AC 2010-647: THE TECHNICAL, PROCESS, AND BUSINESS CONSIDERATIONS FOR ENGINEERING DESIGN – A 10 YEAR RETROSPECTIVE

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The Technical, Process, and Business Considerations for Engineering Design – A 10 Year Retrospective

Abstract

Ten years ago, after undergoing both internal and external review processes, the Department of Electrical and Computer Engineering Department at the Worcester Polytechnic Institute determined that, while the vast majority of capstone design projects satisfied our requirements for Capstone Design, there were several disturbing trends.

Specifically, it was noticed that students were lacking the skills to perform serious design synthesis; they were not adequately addressing issues of quality, safety, reliability and maintainability; little attention was being paid to issues associated with economics; students were having difficulty understanding how different areas of Electrical Engineering related to each other; and significant amounts of faculty time were spent teaching project teams the design process.

To correct these problems, a course was developed which focused on teaching students, during their second year, the process of product design. The course specifically included significant class time discussing the business and non-technical implications of the design decisions they make. As initially developed, during the course students not only learned about the business of engineering, they also applied these concepts to create a working product prototype. At the end of the course, students had to subject their designs to a design review where their engineering work and their business plans were evaluated.

As of 2010, the course has been offered twenty times and has become a central part of our ECE curriculum. In addition, the Department has had at least three internal Capstone Design assessments and two ABET reviews (in our last ABET review nearly all ECE students had taken the design course). This historical data allows us to see the effect that the course has had on our students over a significant time span.

Introduction

The first offering on ECE2799 occurred in 2000. It is important to remember that at that time the ABET Criteria 2000 were just beginning to be implemented within a few universities. The notion of “Capstone Design” as it is known today was relatively new, and was the subject of significant debate.

Although “Capstone Design,” as we know it today, was a relatively new concept in engineering education, in the year 2000 the ability of graduating students to perform a significant design project had been a degree requirement at our university for nearly 25 years. In the year 2000, this design project, called the Major Qualifying Project, or MQP, was an essential part of the educational experience of our students, and provided students an opportunity to demonstrate their ability to apply the skills they have acquired in their studies to the solution of an engineering problem. Then, as is still the case now, these projects are equivalent to three courses; often spanning nearly a full academic year.

Typically, MQP projects are completed by teams of 1-3 students, with two or three students per team being the norm. The projects are of sufficient complexity that it is expected that each student will invest approximately 20 hours per week in the project. Projects are similar in scope to the types of problems entry-level engineers might encounter in industry and, in fact, many MQP projects are sponsored by companies. In addition to on-campus MQPs, it is also possible for a student to perform an off-campus MQP where student teams work full time on site (with faculty supervision) for a period of approximately 10 weeks. While most MQP projects also qualify as Capstone Design projects, it is possible for an MQP to not qualify as Capstone Design. For those few cases where the MQP is not considered Capstone Design, students will satisfy their Capstone Design requirement through an independent study project.

Since the Major Qualifying Project is a degree requirement, the Electrical and Computer Engineering Department has maintained a process for evaluating the quality of MQP projects to ensure that Department standards are being satisfied.[1] This assessment involves a regular peer review of the project reports and the production of a detailed analysis of the results of the peer review. Quality control is affected by reporting these results to the Department faculty along with recommendations. These reviews are held every two years, and provide data which is used for quality control. This data also appears in the ABET review materials and self-studies assembled by the Department prior to ABET reviews.

As a consequence of these periodic reviews, and a comparison of the MQP review criteria compared to the proposed requirements for ABET Criteria 2000, it was discovered that while the vast majority of projects were clearly satisfying the educational goals of the Department, and were also satisfying the criteria proposed by ABET, there were some disturbing issues that were beginning to emerge. Specifically, we noticed:

- Poor design synthesis – many students were attempting to solve problems by finding a solution first and then “force-fitting” the solution to the problem rather than analyzing the problem and identifying appropriate solutions,
- In many projects, little attention was paid to issues such as quality, safety, reliability and maintainability,
- Similarly, little attention was being paid to issues associated with economics and aesthetics,
- Project advisors were noticing that an increased number of students were having difficulty understanding how different areas of Electrical Engineering related to each other, and to other non-Electrical Engineering coursework. Although these students were typically Seniors, some had serious deficiencies in their knowledge of the fundamentals of Electrical Engineering.
- A significant amount of faculty time was being spent teaching project teams the fundamentals of design. Since each member of the faculty advises 2-3 project teams, this resulted in a tremendous amount of duplicated faculty effort.

