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Design of a Junior-Level Design Class: Work in Progress

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Design of a Junior Level Design Class: Work-in-Progress

Abstract

In order to strengthen engineering students' preparation to tackle open-ended, multidisciplinary projects in their senior-level capstone course, a new junior-level design course was developed and implemented at Loyola University Maryland. Engineering faculty, students, and members of our industrial advisory board identified programming to drive and control hardware, as well as maker mechanical skills, as areas that needed to be bolstered. The new, team-based, project-oriented, semester-long course, which was taught for the first time in Fall 2022, consisted of two basic parts. In the first part, the students assembled a common electromechanical platform—an open-source replica of the Mars Perseverance rover—to enhance their build and troubleshooting skills. Once the rover was complete and operational, the second part of the course required that each team propose, design, construct, and test an electromechanical modification to the base rover. Learning modules that covered relevant technical and safety subjects were implemented early in the course. Periodic milestone reporting points (referred to here as *snapshots*) were also included that encouraged effective project management. Students were required to review each other's designs, and students in the follow-on capstone course also provided feedback to the teams as their designs progressed. In this work-in-progress paper, details about the course structure and materials are presented, learning assessment approaches are discussed, and preliminary assessment results from the initial offering are described.

Introduction and Motivation

Every ABET-accredited engineering program is required to include "a culminating major engineering design experience that 1) incorporates appropriate engineering standards and multiple constraints, and 2) is based on the knowledge and skills acquired in earlier course work." [1] This experience most often takes the form of a "capstone" course, often referred to informally as a program's "senior design" course. Adequate preparation in earlier classes is essential for student success in the capstone course, and various curricular approaches have been undertaken by engineering programs to strengthen this preparation as discussed in [2], [3], and [4].

As part of a process of curricular review and improvement, a group of faculty members in the Engineering Department at Loyola University Maryland was tasked with developing a required, semester-long junior design course. There was a general informal perception among department faculty that students entering the year-long senior design course sequence lacked certain desired skills, knowledge, and dispositions. This was coupled with feedback from the department's industrial advisory board (IAB) which regularly reviews students' senior design projects in the fall (mid-project) and spring (project conclusion). Also, a survey was conducted of recent alumni as to their experiences and confidence before and after the senior design course. These inputs to designing the junior-level course suggested that although students had exposure and experience with teamwork, oral and written communication, and a variety of so-called soft skills, they felt less confident in their ability to drive and control hardware using programing and in their maker mechanical skills. This was true regardless of their concentration in mechanical, materials, electrical, or computer engineering—the four concentrations offered for the Bachelor of Science in Engineering (BSE) degree at Loyola University Maryland. Although earlier coursework included active-learning activities in these areas, there was a need for improvement, and it was decided that a team-based, junior-level course which focused on strengthening these skills would be added to the curriculum. [Loyola University recently reduced the required number of "core" courses (similar to general education requirements) for all students, and the department also streamlined some mathematics and science requirements for engineering students, which made room for the addition.] This course would also afford the opportunity to reinforce aspects of the entire engineering design process. After considering various options, the group of faculty members settled on a basic course design comprised of two parts. The course would begin with the building of a common electromechanical platform. This would allow students in teams of four or five to level up (*i.e.*, improve) their build and troubleshooting confidence with both electrical and mechanical components and systems. Once the basic system platform was assembled and functional, each team would propose some addition or modification to the to the platform and would subsequently design, construct, and test that modification. The teams would learn to go through the design process with steps of problem definition, ideation, specification, prototyping, test and measurement, and process iteration. This would allow a multidisciplinary team of engineering undergraduates to have more experience of design with iterative steps than is possible in the collection of separate prerequisite courses. They would also be able to have more authentic experiences of project reporting with periodic reviews or quick poster *snapshots (*sessions where posters that reflect project status at key points are presented) as well as having to work with integration of hardware and software systems. All these elements are intended to better prepare students for the follow-on senior design (capstone) course, where the projects are more complex and more open-ended. Therefore, the longer-term research goal of this effort is to determine whether the activities and approach taken in this course lead to enhanced student performance in senior design.

