



# Project-Based Learning for Second-Year ECE Undergraduate Education

## Andrea Schuman

Andrea is a PhD student in Engineering Education at Virginia Tech. She holds a B.S. degree in Electrical Engineering from the University of Oklahoma. Her research interests include teaching and learning in ECE, international engineering education, and culturally relevant pedagogy.

## Thomas Martin (Professor) (Virginia Polytechnic Institute and State University)

## Lisa D. McNair (Professor)

Lisa DuPree McNair is a Professor of Engineering Education at Virginia Tech and Director of the Center for Educational Networks and Impacts (CENI) at ICAT. Her work focuses on building networks between the university and multiple community sectors and supporting evidence-based outreach in science, engineering, arts, and design. She translated a decade of interdisciplinary initiatives into VT's Innovations Pathway Minor, and has directed 11 PhD dissertations, served on 17 PhD committees, and funded and mentored 6 post-graduate scholars (5 PhD, 1 MFA). Her funded NSF projects include revolutionizing the culture of the VT ECE department, identifying practices in intentionally inclusive Maker spaces, and researching effective modes of co-creation between housing experts and remote Alaska Native communities.

## Justin Kleiber

Justin received his B.S. in Computer Engineering from the University of Oklahoma in 2020. He then earned his M.S. in Computer Engineering from Virginia Tech in 2022. His research interests are in the field of robotics, where he specifically focuses on the modeling and control of uncertain systems.

# **Project-Based Learning for Second-Year ECE Undergraduate Education**

## **1. Abstract**

Open-ended design projects for engineering students can lead to the integration of technical skills between courses, expose gaps in knowledge, and encourage students to engage with a relevant design context. The second and third “middle year” curricula of typical undergraduate electrical and computer engineering (ECE) programs consist of technical classes that teach students the fundamentals of their field. Project-based learning that engages students in more authentic applications of knowledge is often absent from these courses. These years have notable attrition, but relevant design projects can motivate engineering students by reminding them what they enjoy about the field and showing them that their work can benefit society [1], [2]. In this paper, we describe development of a project in a fourth-semester ECE laboratory design course that engages students in designing an autonomous tractor. This project was created to use skills across first- and second-year courses to make a challenging but achievable capstone project aligned with the university’s ECE curriculum revision that expands the range of disciplinary experiences for students. The foundational knowledge students will be required to integrate into their design are a simple controls system, microcontroller programming, Bluetooth communication, and circuit design. Following Prince and Felder’s findings that it is more likely that students can connect their learning to existing cognitive models when engineering work is related to a local context, we chose to situate technological design in autonomous farming because the university is in a rural area [2]. The effectiveness of this project in terms of encouraging student engagement, the alignment of skills to course goals, and appropriateness to the relevant population were qualitatively assessed by pilot studies of usability and faculty assessment.

## **2. Introduction**

This paper describes a hands-on project created for a second-year integrated design course in an electrical & computer engineering department at a research-intensive university in the United States. The course acts as a capstone to a first/second-year program that is the same for both electrical and computer engineering degrees, with goals of bringing together skills learned and preparing students to select a specialty within ECE for their third and fourth years of study. Learning objectives include not only demonstrating technical skills, but also professional skills. Finally, the project should be interesting to students and resistant to formulaic tasks and cheating. In order to be a sustained component of the course and the program, it must be replicable but also modifiable so that instructors can reuse the project in ways that prevent students from using previous solutions as original work.

To meet these goals, we designed an “autonomous tractor” project that uses hardware and software skills from previous courses. Students will work in teams to design a creative solution to an open-ended engineering problem that is relevant to the university’s context. It can be modified between semesters with different goals, requirements, or contexts.

### **3. Background**

The project described in this paper is for a course that engages students in open-ended design and professionalism in the second semester of a student's second year. The course is part of a set of sweeping revisions to the undergraduate ECE program at the university. The department recently made significant changes to the undergraduate curriculum with support from a grant from the National Science Foundation's Revolutionizing Engineering Departments (RED) program. The vision of the this ECE RED project was to transform the program so that it would attract a more diverse group of students and prepare them for a broader range of careers than the department's previous program had done. In the previous program, once a student chose between the electrical engineering (EE) or computer engineering (CPE) degree, they had a fixed set of courses to take with no choices of in-department electives until the fourth year. The sequence of courses in the first and second years was different, which was a major barrier to students who decided to change degrees after the first semester in the program. For students who were interested in topics that are at the boundary between traditional EE and CPE, the previous program also made it difficult for them to choose courses because they would not have the necessary prerequisites for courses in the other degree. In many cases, the solution was to either not pursue those courses or to take all the courses for both degrees, lengthening time to graduation for those students who could afford the additional time and expense.

The curriculum was changed in order that students could tailor their coursework to their own individual professional goals. There is now a common set of courses called the "base courses" in the first and second year for both EE and CPE degrees, followed by a range of specializations (e.g., Machine Learning or Communications & Networking) called majors, and more advanced options in the third and fourth years. Students now receive a BS in EE or CPE with a major in the specialization, both of which appear on their diploma, e.g., BSEE with a major in Communications & Networking. Because students have to choose a major after their second year, one of the goals of the base courses is to expose the student to a wide enough variety of ECE topics that they can make an educated choice. Other goals of the base courses include giving students hands-on experiences and providing them with an integrated perspective on ECE topics so that they see the linkages between material across courses, such as transistors in the electronics course and in the digital systems course.

The project described in this paper is for the ECE 2804 "Integrated Design Project" course in the second semester of the second year. The course is meant to be a "mini-capstone" course that provides a scaffold for students toward a more open-ended design experience in their fourth year, as well as exposes students to a variety of professionalism topics, as will be described in more detail in Section 5. The course also serves as a gateway to choosing a major in the third year, as the course is a prerequisite for all of the courses in the first semester of the third year. Finally, the projects offered in the course are chosen so that they require students to integrate knowledge from all their other base courses and put that knowledge into practice with an eye toward helping students to choose their major in the third year. Thus, some of the projects emphasize certain

aspects of ECE more than other projects do, so that students can begin to explore aspects of their intended specializations. The other projects that are currently part of the course and their relevant skills include a wireless sensor node where students create a solar-powered system that uses power electronics to charge a battery, an SpO<sub>2</sub> measurement that displays information from a specialized sensor through signal transformations, and a 915MHz radio communication project where a software defined radio observes the transmitted spectrum to teach basic electromagnetic theory.

