A Multi-semester Integrated Systems Design Experience

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Abstract

Engineering is design. In the last 20-25 years, senior level capstone design courses have become highly visible at most engineering universities. They serve a key role in teaching students about design, recruiting new engineers, and maintaining accreditation. They represent an opportunity for the students to transition from coursework to successfully executing a practical design project. This transition is quite useful for graduating students who will be entering the workforce.

However, the senior level capstone experience leaves many educational opportunities unaddressed or undeveloped. Learning to do good design work is a skill set that is best developed experientially, on timelines typically longer than available for capstone experiences. As a result, students often lack the time to test or iterate on their design. Because the capstone experience is at the end of the undergraduate education, students taking analysis based courses do not connect their coursework to design, the key engineering discipline. Additionally, at some universities, capstone projects are department specific and projects do not build on an understanding of the inter-relationship of different disciplines.

In this paper the authors discuss their experience and lessons learned from creating a multi-year integrated system design (ISD) project. The experience seeks to mediate the above concerns by being multi-disciplinary and engaging all levels of students including freshman through senior levels. Topics covered include objectives, administration challenges, project selection, management and execution, as well as survey data from student participants.

1. Introduction

Mechanical Engineering at Michigan State University has a 25 year history of using capstone design projects in the curriculum. These experiences have been very useful in giving students an approximation of an industrial design experience to help prepare them for the transition to working in industry. But the location of the capstone design experience in the curriculum and the time (credit hours) available for it provide constraints that limit its pedagogical value [1].

This has led to the initiation of a unique multi-year and multi-disciplinary student design experience to address many of the constraints of a capstone design experience. In the paper, we will refer to this multi-year and multi-disciplinary student design experience as the Integrated System Design (ISD) experience. Primary goals in the creation of the ISD experience are to improve students' engineering educational, experiential, and industry design understanding. By engaging students on this project as early as their second Freshman semester, the ISD experience can connect the classroom learning of engineering science fundamentals and the design project application of those fundamentals resulting in simultaneous learning and application. Because of the multi-disciplinary nature of the design project, as students continue on the project through their education they can see how the engineering sciences interact in design and how changing the design to improve performance in one area may degrade it in another.

The experiential learning elements of the ISD project are many. Multi-year projects are common in industry, so the ISD experience starts early in the students' educations to break the classroom experience that after 15 weeks everything resets and you start over. With the involvement of students over many years, it is common to have Freshmen and Sophomores working with Juniors and Seniors, providing peer learning, leadership, and mentoring opportunities. The ISD experience is run more like industrial projects with student teams assigned tasks, and the teams having responsibility to define timing and track status, allocate responsibilities to team members, execute tasks, and coordinate activities across teams. These provide many opportunities to learn important project management and communication skills.

The ISD experience exposes students to industry design understanding through elements such as identification of target market and derivation of project objectives based on that market. Subsequent project design activity may require design decisions that require tradeoffs between different aspects of product performance where it may be impossible to achieve all project objectives, a common challenge in industry. Learning opportunities for student teams on industry utilized tools for design process management are identified during the project. And teams are also provided opportunities to present to and interact with industry personnel.

The purpose of this paper is to outline the goals, administrative startup challenges, project development, and student involvement for the MSU ISD experience. The experience started with 18 students and quickly grew to about 50. The paper covers this growth and the learning process of scaling the program [2]. The paper concludes with student responses.

We recognize that there are others that have looked at multi-year design projects [3]. Our goal is to take the capstone at MSU and essentially bring many of the same lessons earlier into the education process so students are better prepared to think about design as a systems activity.

2. Administrative Challenges

One of the first challenges with introducing a multi-year design experience like ISD is to determine where it fits within the Mechanical Engineering curriculum. The experience needs to be accessible to students from freshman to senior year and offer them the ability to make a multi-semester commitment. ISD is designed to help de-silo the individual courses and help students discover links between their coursework. These factors mean that the standard academic course structure is too limited to be a vehicle for this experience.

Student design teams are a natural place to give students a design experience. However, design teams are, by necessity, driven by the competition rules and schedules rather than educational objectives. Many students are not motivated by the desire to compete and some actively avoid a competitive culture. Student design teams also require significant time commitments from their participants which can lead to high attrition rates among freshmen and sophomore recruits. Competitive design teams can be very expensive to run.

