INCORPORATING A JUNIOR DESIGN EXPERIENCE INTO A DIGITAL SYSTEMS DESIGN COURSE

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Abstract *— The capstone design experience is an important component of our undergraduate engineering program. Until recently the capstone project was only the second major design experience for undergraduates, the first occurring in the freshman year. Because of this gap in project experience, seniors often had difficulty with non-technical skills (teamwork, effective communication, project management, etc.) despite instruction in these skills at the start of their senior year. We have used the existing ECE course in Digital Systems Design as an opportunity to include a major design project in the junior year. By introducing juniors to non-technical skills, in the senior year the skills are reinforced rather than introduced, and the seniors understand the necessity of learning and applying these skills. This paper describes the revised Digital Systems Design course, focusing on a description of the semester-long project. We describe the project mechanics, examples of recent projects, and how the project experience develops non-technical skills.*

Index Terms — design experience, digital design, junior design project, soft skills

1. Introduction

Design experience is a central educational objective of engineering programs, and is expected by the ABET EC2000 criteria. As these criteria suggest, design experience encompasses both technical and non-technical skills (often called "soft skills"): effective communication, project management, the ability to function in teams, etc. It is accepted that despite the connotation of the adjectives "non-technical" and "soft", these skills are highly valued by employers and are of equal importance to the traditional technical skills taught in an engineering program. Our undergraduate engineering program culminates in a two-semester capstone design experience that draws upon students' technical skills and also develops their non-technical skills through instruction and practice.

At the beginning of the capstone project, while the project proposals are in progress, students are introduced to project management concepts, effective communication skills, team-building exercises, etc. Despite the instruction provided in the classroom, some teams are beset by poor progress in the early stages of the project, poor intra-team communication, and inter-personal problems, all of which lead to frenzied efforts in the last few weeks, and not a few sleepless nights (also called *time scallop* [1]). In contrast, the teams that apply their classroom knowledge of non-technical skills often finish their projects on schedule and with minimal stress. In hindsight, all students appreciate that there is more to engineering than technical skills, but we would prefer that this appreciation is developed before the capstone project. Other engineering schools [2, 3] have indicated the same experience.

The Senior Project

In the capstone senior project, an industry sponsor proposes a problem to be solved, usually involving the construction of a complete system. Recent examples include the construction of an altitude/temperature chamber for Goodrich Avionics, an automated adhesion applicator for American Seating Corp., and a tube-wall-thickness measuring device for Benteler Automotive Corp. Teams of students are formed to represent diversity in our 4 engineering emphasis areas (computer, electrical, manufacturing, mechanical). Over two semesters, these teams propose and iterate a design, procure components, assemble and test their design, and write documentation. A working system is a requirement for graduation from the program; students receive an incomplete grade until the system works to the satisfaction of both the project sponsor and the supervising faculty.

The Digital Design Course

For ECE students, the existing Digital Systems Design course (EGR326) is now used as a junior-level design experience (EGR345, Dynamic Systems, is used for mechanical and manufacturing engineering students). Other schools [4, 5, 6] have also taken the approach of integrating a design project into the undergraduate curriculum, with varying composition of course content, instruction in non-technical skills, and project mechanics.

The EGR326 course builds upon topics introduced in a previous course, EGR226, which addresses combinational logic networks, Boolean algebra, synchronous sequential networks, microcontroller architecture, and C programming for a microcontroller environment [7]. In EGR326, we present the following core topics:

- Combinational logic circuits (encoders/decoders, multiplexers, ALU's, memories)

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- Sequential logic circuits (registers, counters, shift registers)
- Timing diagrams, timing margin calculations, metastability
- State machine implementation in programmable logic
- Microcontroller programming with assembly language
- Analog and digital interfaces (switches, transistors, 3-wire interfaces, 2-wire interfaces)

These topics are augmented with specific instruction on concepts that are likely to be of use in the project aspect of the course, such as voltage regulation, interfacing with RS232 systems, and so on.

There are approximately 6 combined homework-laboratory assignments (worth 25% of the course grade), and two exams, each worth 25% of the course grade. The final 25% of the course grade is assigned to the design project, described in Section 2.

