2006-717: SENIOR DESIGN PROJECTS IN MECHANICAL ENGINEERING – A CASE STUDY OF CAPSTONE EXPERIENCE WITH STRONG INDUSTRIAL PARTICIPATION

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Senior Design Projects in Mechanical Engineering -- A Case Study of Capstone Experience with Strong Industrial Participation

Abstract

The Department of Mechanical Engineering at the FAMU-FSU College of Engineering adopted an integrated curriculum in the late 90s. The curriculum features a capstone one-year senior design course in which students work in teams tackling engineering problems provided and sponsored by industrial partners. This paper describes the evolution of the capstone course over the last seven years, and the reasons behind many of these changes. As the course matured, the department has been able to attract more and more industrial sponsors; today almost all the senior projects are sponsored by industry. This high level of industrial participation as well as many years of improving course management and delivery allow us to draw some important conclusions on what constitute "best practices" for capstone design courses.

Introduction

The Department of Mechanical Engineering at the FAMU-FSU College of Engineering adopted an integrated curriculum in the late 90s. Major themes within the discipline are grouped in two-semester sequences with a corresponding laboratory (e.g., thermal-fluids, mechanics and materials, etc.). The teaching of design has been integrated to the curriculum by devoting a certain fraction of the coursework or labs to open-ended design problems. Likewise, formal introduction to the engineering design method is made at the sophomore level in two courses: Introduction to Mechanical Engineering, and Mechanical Engineering Tools. These courses introduce the design cycle, and expose students to design concepts by using problems within reach at the sophomore level (e.g., statics, simple material selections, etc.). The tools course introduces the students to the machine shop and to the software packages they need to master in order to successfully operate in an engineering environment (spreadsheets, CAD, etc.). Design components are then threaded through the curriculum, with each course devoting a certain fraction of homework (and corresponding credit) to design-oriented problem. Many of the labs also feature activities in which the students work in teams to design systems relevant to the course subject matter. The curriculum is capped with a one-year senior design project in which the students work in teams to design and implement products or systems under the sponsorship of an industrial partner. In its seventh year this capstone course has undergone changes as a result of the lessons-learned. This paper chronicles that evolution (and the reasons behind it), and describes in detail the format and mechanisms used at the present time. A summary of our observations is given at the end to support what we believe are "best practices" in the conduct of team-based capstone design courses.

Evolution of the Capstone Design Experience Course

It has been recognized that capstone design courses represent an excellent vehicle to round out a good engineering education and they provide the appropriate platform for students to apply design thinking and transition into a professional career[1]. Many universities have adopted this model for their engineering curricula[2,3,4] .At our department this course was first introduced as a

one-year sequence within an integrated curriculum in the 1999 academic year. Although the course has always undergone a gradual evolution from year to year (as a result of our ABET-related self evaluation and feedback loop), there was a marked shift three years ago as explained in the next sub-sections.

Original Format: Integrated Lectures and Projects

When this capstone course was first introduced in 1999 it was conceived as an integrated lecture plus project course. The course spanned the Fall-Spring semesters worth 4 units each semester (8 units total). The mechanics involved traditional lectures twice a week (75 minutes each), although since projects were running concurrently, approximately every three weeks the lectures would give way to student presentations (design reviews). The rationale behind the lectures was to introduce, "just-in-time", material relevant to the phase in which the projects were at the time of the lecture. For instance, early in the first semester, most lectures would deal with subjects such as team dynamics, the design cycle, or concept generation and selection. As projects made progress, the lectures would attempt to follow the design cycle as best as possible. When the teams were ready to produce the first major design report, the lectures would feature a module on technical writing or graphics in engineering.

This approach of "just-in-time" lectures worked well early during the early weeks of the course, however it is not possible to cram all project-relevant material in the first semester (much less early in the first semester). As a consequence, some topics that could be useful during the early design phases of the project, could not be covered until the Spring semester, and by that time most projects had already completed the design and had moved to implementation and testing. Subjects such as optimization and engineering-economics could never be covered in time to be applied in the design stages of the project. This inevitable mismatch between lectures and projects was not the only drawback of the integrated (4+4) lecture/project course format.