#### **4. Literature Review**

Courses where students solve open-ended engineering problems can increase retention and motivation by engaging students in engineering projects that are often the reason students choose engineering majors in the first place [3]. There is a gap between the amount of focus professional engineers and engineering students have on identifying, formulating, and solving engineering problems [4]. Textbook problems tend to be constrained where only specific formulas need to be used to solve them. In contrast, engineering design problems are ill-structured, have multiple types of constraints, and can have various solutions [5]. Capstone courses are a threshold to scaffold students to future professional experiences by engaging them in realistic projects that develop interpersonal skills and awareness of their work's context and impact [1]. Some engineering curricula are designed so that the middle-year courses are focused on students learning theoretical technical knowledge through well-structured problems that they will eventually apply in problem-solving during the fourth-year capstone [1], [4].

In order to reach professional-level problem solving and design thinking, which are two of the most important skills for engineers, students should solve open-ended problems throughout their undergraduate program [4]. The assignment in this paper is categorized in Prince and Felder's definition of Project-Based Learning (PBL). The students work in pairs to formulate a plan based on prior knowledge from other courses and new learning. The product is the primary outcome that is judged, more so than the process. PBL should lead to an increase in conceptual understanding, metacognitive skills, and positive feelings about learning the material [2]. Since the project is done in pairs, students will also have the chance to advance their communication and teamwork skills. With all types of inductive learning, there is more self-directed learning and open-endedness than with deductive lectures [1].

PBL in ECE is often used in capstone projects, although examples of its use in middle-level courses are starting to become more common. With these projects, students are reporting that they find the projects fun, effective, and motivating [6]–[8]. Robotics can be an exciting project context and has been used in a wide variety of ECE courses. The assignments can be scaled for student experience by changing the goals, method, and amount of help given [9], [10]. This paper describes a second-year capstone project that emphasizes the importance of designing for the context in engineering, which is chosen to be specifically relevant to the participating students.

## 5. Motivation

The goal of the Integrated Design Project course is for students to experience open-ended design and project-based learning early in their degree program. During their first year, students experience projects in ENGE 1215/1216 Foundations of Engineering as well as ECE 1004 Introduction to ECE Concepts. In their fourth year, students enroll in a two-semester ECE 4805 Capstone Design Course. Through the RED project, the second year was redesigned as an ECE cornerstone program to scaffold between foundational knowledge and choice of a major. This course is a capstone to the ECE second-year curriculum that has been redesigned to help students confidently choose their major and have the skills to succeed in more advanced and specialized courses. The projects in this design course integrate knowledge from the technical classes that are the main focus of the middle years of engineering programs. Since this project applies learning across multiple previous courses and disciplinary areas, it should help the students make the decision of their future degree trajectory.

Application, as described in Fink's taxonomy of learning, is a form of significant learning where students acquire actionable skills, ways of thinking, or professional practices [11]. Successful ECE graduates should have experience in these skills which include practical thinking, creativity, critical thinking, and managing complex projects. In this project, the students will have to use their engineering knowledge to make decisions on how to approach their designs as a form of practical thinking. Though this project is not as open-ended as a fourth-year capstone, it is a step up in the amount of creativity the students can use. As they test and validate their designs in order to improve them, they will use critical thinking skills. The practice of managing complex projects will occur as they coordinate simultaneous tasks and divide them between team members. As part of the RED grant, the former Professionalism course during the second year was removed and interpersonal skill development was integrated into other courses [12]. In the new program, the professionalism topics are integrated with the technical material in the base courses. The structure of this course and its teamwork aspects allows students to develop the desired interpersonal skills. An internal analysis estimated that 55% of the Integrated Design Project course relates to professionalism. Some of the specific skills are sketching, documenting, and presenting technical designs, as well as understanding ECE subdisciplines, global issues, and the societal impact of engineering [12].

Incorporating the context of engineering design has been shown to particularly increase student motivation for women, who are underrepresented in engineering [3]. Rural students are another underrepresented demographic in engineering [13]. Connecting learning to diverse backgrounds shows the value of having a variety of perspectives in engineering work [11]. An explicit goal of the RED project is to appreciate diverse backgrounds and retain underrepresented students in ECE [14]. This project is framed as a self-driving tractor because it is a context specifically relevant to the university's rural location that can stimulate students' reflection on human-technology interactions and outcome-oriented engineering design. We chose autonomous farming to contextualize the project because it is an area of rapidly improving technology that

relates to multiple ECE fields of interest [15]. Students will learn the importance of designing for a distinctly relevant context in engineering.

## **6. Project and Example**

This section contains the project's prompt (Section 6.1), setup instructions, parts list, and an initial software outline. In the pilot studies, participants were also given a hardware diagram, which is referenced. Faculty can choose when to introduce each element in order to scaffold their students through the project. An outline of an example solution (Section 6.2) is provided, along with justifications for choices in the design. This project is designed to be technically flexible so it can be modified in different semesters by changing the sensors, course, and graphical user interface (GUI) requirements. It can be situated in different contexts in order to change the design goals, such as building a Roomba or one for interstate trucking. Since this course is taken by second-year students, they are provided (instead of independently choosing) a kit of sensors and parts that they will have to read the datasheets of and learn how to use. An Arduino is used in each project for this course.

The first author designed the project as a central component of their Master's thesis.

