FROM MECHANICAL ENGINEERING CAPSTONE DESIGN TO DESIGN IMPLEMENTATION

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***Abstract** –Traditionally, mechanical engineering capstone courses focused on teaching students the application of fundamental engineering theory to complex mechanical designs. Recently, there has been a transition towards experiential learning initiatives, such as prototyping, in engineering design. This paper looks at the relationship between the mechanical engineering design capstone course and a course in product design and development, which provides students with the opportunity to build prototypes of their designs, at the University of Ottawa. The importance of the traditional capstone course is considered and the implications of implementing these designs are examined. Many capstone design projects would require extensive work so that they could be implemented. A large hurdle appears to exist between analytical design and design implementation, and the term time constraints limit the complexity of designs intended for prototyping. In fact, students require many design iterations before they can build full-scale functional prototypes of their design. Therefore, we have observed that simple products work best for teaching design implementation.*

Keywords: Mechanical Engineering, Capstone Design, Product Design, Design Implementation, Prototyping.

1. INTRODUCTION

For nearly 10 years, the CEAB has explicitly stated that, “The engineering curriculum must culminate in a significant design experience conducted under the professional responsibility of faculty licensed to practice engineering in Canada, preferably in the jurisdiction in which the institution is located” [13]. Section 3.4.4.4 further states that “The significant design experience is based on the knowledge and skills acquired in earlier work and it preferably gives students an involvement in team work and project management” [13].

To this day, the Capstone Project course in the Department of Mechanical Engineering at the University of Ottawa fulfils these requirements. However, engineering designers have progressively divorced themselves from implementation and use of their design. Miscommunication between these vital components of design is increasingly leading to disastrous, costly, or embarrassing consequences [3]. The main reason for this are increasing costs associated with experiential learning opportunities, as well as a significant increase in design complexities. For this reason, engineers have become specialists, focused on very specific disciplines. Moreover, employers increasingly value experiential learning and hands on skills in new graduates, as they are slowly discovering the value of these skills for engineers entering the workforce. Several programs, such as the CUSP group at Carleton University have integrated design and fabrication into their capstone courses [4]. The project, centered on the design of novel simulator systems, is led by a multi-disciplinary team of lead engineers and is composed of roughly 30 students from the Department of Mechanical and Aerospace Engineering and the Department of Systems and Computer Engineering. The project is, by nature, highly complex has spanned over 10 years so far. As a consequence, individual students contribute only incrementally to the development of the systems and most students do not see the final product at the end of their program.

Many institutions are now trying to re-balance theoretical and practical engineering skills in order to produce better engineers. The following paper outlines the new framework available in the Department of Mechanical Engineering at the University of Ottawa which allows students to implement capstone design projects over a single year with limited resources and a small number of advisors.

2. COURSE STRUCTURES

The compulsory Capstone Project course and the optional Product Design course of the Department of Mechanical Engineering are single term courses offered to students in their final year, the former given in the fall term and equivalent six credits or two courses and the later given in the winter term and equivalent to a single course.

2.2. Mechanical Engineering Capstone Course

The mechanical engineering capstone course seeks to teach how to make and document design decisions while working in a group environment under a tight deadline. Overall, the students are evaluated on the following six skills: design, investigation, analysis, programming, reporting, and team work.

Table 1: Capstone Project attributes and deliverables.

Week	Deliverables	Attributes
2	Literature Review Report	Investigation
4	Design Report	Design, use of engineering tools, impact on society and the environment, economics and project management
8	Analysis Report	Knowledge base for engineering, investigation, problem analysis, professionalism, impact on society and the environment
End of term	Capstone Report and Presentation	Communication, lifelong learning, individual and team work, professionalism, economics and project management

An aggressive start by the course advisors has been effective in developing and maturing large multi-disciplinary projects involving multiple departments [10]. This ideology is valid for any open-ended design project, as engaging the students early in the term sets the expected pace of work. This is most important in a one-term two-credit capstone project course as all activities must be accomplished within twelve weeks.

The capstone course has four primary report-based deliverables, which are linked to the activities undertaken during the term and the CEAB attributes, as described in Table 1. Of the attributes listed by CEAB, only the Ethics and Equity are not consistently evaluated in this course.

The Literature Review report introduces students to the concept of surveying existing literature, both scientific and market-driven. With the exception of students taking the Undergraduate Thesis option, this is the first occasion for students to survey the literature, outside the recommended reading, and prepare a detailed and professional document. In addition, the report structure mirrors, to a certain extent, the thesis model and thus, has the additional benefit of preparing students for graduate studies.

