Junior Design for Electrical and Computer Engineers: A Novel Course for Discipline-Specific Instruction of the Engineering Design Process

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***Abstract*—This innovative practice full paper describes a novel design course for electrical and computer engineering students. In the class, students are taught the basics of the engineering design process in the context of electrical and computer engineering applications. Students are guided through a series of three design (ECE) projects, increasing in scope and difficulty, that involve the design of various electronic hardware and software components. In addition to teaching students the design process, well before their capstone design experience, the class is also designed to provide industry relevant exposure to ECE design tools and methodologies. Several examples of student work are provided as well as results from assessment of student learning. The results show that the course excels at preparing junior-level students to tackle the challenge of complex system design.**

Keywords—Design Education, Electrical and Computer Engineering, PCB Design, hands-on design

I. Introduction

Junior Design is a newly developed course that is taken by all electrical and computer engineering (ECE) students at the University of Pittsburgh, before their senior year. The course was born out of two observed needs: First, there is a need for students to learn the design process before their senior capstone project and to do so within the context of their discipline. Second, there are several practical hands-on skills, both hardware and software, that future employers of ECE graduates covet (e.g., soldering, Printed Circuit Board (PCB) design, use of off-the-shelf IC components, 3D modeling, version control, Agile development, etc.) but are difficult to fit elsewhere in ECE curricula.

This course addresses those needs, and more, in a semester long course. The course is centered on three main projects, each increasing in scope. The first project serves as an introduction to ECE design via the development, manufacturing, and testing of a custom PCB. Students are charged with developing a novel design that employs a 555-timer chip. The second project is team-based and students are required to develop a toy. During this project, students go from concept to a final product complete with packaging and appropriate user-interfaces. The complexity of the project is such that a microcontroller is required and students are taught basic software engineering skills and introduced to development methodologies (i.e., Agile). For the final project, students are encouraged to pursue a personal project (software or hardware) that aligns with their future career goals and builds on the skills that the learned earlier in the course.

In this paper, we present the structure of the course, the details of the assignments and assessment results. The direct assessment of student projects, via a rubric, is presented. The rubric is designed to allow for an evaluation of student ability to successfully apply their knowledge of the design process to their own design. In addition, the results from several student surveys are presented as well as lessons learned, instructor reflections and recommendations for future offerings..

II. Course Structure

The course, "Junior Design", is semester-long course that is required of all junior-level Electrical and Computer Engineering students at the institution of this study. The course is typically taken in the students' junior year and is a pre-requisite to their capstone design course. While completion of the course prior to enrollment in the engineering capstone is required, it is not part of a two-semester capstone course sequence. Students do not work on their senior capstone projects nor do they even spend time on capstone project ideation. Rather, the course is designed to stand alone, and the learning outcomes are intended to be very broad. There are several simultaneous, primary objectives of the course:

1) Teach students the engineering design process, in the context of Electrical and Computer Engineering (ECE) before engaging in a capstone experience.

2) Expose students to technologies and hands-on-skills that are coveted by employers of ECE students but are often missing from curricula

3) Build students' engineering design self-efficacy in their ability to complete a large-scale design project and go from concept to prototype.

The course has several assignments that are all centered around three main projects. The first project is the design of a \`of the course is the design of a toy. Finally, students are tasked with putting the skills they learned to practice by conceiving prototyping and testing a design on their own.

A. Design Project #1: Introduction to PCB Design and the Design Process

The first design experience is simple and intended to introduce students to the engineering design process: Problem definition, identification of constraints, brainstorming of multiple solutions, selection of best candidates, prototyping, testing, iteration and then communication. While the basics of the design process are often taught early in engineering curricula, they are not always taught to students in the specific context of their discipline. So, this instruction is given in the context of the design of an electronic device requiring a printed circuit board. Focus is then placed on just one integrated circuit in particular, the 555 timer[1]. The 555 timer is a programmable oscillator and is referred to as the most widely used IC in history[2]. It is flexible and can be used in variety of applications, especially popular with hobbyists and makers. The appeal of the 555 timer for instruction is its simplicity, yet, ability to be used in a wide range of applications. Internet searches reveal the use of 555 timer in hundreds of interesting, creative projects.

