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A Coupled Course Design to Strengthen Multidisciplinary Engineering Capstone Design Projects

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Abstract

Multidisciplinary Capstone Design courses are becoming a focus of engineering institutions as multidisciplinary skills have become a priority for accreditation and have shown promise for the development of young engineers. Most of the implementations are done using a stand-alone course or a dedicated section of a capstone course which involves a high institutional resource cost. Here we propose a Supplementary Multidisciplinary Capstone Course (SMCC) to be coupled to the departmental capstone courses to promote quick adoptions of multidisciplinary capstone projects without sacrificing discipline specific rigor. Two student surveys and one end-of-quarter grading rubric are used to assess the merits of the coupled course design through the first quarter of a three quarter capstone series. Results of the surveys show that the SMCC course structure resolves student meeting scheduling problems by mandating attendance and retains departmental rigor by having advisors directly assigned in the departmental capstone course. We found that highly motivated teams with defined projects thrive with this model but that industry-defined projects require increased communication for all involved faculty and industry mentors at the onset of the project.

Introduction

Multidisciplinary engineering (MDE) capstone design courses have been shown to yield positive effects on students' innovation, marketability and communication skills among other measures[1,2] and one of the primary outcomes of engineering education as described by the Accreditation Board for Engineering and Technology (ABET) is an ability to function on a multidisciplinary team. Accordingly, US based universities are increasingly adding multidisciplinary capstone design programs to course repertoires[3] and some requiring these courses in place of department specific capstone courses.[4] The most prevalent implementation of multidisciplinary capstone design is a standalone course joining many departments or a single discrete section of a single capstone course.[1,2,5,4] This approach is highly attractive but requires large-scale university support for scheduling, instruction and is dependent on facilities that can handle a large number of students with a wide variety of equipment needed to support the variety of work to be completed in the course. Universities such as Penn State and the University of Washington have created facilities specifically to handle multidisciplinary capstone projects in their Learning Factory.[4] This seems to be the gold standard but to develop such infrastructure is time intensive and requires curricular changes that are impeded by the curricular contract between the university and student at admission. Additionally, while the benefits are stated in prior literature, the faculty was left to wonder about the potential drawbacks of a multidisciplinary capstone design course, specifically is there a decrease in discipline specific rigor? Departmental capstone project selection ensures that the student studying mechanical engineering will have a chance to work on a project with substantial mechanical engineering rigor. Can this be guaranteed with multidisciplinary projects?

The departments of mechanical engineering and electrical and computer engineering at the University of California Santa Barbara (UCSB) have previously offered students the opportunity to work on MDE capstone projects but the projects were split into discipline-specific portions to be advised and graded by the respective departmental capstone course. Communication and scheduling between the teams were the biggest challenges in this model. In an effort to improve multidisciplinary design, faculty from 3 engineering departments at UCSB met over the course of an academic quarter to discuss a more integrated multidisciplinary capstone design program for seniors. One complicating factor was departmental pressure to maintain the discipline-specific integrity of the engineering experience throughout the student body. Another complicating factor included the disparity between course units and timelines created by each discipline. In response to these challenges, we have created a supplementary multidisciplinary capstone course (SMCC) to be coupled to the existing discipline-specific capstone courses such that advising and grading can exist by discipline but also as a multidisciplinary team, a novel concept to our knowledge.

Departmental Capstone Courses

The Mechanical Engineering capstone course consisted of 16 projects. Nine of these projects were sponsored and defined by industrial partners. Five projects were based on internal research efforts and 2 were industry sponsored but competition defined. Both of the competition teams were working on the same SpaceX Hyperloop Pod. One of these teams was charged with the structure and integration between all sub-teams while the other was focusing on the levitation and aerodynamics. The course has a single Mechanical Engineering Instructor and 7 other faculty and engineering staff advisors. Each advisor meets with two teams over a one hour "cohort" meeting once per week to discuss progress of the project. The teams come prepared with a short slide deck (1-5 slides) detailing the progress made in the past week. Lectures are once per week and serve the purpose of reinforcing the design process by introducing techniques for project management, research, design process management, sketching, ideation, prototype planning, photography and videography skills, effective presentations and writing skills.

The Electrical Engineering capstone course consisted of 6 projects. Five of these projects were sponsored and defined by industrial partners, and 1 was industry sponsored but competition defined (SpaceX Hyperloop Pod). The course has a single Electrical Engineering Instructor who advises all groups and oversees all projects. Lectures are once per week and serve the purpose of reinforcing the design process by introducing techniques for project management, research, design process management, prototype planning, and effective presentations and writing skills.