The solution to this challenge was found in the university honors program. At Michigan State University, student wishing to graduate with an honors college designation have to complete 6 courses with an honors designation. Mechanical Engineering courses offer an honors designation to students who complete an additional course related project. This means that for at least six semesters honors students are seeking to engage in an engineering related project outside of their coursework.

To leverage the honors experience we built a network of Mechanical Engineering faculty who agree to support ISD experiences. These faculty would agree to grant students honors credit for their courses using the ISD experience as the out of class project. For the honors college and some faculty members the integration and design aspects were significant enough for credit. A few faculty required students work on an aspect of the project that was closely related to concepts in their course.

A key outcome of the ISD experience is de-siloing courses by linking coursework to a bigger view of engineering. When students join the project each semester they are asked which course they are going to link to ISD to receive honors credit. As closely as possible we seek to link students to an aspect of the project that involves some of the skills they will be learning in that course. For example, for an electric bicycle project a student receiving honors credit for "CAD and Drafting" may be assigned to build a 3-D CAD model of the bicycle frame, they may be teamed up with another student who is getting honors credit for strengths of materials and is tasked with doing a stress analysis. A thermodynamics student may be assigned to look at the energy efficiency of the electrical and mechanical powertrain components.

As part of the ISD experience each student writes a final report. These reports are sent to their honors course faculty member to demonstrate the student's activity during the semester.

Because credit for the ISD experience is linked with the honors experience, supporting faculty have become a great recruiting network. When students ask instructors what honors project they can complete the instructor lets them know about the ISD option. Several supporting faculty have become active recruiters and advertise the program in their classes so we often see a great deal of interest from freshmen who are taking EGR100 and sophomores who are taking ME280. We also email all Mechanical Engineers in the Honors college at the beginning of each semester to invite them to participate.

3. Project Selection

Selecting ISD experience projects that are appropriate creates interesting challenges. As noted in the Introduction, the project has to involve multi-disciplinary complexity. The project also has to involve issues and challenges that are easily related to an industry environment, and at a level undergraduate students can connect with. The physical scale and features of the project, and any prototypes that will be built, also have to fit the available university environment. Of course, the most difficult challenge is defining a project where the end result of the project has objectives, value, and uses that are easily recognized and valued by students so that they want to participate and stay engaged with the project.

Current Project

With those criteria in mind, the first project selected for the ISD experience is building an electric bicycle. This project was chosen because it requires skills from a broad range of engineering coursework; dynamics for sizing the motor, strengths of materials for frame design, thermodynamics for battery temperature control, statics for center of mass calculations, etc. Aside from specific course related topics an electric bicycle also requires students to think about the integration of electrical components.

The complexity of designing and building an electric bicycle is balanced by the fact that most students are very familiar with bicycles, how they work, and at least subjectively can identify differences between a 'good' and 'bad' bicycle design.

Project Description and Timeline

The project description, "to design and build an electric commuter bicycle", along with the high level timeline (Figure 1) provided to the students, have turned out to have the appropriate amount of uncertainty in them to provide sufficient guidance while challenging the students to deal with the uncertainties present in trying to design a new product. The fact the virtually all of the students participating have personal experience with riding bicycles appears to have helped them be comfortable with this project description without the involved faculty having to define what the product is and provide extensive background on its use and issues.

