Learning Project Implementation and Management Skills in the Culminating Design Experience

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1. Introduction

The contemporary undergraduate curriculum of an Electrical Engineering program is packed with required courses, making it a challenge to complete in four years. By necessity, nearly all of this work is theoretical, supported by laboratory work that is too often limited in scope. The more practical aspects of project estimation, implementation and test are, at best, given very limited coverage. Therefore, it is not uncommon for students reaching their capstone design project to possess little, if any, experience with the practical aspects of successful design. We have developed a one semester-hour course, El Engr 463, Design Project Techniques, which addresses some of the practical aspects of design project planning and implementation that are not covered in other courses. In this paper, we describe in detail the course topics and methods used to introduce them. The course is divided into two parts. The first half of the course focuses upon practical hardware considerations. We discuss and demonstrate printed circuit board fabrication, including board layout using a contemporary software tool, circuit board fabrication, and soldering of both through-hole and surface-mount components. We also discuss practical circuit design considerations including board component placement, trace routing, noise mitigation, power supplies, voltage regulators, digital signal transmission, signal isolation, safety grounding and chassis shielding. The second half of the course is devoted to instruction in and implementation of the design process. It begins with an engineering ethics case study that demonstrates the importance of establishing and rigorously following a systematic project process. Students then select a capstone design project and faculty mentor. Using a "just-in-time teaching" philosophy, we then discuss a seven-phase project life cycle including the contents of the documents produced at key milestones in the life cycle. The students then execute the project life cycle by developing technical specifications and a schedule in the context of their specific project. After a discussion of test design and planning, the students develop a high-level design as well as integration and test plans for their project. Progress is assessed with a design review at the end of the semester. Students complete detailed project design, fabrication, and test the following semester.

The main objectives of El Engr 463, Design Project Techniques, are to provide students with the practical hardware skills they need to successfully complete the capstone design project and to introduce a systematic project life cycle process that allows them to organize and design their project in a logical manner. El Engr 463 is a one semester-hour course so no outside preparation by the students is expected except when class does not meet at its regularly scheduled time. El Engr 463 provides the students some additional practical engineering knowledge not normally found in an undergraduate curriculum, which is applied as they start on their capstone design project. The design project is completed in El Engr 464, Design Project, a three semester-hour course in the Spring semester. Approximately 30% of El Engr 463 is spent on hardware lessons, with the remainder of the course spent on the case study, project life cycle process, and selection and initial design of the capstone project. This paper will first discuss the hardware lessons in detail, then the case study and project process. We will also address the selection of a project as well as use of the project process during initial project design. The use of the project process as carried through the next course, El Engr 464, Design Project, is also explained. We conclude with a discussion of future expectations and our preliminary findings from the initial experience with El Engr 463.

2. Hardware Technology and Skills

2.1. Objectives and Guiding Principles

The overall objective of the hardware technology lessons is to provide students an exposure to key project implementation methods and concepts. A total of twelve of the course's forty-two lessons (about 28%) are devoted to these topics. Our guiding principles in building this part of the course were to: 1) focus upon those concepts and circuits which consistently present a problem in student projects; 2) provide links or references through which these concepts may be further explored; and 3) maximize conceptual reinforcement within the limits of classroom contact.

Though observation of student performance in past years, we identified four consistent deficiencies in hardware implementation. The first is a failure to correctly transfer the wiring of project prototypes into finished circuit boards. The second is failure to properly interface low power logic circuits with loads requiring significant drive currents. The third deficiency is facility with low power, relatively low frequency, signal generating and processing circuits. Finally, we had observed difficulties preserving signal integrity usually resulting from cross talk, power supply bounce, or ground loops. Closely related to this topic are the issues related to chassis electrical safety. Each of these problem areas is addressed through a combination of lecture, demonstration, hands-on practice and handout materials.

2.2. Computer-Aided Printed Circuit Board (PCB) Design and Board Fabrication

Computer-aided circuit analysis and design is stressed throughout our curriculum. By the time our students begin El Engr 463, they are very familiar with the OrCAD-Cadence schematic capture tool, "Capture", and its companion circuit simulator, "PSPICE"[1]. Indeed, the capabilities and limitations of computer-aided design (CAD) are illustrated many times in prior courses through circuit simulation exercises, many of which possess a hardware element. In El Engr 463, we take advantage of this experience by introducing the companion OrCAD printed circuit board design tool, "Layout". Since this tool creates board designs based on schematics developed with "Capture", we reap an enormous advantage in instructional efficiency. The use of computer-aided PCB design also helps us achieve an institutional objective. Our department is committed to arming its students with skill in the use of contemporary computer-aided design tools. The realization of electronic circuits via automated PCB design clearly qualifies as a contemporary application of CAD.

