

Design, Manufacturing, Measurement, and Reverse Engineering in Undergraduate Engineering Education

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Abstract

Design and manufacturing courses are integral parts of Industrial Engineering curriculum at Mercer School of Engineering. In this paper, an overview of the design and manufacturing curriculum starting from freshman design through senior design, and introduction to manufacturing processes through automation and systems integration are presented and discussed. The manufacturing laboratory facilities, and design/automation hardware and software available are effectively used to teach Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), CAD/CAM integration, dimensioning and tolerancing, measurement and inspection, and reverse engineering concepts with appropriate hands-on experiences. A sample laboratory experiment in robotics, an example of measurements using coordinate measuring machine, and a typical senior design project are presented 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 education [Davis, 3], engineering design process [Dym, 4; Haik, 7; Hales, 8], design considerations and constraints in the design course sequence [Koehn, 10], visualization skills [Sorby, 13], freshmen engineering design [Barr, 1; Burton, 2], senior capstone design [Moor, 11; Sheppard, 12; Stenberg, 14], and multi-university design project [Kumar, 9].

The objectives of manufacturing engineering education and possible ways of introducing the subject into an undergraduate curriculum [Swearengen, 15] and the urgency for improving it in the educational system that supply industry with engineers [Todd, 16] have been discussed. A reverse engineering model and team projects for the freshmen design [Barr, 1; Burton, 2; Wood, 17], and computer-based teaching [Hailey, 6] in engineering education have also been studied.

At Mercer University School of Engineering (MUSE), the 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 listed in Table 1.

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

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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 course the students are exposed to hands-on construction activities, paper and pencil activities, and computer activities. The topics and activities are arranged in a logical order for the development of 3-D spatial skills. The course outline includes: visualization skills in engineering and science; isometric and orthographic sketching; pattern development; two and three dimensional drawing; translation and scaling; rotation of objects; and computer exercises in visualization. The software packages used in this course include I-DEAS and AutoCAD.

Table 1: Preparing engineering students in design/manufacturing: Mercer experience

Year	Curriculum	Hands-on experience/other related activities
Freshman	Mathematics Science Introduction to problem solving Introduction to design Professional practices	Problem identification Information gathering Engineering ethics Teamwork, creativity Open-ended design projects Freshman summer intern in industry
Sophomore	Mathematics Science Statics and dynamics Visualization and graphics Introduction to manufacturing Humanities Junior level exhibit	Professional society activities (SME, IIE) Industry visits Computer aided design ASME/ISO standards, AutoCAD Computer labs/teamwork Web-based training Industry co-op experience/summer intern
Junior	Manufacturing practices lab Manufacturing processes Machine design/CAD Computer assisted manufacturing Ergonomics/Work study Quality, Management, Business	Open-ended design/mfg. projects Programming CNC machines CAD/CAM integration Fabrication of parts – jigs/fixtures Measurement using CMM Design/simulation competitions Industry co-op experience/summer intern
Seniors	Human factors Facilities planning/Material handling Robotics, automation, and controls Senior design project Graduation exhibits	Team solutions and communications Design/build/test engineering systems Robot programming and cell manufacturing Reverse engineering Safety/environmental/ethical awareness Participation in conferences

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. Students are also allowed to use the manufacturing lab facilities for designing and fabricating parts for their senior design projects.

A Sample Laboratory Experiment in Robotics

A sample laboratory experiment is to write a program using the Robcomm3 software for the CRS-A255 robot arm (Figure 1) and the teach pendant. The robot has to pick up 22 dice of two different colors (red and green) and arrange them on a square board with 9 bins/circles. The dice are placed on a marked board as shown in Figure 2.



Fig. 1. CRS-A255 Robot Arm.

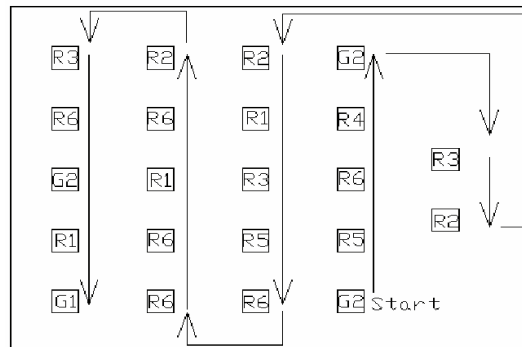


Fig. 2. The Board with Initial Locations Marked.

