A collaborative design project between introductory engineering and physics classes

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Abstract

Engineering design is valued across all engineering programs and is typically project-orientated. An important element in engineering design process is the interaction among the client, designer, and user. This past year, one of the design projects our engineering students (as designers) worked on in collaboration with physics students (as clients and users) was to design rolling objects for a physics lab, with a goal of completing a loop-the-loop while satisfying certain constraints on object properties. For the engineering students, the collaboration was a chance to experience the design process. The engineering design teams met with the clients to clarify the project needs and review background physics laws such as energy conservation and rotational dynamics. Following the design process (see Dym and Little 2009 [1]), engineering students developed a problem statement identifying objectives and constraints. After exploring the design space and considering alternative designs, design teams presented a detailed design to their clients and sought feedback. Finalized designs were prepared using a 3D printer, and a technical report and final product were delivered to their clients. For the physics class, the project combined an emphasis on open-ended problem solving toward a specific experimental goal. Unlike many introductory physics labs, which may have more of a “cookbook” nature with students simply following a proscribed method, this lab required students to creatively apply knowledge learned in the classroom. Overall, through the collaboration on this project, engineering students experienced a full engineering design process and physics students experienced an engineering-type challenge using concepts learned in their own course.

Keywords

Collaborative design, first-year project, peer clients

Introduction

Although engineering is an exceptionally broad field, design is a central activity shared within virtually all engineering disciplines. Consequently, it has become increasingly important in engineering education. For example, the ability to design is a required outcome of engineering baccalaureate graduates[2]. Nationally, engineering schools are placing more emphasis on including design in their programs[3]. The process of design is also under study either holistically[4] or focusing on certain stages of the whole such as the concept generation step[5]. As educators, our goal is to help our students acquire adequate knowledge and skills as designers when they graduate.

Along this thinking, project-based learning in teaching engineering design is popular. Instructors are creative in selecting projects. Dutson et al.[6] summarized project source into the following categories: hypothetical projects (e.g. instructor-generated), projects provided by industry (or community-based), projects chosen by students, projects within the university (from other departments), and design competitions sponsored by engineering societies. Many discussions in the literature can be found regarding projects that fall into the first several categories mentioned above [7, 8, 9]. However, to our knowledge there are far fewer papers about design projects originated from within the university [10]. Here we provide another example of this category, where a design project in the Introduction to Engineering course was developed in collaboration with the University Physics I course at our institution, Eastern Mennonite University (EMU).

The Introduction to Engineering course at EMU focuses on design as a key component of engineering education [11]. In a first-semester, introductory course, students may not be prepared for a project meeting industry demands, yet it is still desirable to have projects motivated by needs outside of their current course. In this pilot project, students from the physics class became clients of the engineering students. In this paper, we detail the project and compare the design process outcomes of this type of project with the instructor-assigned project.

Description of the collaborative design project

The laboratory project for the physics class was developed in response to student difficulties in understanding concepts of rotational motion and energy from previous years of the class. Therefore, this multi-week lab was designed to allow hands-on experience with designing and measuring properties of rolling objects. The specific goal given to each group of two or three students was to create two “nearly identical” objects, one of which completes the loop-the-loop when released from a specified height, and one which fails to do so when released from the same height (Fig. 1). The definition of the phrase “nearly identical” was kept intentionally vague to allow space for student creativity in the problem solution; for example, whether the objects were designed to have similar volumes or masses (or both) was left open.

During the first week, the groups of physics students worked on an assignment guiding them through a derivation of a rolling object’s speed at the top of the loop-the-loop, based on the principles of conservation of energy and Newton’s second law giving the minimum velocity required to maintain a normal contact force throughout the loop. What results is an equation where the key design variables are the initial height from which the object is dropped, the radial size of the object, and, most importantly, the moment of inertia. The key insight for the students was to recognize that rolling objects have a higher moment of inertia when more of their mass is shifted toward the edge. Thus, they have more energy partitioned into rolling motion and a slower linear velocity than a similar object with a lower moment of inertia released from the same height.