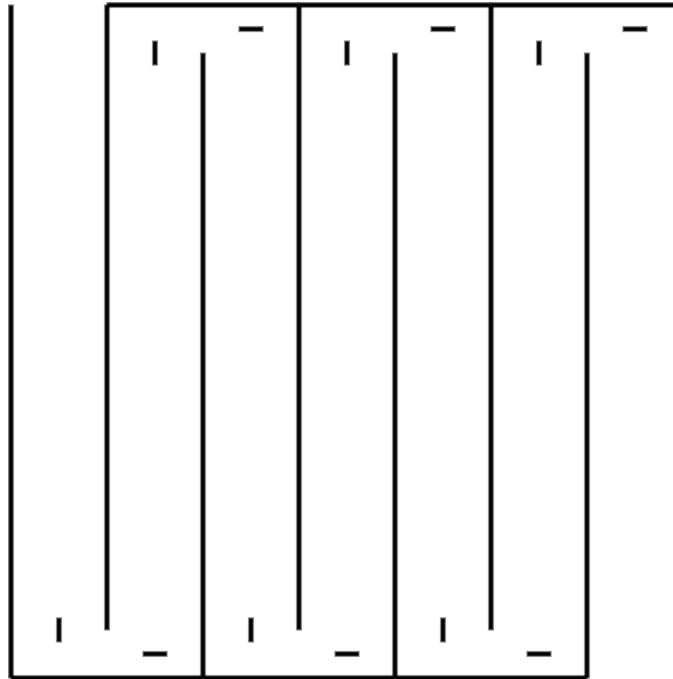
### *6.1 Assignment prompt for students.*

Throughout the year, farmers drive over their land in order to till the soil, to lay the seeds, manage weeds, check crops for disease, apply irrigation and fertilizers, and finally harvest at the end of the growing season. The introduction of the driverless tractor has the potential to save hours of human labor and associated costs. Your task is to create a mini (approximately 10"x6"x5") autonomous tractor that can:

1. Smoothly drive back and forth between the lines of the "field" made from tape on the ground.
  - a. The short markers can be sensed with IR readings.
  - b. Otherwise, orientation should be based on gyroscope values.
2. Emergency-stop when it detects a large obstacle in front of it using an ultrasonic distance sensor or when a button on the robot is pressed.
  - a. For this scale, an obstacle the size of a human foot will be used.
3. Be controlled to start and stop through both bluetooth phone commands and a computer graphical user interface (GUI), designed in Pygame.
  - a. You must implement other useful features in your GUI and justify these choices.
4. Generate and save a trip report after each run with relevant information, including sensor and time data.

The track for this project implementation is below. It will be created by using black tape to mark lines on cardboard. Design your tractor to be robust so that it can perform if there are changes to the absolute or relative lengths of the tracks. The robot should drive between the black lines

around the entire field. The markings in the middle of the track are to orient the robot for when it should turn.



You are required to use multiple control systems to complete various tasks. Explain why your choice of where to use each is appropriate. Perform power calculations to ensure that the Arduino current limit is not exceeded. In your conclusion, describe how elements of your design could impact real aspects of farming when implemented.

### 6.1.1 Parts List

#### **Parts List:**

- Robot chassis
- Motors (2)
- Wheels (2)
- Robot assembly parts (screws, attachment pieces, etc.)
- Arduino Nano
- Arduino cable
- ELEGOO 5PCS HC-SR04 Ultrasonic Module Distance Sensor
- Bluetooth Module (DSD-Tech)
- Motor Controller L298N
- IR diodes (3) (black)
- IR LEDs (3) (clear)
- Potentiometer (3)
- Comparator (Op-Amp) LM324 (3)

- Adafruit BNO055 Absolute Orientation Sensor
- Button
- Rechargeable battery pack (6V)
- Breadboard
- Assorted wires
- Assorted resistors

### 6.1.2 Setup Instructions

1. Check to make sure you have all the parts from the list above.
2. Build robot chassis and motors according to the included instructions from the manufacturer.
3. Attach breadboard to chassis.
4. Wire motors and motor controller to each other and breadboard, as shown in the hardware diagram.
5. Attach the battery to the robot and motor controller. Only plug it in when you want to run the robot.
6. Wire the motor controller and battery to the Arduino as shown in the hardware diagram.
7. Test that the motors can run in the following modes by modifying the test code:
  - a. Drive straight
  - b. Stop
  - c. Reverse
  - d. Turn wheels in opposite directions as one another
8. Attach and wire the IMU according to the hardware diagram.
9. Using the Arduino serial monitor (under the Tools menu), modify the test code so that you can see the gyroscope readings from the IMU and ensure that they make sense.
  - a. Ensure that the baud rate is correct.
  - b. Within the code, use the “Serial.println(...)” function to display data in the serial monitor.
10. Run the full test code, which should lead to the robot driving at a constant speed, turning 180 degrees, then stopping.
11. Plan how to integrate the other sensors, connect to bluetooth, design a GUI, and follow the route.

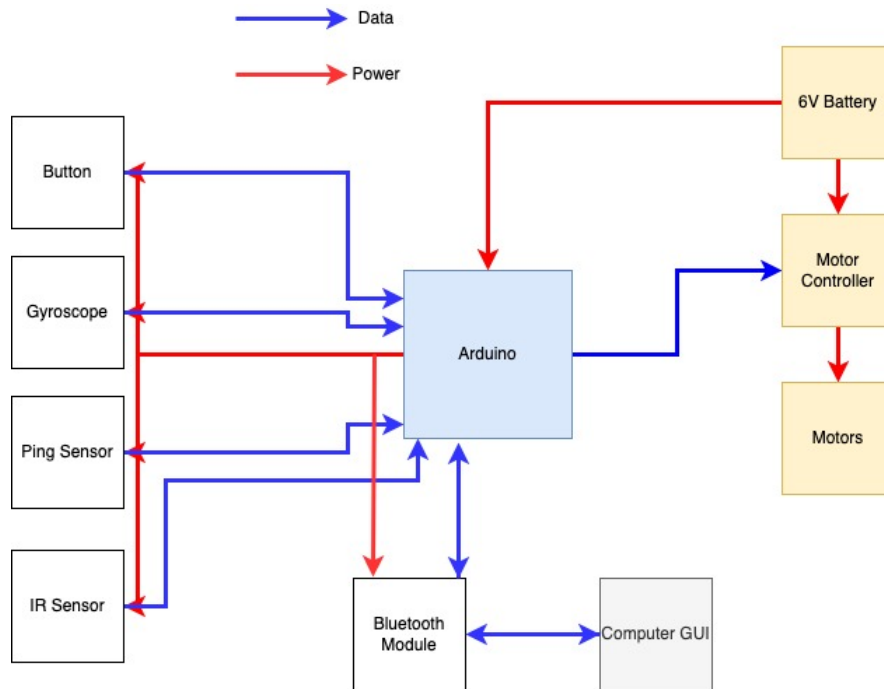
### 6.1.3 Setup Software Summary

The test code for this project sets up the pins and pin directions for the Arduino and runs a function to drive the robot at a constant speed for 1.5 seconds, turn the robot 180 degrees using a control algorithm with the gyroscope readings, and stop the robot. To test the motors and IMU functionality individually, use their respective functions in the Arduino code as identified in the code comments.