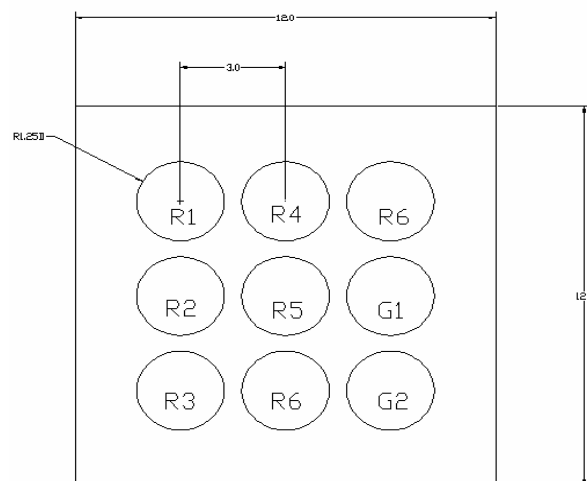


Fig. 3. The Square Board with Nine Circles/Bins.

A typical sequence in which the robot arm will pickup the dice from the marked board is indicated by arrows from the start location. The robot arm will actually move each die once into a specified circle/bin in the square board with 9 bins/circles (Figure 3), located in front of the robot. This laboratory experiment is carried out using the following steps: 1. Determine the initial and the final layout for each individual die. 2. Determine the number each die will display initially. 3. Setup points into the Robcomm3 software. 4. Write the program. 5. Run the program.

Measurements Using Coordinate Measuring Machine

Coordinate Measuring Machines (CMMs) have a wide variety of applications and benefits. Mechanical components and manufactured parts are frequently inspected using CMMs. One common application is to check the first part machined on a numerically controlled machine tool. If the first part passes the inspection, then the remaining parts produced in the batch are assumed to be identical to the first. Gears, threads, and automobile body checking are other examples where CMMs are widely used. CMM is used for: measuring part dimension to an accuracy of $1/10000''$; 2-D and 3-D modeling of parts; and reverse engineering of the existing parts. The coordinate measuring machine available in the lab is shown in Figure 4. Typical measurements made by the students include: diameter of the tennis balls, and dimensions of the parts made using CNC machining center (length, width, depth, diameter, radius, and surface contours).



Fig 4. Coordinate Measuring Machine.

An Experiment Using CMM

New tennis balls are ideal to play tennis. However, after hours of play, they start deteriorating. As they lose the felt they fly faster and bounce faster which makes it harder to control them. The purpose of this study was to determine the change in diameter of new tennis balls after 1-hour playing intervals. A total of six Wilson practice tennis balls were used in this study. Two NCAA Division I college players volunteered to practice with these selected balls during three 1-hour sessions. The tennis practice consisted of rallying back and forth trying to keep the ball in play as long as they could and trying to balance the use of the six balls evenly. Measurements were taken at least five hours after they had been used to ensure that the elevated temperatures would not affect the true diameter of the balls. The room where the measurements took place was kept at 22 degrees Celsius to ensure that the measuring probe tip did not expand and affect the measurements.

The *PC-DMIS v 3.2* software used is equipped with data processing to accomplish the geometric computations required to determine the diameter of the tennis balls. By measuring four points on the surface of the tennis balls, the best fit center coordinates (a, b, c) and the radius R (Diameter $D = 2R$) of the tennis balls can be calculated. The coordinate values of the four point locations are used to solve the four equations with four unknowns:

$$(x-a)^2 + (y-b)^2 + (z-c)^2 = R^2 \quad (1)$$

Each tennis ball was placed in a 6 cm diameter cylindrical plastic can and secured at the bottom with *K-Mart Dough* to prevent the ball from moving. The probe was calibrated using a sphere with known diameter prior to begin the measurements. Three measurements were performed on each tennis ball after 1-hour playing intervals. The results are summarized in Table 2. The practicing time versus diameter of the ball are shown in Figure 5. It is interesting to note that the ball diameter actually increases slightly after one hour of play and then starts decreasing. This is due to the felt that expands initially and then starts to wear off. The measurements helped to determine the reduction in diameter after hours of play.

