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A Project Based Online Experimentation Course

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Development of a Project-Based Online Experimentation Course

ABSTRACT

This work focuses on creation of a project-based online Engineering Experimentation course in a Mechanical Engineering Department. The course is offered online and students are required to purchase a $100 kit that consists of a microcontroller (Arduino or Raspberry Pi), boards, cost effective sensors, actuators, and transducers. The class is structured to have six experimentation modules and an open-ended experimentation project. The contents of the experimentation modules are designed to educate the student on the most essential and fundamental skills necessary to construct complex experimentation setups. These experiments involve integration of several measurement sub-systems. In each formative module one experimental technique is addressed. Module one teaches students the fundamentals of microcontrollers and data acquisition with these cost effective devices. Module two focuses on temperature measurements through the use of a variety of temperature sensors. Students also learn about the theory and application of voltage dividers in this module. Module three uses ultrasonic proximity and infrared motion sensors to teach displacement measurement. Module four's objective is to teach experimental techniques for using DC, servo- and stepper motors. Module five involves concentration measurement of different chemicals. In the module six, students measure strain on a thin-walled pressure vessel, a soda can. This involves discussions on analog to digital conversions, use of a Wheatstone bridge and uncertainty analyses. Students document each module with a written and video report. The written report must be sufficient that the module could be executed by another technical student without further assistance. The video report must illuminate the student actually doing the wiring and discussing the project as they configure and execute it. This latter reporting mode significantly reduces the need for additional verification that the student performed the module. Students have an open ended project as well that involves integration of at least three measurement or actuation sub-systems. These projects are student-proposed early in the class offering with periodic status updates. Students are not restricted to the sensors that were in the formative modules. They can use a variety of sensors or actuators for their projects. Project work can be conducted in teams of two students that are connected online. The instructional team reviews the student-proposed topics to ensure the feasibility of it. The final delivery of the project is a working prototype and a report that delineates the task of the prototype, theoretical information that pertains to the design, materials and methods, results and conclusion on the project.

INTRODUCTION

Increasingly our appliances, machines and even the clothes we wear are equipped with sensors. As educators, we need to educate our emerging workforce to design, fabricate and maintain these new "smart" appliances. Through the maker movement [1] many high school students are familiar with smart technology equipment before arriving on our campuses and our challenge is to engage them in developing a more rigorous engineering approach to the design, testing and deployment of sensor systems. In response to this challenge we have introduced a new course: Online Project-Based Engineering Experimentation. The course is project-based and designed to operate in both a blended format, online with classroom labs, and fully online.

Recently the topic of project-based learning for first-year college experiences delineated how to incorporate project-based learning (PBL) into the classroom and curriculum [2]. Limiting the field to engineering still involves numerous investigators. The work of Fini *et. al.* has quantified much of the PBL assessments in terms of self-efficacy, teamwork, and communication skills in the civil engineering environment [3]. The work of Han *et. al.* on Hispanic students showed that PBL had a significant impact on students who were not at risk, albeit the impact was not realized by those identified as "at risk" [4]. Most of the existing research on PBL addresses residential (i.e. in class) and flipped classrooms environments. As noted in the 2019 ASEE Annual Conference for the division of "Experimentation and Lab-Oriented Studies" the online involvement of PBL towards engineering experimentation was virtually absent [5].

The objective of this paper is to demonstrate the applicability of an online engineering experimentation course that empowers engineering students to attain hands-on, applied engineering experimentation experiences within their normal dwellings. This course uses inexpensive, yet reasonably accurate sensors and data acquisition systems. An objective of the course was to deliver students the workforce skills that would be useful in start-up companies or non-profit organizations where resources for experimentation equipment is limited. The skills developed within this online offering allow the students to make meaningful experimentation measurements in a resource limited environment. In addition the use of modular equipment, such as low cost microprocessors and sensors, is an ideal opportunity for open-ended design projects to illuminate engineering experimentation. The sensors and components comprising these laboratory endeavors allow students to test, refine, and change ideas in rapid succession with minimal cost within the design process.