## 6.2 Implementation.

### 6.2.1 Block diagram



The robot will start when commanded via Bluetooth, follow the lines of a “field” based on IR data, and stop when it sees an object or when the button is pressed or when commanded by the GUI. It will collect and send data that can be displayed by the GUI when requested and all data will be saved to a csv file. There are multiple hardware subcircuits that have to be included without exceeding the current load for the Arduino.

### 6.2.2 State Machine

A state machine was chosen because there are a finite number of states the device can be in. It is helpful for the students to continue seeing the use of state machines in different contexts. The robot should behave and report data differently depending on the state it is in.

**Default:** During the initial state, the motors are off and it can transition to the drive or turn states.

**Drive:** During the Drive state, the motors are on and changing based on the gyroscope readings. It can transition to any of the stop states or the turn state.

**Turn:** With this design, the robot turns 180 degrees. This state is triggered by sending the turn command. It is also triggered by sensing a specified number of markers in the middle of the track, signaling that it is at the end of the row of the field. It can transition to the BLE Stop or E-Stop states while turning if commanded by bluetooth or the button is pressed. If the robot completes the turn, it returns to the previous state.

**BLE Stop:** After receiving the stop command via Bluetooth, the motors are off. It can transition to drive based on the Bluetooth command or into the E-Stop state by pressing the button.

**E-Stop:** This state is triggered by pressing the button. It can transition to Drive or BLE Stop with the Bluetooth command.

**Ping Stop:** This state is triggered by detecting an object while in the Drive state. It can transition back to drive when an object is not detected, into the E-Stop state with a button press, or into BLE Stop with the Bluetooth command.

### 6.2.3 Hardware

The parts for the project were chosen to be inexpensive so that multiple groups could be given the supplies without the cost being burdensome to the department, particularly in a course with several hundred students in it each semester. The sensors are different from one another, flexible for changing their use for future projects, and budget-friendly. The list is in section 6.1.1.

#### 6.2.3.1 Power

The sensors will draw power from a rail connected to the Arduino Uno output, which has a maximum total current of 500mA and a maximum current per I/O pin of 20 mA. A 6V Battery is connected to a separate power rail and powers the motor controller, motors, and Arduino. The Arduino should not be used to power the motors. Using the datasheets, the students should find that if they connect the motor to a separate power rail the Arduino current limit will not be exceeded.

### 6.2.4 Subsystems

#### 6.2.4.1 Motors

The motors are connected to an L298n H-Bridge motor driver. The students are encouraged to test driving the motors in multiple modes. They will have to monitor their battery power levels and charge when necessary or the motors' speed will be affected.

#### 6.2.4.2 Bluetooth

A Bluetooth module is used to establish two-way communication between the robot and a user interface. The choice to use bluetooth in this project is motivated by its flexibility in communicating various types of data, the variety of technical skills it can teach students, and in its widespread use in the engineering industry. Specifically, bluetooth low energy is chosen due to its ability to be deployed on battery powered devices while consuming little power.

The first step of setting up the DSD TECH HM-10 Bluetooth module was sending information between the sensor's app on my cell phone and the Arduino serial monitor. This capability will help the students get started more quickly and allow them to test Bluetooth commands before creating their GUI. The code was written so that the robot could take simple commands from the phone and respond based on them. The robot could collect data and send it to the phone, which was helpful for future subsystem tests and required for the final data collection and logging. During these tests, students can become acquainted with the challenges of transmitting data wirelessly and can begin to plan for their own information packets to address these challenges

Though the Arduino library is set up to easily connect to the HM-10 Bluetooth module via Serial, the Python user interface connection is more involved. The students may find it useful to use the AT commands from the Bluetooth module datasheet to configure their device and distinguish it from their classmates' modules. Additionally, the students will need to write code to discover both the MAC address and the identifiers of the services provided by the bluetooth module. Once that is complete, the UI must be programmed in an asynchronous manner. The UI runs and handles user events such as button presses to send or request things from the robot. Callback functions are implemented and activated by various events, such as user input, receiving Bluetooth information from the Arduino, or detecting if the bluetooth module has disconnected. Setting up this part of the project will give the students more experience in the software systems, communication and networking major areas.

#### 6.2.4.3 IR System

##### *Hardware*

To decide how to design the IR system, initially the robot was set up with two sensor systems on either side of the robot. The hardware circuit output was measured with the IR sensor facing the IR LED and with the IR LED unplugged using a voltmeter to make sure the hardware worked. Next the circuit was connected to the Arduino and robot and tested the digitally input readings of tape colors on track. The IR sensor was physically isolated but ambient influences on the light were too variable to reliably control the robot based on the IR system. A third IR LED system was set up with a comparator under the middle of the robot so that markers on the track could be read to control the robot. The shadow of the robot improved the readings' consistency. An interrupt was attached so that the robot would turn when the third marker on the track was detected.

#### 6.2.4.4 Proximity Sensor

To test the PING))) Ultrasonic Sensor, test code was written to display the distance measurement to a serial monitor and then make the motors start and stop based on the Ping distance. There are examples of how to calculate distance for this sensor and we can expect that students will use it. It is still valuable for students to use this sensor because of its relevance to the context and usefulness in easily stopping the robot when testing code. For the project, the robot needs to stop immediately if an object is ahead. The distance threshold was set to four inches.