It was our observation that it was difficult for student to stop behaving like "students" and start behaving as "project engineers", and they would place more emphasis on the lectures, homework, and tests than they would on the projects. In the eve of major midterms or exams, design projects would come to a standstill and overload to study for a test was an excused often given to slip a project milestone. Further, since grading had to be done combining the lecture portion (tests and homework), with the project grade, it was observed that some students (especially the strongest students boasting the highest GPA) would spend the effort into doing well on the tests, getting high grades, so that they could 'coast' on the project. The end result was lackluster performance on many of the projects, without reaching the level of expectation set by the department or our industrial sponsors.

After delivering the course as an integrated unit of lectures plus project for three years, it was decided to split the lectures into a separate (Fall semester) course, with traditional delivery and grading, and leave the capstone design experience as a project-only course as described in the following sub-section.

New Format: Project-based Course

Based on the shortcomings described above associated with integration of lectures and project (especially for the purposes of grading), beginning with the 2003 academic year the capstone course was split into two components spanning three semester-courses. The course went from a 4+4 format to a 3+3+3. Almost all the material formerly covered in the lecture portion was condensed into a one-semester 3-unit course taught in the Fall (concurrently with the design phase of the projects). The course is titled "Design Methods in Mechanical Engineering" and it still supports, by the most part, the evolution of the senior projects on the capstone design course. The capstone design course runs on a two-semester basis (Fall and Spring, 3 semester hours each) and is entirely project-based, very few lectures are used to introduce the projects and guide the teams through the design cycle.

Under the new format, both activities and grading are separate for the lecture-based and the project-based courses. The students do not have as much problem separating responsibilities, especially since only the project portion is team-based. We have observed a marked improvement in project performance and delivery since the lecture component was split from the senior project.

In the new format, teams are clearly motivated to carry on the projects in a timely manner and grading is done accordingly, with all the credit going towards rewarding project performance (creativity of the design, schedule, presentation, etc.). To further assist the students in concentrating on the senior project work, a special and separate space has been devoted to the capstone design course (see Figure 1). This "design studio" is a large room where teams can hold project meetings, brainstorm design ideas, store equipment, or do light assembly and testing (otherwise machine shops and laboratories are also made available to the teams). This design studio is not only a "safe zone", it is also a "team zone". In its first year of operation, this design studio is proving a useful addition for effective delivery of the capstone design experience.

Figure 1. – A senior design studio serves as meeting place for project teams as well as provide some light fabrication, assembly, and test facility to complement laboratories and machine shops

Growth in Enrollment and Industrial Participation

Since its inception in 1999 the senior design course has seen steady growth in enrollment as well as in industrial participation, this growth is shown in Table I. Since the capstone course is a required part of the curriculum, enrollment perfectly tracks graduation numbers for the department. We are now graduating over 60 students each year, with that number expected to increase to 80-85 over the next 2-3 years. As a result of this growth we have been forced to increase the average team size from 3 to 4 students. This increase has not adversely affected team dynamics or our ability to motivate and track performance so we have adopted it as a norm (4 students per team). On rare occasions we assemble teams with 5 students, but we feel such arrangements are the practical limit at which some sub-standard performance can set in and it is easy fro a student to 'disappear' into the team and coast.

Of further significance is the growth in industrial participation. When the course was started in 1999 we had only 2 projects (12%) sponsored by an outside industrial partner. We have consistently increased that percentage and today we are running close to all projects with an industrial sponsor (close to 90%). We feel this is the limit and will not try to achieve 100% of

industrial sponsorship. There are many instances of valuable projects that we would like to pursue with the class that do not involve industry, such instances include service-oriented projects (community-based), projects involving spin-offs from research activity by our own faculty, or student-based organizations such as SAE or ASME.

