AC 2010-932: INTEGRATING HANDS-ON DESIGN EXPERIENCES INTO THE CURRICULUM

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Integrating Hands-On Design Experiences into the Curriculum

Abstract

In many Biomedical Engineering (BME) programs, design is a key component throughout the curriculum. This may involve a combination of design problems on paper, a reverse engineering project, education in design methods, and hands-on fabrication experiences. In the BME program at the University of North Carolina at Chapel Hill, our goal is to also provide more hands-on design opportunities in the laboratory and machine shop. We accomplished this by creating new courses for a "design sequence" and by collaborating with an existing, required course.

The design sequence consists of four courses that span the final three years of the curriculum. In the first two classes, typically taken in the second and third years, the goals are to learn the basic design tools and manufacturing techniques for building biomedical devices, such as a rotating cell culture bioreactor. In the process, students learn how to use a variety of tools and equipment in the student machine shop, including computer aided design software, a 3-D fusion deposition modeler, laser cutter, mill, lathe, and a variety of hand and power tools.

The third design course is taken in the fall of senior year, and it is taught in conjunction with a required class in control systems. This gives students a chance to apply the theoretical material that they are simultaneously learning in control systems. For example, this year each student group developed a robot arm system controlled by a biopotential signal, such as an EMG or EOG, that they acquire from their own body and process. For the fourth design course, each group works on a different project, chosen from a wide variety of project ideas that change from year to year.

This design program has many benefits. By the time students start their final design project in the spring of senior year, they already have a number of hands-on experiences in design. This elevates the level of what they can accomplish for this project. In addition, since our students start getting experience with equipment in the machine shop in their sophomore year, they are an attractive asset for many research laboratories. Feedback from students indicates that these hands-on experiences were fun and beneficial for them.

Introduction

In engineering design courses, students have an opportunity to consider an open-ended problem and develop an original design to address the need. In fact, design and development "is what most distinguishes engineering from science, which concerns itself principally with understanding the world as it is". [1] As a result, many programs have emphasized design in a number of ways, for example by incorporating design courses for first year students and throughout their curriculum.[2-3] In recent years, many papers at the ASEE conference have been devoted to presentations on this topic, including an entire session in 2009.[4-9]

At the University of North Carolina at Chapel Hill, we have a small but growing program in Biomedical Engineering (graduating 32 students in May 2010). When the faculty first developed the curriculum, we incorporated a typical two-semester senior design course. However, we soon realized that the students were entering senior design without the skills needed to be productive in that experience. As a result, we decided to enhance the design component of the curriculum.

The design process involves many components, including identifying the need; proposing solutions; developing prototypes; testing and evaluating prototypes; and building a finished device.[10] Other “soft skills” are necessary, such as working in teams; developing skills in written and oral communication; and developing a project schedule.[11] Our students were learning these skills, but not until late in their senior year, which was often too late.

In addition, it is often overlooked that students benefit from a background in modern manufacturing processes and hands-on experience with the tools of manufacturing. While electronics classes provide students with experience in developing circuit-based prototypes, our students had no experience in using machine shop tools and developing appropriate designs for those tools. This gap in their skills effectively limited the scope and quality of the projects in senior design.

Objectives of design courses

To address these shortcomings in our curriculum, we created a “design sequence”. In making these changes, we had several objectives:

- To emphasize both design and manufacturing before the senior year
- To provide students with more hands-on experiences

To meet these goals, we developed two new courses: BME Design and Manufacturing I and II. These courses are typically taken in the sophomore and junior years. They provide an excellent background for the students to be well prepared for senior design. We also enhanced the senior design program. Further details on all of these courses are below.