#### 6.2.4.5 Button

The button is used to stop the robot when driving as an emergency stop. The lead author tested the hardware with the voltmeter. Next, the lead author wrote Arduino code to display results from the button to the serial monitor. For the final Arduino code, an interrupt was attached to the pin and set up to stop the motors immediately. The button is a good example of a purely hardware subsystem and its use in software projects.

#### 6.2.4.6 IMU

The unreliability of readings from the IR system led to choosing a sensor with inertial measurement unit (IMU) functionality for the turning control system. In this implementation, the instructor has to choose how much they want the students to program the normalization and filtering of the IMU data. The BNO055 intelligent 9-axis absolute orientation sensor is a System

in Package. It has magnetometry, linear acceleration, absolute orientation, and other sensing capabilities that could be incorporated into future projects. For sensor fusion, it has Compass, Magnet for Gyroscope, Nine Degrees of Freedom, and IMU operating modes. In this project, the BNO055 is used in IMU mode to report gyroscope readings and is referred to as an IMU sensor. In IMU mode, it calculates the relative X,Y, and Z orientation based on the accelerometer and gyroscope data. Since it has the capacity to do these calculations on the chip, students can immediately access the robot's orientation measurements. We considered the HiLetgo MPU9250 IMU, which is very cost-effective (currently about 4 dollars) but it does not have on-board hardware for sensor fusion so it would have to be done in separate software. Finding these values would be a significant amount of work for the students and could be an interesting project for future courses. Since filtering and smoothing IMU data is not a specific desired learning outcome for this project, and the BNO055 IMU fits within our project budget, this version with innate data analysis was chosen for this implementation.

#### Driving

If using the gyroscope to drive straight, there are multiple methods of control that could be implemented. A proportional feedback controller was used for this example, which is a good introductory design for underclassmen students.

#### Turning

The turning function is an opportunity for the students to learn about multiple types of control and practice correcting for edge cases. With the reliable gyroscope, the robot should theoretically be able to turn and stop when the gyroscope reads 180 degrees past the initial yaw. Since this is a physical system, there is momentum that needs to be taken into consideration. A proportional and derivative controller was chosen so that the robot would not only reach the correct yaw, but only stop when it was approaching at a low angular velocity.

The gyroscope reads angles from 0 to 359 degrees. The students will have to think about how to turn to angles close to 0 or close to 359 using the shortest arc length. If the goal is 0 degrees, the robot should be using the same speed in its approach if it is at 10 degrees or if it is at 350 degrees. The algorithm is below:

#### Reset Yaw

The type of task we hope the students identify as being necessary without being explicitly told is adding a method to reset the baseline yaw for the robot. For testing and actual usage, it is important to have a method to reset the baseline orientation for the device.

#### 6.2.4.7 Report Generation

Python is a valuable language for the students to practice and the Pygame package allows them to create an interactive GUI. There is flexibility in the project where students could decide to add new buttons based on contextual needs, a live-updating map, a more advanced controller, and more.

The report begins with the first start command. It reports the following information:

Time	State	IR Reading	Yaw	Goal Yaw (optional)	Hazard Distance (optional)	End Character
T:#	State	IR:#	Y:#	G:#	H:#	\$

The Python code is set up to parse and record each data input. The robot only sends logging information when it first enters the Bluetooth and E-Stop states, instead of continuously logging while nothing is changing. Each yaw reset is logged. A button was included to display the most recent data received since the readings were too rapid to be readable if all were used. It saves to a 'robot.csv' file but could be changed to save to a new file each time or so that the user manually selects the file name. The students have flexibility in what data they decide to report, based on their justification of their choices in alignment with the context.

### 7. Assessment of Project

This project will be measured for three objectives: 1) alignment with student learning outcomes, 2) usability and adaptability, and 3) faculty assessment of fit with course and program objectives.

#### 7.1 Learning outcomes and course assessment plan.

The Integrated Design Project course learning objectives and relationship to the project are described below. The standard course assessments include a weekly progress report from each pair of students and tri-weekly milestone assessment where the students report their progress in meeting the milestones they have set. The weekly reports include what was accomplished, designs, simulations, measurements, and goals. The instructor sets the milestones and dates. At the end of the semester, students submit a final report. This includes the complete block diagram, detailed design of subsystems, and validation of the integrated project. Student groups are required to deliver a mid- semester and final presentation that includes information from the weekly and final reports. The Integrated Design Project course learning objectives and relations to the project are described in the table below.

Objectives for course	Integration and assessment
Demonstrate the use of standard, industrial-caliber, test equipment such as oscilloscopes, function generators, power supplies, and digital multimeters to measure quantities of interest in electronic circuits.	At a minimum students will use power supplies to test sensors and circuits and use multimeters for unit tests. These tests will be reported in the test and validation plans.
Design and implement a solution to an open-ended engineering problem involving both analog and digital hardware.	This project has analog and digital hardware for the students to solve the tractor design problem.

Create a test and validation scheme for a student-developed design.	The weekly reports include designs, tests, and milestone projects. The students will have to complete a test and validation scheme and the instructor will assess their acquisition of this skill.
Document a design, including a comprehensive project specification and validation.	The presentations and reports include high-level and detailed design and validations that the students will have to document throughout the course. An instructor meets with each two-person group once per week and asks questions about their hardware and software. This exposes gaps in the students' knowledge or even copied designs.
Develop and present an oral technical presentation detailing the design, implementation, testing, and validation to an open-ended engineering problem.	
Compare the different sub-disciplines of the ECE profession.	This project mixes approaches from EE and CpE and acts as a capstone that combines learning from multiple previous classes. Our theory is that this experience that combines ideas from different sub-disciplines will enable students to more confidently and knowledgeably select a major.
Recognize and assess contemporary, global, and ethical issues and societal impacts of solutions/designs.	Situating this project in a specific and local context will increase students' understanding of engineering issues and the byproducts of engineering solutions.

