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Manufacturing a DC Power Supply with Internet of Things (IoT) Control Dashboard for Embedded Systems Education

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Dr. Lucas' primary goal as a professor is to engage with students in the classroom and inspire them to develop their passion, understanding, and appreciation for STEM-based research and industry roles. This is accomplished by providing well-crafted and innovative learning experiences in engineering technology courses and through extracurricular outreach. His research background is in 3D (out-of-plane) micro-electromechanical systems (MEMS) sensor and actuator design. His current teaching load primarily consists of courses related to advanced embedded digital systems.

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Abstract

Digital and embedded systems are at the core of many modern appliances, tools, and technologies. As a discipline, Embedded Systems is a broad topic that incorporates many electrical, mechanical, and computer science-based concepts. However, the style chosen to teach embedded systems is often from the perspective of a single discipline and does not fully explore the relationship between various fields of expertise required to produce a complete end product. Project-based learning is an excellent structure to compel students to explore the interaction of various disciplines using modern tools. This paper describes the implementation of a semester-long design and manufacturing project to create an Internet-of-Things DC Power Supply. The project was chosen to facilitate student exploration of the connections between different aspects of manufacturing a modern embedded system. This document includes details and analysis of the implementation, results, and student feedback. Completion of the project requires students to harness their prior knowledge in Electrical Engineering Technology (EET) while also exploring topics that are unfamiliar but critical to operation. The ultimate goal is that junior and senior level students in the EET degree path at Purdue Polytechnic Institute will develop strategies to learn unfamiliar topics by making connections to prior knowledge and experience – an extremely valuable skill for the long-term success of graduates that take jobs in modern manufacturing environments.

Keywords

Faculty Paper, Experiential Learning, Interdisciplinarity Project, Engineering Technology

Introduction

The Internet-of-Things Power Supply (IoT PS) is a semester-long project that is integrated into an Electrical and Computer Engineering Technology (ECET) course, ECET 329 Advanced Embedded Systems. This project-oriented course is designed to emphasize topics from various disciplines that are required for the successful development and manufacturing of an embedded system application. Topics discussed in the course include real-time operating systems, printed circuit board (PCB) design and fabrication, power and batteries, thermal considerations in electronic systems, digital signal processing, project enclosure manufacturing, and hardware selection based on application requirements. The IoT PS project is intended to provide active lab experience that spans the topics for the course.

Students take this course in the junior or senior year as a requirement towards a BS in EET. This project leverages that incoming knowledge and ability by presenting the project as a set of three interconnected modules over the 16-week semester. Each module is presented from various discipline viewpoints to reinforce the ability to make functional associations between disciplines. For example, class activities on batteries include terminology and analysis rooted in Chemistry, while a module on heatsinks begins with Physics and Geometry, and computing applications are in the style of a Computer Scientist.