EGR326 Course Goals

Unfortunately, until recently the capstone project was the only major design experience for students, apart from an introductory freshman hands-on project in the first semester. By introducing a junior-level design experience, we hoped to achieve three things:

- provide students with a significant design experience
- introduce students to non-technical skills so that these may be reinforced in the senior year
- convince students that non-technical skills are important, so that they may be applied effectively in the capstone project

In Section 2 we describe the project component of EGR326. In Section 3 we present examples of recent EGR326 design projects. In Section 4 we discuss an assessment of EGR326 as well as ideas for future improvement.

2. The Digital Design Project

The EGR326 project requirements are that each group of students specifies, designs, and builds a digital system. Groups typically comprise 2 or 3 students, depending upon the class size, so that the number of project teams is limited to 10. This limit allows both costs and the instructor's time commitment to be manageable. The choice of the system to be built is left up to the students, although the instructor guides the project selection to ensure a reasonable level of challenge. Invariably, and by intention, the projects comprise a microcontroller and at least one interface to an external device, thus serving as a good introduction to embedded system design and hardware-software co-design.

The project begins with a selection of a system to be designed, one week after the course begins, and culminates with a final public presentation and demonstration, on the last day of class. Projects are to be soldered on double-sided copper-clad boards manufactured using an in-house circuit board mill [8]. The students must generate all of the schematics and board layouts using the Eagle software package. Each team has a budget of $50 for electronic components (from departmental funds), regardless of whether the components are purchased or available from our parts cabinets. That is, the students must demonstrate that anyone could build their system (not including board manufacturing costs) for less than $50. This policy discourages projects that rely upon overly expensive components, and it discourages students from using their own funds to add expensive components to a project in the hopes of obtaining a better grade.

Project Mechanics and Deliverables

A summary of the major milestones in the project is shown in Table I. On the first day of class, the students are required to complete a survey that determines their skills and interests in digital design, soldering, C programming, assembly language programming, work habits, and project management. By the second class, the students have been assigned to teams. Each team is chosen to represent a variety of skills, but commonality in work habits and academic performance. In the past we have allowed students to choose their own project teams, but this has often led to poor matches. Students generally choose to work with their friends, which leads to good team dynamics, but does not ensure the variety of skills necessary for success. Especially poor matches occur when there is a large disparity in talent and ability.

TABLE I
PROJECT MILESTONES

Milestone	Course Week
Team Assignments	1
Project Selection	2
Functional Specification	5
First Parts Order	6
Design Review	9
Second Parts Order	10
Demonstration and Presentation	13

By the middle of the second week, each project team must have decided upon a project. The first few days of the course require frequent back-and-forth discussions between each project team and the instructor to ensure that a reasonable project is chosen and that the team's direction is clearly determined.

The first project deliverable is the functional specification, a written technical report describing the intended operation of the project from a black-box viewpoint. This functional specification is worth 20% of the project grade. The first month of the course, then, is for researching aspects of the project related to external interfaces and for deciding upon the functional behavior of the project. It is interesting to observe the frustration that students encounter at having to describe *what* their project will do, without necessarily knowing *how* it will work. But this experience is important as it serves to introduce the writing of requirements specifications and to focus the students' energies on the project while project-related technical concepts are presented in class. The functional specification document is graded on clarity, completeness, depth, and quality of writing. Students are allowed to submit draft versions for comments prior to the final submission deadline.

Following the drafting of the functional specification, students are allowed to submit a request for parts. These are collated by the instructor and submitted for purchase as a single order. The parts ordered at this point are not for the full implementation of the project but are for characterization and evaluation. For example, students designing a system using an infrared receiver will typically select and order a few different devices at this point so that they may become familiar with them.

The next month is for the detailed design of the project. At the end of this period, a public design review is conducted in which each project team presents a 15-minute talk describing the technical details of their project: schematics, board layouts, software algorithms, bill-of-materials, etc. The instructor and the other project teams comment on the design. The public is also invited to attend, including industry representatives. Not only does the design review serve the purpose of catching major design errors, it allows each team to study the designs of other teams, especially their bill-of-materials. It is common to see a "survival-of-the-fittest" process take place with respect to electronic components. Whereas several teams may have each specified a different DB9 serial port connector, for example, after the design review the teams will switch to the one that is deemed most cost-effective.