## 7.2 Usability and adaptability.

The target audience for the project-based learning assignment is second-year undergraduate ECE students in an integrated design course. A pilot study was conducted to discuss the project and perform lab usability testing with graduate students and upper-level undergraduates. Student participants were offered gift cards as an incentive. All evaluation activities were conducted after approval by the IRB and audio-recorded with participants' consent.

### 7.2.1 Graduate Student Assignment Response

ECE graduate students were asked to unbox and respond to the project prompt and kit in a study informed by think-aloud protocols [16]. The purpose of the study was to identify potential issues and improvement with the prompt and materials. Individual, 45-minute sessions were done with two participants in on-campus conference rooms. They were given the assignment prompt, hardware components, starter Arduino code, and hardware diagram, described in Section 6.1. The goal of this study was focused on understanding the perceptions of the project by more

advanced students, so modified think-aloud prompts and protocol were used. Before opening the materials, the moderator gave instructions to the student following a script which is based in think-aloud literature [16]: "Here is the assignment prompt and materials. Please describe how you would set up the project. Please say aloud everything that you think or do in designing without filtering your thoughts". Departing from traditional think-aloud methods, the moderator provided clarification to the participant when asked and engaged in follow-up questions. The interview was audio-recorded with IRB approval. The moderator observed and noted the participants' behavior and relative time spent on each task, trying to relate these observations to their progress throughout the study [17]. After the participant had finished reading and responding to all materials, they were asked questions on clarity, potential issues, and future improvements and modifications. The two participants were an ECE MS student (referred to as Graduate Student 1, or GS1) and an ECE PhD student (referred to as Graduate Student 2, or GS2). The participants were recruited through connections the first author had with the department but did not have prior knowledge of the project.

### 7.2.2 Upperclassman Lab Kit Usability Study

Lab usability testing was conducted with upper-level undergraduates whose engineering skill set is advanced beyond that of the project's final target audience of second-year undergraduates. Upperclassmen not only answered questions about the prompt but performed the initial setup and testing, according to the instructions in the project prompt (Section 6.1.2). The participants also described how they would go about completing the rest of the project. Individual, hour-long studies were done with two participants in on-campus conference rooms. They were given the assignment prompt, hardware components, starter Arduino code, tools for setup (pliers, tape, screwdriver), and the hardware diagram, described in Section 6.1.3. The robot chassis was already assembled to limit the extraneous work for the students in our limited time. Similar to the study with graduate students, modified think-aloud protocols were used with instructions of: "Here is the assignment prompt and materials. Complete the setup of the project. Please say aloud everything that you think or do in designing without filtering your thoughts" [16]. The students were recruited through professional ECE societies, since it was anticipated that they may have more interest and motivation to improve the curriculum. The two participants were a fourth-year electrical engineering student (US1) and a third-year electrical engineering student (US2). Once again, the moderator audio-recorded the interview, provided clarification to the participant when asked, and engaged in follow-up questions. The moderator also observed and noted the participants' behavior and relative amount of time spent on each element during the study. The goal of this study was to learn how far a more advanced student could progress in the setup within the one-hour study, where difficulties arose, and how they would plan to work through the rest of the project.

### *7.3 Student learning outcomes and program objectives.*

The researchers sought input from Integrated Design Project course instructors and graduate teaching assistants in a focus group on the feasibility of implementing the project. The instructors were provided with the prompt from Section 6.1 and all project materials. Information was collected about the potential for the project to be adapted to other semesters and which materials they would be inclined to use. The discussion was moderated by one of the researchers and included dialogue about the alignment of the project to the course goals, appropriateness of the project for the student population, and the specific parts chosen.

## **8. Results and Discussion**

### *8.1 Graduate Student Study*

#### 8.1.1 Graduate Student 1

GS1 was meticulous in his engagement with the details of the prompt and materials. He read through the assignment and checked that every hardware component in the list was present. He said that he had not worked with Arduino code in several years but he was able to understand the setup code from its comments and talked through what each section meant and how he would modify it for the project. GS1 spent much longer on the software code than the hardware diagram but said there were not more than minor issues with clarity for either. A few software comments were modified based on GS1's feedback, in particular the section about Bluetooth communication. He suggested that the "field" for the tractor be variable so that students could not hard-code timing elements and would have to use the control algorithms. For future variations or added difficulty, he recommended adding sensors or safety elements, having a mid-mission task to complete, or incorporating position and speed calculations. Overall, aside from making minor changes to labeling the LEDs in the parts list and wording of Bluetooth comments, GS1 thought the difficulty level would be achievable and appropriate for second-year students.

#### 8.1.2 Graduate Student 2

GS2 focused on a high-level view of the project and the learning outcomes. He read through the prompt, hardware diagram, and software but did not specifically check for the individual hardware components. GS2 spent more time talking through the relative difficulty of the tasks and potential issues the students will have to design for. He liked the project and did not see any errors or issues. Like GS1, he emphasized that the students should design their tractor to be robust to the course and environment. He said there was a "good amount of ambiguity" for the students to account for in their designs. He thought the challenge level was appropriate though the GUI and Bluetooth communication could provide unnecessary difficulty, so he recommended having examples or outlines available if the students need them. GS2 said we could anticipate imperfect, real-life issues that the students will have to overcome to make the project work and which would help them to improve as engineers. These types of issues include bad sensors or



unhelpful readings, power issues, and durability to the environmental influences when driving. He suggested that if difficulty is added, it could be focused on theoretical knowledge of the controller development and tuning, though he did emphasize that the current setup of gaining an intuition for control without theory was a strength. As a result, the authors prepared example code and added wording around robustness to the project description.

### 8.1.3 Summary

Overall, the graduate student participants indicated that the prompt was clear and the kit was complete. They thought the difficulty level was appropriate and the project context was engaging. Based on their suggestions, adaptability and robustness should be emphasized in assessment of the students' project. One option for instructors is having the students use the same robot and code on multiple types of courses or “fields” to ensure that nothing significant is hard-coded. Since the graduate students also thought that Pygame and connecting the Arduino to Python via Bluetooth could be unduly difficult, we also offered instructors relevant documentation and examples that can be given to students if issues arise.