A handful of assignments are used to introduce students to the equations that govern operation of the 555 timer and how to simulate it in SPICE. While the use of SPICE is common in ECE education, it is often first introduced in the context of Linear Circuits or discrete electronic components, such as diodes or transistors [3]. However, it is not often used in the context of entire integrated circuits, which is how SPICE is intended to be used and used in real-world situations. Beyond just electronics, the incorporation of simulation important prototyping step in several design contexts.

The follow-up assignments are then geared towards instruction of Printed-Circuit Board (PCB) design. Students are first asked to create a standard 555-Timer astable oscillator circuit as a PCB [1]. In addition to the basics of PCB placement and routing, students are taught electrical engineering considerations such as signal integrity, grounding, reliability and cost optimizations and several other engineering-relevant considerations that go beyond simply transposing schematic connectivity to a layout form. While instruction on Printed Circuit Board design in electrical engineering education is not unique, and occurs at several universities, it is also non-standard and varies greatly from institution to institution[4,5]. Thus, programs choose to introduce it in their own way such as experiential learning, as a smaller part of a larger project or explicit instruction. In the course of this study, about a third of the semester is dedicated to the engineering principles needed to design professional printed circuit boards. Thus, students come out of the course with industry-relevant skills that are highly sought after by employers.

After students learn the basics of the 555 timer, how to properly simulate its behavior and make a PCB, they have all the tools necessary to create their own design. Given the simplistic nature of the 555 timer output, an oscillator, students struggle with coming up with their own design that is completely unique.

The pedagogical challenge for instructors of electronic design is in crafting a design scenario such that early-stage students can participate and be required to make several design decisions on their own. So as to scaffold students in their journey, this teaching challenge is resolved by asking the students to find an existing design online that uses a 555 timer, and then propose a modification to the design to make it their own in some way. Student proposals range from modifications to user interfaces (e.g., buttons, switches, sensors, etc.) to altering the core functionality of the design in some way that significantly changes the circuit design, and thus an novel PCB design.

Figures 1-5 show an example of the process and steps students use to complete their very first design. The fist example provided is from a student that decided to create a "fire alarm". In their research, they found two circuits of interest: a 555-timer LED flasher and a 555-timer buzzer. This student decided to combine those circuits, alongside a thermistor, to create a circuit that flashes light and makes a siren sound when placed close to a heat source. The top of figure 1 shows the

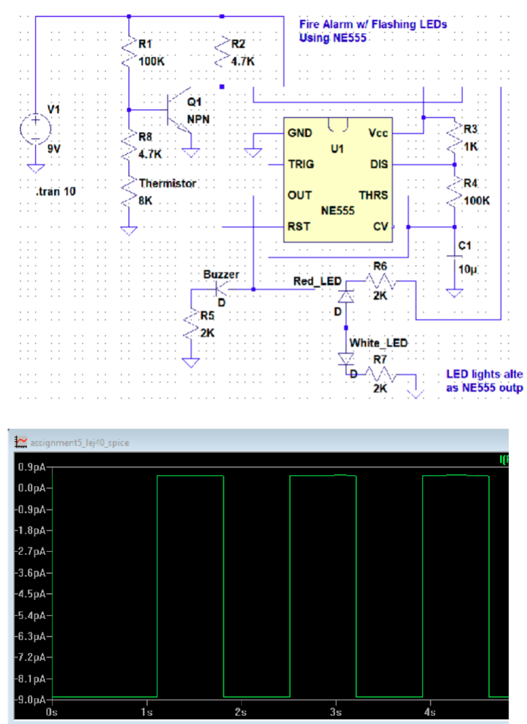

Fig. 1. Example student 555 timer design and preliminary simulation results displaying the current that goes through one of the LEDs

initial schematic they used to simulate their design and the bottom displays some of their preliminary simulation results. At this stage, the student works out the details of the design, including necessary resistor and capacitor values. The top of figure 2 shows a portion of their breadboard level prototype. This stage of the design allows the student to debug certain issues and nonidealities that appear when actual circuits are used. Finally, the student designs a PCB implementation (figure 2 middle) and then solders, packages and tests it (figure 2 bottom).