The design review is worth 20% of the project grade. The instructor's grade is subjective, reflecting the degree of preparedness of each student and of the project team as a whole.

Following the design review, a final parts order is placed. Students who miss this deadline are on their own and must either pay for parts out-of-pocket or modify their schematic to accommodate parts in our parts cabinet. This policy discourages procrastination and has proven to be effective.

The last three weeks of the semester are for constructing the circuit boards, soldering, integration, testing, and debugging. A final oral presentation is required on the last day of class. This is a brief presentation to the public that includes a demonstration of a working system. The oral presentation is graded subjectively and is worth 10% of the project grade.

Finally, a working system demonstration is worth 25% of the project grade, all-or-nothing. In the end, a working circuit is worth two levels of grading in the final grade, e.g., the difference between a B+ and a B-. Students are reminded that in their next year, the senior capstone project requires a working system for graduation, hence the relatively large weight given to a working junior project should not be decried. It is curious that in the three years that EGR326 has been conducted as a project course, the number of working projects has followed the "all-but-one" rule. That is, all but one of the projects have worked by the end of the semester. We discuss the reasons for the failing projects in Section 4.

Non-Technical Skills

One of the main reasons for incorporating the project experience into EGR326 was to improve the students' preparation for the challenges of the capstone project. Thus, it is not the goal of EGR326 to duplicate the instruction in non-technical skills presented in the senior year, but to introduce these skills and give the students an opportunity to put them into practice. At various times in the semester, we present handouts and lead brief class discussions on these non-technical skills. This just-in-time delivery allows the teaching of non-technical skills to be quickly placed in context.

As the first project deliverable is a written functional specification, we present guidelines on writing technical reports and critique past functional specifications. As was mentioned above, students are allowed to submit draft copies of their functional specification for review, as this greatly aids in their ability to reach the required level of writing quality.

As the detailed design of the project begins, project teams will begin to conduct regular meetings and a team leader is selected. During this phase, we present guidelines for conducting effective meetings, understanding the roles of team leaders and "employees", and planning the project timeline. We use the ASME Management Skills Handbook [9] as source material, distilled into basic concepts and without completing the assignments therein. For example, the handbook section on effective management contains 60 bullet points on this topic. We limit our classroom instruction to those topics most likely to have immediate impact (e.g., "The effective leader keeps in mind both the immediate problem and the long-range effectiveness of the group.")

It is also at this point in the project that interpersonal problems start to appear. Again, we present guidelines for recognizing and managing conflict and effective communication.

Beginning with the third week of the semester, every student is required to submit a peer evaluation of their team members. The peer evaluation comprises a set of questions that are to be answered on a scale of 1 to 5 (e.g., "The team member completes all assigned tasks on time and with a high degree of quality.") A score of 1 (worst), 2, or 5 (best) requires additional written comments justifying the score. These evaluations serve two purposes: they allow students to state their concerns with other team members in a formal, distanced manner, and they force students to reflect upon the nature of the questions and how they are being evaluated by their team members. Regarding the former, many students will say little when directly asked about any problems, but will write volumes on their peer evaluations. These evaluations, then, can be used by the instructor to initiate a discussion of the perceived problems.

We have found the peer evaluations to be a very small burden on the students (they can, after all, complete the form in less than a minute if there are no comments to be made) but invaluable to the instructor as a form of regular feedback from students who are often too busy or reserved.

To motivate the students to seriously consider the non-technical contributions to the project, the final 25% of the project grade is a subjective evaluation of "performance". Missed meetings, slipped deadlines, shoddy work, poor co-operation, etc. reduce this grade. Here, too, the peer evaluations are useful for indicating repeated problems. At the end of the course, the students receive a written assessment of their performance in justification of the grade assigned.

We reiterate that it is not the goal of EGR326 to create competency in non-technical skills, apart from technical writing and presentation which is assessed through the functional specification and design review. The only assessment of teamwork skills or project management skills, for example, is in the final subjective evaluation of individual performance. The goal of EGR326 is to plant a seed in the students' minds, demonstrating to them (through their own experiences) that *all* skills, both technical and non-technical, are important in project work. The senior project course, which *does* have the goal of developing and assessing mastery of non-technical skills, will hopefully benefit from this preparation. Whether or not this preparation is effective will be studied over the next few years (some preliminary observations are presented in Section 4).