The Computer Engineering capstone course consisted of 8 projects. Three were sponsored by industry and a fourth was a collaborative effort between the CE capstone class and the UCSB Department of Ecology, Evolution and Marine Biology. Other projects were student defined. One of the industry sponsored projects was the CE contribution to the SpaceX Hyperloop Pod competition described above. The technical focus of this team was on the telemetry, control and communications of the pod. The course has a single ECE instructor and one teaching assistant. In the fall quarter students complete the logical, electrical and physical (printed circuit board) design. In the spring quarter, the effort shifts to software development, hardware/software integration and prototype construction. The CE teams working on multidisciplinary projects received independent study credit for working during the winter quarter.

The challenges facing the full integration of multidisciplinary projects with respect to the departmental courses were (1) the size of the course, (2) the type of the course, (3) the scheduled academic quarters and (4) the number of units given per academic quarter. Table 1 depicts the nature of the three independent capstone courses.

Table 1: Departmental Capstone Course Details

Departmental Courses	Course Size	Type	Academic Quarters	Number of units / quarter
ME Capstone Course	77 students 16 projects	Required	Fall, Winter, Spring	2
EE Capstone Course	24 students 6 projects	Elective	Fall, Winter, Spring	3
CE Capstone Course	35 students 8 projects	Required	Fall, Spring	4

SMCC Structure

In its pilot year, three departmental programs [Mechanical Engineering (ME), Electrical Engineering (EE) and Computer Engineering (CE)] within the same university participated in the multidisciplinary capstone effort. At the beginning of the school year, students from each department were presented with a list of projects for their yearlong capstone sequence. On the project listing, students were told that registration was required for the SMCC to participate on one of the multidisciplinary projects. The SMCC course was scheduled from 8-9AM one day per week, a timeslot without conflicts for all involved departments.

This year, the SMCC comprises 4 student teams (51 students total). Table 1 shows the number of students and nature of each project. One team (20 students across 3 departments) is working on developing a pod for the SpaceX Hyperloop competition. This team is advised by five faculty members with input from industry sponsors only during final presentations. The other three teams (made of 9-13 students respectively from 2-3 departments) are working on local industry-based product development projects. These projects were actively advised by 3-5 discipline specific faculty members and by engineers at the sponsor company. These projects make up approximately 30% of ME capstone projects, 67% of EE capstone projects and 25% of CE capstone projects for the academic year. Table 2 shows the breakdown of the SMCC student teams:

Table 2: Multidisciplinary projects undertaken for the pilot year of the SMCC structure

Project	# ME Students	# EE students	# CE students	Project Type
Hyperloop Pod Competition	10	5	5	Industry funded, independent student competition
Project 1	5	3	5	Industry funded, industry defined
Project 2	5	4	0	Industry funded, industry defined
Project 3	5	4	0	Industry funded, industry defined

The SMCC was piloted as a one unit (on a standard 3-4 unit/course scale) course designed to serve as a meeting place for multidisciplinary teams. The course schedule is shown in appendix A. Full class lecture time was primarily utilized as a full multidisciplinary meeting time for each team. Two of the class periods were used for 10 minute presentations that allowed for teams to present the general direction, upcoming risks and a project plan to the class. Students were encouraged to question each other. The remaining class time was used for team meetings. The lead instructor (Mechanical Engineering Capstone Instructor) and two teaching assistants observed team meetings and questioned students where appropriate.

Grading

Each team received a grade from their departmental capstone course and a separate grade for the SMCC course. Nearly half of the SMCC grade was determined by team performance in the form of a 10 minute pitch and a final presentation. This grade was the same for all members of the multidisciplinary team regardless of the individual merit of the departmental sub-team. The target of this policy was to encourage team-building by having the full student team working towards a common goal and to replicate the nature of multidisciplinary projects in industry. The remaining portion of the grade was individual, based on attendance and a peer review. The attendance grade weighed heavily into the final grade because the focus of the course was getting students to collaborate.

Analysis of the Fall Quarter SMCC

Because the ME capstone course was the largest capstone course of the 3 participating departments, we chose to assess the merit of the college of engineering's multidisciplinary SMCC approach by comparing it to single team ME capstone projects. All data collected was from the first quarter of a three quarter long project. Table 3 shows the three instruments used to assess our SMCC approach. This study involved research conducted in an established, commonly accepted educational setting specifically for understanding the effectiveness of instructional techniques, and thus was not subjected to an ethics board for approval as per the university exemption policy.