Methods

Facilities

We currently have a dedicated undergraduate design lab with approximately 935 square feet of workspace (figure 1). This lab includes all the basic tools needed for mechanical design,

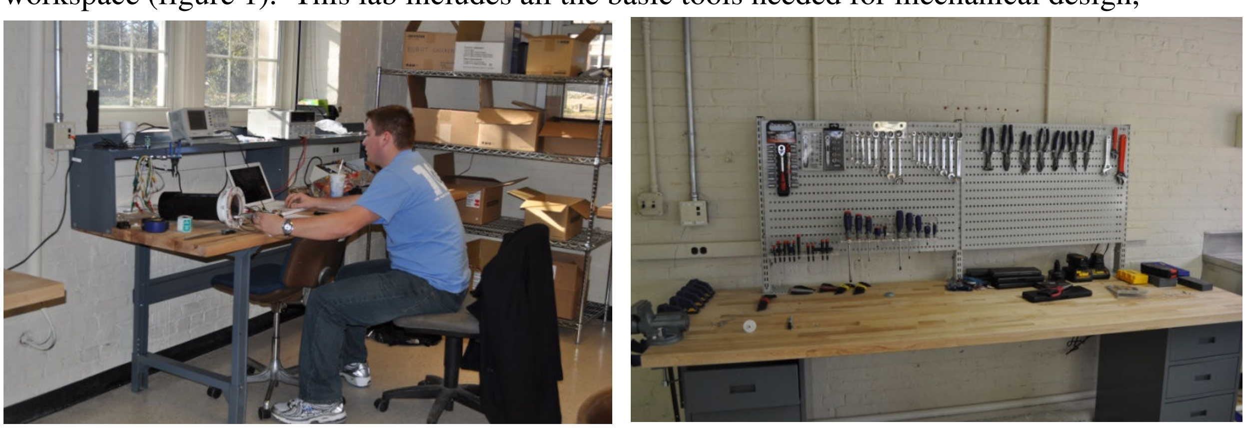


Figure 1: photos of student design lab

including hand tools and power tools. Supplies include PVC piping, acrylic, wood, and an assortment of hardware. The lab also has supplies and equipment needed for electronics design, such as hand tools, breadboards, power supplies, oscilloscopes, function generators, and microcontroller programming equipment. The lab has storage areas as well as work benches, and it can accommodate up to 15 students at a time.

Figure 2: photo of machining room

This lab is open to the students anytime through key code access. Graduate teaching assistants (TAs) staff the lab in the afternoons and early evenings, as well as on weekends to coincide with student's needs.

This laboratory includes a separate, locked machining room with controlled access (figure 2). The room has a fusion deposition modeler (FDM, Stratasys Dimension) and laser cutter (Universal Laser Systems). We plan to add a computer numerical controlled (CNC) mill in the near future. Students only have access to this room under supervision of a TA or faculty member.

In the rare case that these machining tools are not sufficient, students have limited access to machining equipment in a BME research lab, which is professionally staffed, as well as a fee-for-service machine shop in the Department of Physics and Astronomy.

Courses

A. BME Design and Manufacturing I

Students typically take this course in the spring of sophomore year, but that may take it anytime (fall, spring, or summer) before the spring of junior year. It is a self-paced, one credit hour course. The objectives of this class are:

- To develop skills with solid modeling (SolidWorks) software.
- To transform a SolidWorks model into a physical object using a modern rapid manufacturing system.

The format of this class enables the students to develop important skills that they will need in the future, while using minimal faculty resources. The class does not formally meet and students work on assignments independently. Each week, the students are assigned to complete 1-3 of the SolidWorks tutorials. When finished, they take a screen shot of their SolidWorks component and email it to the TA.

There are several additional assignments to give students more experience with design using SolidWorks, as well as understanding how to take measurements and develop effective designs:

- **Measure and Model** (2 assignments): The TA gives the several physical objects to the students, as well as measuring devices. The students take measurements of those objects and develop an equivalent SolidWorks design.
- **Solid Modeling** (1 assignment): Students develop an original design of their own choosing, and use the FDM (fusion deposition modeler) to create a solid 3-D model of that object made from polycarbonate. This gives the students an understanding of the trade-offs involved when designing a component for "printing" using a rapid prototyping device. It also provides students with experience in using rapid prototyping, a tool that they will use in subsequent classes, and likely in their future careers.

