Teaching Engineering Design – The Evolution of a Senior Design Course in Electrical Engineering

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Abstract

Engineering students typically take a core set of courses that include both laboratory exercises and semester design projects. These courses provide the students with practical laboratory and experimental skills, as well as teaching them to apply these skills to a well-defined design project. However, the core engineering courses do not normally teach some of the topics necessary to successfully design less well-defined, “real world” projects. This paper describes the evolution of the integrative senior design course in the Electrical Engineering Program at the United States Military Academy (USMA). In the early 1980’s the senior design project in the Electrical Engineering Program at USMA was an individual project completed at the end of the final electronics course. The design project has since evolved into a two-semester design course with interdisciplinary group projects. Throughout the two-semester course, students work with a dedicated faculty advisor to develop a written project proposal, several in-progress reviews, a prototype demonstration, and a final report. The course includes lectures covering topics unique to the engineering design process such as project management, design economics, and engineering ethics. It also includes laboratory exercises designed to give the students practical skills they do not typically acquire during the core electrical engineering course sequence. Examples of these laboratory exercises include designing a printed circuit board, packaging circuits, and integrating sensors with microcontrollers. Both the senior project and the laboratory exercises reinforce the technical, economic, political and social aspects of the engineering design process. The course today provides students with the skills they need to successfully perform as part of an interdisciplinary design team.

Introduction

Twenty-five years ago, senior design projects in the Electrical Engineering Program at USMA were little more than extended laboratory exercises, customized for individual students. Today, teams of three to five students complete design, simulation, fabrication and testing of systems solving a variety of real-world problems. This paper examines the evolution of senior design projects and the surrounding curriculum and identifies what we believe to be the essential components of a program that effectively balances breadth and depth of engineering science with a progression of engineering design problems culminating in a year-long design experience for seniors. This review reveals that the essence of creation, implementation and maintenance of a successful design program is design itself. The process is iterative, constantly seeking to improve the program. Moreover, the surrounding curricular and administrative constraints require annual review of the assumptions and design decisions based on those assumptions. The result is an ever-evolving program that seeks to maximize the students' design experience, enjoyment and success.

A Short History of EE Senior Design Projects at USMA

The design content of the EE program in the late seventies and early eighties consisted of a single project completed by second-semester seniors as a part of the electronics sequence. Unlike the scripted laboratory exercises in the preceding courses, the senior design was open-ended and allowed, or required, the student to investigate various circuit topologies to achieve the desired design performance. The scope of these projects rarely exceeded a single circuit. Most were constructed and tested on tie-point wiring boards without further progress toward a useable package or finished product. One project typical of this era was a 1.5 MHz Colpitts oscillator.

By the mid to late eighties, the scope of the projects had increased substantially. While the design projects were still encapsulated in the final course of the electronics sequence, a majority of the designs were of a complete system. In order to deal with the greater scope of the projects, the number and variety of projects was reduced. With only one or two instructors to handle thirty to forty students, having a different project for each student would have been impossible. Typical projects of the era were graphical, audio equalizers and adjustable DC power supplies capable of providing ten to twenty watts.

In the late eighties, we built a small printed circuit board fabrication facility. With the ability to produce one- and two-sided boards in-house, we rapidly increased the number of products that were packaged. However, with a single student completing the project, and only a third of a course devoted to the project, it was difficult for students to produce professionally finished products. During this period we also decided to involve more faculty members in the student projects. Initially, we had four to five faculty members acting as advisors. Each advisor became an "expert" on a particular project. Most instructors spent a year acting as the secondary advisor on a project, before taking the lead. Eventually, we increased the number of different projects to the extent that ten of the fifteen faculty members were each supervising different projects, usually with four to five students doing each project. The increased number of projects left no time for faculty to spend a year as a secondary advisor, and we began assigning faculty members projects with which they had some previous experience. Frequently the projects developed under this model were a continuation or extension of research performed by the junior faculty in their graduate school programs. Some new projects were the outgrowth of research being performed locally in the Photonics Research Center. An example of packaged products in the period was the so-called color-organ that displayed different color lights depending on the frequency content of an audio signal, while an optical character recognition system was one of the "research-based" projects.