DESCRIPTION OF THE COURSE

An engineering experimentation course is required for mechanical engineering programs to be ABET certified [6]. Traditionally, this course was taught with state-of-the-art data acquisition devices and high-quality sensors such as platinum resistance temperature detectors. The individual components are stored in an engineering laboratory and students need access to the laboratory to use measurement equipment. This newly introduced course is an alternate that fully addresses the ABET requirements for engineering experimentation, but gives the student a great deal of freedom. It is designed to be offered online, with modular laboratory equipment that can be disassembled, reassembled and is cost-effective, and portable. The objective is to facilitate online students using their personal spaces, such as dorm rooms or apartments, to complete their experimental measurements, data collection and analyses.

We are currently teaching the course via an online delivery mode to 85 students. The key differences compared to traditional engineering experimentation courses are (1) it has an open-ended project; (2) students use cost-effective and modular equipment that are very suitable for open-ended projects, and (3) they can do the entire course in their local environment. The online course is structured to have 6 learning or formative experimentation modules followed by a summative open-ended experimentation project. The contents of the formative modules are designed to teach the most essential skills and fundamental physics associated with each module's learning objectives. In each module one experimental physical change is addressed (temperature, pressure, velocity, etc.). A primary course learning objective is to prepare the student to be able to construct complex experimentation setups that involve integration of several measurement sub-systems.

Learning Outcomes

The Online Project-Based Engineering Experimentation course has the following learning outcomes,

- Students develop the confidence to assess a problem and recognize what must be done to design, conduct, and document an experimental investigation.
- Students develop the skills to be able to report the statistical confidence of experimental measurements.
- Students develop proficiency in the area of electronic instrumentation and computer-based data acquisition systems.
- Students develop the knowledge to recognize the limitations and constraints of investigation modes, be it analytical, computational, and/or experimental.

Course Logistics

Students taking this course utilize economical sensors and controllers to design and conduct engineering experiments. Students purchase and retain these controllers and sensors for subsequent applications in other courses and their individual projects. The student expense is less than a typical course textbook. The equipment to complete the course requires a collection of sensor, circa $75.00 including sensors, wires, and other supporting circuits. The student have their choice of prototyping boards, an Arduino with a USB cable and power supply and/or a Raspberry Pi including a power supply, video cable, and 32 GB microSD card that has a preloaded operating system for the Pi. Students purchase the sensor box and one (or both) of the controllers. Any version of the Arduino Uno, or the Raspberry Pi Version 2+ and beyond is compatible with the course experiments. The sensors are itemized in the following section under modules.

Prototyping Boards

Arduino Uno is the most popular and documented board of the Arduino family. It is a board based on ATmega328P microcontroller. It has multiple analog and digital inputs and outputs, a 16 MHz quartz crystal, and it is programmable via an USB port. The Arduino software (IDE) that is available for download or online use allows one to write and upload programs to Arduino Uno. Arduino Uno has a 10 bit multi-channel analog to digital converter. The default full scale range voltage is 5 V but one can adjust this value using external reference pin. Its theoretical maximum data acquisition rate is 9.6 kHz. Our kit included a USB cable for connection to a PC.

We also used Raspberry Pi 4 Model B in this study. Raspberry Pi is a single board computer that has a 1.5 GHz processing speed, WiFi and Bluetooth connections, a Linux operating system (Raspbian), and 40 general purpose input-output connector pins. The kit included a 5.1V power supply for the Pi, an HDMI cable, an 8 channel 10 bit Analog to Digital Converter (to match the Arduino accuracy), and a 32 GB microSD card preloaded with operating system Raspbian. Students are responsible for obtaining keyboard/mouse and a monitor for their Raspberry Pi’s. Both board kits also included a base plate for securing the microcontrollers and a breadboard.

For the 85 students enrolled in the class, 68 Raspberry Pi units and 43 Arduino units were purchased by the students indicating a strong desire to be able to use both units.

Students were introduced to the main differences between these two prototyping boards in the first online lecture. The rule of thumb is that Raspberry Pi is a stand-alone computer with better processing and memory capacity, and therefore, it is suitable for complex tasks that requires intensive computing. Arduino boards are simpler to use but can handle simpler tasks that are repetitive in nature. Students are given two example projects that illuminate the advantages of an Arduino and the Raspberry Pi. As indicated previously, students could choose to use both of the boards, which many students did.