A small group of faculty who were studying potential changes to the undergraduate curriculum determined that the solution to these problems required modifications to the undergraduate curriculum well before the Senior year. Further, it was proposed that, at a minimum, there was a need for a class that most students would take to learn the fundamentals of design. Given the potential ramifications of adding such a course to an already crowded curriculum, a committee was formed to fully study these observations and make recommendations for modifying the curriculum that would address all of these concerns. The ECE Design Course, ECE2799, was the result and was proposed to be taught initially on an experimental basis.[2]

Creation of a new Course

ECE 2799 was created with two primary goals in mind. First, it was important to design the course in such a way that the students could see the relevance of their previous course work by providing an opportunity to apply that core knowledge to solving an engaging problem, and second, the course must teach the students some of the fundamentals of systems engineering by showing them how to decompose complex problems into a series of manageable steps. With these primary goals in mind, we conceived of an ECE Design course that would:

- Require students to apply material from their core ECE courses,
- Require material from at least one advanced core courses (since the core sequence requires 4 out of 5 available slots in a typical student's schedule, we could only assume they would have one advanced core course prior to EE2799),
- Have a project where the students would have to apply top-down design to solving an incompletely specified problem,
- Require working effectively as a team, since not every student would have all of the necessary background to successfully complete the project,
- Require students to apply common sense, as well as a knowledge of physics, mathematics, mechanics, and other topics to the project,
- Directly address the business aspects of engineering design including: scheduling, Team management, budgeting, developing customer requirements, and predicting return on investment,
- Directly address ethical and legal issues,
- Directly address manufacturing, safety, reliability and other engineering issues,

As is to be expected with a (then) revolutionary idea such as a course specifically designed to emphasize the systematic means for synthesis of a design from its requirements, faculty enthusiasm and support was high, but skeptical. However, the existence of new ABET "capstone design" requirements and what appeared to be a nearly one-to-one correspondence with those objectives, and the prospect that the new design course could improve faculty productivity when students began their MQP, allowed the creation of ECE 2799 to be approved by the ECE faculty.

It was recognized from the beginning that the course should have two principle parts: one being classroom and homework exposure to the details of system design methodology, including such topics as value analysis and return-on-investment; the other being the development of working models of circuits designed to satisfy a set of given, high-level requirements. For example, student design teams were given generic requirements such as "an altimeter to measure height above the geoid from zero to ten thousand meters with an accuracy of ten meters." In addition, "the device is to be saleable in quantity for 50 dollars or less."

As originally conceived, the ECE Design course had three main components: a one hour lecture held four times per week, a supervised three hour laboratory session held once per week, and unsupervised open laboratory access. Unlike a typical Electrical Engineering course, the lectures originally contained rather little technical content, instead focusing on explaining the process of engineering design. The supervised laboratory was a hybrid of technical and non-technical issues, while the unsupervised laboratory is primarily technical and consisted largely of students working on their projects. It was simply expected that students would rely on the background they received in their earlier core courses to develop the circuits needed to complete their project.

The centerpiece of this new course was intended to be the project. On the first day of class, students were given an incompletely specified problem specification and a project budget. During the course of a seven week term, students were required to reduce this specification to practice on-time and within budget. Project teams were selected not by the students, but by the faculty teaching the course. While having the faculty select the project teams may seem like an unnecessary burden, it has two important goals. First, it allows the instructor to create teams having balanced skill sets. This means that teams will contain students with a mix of skills that, in combination, should be sufficient to be successful. It also required teams of varying academic level to learn how to work together. Second, students tend to take classes and pick teams based who their friends are, rather than what their friends' skills are. This tends to lead to teams where everyone has essentially the same background. Having the faculty carefully select teams based on their skills and academic level gets the students outside of this "comfort zone", and ensures that each team as a whole has a sufficient combination of skills.