A total of six lessons are devoted to the general topic of printed circuit board design and fabrication. The first lesson is devoted to an overview of contemporary second-level interconnection technology including wire-wrap, multi-level PCBs, and Multi-Chip Modules. Particular attention is paid to the differences between commercially fabricated PCBs and those

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that can be fabricated by our students in-house. The next three lessons illustrate in detail the process by which OrCAD Capture schematics are transformed into printable PCB photo masks. Students follow a heavily illustrated process description of our own creation, complemented by hands-on computer practice. Projected images of the instructor's PC screen help guide student progress during these lessons. Prepared schematics and board templates are also used to speed the demonstration. We take special care to build "mid-point" project templates. These partially completed schematics, net lists, and PCB layouts are very useful for quickly guiding confused students back to the correct path of the exercise. We are careful to illustrate the advantages and pitfalls of both manual and automated board layout.

Assuming a general understanding of the PCB design process, we proceed to illustrate the fabrication of the boards themselves. Since our printed circuit fabrication room is barely large enough to accommodate two people, the illustrated process description and a companion video taped presentation must suffice as a basis for instruction. The very same circuit used in the example photo mask design process, a frequency selective digital counter, is realized in an in-house fabricated 2in x 3in practice PCB. As part of this fifth lesson on PCB technology, our students are each presented a practice board and proceed to open a dozen through-hole pads and vias using a bank of small drill presses. For many of our students, this proves to be their first exposure to power machine tools of any kind.

We intentionally choose components for our practice printed circuit boards that represent electronic packages commonly encountered in contemporary electronic systems. These include a 16 pin, SOG surface-mount integrated circuit with 0.050in pitch pins, a style 1206 surface-mount resistor and capacitor, a conventional 0.100in pitch through-hole DIP (Dual Inline Package), an eight pin header jack, and various low wattage axial resistors and capacitors. In this final lesson on PCB design and fabrication, we provide students with some limited practice in component soldering. The lesson begins with a presentation on commercial component attachment processes, including wave soldering and conductive epoxies. We then illustrate both through-hole and surface-mount manual soldering techniques, including examples of cold joint and unintended short circuits. Each student is provided a soldering station, board vise, and all components necessary to populate their sample PCB. We also provide a pre-connected test set through which students can verify the correct operation of their finished circuits.

2.3. Troublesome Circuits and Circuit Concepts

The remaining six hardware lessons of the course are devoted to troublesome circuits and circuit design methodologies. While some of these topics have been discussed briefly in other courses, most are presented for the first time in this series of lectures. As a minimum, each student receives a hard copy of the lecture slides and an in-class guide every lesson. The latter is a lecture outline, which facilitates note taking. Relevant Internet links or textbook references are included in these materials. Wherever possible, hardware examples are distributed during lecture and are illustrated using the classroom's micro-video camera and video projector.

2.4. Driving "High Power" Loads

A single lesson is devoted to the "full-on" or "full-off" control of high power dissipation loads using digital logic signals. While the origin and significance of logic family I_{OH} and I_{OL} are discussed in other courses, the historically consistent misapplication in El Engr 464 of these

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concepts clearly warrants this lecture. We illustrate a successful design with a short lecture, a process description, and two in-class design exercises. In the first, cadets use a TTL logic signal to activate an incandescent lamp through a power BJT (Bipolar Junction Transistor). In the second, they activate a DC electric motor using an HCC class CMOS logic signal. We include a discussion of maximum transistor ratings and back-electromotive forces generated by inductive loads. The consequences of ignoring these effects are also emphasized.

2.5. Signal Generation and Processing
Another consistently troublesome hardware concept of increasing importance is the transmission of digital data over long distances. Although many cadets have completed their introduction to transmission line theory prior to this course, most fail to realize the implications of distributed impedance upon short rise and fall times of digital signals. We include a discussion of digital data bandwidth, single ended and differential line drivers, twisted pair and coaxial cabling, proper line termination, Schmitt trigger input logic and basic elements of digital system noise.

