Implementing an Effective Large-Enrollment Engineering Capstone Design-and-Build Program

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Abstract

To advance a culture emphasizing hands-on design-and-build experiences, the Mechanical & Aerospace Engineering (MAE) Department at the University of Florida (UF) added starting in Spring 2020 a mandatory second semester course to its existing one-semester capstone design requirement. Previously an elective, the newly required second capstone course challenges students to realize a functional prototype based on the paper design they complete in the first semester of capstone. Given the Department's enrollment of over 1,800 mechanical engineering undergraduates, this curriculum change necessitates shepherding over 150 seniors per semester through the capstone program to prevent a graduation bottleneck.

According to a 2019 review article by Howe and Goldberg, only 12 ABET accredited engineering programs reported managing capstone enrollments of over 100 students per semester, and only 2 reported exceeding 200. Therefore, by adding the required realization course to its capstone sequence, UF's MAE Department accepted the unique challenge of delivering a realistic design-and-build experience to a student cohort distinctively larger than most other US engineering capstone programs. This paper reports some unique solutions being implemented to effectively deliver this program with semester enrollments exceeding 150.

Keywords

Capstone Design, Large Enrollment, Design Realization, Course-Wide Project, MEchanical engineeRing desiGn pEdagogy (MERGE)

Introduction

To further emphasize hands-on design-and-build experiences in response to graduate exit, alumni and employer feedback, the Mechanical & Aerospace Engineering (MAE) Department at the University of Florida (UF) added a mandatory second semester course to its existing one-semester capstone design requirement. The second capstone course, which became a graduation requirement in Spring 2020, challenges students to realize a functional prototype based on the paper design they complete in the first semester. The organization, structure, and progression through the newly required two-semester UF MAE capstone design program is shown graphically in Figure 1. Given the department's enrollment of over 1800 mechanical engineering undergraduates, this curriculum change necessitates shepherding over 150 seniors per semester through the realization phase of capstone.

To deliver a hands-on build phase for large capstone class sizes, several techniques, described herein, are being implemented including 1) assigning a single project each semester to the whole capstone cohort, 2) organizing student teams with complementary parallel management and topical structures, 3) implementing Product Data Management [PDM] for document control, and 4) handling complexity using enterprise project management software.