The year-long senior design sequence is the key way we introduce students to the experience of complex and ill-defined design problems, the very things that employers consistently are looking for [5]. However, students could use a bridge or scaffold between their more prescriptive and closed analytic courses and the different experience and skills of problem-based learning approaches. Knowledge and comfort with the design process is itself a process, from novice to expert, that involves students developing their own understanding of the relations among courses and their learning goals [6]. One should not expect the comfort and depth of understanding that may be necessary for success in senior design without more prior exposure. Finally, it has been reported that involvement in makerspaces, whether in a voluntary or class required setting significantly helped students' motivation and confidence (engineering design self-efficacy scores) [7]. This course was therefore intended to provide increased exposure to a variety of maker skills with an anticipated boost in self-efficacy leading to greater success in their formation as engineers.

Additional pedagogical foundation for this approach is to be found. There is experience with the positive results from robotics competitions across many ages and formats. For example, the

Trinity College Fire-Fighting Home Robot Contest promotes skills of design, integration, and implementation in the context of an autonomous robot competition [8]. Even without the competitive element, robotics is a well-regarded platform for multidisciplinary and multiskilled activity.

The junior-level design course was taught for the first time during the Fall 2022 semester. In sections that follow, details of the course structure and materials are presented, learning assessment approaches are discussed, and preliminary assessment results from the initial offering are described. As a work-in-progress, a more detailed and comprehensive evaluation will take place at the end of the 2022-2023 academic year (after the course has been taught twice).

Course Description

The catalogue description for this new course is given below.

> **EG 397 - Engineering Design Fundamentals** (3.00 credits)
> In this project-oriented course, students apply the engineering process and engineering principles to open-ended, interdisciplinary projects. Students work in teams and gain design and project management experience through the development of fundamental electromechanical systems. *Restrictions: Restricted to Juniors and Seniors.*

This description reads as a scaled-down version of our capstone design course, but the associated projects, while still open-ended, are intended to be smaller in scope and more constrained and scaffolded than those in the senior-level capstone course. Based on the needs described in the introduction section regarding student preparation, a set of ten course learning objectives was established.

Learning Objectives

By the end of the course, students will have demonstrated the ability to

1. Design mechanical components to meet specific performance requirements and create associated engineering drawings (when possible), document their designs in a professional format, and support the design by appropriate analysis;
2. Qualitatively and quantitatively analyze systems that were designed;
3. Maintain engineering design records and present findings and modelling in a clear and professional way;
4. Use equipment manuals, libraries, and internet resources to look for solutions and solve problems independently;
5. Prepare well-written product design specification sheets;
6. Take leadership and initiative; share their personal opinions, make suggestions, and contribute to the design process.
7. Perform quantitative and qualitative analyses of peer reviews and create a plan for mitigation of design flaws and making improvements.
8. Seek expert opinions and stakeholders' input;

9. Work in teams and responsibly share workload; communicate effectively and produce good quality results;
10. Learn new skills and techniques and applied them successfully during the implementation of the design.

Student Demographics

Fourteen (14) students were enrolled in the first offering of this course, and their demographics are provided in Table 1. The course was designed for juniors, but one senior elected to take it (concurrent with their capstone design course), even though it was not required to satisfy their graduation requirements. The course is intended to support enrollments of up to 20 students.

Table 1. Student Demographics for EG397

Gender		Engineering Concentration*				Class Year			
Female	Male	CE	EE	ME	MatE	1st	So.	Jr.	Sr.
3	11	3	4	10	0	0	0	13	1

* The sum of concentrations exceeds 14 because some students had dual concentrations.

Course Format and Approach

A single section of the course met twice per week for 110 minutes (about 2 hours) per session over 15 weeks (about 3 and a half months) during the Fall 2022 semester. The classroom was our mechanical engineering laboratory space (~500 ft^2), which is suitable for both lecture and hands-on activities.