Given that one of the goals of the course was to encourage students to brainstorm solutions to problems, and that students have differing backgrounds and levels of competence, it was important to select projects which had a few basic characteristics:

- The project must be solvable using analog circuitry or digital circuitry (or a hybrid). The students must do the tradeoffs needed to determine what method of implementation is optimal based on their analysis (and their skill set),
- The project must require some type of sensor and must display a result,
- The project will ideally require addressing both electrical and mechanical issues,
- The project must require applying a knowledge of mathematics and physics

As an example, some of the early project descriptions included:

- Design and construct an electric fan which increases its speed automatically as the temperature of the room it is in increases. Your fan must be able to operate in a manual mode that allows the fan to operate at high speed, low speed, or be off. The fan must also have an automatic mode where the speed varies continuously between off and high depending on temperature (the speed of the fan must increase approximately linearly with temperature). Your design must not add more than $50 to the normal retail price of a two speed fan.

- You are to design a mouse trap that operates by electronically sensing the presence of a mouse. If a mouse enters the trap, an electronic sensor must trigger a trap mechanism which prevents the mouse from escaping. Your design must be safe to operate, and must be such that fingers inserted into the trap will not be injured. Your design must not add more than $25 to the cost of a conventional trap

Although these problem statements are seemingly simple and straightforward, there is enough ambiguity that second year students soon realize that the descriptions are sufficiently open-ended that there are many questions they need to answer before they can adequately define the problem. Further, since they are given a budget, and not a parts list, they soon realize that it is impossible to simply “hack” at the problem. Rather, they’re encouraged to apply system engineering principles to help them apply the collective knowledge of the team to solving the problem.

In order to help guide this process, the course syllabus has been constructed to ensure that students have the information they need, when they need it, to help guide them through the design process. The syllabus starts out with topics related to market research and product definition, since it is these phases of design that are critical in deriving a system specification to guide their designs. The syllabus then migrates towards more tangible examples of engineering problems, implementations and tradeoffs. In this part of the course, as students are in the process of doing their design analysis, they are regularly given relevant examples of the solutions to design problems. Finally, towards the end of the course, when students have committed to designs, lectures focus on other topics important to design such as ethics, standards and other topics.

Evolution of ECE 2799

Although the course ECE 2799 remains in much the same form as it was originally conceived, it has undergone a number of significant changes including its lecture content, the selection of design projects, and the addition of an entrepreneurial component. [3]

<u>Lecture Content</u>:

Originally, lectures focused primarily on the business and process aspects of engineering design while deliberately avoiding highly technical content. A system level approach was taken to introduce the steps of the design process along with a variety of business topics. While students were being introduced to these topics in lecture, they were at the same time expected to perform detailed design work on their own, using skills they had obtained in previous courses or by seeking help from other students, faculty members or lab support staff.

In retrospect however, there were two significant oversights with our original approach. First, most faculty members were inexperienced with the various steps of the design process as well as the business topics unless they had come from an industrial background. Therefore, most were reluctant to teach the course since they did not have sufficient experience with the material.

Although guest lecturers were invited to speak on the various topics, more often than not a faculty member was left having to cover a topic with which he or she was not comfortable. Inevitably, faculty members would substitute familiar material in lieu of the original topics.

Secondly, students had difficulty applying certain lecture topics to their specific design problems due to a lack of experience applying core course concepts to real engineering problems. Further, topics such as applying value analysis to determine the tradeoffs between various design options, or performing design synthesis to arrive at a viable solution are best learned in the context of detailed examples which needed to be developed.

To address these shortcomings, several modifications were made. First, faculty members having design experience were asked to teach or manage the course on a regular basis while being shadowed by less experienced faculty. This approach continues to work well and increases the comfort level that faculty have with the course.

Secondly, detailed examples were developed ahead of time similar to the projects that students were being asked to design. In this way, a system level topic could be covered and then followed up with a detailed example illustrating what students were expected to do. For example, in one offering of the course, students were asked to design some form of solar powered lighting for an application of their own choosing. The example used in class was that of a solar candle that would sit in a window and provide light on a nightly basis with energy stored during the daytime. This example served as a vehicle to teach most of the topics covered in lecture. The current curriculum is outlined in Table 1.