ONLINE MODULES

This course included 6 learning or formative modules and an open-ended summative design project that wraps around the technical skillsets within the 6 learning modules. Learning modules are structured such that they consists of four levels that provide a scaffolding for student learning. Level 1 modules (modules 1-3) include detailed procedural instructions that take students step-by-step delineating how to construct the experimental setup and how to acquire and process the data for a given topic. Level 1 entry modules introduce the students to the basics of prototyping boards, their usages, coding, and understanding. Multiple sensors are introduced at this level with full descriptions of the circuits, the voltage, amperage, and power requirements. Time is spent educating the students on deciphering the sensor datasheets. Level 2 modules (modules 4-5) involve less detailed instruction sets with references to Level 1 circuit diagrams, constraints and procedures. In level 2 modules students need to plan an experiment and determine the necessary procedure to complete the experiment and attain the learning objectives of the module. The level 3 module (module 6) required the student to read technical specification sheets for the sensors and actuators, to create their own circuits, experimental procedure, and source coding to satisfy the objectives of the module. Completion of level 3 modules build students' confidences to independently run experiments. Level 4 is the summative open-ended design project where students can work in pairs or work independently on a design challenge they proposed within a week of the course start. While the formative modules (1-6) involve a single sensor or actuator operations, the summative open-ended project requires students to design a complex setup which uses a minimum of 3 sensors and/or actuators to operate the student-proposed open-ended project.

Within each module, multiple sensors are discussed that address the goal of the module. Students are free to select which sensors they will use to accomplish the experiment.

Each module is described subsequently.

Module 1

The first module introduces the students to the fundamentals of programming a prototyping board, a review of circuits, breadboards, simple sensors (LEDs, Buttons, Potentiometers) and data input/output. An online lecture introduces the prototyping boards, and consequently, students are given laboratory exercises. The learning objectives of the first module are:

Students learn how to use and program an Arduino and/or a Raspberry Pi, including,

- Basic structures, void setup, void loop, conditional statements
- Digital I/O, including pulsed width modulation signals
- Analog I/O
- Serial Connection and Monitor, and
- Python/Arduino interface

Students are exposed to sensor datasheets and the constraints on the applicability and use of sensors including,

- Forward voltage and current constraints
- Voltage divider analysis and construction
- The use of pull-down, pull-up resistors and circuits

This module includes three exercises that build one on another. The experiments cover blinking an LED, turning an LED on and off using a button, controlling the brightness of an LED with a pulse-width modulated signal, brightness control with a potentiometer, and using inputs to control the prototyping board.

Module 2

The second module introduces the fundamentals of temperature measurements. The module starts with a lecture that involves the use/importance of temperature in many disciplines including everyday life, not just mechanical engineering. Several temperature measurement sensors are introduced including, resistance temperature detectors (RTDs), thermistors, infrared temperature sensors, thermocouples, and silicon bandgap sensors. Their application ranges, costs, accuracies and durability are discussed. This affords the students the opportunity to develop a trade space analysis to select the appropriate sensor(s) for the experiments presented. Understanding trade space analyses generalize to other sensors and more globally for the student to product design in real-world situations. The students select a minimum of two experiments presented, each with a different sensor for the measurement of temperature.

The learning objectives of this module are:

- To acquire and interpret physical changes in two sensors as a function of temperature change.
- To select/create software coding and circuit design to successfully input sensor information and output meaningful temperature information.
- To reduce measurement errors thru the use of statistics, regression analyses, and calibration.
- To view the trade space and determine methodologies to down select component selections.

Module 3

In the third module students were introduced to proximity sensors that measured distance and/or motion. The lecture for this module included a theoretical background for passive infrared and ultrasonic proximity sensors. The advantages and disadvantages for both sensors were discussed.

The experimental exercises include displacement measurement using infrared and ultrasonic sensors as well as motion detection activities.