B. BME Design and Manufacturing II

Students typically take this course in the spring of junior year. Because this course is more lab intensive than the above class, it is only offered in the spring. It is a two credit hour course with the following objectives:

- To learn about modern design practices
- To learn about and use a variety of manufacturing processes and equipment

Each lecture covers an aspect of modern design practice and a manufacturing process. The lecture topics are outlined in Table 1.

Table 1 – Lecture topics, BME Design and Manufacturing II

Modern design practice	Manufacturing processes
The Process of Modern Design, Reverse Engineering	Overview of Manufacturing
Problem Definition & Design Spec.	FDM (Fusion Deposition Modeling)
Concept Generation & Selection	Laser machining
Functional decomposition	Machining processes: mill & lathe, hand tools
Benchmarking	Welding, brazing, soldering
Gantt charts	Casting and Molding, Forming
Detailed Design, Design Reviews	Heat treatment & surface finishing
α-β Prototype, Evaluation, Engineering Change Notices (ECN)	Water-jet, EDM, DMF
	Materials Selection in Design
	Biomedical Sterilization

There are weekly assignments that help to reinforce the material covered in lecture. In addition, there are three major projects. These provide students with additional background, as well as hands-on experience, in the manufacturing processes covered by lectures. The projects are:

- **Build a small rotating bioreactor vessel:** Each student goes through the entire process of building a rotating bioreactor vessel, which is functionally equivalent to commercially-available rotating cell culture bioreactors used in tissue engineering research. The instructor guides the students through each step of the building process and instructs the students as to why certain materials and processes were chosen and what alternative processes might be used. Other points covered include different approaches that would be used for manufacturing the same items in larger quantities; the use of various hand tools and fixturing to facilitate the assembly; the names and functions of the various COTS (commercially-available off-the-shelf) components that are used in the assembly; and the costs generally associated with each material and process that is employed.

- **Research the manufacturing process used for a biomedical product:** Individual students select a common, simple biomedical product and will research the processes and materials used in the manufacture of that product. Each student writes a 3 page report.
- **Complete a reverse engineering project:** Students will work in groups to disassemble and analyze a piece of equipment, selected by the instructor. The group writes a detailed report that describes the device design in enough detail so that it could be reproduced.

C. *Senior Design, fall and spring semesters*

In the above classes, the students develop a background in design and manufacturing processes, and they obtain hands-on experience in the machine shop. As a result, the students know how to convert a paper design into a physical object. The goal of senior design is to synthesize and apply the material from the above classes by completing open-ended design projects. In addition, there is reinforcement of design and manufacturing processes, both formally through additional lectures and lab exercises, and informally through student meetings with the faculty and teaching assistants as they get feedback throughout the year.

While most programs incorporate a year-long senior design, working on a single project throughout the year, in our program the students work on one project in the fall and a different project in the spring. This provides the students with an additional hands-on design experience. The fall class is two credit hours, and the spring class is four credit hours.

In the fall, students are given a design challenge. Each group works on the same challenge project, but takes different approaches depending on the ideas that the group generates, and the different strengths of the group members. The challenge has varied over the years but has always included components in mechanical design, electronics design, microcontroller programming, and signal processing. There are no formal class meetings because at this point, students already have the background in design and manufacturing processes to work on this project. The TAs and instructors work closely with the students in lab to help them become successful in this project.

In fall 2009, we modified the challenge to synchronize with material taught in with Linear Control Systems, a required course in our program that students were taking at the same time. The objectives were to bring further cohesion to the curriculum, and to propose a challenge that increases student motivation and provides a real-world perspective. The linear controls course employed a unifying theme of developing engineering solutions to the basic design challenges required for a neuroprosthetic arm and hand. Numerous examples of such systems exist from the clinical and engineering research community. This coincided with the senior design challenge, which was specifically defined to confront the students with similar design problems.