This is followed by two working documents: the Design and Analysis Report. The Design Report includes preliminary sketches and detailed hand drawings of proposed solutions. The technical feasibility of the design is then evaluated by the staff and meetings are held to address design issues and suggest improvements. Four weeks later, groups submit an Analysis Report that outlines the assumptions and approximations of the working environment, the customer requirements, and the relevant stress and geometric analysis to verify feasibility and soundness of the design. This work is once again reviewed by the staff before proceeding to the final stage of the course which includes CAD modelling, parameterization, and preparing the Capstone Report. Both the Design Report and the Analysis Report are reviewed, but unmarked and constitute summaries of the most-up-to-date group work developments. This generally follows the coaching model where the staff provides some content in the form of suggested modifications and asks questions and clarifications to encourage students to seek out knowledge [11].

Feedback appears to indicate that students prefer the one-term six-credit course over the possibility of having the capstone spread over two terms. Reasons cited by the students include: “more hours over a short time kept the project on my mind”, “allows to focus on final project without too many other distractions such as multiple courses”, and “tighter deadline is more useful to prepare for real life work deadlines”. Although the scope of the projects appears large for a twelve week period, similar programs such as those at Memorial University have been successful [7].

Capstone Projects

Students are offered pre-defined projects that can be classified into four broad categories:

1. Industry sponsored design problems;
2. Research-driven problems;
3. Design competitions;
4. Community driven ideas.

Due to time limitations imparted by a twelve week course and the limited staff, approximately five different projects are offered each year.

2.3. Product Design and Development Course

The product design and development course seeks to teach mechanical engineering students the product development process, while giving students the opportunity to build prototypes of their product designs.

This course was the first of its kind, in the department of mechanical engineering, to offer students the opportunity to design and build a product intended to go to market. The course is broadly based on the product design and development course offered by MIT [14]. As a project based course, students form groups of two to four students (groups of three seem to work best) and are given a budget for building prototypes of their product design (in 2015 and 2016 this budget was $350 per group). Students are then evaluated by gauging project progress through weekly deliverables, as described in Table 2.

Table 2: Product design course deliverables.

Week	Deliverables	Attributes
2	Market Opportunity	Problem analysis, investigation
4	Mission statements and customer needs	Problem analysis, investigation, impact of engineering on society and the environment ethics and equity
5	Target specifications and concept sketches	Problem analysis, design, lifelong learning
6	Concept selection, project schedule and proof-of-concept prototypes	Investigation, design, economics and project management
8	Engineering drawings and calculations	Knowledge base for engineering, design, use of engineering tools
9	Bill of materials, make or buy, revised schedule	Design, economics and project management
11	Financial model	Economics and project management
End of term	Alpha prototypes, final design reports and presentations	Knowledge base for engineering, communication skills, professionalism

Weekly deliverables have been found to significantly increase the student's chance of building successful prototypes by the end of the term, as it helps provide the intended pace for the course. Furthermore, weekly reports/presentations provide a unique opportunity to stress key attributes that are often overlooked. These include, individual and team work, communication skills and professionalism. It also allows course instructors to gauge student progress on their product design and development process. This has been noted by a number of other experiential course instructors [1], [5], [8], [12].

Fundamentally, the product design course represents a design course for students in their final year of mechanical engineering studies. Therefore, students are expected to design their products using solid engineering analysis knowledge they have gained over the course of their degree and which they practiced during the capstone course. Since students are expected to both design and build their products during the one term course, recommended projects tend to be relatively simple. The following guidelines are provided for the projects:

- There should be a demonstrable market for the product, but does not have to have a tremendous economic potential;
- The product should be a material good and not a service;
- The product should likely contain less than 20 unique parts;
- The product should be able to be prototyped for less than $350;
- The product should not require any technological breakthroughs;
- Students should have access to at least 5 potential lead users for the product.

In order to ensure that students have the adequate manufacturing skills required to build alpha prototypes, students are given weekly workshops on various manufacturing techniques. These include:

- Basic machine shop procedures and safety;
- Hand tools, band saw and drill press;
- Sheet metal working;
- Mill and lathe;
- Welding;
- 3D printing and laser cutting.

Furthermore, some students are provided more advanced training, such as CNC machining or composite lay-up, depending on their specific projects.

Feedback provided for this course over the years has been consistently positive with respect to the students learning outcome. Students really enjoy applying their theoretical knowledge in developing physical items. They also learn to appreciate the extra design work it takes to go from a CAD design to a manufactured prototype.

