Prototyping a prototype-based project with minimal equipment requirements

Abstract: This full paper describes the design, implementation, and reception of a prototype-based design project for first-year engineering students in an introductory course. This project was introduced in a course that previously lacked authentic physical design due to the limited access to prototyping equipment. Prior student projects were confined to design and computer modeling and simulation elements only, with hands-on activities restricted to measurement-based labs. The new project incorporated concept development by the students along with physical prototyping of their design using and a combination of reusable components and disposable inexpensive supplies.

The new project consisted of a line-following robot using Arduino kits and a custom-made chassis designed by the students. The students needed to assemble the components, calibrate the sensors, update and install the code, and design and build the chassis for the robot. The students were encouraged to minimize their design according to cost, weight, and time required for the robot to navigate along a course. The open-ended nature of the project allowed for students to optimize the code, improve the aesthetics of their design, or change up the circuitry of the robot in order to have the best performance. Students used beta prototyping to make their chassis out of low fidelity materials, such as cardboard, popsicle sticks, duct tape, and glue, and some were able to finalize their prototype using 3D printing.

This paper documents the process of the design and implementation of a student project introduced to a first year undergraduate Engineering Design course. Implementation and evaluation of the new project is broken into three phases carried across three semesters. Over 300 students and 12 separate faculty members have undertaken this project. The paper starts with the course background, theoretical considerations in deciding on this student project, followed by the implementation of each phase, student feedback, and finally instructor feedback from all the sections. The authors conclude by sharing the reflection of the multi-semester project.

Introduction At the Pennsylvania State University, first-year engineering students are introduced to engineering and the engineering design process through EDSGN 100 (Introduction to Engineering Design). This paper discusses the EDSGN 100 course given at Penn State's Behrend college located in Erie, PA. In EDSGN 100 students learn about the engineering design process, explore engineering as a career option, and are introduced to methods to succeed as a student during their time at Behrend. For the last decade and more, students achieve these learning goals through two projects that aim at providing both theoretical and hands-on experience with the engineering design process. However, the hands-on aspect of these projects has been limited to taking things apart, testing, simulating, while the design component was limited to computational design due to the lack of facilities available for prototyping.

This paper documents the process of the design and implementation of a new student project that has the flexibility to challenge students. In this project, students are exposed to various expertise in engineering including programming, electronics, and modeling, while using minimal resources and operating without access to a traditional machine shop. The paper starts with the rationale of the new student project, theoretical considerations behind the project, followed by the implementation of each semester and student feedback. The authors will conclude by sharing the reflection of the multi-semester project with other engineering educators who also hope to improve the first-year experience of engineering students.

Course background The vast majority of Penn State first-year engineering students need to take EDSGN 100 to learn about the engineering design process, explore engineering as a career option, and at the same time learn about how to achieve academic success. At the Behrend College, up to 400 students go through EDSGN 100 every year, with a larger cohort in fall and a smaller cohort in the spring semester. Each cohort of students attends a common face-to-face lecture once a week (online for honors students). They participate in a weekly computer lab in sections of up to 25 students each and again work on the two group projects during the 2-hour recitation. There is tremendous coordination required as the computer labs and recitations are all led by different teaching assistants and engineering faculty members.