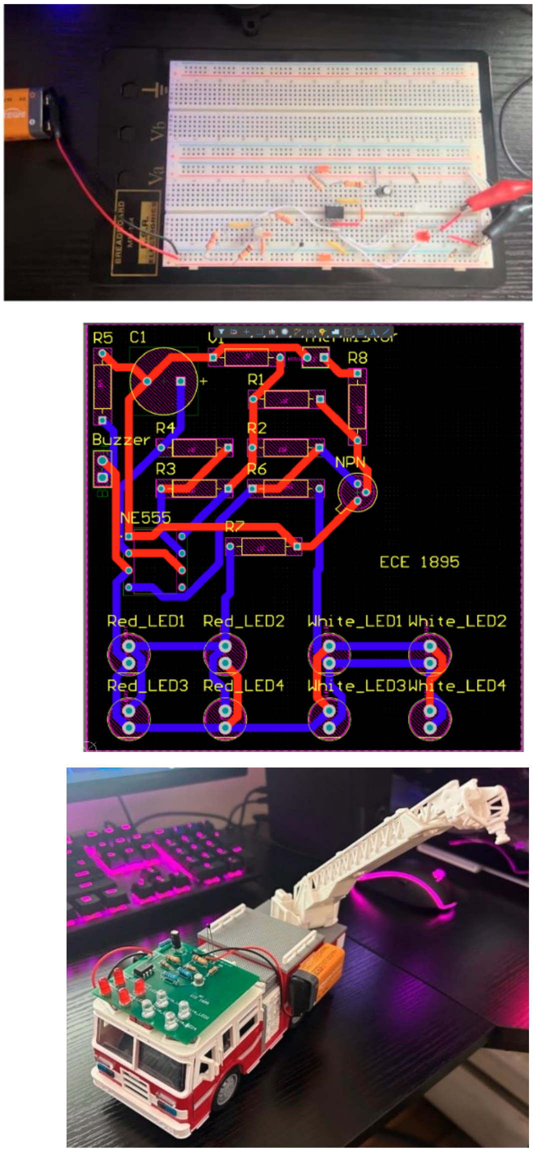

Fig. 2. Student example showing a breadboard level prototype designed to replicate the simulation of figure 1 and the final PCB layout from. The bottom of the figure shows the final assembled prototype.

Figures 3 show a few more representative examples so that the scale, scope and variety of designs can be seen. The first example is an EMG muscle contraction visualizer, based on readily available LED chaser circuit (a 555-timer circuit by which LEDs light in sequence). This student modified the common chaser circuit by having the time constant of the oscillator modulated by an EMG sensor.

The 555 timer is commonly used to create Pulse-width modulated motor control circuits. Another popular 555 timer circuit is one to create Infrared sensors One student made a creative design that combined the two to make a device that can wireless control the speed of a DC motor.

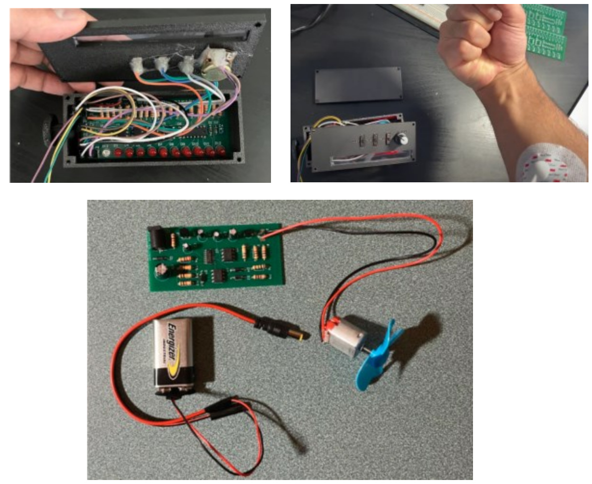

Fig. 3. Additional examples of student projects. The top shows an EMG meter and the bottom shows a wireless DC motor controller. All designs require the use of a 555-timer integrated circuit.

The examples shown here are just a few examples from among many. Each student works independently and no two designs are identical. This project serves as an excellent introduction to the engineering design process, all the while teaching them how to create functional and efficient printed circuit board designs and is a good lead in to their second major design experience.