Table I – Evolution of industrial participation in the capstone design course

Academic Year	Student Enrollment	Number of Projects	Avg. Number of Students per Team	Fraction of Industry-Sponsored Projects
99-00	56	17	3.3	12% (2/17)
00-01	40	12	3.3	25% (3/12)
01-02	56	18	3.1	44% (8/18)
02-03	46	13	3.5	54% (7/13)
03-04	47	13	3.6	54% (7/13)
04-05	60	15	4.0	80% (12/15)
05-06	65	16	4.1	88% (14/16)

Present Course Structure and Mechanics

In its seventh year, the capstone design course in Mechanical Engineering at the FAMU-FSU College of Engineering has undergone a number of evolutionary changes as a result of our ABET internal review process which incorporates the lesson-learned after each teaching cycle. This section provides a detailed description of how the course is run today as a project-based capstone course (without a traditional lecture component to it).

Project Harvesting

Since the entire pedagogical premise of the capstone experience revolves around engineering design projects, and great effort goes into mimicking as much as possible the conditions encountered by engineers in industry, the quality of industrially-sponsored projects is paramount[5]. Very significant effort goes during the summer prior to the beginning of classes to "harvest" enough quality projects from industry to staff enough design teams including the entire graduating class. Securing good projects not only involves identifying industrial partners, but more specifically, individuals within those organizations that are willing and able to work with the students throughout the academic year. The projects must be somewhat meaningful to the industrial partner, yet not be mission-critical, and funding must be available to construct prototypes or other hardware as required by the project. More importantly even if we can identify an individual, a project idea, and funding, the endeavor must have the buy-in from the organization.

The task of securing enough projects to feed the capstone experience course, although always daunting, has become somewhat easier in recent years due to two important factors:

- Active involvement from the department's industrial advisory board, which has been very pro-active at helping us secure participation from divisions and engineers from their home organizations, and

- A significant fraction of "repeat business" with many companies returning in subsequent years to sponsor more projects after realizing the benefits of their involvement (new design ideas, exposure to faculty and students, recruiting opportunities, etc.)

At this point we have a solid base of industrial partners to secure enough industrial projects, although every year we have some sponsors that would not return, or are not in a position to sponsor, which coupled with steady enrollment growth makes project harvesting always challenging.

Team Assignment and Formation

Once projects are identified and selected for the academic year, the next challenge is to make the team assignments. A large part of the success and failure of the senior capstone experience rests on the ability to assemble high-performance teams. Since one of the main motivations behind the capstone experience is to expose students to team-based design and procedures, the make-up of each team is very important. We have used slightly different techniques to assign teams and over the years we have learned what works or not. It is fair to say that if students were allowed, they would make their own teams based on friendship and level of comfort. There would also be a tendency for teams to cluster by GPA (with some teams nucleating all class overachievers, while other teams would be composed of students with low GPAs). We clearly observed this during the first year of the course in which we offered some latitude for the student to choose projects.

Beginning with the second year of the capstone course we have limited the ability of the student to choose projects and instead the instructor assigns the teams and forces students to work in group without the comfort level of picking teammates. The process is somewhat complicated because certain constraints need to be observed:

- Allow members of students chapters (e.g., SAE, ASME) to work on specific projects sponsored by such organizations
- Allow students on the BS-MS (co-terminal) track to work on projects sponsored by certain industrial partners that also serve as hosts for summer internships
- Consider the student's career interest or objectives as much as possible (e.g., students going into a bioengineering program in graduate school, students supported by certain fellowships from specific industry sectors, etc.)
- Ensure teams are composed by students from both universities represented at our college: FAMU and FSU

Aside from these constraints, the method used to assign teams is rather straightforward. Each student in the class is assigned to one of four groups according to GPA (top quartile, second quartile, etc.). Each team is given four 'slots', one from each GPA quartile group, and a random drawing is used to pick a student's name and then allow him/her to pick a project with a n open 'slot' for the GPA group the student is in. The end result is that all teams have the same 'average GPA', and to the extent that name drawing is random, most of the students (but not necessarily all of them) will be satisfied with their projects and teammates. Even though prior GPA is not at all a good indicator of performance in the capstone course (in fact most of the top performers in

senior design come from the second quartile group, and not the top), the method ensures a uniform distribution of GPA among all teams and indeed project execution and performance tends to be quite uniform for the entire class.