Product Design Projects

Due to time limitations imparted by a twelve week course, products typically developed in the product design course are generally simple consumer products which contain less than 20 unique parts. This is based on our observation that designs with fewer parts ultimately result in better quality prototypes and better overall learning outcomes for the students. Usually, these products represent an improvement or a combination of existing products, but in some cases students develop unique products. Past products of interest have included a garbage can which can be lifted pneumatically, a camera stand/walking stick combo, a can crusher, a vertical garden system, a microscope for smartphone cameras, a restaurant utensil roller, a ski grinder and many more.

A particular successful product which has resulted from this course is the Spivo Stick [15], a selfie stick capable of rotating a go-pro camera from the front-facing to the rear-facing positions. Particularly popular with the extreme sports enthusiasts.

3. PROJECT SPANNING BOTH COURSES

In 2015, student groups who selected the industry sponsored or research-driven design projects in the Capstone Project course were offered the possibility of pursuing the fabrication of their design in the Product Design course the following term. Of the 21 groups, six groups were eligible for this trial and two groups carried out the fabrication of their designs.

These two groups carried out the research-driven design problems, the purpose of which was to develop a scaled-up version of the unmanned airship prototype shown in Fig. 1. The proof-of-concept prototype was capable of carrying up to 0.1g of payload or ballast.

Fig. 1. Proof-of-concept prototype presented to students at the onset of the Capstone project course [6].

The proposed problem was to scale the design to 1kg of payload and generate a solution capable of sustaining unmanned outdoor missions. In the Capstone Project course, each design team was composed of a single group of three to four students and each group had to address the entire design of the platform. The solutions proposed by each groups are shown in Fig. 2.

Because of the product design course structure, a reasonable method for accommodating both design groups within the context and timeframe of the course needed to be considered. Also, the envisioned design contained a very large number of unique parts. Therefore, both design groups were combined to form a single airship design team. It was decided early on that one group would work on the airship's buoyancy structure and the other would work on the airship's propulsion. Furthermore, the groups also decided that rather than choosing a single capstone design to develop, they would work on combining and improving the best aspects of each design. It was clear from the outset that design iterations would be required in order to ensure that their concept could be manufactured. In fact, one particular member of the team estimated that only about 10% of the original capstone design could be directly attributed to their final prototype.

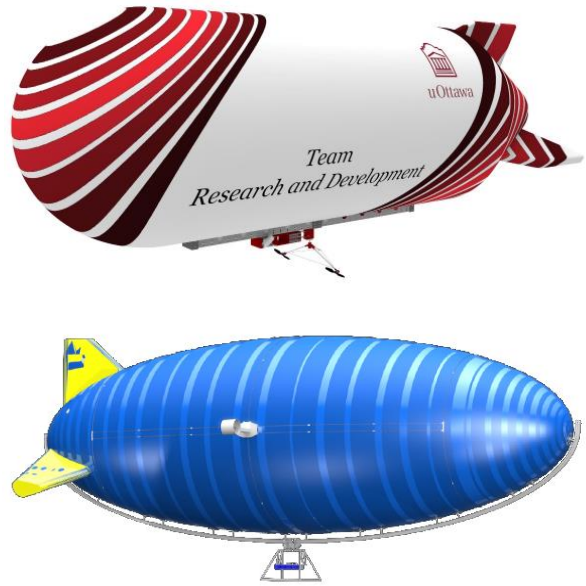

Fig. 2. Final designs submitted as part of the Capstone Project course.

Of course, the reasons for this magnitude of change in their designs can be explained by the expected outcome of each course. Whereas the focus of the Capstone Project course was to ensure a functional design which made use of fundamental engineering principals gained over the course of their degree. The focus of the Product Design course was to ensure design for manufacturability and assembly within the budgetary, time and resource constraints provided.

Ultimately, the students proved successful in prototyping a functional airship which satisfied the design objectives. The completed airship is shown in Fig. 3 below the original vehicle. The completed prototype resulting from this exercises demonstrated the feasibility of the design. However, having been fabricated over the course of approximately one month, the prototype did exhibit numerous small assembly, payload management, electronic, and sealing issues that would need to be resolved before non-tethered flight tests could be performed. It is clear from this trial that one term would not have been enough for a single capstone team to have successfully manufactured and prototyped an entire airship. But by breaking the task down into simpler modules, each team could meet all their targets within the constraints mentioned earlier. Undoubtedly, more groups and advisers would have been required to tackle large multidisciplinary projects. It is also important to note that this project, while relatively complex compared to typical Product Design projects, remained manageable and allowed sub-groups to interface on a regular basis. Otherwise, it is clear that a successful and complete prototype would not have been achieved by the end of the term. Nonetheless, students noted increased enthusiasm, motivation, and skills when given the opportunity to work on innovative research problems.