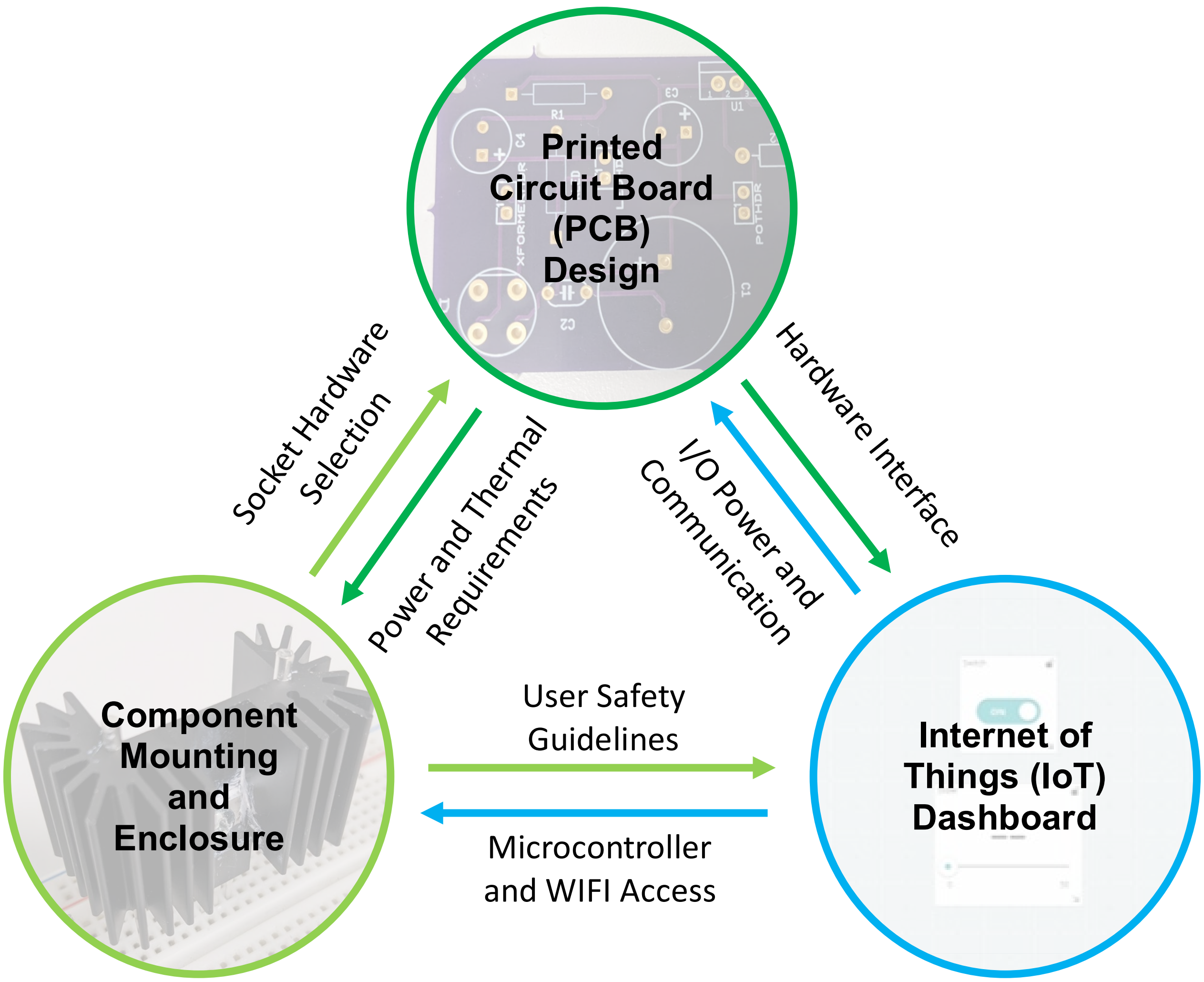

Figure 1 - Focus areas with arrows indicating constraining parameters that must be considered in the design of the IoT PS

Ideas must be translated from those base disciplines into embedded systems concepts in order to complete objectives relevant to the IoT PS, along with additional course outcomes. The focus areas for the IoT PS are the PCB design, IoT dashboard, and the project enclosure. Each of these areas have application specific challenges that constrain the options for the other project elements. Figure 1 shows the three focus areas with arrows indicating constraining parameters that must be considered in the wholistic design of the system.

Course Week	Topic introduced lecture/lab content	Project Progress
1	Embedded System Design	Arduino IoT Cloud Intro
2	Scheduling and real-time operating systems (RTOS)	Core Embedded Systems Topics (Not project specific)
3	RTOS details	
4	FreeRTOS Package	
5	PCB Design	PS component and thermal calculations, PCB layout, generate bill of materials
6	PCB power issues, Heat Sinking	
7	Batteries	
8	UI Design and Intro to IoT Cloud	PCB assembly, electrical and thermal performance testing, system packaging
9	Hardware I/O	
10	Software I/O	
11	Intro to Matlab and digital data arrays	
12	Digital signal process(ors/ing)	IoT UI development and implementation
13	DSP/DIP application	
14	IoT Application	Finalize documentation, draw conclusions
15	Application showcase	

Table 1 - ECET 329 16-week topic sequence and parallel project development plan

The course that contains this project is designed to offer a multi-disciplinary experience. The 15-week topic sequence is detailed in Table 1. Students will be presented with lecture and targeted lab activities each week to build their core knowledge in embedded systems. Project development and progress is made in parallel to allow for synergies between new topics and project needs.

The parallel project work was distributed as shown in Table 1. IoT connectivity and UI work took place in Weeks 1, 13, and 14. Theoretical system calculations and component selection was performed in Weeks 5, 6, and 7. Weeks 8, 9, 10, and 11 provided time for assembly and testing, which lead to revisions to the design in a few instances described in a following section. The last two weeks of the course was used to document their experience. Student groups were provided with an early version of this articles abstract, introduction, and section outline. They were then asked to write and create figures for an assigned section, which then went through a process of class-wide revision before assembly into this paper by the lead author.