The course centered around taking an existing electromechanical system and introducing a significant modification to add new capabilities. The basic platform was a simplified version of an open-source replica of the Mars Perseverance rover (see Figure 1). [9]

Figure 1. The open-source replica of the Mars Perseverance rover. [9]

The 14 students were first divided into three teams (two teams of five and one of four). The multidisciplinary electromechanical nature of the project made it highly desirable that each team have members from both the mechanical/materials engineering area and the electrical/computer engineering area. Because there are fewer electrical/computer engineering students in our program, teams were created to ensure that there was at least one electrical/computer engineering student in each group. Otherwise, the assignments were made randomly.

During the first third of the course, each team assembled a separate rover from prefabricated mechanical parts and basic electric motors, which were controlled by an Arduino microcontroller. As mentioned in the introduction, even though other courses and labs included numerous hands-on activities, we noticed that our students often lacked practical build experience, especially when more complex systems were involved. This active-learning build exercise was intended to strengthen the students' hardware assembly, Arduino programming, and troubleshooting skills, increasing both their knowledge and their confidence. By the end of this five-week period, each team had a functional rover that could be controlled remotely.

During the course's subsequent two-thirds, the student teams produced their own modification to the base rover which they then constructed, tested, refined, and presented. This work involved both mechanical and electrical design, programming, fabrication, prototyping, and testing.

The early portions of the course also included learning modules about topics that were relevant to the successful assembly and operation of the rover and the subsequent modification. These modules are summarized in Table 2. Most of the instructional materials for these modules were provided online as pre-class tasks followed by associated in-class activities, utilizing aspects of a flipped classroom approach. [10]

Table 2. Learning Modules for EG397

Week	Topics
1	The Engineering Design Process Machine Shop and Safety Training
2	Fabrication and 3D Printing Ideation and Brainstorming Problem Definition and Specification of Requirements
3	Microcontroller Hardware and Programming Evaluation of Alternatives and Selection of Design Approach
4	Servo Motors and Power Supplies
5	DC Motors and H-Bridge Circuits Test Design, Implementation, and Data Analysis
6	Remote Control Using Arduino and NRF24L01

Course Assignments

Assignments in the course were both individual and team-based and are summarized below.

Individual assignments:

- General Safety Training and Certification
- Machine Shop Safety Training
- Laser Safety Training
- Basic CAD Skills
- Quizzes – Covering learning module topics

Team-based assignments:

- Product Design Specification Sheet – A 1–2-page document describing aspects of their proposed rover design modification including functions, target market, materials, maintenance requirements, cost, and health and safety
- Snapshot 1 (Initial) - Poster justifying and describing their proposed modification.
- Snapshot 2 (Intermediate) – Poster describing progress toward successful implementation of the modification
- Snapshot 3 (Final) – Poster describing the finalized modification and the results of performance testing, together with a video showing operation of the modification
- Final Product Design Report - A comprehensive written report describing the team's rover modification in detail

The individual safety training assignments consisted of having the students watch short online videos and then complete online surveys to demonstrate knowledge about the topics covered. The team-based snapshot assignments were milestone reporting points where the teams prepared documentation to explain their modification and progress toward its successful implementation [11]. The teams created posters that addressed specific requirements associated with each milestone (initial, intermediate, final). These posters were evaluated by the instructor, by the other teams in the class, and by students from the senior capstone course as described later in this paper. An example of one of the snapshot posters is shown in Figure 2.