As part of the controls course, student teams were required to prepare mid-term and final reports on how they planned for and applied the concepts of control theory in their senior design projects. Also, selected lectures were presented in the controls course on related topics (servo systems, strain gauge measurement, biopotential recording, etc.), as the students needed to learn those concepts to support their senior design projects. A significant advantage of the cross-linked courses was that concepts in linear controls could readily be discussed in the context of problems the students were facing in the senior design lab. In addition, it was easy to illustrate to the students how the same concepts of feedback control could be used to advantage in both linear and nonlinear systems.

Table 2 shows the design challenge that the students addressed. Students were divided into groups and each group worked independently on this project.

Table 2 – Senior design challenge, fall 2009	
Challenge	Design and build portions of a neuroprosthetic arm system capable of performing a simple motor/sensory task. The ultimate test is to perform the simple task using the apparatus in the minimum time. The system will be based on a commercial robotic arm (Lynxmotion model AL5C). You must develop the grasping mechanism and the control and sensory systems for both the robotic arm and grasping mechanism.
Motor/Sensory Task	The task will be to move three eggs from one location to another location and determine which of the three eggs is the heaviest in the process.
Minimum Design Goals	Develop a mechanism that is capable of grasping and holding an egg without breaking it while it is moved to a different prescribed location
	The grasping mechanism and robotic arm should be completely under the control of electromyogram (EMG) or electrooculogram (EOG) potentials recorded from the student operator(s) during the time the eggs are being grasped and moved
	The grasping mechanism should have some method providing sensory feedback to the operator(s) so that the relative weights of the eggs may be determined
	The grasping mechanism must be of a form to not overload and otherwise damage the commercial robotic arm. All robotic arm loading should be within the published performance specifications of the robotic arm system manufacturer.

In the spring semester, students start work on a new design challenge. While in the fall, all of the groups are addressing the same challenge, in the spring, each student group addresses a different challenge. The project ideas come from a variety of sources, both on and off campus, and a number of faculty across campus serve as mentors.

There are two separate sections of senior design. One section focuses exclusively on developing assistive technology projects for people with disabilities, and these projects are done in coordination with clinical supervisors in the local community. The completed projects are donated to the clients and their families at the conclusion of the semester. Because of the clinical nature of these projects, there are lectures to give students the clinical background that they need.

Additional lectures and exercises cover engineering standards and product safety to insure that the device will be safe and useful for the recipient. The other section of senior design encompasses the remainder of the projects. Because this work is scattered across campus, students only come together a few times during the semester to present their work.

For both sections, the semester concludes with a poster session and demonstration of all of the projects. In addition, each student group submits a detailed report describing their work.

Results

The following figures show some of the student work developed in the design courses.