During this same period, we also had a team laboratory exercise with a "forced" division of labor in the last electronics course. Aware that a growing number of industrial constituents wanted students with team design experience, and faced with too many projects and not enough faculty members, we introduced team design projects in 1994. As a part of the change we extended the duration of the project from one third of a course to an entire course conducted during the last semester. This change required us to give up topical coverage in the electronics sequence. The benefit to the projects was substantial, however. Projects completed under the former model were the result of less than forty hours of student work. With a full semester and a team of students, project complexity expanded. Reports routinely indicated over one hundred hours per student giving many teams in excess of four hundred hours of student time on the projects. Project teams of this era also included students not majoring in electrical engineering. In many instances the non-engineering majors brought interesting perspectives and exposed the engineering majors to non-technical aspects of engineering they might otherwise have missed. Two of the most successful projects during this period were different versions of a laser light show.

Period	Credit Hours	Student Hours	Team Hours	Scope	Parts Cost	Team Members
1978-1983	<0.5	20	20	Single Circuit	$5	1
1984-1988	0.5	30	30	Small System	$20	1
1989-1993	1.0	40	40	Packaged Small System	$40	1
1994-1995	3.0	120	400	Packaged Small System w/Innovation	$75	3-4
1996-1999	3.0	120	500	Packaged System w/Innovation	$300	3-5
2000-2004	3.5	140	800	Complete Multi-disciplinary System	$1000	5-8
2005-	7.0	250	800	Complete Multi-disciplinary System	$1200	3-5

Table 1: Design Project Progression

As the team projects matured, we gained confidence in our model. A logical progression in the increasing complexity of projects was to solicit project ideas from outside the faculty. In 1996, we had a visiting fellow who surveyed his research organization for project ideas. Most of the project requests received were far beyond the capabilities of our students, especially when limited by the time constraint of a single semester in which to complete the project. At about the same time, we had begun pursuing interdisciplinary projects with the mechanical engineering program, mostly associated with national-level competitions. Most of these projects also required more time than a single semester offered if we wanted to be competitive. To get project teams started, we enrolled two or three members per team, at least one per discipline, in our individual studies course during the fall semester. The additional time proved highly beneficial. In addition to having faculty members already familiar with the project at the start of the second semester, we had students who were already well into the design. We completed multi-disciplinary designs entered into both solar-powered vehicle and autonomous vehicle competitions during this timeframe.

As we took on new projects, students frequently found that it was necessary to augment their knowledge of circuits, electronics, and signal analysis to complete the projects. Those of us with design experience understood this to be a normal part of the design process, but we had never formally introduced the concept as a part of the instruction in design. In 1998, we reorganized the second course in electronics around a design theme. Prior to that, the course covered a variety of concepts in electronics and then showed how they were applied in a single design project. The new model introduced a variety of small requirements and forced the students to learn the electronics necessary to complete the design requirements. Students quickly grasped the idea that learning new things is an inherent part of design. An unintended byproduct of this approach was that students got four more opportunities to complete a design at the same time they were learning the electronics. As a side note, the idea of introducing academic topics via design requirements or applications has migrated into several other courses since that time. Not only does this technique provide valuable learning, it is also highly motivational to students who want to see an application of the concepts they are required to master in real products.

Over the course of several years, we began allocating some lessons from the second electronics course to the senior project. To do this we had to remove topics from the electronics instruction. By the fall of 2003, approximately a third of the course was devoted to project-oriented instruction, and actual work on the projects. Additionally, the number of majors in the EE Program grew during this timeframe. For each faculty member to serve as the primary advisor for a single design team, we had to increase the size of the teams, some teams growing as large as eight or nine students. We realized that under this model some students on the large teams were insufficiently challenged. The most recent increase of the time allotted for design projects occurred when we developed a new curriculum for the class of 2005, this year's senior class. After observing many teams run out of time before the end of their final semester, we decided to dedicate a second course to the senior project. We also recovered the lessons lost from the second electronics course, thereby restoring two full courses to coverage of electronics. In the process, the students lost one of their "free" electives. To hold the amount of time for each team constant (and because we had experienced a drop in enrollments), we reduced the number of students on each team to between three and five. An example of this year's projects is the Autonomous Taxi.