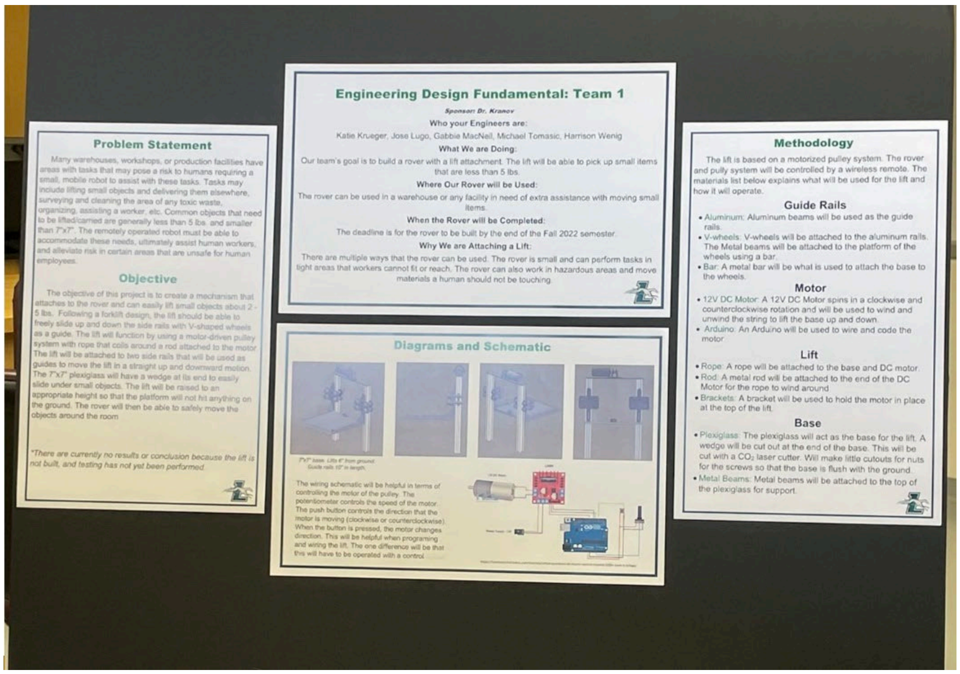

Figure 2. An example of a snapshot poster.

The teams were ultimately required to add their modification to the rover and test its functionality and performance relative to specified requirements that they set. In their final design reports, the teams described their modifications in detail, including their test results.

Performance, Assessment, and Evaluation

Each student team implemented a different rover modification of their own choosing. These modifications did not have to fit into the original Martian exploration mission of the actual Perseverance Rover but could instead consider the platform for other uses. The modifications implemented by the teams are listed below:

- Team 1 – Added a lift mechanism (see Figure 3)
- Team 2 – Added a "bug zapper" (see Figure 4)
- Team 3 – Added a smartphone camera (see Figure 5)

