junior year. This module is open-ended and consists of three sub-modules with appropriate instructions. Three-member student teams work on this module for a period of 2 to 3 laboratory classes (6 to 9 hours).

The design sub-module consists of the following steps:

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

The fabrication sub-module consists of:

- Load the program in the CNC machining center;
- Debug the program and verify whether the program is correct for the intended part;
- Learn how to operate the CNC machining center by going through the step-by-step operator training manual;
- Load the part on the vise and go through the operating sequence and run the machine to make the part;
- Once the part is successfully made, take the part to CMM machine.

The measurement sub-module consists of:

- 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;
- Measure the part dimensions using the CMM;
- Print a measurement report and verify whether the measured dimensions are within the design dimensions and tolerances;
- 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:

- Team effort and team interaction;
- Design skills that include - Creativity in design; Part design and part specifications; Use of design software packages;
- G-code programming skill – manual or use of a software package;
- Machining skills that include - Selection of proper material, tools, fixture, and machining conditions; Accuracy of machining;
- Measurement skills that include - Use of manual/DCC mode for measurement; Comparison of design specifications with the measurements made;
- Learning experience indicating the difficulties encountered in design, fabrication, and measurement phases.

The methods of assessment are based on:

- Grading of the lab report submitted at the end of the completion of the module;
- Verification of the design for creativity, dimensioning, and tolerancing;
- Verification of the part made on the CNC machining center for dimensional accuracy and surface finish;
- Verification of the CMM report on whether the part made by the team meets the design specifications and tolerances.

One such design made by a team of three students is the Mickey Mouse shown in Fig. 1. The part is designed using AutoCAD 2000. The material chosen for the fabrication of the part is particle board. For machining the part in the Fadal's VMC15 CNC machining center (Fig. 2) a program is written using G-codes.
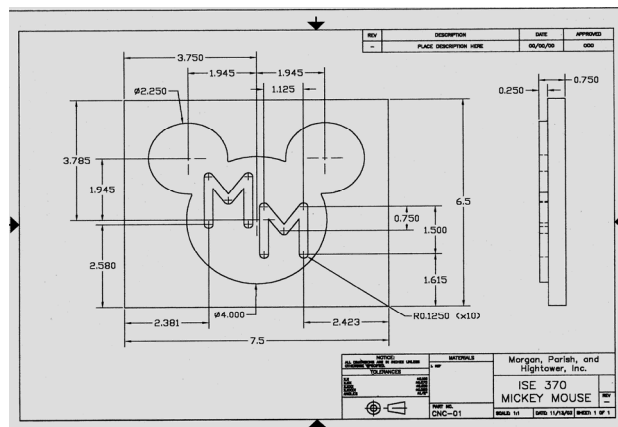

Fig. 1: Design of Mickey Mouse

The cutting tools used are: 1", 0.25", and 0.125" diameter end mills. The spindle speed of 1,200 RPM, a feed rate of 12 ipm, and a depth of cut of 0.25" are used. The part made (Mickey Mouse) is shown in Fig. 3. The part dimensions are measured using a coordinate measuring machine (CMM). The CMM is shown in Fig. 4. It is capable of measuring the dimensions to an accuracy of 0.0001". 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.
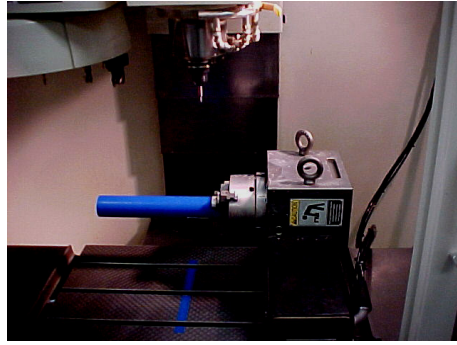
Fig. 2: Fadal's VMC15 CNC Machining Center with Rotary Axis

Fig. 3: Mickey Mouse (Part Made)

Fig. 4: Coordinate Measuring Machine

Table 1: Measurement Using CMM

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

DESIGN AND FABRICATION OF SPLINE (DFS MODULE)

This 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 students are divided into 3-member teams to work on this module for a period of 2 laboratory classes (6 hours). The typical DFS experiment consists of:

- Designing a spline with 6, 8, or 12 grooves using one of the design software packages such as AutoCAD or Pro-Engineer;
- Verifying the part dimensions and tolerances;
- Writing the part program in G-code either manually or using Pro-Engineer;
- Verifying the part program including selection of fixture type, cutting tools, and machining conditions;
- Using rotary axis (4th axis machining) and CNC machining center for the fabrication of the part which includes material selection, cutting conditions such as number of grooves, spindle speed, feed, and depth of cut, as well as selection of proper milling cutters;
- Using the dial gage/caliper to measure certain dimensions of the part made such as length, width, and depth of the grooves, taper angle, and outer diameter of the part;
- Writing a project report covering all aspects of design, fabrication, and measurement of the spline including error analysis.