The DC power supply circuit and PCB are designed to support a LM317 adjustable voltage regulator integrated circuit (IC). The operating requirements of this chip inform the rest of the circuit constraints, as well as the hardware interfacing from the IoT dashboard and the heat dissipation requirements. The IoT dashboard is hosted by the Arduino Cloud service which provides graphical interface tools for creating a control dashboard. It can then be accessed through an Android application, and the controls are synchronized with an Arduino Nano 33 IoT model microcontroller via WIFI. The circuit and IoT components add constraints to the enclosure design, while user preferences impact what connections are to be available and connected back to the circuit. The details of each element are explored in the following sections.

Printed Circuit Board (PCB) Design

Students began the project focused on the core power supply PCB design. The circuit design began by designing around the LM317 voltage regulator (simulated as the similar LM117). To supply a final maximum chosen output voltage of 12V, the LM317 Adjustable Voltage Regulator requires 14VDC input coming from the transformer and rectifier circuit. A transformer was selected to step down a standard 120VAC wall outlet power source into a range appropriate for the LM317 regulator. A transformer was selected to have an appropriate turn ratio and VA rating. After the full bridge rectifier, a roughly DC signal exists which must be smoothed. Capacitors were selected to filter and smooth the rectified voltage to make it a steady DC.

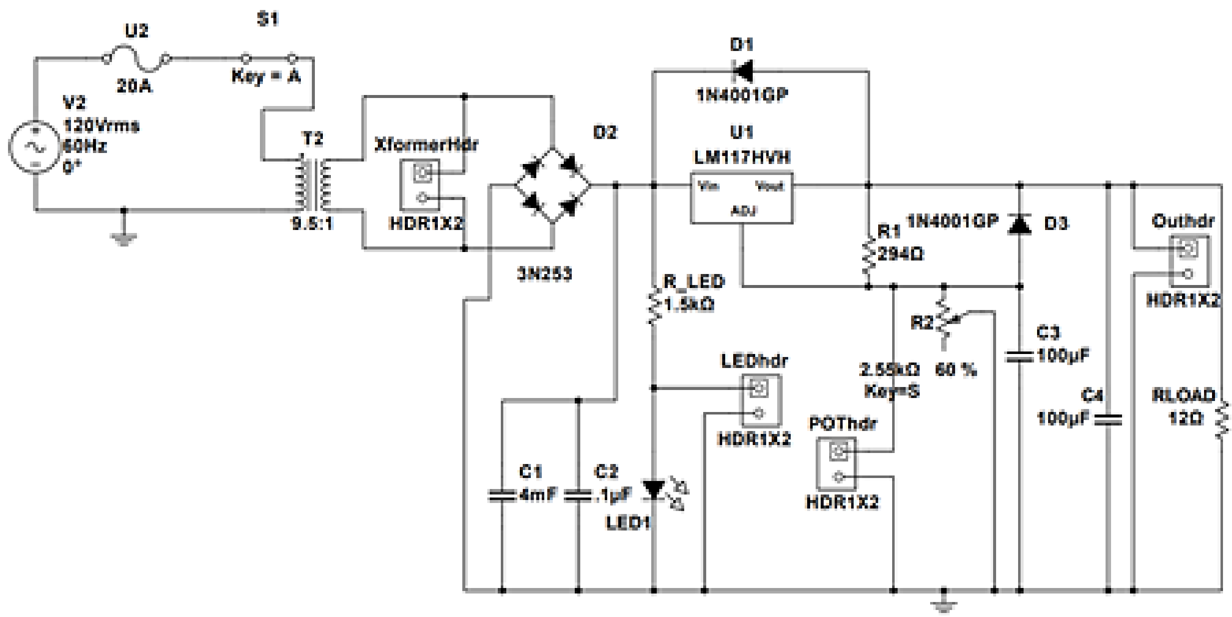

Figure 2 - Multisim circuit capture of the planned PCB.

After successful simulation of the circuit design (Figure 2), component footprints needed to be selected. Most of the components used were at their default footprint, but a few parts needed changing, including the LM317 voltage regulator, as the default pinout from Multisim was incorrect. The circuit was exported from Multisim and imported into Ultiboard. Most of the trace widths were set to 20 mils in width, however some of the higher power lines were widened. Components and traces were arranged differently between the four groups according to preference as seen in Figure 3.