Table 1: Current ECE 2799 Curriculum

Lecture	Topic
1	Introduction to ECE 2799
2	Project Kick-Off (During 3 hr Lab)
3	The Engineering Design Process - Needs Assessment / Problem Formulation
4	Engineering Notebooks & Project Documentation
5	Engineering Design Process - Abstraction & Synthesis
6	Value Analysis
7	Teamwork & Group Dynamics (During 3 hr Lab)
8	Project Management & Scheduling
9	Analysis & Evaluation
10	Input Sensors & Preconditioning Techniques
11	Output Actuators, Displays & Drive Techniques
12	Analog Processing Techniques
13	Digital Processing Techniques
14	Battery & Power Supply Considerations
15	Control Documents
16	Component Selection & Specifications
17	Using Circuit Simulation Effectively
18	Prototyping Techniques & PCB Layout
19	Electrical Safety

20	Electronic Troubleshooting Strategies
21	Corporate Finance and Return on Investment (ROI)
22	Standards, Regulations and Liability
23	Organizational Interfaces
24	Reliability & Maintainability Engineering
25	Engineering Ethics
26	Design for Manufacturing (DFM)
27	Intellectual Property & Patent Law
28	Starting Your Own Company

<u>Selection of Design Projects</u>:

Another aspect of the course that has undergone significant changes is the selection of design projects. To increase the level of creativity, students are now given a design challenge with a particular theme, where they can brainstorm their own project ideas. For example, a recent offering of the course asked students *to detect a hazardous situation of their own choosing and to provide appropriate notification (as determined by their market).* The actual design challenge appears below:

ECE 2799 – Term D-2009

Design Challenge

Hazard Detection and Safety Notification Device

Your project group has been asked to design a *Hazard Detection and Safety Notification Device* capable of detecting a safety hazard of some type and <u>providing appropriate notification</u>. Hazardous conditions may include:

- Electrical Faults (that pose a shock hazard)
- Excessive Temperatures
- Excessive Pressures
- Excessive Electromagnetic Radiation
- Abnormal Biological Functions (irregular heartbeat, breathing, oxygen level etc...)
- Or any other safety hazard worth detecting!

Your device should include its own power supply or battery as part of its design, and include any features that your market research deems necessary for a successful product. In addition, your design must be cost effective with a prototype cost not to exceed $50.

The variety of applications ranged from a hot water bath alarm designed to prevent scalding to a fire alarm for the deaf that caused a pillow-insert to vibrate when a standard fire alarm was sounding. The level of creativity was evident and students responded positively in course evaluations.

The thematic approach to selecting projects has proven to be quite successful. Students exhibited a much higher level of motivation than in our previous course offerings. The excitement among student teams was tangible and spread throughout the department. This has changed the reputation of the course from the “2799 death march” into a course with students always asking, “Have you taken ECE 2799, yet?”, or “What was your project for ECE 2799?”

Entrepreneurial Aspect

In addition to enhancing the lecture content and project variety of the course, one major improvement has been the opportunity to work with our Collaborative for Entrepreneurship and Innovation (CEI). This university-wide organization is comprised primarily of professional alumni who want to cultivate the entrepreneurial spirit at our school.

During each offering of the course, several alumni volunteer as guest lecturers as well as judges to serve on a panel to evaluate student projects at the end of the course. In addition, monetary prizes are awarded to the best teams to encourage a moderate amount of healthy competition. Grants are provided through generous donors through this organization.

The inclusion of this entrepreneurial aspect has greatly increased the motivation and seriousness with which students conduct their projects. On several occasions, alumni have asked for student resumes with the consideration of possible summer employment. We are extremely pleased with this outcome.

Assessment of ECE 2799

Over the past ten years, the effectiveness ECE 2799 has been assessed through reviews of its methodology as the design paradigm for capstone design projects. Conducted biannually, these reviews have revealed that when ECE 2799 procedures and discipline are applied as taught, students achieve an excellent ability to properly synthesize a design from its requirements. As such, the course achieves the objectives that were set for it initially.

As will be seen from the following evaluation, the success that has been achieved is, at least in part, the result of regular examination and refinement. Consequently, in the discussion that follows, more attention is placed on the needs for improvement and redefinition than on other aspects that have required none or only minor modification.