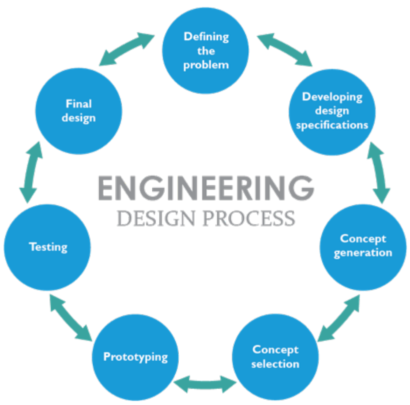

Figure 1: Design process as taught in the course

The two traditional student projects in place have been part of the EDSGN 100 for more than ten years. They each serve a different purpose. The renewable energy application project is designed to nurture high-level thinking and consideration of customer needs, whereas the toothbrush redesign project means to provide students a product deconstruction experience in order to have hands-on exposure and consideration of manufacturing processes. These projects work well in some respects, yet both lack the physical "building and testing" experience due to physical constraints. An overview of the two projects and the previous course set up can be read in [4]. As a result, students learn about the engineering design process (see Fig. 1) in theory without fully completing it with practice. They are encouraged to come up with creative ideas but are not given the chance to verify their conceptual understanding by putting them to test [5], to detect problems, investigate and rebuild. Their reality of the engineering process misses three important pieces – prototyping, testing, and iteratively developing the final design.

Student and instructor feedback confirm the disappointment. During the two years prior to the new project, one of the authors observed a consistent pattern in student feedback to the course: students want to "physically practice what [they] learned", "do projects that are more relevant" and have the course "geared to explore the different types of engineering." One student even suggested "make the projects into competitions between groups to get people involved." It seems that without the real hands-on prototyping, students perceive the first half of the design cycle as less meaningful "busy work" or "paperwork". Two of the authors also noticed that students don't appear driven while working on their projects. In addition, many students fail to see the value of an engineering field other than their selected major. There is a need to bring in an authentic project-based learning project where students are exposed to multiple STEM topics and engineering specialties and complete the design-build-test cycle [11], a method which has been proven effective in first-year design projects [12] and more than one hundred curricula around the world who adopted the Conceive-Design-Implement-Operate (CDIO) framework [3, 5, 13].

New project rationale To improve student engagement, the student project needs to be intrinsically motivating. In the context of education, students' motivation decides how much effort they are willing to invest in order to reach a pre-determined goal. One of the factors that affects motivation is autonomy; students who are given the choice to determine what and how they want to engage an activity have higher motivation than students coerced to complete a task [1, 2].

The student project needs to be challenging, but success should also be within reach at the freshmen level. According to the expectancy-value theory [20], people's beliefs about how successful they can be in a task and the value of the task influence the choice they make, how persistent they are, and how well they perform. If either the value or the chance to succeed is perceived as zero, then the motivation to be engaged in the task will end up as zero [1, 2, 18, 19]. A well-balanced, challenging task for the team will teach students more than engineering knowledge. Students will likely improve in creativity, project management, and team communication [5-7, 11-14, 16, 17].

New Project Overview In the Line-Following Robot (LFR) project, students are tasked with designing a chassis for a robot controlled by an Arduino-based microcontroller that can follow a dark line. Students are provided with the microcontroller, three sensors, two wheels, two motors, a motor driver, batteries, and the wiring necessary to connect all the components. They are also provided basic code that they can update and upload in order to calibrate the sensors, test the motors, and run the full robot. Students are required to determine the optimal height of the sensors and the threshold for the sensor output. For the chassis design, students are provided with low-cost materials (cardboard, popsicle sticks, tape, glue, pipe cleaners, zip ties) in order to create a beta-prototype. Based on the results from prototyping students create a CAD version of their final design and are provided the opportunity to create a 3D-printed final version. An example of a LFR is displayed in Figure 2. The LFR project carries the following characteristics: 1. exploring and experimenting with the Arduino kit makes the design process challenging enough to require group collaboration; 2. the provided computer code helps the project to be more achievable; 3. students have the freedom to be creative; 4. students are given the chance to revise their beta-prototype before producing the final prototype.