This module provides the students: the basic understanding of designing a complex shape such as spline; the use of G-codes to program the part designed; make the part with the help of rotary axis and the CNC machining center; measure certain part dimensions using dial gage/caliper; and verify whether the measured dimensions are within the specifications and tolerance limits of the part designed through error analysis.

The design of a typical spline with 12 grooves 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 absolute percentage errors for all measured dimensions are found to be less than 2%.
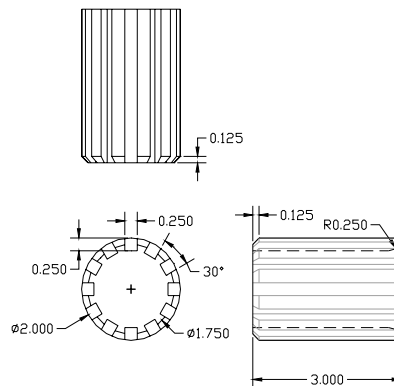

Fig. 5: A Typical Spline with 12 Grooves

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 SAMPLE LABORATORY EXPERIMENT IN ROBOTICS

Robotics (ISE 429) course is offered in the senior year as an elective course. A student team of four 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" during a period of 2 laboratory classes (6 hours). 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. *Robcomm3* 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 Figure 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 Figure 8.
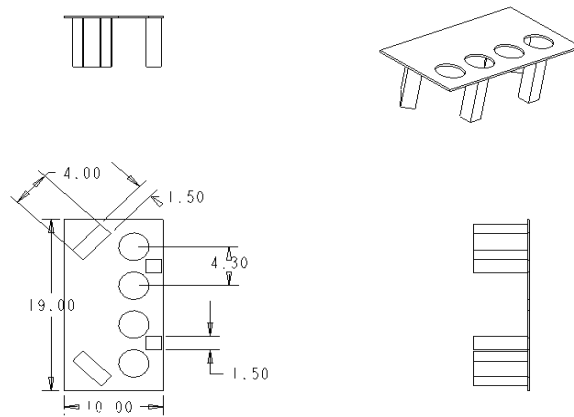
Fig. 7: AutoCAD Drawing of the Fixture

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 there, 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.

The major robot movements required to create "KATE" are listed in Table 3. The process flow diagram of writing "KATE" is shown in Figure 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.
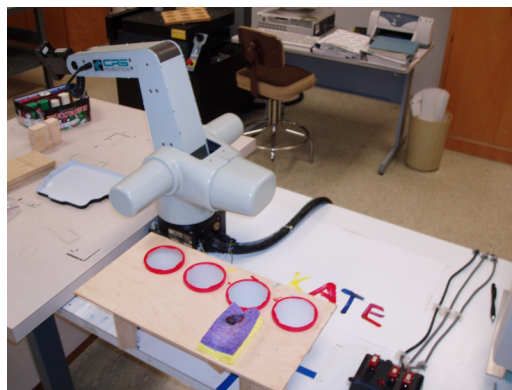

Fig. 8: Robot and Fixture Setup

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
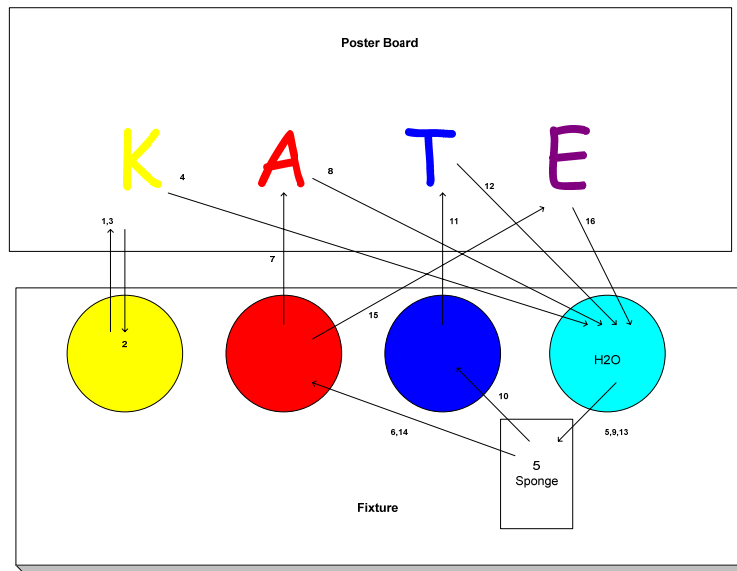
Fig. 9: Process Flow Diagram

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."

CONCLUSIONS

The mechanical and industrial engineering curriculum provides the following learning opportunities to the students at MUSE: 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, design and fabrication of a spline, as well as the experiment in robotics presented and discussed in this paper clearly shows the learning opportunities provided to the students. The effective use of theory classes, design and manufacturing lab facilities, and co-op opportunities available at MUSE provide the students the needed expertise and prepare them well to meet the challenges in the industrial workplace.

ACKNOWLEDGMENT

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