A Two-Semester Senior Design

The current EE design course at USMA is a two-semester course that includes both instruction in engineering design and a group design project supervised by one or more faculty advisors. The first semester focuses on teaching the students the engineering design process and having them complete the preliminary design of their projects. The engineering design instruction utilizes the five-stage design process shown in Figure 1 as a reference model. This design process is presented in [1], which we use as the class text. Classroom lectures are supplemented with in-class practical exercises and homework to give the students feedback on topics such as writing a problem statement, listing problem specifications and constraints, and developing a functional block diagram. These assignments are completed before the students are required to perform the same tasks for their senior design project. Within the first month of the semester, students are assigned to design teams of three to five students with a unique project for each team. The project groups work with their advisor to develop a written project proposal by mid-semester, and an oral presentation of the preliminary design late in the semester. The goal is for each team to evaluate multiple solutions for the subsystems of their project, select subsystem solutions that meet the design specifications, and order necessary parts by the end of the first semester.

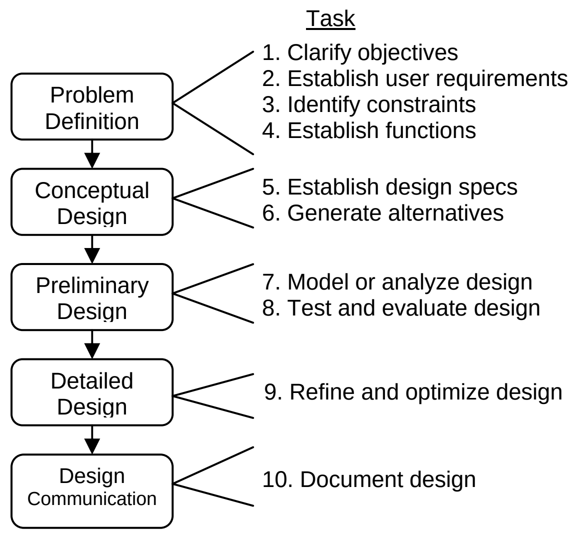

Figure 1: The Five Stage Design Process

The classroom instruction during the first semester also includes several short laboratory exercises and a small group project. The laboratory exercises include topics such as designing multi-voltage regulated power supplies, creating a custom printed circuit board, managing design projects, and reading sensor inputs with a micro-controller. These lab exercises were selected to include topics common to many of our design projects, which are not covered in our circuits and electronics courses. The group project requires the students to design an autonomous ground vehicle, capable of navigating an obstacle course, using the Parallax Boe-Bot kit [2]. This project was selected to require the students to integrate subsystems into a working prototype. We have historically found that our students are very successful at building working subsystems, but they experience difficulty integrating these subsystems into a working prototype. One of the biggest challenges they have is under estimating the amount of time it takes to successfully integrate subsystems of a project. The autonomous ground vehicle project requires them to both test the sensor subsystems of the robot, and also to develop an integration test plan for the entire project. As part of this project, the students are required to give an oral preliminary design review and submit a written project report using the same format required for their senior design project. The project culminates with a competition between the autonomous ground vehicles to navigate the obstacle course in the shortest time. This group project gives the students valuable experience applying the design process on a smaller scale than their senior design project.

The second semester of our current design course focuses on detailed design, fabrication, testing, and design communication. The students begin the semester by developing test plans for the subsystem components they ordered at the end of the first semester. Each student is responsible for a specific subsystem of the project, and must determine whether or not the subsystem will meet the overall project design specifications. About one-third of the way through the semester the students present both a demonstration of their working subsystems, and conduct an oral critical design review highlighting any subsystems that can not meet design specifications. This is essentially the team’s last opportunity to purchase new parts for their project.

The design projects next enter the subsystem integration phase. As our design projects have become more complex, the integration of subsystems has become increasingly more time consuming and difficult. This is also arguably the most beneficial part of the senior design project in terms of giving the students "real-world" design experience. Typical challenges encountered by the students include multiple power requirements, heat dissipation, interfacing different communications protocols, and packaging the project in a finished form. The development of an integration test plan, especially for inter-disciplinary design teams, is also challenging for the students. This phase of the design project ends with a prototype demonstration and an oral presentation of the final design.