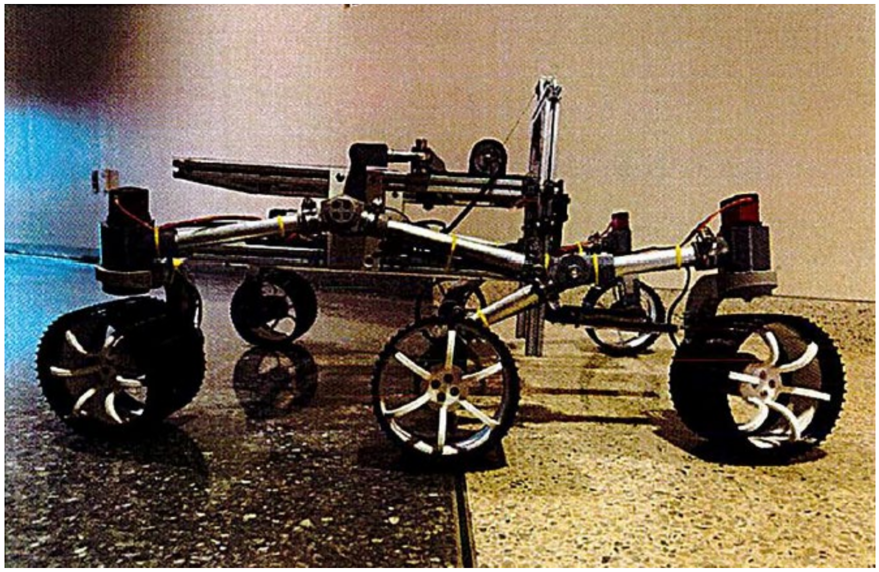

Figure 3. Rover with lift modification

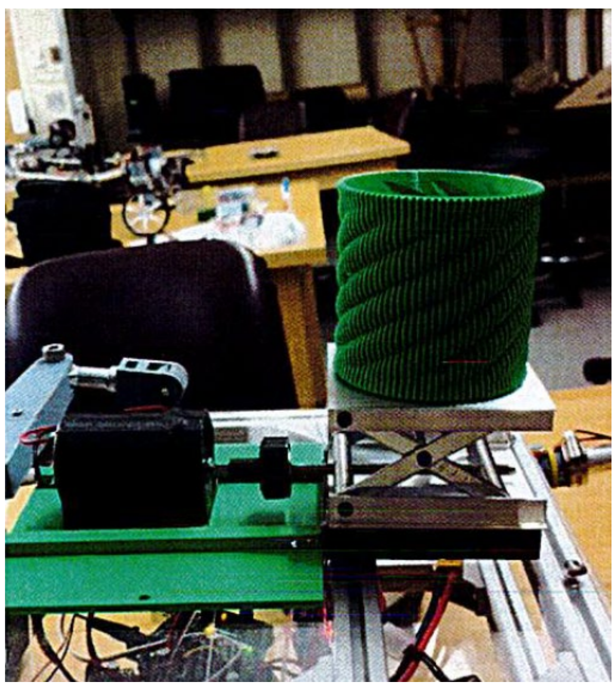

Figure 4. Rover with “bug zapper” modification

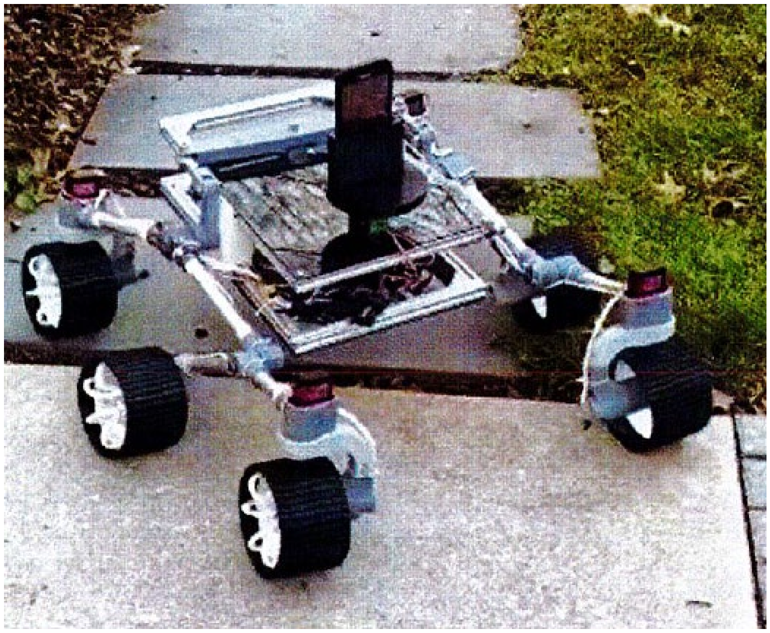

Figure 5. Rover with camera modification

Assessment by Students

At the end of the course, students were asked via an online anonymous survey to evaluate the extent to which the course learning objectives had been satisfied and to provide suggestions for improving the course. The "question" wording and format for the 10 learning objectives was the same for each, as was the 5-point Likert scale. For example, for objective 9, the survey element was as follows:

Based on what I have learned in this course, I feel confident that I can…

9. seek expert opinions and stakeholder input.	Strongly Disagree (1)	Somewhat disagree (2)	Neither agree nor disagree (3)	Somewhat agree (4)	Strongly agree (5)

The students were also asked 11 additional questions to provide more feedback, including qualitative written comments about their experiences in the course and ways that it might be improved. The average scores from the learning objectives assessment portion of the survey are shown in Figure 6. Twelve out of 14 students responded (86%). We were pleased to observe that the averages for all 10 learning objectives were above 4.0 (agree), indicating that the students believed that each had been met.