B. Design Project #2: Design and management of Hardware/Software Systems

The second major design experience builds on the first experience, but is expanded and adds several new dimensions. The students are tasked with the design of a toy. Unlike the first experience where they are asked to work by themselves, students are placed in a team. The complexity of the design necessitates the use of a microcontroller and so students must also must adopt hardware design and software development roles to implement the project. This project is designed to mimic a real-world experience. Thus, students are introduced to simple AGILE[6] development techniques to manage their project and are asked to use them throughout the design. Students are also asked to manage their software using a version control platform (i.e. GIT [7]). This design experience is especially unique for the electrical engineering students in the course, it is their first and only opportunity for most of them to receive formal instruction on software engineering principles and project management methodologies such as AGILE, topics that are often excluded from electrical engineering curricula.

The requirements of the toy are given to the students. The toy is to loosely mimic the popular toy Bop-It!. This toy is such that the user receives a cue to perform some sort of action, from among a small set of varied possibilities, and they must respond within a finite period of time, else lose the round. Leading up to the design of this “Simon-says”-like game, students are given small assignments that provide basic instruction on how to use

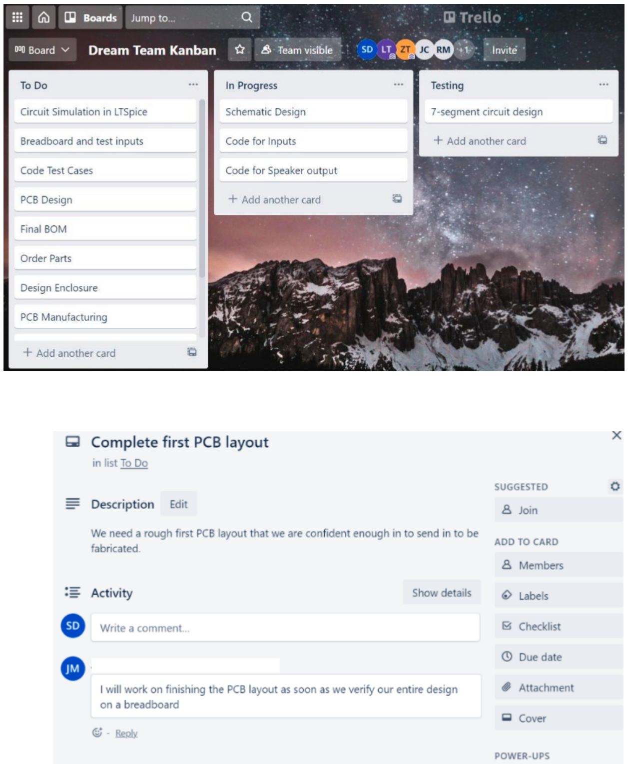

Fig. 4. An example student team Kanban and Kanban "card" used to manage design project #2

and manage a code repository using GIT. Since this is not a full-on software engineering course, it is vitally important to be judicious in how AGILE development is introduced. After the basic concepts are discussed, one important element is put to practice, the use of Kanban[8] to manage team assignments. A Kanban is a workflow management method whereby the engineers uses cards (either physical or virtual) to enumerate work items, assign responsibility and deadlines. Figure 4 shows an example student Kanban assembled for the second design project.

There are two additional challenges presented to the students that they must account for in their design. First, since they are being tasked with the design of a product and they are electrical and computer engineers, the expectation is that they will not use development boards (e.g. Arduinos, Rasberry Pis, etc) in their final product , but rather, select an off-the-shelf microcontroller this is best-suited for their design. This requires that students learn how to load software using hardware programmers. The other challenge presented to the students is that they must seriously consider the overall packaging and presentation. Since the product is to be a toy, it is asked that their final design reflects that of a product a user would want to purchase. This part is especially challenging for ECE students as 3D modeling is also typically not part of their curricula.

Figures 5 and 6 show representative outcomes from the second design project. As can be seen from the examples, there is a wide variety of creative themes and interfaces used. For example, (a) shows a design in the context of sustainable energy, whereby students must spin a turbine, lower a nuclear fuel rod or shine light on a solar panel. One group (b) designed a dog-themed toy whereby the user must press a big button, bark or shake the enclosure. Figure x shows an example where student designed a toy whereby students need to mimic actions that take place when fishing. Finally, figure x shows an example where students made a creative glove interface that has actions tied to different fingers and gestures. These examples are just a small subset of the many creative designs that students complete. Although all very different, they all are based on the same requirements, have the same constraints and help students to learn the same outcomes.