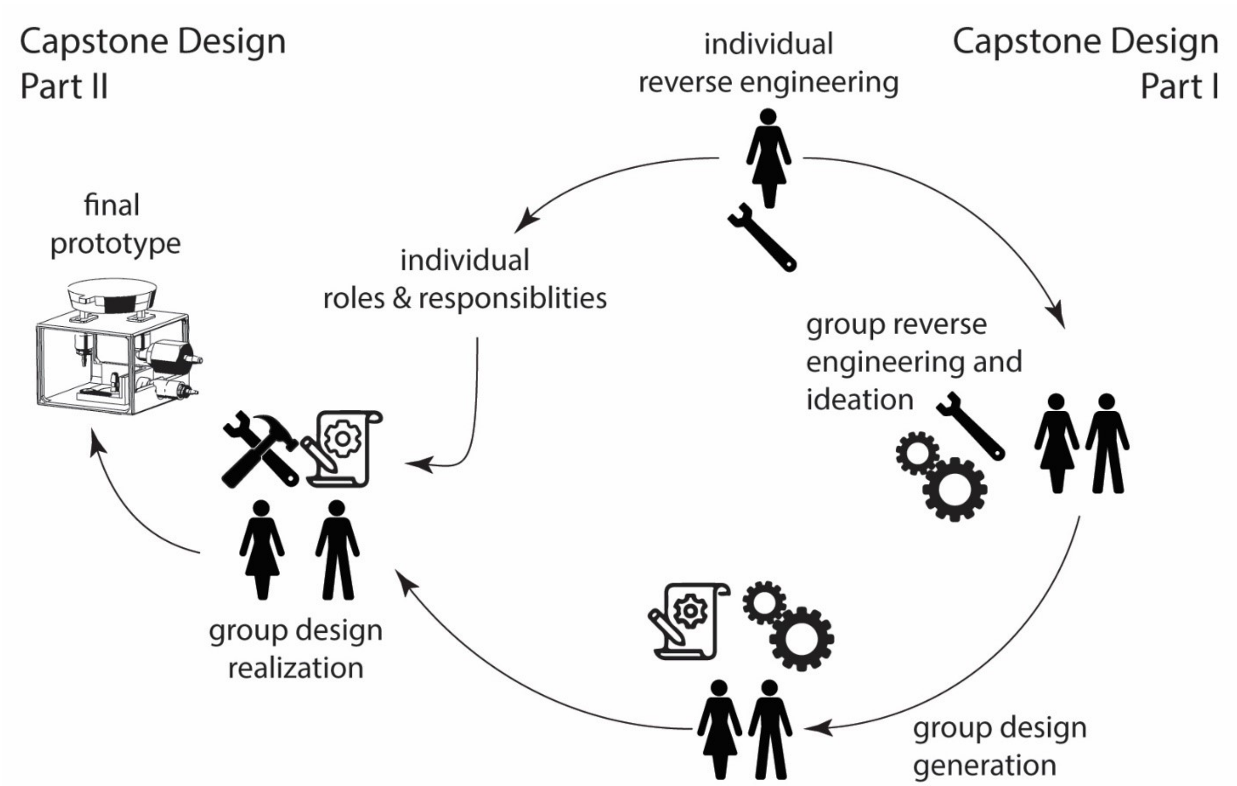

Figure 1: Schematic showing the organization, structure, and progression through the two-semester capstone design program in the MAE Department at UF.

Background

A nationwide US survey focused on engineering capstone practices and trends has been administered about every ten years, first by Todd et al in 1994[1], then by Howe in 2005[2], and most recently in 2015 by Howe and Goldberg[3]. The 2015 survey received 449 responses, and in 2015 there were 2542 ABET-accredited programs with the term "engineer" or "engineering" in the title[4]. ABET General Criterion 5 stated in 2015 that "Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints"[5]. We infer, therefore, that to be accredited all 2542 listed programs had some type of capstone program in 2015 when the Howe and Goldberg survey circulated. So, while the survey 1) only directly probed 17.7% of all ABET accredited capstone programs in 2015 and 2) represented a self-selected sample of programs choosing to respond, it is the most comprehensive representation available from which to draw conclusions about uniqueness of program features and attributes.

While each engineering capstone program structure is unique, most programs with build components organize teams around a faculty mentor who advises a group of 3 to 7 students[6]. These teams design, build, and test a functional prototype defined through a set of Customer

Needs. In some cases, the team's faculty mentor also teaches formal design lectures, in other cases lectures are given by a separate instructor, and in yet other cases, there are no formal lectures. Nonetheless, in the authors' experience with capstone at multiple different institutions[7-12] and from informal surveying of peer schools, few (if any) programs other than UF MAE deviate from the standard capstone model: individual student teams work simultaneously and independently on different design projects, and each team is assigned a dedicated faculty mentor.

According to the 2015 Howe and Goldberg survey results, only 12 ABET-accredited engineering programs reported managing capstone enrollments of over 100 students per semester, and only 2 reported exceeding 200. Therefore, by adding a required realization course to the capstone sequence, UF's MAE Department accepted the unique challenge of delivering a design-and-build experience to student cohorts distinctively larger than most other US engineering capstone programs manage.

Methods

Students enrolled in the build phase of the UF MAE Department capstone program are generally placed into class sections not exceeding 49 students. This unusual classroom size cap is motivated by two underpinning factors. First, UF is spearheading a campus-wide effort to offer more and smaller class sizes (less than 50) to better serve students[13]. Second, each 49-student section is split into two teams of about 24-25 members, and each team is responsible for building its own functional prototype. Each team of 24-25 is then further broken into four groups of about 6 members, and each group is responsible for the detailed design and fabrication of a sub-system of the overall assembly. Systems to be built are based on selected paper designs completed in the previous capstone sequence semester. One instructor is assigned three classes of ~49 students, and managing three such classes (six projects) is considered a full semester teaching load.