Table 2: Tennis ball diameter in mm after practice time

	After			
	New	1-hour	2-hour	3-hour
Average Diameter	65.0870	65.5260	64.8940	64.5870
Standard Deviation	0.1080	0.4800	0.2702	0.3145

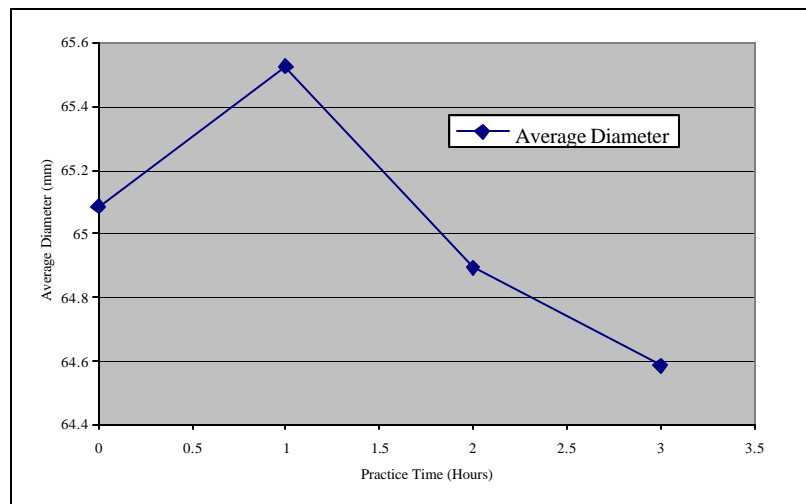


Figure 5. Practice Time Versus Tennis Ball Diameter

The available reverse engineering software is used to take an existing physical part and construct a computer model of the part geometry based on a large number of measurements of its surface by a CMM. Non-contacting probes such as lasers have a significant advantage over contacting probes in reverse engineering.

Using CMM students are trained in making measurements of the parts made in the CNC machining center. They also take an existing part and construct a computer model and then the CAD design. The part is then made using CAM software on the CNC machining center thereby learning the reverse engineering concepts.

A Typical Senior Design Project

At Mercer University School of Engineering, senior design projects are multidisciplinary in nature with duration of two semesters. During the first semester, a team consisting of three students is expected to work on a project proposed by the client and come up with a preliminary design acceptable to the client. They work closely with the client and the technical advisors to accomplish this task. Once the preliminary design is approved, during the second semester, the students' team will build, test, and install the design to the satisfaction of the client and the technical

advisors. It is very common that three students from three engineering disciplines sign up for a design project involving knowledge and skills from different engineering disciplines. One such project is given to a design team consisting of three students. The task is to integrate a CRS-A255 robot arm with a Fadal VMC 15 CNC machining center [Godfrey, 5]. The team should design an automatic clamping device to hold the part that is being machined. They also should design a control system to operate the automatic clamping device. They are expected to consider the safety issues while operating the system, as well as learn to program the robot arm and the CNC machining center. The summary of the work accomplished by the team is presented and discussed below.

The Clamping Device

Three different alternatives proposed for the clamping device are: 1. Use a pneumatic vise. 2. Use two air cylinders and a permanently mounted piece of L-shaped metal. 3. Use one air cylinder and a permanently mounted piece of V-shaped metal. The feasibility criteria considered for the clamping device are: to produce a clamping force from 10 to 150 psi; to fit onto a 16"x 29" CNC machining center table; capable of opening and closing automatically; and to hold a 3"x 3" part. The merit criteria considered for the clamping device are: cost, centering ability, and safety.

Based on the feasibility criteria, merit criteria, cycle time analysis, force analysis, robot work envelop, robot control program capability, and sensitivity analysis, the third design alternative has been chosen. This includes an air cylinder with a V-block attached to the end of the shaft, and a V-block that will be mounted on the CNC machining center table.

Control System Design

Three different alternatives proposed for the control system design are: 1. Write a computer program for the CRS-A255 robot arm to control the air solenoid. This will be accomplished through an integrated relay switch in the robot's general-purpose input/output port on the back of the C500C robot control unit. The relay switch will be normally open and supply the 120-volt AC to the solenoid so that it will stay closed thereby keeping the clamping device open. When the computer activates the relay switch, the switch will open removing the 120-volt AC from the solenoid so that the solenoid will open. This will allow the air pressure through to close the clamping device. 2. Use the manual approach, in which the human user will flip a switch and the clamping device will either open or close. Similar to the design alternative 1, when the switch is flipped, the current will flow through the solenoid and close it thereby opening the clamping device. When the current is cut off, the solenoid will open and allow the air pressure to close the clamping device. 3. Use the combination of alternatives 1 and 2. In this, the user will select whether the clamping device should operate in automatic or manual control mode.