It is noted that the variation across the 10 objectives is small, with average scores ranging from 4.1 to 4.3. Although the course was designed to address all objectives, we had no expectation that the scores would be this uniform. This may indicate that the students found no weak points in their experiences. It should also be mentioned that the results include two students who evaluated all 10 objectives as "strongly disagree." These ratings were highly inconsistent with the associated written comments from the same students (the survey was anonymous, but responses can be grouped by responder). We cannot say for sure, but we believe that these two students may have completed the ratings incorrectly, selecting "strongly disagree" when they meant to select "strongly agree." Again, we do not know that this was the case, and we would not offer this explanation except for the inconsistency between these scores and the corresponding written comments. In any event, we plan to clarify the scale for the next group of students to avoid this potential problem in the future.

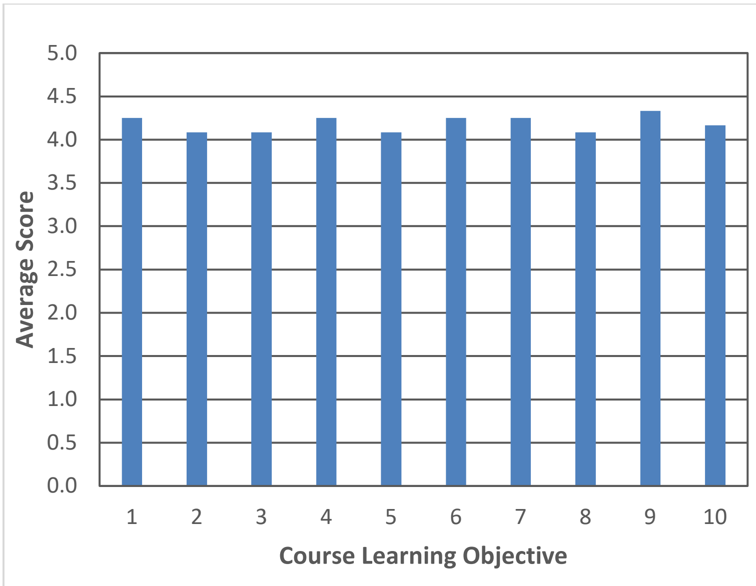

Figure 6. Results from end-of-term student survey concerning the attainment of learning objectives.

The students in the course were also asked to review each other's snapshot materials. Rubrics were developed to guide and standardize these reviews, and the rubric for Snapshot 1 is shown in Table 3 as an example. In addition, senior students from our capstone design course (EG497/498) were asked to review the snapshot posters and videos for the junior design course using the same rubrics. This feedback was provided directly to the student teams, allowing them to consider input from an external audience. We note that students in our program have used similar rubrics in earlier courses, so no special training was offered in this case.

Table 3. Rubric for Snapshot 1

		Scale				
Element	0	1-3	4-5	6-7	8-10	Weight
Layout	A mess	Hard to read, follow. Not creative and appealing	Readable but less creative & attractive	Easily read, attractive & professional	Easily read, creative attractive & professional	3
Content	Essentially no meaningful content	Contain 1-2 from these 5 items: problem statement, objective, methodology, results, and conclusion	Contain 3-4 from these 5 items: problem statement, objective, methodology, results, and conclusion	Contain all these items: problem statement, objective, methodology, results, and conclusion with clear explanations	Contain all these items: problem statement, objective, methodology, results, and conclusion with excellent explanations	5
Impact	No academic/ commercial/ societal impact	Minimal academic/ commercial/ societal impact	Moderate academic/ commercial/ societal impact	Significant academic/ commercial/ societal impact	Very Significant academic/ commercial/ societal impact	2

The average scores for the three teams for Snapshot 1 (made using the rubric in Table 3) are shown in Table 4.