To effectively deliver a capstone design program in the UF MAE Department with average semester enrollments exceeding 150, the following solutions are being implemented and assessed.

1) Assigning a single project per semester to the whole capstone cohort

According to Howe and Goldberg, "finding capstone design projects is an ongoing task, and can often be a time-consuming challenge for capstone design instructors." Anecdotal experience confirms that substantial instructor effort is needed to find projects with the proper combination of attributes (technical rigor, open-endedness, low cost to implement, safety, duration of time to complete, and interest from students)[14,15]. Indeed, the literature confirms that design problems beyond the scope of students' experience tend to strengthen expressions of non-engineering skills to the detriment of weakening expression of engineering skills among engineering students on interdisciplinary design teams[15]. Thus, selecting the "right" project is critical to success of the students and the capstone course. Even with relatively large teams of about 24 students per project, developing and maintaining an ample project reservoir for 150 students would require faculty to be continuously identifying and securing at least 6 suitable projects per semester. We believe there is limited pedagogical benefit in faculty finding and managing multiple different capstone projects per semester because requiring faculty to simultaneously juggle multiple projects will inevitably be detrimental to instructor efficacy.

On the contrary, there are numerous benefits to having every capstone team working simultaneously on the same project each semester. Not only are faculty freed from vetting and bringing to realization many possible projects, but running the same project across sections allows faculty (from their vantage point over 6 simultaneous and similar projects) to develop deep expertise in a single design problem with most of the research and discovery processes done by students themselves. Faculty can port or adapt unique analyses or solutions developed by one group to other groups, saving hours that might have been spent exploring or researching solutions to one isolated group's technical problems. Moreover, issues of fairness in project selection assignments disappear since students no longer have concerns stemming from not being selected for the capstone project they wanted. Additionally, because everyone has the same project, complaints related to unfair selection or one project being far easier or harder than others are nonexistent. Initial concerns that multiple teams working on the same project would copy each other's concepts to avoid the difficulties of creative ideation proved unfounded. Anecdotally, good and creative design ideas originating in one group did propagate to other groups. However, verbatim adoption by one group of another group's ideas was not observed. By contrast, when incorporating design ideas developed by other teams, groups were observed making improvements to the originals or incorporating them into designs in different ways. When it comes to borrowing others' ideas, student teams were observed to be intellectually honest and to police themselves.

Prior to the beginning of each semester the capstone design course sequence begins, a committee of faculty who generally teach design select the project to pursue that semester. Candidate projects are drawn from faculty ideas, needs for specialized equipment in the department's research labs, collaborators within the university, and outside organizations with expressed needs and interest in cooperating. Once the single design project is selected, the lead capstone instructor that semester works with the customer to develop a set of Customer Needs. This Needs Statement is fed into the capstone realization perquisite course, represented in Figure 1, which is focused on developing a paper design. Selected paper designs are then refined and built in the realization capstone course. Since all student teams work on the same project idea, this approach produces multiple unique functional prototypes that all address he same set of Customer Needs. This outcome has both pedagogical advantages and benefits in attracting customers to our program. In a conventional capstone course with multiple different projects, it is difficult to build learning outcomes around the question "what would have been the outcome of a different design decision?" With the UF MAE approach, different design solutions addressing the same Customer Needs are available to motivate and facilitate this discussion. This critical lesson, which cannot be practically attained without simultaneous parallel projects, gives UF MAE students unique appreciation and professional preparation that early design decisions can massively influence outcomes. Having multiple different functional prototypes is also beneficial for program customers who can then choose from a range of viable prototype solutions which option to advance for manufacturing.

2) Organizing student teams with complementary parallel management and topical structures
A multi-faceted approach establishes at least two roles for each student in each project team. Prior to the course's beginning, students sign up for specific lab sections with 12 students per section. The labs meet for two hours once per week.