Since electronic function generators and power supplies are used throughout our curriculum, our students lack knowledge of circuits from which their projects may derive precision frequency oscillations and regulated DC power. Two lectures were created to address these deficiencies. Circuits considered include 555-based astable and monostable multivibrators, ring oscillators, crystal controlled sinusoidal oscillators, clock signal modules, and phase locked loops. Batteries, line regulators, switching regulators, and charge pumps are the subjects of the second lecture.

2.6. Signal Integrity, Noise and Chassis Safety
Few topics are as important to the personal safety of cadet designers than electric chassis safety. Two lectures were designed to incorporate elements of the National Electrical Code for chassis safety grounding along with related considerations of noise and signal integrity. Here we borrow heavily from the University of Missouri, Rolla short courses on grounding, shielding, and electromagnetic susceptibility[3]. These lectures illustrate the requirements demanded by the electric code, the subsequent and all too common creation of ground loops, and their implications for signal quality. We highlight the nature and purpose of noise suppression features important to chassis, PCBs, and cables. We also arm our students with a few simple methods to search for the sources of noise they may encounter in their projects. Commercial electronic products are used as illustrations of these concepts.

2.7. Lessons Learned from Hardware Technology and Skills Instruction
As of this writing, we have no basis to judge how much impact the hardware lecture series will have upon the success of cadet design projects. The student design process will continue into the spring semester culminating only a month before this paper will be delivered. However, a few indicators have surfaced which are encouraging. Cadets scored reasonably well on the written examination covering the hardware technology lessons. The twenty-four students scored an average of 79.1 out of 100% with a standard deviation of 8.2%. The end of course survey asked if the hardware lessons "contributed significantly" to student ability to complete their design projects. An average score of 4.21, with standard deviation of 1.27 was recorded (3.0 = Slightly Disagree, 4.0 = Slightly Agree, 5.0 = Agree).

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While purely anecdotal, one other encouraging bit of evidence is available regarding the hardware technology lessons. Cadets in the electrical engineering major must also take a "core" design course the same semester they are enrolled in El Engr 463. This course, Engr 410, provides an opportunity for all United States Air Force Academy cadets, regardless of major, to experience the design process through a variety of relatively simple projects. This semester, three Engr 410 sections included electrical engineering majors who chose to invoke at least some of the hardware technology circuits and processes presented in El Engr 463. While the skill and persistence of the cadet designers played a large role in the outcome, all three projects reached successful conclusions. Based upon the relative complexity of these projects as compared to past years, and upon cadet critique comments, the hardware lessons of El Engr 463 appear to make positive contributions to the completion of core design projects.

3. Project Design Process

3.1. Case Study

In El Engr 463, a case study is used to illustrate the necessity for following a structured, rigorous project life cycle process and as a vehicle to discuss engineering ethics in practice. The case study we use is the 1999 loss of the Mars Climate Observer (MCO). While there are many good case studies available, we chose this one due to its currency and media coverage. The basic background information we provide the students is the December 1999 IEEE Spectrum article "Why the Mars Probe went off course"[4]. Students are asked to write a bullet paper addressing some very specific questions about the article. The purpose of this exercise is to make sure the students read and understand the article so the subsequent group discussion in class will be meaningful. During class, the students are divided into groups of three or four, and asked to summarize the events surrounding the MCO mission failure by answering the following questions:

1) What was the basic problem?
2) What were underlying causes/contributing factors?
3) What policies may have contributed to the problems?

After 10 or so minutes of group discussion, each group chooses a spokesperson to present their opinion to the rest of the class. All students are encouraged to comment on each group's findings. After the class discussion, some students revised their opinion on the real problem, and some realized there were many things they had not considered. Next, a fictional situation (related to the case study) that allows for a discussion of ethics is presented to the class. This situation is Part 4 of a case study on the MCO from the case study collection of the National Center for Case Study Teaching in Science[2]. All students are encouraged to take notes during the whole process, and then write a two to three page paper discussing the case. The paper addresses technical issues, policies, management decisions, and ethical and other non-technical issues engineers faced during and after the doomed mission. This case study sets the stage for the discussion of project design process.

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3.2. The Design Process Objectives and Guiding Principles[1]

Our instruction in the design process builds on the motivation gained from the case study accomplished earlier in the course. One of the inevitable conclusions reached in the case study is that most successful projects will follow a defined, documented, well-understood, systematic process. Our objective is to present a process to the students, ensure understanding of the activities required to produce the products of each of the project phases, and then tailor the process to this and the following three semester-hour design course. Our experience with the following three-hour El Engr 464, Design Project course for more than 20 years, suggested that we needed to tailor the project phases and products to fit the experience level and time available to the students. While all project phases are included, the artifacts produced are significantly tailored to the academic environment.