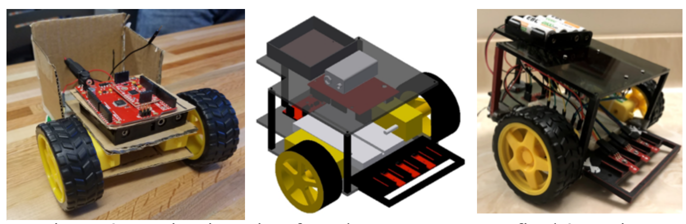

Figure 2: Design iteration from beta prototype to final 3D print

Project implementation The LFR project was initially developed during the summer of 2017 and piloted in the fall of 2017. At this point in time, the project has been assigned in fall 2017, summer 2018, fall 2018, and spring 2019. This section discusses the implementation, reception, and feedback received across the first two semesters, as well as some of the preliminary updates made based off of the initial feedback. Detailed feedback from Spring 2019 will be presented in a future paper.

Pilot Semester: Fall 2017 The project was first introduced at Penn State Behrend in fall 2017 across three honors sections each headed by a separate instructor with up to 20 students. During this semester students started off with the toothbrush dissection project and ended with the LFR project. Each group was asked to submit a 3D print to a printing service on campus and were given extra credit for successfully creating a 3D-printed chassis. The overall reception was positive. Students commented that they enjoyed the open-ended aspect of the project. Some of the requests from the students included clearer instructions, and more guidance and access for the 3D printing process. A detailed description of the implementation and initial feedback can be found in [21].

Fall 2018 The project was introduced to all EDSGN 100 sections: 6 standard sections and 3 honors sections. In this semester the renewable energy application project was reintroduced in order to provide students with both a system-based design project as well as one with strong customer needs. Students in the standard section of the course were prompted to design for 3D printing but delivered beta prototypes at the end of the semester, students in honors section of the course were also required to 3D print their design and were provided feedback on their design prior to printing.

Students were surveyed at the end of both the renewable energy application and LFR projects in order to assess their experience with the project. There were 134 students who participated in the first survey, and only 62 students who participated in the second survey. The surveys included the prompts displayed in Table I along with open-ended questions on “What did you enjoy most about the * project?” and “What could be done so that the * project would be more valuable for you to learn the material?” The * was replaced with “renewable energy application” in the first survey and “line-following robot” in the second survey. For the prompts, students could rank the statement from 1 (strongly disagree) to 5 (strongly agree). The results of the surveys were observed between three student populations: honors, standard, and all the students combined. When comparing average values in the surveys given after each of the two projects, 2 of the 11 prompts were found to have a statistically significant change ($p<0.05$) for all three populations) and five prompts had a statistically significant change for only one or two populations. These prompts are highlighted in Table I and presented visually in Figure 3. Students were also asked to identify what non-technical skills were required for the projects.

The two prompts that had a scored higher across all populations were P7 and P9, which discuss creativity and satisfaction respectively. This matches the assertion from the literature review that an open-ended project (P8) can result in higher creativity and satisfaction. It is interesting that prompts that correlated with internal motivation and accomplishment, P3, P4, and P10 did not have a statistically different change for the honors population while it did for the standard. This could be attributed to either greater internal motivation for students in honors classes, or due to the smaller number of participants in the honors survey resulting in a smaller sample size. The only prompt that had a lower average rating for the LFR project was P6, which related to the real-life application of the project. The similar ratings show what was consistent across the projects. Students felt that the projects were similarly challenging (P1) and both required team work (P2). Although more time was provided for the LFR project, students felt equally satisfied (or unsatisfied) about the amount of time given (P5). Students also provided similar rankings for how the projects allowed them to understand the design process (P11). When asked to identify the skills

TABLE I. Survey Prompts given after the renewable energy application and LFR projects with Index. Bolded items were found to be statistically different across all 3 populations (combined, honors, and standard) while italicized items were different for only 1-2 populations.

Index	Prompt
P1	The * project is challenging.
P2	The * project requires a team to work together in order to come up with a good design concept.
P3	*The * project kept me engaged.*
P4	*I enjoyed working on the * project so much that I was stimulated to keep on working.*
P5	The project allowed the team enough time to polish the design of the *.
P6	*When I worked on the * project, my goal was to generate a design that could be converted to (part of) a functional product in the real world.*
P7	**The * project allows me to be creative in generating design concepts.**
P8	*There was enough freedom to design the * within the limitations of design constraints.*
P9	**It is satisfying to be able to design a *.**
P10	*I feel accomplished after the * project was completed.*
P11	The * project helped me achieve a better understanding of the engineering design process.