Periodic Reviews, Staff Meetings, and Deliverables

Another major thrust of the capstone experience is to expose students to industrial projects and to the methods and procedures engineers employ in industry to solve problems and carry out projects. Therefore, the capstone course is structured so that students execute projects in a very consistent and well-documented manner. The aid the teams in that respect, the course follows a schedule of frequent design reviews and written deliverables as outlined in Table II.

The typical schedule of the capstone design course includes many, and frequent, points to evaluate progress and aid the teams in making steady progress towards project completion. These step-by-step approach includes frequent "staff meetings" in which the course instructor meets one-on-one with each team for about 20-30 minutes to discuss project-specific problems or issues. The teams also have frequent meetings with support faculty, as well as meetings and/or teleconferences with the industrial sponsor. This high frequency of contact among all stakeholders ensures projects can stay on track despite the distractions of other courses, team dynamics, busy schedules, etc.. In addition, there are six major design reviews in which teams present progress to date and plans. The third element are written reports (deliverables), a total of 10 over the span of two semesters, including two major reports, a design package at the end of the first semester, and a full account of all project activities and results at the end of the year.

It should be noted that there are less milestones during the 2nd semester, there are two reasons for this "easing" on reporting requirements. During the first semester all projects go through a design cycle that is fairly independent of what product or system is being developed. It is appropriate to utilize a "template" of deliverables applicable to all. However, during the second semester projects diverge considerably in their direction as they move to an implementation phase, making a "template schedule" less meaningful. In addition, we do want students to develop a sense of ownership of the project and develop the time-management skills that will bring projects to a successful conclusion without the need for artificial milestones set by the instructors. Most teams develop that culture by the second semester.

Table II – Typical schedule of project activities and written deliverables

Week	Activity	Deliverable (Reports)
Fall – Week 1	Project introductions/Team assignments	
Fall – Week 2	Team building and project kickoff	Team-building activity report
Fall – Week 3	Staff meetings	
Fall – Week 4	Introduction to scheduling	
Fall – Week 5		Needs assessment Project scope
Fall – Week 6	Staff meetings	Product specifications Project schedule and procedures
Fall – Week 7	Review #1 (preliminary design)	
Fall – Week 8		Concept generation and selection
Fall – Week 9	Staff meetings	
Fall – Week 10		
Fall – Week 11	Review #2 (mid-point)	
Fall – Week 12	Staff meetings	
Fall – Week 13	Thanksgiving break	
Fall – Week 14	Staff meetings	
Fall – Week 15	Review #3 (final design review)	Final design reports Spring semester proposals
Spring – Week 1	Mini-review (scope and schedule)	Scope and schedule report
Spring – Week 2	Staff meetings	
Spring – Week 3		
Spring – Week 4	Review #4	
Spring – Week 5		
Spring – Week 6	Industry week activities	
Spring – Week 7	Staff meetings	
Spring – Week 8	Review #5	
Spring – Week 9	Spring break	
Spring – Week 10	Staff meetings	
Spring – Week 11		
Spring – Week 12	Staff meetings	
Spring – Week 13	Review #6: Final Project Open House	Final report and web page
Spring – Week 14	Exit interviews/Course evaluation	

Open House

At the conclusion of the academic year the capstone course features a final review/open house for the teams to make presentations describing the project and the results obtained, as well having an open house with posters and the actual hardware produced by the teams (see Figure 2).

Figure 2. – End-of-Year Open House where graduating seniors showcase capstone projects (in this instance a Battlebot designed and built to enter competition in a TV show)

This open house is a very special occasion for the department as not only the sponsors travel to attend, but we also invite our entire industrial advisory board. These engineers from industry serve as a panel of judges and give feedback not only to the student teams about their projects, but also to the department on any strengths and weaknesses gleaned from the capstone design projects. This input from industry is extremely valuable to the department as part of our ABET2000 self-evaluation process[6,7] .

The open house is usually a very festive all-day event as the vast majority of students will be graduating within the following three weeks, and this is an opportunity to showcase their hard work on the projects and spend some quality time with teammates after sharing many hours of sacrifice throughout the year. We end the event in the early evening with an informal dinner for the entire class, faculty involved, as well as all industrial partners and advisory board members. The senior design open house is also well attended by sophomores and juniors in Mechanical Engineering (as well as from other majors), providing a strong sense of connection among all undergraduate students.