Then, the physics students began collaborating in groups with the engineering students to connect their idealized equations to real-world challenges of designing printed objects that would fit the apparatus and remain in contact throughout. While simple cylinders and spheres typically formed the basis for such objects, students recognized that more complicated designs might be more successful at maintaining good contact with the grooved track. Measurements of the properties of the ramp, loop, and plastic printing material were made, and plans were created to experimentally characterize the properties of their designed objects.

After working together to learn about the task, the engineering students took the specifications, turned the rough designs into 3D models, produced the objects, and delivered the final products to their clients. Then, in the second week the students worked to experimentally measure the moment of inertia of their objects, validating their designs. At the end of the project, the physics students wrote comprehensive lab reports including a methodology, results, and discussion, while the engineering students gave presentations and turned in written reports detailing the design process in action.

Fig 1. An object rolling down the loop-the-loop apparatus.

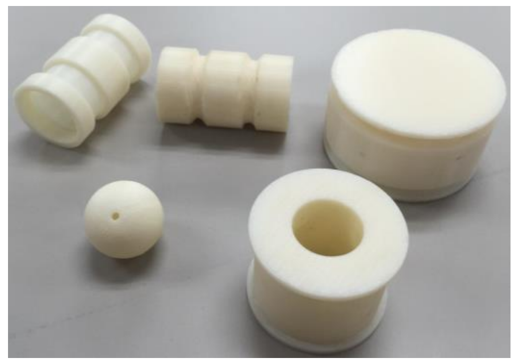

Fig. 2. A sample of some various shapes designed by the teams.

Engineering student outcomes: learning the design process

We compare the outcomes from the collaborative project with instructor-assigned projects in the following aspects of the design process: problem definition, idea generation and evaluation, and outcome communication. The instructor-assigned project was to build a solar powered cellphone charger, in which students used 3D modeling software to design cases to house the electronics of a charger circuit soldered together from a kit (for more details see [11]); this was the first team project in the Introduction to Engineering course, whereas the collaborative project was the second.

Defining the design problem

In the problem definition stage for both projects, engineering students were required to turn in a work plan including a project statement detailing objectives and constraints. However, the collaborative project required students to acquire knowledge from another discipline, which was not a component of the instructor-assigned project. Engineering students first visited the physics lab and tried to understand the physics laws behind the project. All the engineering students were in their first year, and none had taken physics yet. While interacting with the physics students, the engineering students grasped the broad concepts involved such as conservation of energy and moment of inertia, though they were not necessarily able to derive the equations. They gathered background information from their clients, as well as from the instructors of two courses.

Another observation specific to this project in contrast with the other is that students revisited the problem definition even after they moved on to later stages. For example, there was one student who erroneously designed for an object sliding down the track as opposed to rolling, and thus their design needed revision. In contrast, for the solar charger project students carried out their design without revisiting or redefining the problem after developing their project statement.

Generating and evaluating ideas and specifications

Because the physics students were working on their assigned lab, they had preferences for the shapes of the objects to satisfy the task. Since the physics students did their initial calculations based on standard shapes such as spheres or cylinders, there was not much room left for the engineering students to generate dramatically different designs. Instead, the engineering students focused on adjusting the sizes or adding small features to the prescribed shapes. One example was recommending the addition of holes to a hollow spherical design to facilitate removal of the supporting material inside. Another example was recommending the addition of grooves or edges to keep cylindrical objects more firmly on the track (Fig. 2). Therefore, idea generation was shared between the two groups of students.

The physics students as clients did have specifications similar to how industry-sponsored projects often come with a set of specifications. In contrast, the solar charger project had a much larger design space. For example, one team developed a turtle-shaped case to house the circuits, while another team had their charger designed to mount on a bike.

A unique phenomenon in this collaborative project was that physics student clients in some instances were still in the process of working through their part of the project. Some had not fully understood the project and consequently gave wrong specifications due to a mistake in their calculations. Luckily for these students, the error was discovered during a subsequent iteration of the review process before it was too late to make changes.

Communicating the outcomes

Students also improved communication skills through this collaborative project. After the initial meetings with physics students on the scope of the problem, engineering students delivered their model drawings created in Autodesk Inventor (3D CAD software). They sought feedback from their clients, and teams rechecked the measurements of the track, in some instances making adjustment in the dimensions of their designs.