Instrument 1 consisted of two close ended questions added to the end-of-quarter survey given to the ME capstone class. The goal of this survey was to understand students' opinions of the value and the level of opportunity given to ME seniors to engage in multidisciplinary design using the SMCC structure while 5 multidisciplinary project opportunities were offered.

Instrument 2 was a more comprehensive open and closed ended survey given to SMCC students. Open ended questions were meant to assess the challenges that students faced that were unique to multidisciplinary projects and any way that we could change the SMCC that would best serve students. Closed-ended questions elicited quantitative measurements on the aforementioned topics and course specific objectives.

Instrument 3 represents the rankings given to all ME projects including SMCC ME teams to assess the progress and quality of the student capstone projects. At the final quarter presentation, all faculty, project sponsors and TAs in attendance were given a grading rubric seen in Appendix B. Scores were compared by implementing a quantitative scale (excellent =5 to poor = 1). Using these scores and after an ME faculty discussion, the teams were separated into three groups (a) over-performing expectations (b) performing-as-expected (c) under-performing expectations. Student grades were based on group rankings.

Table 3: Data collection instruments

Instrument	Nature	Population
1	Closed Ended survey- ME capstone student	71 ME seniors enrolled in ME capstone course
2	Open and Closed Ended survey – SMCC student survey	24 ME, EE and CE students enrolled in SMCC course
3	Quantitative and qualitative grading	10 ME, EE and CE instructors, 11 project sponsors

Results

The responses from instrument 1 are shown in tables 4 and 5. The frequency number of students who chose each response is shown next to the survey options.

Responses from instrument 1

Table 4: Student responses from Closed Ended ME survey

Working on a multidisciplinary team with teams outside of mechanical engineering (ie. with an electrical or computer engineering team) is an important skill for a mechanical engineer to learn in school.	
Response category	Frequency
Strongly Agree	32
Agree	25
Neutral	10
Disagree	1
Strongly Disagree	0

Table 5: Student responses from Closed Ended ME survey

There was enough opportunity for me to be involved in multidisciplinary projects working with teams outside of mechanical engineering (ie. with an electrical or computer engineering team) this year.	
Response category	Frequency
Strongly Agree	8
Agree	29
Neutral	25
Disagree	6
Strongly Disagree	0

Results from Instrument 2, open ended questions

Student open-ended responses were broken down into basic categories. Frequency number are shown besides the generalized answers.

Table 6: Student responses from Open Ended SMCC survey

What were the greatest challenges you had to overcome in working on a multidisciplinary team?	
Response category	Frequency
Waiting on the other team before starting work / project syncing between multiple teams within a project	11
Coordination of a large number of people	8
Understanding the capabilities of the other disciplines	3
Overbearing personalities	2
Difficulty breaking problems down into manageable chunks	1

Table 7: Student responses from Open Ended SMCC survey

Why did you choose this project?	
Response category	Frequency
Project seemed interesting	16
Desire to work with friends	4
Wished to work on a multidisciplinary project	3
Project aligned with discipline specific goals	2

Table 8: Student responses from Open Ended SMCC survey

If you'd like something to change [about the SMCC course], how should we change it?	
Response category	Frequency
No changes recorded	7
Meeting time (8AM) is too early	7
More instruction on real-world engineering and best practices for multidisciplinary engineering	4
Less in class instruction – more time to meet during class	1
No attendance requirement	1
Add weekly assignments	1
No additional assignments	1
Make it count for technical elective for all departments	1
Don't grade the project as a multidisciplinary team, split grading by discipline	1
Create a structured role for TAs	1

The other two questions asked were about the method of team communications and about ideas about a way to run a multidisciplinary project other than using a SMCC. Teams used Slack, Trello, Facebook and some teams relied exclusively on in-person communications during the SMCC class meetings exclusively. No different approaches were listed as a way to run multidisciplinary capstone projects.