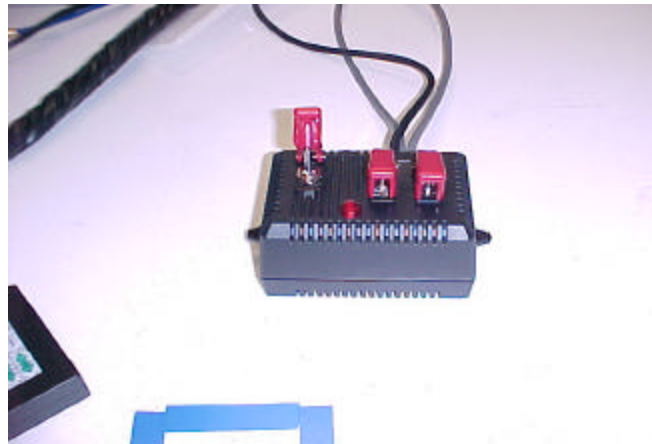
The feasibility criteria considered for the control system design are that it should fit on or around the table to which the robot arm is attached to, the table should fit securely inside the CNC machining center opening, and the robot arm should not make contact with the CNC machining center while loading or unloading a part. The merit criteria considered for the control system are: cost, easy use, safety, constructability, and client preference.

The third alternative with a dual control system in which the user may select either automatic (computer control) or manual (user control) mode has been selected. The overall project cost is estimated to be \$150 considering only the material cost for building the clamping device and the control system.

During the second semester, the students designed and built the selected clamping device with one air cylinder and a permanently mounted piece of V-shaped metal using the facilities available in the manufacturing laboratory. The clamping device when tested met all the feasibility and merit criteria that were chosen by the students. The clamping device is mounted on the CNC machining center table and is shown in Figure 6. The switch box shown in Figure 7 has been made as part of the control system design to operate the clamping device automatically for opening and closing when the part is placed on the clamping device by the robot arm. When tested, the switch box also met the feasibility and merit criteria chosen by the students.



Fig. 6. Clamping Device Mounted on the Machine Table.



Legend: From Left to Right:
1. Power on or off Switch; 2. Automatic or Manual Mode
3. Open or Close Position (in Manual Mode Only)

Fig. 7. Switch Box for Clamping Device.

The clamping device and the control system were installed and tested together with the CRS-A255 robot and the CNC machining center for automatic loading and unloading of parts, as well as automatic opening and closing of the clamping device when the part is loaded/unloaded. The CRS-A255 robot preparing to remove the part from the clamping device is shown in Figure 8. At present, this set up forms an integral part of the CNC machining cell with robot interface for loading, unloading, and automatic actuation of the clamping device in the manufacturing laboratory.

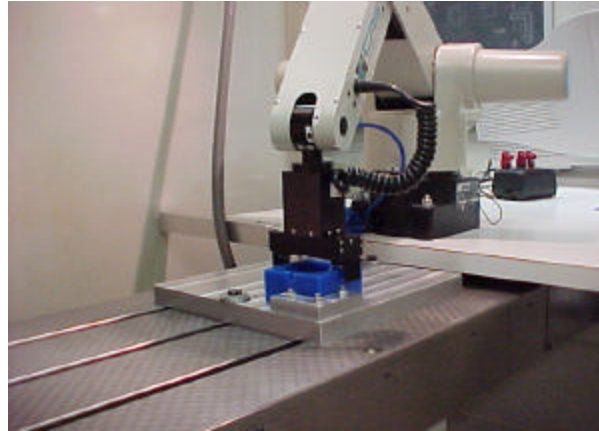


Fig. 8. Robot Preparing to Remove Part from Clamping Device.

Conclusions

The industrial engineering curriculum based on ABET curricular guidelines provides the following learning opportunities to the students at MUSE:

- Theory on design, manufacturing and automation, dimensioning and tolerancing, measurement and inspection, and reverse engineering through design and manufacturing courses;
- Hands-on experience in design and manufacturing laboratories, and open-ended design projects from freshmen through senior years;
- Real world experience through industry co-op, summer internship, and participation in professional society activities;

Typical examples of lab work (Robot and CMM) and senior design project (Robot and CNC machining center) presented and discussed in this paper clearly indicate the learning opportunities provided to the students at MUSE. The effective use 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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