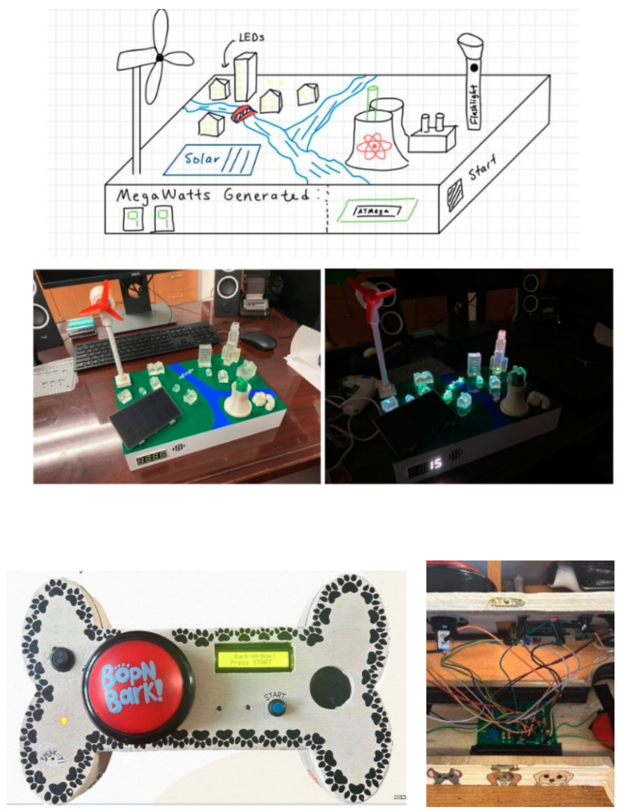

Fig. 5. Example outcomes from the second design project. Top shows an example situated in the context of sustainable energy and the bottom shows one with a pet theme. All designs utilize a variey of sensors, microcontrollers and packaging design.

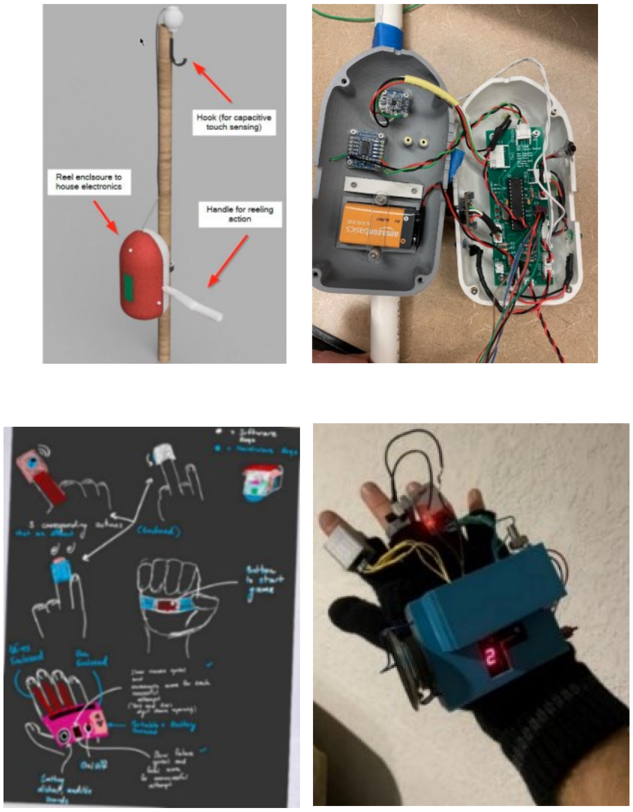

Fig. 6. Additional example outcomes from the second design project displaying the variety and creativity of the projects completed by students

C. *Design Project #3: Individual Design Project*

The final project of this 15-week, junior-level course is an individual design project. The students are encouraged to conceive, prototype and test a project that they can completely, individually, within the span of 6 weeks. The students are not provided any requirements or constraints. Each student is encouraged to propose a project that is of special interest to them and in some way help them further their career goals. Students propose, and follow through on projects that range from being grounded in hardware design, software development or a mix of the two. Care is taken by the instructor to review proposals and help the student to modify them to be of appropriate scale and scope. This project being individual not only helps ensure that the student selects a project that they will be motivated to work on, it also provides an opportunity for the instructor to assess the students individually.