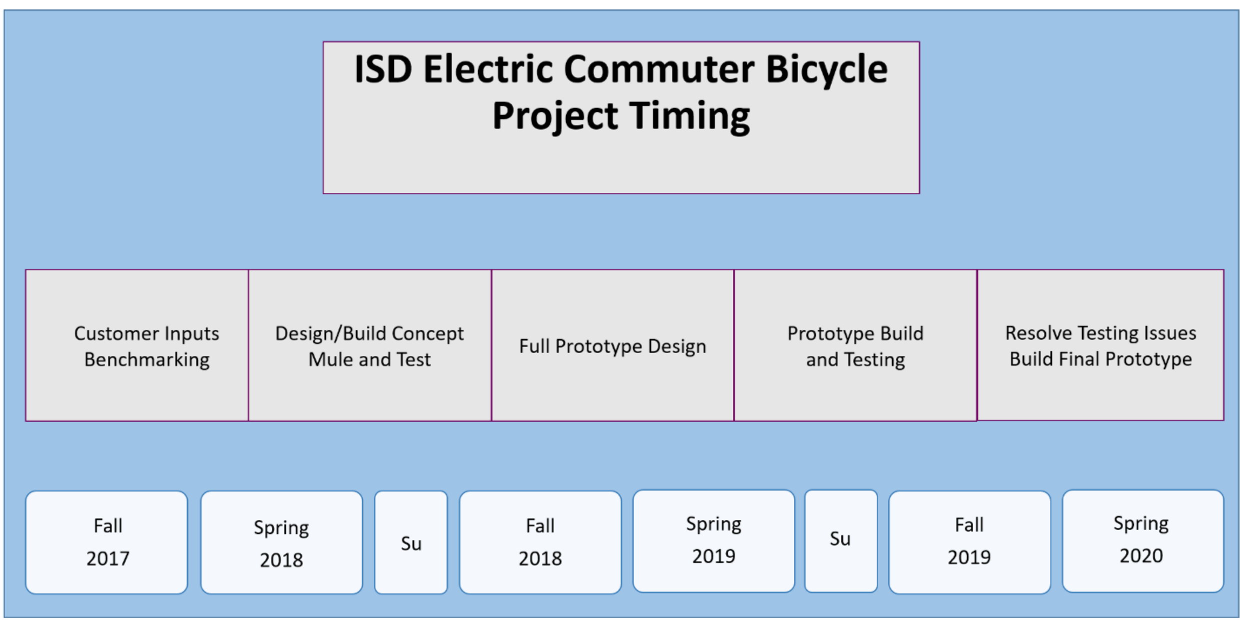

Figure 1 – ISD Electric Commuter Bicycle Project Timeline. The first ISD project is designed to last 3-4 years. This project timeline is discussed with students in the orientation meeting each semester.

4. Project Management

Managing a project of this scale requires a clear structure, data management, and student meeting schedules. The tasks are divided into segments small enough for a team of students to complete in a semester. It is expected that each student commit to 3 hour/week effort over the course of a semester. Students are arranged into teams based on course work and class standing. Team size was set at 4-5 students per team.

For the first semester of the project the student tasks involved identifying customer needs, investigating current products on the market, researching powertrain architecture, developing a set of performance metrics for the powertrain, and deciding on whether to build a design around a 2 wheel bicycle or 3 wheel tadpole tricycle. The teams are shown in Figure 2.

The two instructors managing the project met with each student team on a bi-weekly schedule (with students meeting as a team on the off weeks). The instructors maintained an open door policy with students who had questions in the interim.

The instructors set up a D2L/Brightspace community page for procedure documents and communication. Students had access to a shared project drive to archive efforts.

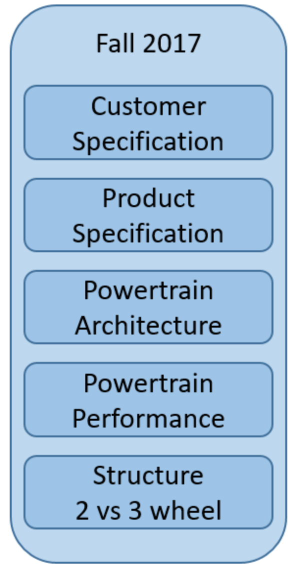

Figure 2 – Initial ISD Teams for the Fall 2017 semester.

Student Expectations

At the beginning of each semester the instructors detail the expectations for all students involved in the project. The expectations are:

1) Dedicate an average of 3 hours/week to the project.
2) Communicate regularly with your team.
3) Be available the following semester to answer questions regarding your work to any new team-members.
4) Complete a final report detailing your efforts.
5) Create and present at the mid-term and final project review.
6) Participate in Design Day.

The instructors also detail the purpose of the experience and what students can expect to get out of it.

5. The Electric Commuter Bike Project Experience to Date

The Electric commuter bicycle project has now been active for three full semesters and is entering its 4th semester. The following section details demographics on the students who have participated in the experience, how our structure has evolved to handle the number of students, and how we've adapted to challenges that arise each semester.