Results from Instrument 2, closed end questions

Scores represent the mean of 25 student surveys using the following scale: Strongly Agree=5, Somewhat Agree=4, Neutral=3, Somewhat Disagree=2, Strongly Disagree=1

Table 9: Student responses from Closed Ended SMCC survey

Averages to 7 closed-ended questions from Instrument 2		
Statement	Mean score	Standard Dev
ENGR195A was an absolute necessity for scheduling meetings with your full team	4.52	0.77
I wouldn't change a thing about ENGR195A for next year	3.60	0.96
I learned a great deal about multidisciplinary engineering design due to my enrollment in ENGR 195A	3.84	0.94
I learned a great deal about how other engineering disciplines approach design	4.20	1.08
Grading Multidisciplinary work separately from discipline specific work encourages team unity	3.68	1.07
Grading Multidisciplinary work separately from discipline specific work retains the discipline specific rigor of a traditional single department capstone project	4.08	0.81
Our team benefitted from the additional opportunities to interact with professors and TAs in ENGR195	4.60	0.58

Instrument 3, First quarter Team rankings

Out of 16 mechanical engineering capstone project teams, 12 of the teams received the mark of exceeding expectations. One team met expectations of the reviewers and three ME teams received the designation of under-performing expectations. ME teams that were also involved in the SMCC course (indicating that they were involved in larger, multidisciplinary projects) landed at the extremes of the scale. Hyperloop Pod Competition teams received the highest ME departmental capstone scores and the highest multidisciplinary scores on the presentation rubrics. Directly following the quarter, the Hyperloop team was selected as one of the top 22 teams across the world to build a pod and compete in the SpaceX Hyperloop final competition. The three multidisciplinary projects sponsored by industry received the lowest rankings of all ME teams. It should be noted that Electrical Engineering and Computer engineering teams associated with these multidisciplinary projects were graded positively by their instructors. It was agreed by all instructors in the course that the EE and CE teams met or exceeded expectations. However, the overall perception of the multidisciplinary project was negative from sponsors and faculty members. This indicated a lack of project definition and integration of the teams on those three projects.

Discussion

The SMCC solved the major problem of multidisciplinary engineering capstone projects (scheduling) as evidenced by closed-ended question 1 in instrument 2. We found that by including 5 multidisciplinary capstone projects to ME seniors out of a total of 16 projects, most of the students were satisfied with the opportunity to participate in a multidisciplinary project, as seen in table 4, although 6 students (20%) who saw the importance of multidisciplinary projects reported that there were not enough opportunities, as seen in table 5. Interestingly, only 12% of students enrolled in the SMCC chose their capstone project based on their desire to be involved in a multidisciplinary project. Rather, students in the SMCC overwhelmingly chose projects because the project seemed interesting. Perhaps not surprisingly, 64% of students (15 students) enrolled in the SMCC strongly agreed with the statement represented in table 4 as compared to only 37% of students (26 students) not enrolled in the SMCC (enrolled only in the ME capstone course). Thus, students who are on a multidisciplinary team are more likely to value the skill of working on a multidisciplinary team.

The coupled course structure inherently maintains discipline specific rigor because the students are all enrolled in their respective departmental capstone course which requires adherence to the same course structure. For example, among other requirements, all mechanical engineering students enrolled in the departmental capstone course are required to create physical prototypes that are used to test hypotheses, they must demonstrate analytical modeling and they must submit appropriate engineering drawings. Each one of the ME capstone teams meets with an ME faculty advisor once per week to tackle the mechanical engineering problems within the multidisciplinary project. The same is true for the EE and CE teams. All projects are hand-picked by the instructors to ensure challenging design for all participating departments. For example, the Hyperloop project, which may seem to be dominated by mechanical engineering problems challenged computer engineers to develop custom algorithms and printed circuit board systems for telemetry and control. The EE Hyperloop sub team developed the power electronics, selected batteries and worked on the electromagnetic levitation system.

We found it highly interesting that the multidisciplinary presentations scored at the extremes of all ME capstone projects. The Hyperloop Pod team was a group of students selected from a high number of interested students over the summer before the school year started. Once the project was announced in the summer, an email was sent to all senior ME students. 27 responded with a desire for the project. The faculty involved with the project decided to limit the number of students to 10 ME students (2 groups of 5), one group of EE students and one group of CE students for a total of 20 students. To determine the members of the ME team, students were instructed to independently form teams of five and to email their instructor with a proposal indicating their desired sub-team and why their team should be chosen. Based on the essays, teams were officially selected. These students were able to work on their project during the very first week of classes while their classmates were still choosing projects and forming teams. This meant that the Hyperloop team had a head-start of a two weeks over the other teams.

The other three multidisciplinary teams chose and were assigned to projects by end of the first week of classes. They subsequently scheduled meetings with their industry sponsors which took place in the second or early third week of the course. This left only approximately 7 weeks before their final quarter presentation.