Table 4. Snapshot 1 Score Summary

	Team 1 (Lift) Reviewed by:		Team 2 (Bug) Reviewed by:		Team 3 (Camera) Reviewed by:		
Element	Students	Seniors	Students	Seniors	Students	Seniors	Max Score
Layout	27.3	25.8	21.0	21.0	19.2	22.0	30
Content	48.0	38.7	41.3	37.1	26.0	36.3	50
Impact	16.8	16.1	15.0	13.1	11.6	15.2	20
Total	92.1	80.6	77.3	71.3	56.8	73.5	100

Both seniors and students in the class assessed Team 1 as having the highest performance on Snapshot 1. The seniors' evaluation scores tended to have less spread across the three teams, perhaps because the student teams in the course interacted frequently and thus had additional information about their peers' projects that the seniors did not. They felt comfortable enough to provide more differentiated feedback to the three teams, rating Team 1 highly, and Team 3 as much less accomplished, especially in content. The assessment element of content was the area in which there was the largest spread both between teams and between the ratings of students in the course and senior students. This may be an area in which a "norming" exercise for assessment scoring may be useful.

Qualitative written comments were also solicited from the students and seniors, and they were generally thoughtful and constructive. Some examples follow:

> "Well laid out; clear objective and good goals with a realistic chance at success."
>
> "No conclusion. Looks [well] organized but could flow better. Problem statement too long—seems to include requirements. Objective also kind of long; it seems to include design explanation."
>
> "Good idea but crowded poster."
>
> "Handwritten material is difficult to read. No methodology or conclusion. Is the objective and problem statement supposed to be the goal?"
>
> "Good but missing a conclusion. I think I may be missing the point of your project. How does this differ from a normal bug zapper? Do they already have something like this? Is this remote controlled and moves around?"

Past anecdotal experiences of the faculty have shown that this kind of feedback, from peers, can sometimes have more of an impact than similar observations communicated by faculty members. Serving as reviewers also communicates to the students that their observations are important, encourages them to think critically about their own work, and reinforces the concept of professional responsibility when examining someone else's work.

Written feedback from the students about the course itself was quite positive. In terms of course strengths:

> "The major strengths of this course are the creative independence and the collaboration within our groups."
>
> "Very hands-on and exciting."
>
> "Learning about different engineering control systems and manufacturing techniques like 3D printing, laser cutting, machine shop, servos, DC motors, Arduinos, etc... Also learning how to work with a team with different engineering majors. Preparing poster boards and presentations in preparation for senior design was helpful."

Areas for improvement centered on improving the reliability of prefabricated, 3D-printed parts, some of which cracked or shrank, requiring that they be re-printed. Although this was a source of understandable frustration for both the students and the instructor, it can also be seen as a real-world example of the limitations of fabrication technologies and the potential variability in component and material sources. This provided a chance to discuss with students how such setbacks should be handled, as they are bound to occur at some points in their careers. Another learning point was that reliable 3D printing is not assured or automatic, and there are parameters associated with it that must be determined, sometimes by trial and error. For example, using PLA at 20 percent infill often led to parts that did not perform well; however, 60 percent infill provided much better performance. A more detailed analysis of the written comments that may include coding is planned but has not been executed.

Faculty Reflection and Evaluation

A primary goal for this class is to prepare students for their senior design class. Their earlier courses and preparation still left students with various levels of exposure to the practical aspects of the engineering design/manufacturing process.

One significant challenge was identifying ways to introduce the instructional materials such that every student finds something interesting and challenging that keeps them engaged. This problem was addressed by

- providing written materials that covered the basics of a specific topic;
- providing instructional videos that built upon the basics and offered an option for additional exploration of the topic; this involved adding an opportunity for more advanced implementation of technology, coding, or manufacturing; and
- supplementing the instructional part of the class with a well-organized in-class activity or practical exercise that fits within the available time.

To level the playing field in terms of expectations and performance, targeted goals for the assignments were set so that everyone in the class had sufficient time to finish what was required, regardless of prior experience. Performance beyond those goals was treated as extra credit towards the individual students' scores. This extra credit was capped and could not be used toward other assignments. The importance of teamwork, collegiality, and peer-to-peer assistance was strongly emphasized, especially to students who tended to accomplish their tasks faster. It was pointed out that sharing their experience is of great importance and helps build leadership skills. It was further suggested that they should see themselves as voluntary peer teaching assistants.