Once the designs were rendered for printing using a 3D printer, the excitement was noticeable from both the designers and the clients who were shifting roles to become users. The engineering students joined the physics lab again to deliver their products and do testing together, including a test for the completion of the challenge: would one object complete the loop where the other failed? Afterward, students recognized there was still room to improve the designs. For example, a design of a small sphere was resized to be larger to avoid bouncing, whereas a large sphere design was resized to be smaller to avoid slipping. Another improvement for a cylindrical design was that the size of grooves needed to be adjusted to fit the V-shaped track better.

Overall in this project, engineering students gained significant knowledge and skills in communication with their clients and users. In addition to the final products they delivered, engineering students also turned in a written report detailing the design process and made an oral presentation.

Physics students outcomes: retaining conceptual knowledge

The benefits of a joint project ideally extend to both courses. One measurable outcome for the physics students was their performance on final exam questions related to the topic, such as how rotational energy affects motion. As is often the case at small schools such as EMU, the caveat of small sample size applies, making meaningful quantification of such a project challenging; however, we were able to observe promising trends. The final exams were taken about one month after the unit containing rotational motion, so considering if this lab improved scores on these questions checks retention of knowledge over a short time span. In three straight years an identical question related to rotation motion was asked; in the two years prior to running the lab, approximately 30% of students correctly answered the question (9 of 31 in 2013 and 6 of 12 in 2014) while that percentage increased to 50% in the semester with the joint project (8 of 16 in 2015).

Running a two proportion z-test fails to reject the null hypothesis that the before and after populations are the same at the $\alpha = 0.05$ level; additional semesters of data would be necessary to make a claim of statistical significance. However, even if the results were statistically significant, other confounding factors could claim to be the reason for improvement beyond having a collaborative, hands-on design lab; it would also be possible to hypothesize that simply spending additional time on rotational material--as certainly happens in a multi-week laboratory project--is sufficient for improvement. Nevertheless, we believe the value of this design project is not solely dependent on this narrowly defined learning outcome of retention of knowledge for the physics students. Furthermore, when the current engineering students progress to take physics, they may see gains on this unit; such analysis is not yet available.

Discussion

Positives and Negatives

Overall, we believe the joint project was a largely positive experience for our students. For example, when asked what they liked about the course in end-of-semester evaluations, physics students noted, “the lab with the engineering students,” as a stand-out experience. Engineering students also stated that they enjoyed working with physics students as a situation more similar to a “real-world situation,” in particular referring to having clients with which to co-design a product. One student made reference to the fact that the solutions to the problem were not over-specified. He made the deeper connection that real-world engineering problems do not always have one solution, stating that he “recognized these problems are always poorly defined,” in the sense of many possibilities being present in the design space. In that way, he noted that the problem was successful at demonstrating aspects of the design process as it may be encountered outside of the classroom. Similarly, engineering students obtained experience working with deadlines and needing to schedule meetings with the clients outside of class time. One student reported that, “the most impactful constraint was undoubtedly having to work around the schedule of our clients.”

One negative area for the engineering students was that many wished to know more about the physics concepts and equations used - several noted that they felt under-qualified to understand what was going on. This lack of readily-accessible background knowledge made it difficult for them to offer constructive suggestions for the design though several took this as a challenge to learn more about conservation of energy outside of the classroom setting. In future years, a change may be to choose a project that allows them to have more direct input on the object design.

Broader Implications

In this work, we have described a collaborative design project between two courses. University classes, particularly at small institutions with modest class sizes, can provide a natural source of clientele to run engineering design projects. However, logistical challenges with such projects may limit their effectiveness if trying to scale up significantly; both the Introduction to Engineering and University Physics I classes involved in this test had fewer than 20 students.

We believe it has been successful for introductory students to have a deeper understanding of the full engineering design process, to gain communication skills, and to be motivated to be active rather than passive learners. This type of pseudo real-world problem has special advantages for students early in their academic experience because, while they are motivated to do well and successfully complete the task for their peers, the implications of failure are not as great as they might be if the project source were to come from outside the university such as a commercial firm. Finally, the collaborative project functioned to promote cross-disciplinary understanding of engineering, as the physics students gained a taste of the engineering process in action.

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