Student participation and demographics

Student participation and interest in the ISD experience has been overwhelming. The project started with 18 students in the Fall of 2017 and grew to 49 by the next semester. Many new students had been recruited by the original 18. Other students joined after faculty actively advertised the experience in freshman and sophomore courses. Of the original 18 students, 15 repeated the experience in at least once. Ten students (more than half of the original 18) have participated in the project for all three semesters.

Throughout the project ISD has been able to attract and maintain a fairly balanced group of students based on class standing, Fig. 3, and university demographics, Fig. 4.

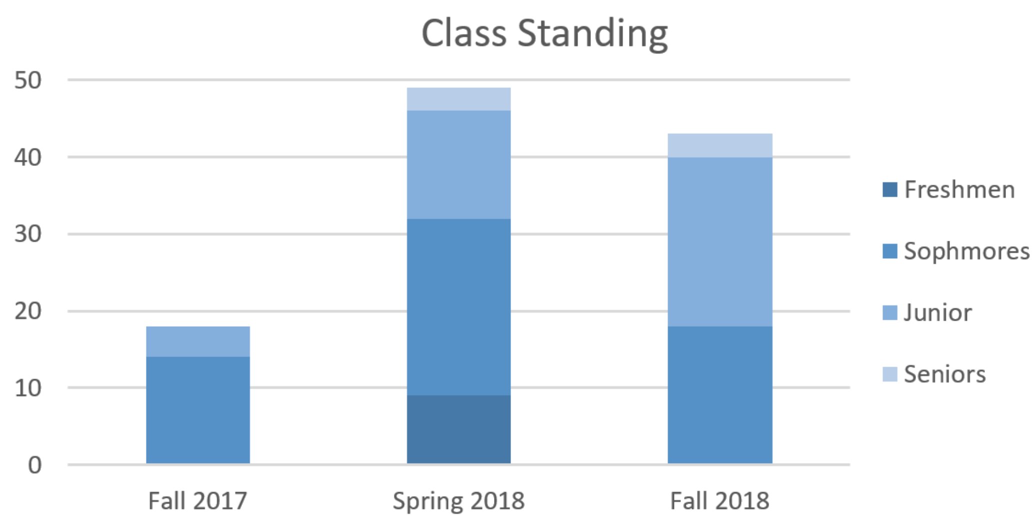

Figure 3 – Student involvement by class standing. Figure shows the breakdown of students by class standing (defined by credit hours completed) for the three semesters of the ISD project. The figure shows only students who completed the project that semester.

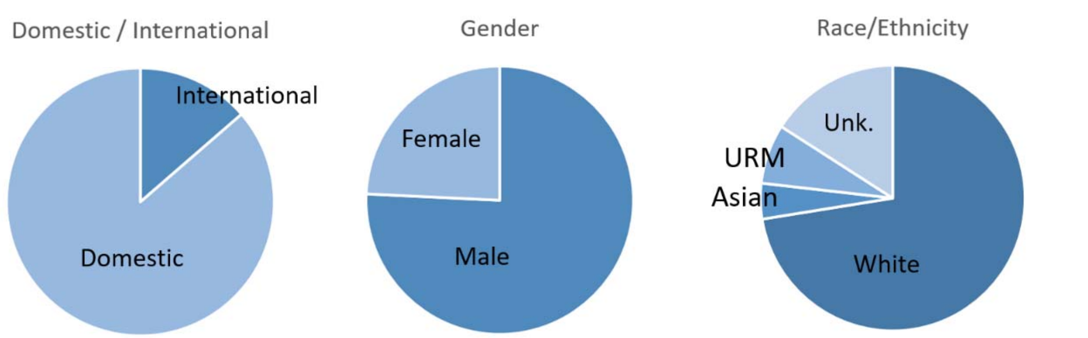

Figure 4 – Student Participant Demographics. A total of 66 unique students have complete the ISD project. The three pie charts show the demographic profile of these students. URM stands for under represented minorities. These values are commensurate with the demographic of the department.