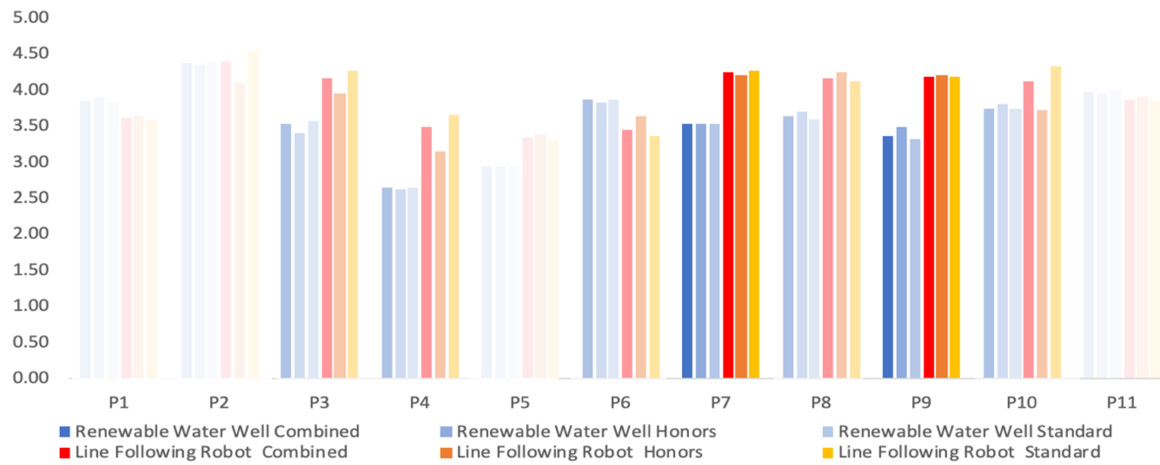

Figure 3: Plot of average rating for the survey prompts. P7 and 9 were found to be statistically different (p<0.05) across all three sections while P3, P4, P6, P8, and P10 were found to be statistically different (p<0.05) across combined sections.

required for the project, teamwork and verbal communication were mentioned by 81% of respondents, 80% mentioned project management, and 52% said writing was a necessary skill.

In the open-ended comments several themes popped up in terms of what the students enjoyed about the project. There were 23 comments focused on making and prototyping, 11 comments on design and 11 on creativity. For suggestions on improvements, 12 comments suggested a change in resources (better quality parts, more variety of choices, sustainable focus), 11 comments on coding, and 9 comments requesting more time offered in the project. The recitation instructors provided their own open-ended feedback via interviews. There were many positive comments about the new project, as well as constructive feedback. They felt that more time was needed, especially for the 3D printing option, and that students needed to improve their time management skills both inside and outside of the classroom. While some believed that the coding requirement was at an appropriate level for beginners, there was a request for a line by line explanation of the code.

Reflection Adding an open-ended project did result in more satisfaction and creativity from the students. Along with a variety of chassis designs, students made the project their own by changing or rewriting the code, using fewer batteries than what was provided, and in Spring 2019 several students developed their own printed circuit board and used a servo motor instead of the options provided. While there is room to expand the project further, it currently does appeal to a wide range of student backgrounds. In future versions of the course, video tutorials will be available for students who wish to know more about coding, robotics, and 3D printing. The LFR project should also be adjusted to provide more application to real-world problems.

First-year engineering projects should strive to be challenging, open-ended, and provide students with hands-on experience that allows them to explore the design process. The projects should emphasize the non-technical skills that engineers will need both during and after their education. By incorporating modern technologies (in this case Arduino and 3D printing) these projects can be a strong introduction of how students will be able to use their technical skills to overcome challenges in the future.