## *8.2 Undergraduate Student Study*

### 8.2.1 Undergraduate Student 1

US1 was able to put the hardware together and test multiple iterations of the software during the 50-minute setup portion of the study. The robot was running with the final Arduino setup software uploaded but US1 was not able to make the motor polarities correct with his software and hardware build. Based on his understanding of the project, the moderator expects that it would have taken less than 30 more minutes to get the setup test code completely working. While building the robot, the primary difficulties were with wiring the motor controllers to the motors due to the tricky connectors but he stated that he would solder them in a real class setting. US1 suggested that a "stretch goal" for this project would be printed circuit board (PCB) design. The instructor could encourage students to create PCBs instead of using the breadboard, which would likely be a new skill for the students and would make their robot more robust to the environment. The moderator did have to do minor prompting and clarification along the way, specifically reminding him to return to the setup instructions and break down the tasks. In the course setting, the professor and the partner working on the project could help. One interesting aspect is that US1 immediately went to Google even if the information was available in the materials, but that may have been due to the time constraint and wanting to find the answers quickly. He thought the project would be fun and good for students interested in robotics or embedded systems. US1 said the project would take a lot of testing for the students to get the project working, which is similar to comments from GS2. When answering questions about the plan for the rest of the project, US1 said that the path forward was relatively limited instead of open-ended. Overall, the project was clear to US1 and he was able to complete almost all of the setup and identify broadly how he would complete the rest of the project.

### 8.2.1 Undergraduate Student 2

US2 is an undergraduate teaching assistant for the ECE 2564 Embedded Systems course that is also taken by ECE students in the second semester of their second year, so he is familiar with the target audience. He had technical issues with his computer's Arduino drivers and updates, so the majority of time was spent on discussion instead of building. US2 is a leader of an engineering competition team. He liked the aspect of having students mechanically build the robot chassis because he had seen students have complete inexperience with using components and hand tools such as screws and screwdrivers. If an instructor wanted to add more hardware aspects, he recommended that the battery could use a solar charger or be charged from a battery with a higher voltage. Solar charging is especially interesting since, as US2 pointed out, it is relevant to the farming context. Previous projects in the Integrated Design Project course have used solar charging as a project element. When asked how he would solve the rest of the project, US2 described a detailed plan and his ideas were aligned with the target milestones and subsystems. He stated that after checking the functionality of the parts, he thinks fourth semester students would know to design a state machine. He would download datasheets for all the sensors and check the power limits for the Arduino. Then he would set up the Bluetooth module in case it was a difficult step and check that he could send basic commands. Next he would build a basic Pygame GUI and implement his state machine. He would plan to do the final version of the tractor's trip report last, though he would use the sensor readings to test his design. In terms of the project materials, he recommended against giving the students all of the instructions, diagram, and setup code. It would be a more authentic professional experience to make the project without instructions. He suggested that the students could be given a partially completed hardware diagram or just the prompt and parts list. As a teaching assistant, US2 thought the test software might help beginner programmers. For some students, this will be one of their first software projects and they might struggle with the high-level software design setup. Overall, he liked the project and the topic in particular. As a student in the controls, robotics, and autonomous systems ECE subdiscipline he thought this could stimulate interest in students in that area. He did think it could be relatively simple to get up and running but hoped it would take a lot of experimenting like the other projects. He recommended adding more open-endedness to the prompt and setup and not underestimating students' creativity.

### 8.2.3 Summary

Both undergraduate students identified that there was significant help and guidance being given in the setup, both in the software and hardware. Based on these comments, the section identifying the setup materials as optional were added before the faculty study, explaining that instructors can decide when and how to implement it. The students may take longer to get the project up and running without that help but they will also learn from the setup process and the instructor can implement what is necessary. The difficulties the undergraduate student participants ran into were communicated to the instructors, so they can anticipate common problems in the course implementation. Both students indicated that the project was not

open-ended enough based on their experiences in the course. Elements of the deliverable could be added or removed depending on how fixed a faculty member wanted the project to be. The lack of open-endedness will be a potential issue for instructors to be aware of during the actual course implementation to see if it needs to be addressed.

### *8.3 Faculty Study*

#### 8.3.1 Faculty Roundtable

The faculty roundtable generated engaging discussion both between the moderator and participants and between participants. Five instructors (including faculty and graduate teaching assistants) participated. Everyone spent time reading all materials at first and discussion started naturally as they got near the end of reading and asked questions. Each component (from Section 6.1.1) could be adapted by the instructors to set the tri-weekly milestones instead of being given directly to the students. There was discussion of variations for the track as instructors questioned how students could get their robot back on course if their robot drifted and was going to miss the turn markers. There are options of using raised materials if there needs to be a form of course outlines, since the students should not be detecting them. The example robot chassis kit included encoders, which seem to be a good option students could explore. There are multiple approaches that instructors and students could take to drive through the "field" and the instructors decided that it would not be a problem if the students' robot is not able to finish the whole track, since that could help with differentiating the projects. In terms of project outcome assessment, we discussed using accuracy, speed, and smoothness. Overall, the instructors agreed this was an appropriate challenge for a 9-week project. The students would not be given the setup materials and the additional elements discussed in the graduate and undergraduate student studies could be added if it seemed too straightforward. They agreed to implement it.

#### 8.3.1 Faculty Summary

The faculty study met the goals of the instructors understanding the project, deciding that it is a good fit for the class, and agreeing to implement it. They had the same opinion as the undergraduate student participants and would not give the students any materials besides the prompt and parts list. The faculty concluded which materials from the parts were necessary and which could be replaced. For the Integrated Design Project, the instructors think it will be challenging enough for the students but have the options of adding theoretical learning on control systems, hardware problems such as solar charging, or software challenges such as encoders or more depending on their preferences.