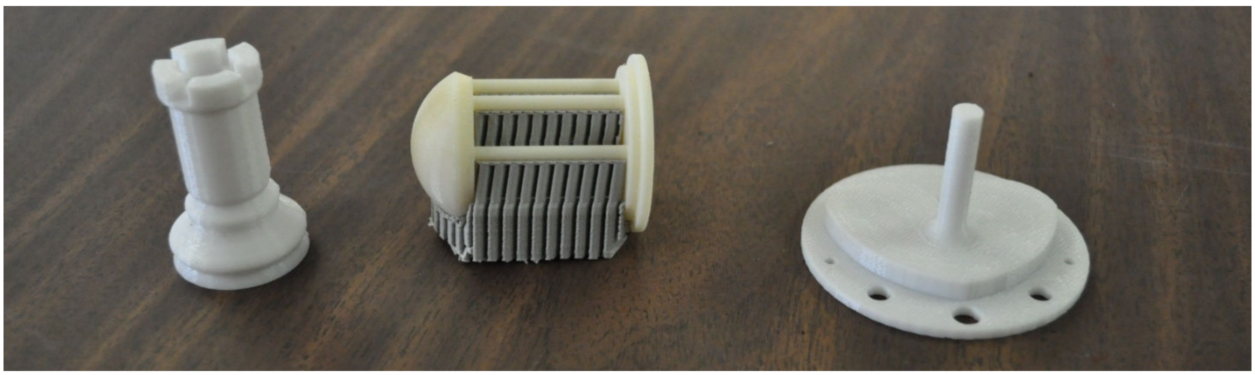
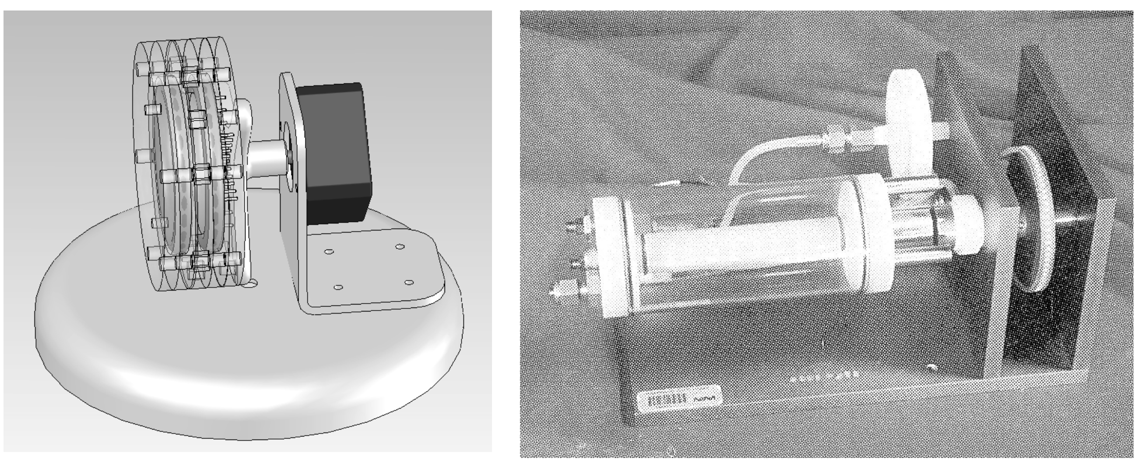


Figure 3: Several FDM projects from BME Design and Manufacturing I. The sample in the middle still has vertical columns of filler material inside, which is later removed by pliers.

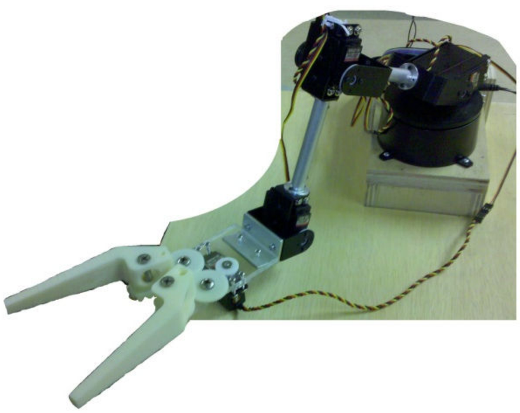


(a) (b)

Figure 4: Design for a rotating bioreactor in BME Design and Manufacturing II. (a) SolidWorks design; (b) commercial bioreactor that provides a model for the design.

(a) (b)

Figure 5: One of nine solutions to the design challenge in fall semester senior design, fall 2009. (a) SolidWorks model of an egg gripper; (b) photo of the gripper, whose primary components were produced with FDM.



Movement	Angle of Eye Position	EOG voltage	Motor Motion
Look Far Right	25	4V	Clockwise
Look Right	65	3V	None
Look Straight	90	2.5V	None
Look Left	115	2.5V	None
Look Far Left	155	1V	Clockwise

(c) (d)

Figure 5 (continued): (c) photo of the gripper attached to the commercial robot arm; (d) results of signal processing the EOG signal to control the motors.

(a)

(b)

Figure 6: Two of nine projects in spring semester senior design, spring 2009. (a) A custom tricycle braking system for a girl with Cerebral Palsy. She cannot manipulate standard handbrakes, so a new system was developed that she can engage through a hand twisting motion; (b) A locker assist for a girl with Cerebral Palsy who cannot independently access the material in her locker. It consists of a sliding shelf with a rotating bookend so that she can easily place books in her locker and remove them.

Discussion

The BME Design and Manufacturing I and II courses were developed in 2005 and required starting in 2006. They have continued to evolve since then. The senior design courses had been taught prior to that time, but have been modified since then to take advantage of the students' incoming skills in design and manufacturing.