Evolution of Project Management and Organization

A key aspect of the ISD experience is peer learning, teamwork, and communication between teams. As such the team tasks and organizational structure play an important part of the process. As the project grew and matured, the team structure was modified to handle additional students and challenges. Figure 5 shows the evolution of teams and organizational structure for the first three semesters of implementation.

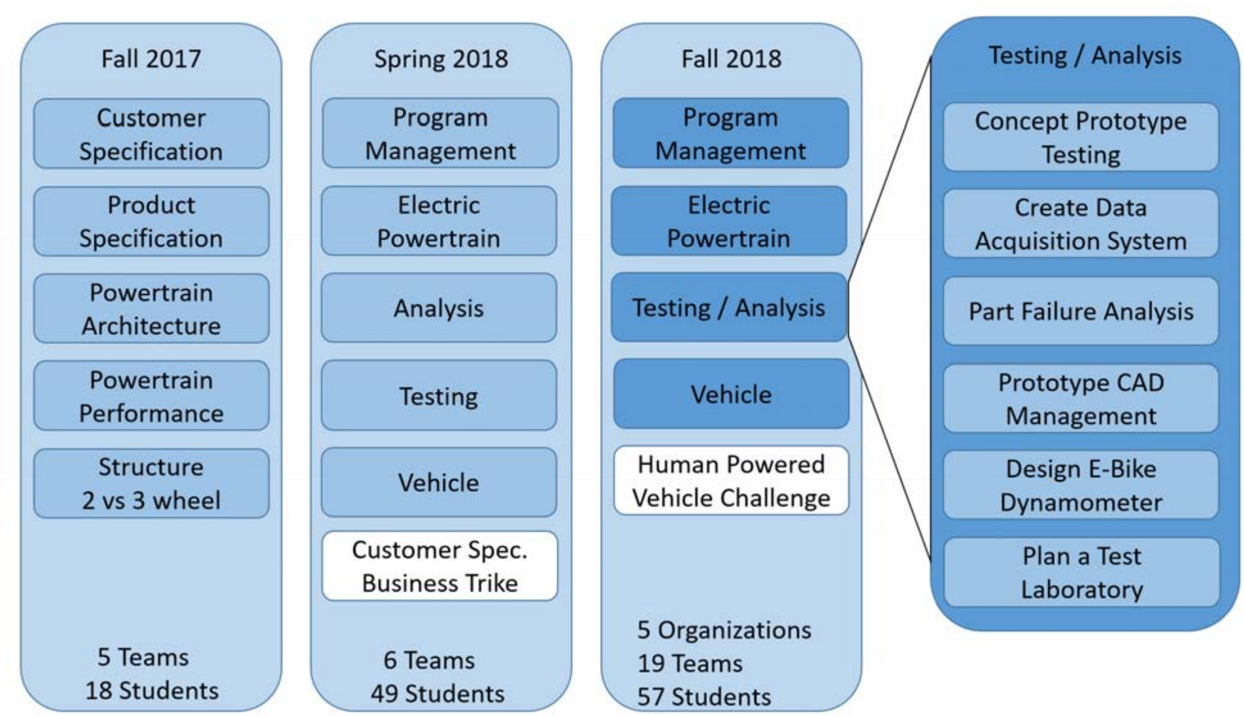

Figure 5 – Evolution of Team Structure. The teams are shown for Fall 2017 and Spring 2018 semesters. In Fall 2018 teams 19 teams were organized into 5 specific organizations (example shown for Testing / Analysis). Teams in white functioned as auxiliary teams to explore spin off projects and were not involved directly in the e-bike project.

In the first semester students were grouped into 5 teams of 3-4 students per team. The primary means of communication among participants was e-mail and weekly meetings. In the second semester 6 teams were specified and because of increased interest an average of 8 students were assigned to each team. A program management team was created to facilitate team-to-team communication, defining the project timelines, and budgeting. At this size it became difficult to keep individual team members connected to the overall team goal. To handle this problem in semester 3, Fall 2018, 19 teams were created, operating in hierarchical structure.

Project Adjustments and Additional Lessons Learned

As the project progressed several challenges arose and the program was modified accordingly.