At the course outset, each student fills out a questionnaire evaluating their interests and confidence in the following key categories:

- **Product-Specific aspects** (product, user, scenario requirements; user interface, ergonomics, Human Factors; project management, project leadership, material acquisition)
- **Product Development** (safety codes, operator use; design for manual assembly; material selection; tolerancing; product costing)
- **Engineering Design** (mechanism, statics, kinematics, dynamics; thermal, fluids; structural, vibrations; controls, electronics, software)
- **Creative** (CAD; technical writing; graphics, art; Intellectual Property)
- **Implementation** (simulation; design for manufacture; prototyping, testing)

Since students sign up for specific 12-student lab sections, each lab section hosts two 6-member sub-system design groups. These sub-system design groups are responsible for identical or similar sub-systems for two different functional prototype builds. The sub-systems functional requirements are selected to promote the cross-lab communication required for successful outcome of the project. In other words, each member of a sub-team has a corresponding "liaison" in another sub-team during a different lab section. Instructors combine survey information and lab section enrollment when assigning "Responsible Engineers (RE)" to individual components or functional design requirements. Assignment to a specific part as its RE facilitates a sense of ownership and responsibility, solidifying the student's role on their product development team.

3) Implementing Product Data Management (PDM) for design document control
PDM software is utilized in many engineering companies to review and drive product design changes. PDM centrally captures and stores all revisions to parts and assemblies through a controlled "check-in/check-out" process. Integration of enterprise-level PDM software in an academic setting lets faculty manage process flow toward meeting course objectives, particularly when the course is structured to mimic industry style product development groups. PDM has been shown to be successful when used for engineering design competition teams[17]. However, to our knowledge, it has never been used for purely instructional capstone design purposes outside the UF MAE Department.

For large enrollment capstone courses, PDM offers a method to effectively engage all students in the class by assigning each student as an RE to specific parts. PDM also helps an instructor manage large design courses by establishing part checkpoints. For example, PDM process controls allow the instructor to force revisions of poor design and to prevent unfinished components from being released for fabrication. A more complete description of PDM implementation in UF's MAE capstone course sequence is given in a companion paper[18].

4) Handling complexity using enterprise project management software
During the previous Spring 2019 semester, Slack (a chat-based project team communication software) was deployed in UF's MAE capstone program to encourage frequent communication and collaboration among students. While Slack itself was useful for this communication function, it proved a poor stand-in for purpose-built project management tools. To be useful for capstone programs, a project management tool needs to answer thee fundamental questions: 1) What is the task? 2) Who is doing the task? 3) When will the task be finished?

Starting in Fall 2019, Trello was selected as the project management tool for UF's MAE capstone program. Trello uses a Kanban-style card system with flexible data format. Users can create cards with 1) Task Names, 2) Assigned Individuals, 3) Due Dates, 4) Comments, 5) Photos, and 6) Files. With Trello plugins, additional data are viewable in a calendar format for students. The Slack+Trello combination was introduced for communication and project management, but students struggled to know when to use which tool. There were suddenly too many collaboration pathways tied to the class: Canvas LMS, Trello, Slack, and Solidworks PDM. In addition, students were using Google Docs to collaborate in real-time on Microsoft (MS) Word, PowerPoint, and Excel editing. This observation suggested using an MS tool for student communication, collaboration, and project management.

MS Teams was selected and implemented, allowing functions of 5 collaboration tools to be consolidated to 2 (MS Teams and Solidworks PDM). MS Teams has capabilities including chat, Kanban card style project management, Canvas scoring/grading, and real-time editing of MS documents such as Word and PowerPoint. MS Teams can either be launched from the desktop as a local application or from the Cloud, making it computer platform independent.

While using best-in-class software for each specific task allowed for the most flexible workflow customization, consolidating down to a "single-source-of-truth" for collaboration reduced cognitive load borne by students working in collaboration and faculty managing the project overall. Moreover, the reduced number of tools students must learn and use enables faculty to more rapidly onboard students into being productive on their subsystem teams and committees.