Aside from the amount of working time, as instructors, we found that the Hyperloop Pod competition had clearly defined competition specifications which served as the only voice for direction. This kept all faculty advisors and students in constant understanding of the end-goal. The other three teams dealt with many different voices defining the project goals which caused confusion. The industry sponsored projects had an ME faculty advisor, and EE advisor, a CE instructor (in one case as seen in table 2), as well as the sponsoring company (which sometimes included multiple mentors). All mentors (faculty and industry) expected the teams to take the lead and to use the mentors as guides. What actually resulted were teams looking to mentors for direction which led to an ill-defined project. After the final quarter presentations, a meeting was scheduled with the full group of mentors for projects 3 and 4. The result of the meeting showed that there was a difference in opinion of the mentors regarding the goals of the students' projects. For example, in one instance, the industry partner was looking for a technological proof (a conceptual prototype) but students were being directed by faculty to focus on a finished product with heavy emphasis on the end user. In this case, mentors experienced the same communication problem that typically plagues students working on large scale multidisciplinary projects. A key learning from this experience for the faculty was the absolute importance of regular meetings between all advising stakeholders to form a unified vision of the project.

A guiding principle of systems engineering is finding order in complex systems by breaking the problem into manageable chunks. The Hyperloop team succeeded because the students took a leadership role in defining the chunks and communicating them successfully. They formed interdisciplinary sub-teams directed at the chunks. In the case of teams 2, 3 and 4, however, students were not proactive in defining their project, rather reactive to the different thoughts of the different mentors. As instructors, we must find a way to lead teams to the interdisciplinary "chunking" approach.

The final complicating factor for the ME teams within multidisciplinary teams 2, 3 and 4 was the nature of the project. All three projects were heavily based on electronic and computer systems. The ME tasks were to design enclosures. The main ME challenges were heat dissipation and shock-proofing for falls. It is the author's opinion that these tasks were harder for students to grasp as compared with other ME capstone projects that were based on machine or quadcopter design, something students are typically used to seeing in a design course.

To remind the reader, the analysis done in this paper was completed in the first quarter of the three quarter project. In the second quarter, the Hyperloop project held the number one ranking of all ME projects, however the industry sponsored teams moved from the last three slots to the 3^{rd}, 10^{th} and 12^{th} rankings of 16 total projects, indicating that perhaps the slow start is not indicative of a weak finish.

Conclusion

The SMCC is a good way to begin multidisciplinary projects for engineering schools that do not yet have a multidisciplinary capstone stand-alone course, taking advantage of the departmental-based capstone infrastructure. The SMCC structure has the advantage of maintaining all learning objectives of the individual departments while solving the logistics problem of assembling all students. The drawbacks include the distributed network of advisors that may give the teams mixed signals. To address this problem, project ownership and systems thinking must be stressed in class such that students are proactive and not reactive to mentors. Finally, we learned the importance of increased communications not only between the students but also between faculty and industry mentors.

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Appendix A

Class #	Day	Date	Lecture topic
1	W	10/7	Intro to the syllabus and team meetings
2	W	10/14	Team meetings - Discuss Sponsors and resources
3	W	10/21	10 minute in-class presentations on project plan and design specs / Team meetings
4	W	10/28	10 minute in-class presentations on project plan and design specs, begin seeking presentation times with all parties / Team meetings
5	W	11/4	Team meetings - Schedule a Final Presentation Date and time with your advising team and Sponsors
	W	11/11	*NO CLASS - Veterans Day*
6	W	11/18	Team meetings
7	W	11/25	Team meetings
	W	12/2	*NO CLASS*
	TBD	11/30-12/4	Final Presentation (15 min * number of sub-teams)

Appendix B: Presentation Rubric given to each evaluator

Criteria *Qualities outlined in this column describe an "Excellent" team*	**Rating**				
Defining and understanding the problem: Team has a clear and insightful understanding of the problem with consideration of relevant contextual factors (e.g., customer's requirements, other patents/products, resources, etc.)	Excellent	Very good	Good	Fair	Poor
Identifying potential solutions: Team has proposed reasonable, well thought out solutions for solving the problem within the established context (e.g., customer's requirements, other patents/products, resources, etc.)	Excellent	Very good	Good	Fair	Poor
Evaluating candidate solutions: Team has completed insightful and thorough evaluation (e.g., modeling, testing, prototyping, etc.) of candidate solutions	Excellent	Very good	Good	Fair	Poor
Planning: Team has identified a candidate design (or a few) to pursue and has a solid plan for completing the work ahead	Excellent	Very good	Good	Fair	Poor
***Communication*:** Team communicates all of the above in a clear and effective manner	Excellent	Very good	Good	Fair	Poor