To show the breadth of projects completed by students, three are shown that represent the types of projects typically proposed. The first is an analog electronic design that is a miniature “robotic arm”. Using simple analog circuits and a microcontroller, this student designed a rudimentary arm with two joints. For a senior capstone course, the expectations for a robotic arm would be much greater. However, this project is a significant undertaking for a junior-level student to go from conception to prototyping within the span of 6 weeks and sets them up for much more ambitious projects later on in their program of study.

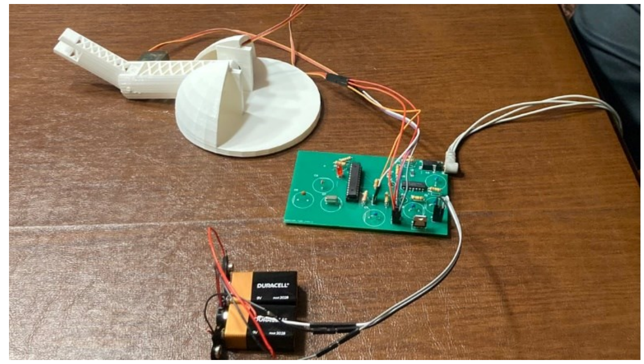

Fig. 7. Example hardware-oriented final project, a miniature robotic arm.

Some students propose designs that are a mix of hardware and software, such as the IoT cat feeder of figure 8. that allows a user to remotely schedule and dispense cat food via a software application. Care has to be taken in helping the students scope the project for a span of six weeks. Thus, the complexity of some projects are such that certain elements, such as PCB design, can be removed in favor of other core components (e.g. software application development).

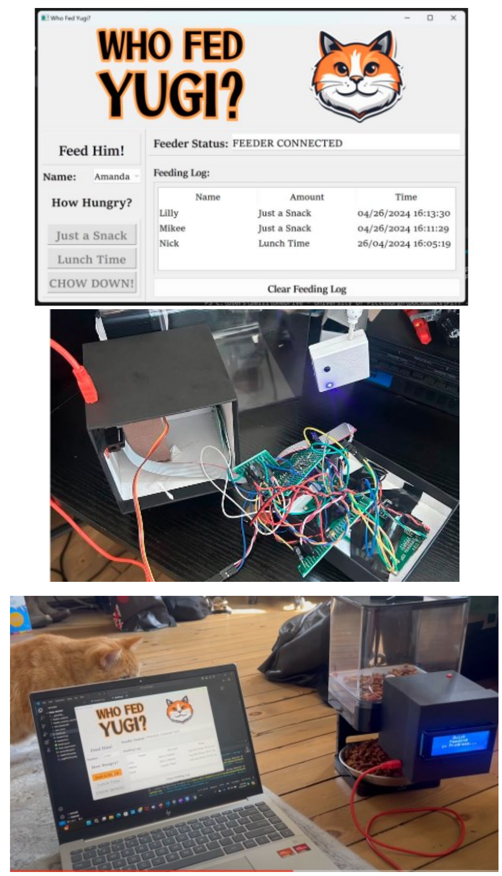

Fig. 8. Example Hardware/Sofware final project, an IoT cat feeder

Many ECE students do not wish to pursue a career path that involves hardware design and wish to be on a path to help them become software engineers. Those students are given the option to do software-only projects. The project of figure 9 shows one such project. This student proposed the design a 3D traffic simulator. The project was organized as a complex software engineering project complete with well-defined requirements and utilization of object-oriented programming. The bottom of figure 9 shows the organization of the software classes developed for this particular project. No matter the form of the final project, the workload and final expectations are roughly the same, as well as the learning outcomes, putting knowledge of the engineering design process to practice.