Grading

Grading and evaluating student progress in a team-based capstone courses is always difficult and has been the subject of much thought among educators[8] . There is always the trade-off between the need to encourage team behavior by rewarding performance as a group, versus the need to identify students that are not contributing to the team effort and do not deserve full credit. This balance needs to be achieved without overburdening the team with peer evaluations that sometimes may have negative effects on team dynamics and ultimately destroy the spirit we are trying to foster when teams are assembled. All grades earned are based on team performance. The only grades based on individual performance are those earned during design review presentations (when both a team grade and an individual grade are given), or at the end of the semester when we evaluate peer review feedback to assign a teamwork grade. We only use the input from these team evaluations to intervene in extreme cases of poor team dynamics, or to warn individual students when their performance is not matching team expectations. Otherwise, we avoid differential individual grades as much as possible and prefer to reward/punish team as a whole. In our experience, only about 10-15% of the teams exhibit either poor dynamics or a single non-performing individual warranting intervention from the instructor and a separate individual grade.

Our Experience (Lessons Learned)

In the complexity of a capstone design course it is not always easy to capture the essence of a successful implementation by merely describing the course mechanics (as done in the previous section). Therefore this section captures some important lessons learned from running this capstone course over the last seven years with highlight of what we consider "best practices."

Team Formation and Motivation

An important part of the capstone experience is to develop in student the interpersonal skills that will turn them into effective team members. As strongly encouraged by ABET2000, today's engineers need to be able to function in teams, and the capstone experience must capture this aspect of engineering work. Just as in engineering practice, within the capstone course there is a very strong correlation between effective teaming and project success. We have observed over the years that when a team is able to gel as such, and members function well together, the project will be successful independent of the scholastic background of the students, or even project difficulty. The flip-side is also true, it is our experience that even teams composed of students with strong academic background, tend to fail when the team does not function properly and personal animosities or uncooperative behavior are allowed to fester.

It is fair to say then that any capstone design course needs to be based on a very careful methodology to assemble, motivate, and monitor teams. Overall success of the course and the projects will depend, to a great extent, on the ability of the faculty in charge to properly keep teams motivated. To that end we encourage social interaction of the teams during the first couple of weeks after project assignment, and we help them through some lectures on the importance of team dynamics, how to give and receive constructive feedback, and to evolve behavior from a phase of compromise to a phase of team cooperation. During the year-long

course we are careful not to engage in grading activities that would encourage individual behavior or friction resulting from teammates having to grade each other. We do, however, put effort into monitoring team dynamics with an eye in identifying non-cooperative members who are taking advantage of the teaming arrangement to 'coast' towards a grade without having to work. It is important to strike a balance between making students feel that success can only be accomplished as a team, versus not creating a situation in which high-performance students feel the need to let others 'coast' in order not to destroy team harmony. The capstone design faculty really need to place a lot of time and effort towards striking this balance.

Industrial Involvement

Two major aspects of industrial involvement that deserve special attention are selection of the sponsor (the person from industry that will interact with the students and act as "customer"), and handling of intellectual property (IP) issues and non-disclosure agreements (NDA).

As important as defining good projects for the students to work on is the industrial liaison that will work with the students and serve as "customer". In a large class with only one faculty acting as instructor/coordinator, the quality of mentorship offered by our industrial partners is of critical importance for the success of the project. Having strong backing from management is not enough if the individual mentor does not "buy into" the concept of capstone project sponsorship. He/she needs to perceive the value of industrial involvement and the benefits of the students work, however minor they might be in the context of the organization's goals. These benefit could be direct, in the form of project results, data, or prototypes; but they could also be indirect, such as potential recruitment targets, image creation within the entire graduating class, or development of industrial-academic contacts.