Assumptions

As background prior to taking ECE 2799, all students are expected to have successfully completed all courses that comprise the minimum set of “core” requirements for ECE as well as at least one course designated “advanced core.” One difficulty with course prerequisites is that the advanced core consists of a variety of theory and applications courses. Consequently, it is possible that a team of students who meet these requirements could have individual members who have insufficient skill matches with the project they are intend to pursue. In part, this is intentional – one goal of the course is to expose students to the utility of courses they didn’t take early enough in their program for them to make changes to their future program plan. However, it can lead to teams that have widely varying capability despite a common “core” background.

As the advanced core courses are offered twice each academic year, students could be expected to have achieved the minimal set of ECE 2799 requirements by the completion of their sophomore year. The result is that while the faculty making team assignments does its best to achieve the skill balance of teams, there are occasions where this is not possible. The result, for example, is that lacking any background in microcontroller-based design, a team might be forced to develop an analog solution that could be suboptimum. However, this situation does communicate the utility of taking more digital design courses.

Students have also noticed that teams with at least one member who has taken the advanced microelectronic course that is part of the advanced core have a distinct advantage over teams that do not. This phenomenon is, we believe, because ECE 2799, like all other technical undergraduate courses at WPI, is limited to seven weeks. Also, some would offer that the short time allowed, seven weeks, tends to yield design solutions that are analog-based for the most part. Some students recognize that a broader technical foundation is of considerable value and postpone ECE 2799 until their junior year. In fact, student evaluations of the course over the past ten years have emphasized the fact that the course requires a great deal – maybe too much – effort. Indeed, some students deliberately reduce their course load to accommodate the demands of ECE2799. Others suggest that the course should be offered as a two-course sequence where that first would concentrate on design methodology and the second on application of the methodology to device design. Despite some student complaints regarding workload, the majority of students are pleased with the status quo.

Faculty Involvement

As would be expected, the faculty has played a large part in the process by which students develop the ability to implement designs using a structured design methodology. To achieve this objective, two principal decisions were made. One was that all members of the faculty would participate with the teaching and management of the course. Unfortunately, this has not been achieved and today, only twenty-five percent of the ECE faculty have been involved with teaching the course. The result is observable through examination of the results of the review of all capstone design projects that is performed bi-annually. Since only the final reports are examined, it is easy to observe whether or not the capstone team has conducted the design through use of the ECE 2799 approach to design synthesis. Coupled closely to this is the requirement that faculty advisors of MQPs would not take on project teams whose members have not successfully completed ECE 2799.

It is clear that when the faculty require adherence to the principles taught in ECE 2799, there is a significant percentage of projects that, when completed, are functional.

When the faculty don't require adherence to the principles taught in ECE 2799, the MQP reviews reveal the same sort of shortcomings that formed the basis for creation of the design course ten years ago.

The authors believe that if the original goal of having all faculty involved at some point in teaching was achieved, that there would be a greater overall adherence to the principles taught in ECE 2799. In short, ECE 2799 was not only developed to educate students, it was also intended to educate the faculty.

Recommendations

There are a number of conclusions that can be drawn from our experience with ECE.2799 after offering the course for the past ten years:

- All faculty who advise capstone design projects (MQPs) should have participated in the teaching of ECE 2799 (or at least sat in on the lectures. This would communicate to the faculty the breadth and depth of the design process and would make them better understand the methodology their students are familiar with.

- All capstone design projects (MQPs) should follow the design methodologies taught in ECE 2799 and this methodology should be encouraged by the project advisor(s).

- Faculty should reaffirm the need for ECE 2799 success as a prerequisite to being accepted on a capstone design project (MQP) team. Current reductions in ECE 2799 class size seems to indicate that some students just pass it by. Requiring ECE 2799 would return to the principle that all students must have ECE 2799 as essential background before starting a capstone design project.

- There is a need to identify fixes for the scheduling of prerequisites. We always seem to have trouble with team assignments. Currently extensive changes in the undergraduate core curriculum are being planned. It is unclear at present how these changes will effect ECE 2799 preparation.

- There is a need to ensure that projects that have both digital and analog solutions. This will help in avoiding problems in prerequisites.

Conclusion

References

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