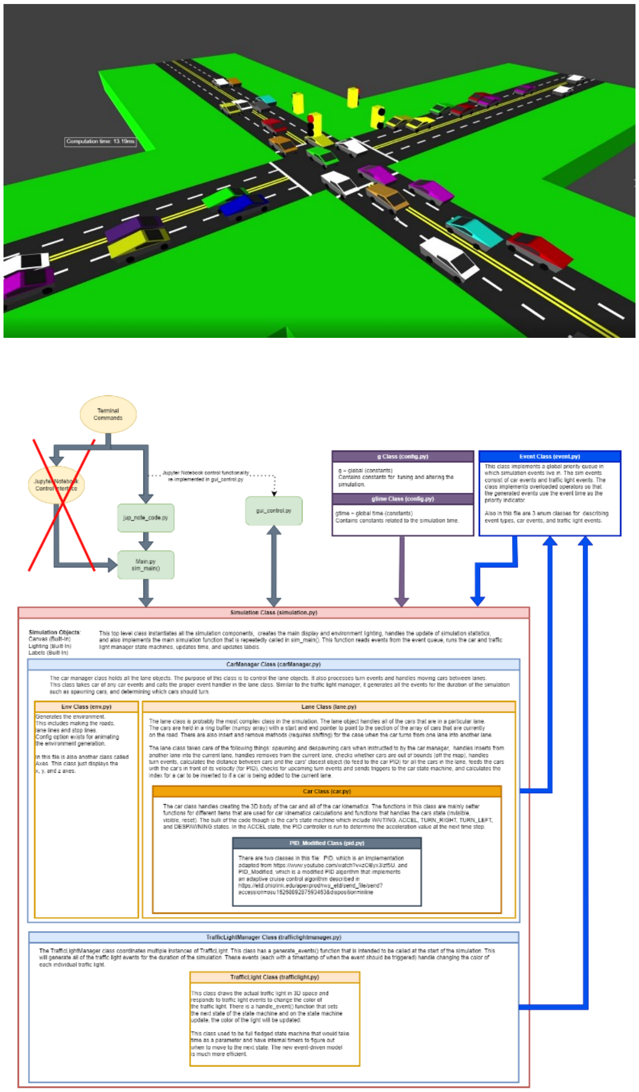

Fig. 6. Additional example outcomes from the second design project displaying the variety and creativity of the projects completed by students

III. Assessment of Student Learning

To assess student learning and the effectiveness of the course, both direct and indirect measures were used. For the direct assessments, results from the final, individual project were looked at. A rubric was used to evaluate the completeness and quality of their final result. The rubric is shown in Table 1. Unsatisfactory projects were those for which students fell significantly short of their original goals and the project was nonfunctional. Students classified as 'developing' were those that successfully implemented some core features of their final design, but some significant ones were either missing or flawed. Satisfactory outcomes are those for which the majority of the proposed project was successfully completed and demonstrated. Finally, exemplary projects were those for which all proposed features were successfully demonstrated.

Table 1. Rubric used to assess student outcomes on the final project

Assessment Rubric	
Unsatisfactory	Project mostly nonfunctional
Developing	Implemented some core features, several missing for significantly flawed
Satisfactory	Project mostly completed and functional, flaws are not significant
Exemplary	Project successfully completed, no major flaws, all requirements satisfied

The class sampled for this work had 65 students enrolled. Table 2 shows the results of assessing the projects according to this rubric.

Table 2. Results from assessment of student projects

Assessment Results (n = 65)		
Rating	**# of Students**	**%**
Unsatisfactory	14	21.5%
Developing	2	3.1%
Satisfactory	22	33.8%
Exemplary	27	41.5%

In a post-survey of the course, students were asked to rate the degree to which assignments contributed to their understanding of the course subject matter. A total of 21 students responded to the survey and reported a mean rating of 4.62/5.00 using a 5 level Likert scale (1 strongly disagree up to 5 for strongly agree). Some of the open-ended comments were as follows:

" I learned a lot about the engineering process in the work force in this class. It really showed me how much time things take and often times the network of people and companies that are needed to design quality products."

"Starting with projects with a forced theme helped initialize creativity but focus on actual skills learned before letting us loose"

" The openness to project ideas and driving personality helped me stay with projects that I may have otherwise dropped which lead me to learn more that I would have."

IV. Discussion

The results of the assessment that the course was overall successful in its goal to teach students how to apply the engineering design process to conceive, prototype and test a solution. A total of 75% of students enrolled in the studied offering were able to perform at a satisfactory or above level of performance. This is a very significant outcome given the early stage of the students who have yet to embark on their engineering capstone experience. It is interesting to note the bifurcation of outcomes with the final project, students tended to do very well or poorly. It is believed that more work needs to be done in helping students to appropriately scope their design project. Due to the open-ended nature of the final project, students are very excited about it. However, an assessment of whether or not a particular project is appropriately scoped also depends on the capabilities of the individual student, and that has to be somehow taken into account. Nonetheless, as demonstrated by the student surveys and comments, the students came aware from the course with a feeling that they learned how to be better engineers.

Acknowledgment

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