The learning objectives of this module were to utilize proximity sensors for displacement measurements, motion detection, sensitivity measurements, and peripheral interference effects. Data was gathered and subsequent error analyses performed.

Module 4

Module 4 experiments involve actuation in contrast to the previous modules where sensor inputs were studied. In this module, students conducted experiments with DC, stepper, and servo motors. In the lecture of this module, general characteristics of AC, DC, stepper, and servo motors were introduced. A generic torque vs. rotational speed curve is discussed in the lecture. Differences in terms of motion control between stepper and servo motors are discussed. Finally, motors are discussed in terms applications in which they are used.

The learning objectives of this module are to gain competency in controlling motors with prototyping boards. Students learn how to program an electronic motor driver. They construct a circuit that involves a DC motor, a motor driver, a rotary potentiometer, a prototyping board, and other required components.

Module 5

Module 5 involves concentration measurement of different chemicals. The lecture for this module included discussions of various scales that involve characterizing concentrations. These include molarity, pH, ppm, and similar scales. The experiments involve determining volatile ethanol concentration in a simple bioreactor that could be made at home. Students grow *Saccharomyces Cerevisiae* (baker's yeast) in a sucrose buffer and measure the ethanol concentration in the simple bioreactor during ethanol fermentation. A metal-oxide (MOX) gas sensor is used for this purpose. Students, furthermore, seek correlation between the time variation of the ethanol concentration and yeast cell density. Again, the online and student engagement focus of this course allowed other measurements to be collected. As illuminated at the raspberrypi.org site, a methane (or fart) detector is available, or as shown in the Sparkfun alcohols sensor a breath analyzer could be constructed [7,8].

The learning objective of this module were to utilize a chemical sensor for biomass and/or concentration characterizations.

Module 6

Module 6 involved experiments to measure strain on a thin-walled pressure vessel, a soda can. Students measured the change of strain as a soda can is opened. The lecture involved a discussion on strain, strain-gage principles of operation, and Wheatstone bridges. Discussions also included analog to digital conversions relative to the Wheatstone bridge and the requirements of resolution.

The learning objectives of this module were to utilize bridge circuits for data acquisition, analog to digital conversion parameters, and equipment design such that data acquisition was possible. Additionally measurements uncertainty analyses were performed.

OPEN-ENDED DESIGN PROJECT

The purpose of the open-ended design project was to construct a device that utilized a minimum of 3 sensors and/or controllers. Students proposed their projects, the class refined them and the instructors restrained the ideas to realistic endeavors. Several student generated projects included building an automatic plant watering system. A photo-sensor controlled a motor to raise or lower a shade depending on the sunlight intensity. A hygrometer measured the soil moisture and controlled a solenoid to open a gravity feed water source if the plant needed to be watered.   Another student project was the use of pressure sensors in shoes to record the pressures of a golfer during tee-off. Others suggested using servo and stepper motors to have an automatic eyeglass cleaning device. The ideas and projects flourished from meteorology devices to body monitoring devices. The student options are endless and engaging.

STUDENT DELIVERABLES AND ASSESMENT

Deliverables

The six learning modules and the open-ended project require video and written reports due at the end of modules and the project. The written report has the typical components of a laboratory report, namely, cover page, lists of figures and tables, abstract, introduction, materials and methods, results, conclusions and recommendations, references, and appendices. The target size for the report is about 5 pages in length (excluding cover page, list of figures, figures and tables). The function of the video report is to obtain an audio/visual verification of the experiment and coding in students own perspective to ensure the student’s mastery on the experiment. A target length of the video is 5 minutes. In the beginning of each module, students also need to post and reply to questions on the contents of the module in the discussion board of the learning management software. This last deliverable accounts for the participation grade.

In addition to the above deliverables, the open-ended design project has four additional deliverables. Students define their own projects that identify a minimum of 3 sensors/controllers/motors/etc. Using a one minute video-recorded and one page written proposal each student proposes their open-ended project. Groups of 10 students (faculty selected) review the 10 student-proposed projects and nominate a minimum of 5 projects to pursue from the group of 10. Essentially, one can pursue their faculty-approved project, or team up with another student and do one jointly. Each proposed open-ended project has milestones due at multiple gates (1/4, 1/2, 3/4 and final) to keep the student progressing towards their successful completion of the project.