Fig. 3. Prototype produced by students as part of the Product Design course.

4. DISCUSSION

Providing students the opportunity to prototype their capstone course designs is still in its infancy in the Faculty of Mechanical Engineering at the University of Ottawa. However, it is clear that students appreciate the ability to do so. In fact, many students have mentioned that prior to having actually implemented their designs, they didn't realize how much more needed to be considered. Key aspects that are difficult to grasp without creating a physical prototype include:

- Design for manufacturing;
- Design for assembly;
- Product-user interaction;
- Financial, physical and time constraints.

Of course, many of the empathetic design aspects such as aesthetics and ergonomics, which are so easily overlooked by engineers, are harder to avoid when creating physical prototypes. Although, this appears to be a step in the right direction, many challenges still remain.

4.1 Capstone Challenges

Providing a broad base of projects which are of interest to all students, remains extremely challenging and requires an immense amount of preparation. Naturally, having a single faculty supervisor is often not ideal since design projects often require knowledge and skills from a variety of technical areas [9]. It is therefore necessary to rely heavily on graduate students, technicians, and other faculty members to support and interact with students. Also, many of the technical challenges associated with fabrication are dismissed due, in part, to the lack of practical experience of the students and the high level of staff support required.

4.2 Product Design Challenges

Providing physical and financial resources which allow a large number of students to create complex prototypes remains a significant challenge. Time constraints provided by a single term course also impacts the possible complexity of prototypes. Experience so far has dictated that two physical prototypes are reasonable over this time period. One proof-of-concept and one alpha prototype. Not surprisingly, students go through many design iterations using prototype simulations (CAD). This in itself has presented challenges to students who enter the course unprepared for such a number of re-designs, having not had much experience with the iterative process inherent in real-world design.

4.3 Global Challenges

The University of Ottawa COOP program provides students with the opportunity to work as engineering interns in industry every second term, starting in the summer after having completed their second year of studies. This creates a group of students which are out of sync with those following the normal academic path, taking courses in consecutive fall and winter terms. This creates a difficult problem of course continuity for upper year courses and has been the motivation for having a single-term capstone project course in the past. Under this new framework, normal path students would see the Capstone Project course first, whereas COOP students would see the Product Design course first. A similar situation occurs for double major students. As of yet, no solution has been found for this paradox.

Creating project space for fabricating prototypes has, in the past, been possible due to a low enrollment limit, minimal student shop facilities and a limited number of shop technicians willing to invest in student education. Scaling the product design course has proven difficult due to the apparent exponential increase in resource demands. Furthermore, since most students enter the course without any formal machine shop training or experience, training must be scheduled early in the term if time is to remain to work on their prototypes. As the number of students requiring training increases, so do the number of man-hours.

The advent of accessible 3D printing, CNC carving and laser cutting technology has lessened the burden placed on traditional manufacturing facilities, as these fabrication methods are less resource intensive and typically require less training and safety precautions. This has been noted by other researchers [2]. In addition to this, the University of Ottawa has been awarded an NSERC Design Chair, which significantly helps with the development of experiential training facilities. Nonetheless, laboratory and project work space remains the limiting constraint in providing an experiential design experience to students.

Historically, prototypes have been primarily funded by internal funding sources and have placed a burden on already tight budgets. However, physical prototypes created by students have proven useful for creating external interest with both government agencies and private industry. Specifically, it has been found that government grants dedicated to training students and developing design initiatives can be leveraged to attract private funding in an easier manner when experiential learning opportunities are on the table.

Finally, tradition has usually dictated one course, one instructor. Unfortunately, this mentality does not lend itself well to complex multidisciplinary and diverse design projects involving some form of fabrication or prototyping procedure. Rather, these courses require a larger number of instructors and advisors spanning a broad range of engineering (and possibly non-engineering) knowledge, as well a group of technicians versed in a broad range of design and fabrication techniques. With this new framework, a minimum of two full time Faculty members are involved. However, a shift in course load distribution and organization would be required in order to satisfy these new and increasing trends.

5. CONCLUSIONS

The development of the new framework for implementing capstone design projects is still in its infancy in the Department of Mechanical Engineering at the University of Ottawa, but has proven successful with the design and fabrication of an unmanned airship. Although this project had complex design requirements, breaking the project down into modular sections and splitting up the manufacturing tasks to a number of sub-groups has shown a viable path in allowing students to meet all their targets within the limited financial, time and physical resource requirements provided in the course.

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