## **9. Conclusions**

In this paper, we have described our goals in the creation of an autonomous tractor design project for second-year students. It is a useful project for teaching students problem-solving and communication skills, the relevance of context in engineering design, and how to bring together technical skills from their early degree courses. We chose affordable parts and sensors that could

be reused for variations of the project, depending on a course's specific needs. The primary written materials an instructor should need to implement this project are included in this paper, along with an example solution. When performing pilot studies with graduate students, undergraduate students, and faculty, participants were able to give ideas of expansions to the project that could be added which is a sign of its adaptability. It can be scaled up and down for difficulty in different courses. Based on our studies, this project will help students gain a wider view of the field of ECE while grounding the application of diverse skills in a context that is real or easily imagined by students. In the upcoming summer, this project will be piloted in the full summer course before being implemented into the larger fall course iteration.

## 10. Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant IUSE/PFE RED-1623067. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

## 11. References

- [1] S. M. Lord and J. C. Chen, "Curriculum Design in the Middle Years," in *Cambridge Handbook of Engineering Education Research*, A. Johri and B. M. Olds, Eds. Cambridge: Cambridge University Press, 2014, pp. 181–200. doi: 10.1017/CBO9781139013451.014.
- [2] M. J. Prince and R. M. Felder, "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases," *J. Eng. Educ.*, vol. 95, no. 2, pp. 123–138, 2006, doi: 10.1002/j.2168-9830.2006.tb00884.x.
- [3] A. Kolmos and E. de Graaff, "Problem-Based and Project-Based Learning in Engineering Education: Merging Models," in *Cambridge Handbook of Engineering Education Research*, A. Johri and B. M. Olds, Eds. Cambridge: Cambridge University Press, 2014, pp. 141–160. doi: 10.1017/CBO9781139013451.012.
- [4] K. A. Dunnigan, A. Dunford, and J. Bringardner, "From Cornerstone to Capstone: Students' Design Thinking and Problem Solving," presented at the 2020 ASEE Virtual Annual Conference Content Access, Jun. 2020. Accessed: Jan. 31, 2022. [Online]. Available: <https://peer.asee.org/from-cornerstone-to-capstone-students-design-thinking-and-problem-solving>
- [5] D. H. Jonassen, "Engineers as Problem Solvers," in *Cambridge Handbook of Engineering Education Research*, A. Johri and B. M. Olds, Eds. Cambridge: Cambridge University Press, 2014, pp. 103–118. doi: 10.1017/CBO9781139013451.009.
- [6] B. L. Hutchings and S. Schultz, "Project-Based Learning Curriculum for the Junior Year Based on Building a Laser Tag System," presented at the 2017 ASEE Annual Conference & Exposition, Jun. 2017. Accessed: Aug. 31, 2021. [Online]. Available: <https://peer.asee.org/project-based-learning-curriculum-for-the-junior-year-based-on-building-a-laser-tag-system>
- [7] J. Song and D. E. Dow, "Project-Based Learning for Electrical Engineering Lower-Level Courses," presented at the 2016 ASEE Annual Conference & Exposition, Jun. 2016. Accessed: Aug. 31, 2021. [Online]. Available: <https://peer.asee.org/project-based-learning-for-electrical-engineering-lower-level-courses>
- [8] D. Seo and D. Mangra, "Project-Based Learning of Digital Logic Circuit Design," presented at the 2017 Mid-Atlantic Section Fall Conference, Oct. 2017. Accessed: Aug. 31, 2021.

- [Online]. Available:  
<https://peer.asee.org/project-based-learning-of-digital-logic-circuit-design>
- [9] C. Parikh, "Autonomous robot: An intellectual way of infusing microcontroller fundamentals into sophomore students," in *2015 IEEE Frontiers in Education Conference (FIE)*, Oct. 2015, pp. 1–4. doi: 10.1109/FIE.2015.7344261.
- [10] L. Junior, F. Guerra, L. Bravo, M. Hernandez, O. Neto, and P. Martins, "A Low-Cost and Simple Arduino-Based Educational Robotics Kit," *J. Sel. Areas Robot. Control JSRC*, vol. 3, pp. 1–12, Dec. 2013.
- [11] L. D. Fink, *Creating significant learning experiences: an integrated approach to designing college courses*. San Francisco, Calif.: Jossey-Bass, 2003.
- [12] J. M. Williams, E. Litzler, C. Margherio, E. Andrijcic, and K. Doten-Snitker, "Board 157: Creating National Leadership Cohorts for Making Academic Change Happen: Sharing Lessons Learned Through RED Participatory Action Research (REDPAR) Tipsheets," presented at the 2019 ASEE Annual Conference & Exposition, Jun. 2019. Accessed: Feb. 07, 2022. [Online]. Available:  
<https://peer.asee.org/board-157-creating-national-leadership-cohorts-for-making-academic-change-happen-sharing-lessons-learned-through-red-participatory-action-research-redpar-tipsheets>
- [13] J. Barshay, "PROOF POINTS: Rural American students shift away from math and science during high school, study finds," *The Hechinger Report*, Jul. 12, 2021.  
<http://hechingerreport.org/proof-points-rural-american-students-shift-away-from-math-and-science-during-high-school-study-finds/> (accessed Feb. 05, 2022).
- [14] D. Reeping *et al.*, "Using threshold concepts to restructure an electrical and computer engineering curriculum: Troublesome knowledge in expected outcomes," in *2017 IEEE Frontiers in Education Conference (FIE)*, Oct. 2017, pp. 1–9. doi: 10.1109/FIE.2017.8190444.
- [15] "Autonomous Self-Driving Tractors: Is Automatic Farming a Reality?," *Pinduoduo*, Feb. 17, 2021.  
<https://stories.pinduoduo-global.com/agritech-hub/how-self-driving-tractors-are-making-autonomous-farming-a-reality> (accessed Feb. 05, 2022).
- [16] M. W. van Someren, Y. Barnard, and Jacobijn Sandberg, *The Think Aloud Method: A Practical Guide to Modelling Cognitive Processes*. Academic Press, Inc, 1994.
- [17] E. Charters, "The Use of Think-aloud Methods in Qualitative Research An Introduction to Think-aloud Methods," *Brock Educ. J.*, vol. 12, no. 2, Art. no. 2, Jul. 2003, doi: 10.26522/brocked.v12i2.38.