3.3. The Project Process

There are many phases that could be defined to complete a project. We have chosen a project process with the following phases:

- Requirements
  - Customer Problem Statement (Functional Requirements) Analysis
  - Technical Requirements Analysis
- Preliminary (High Level) Design
- Critical (Low Level) Design
- Fabrication/Code/Unit Test
- System Integration
- System Test/ Acceptance Test
- Operation/Maintenance

In the two lessons devoted to discussing these project phases, we emphasize that the process phases and the processes or individual activities within a phase will usually need to be tailored to the specific project to meet constraints of time, resources, and cost. To meet our course constraints of limited student and instructor time as well as a budget of not more than $ 500.00 per cadet project, we have tailored the above process as explained in the following paragraphs.

3.4. Requirements Phase

We present the requirements phase as very interactive between the designer and the customer.

3.4.1. Problem Statement Development

In order to put the design process into context, students choose their capstone design projects before the project process is introduced (about halfway through the course). As the course begins, faculty members develop project descriptions which are posted to the course website. Students can look at the project descriptions at any time and are encouraged to talk to potential faculty customers early in the course. The faculty develops problem statements with no

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[1] The majority of the project management material was drawn from Dr. Royer's extensive project management experience. However, he found the book Design for Electrical and Computer Engineers by J. Eric Salt and Robert Rothery, which was developed as the authors taught a design process to students, to be a useful reference.

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particular constraints. Thus the statements range from rigorously defined technical requirements to a single paragraph that presents a statement of the desired functions of the device or system. If they have not already obtained an interested student, the faculty is offered an opportunity about half way through the course to present a five-minute briefing to sell their project to the students. The students are given a couple of days after the presentations to contact individual instructors and chose a project. At that point our faculty assume the dual roles of customer and mentor. To assist the project mentor we have faculty serving as associate mentors for most projects. This allows some role-playing on the part of the faculty as the students present their end-of-phase briefings.

3.4.2. Problem Statement Analysis

To ensure the student and the faculty customer/mentor share a common understanding of the problem statement, the students analyze the problem statement for clarity and completeness. Interaction with the customer/mentor answers any questions quickly, and the problem is restated if necessary so the analysis and derivation of the technical requirements can begin.

3.4.3. Technical Requirements Analysis

In industry, the usual product emerging from the Requirements Phase is a Requirements Specification, which is then sent to the customer for review and often discussed in a review meeting to resolve any questions or points of contention. Although the table of contents of a typical requirements specification is discussed with the students, we have tailored the process for them so that their deliverable from the requirements phase is a System Requirements Review Briefing. We expect full coverage of technical requirements including the mechanical and packaging esthetics of the final product. Also emphasized is the need to have requirements reduced to the point that each requirement can be verified by a single test, demonstration, or inspection. The briefing is presented to the faculty customer/mentor and the associate mentor. Action items are assigned to ensure there is a clearly understood and complete statement of requirements before entering the High Level Design Phase.

3.5. Preliminary (High Level) Design Phase

We emphasize to the students the iterative nature of the design process. While course work and associated laboratory exercises typically have very limited objectives, most of our culminating design projects are complex enough that they require partitioning into several single technology functional blocks. In this phase, we expect the students to develop concepts at the functional block diagram level, then synthesize and analyze them to make design choices based on their experience (capability to implement), time available, cost, and ability to meet the technical requirements with some consideration of expected tolerances. We discuss the contents of a typical system specification, but again tailor the process to allow the students to present their progress toward the system specification in the form of an Initial Design Review (IDR) at the end of this one semester-hour course. At the IDR the students present their design concept; system block diagram with required inputs, processing, and outputs; and an analysis that shows their high level design will meet the requirements. The students also develop a project schedule to include a draft Integration Test Plan. To illustrate the processes that an effective project team in industry would have, we provide the students a project schedule template with the major project phases and all course milestones already included. The students then include in the schedule their specific activities to develop the milestone deliverables. In order to prevent a

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scramble at the end of the follow-on course, El Engr 464, to prepare a Technical Report, we also require appropriate draft sections of the project Technical Report be turned in for grading. The IDR, schedule, and draft Technical Report complete the one semester-hour El Engr 463. The remaining project phases as studied in El Engr 463 are actually executed in the following, three semester-hour El Engr 464 that completes the student culminating design experience. Early in El Engr 464, the Preliminary (High Level) Design Briefing, an updated schedule, and appropriate draft sections of the Technical Report complete this phase. The remaining phases are presented below.