BME Design and Manufacturing I has been effective in giving students a background in SolidWorks and an introduction to FDM. Because it requires minimal faculty resources, it has been straightforward to implement this class. BME Design and Manufacturing II has required more resources and required additional hiring of a machinist (50% devoted to undergraduate instruction) and TAs. The hiring of a design faculty in the coming year will provide students with more hands-on guidance in the lab, which was the primary criticism in feedback from the students.

The fall semester of senior design was successful under the new challenge implemented in 2009, as described above. The projects required the students to understand the design problem, gather information and conduct experiments, plan an overall solution, develop prototypes, revise designs and plans and ultimately report their results. Experience to date shows that the greatest challenge is to get the students engaged in their projects early, at which point the experience feeds on itself. Future offerings of the course will feature a more robust robotic arm capable of greater grasper weight and more precise arm position control.

Since the enhancement of the design curriculum, we have seen a significant improvement in the quality of work that students produce in spring semester of senior design. While we compress the final senior design project into a single semester, students are actually able to accomplish more because of their previous experiences in design. In fact, it appears that the compressed structure of the class is also beneficial because students are working on tight deadlines right from the beginning of the semester. They do not have the luxury to procrastinate because they only have about 12 effective weeks to work on their project, and they work hard all semester. It is evident that this class has been successful, because at least one of the assistive technology projects each year has gone on to win an award in a national student design competition.

Student feedback

These courses have been well received by students. Student feedback demonstrates that have they appreciated the opportunity to gain a background and experience use state-of-the-art manufacturing tools. Furthermore, most students have gone well beyond the requirements for design projects in order to gain more experience and a better understanding of how to use the manufacturing tools. Below is some representative feedback from the students:

- **BME Design and Manufacturing I**
  I found this course to be very beneficial overall. SolidWorks is a tool that students will continue to use throughout their undergraduate tenure…. The online tutorials are very worthwhile, and I consider them to be a very good way of teaching the material.
- **BME Design and Manufacturing II**
  The homework assignments, the bioreactor project, and the manufacturing report were all nice additions to the course. Overall, the course content was excellent.
- **Senior Design, fall semester**
  One of the coolest courses I've taken. I really enjoyed it because of its loose structure with just a goal, allowing any path to be taken to reach it. With the lab, we had access to almost anything that we needed. This class basically asked the question: “You've spent 3 years learning BME. What can you show for it?”

Recent graduates have also stated that their hands-on experiences in design have made them valuable assets in their jobs or graduate programs:

- I owe my advanced skills in design and manufacturing to the hands-on nature of several courses, which put a greater emphasis on an applied learning technique rather than a pure theoretical approach. These project-based courses truly give our graduates a competitive edge not only due to the skills developed in practical engineering, but also in time, group, and project management; skills equally important in any modern work environment. If there is anything I regret from my undergraduate career, it is that there were not even more of these design courses.
- What I gained from the design courses was the ability to see many (if not every) step in the process of rapidly prototyping parts and devices. While many of my colleagues in BME graduate school have read about this, or even had a lecture on it, I have actually done it from start to finish.... To me, hands-on learning made all the difference.

The primary criticisms were that students would like more guidance and more opportunities to work on projects in the design laboratory, earlier in the curriculum. This has already been addressed with the hiring of two teaching assistants this spring who are able to provide more guidance to the students. In the long term, it will be addressed with the hiring of a new undergraduate design faculty, who will be able to fully dedicate the necessary time to these courses.

Summary

We have implemented a sequence of courses so that students can develop skills in modern design and manufacturing. Students learn these skills through traditional lecturing, and more importantly, through hands on projects and challenges in the design lab. This starts in the sophomore year, and students already have several hands-on experiences as they start their senior projects. The result is has been to elevate the level of what students accomplish in senior design, as well as to better prepare students for graduate school and industry. Feedback from students indicates that the design sequence has been effective in giving them valuable skills in design and manufacturing.

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