Assessment of Student Work

A holistic approach is followed in creating the rubrics. Criteria for evaluating the learning module video deliverables are:

1) The overall objective of the experiment is identified and satisfied.
2) Technical Merit: Video explains the overall working principle of the experimental design in connection with the computer coding.
3) The experiment conducted is reasonable using available resources.
4) The video is concise.

The rubric levels are: 100% when the presentation meets all the criteria. The working principle of the experiment/design is clearly shown. A level of 80% is good including a well-prepared video, albeit some items are missing, such as unexplained components inadequate wiring or the like. A fair or 60% presentation is weak in several of the criteria listed previously. The design or experiment is not clear or experiment fails to operate as intended. A 40% presentation fails to meet the majority of the criteria.

The overall criteria for evaluation of written reports are as the following.

- Inclusion of all content indicated in the breakdown of the written report.
- Accuracy of the principles/experimental techniques described.
- Easy to follow organization (use of bullets, numbered steps, headings, etc.).
- Word choice, readability, and clarity of the instructions.
- Comprehensiveness and balance between sections.
- Grammatical correctness.

The rubric levels are:100% for reports that meet all the criteria. There are appropriate transitions between sections. The report is succinct enough such that one can replicate the experiment(s). Sentences are clear, and there is no ambiguity. An 80% report is good but there are missing sections or the transition between ideas/sections that are not well-delineated. A marginally acceptable level of 60% exhibits several weak components of the criteria. The reader is not able to express the design/experiment conducted. Finally, an unacceptable report scoring 40% fails to meet a significant number of the criteria.

Evaluation of the Success of the Course

We conducted a survey on the last day of classes to gauge the students’ experience. The survey included four questions that asked students to evaluate their overall experience in the online experimentation course. In this offering of this course, students were able to visit the lab to complete the lab modules. While a number of students visited the lab to complete the lab work, a significant number of students completed the laboratory work only at home. Survey questions with the average student response are provided below. The values in the parentheses indicate the response number. HL031 in the below survey questions refers to the laboratory location.

> (Q1) How would you rate your overall experience with ME 3902 Project-Based Engineering Experimentation compared to other classes that had a laboratory section?
>
> Average Response = 8.8 (N=13)
>
> (Q2) The experimental modules on Canvas were designed such that you could complete the laboratory work at home. If you completed any module at home and another one in HL031 then:
>
> > • (a) How would you scale your experience at home vs in HL031? (1 – very negative, 10 – very positive)
> >
> > Average Response = (a) 5.75 (N=8)
> >
> > Else:
> > • (b) If you performed all your exercises in one place only, how would you envision completing the exercises at the other location? (1 – very unlikely, 10 – very doable)
> >
> > Average Response = (b) 7.2 (N=5)
>
> (Q3) Do you think having the ability to conduct experiments at home helped (or could help) you to learn the engineering experimentation material better? YES/NO
>
> Response = 8 Y and 4 N (N=12)
>
> (Q4) How would you scale the amount of technical skillsets (related to engineering experimentation) you gained in this class? (1 – minimum and 10 – maximum)
>
> Average Response = 8.3 (N=13)
>
> Please also see the appendix for the survey text. The student responses to the survey are summarized in Figure 1.

A positive overall positive experience towards the course was observed as responses to Q1 suggests; however, the lack of instantaneous support by the instructors and the teaching assistants at home caused a relatively lower mean response for Q2a. On average the amount of technical skillsets students learned from the course was scaled at 8.3. For comparison, the mean student response to a similar survey question in a traditional engineering experimentation course that was taught by one of the authors in Fall 2019 was 6.95. The question in this survey was “The amount I learned from the course was” and it was scored over a scale of 1 to 10.