3.6. Critical (Detailed) Design Phase

Again, the iterative nature of the design process was emphasized in El Engr 463. The students now produce the detailed designs for each of the functional blocks in their high level design. They complete simulations as appropriate to show their designs meet specifications and produce layouts of all circuits. They complete drawings for any mechanical interfaces, which includes their packaging design. The discussion of project phases emphasized the need to consider testing in all phases. Rather than producing a Detailed Design Document, as discussed in El Engr 463, they present a Critical (Detailed) Design Briefing, a Final Integration Test Plan, an updated schedule, and draft the relevant sections of their Technical Report.

3.7. Fabrication/Code/Unit Test Phase

Our experience suggests that weekly meetings between the mentor and the student are required during this phase for most students. These meetings ensure that they continue to progress, have an opportunity to discuss problems, and significantly increase the probability of a successful project. Identification of any expected long lead procurement items and fabrication challenges were made in the prior design briefings. Mitigation plans were developed by the students, so few such problems occur in this phase.

3.8. System Integration Phase

The plans presented earlier in the IDR and PDR are now executed. When presenting this phase to the students, we emphasize the importance of rigorous subsystem testing and following a systematic integration plan that progressively tests the system as it is integrated in a logical manner. In our past experience, proper systematic integration of student projects has been one of the weaknesses of the design experience. Requiring an integration plan should reduce the frustration that has so often accompanied this phase in past years.

3.9. System Test/Acceptance Test Phase

As all project phases are discussed in El Engr 463, this test phase is mentioned. For example, we make the point that requirements must be defined so they can be verified and designs must include provisions for injection of test signals and include test points for measurements. We then devoted another El Engr 463 lecture period to a review of the project phases with increased emphasis on testing, test plans, and test reports. This session was held immediately after the students had completed their Requirements Reviews and were about to start the High Level Design Phase. A preliminary draft of the integration plan and the subsystem test plan is required for the IDR. In the follow-on course, El Engr 464, the student executes the system test portion of the combined test plan to show the system meets requirements. Typically, a portion of the

System Test is used the following lesson to obtain acceptance of the project by the customer/mentor and the associate mentor.

3.10. Operation/Maintenance Phase

Maintainability, safety, and the operational impact on the environment are all required points for each of the design briefings. The Technical Report contains a Users' Manual if appropriate and enough information that an electrical engineer could maintain the system. The Technical Report is turned in for a portion of the student's final grade in El Engr 464.

3.11. Project Design Process Lessons Learned

Surveys at the end of this first offering of El Engr 463showed the students responded positively to the use of the case study as illustrating the need for a rigorous design process, understood the phases of a project life cycle, and were convinced that one must correctly define requirements for a successful project. Responses to other questions were essentially neutral. The results of the Requirements Reviews were reported as good to very good by the faculty while the results for the Initial Design Reviews were almost universally reported as poor. The students indicated they felt they needed more specific directions and more time and the faculty suggested there might not have been enough time allocated for the students to produce the expected results. The student reaction is typical when students are presented a design problem of this magnitude, given general guidelines, and required to produce an organized, defendable initial high level design. Our plans for next year include providing more time for the initial design and working through a high level design for a medium size system as a class exercise to demonstrate partitioning and to develop a single function block diagram high level design.

4. Conclusions

Although the students taking our one-hour introduction to the culminating design experience have not completed the second three-hour course wherein they complete their projects, some preliminary conclusions can be made. Students have already seen the benefit of the hardware lessons by using them in another concurrent design course. Based on significant prior experience and the results of this past semester, some of the typical implementation mistakes due to practical engineering realities will be avoided. We also expect fewer last week of the final semester "death marches" to complete projects due to a better understanding of the project process and the need for sustained effort to produce a successful project. Lastly, the emphasis on planning for testing is expected to increase the rigor of the entire experience. We have found faculty acceptance of the changes we have implemented to be outstanding. The faculty feels the burden for implementing a practical design, properly planning testing, and adhering to a systematic process has been shifted to the students and are looking forward to a more enjoyable and rewarding experience for both themselves and the students as we progress through the next semester.

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BIOGRAPHIES

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