Discussion

There are four major costs paid by a program running engineering capstone realization courses: 1) overhead, 2) consumables, 3) personnel, and 4) faculty. While the total cost for all four categories generally increases with the number of students a program serves, the cost-per-student generally decreases as enrolment goes up. Overhead includes fixed costs of facilities and infrastructure; these investments must be made whether a capstone teaching space is fully and continuously occupied or not. So, overhead cost-per-student tends to decrease as capstone enrollment goes up because facilities become more fully utilized by more students. Consumables refer to raw materials and tools students use to build their designs. The cost-per-student for consumables stays the same as capstone programs expand. Personnel costs include lab technicians, teaching assistants, and academic counselors who support students. Efficiencies of scale drive personnel cost-per-student down as programs grow. Therefore, larger capstone programs serving more students typically enjoy lower cost-per-student for these three associated costs, and the UF MAE capstone program enjoys the per-student cost benefit of being a large program. In addition, however, the factor differentiating cost-per-student for the UF MAE capstone program versus peers is the relatively low faculty teaching load assigned for capstone. This lower load is not realized by overcommitting faculty, nor is it facilitated by reducing the quality of projects students build. The lower teaching load is realized by the novel techniques and course organization described in this paper.

Certainly, all capstone programs are structured differently. To provide a generic point of comparison, however, a hypothetical capstone program can be generated based on characterizations by Howe[19] of the most typical capstone program organization. In this hypothetical generic capstone program, students are organized into project teams of 5 individuals, and each team is guided by a unique faculty mentor. Owing to inefficiencies including 1) time needed to identify and vet multiple appropriate projects, 2) researching solutions to individual team technical challenges, and 3) manual or analog document control among others, it was assumed that mentoring three such teams is equivalent to teaching a full course. So, mentoring 9 individual capstone projects in a Fall or Spring semester under the conventional capstone organizational paradigm equals a full teaching load for one faculty member. As a point of comparison to vet these numbers, the Electrical Engineering Department at the Milwaukee School Of Engineering reported limiting individual faculty members to mentoring no more than 7 simultaneous capstone teams. Each team had 3 or 4 student members, and a total cohort of no more than 70 seniors was managed by 3 faculty members in a given academic quarter.[20]

Under the hypothetical generic capstone program described, supporting 350 students per year in teams of 5 yields about 70 individual projects and requires about 7.77 full time instructor assignments. By contrast, the UF MAE capstone program requires 1 full time instructor in Fall and in Spring and 0.5 in Summer; a total of 2.5 full time instructor assignments to support the same number of students. Importantly, the efficiency improving and time saving innovations described here for the UF MAE capstone program realization course can also be implemented at schools with lower capstone enrollments while still allowing them to save costs by reducing the faculty workload devoted to capstone.

The UF's MAE Department also made an intentional strategic decision to keep the design realization capstone course student outcome assessment separate from the ME B.S. program's ABET Criterion 3 self-assessment. Instead, all the outcomes normally assessed in the final capstone course are lumped into the first semester of the capstone sequence, the paper design phase. This choice allows the capstone realization course to remain flexible as the program evolves into its final sustainable form.

Conclusion

The newly required second capstone course in UF's MAE Department challenges students to realize a functional prototype based on the paper design they complete in the first semester of capstone. Given the MAE Department's enrollment of over 1800 mechanical engineering undergraduates, this curriculum change necessitates shepherding over 150 seniors per semester through the capstone program to prevent a graduation bottleneck. Since only a handful of existing capstone realization programs contend with semester enrollments of this magnitude, making realization a graduation requirement presents a unique set of challenges. This paper describes pedagogical innovations being implemented to manage large enrollment capstone design courses including 1) assigning a single project per semester to the Capstone cohort, 2) organizing student teams with complementary parallel management and topical structures, 3) implementing Product Data Management [PDM] for document control, and 4) managing complexity using enterprise human resource and project curation software.

Efficiencies of scale make capstone realization courses with larger enrollment more cost-efficient on a per-student basis than smaller programs. Moreover, our techniques to reduce capstone instructional load allows UF to more effectively and cost-effectively manage large capstone classes while continuing to produce quality project outcomes.

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Biographical Information

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