To address specific needs and shortcomings in student expertise, it was necessary to establish a quick and effective feedback loop. Maintaining constant open communication and discussions allowed for reasonable adjustments to some of the topics covered as well as the depth of the corresponding instruction. The quizzes were a valuable tool for evaluating the general understanding of subjects and limitations of associated devices but were frequently ineffective at predicting a student's ability to deal with practical problems as they arose. This necessitated more one-on-one instructional time and case-by-case assistance by the instructor and the "peer teaching assistants."

During this first iteration of the course, the instructor was unable to find a suitable tool to assess both the practical fabrication skills and understanding of theoretical topics associated with individual performance in the course. Team performance was assessed well, but individual capabilities and contributions were not evaluated as reliably or thoroughly.

The snapshot days were an excellent assessment tool for evaluating performance at the team level. The peer-to-peer evaluations were useful, offering useful statistical data and written feedback used by the student teams to steer their projects in the right direction. All teams presented their work well in poster format, and with the quality of the peer feedback improved significantly between Snapshot 1 and Snapshot 3.

In contrast to the poster presentations, the written assignments and reports indicated some substantial gaps in the students' technical writing skills, especially in terms of engineering vocabulary and writing style. The work on the Product Design Specification and the Final Product Report indicated clearly that more time needs to be spent on the expectations for the written assignments. Providing students with an outline or a grading rubric did not yield the desired results.

Providing most of the instructional material online as pre-class tasks and activities seemed to work well for the students. Assigning strict deadlines for completion and submission of work facilitated good time management and steady progress.

Conclusions and Future Plans

Results from this first offering of the new junior design course are promising. Students expanded their knowledge of electromechanical machines, their skill in designing and constructing such machines, and their ability to power and control them using software driven hardware. Working in multidisciplinary teams, they applied the engineering design process and engineering principles to an open-ended project of manageable scope. They gained design and project management experience and applied technical analyses, techniques, and knowledge from their prior coursework. They also learned how to constructively interpret the results of experimental tests and how to troubleshoot both software and hardware problems when they arose.

There are, of course, many areas for improvement. The course's second offering is being taught during the Spring 2023 semester. One change that has already been implemented is that each student is asked to produce their own rover modification idea, independently, and to submit their idea to the instructor using a specific, one-page summary format. The ideas are then pooled by the instructor and re-distributed to the class with the names removed. The intent is to encourage more individual creativity and to give each student the opportunity to have their idea objectively considered. This also addresses the previously mentioned area for improvement concerning evaluation of individual performance. To address that concern more fully, a portfolio approach is also being implemented this term. For the learning module materials, each student completes a pre-exercise survey asking about their prior knowledge, provides evidence of their attempts to perform the exercise, and then writes a reflection about what they have learned.

The opportunity has presented itself to use CATME [12] to create and assess student teams. This software, developed at Purdue University, has three elements: one for team creation, another for peer evaluation, and a third for students to practice peer evaluation on “standardized student team members” which allows for some rater norming and reliability. This tool is not being used in EG397 during the Spring 2023 term but is being examined for future use.

Students in the current senior design capstone class did not take this course, but we are collecting data about their skill levels relative to the learning objectives presented earlier. We plan to repeat that exercise with this cohort when they reach senior design to examine the longitudinal impact of this course.

We are also seeking to strengthen links with our junior-level systems engineering and analysis course, which our students also take in their junior year, as well as with the follow-on senior design course. Students at the junior-level and senior-level have expressed consistent interest and concern in aspects of professional practice and career development. One way this can be addressed is to engage with external audiences, recent alumni, and others to provide narrative context to engineering practice. The systems engineering course takes a more theoretical and mathematical approach to the abstract elements of project design process and management. Case studies from INCOSE (International Council on Systems Engineering) in well-known large systems engineering projects are a part of the course. Having the junior design course as a complement to that provides students with a chance to experience how such techniques function on a smaller scale as well. Students can take the junior design course either semester, while the systems engineering course is currently only offered in the spring.

Overall, this first experience of a junior design course has been an extremely successful innovation to the curriculum that promotes students' confidence in both design and project process and practical aspects of mechanical and electrical fabrication, integration, and troubleshooting.

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