3. Project Examples

A web page for past EGR326 projects may be viewed at:
`http://claymore.engineer.gvsu.edu/~steriana/326`

Some of these projects (all successful) are briefly described here to give the reader a sense for the scope of the projects.

One of the most ambitious projects to-date has been an Ethernet interface bridge for Goodrich Avionics. Figure 1 shows a picture of the project. The goal of this project was to make a variety of sensor and interface devices accessible over the Internet, to allow remote communication and control. This project relied upon a commercial Ethernet interface module (the Rabbit RCM2200). The students designed the rest of the circuitry. This included a backplane for plugging in daughtercards, and two daughtercards providing A/D and D/A converters as well as a UART interface. In Figure 1, the Rabbit module is visible on the left. The A/D and D/A daughtercard is visible in the middle, mounted vertically on the backplane. The power connector and regulator is visible in the lower left.

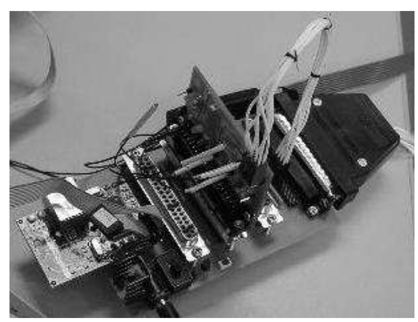

FIGURE 1
ETHERNET INTERFACE BRIDGE PROJECT

Another project, also using the Rabbit Ethernet interface, was designed for Smiths Aerospace. This project allowed an engineer to effect a hardware reset of up to 40 separate systems via Internet connection. This system was developed to save engineers from having to walk between their desks and a distant laboratory simply in order to reset some hardware.

The project shown in Figure 2 implements a programmable attenuator for a microphone, designed for Rockford Fosgate. This project was designed to attenuate an extremely loud recording to levels suitable for a standard PC sound card input. The amount of attenuation was programmable in 10 dB steps using pushbuttons. The level of attenuation was displayed on an LCD display. The project was powered by a wall transformer.

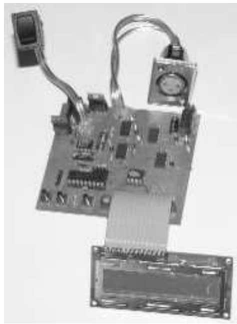

FIGURE 2
PROGRAMMABLE MICROPHONE ATTENUATOR

The project shown in Figure 3 implements an infrared keyboard emulator. Computer keystrokes are simulated in response to button presses on a standard remote control. A pass-through connector allows a keyboard to remain connected, and the entire system is powered from the power provided by the PC through the keyboard connector.

The project shown in Figure 4 implements a PLC interface to a printer. Developed for JR Automation Technologies Inc., this device is intended to replace a computer whose sole purpose is to print one of two labels. An external PLC signals the device to print a label, and also indicates which label to print. The device then communicates with a printer over an RS232 connection. The PLC interface signals are on the left, the RS232 interface is on the right, and a connector to an external LCD display is shown at the bottom.

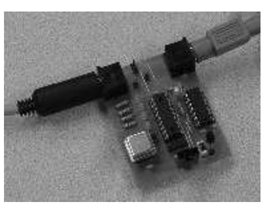

FIGURE 3
INFRARED KEYBOARD EMULATOR

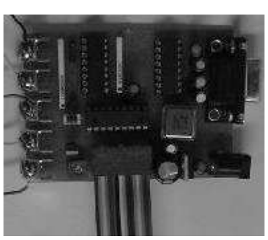

FIGURE 4
PLC PRINTER INTERFACE

4. CONCLUSION

Assessment

After three offerings of EGR326 in the project format, we believe that the approach is a success. From the students' point of view, the course consumes a lot of time, especially near the end of the course, but they are invested in their projects and they truly want to succeed. Students will spend long hours in the laboratory without being forced to do so. Even students who have mathematically already passed the course, even without a working project demonstration, will put in as much time as necessary to get it working. The first set of students who completed a project in EGR326 graduated last year, and from their senior exit surveys we have anecdotal comments that EGR326 had a positive impact on their education.