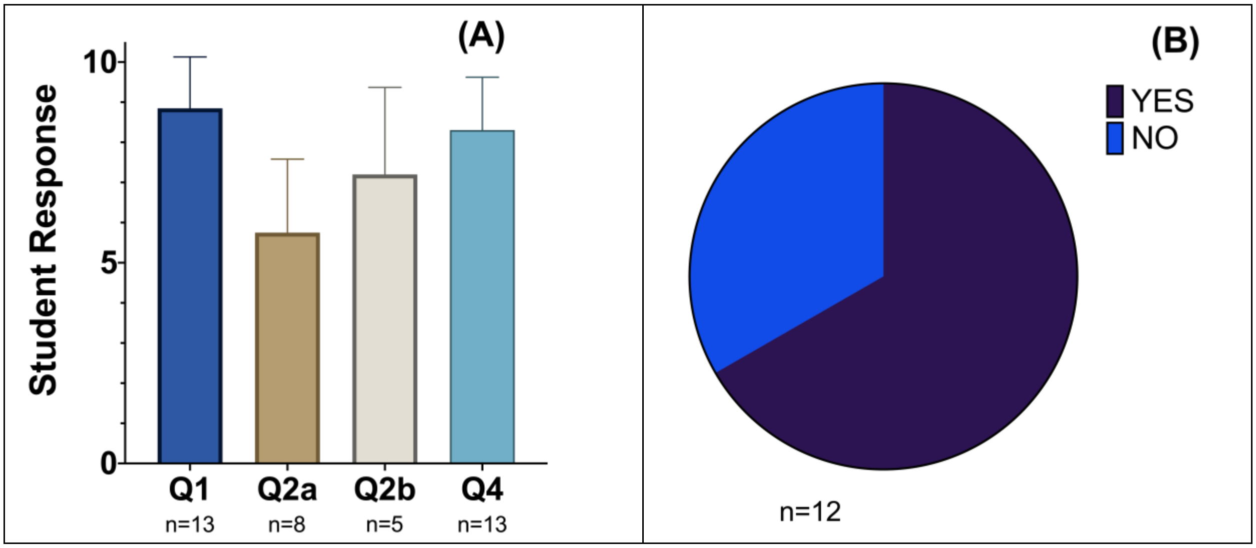

Figure 1. Students responses to the questions in the course evaluation survey. The mean student responses to Q1, Q2, and Q4 are given in the bar graph in (A). The error bars represent the standard deviation. The pie chart in (B) represents student responses to Q3. Please see the appendix for the survey.

CONCLUSIONS AND FUTURE WORK

We introduced an online experimentation course for junior mechanical engineering students. Unlike traditional engineering experimentation courses in which higher-end equipment is used, this course utilized cost-effective and portable sensors and popular electronic prototyping boards, such as the Arduino and Raspberry Pi. Students not only learned measurement science via formative learning modules but also conducted project work via an open-ended design project. Essentially, this course can be implemented in any university in a traditional or online environment. The experimentation kit we proposed is inexpensive, light, and has small volume making it ideal for online education. We are currently working on course improvements as guided by the student evaluations. Additionally, we are planning on a instant feedback artificial intelligence system for the students based on a compilation of the student questions raised during the course offering and their subsequent suggestions.

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APPENDIX

1) How would you rate your overall experience with ME 3902 Project-Based Engineering Experimentation compared to other classes that had a laboratory section?
(1 –negative, 10 – awesome)

Not at all likely **Extremely likely**

0 1 2 3 4 5 6 7 8 9 10

2) The experimental modules on Canvas were designed such that you could complete the laboratory work at home. If you completed any module at home and another one in HL031 then:

- **How would you scale your experience at home vs in HL031? (1 – very negative, 10 – very positive)**

Not at all likely **Extremely likely**

0 1 2 3 4 5 6 7 8 9 10

Else:

- **If you performed all your exercises in one place only, how would you envision completing the exercises at the other location? (1 – very unlikely, 10 – very doable)**

Not at all likely **Extremely likely**

0 1 2 3 4 5 6 7 8 9 10

3) Do you think having the ability to conduct experiments at home helped (or could help) you to learn the engineering experimentation material better? YES/NO

4) How would you scale the amount of technical skillsets (related to engineering experimentation) you gained in this class? (1 – minimum and 10 – maximum)

Not at all likely **Extremely likely**

0 1 2 3 4 5 6 7 8 9 10