By the end of Spring semester 2018 the instructors realized that the instructor to student ratio had grown too large. To help give more timely feedback to students and encourage peer mentorship, the instructors worked with a graduating senior with significant design experience to provide mentoring to several groups. This ISD mentor worked with students through the fall.

Once the 40+ student threshold was crossed, common student shortcomings posed a significant threat to the project and experience. The biggest challenges to arise were:

1) Students did not respond punctually to emails from other students.
2) Students assuming that someone else would complete a task rather than taking ownership.
3) Students wanted to be told what to do rather than asking their own questions.
    a. Do what they are told vs. plan and execute on their own.
    b. See the role of small tasks in the bigger picture.

These challenges were not un-expected and were used as teaching moments to discuss professional skills. To improve communication, students were allowed to determine the means of communication that they felt most comfortable using and they settled on a free program called Slack. The instructors focused on teaching students to write messages with specific objectives and questions, providing a timeline for a response, directing the question to a person rather than a group, and following up in a kind but timely manner.

To improve individual ownership for tasks, team sizes were reduce to 2-3 students. The instructors built a culture in meetings of immediately assigning new tasks to specific individuals. Students were instructed to assume that they had responsibility for a task and verbally confirm that with the group or to verbally confirm who had ownership of a task.

The final challenge is moving students to be inquiry based learners. Students should be self-sufficient to determine next steps and create new goals and objectives. To aid students in this development each student is asked to fill out a progress report. The progress report has monthly objectives and tasks that are defined by the student and commented on by teammates and instructors. At each meeting the students give an update on their completion of the objectives and any new tasks that have arisen. The purpose of the progress report is to provide a framework for students to ask and get feedback on the question, "what should I do next?".

6. Conclusions

We are one and a half years into the ISD experience. Faculty observations and student feedback indicate that we are making progress on achieving our education objectives. Students are linking what they learn in their courses to ISD project activities. Students typically have positive feedback about finding these connections. We have observed many teams struggle with, and develop an appreciation of, the importance of having good communications and coordination across individuals and teams to achieve their objectives. Finally, feedback from students indicates that they are finding the ISD experience to be beneficial as they participate in industry internships and build their understanding of what it means to be and work as an engineer. The student comments below from ISD semester surveys illustrate some of these points.

Student Feedback

Student feedback for the experience has been very positive. A key indicator of the success of the program is the ability for students to clearly articulate the benefits of their learning experience and to link them to current coursework and future employment. Survey feedback is solicited from students at end of the semester. Several examples of feedback given by students on end of semester surveys are shown below. The bold survey question is followed by a summary of the feedback in italics.

Survey Question 1: Was your ISD project experience useful or relevant in a course?

Student responses to this question indicated that students recognized the link between ISD and their coursework, recognized the complexity and importance of teamwork, and recognized the systems nature of design projects and how different engineering technologies come together in systems design.

> A lot of the Matlab code that I worked on for power analysis was useful in other classes. Data acquisition and analysis is a really good tool that I think has allowed me to have a leg up on my peers.
>
> Yes the computations for testing the bike were similar to the calculations in Dynamics ME361. It was nice to apply calculations we learned in class to a real life example. It was also nice to think through how we would collect the data to calculate the properties of the bike. Instead of just plug and chug numbers we were required to think through all our calculations and really understand them. That helped a lot.
>
> In my experience on the program management team last year, I found this experience very helpful to learn how to send proper emails to communicate my message better and organize displays and people for Design Day.
>
> The ISD project was relevant in my statics course as we investigated the different loads on the bike and found the center of mass.
>
> It was useful in ME471 where I also had to work in a team. I was able to think deeper and more critically on what issues could arise later on in the project and how to approach them if they do arise.
>
> I believe my experience in the ISD project has helped me realize the importance of testing. In my MSE250 course, the final lab was about using various tests learned throughout the course to determine what kind of metal it was. The ISD project testing was similar in order to determine the capacity of the electric bike.
>
> Yes, dynamics. It was cool to see how course work can be used in real-world applications.

> Yes, it helped me understand all the steps and how much teamwork really has to go into the idea and designs of a project. I also feel like it helped to understand what kinds of roles people can fit into and how many different people need to have their hands on a somewhat complex project

Survey Question 2: Did you learn any unexpected lessons? What were they?