It is too soon to assess the impact of EGR326 (and its counterpart, EGR345 for mechanical and manufacturing engineering students) on the senior project experience, although we are observing a steady increase in the scope and maturity of these projects. One project group who graduated in August 2001 (and were the first to take EGR326 in the project format) built a temperature/altitude chamber, including custom design and construction of control and sensor electronics. Even for senior project groups that do not design and build digital circuits, the groups seem to function more smoothly than in the past, hopefully because of their increased experience with design projects and the lessons they teach. All of the senior projects in 2001 were completed on time (unlike previous years).

It is clear that more formal assessment tools are necessary to better gauge the impact of our curriculum changes. The weekly peer evaluations, intended mostly as a tool for students' self-reflection, might be used as an assessment of team effectiveness, although the evaluation form will have to be modified to this purpose. In 2002, EGR326 will incorporate additional student surveys, and we hope to incorporate these surveys into the senior project experience as well. Senior exit surveys and industry feedback will continue to serve as useful assessment tools.

Reflections on the Project

The incorporation of a project in EGR326 has required both time and money. Time, from the instructor's viewpoint, is required to actively supervise the projects: meet with project teams, manage problems in team dynamics, collate and submit parts orders, read the datasheets of parts proposed by students, etc. Indeed, without a time commitment by the instructor, the project experience would most likely be very frustrating for the students.

Money is required for the procurement of parts and the construction of circuit boards. If a milling machine is not available, commercial fabrication is an option but will cost about $70 per project team (assuming a single circuit board). We have been fortunate to receive a commitment of departmental funds for this course and access to a circuit board milling machine, allowing significant projects to be constructed with no expense to the student.

A balance needs to be achieved between letting students make (and learn from) mistakes, and forcing decisions. The first parts order, in the first half of the course, is a good opportunity to let students order whatever parts they think they need (within reason) without questioning their choices. After the parts arrive and power jacks won't mate with power sockets, surface-mount instead of DIP devices are ordered, and cheap switches break after just a few cycles, students appreciate immediately that they are in charge of their projects, they must pay attention to details, and that they must make wise choices. For the second and last parts order, closer scrutiny of part lists is in order, as there is not enough time left in the course to repeat these lessons.

Since the inception of the project format for EGR326, we have conducted 4 projects the first year, 9 projects the second year, and 9 projects the third year. The three project failures (there was 1 failure each year) have resulted from lack of technical ability (two incidents) and failure to follow the instructor's advice on project selection (one incident). In a sense, the failures are as important as the successes, as they highlight that failure *is* an option, and therefore, failing to graduate on-time due to a non-functional senior project is also an option. Failure, however, as a motivational tool is certainly not the goal of EGR326, or of any course in our curriculum.

Course Directions

In the short term, we plan to implement minor changes to improve the project experience. These include more formal and regular project review meetings, as well as a greater emphasis on documenting student work. These changes will hopefully improve student accountability, communication skills, self-evaluation and reflection, and team communication and motivation [1].

As EGR326 has evolved it is now attempting to i) teach fundamental digital design concepts, ii) teach electronic prototyping, schematic and board layout skills, iii) teach non-technical skills. The course is beginning to feel over-full, in the impression of both students and instructor. We are spending less and less time with the textbook material, to the point that the text for the course may no longer be needed. In the long term, then, one of the changes we are considering is to steer the course away from being a digital design course and focusing mostly on the project. That is, reduce the number of digital design concepts in favor of expanded coverage of project-specific skills and technologies, moving many of the concepts down to the sophomore year in EGR226 (which is itself being reformed, giving us a window of opportunity).

Another approach is to spin-off the project component of EGR326 into a separate design project course, leaving EGR326 to focus more on fundamental concepts. The benefit of this approach is that the design project course could become interdisciplinary by involving the other engineering disciplines, and that more time could be spent on non-technical instruction, including more student involvement to aid in internalization [10]. In fact, the Design4Practice model [2, 11], in which design and non-technical skills are developed throughout all 4 years of study, seems like a very good direction for our program. A separate junior-level interdisciplinary design course would be a good step in that direction.

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