The final stage of the design project course focuses on design communication. Each design team produces a comprehensive written report of their project, which includes social, political, economic and technical aspects of their design. The design teams also present their projects at a local exposition style "Project Day" with external judges to evaluate the projects. In addition to project demonstrations, the "Project Day" displays include poster boards, slide shows, and video presentations. The design teams are judged on both the technical merit of their project, and on their presentation. The students are also required to document their design projects with both lab notebooks and a project website. These products serve as a useful reference for projects that are continued for more than one year. A summary of how the five stage design process maps to time in the two semesters and major requirements is given in Table 2.

Design Process Phase	**Time Frame**	**Major Requirements**
Problem Definition	August – September	Refined Problem Statement Initial Block Diagram
Conceptual Design	October	Gantt Chart Written Project Proposal
Preliminary Design	November – February	Preliminary Design Review Parts Requisition Critical Design Review Subsystem Demonstration
Detailed Design	March	Final Design Review Prototype Demonstration
Design Communication	April – May	Final Design Report Project Demonstration

Table 2: Mapping the Design Process to Major Requirements

There are several aspects of the EE program at USMA that enable us to run the design course in the current two-semester format. These include student schedules, faculty schedules, and content of our other EE courses. The structured academic program at USMA allows us to schedule all students to take the design course during the same class hour. This is possible, in most cases, even when the students are in different majors or departments. We have also been able to ensure that all students have the class period immediately following the lecture hour open. This has been extremely beneficial in allowing the project teams to meet with each other and their project advisors.

Faculty involvement is critical to the success of the design projects. In addition to the student schedules, we have been successful at scheduling project advisor's teaching schedules such that they do not teach during the two hours that the design project course meets. With the variety and complexity of our student projects, it would be practically impossible for a single faculty member to advise all of the projects. Each of the project advisors becomes an “expert” on the project and develops a “solution path” to ensure that the project is solvable by a team of students in the allotted time. Project advisors are often required to conduct lectures for their design team on specific topics, as well as teaching them how to use test equipment, software etc. unique to their project. In our more complex projects, we have more than one project advisor to provide expertise in different aspects of the project. Throughout the design course the project advisors act as clients, mentors, and senior design engineers. This model requires frequent communication between the project advisors and the design project course director to keep the different teams on a common schedule with common grading standards.

The content of our required electrical engineering courses provides the foundation for success in the engineering design course. We introduce the concept of engineering design with a group project in the first course our majors take, Digital Computer Logic. The design, build, and test process is reinforced during the lab exercises in our required circuits and electronics courses. The students progress from structured labs with detailed test plans provided in the circuits course, to developing their own test plans in the second electronics course. The two electronics courses each conclude with a comprehensive design project that requires groups of three to five students to design, simulate, build and test an electronic system. In addition, many of our elective courses have comprehensive design projects that require the students to apply the design process in a small group. As a result, our students entering the engineering design course have had numerous opportunities to work as part of a group on an engineering design project.

Summary

In summary, our design course has evolved since the late seventies from an individual project in the final electronics course to a two-semester, interdisciplinary, team project. The complexity of the projects has increased significantly as we have increased both the time allotted and number of students assigned to the projects. We utilize lectures, in-class exercises, lab exercises, and homework to teach our students various aspects of engineering design before they are required to perform specific tasks for the design project. Our students are evaluated throughout the two semesters based upon both oral and written requirements. They are also evaluated on documentation techniques such as lab notebooks and project web pages. Over the last fifteen years, we have employed design philosophy to systematically adjusting the senior design projects to accommodate changing enrollments, faculty allocations and curricular constraints. We have made adjustments, tested the new process and adapted again. We believe that our current model produces students with a solid grasp of the most important aspects of engineering design. But it is likely to change in the future as our students, the faculty and the environment change around us.

1. Clive L. Dym and Patrick Little, *Engineering Design: A Project-Based Introduction*, 2nd Edition, John Wiley and Sons, Inc., NJ, 2004.
2. Boe-Bot robotics kit by Parallax, Inc., http://www.parallax.com/html_pages/robotics/boebot/boebot.asp.

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