Acknowledgements We'd like to thank the Schreyer Institute for Teaching Excellence at Penn State for funding the equipment of the project. We'd also like to express our gratitude to all the instructors for helping to run the project in Fall 2017, 2018, and Spring 2019 and our dedicated multimedia specialist for photography and videography.

References

[1] S. A. Ambrose, *How Learning Works: Seven Research-Based Principles for Smart Teaching.* (1st;1; ed.) 2010.

[2] W. J. McKeachie, M. D. Svinicki and B. K. Hofer, *McKeachie's Teaching Tips: Strategies, Research, and Theory for College and University Teachers.* (12th ed.) Boston: Houghton Mifflin, 2006.

[3] Worldwide CDIO Initiative. www.cdio.org

[4] P. Lynch, C. de Vries and D. Lewis, "Integrating an effective first year seminar into a freshman engineering design course." *First Year Engineering Experience Conference.* Daytona Beach, FL 2017.

[5] G. Lemons *et al*, "The benefits of model building in teaching engineering design," *Design Studies,* vol. 31, *(3),* pp. 288-309, 2010.

[6] C. Dym *et al*, "Engineering design thinking, teaching, and learning," *Journal of Engineering Education,* vol. 94, *(1),* pp. 103-120, 2005.

[7] R. M. Abdulaal, A. M. Al-Bahi, A. Y. Soliman & F. I. Iskanderani (2011) Design and implementation of a project-based active/cooperative engineering design course for freshmen, *European Journal of Engineering Education*, 36:4, 391-402, DOI: 10.1080/03043797.2011.59849.

[11] L. Carlson and J. Sullivan, "Hands-on Engineering: Learning by Doing in the Integrated Teaching and Learning Program," *International Journal of Engineering Education,* vol. 15, *(1),* pp. 20-31, 1999.

[12] D. W. Knight, L. E. Carlson, J. F. Sullivan, "Improving engineering student retention through hands-on team based first-year design projects", *Proc. Int. Conf. Res. Eng. Educ.,* 2007.

[13] N. Ho, & R. Ryan, (2009). Designing a sequence of design courses to improve student performance and retention at a minority institution, *Proceedings of the American Society for Engineering Education (ASEE) Annual Conference and Exposition*, June, 2009, Austin, TX.

[14] D. M. Malicky, J. G. Kohl and M. Z. Huang, "Integrating a machine shop class into the mechanical engineering curriculum: experiential and inductive learning," *International Journal of Mechanical Engineering Education,* vol. 38, *(2),* pp. 135-146, 2010. Available: http://ezaccess.libraries.psu.edu/login?url=https://search.proquest.com/docview/868491879?accountid=13158.

[16] A. E. Butterfield, K. Branch and E. Trujillo, "First-Year Hands-On Design Course: Implementation & Reception," *Chemical Engineering Education,* vol. 49, *(1),* pp. 19, 2015.

[17] T. F. Schubert Jr, F. G. Jacobitz and E. M. Kim, "Student perceptions and learning of the engineering design process: an assessment at the freshmen level," *Research in Engineering Design,* vol. 23, *(3),* pp. 177-190, 2012.

[18] E. F. Barkley, *Student Engagement Techniques: A Handbook for College Faculty*. (1st ed.) San Francisco, Calif: Jossey-Bass, 2009; 2010;.

[19] R. Wentzel and J. E. Brophy, *Motivating Students to Learn*. (Fourth ed.) New York: Routledge, 2014.

[20] A. Wigfield and J. S. Eccles, "Expectancy–Value Theory of Achievement Motivation," *Contemporary Educational Psychology*, vol. 25, *(1),* pp. 68-81, 2000.

[21] C. De Vries and Q. Dunsworth. "Making it for real: Redesign of a First-Year Engineering Project." *2018 IEEE Frontiers in Education Conference (FIE),* 2018, San Jose, CA.