Student responses to this question indicate that students are seeing the importance of planning and timing, especially across teams. Students recognized that the project has many different parts and thus the complexity of the project requires multiple teams, the value of expertise, and systems level thinking.

> I was somewhat surprised by how quickly a task could be completed if one went into it with a gameplan. As far as our team last semester was concerned, we allotted a significant amount of time to planning out our tests. When it came to actually performing them, we were sometimes able to finish more than one day's worth of tests in a matter of hours. This may have been due to the relative simplicity of the tests, or the interconnected nature of the information that was being collected, but regardless I didn't expect to have as many tests done in the given amount of time as we actually completed.

> Yes, how one teams timing can affect anothers.

> I learned a lot about the difficulties of communication. It is not as easy as it seems.

> Bikes are way more complex than you think, and a lot of design work goes into the product development.

> Unexpected problems come along so start working early.

> Communication is the most important skill amongst students/teams/faculty to have a clear understanding of how to move forward and ensure everyone knows what the goal is.

> Finding an expert who can offer advice is more helpful than any amount of online research. Experience is worth more than a quick google background.

> I believe the whole process was a huge lesson for me. I learned how an actual engineer would operate in a job.

Survey Question 3: Did your ISD project help you understand what it means to be an engineer? How?

> I would say so. There was significantly more freedom (and by proxy, uncertainty) in the project than I had expected, which I feel shed light on the nature of the engineering process outside of the classroom. That, and I found myself spending about as much time on managerial tasks as I did on "engineering" tasks. Logistics turned out to be one of the more difficult parts of the project, which I suspect is true in any project above a certain scale—engineering or otherwise.

It did, it’s shown {me} what it’s actually like to work on an engineering team. Organization and engagement of all stakeholders is key.

Yes, It helped give experience on how to work with other students and how to coordinate with different groups. The project gave lots of experience with calculations and research but what gave me a different perspective of engineering, was the social requirements of being an engineer. It was good practice learning how to stay in touch with different groups of students and coordinating work times within all the groups.

Survey Question 4: Was your ISD project experience helpful during a summer internship? In what ways?

Yes! My experience was helpful in helping me to understand safety concerns taken into consideration in industry. I learned what a DFMEA was through ISD and was able to understand what people were saying when this was brought up during my internship at [Car company].

Yes it helped me remember the skills I need in order to work on a team such as communication, cooperation, and patience.

My summer internship required me to keep safety at the forefront in every activity. I was able to draw from my experience on the safety team as a basis. I also used the dfmea process and knowledge to weigh different concepts during my internship.

I worked with [Robotics company] with the manufacturing department over the summer. ISD helped me in my summer internship by teaching me about the importance of safety in manufacturing processes. I also feel that I can translate some of my experience from [Robotics company] to ISD in future semesters.

7. Future Plans

In the short term, the instructors plan to continue improvements to the program and complete the 3 year design cycle for the first project. Additional spin-off projects will be explored as potential projects after the e-bike has been completed.

One change as the project enters its 4th semester is the instructors are taking steps to ensure a continuity of knowledge between semesters. This means that the skills and knowledge developed in one semester needs to be transferred to the next set of team members. Initially students were moved to a new team each semester to expose them to various parts of the project. However, this meant that new members had difficulty picking up where the previous semesters team had stopped. The progress reports and papers didn’t transfer information as well as was hoped. Moving forward, at least one student from the previous semester continues with the same team. This student knows the direction and experience of the previous semester’s team and can serve as a team captain. These students are selected based on their ability to do self-inquiry and develop vision for the project.

A significant question that needs to be resolved is team formation. Thus far, three methods have been utilized to form teams: Group by course enrollments, group by interest, group by interest with team captains. The project is still developing significantly in this area.

The senior mentor model that was used in the Fall of 2018 was very successful. As such the instructors are working to develop senior level or masters level mentor positions within the program. These can either be a senior working on an independent study or a masters/PhD student working as a TA. In the Spring of 2019, a first year PhD student (the Fall 2018 senior mentor) will be providing mentorship to several of the teams.

As the project continues, the instructors seek to maintain a focus on the goal of improving student education with open-ended, experiential, and iterative design work and to expose students to industry tools and practice.

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