Another aspect which deserves special attention in a capstone course is IP and NDA documentation. We clearly prefer projects that do not expose corporate privileged data or otherwise classified materials. It is important for companies to understand that these projects are, above all, an educational vehicle. By the most part our industrial sponsors understand this and provide projects, that when falling within their product line, appropriately mask or box the problem so students can do relevant work without exposing corporate secrets. This is very important given the need for team to present their work, not only in class, but to prospective employers as well. We have been unsuccessful to come up with a good model since the university refuses to execute any type of NDA document, or to agree to release any IP resulting from these projects. This has been an impediment in some cases to either obtain a project or to execute projects under ideal conditions. It is an area where we will continue to work in order to obtain some release from the university so that we can engage a wider range of corporations and projects.

Multi-disciplinary Capstone Experience

Another aspect in which we have had mixed success and much work remains to be done is in exposing our students to multi-disciplinary design. Many of the projects we harvest from industry are, by virtue of coming from the "real world", multi-disciplinary in nature. In particular, many projects are ideal platforms for the interaction between mechanical and

electrical engineering students. Every year we make attempts to integrate ME and EE students in our projects. However, we have run into impediments to do it in a widespread manner as a result of institutional differences within our own college, and the disparity of curricular requirements among the different departments when it comes to capstone experience. The Mechanical Engineering department is the only one with a well-developed year-long and project-based capstone course, and a s result, we have not been able to involve as many students from other majors as we would have liked. We are presently working at the college level to bring some uniformity and then re-try doing more multi-disciplinary projects. Otherwise, we have been successful , again, within limitations, at involving students from Physics (as part of their honors thesis), or Business (as part of their marketing seminar). As expressed above, this is an area where we will continue to work since major improvement are possible.

Recently, we have begun moving aggressively towards enlisting projects that involve other universities[9], particularly overseas. We strongly believe that the capstone experience can be the platform not just for introducing team-based design but "global" team-based engineering. This will be a cornerstone of our efforts to expose students to the reality of being an engineer in the XXI century, in a mostly global economy. In the present school year we are running two senior projects involving teams overseas (Brazil and Romania) working "side-by-side" with our teams solving an engineering challenge. We expect to expand the number of international projects over the course of the next few years and many of our industrial partners will be engaged in this effort by involving their branches overseas.

Feedback from Students/Exit Interviews

The year-long capstone course ends with an open house typically scheduled at least 2 weeks prior to the end of the academic year. This leaves the class (both instructor and students) free to use the last week of classes to conduct debriefing meetings. Since the class is composed entirely of graduating seniors, we combine a capstone course evaluation with exit interviews. Every student meets with a faculty member for about 20 minutes, in addition to filling out a questionnaire used to evaluate both the curriculum as a whole (as well as the capstone experience). During the one-on-one meeting students can discuss with the faculty any issue of concern about the department or the curriculum, or relay impressions about those aspects of the program that were a positive experience. This feedback is then processed and summarized and use as input to our ongoing improvement efforts. Many ideas or suggestions are used to improve the curriculum and areas the students pointed as problematic are corrected as soon as possible. Our curriculum is therefore constantly evolving as a result of the student feedback.

Through these exit interviews it has become clear that most students consider the capstone experience as challenging, but definitely a positive and enriching experience that helped them mature as engineers and prepared them well for a successful career. Students consistently point out the initial difficulties of working in teams on open-ended problems, but feel very confident on their new-found abilities and ready to tackle a career in industry. It is not unusual for student to be hired directly into jobs related to their work on senior design projects, or as a result of impressive portfolios built around their capstone project. We have many success stories along these years, including the case of a recruiting firm opening a local branch office in Tallahassee,

FL as a result of their great success hiring mechanical engineers directly from our capstone course.

Conclusions

The capstone senior design course in the Department of Mechanical Engineering at the FAMU-FSU College of Engineering has proven to be an excellent vehicle to educate our students in team-based design, and the application of engineering fundamentals to real-world problems. The program has evolved over the last seven years and reached a high level of maturity. In seven years we have worked over 100 projects and graduated more then 350 mechanical engineering majors, while also involving nearly 50 students from other majors. A complete record of projects and their sponsors is compiled in the course website[10]. This capstone course has allowed us to create a good foundation for attracting industrial partners that provide project ideas, funding, and mentorship to turn the experience into a much more realistic platform for educational delivery.

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