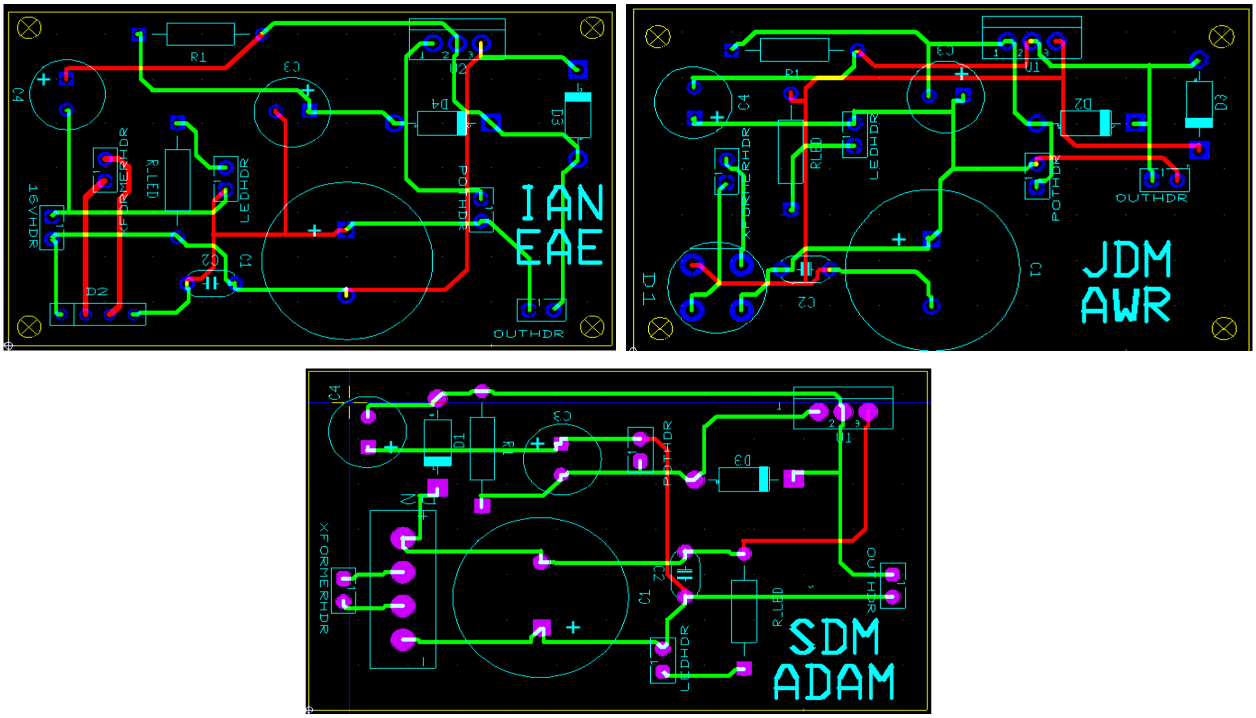

Figure 3 - Student team PCB layout examples

Internet of Things (IoT) Dashboard

IoT interconnection for the project was supported by Arduino IoT Cloud; an application which allows the user to easily encode and virtually interface with Arduino based hardware devices such as the Arduino Nano 33 IoT, which was utilized in this project to allow virtual user control of the variable power supply. Arduino Nano 33 IoT is an inexpensive point-of-entry IoT device which is small, low-power, and breadboard-friendly. The board is based off of the ATSAMD21 microcontroller chip and has 14 digital input/output pins for virtual control [1]. The board can be powered from a USB-C cable as was used experimentally in the project or with a DC voltage applied to the Vin pin which is rated for up to 21V. The coding software used for the project was Arduino Cloud IoT, a browser-based C++ programming interface with some additional Arduino-specific functions.

The variable power supply has two primary user-controlled inputs: system power switching and desired voltage level. System power has two possible states that the user can input: ON or OFF. A Solid-State Relay (SSR) was utilized in the project as the mechanical switching element within the power supply and was controlled by a digital pin of the Arduino Nano. User control of the digital pin was encoded by first declaring a Boolean (true/false) variable with read and write capabilities within the "Setup" tab of the Arduino IoT cloud user interface. This variable was titled "SSR". Within the Arduino IoT sketch editor, code was written to define the variable and associate it with a digital pin on the Nano, set the associated pin as an output, and write the pin as 0V or 5V based on the Boolean value assigned by the user. An Arduino IoT Cloud dashboard ON/OFF switch widget was created and linked to the SSR variable to permit control of the variable within the application. An overview of this process can be seen in Figure 4.

Additionally, a digital potentiometer was utilized in the project to input a variable resistance into the circuitry which controlled the voltage level of the power supply. User control of the digital potentiometer was encoded by first declaring an integer value (0-255) variable with read and write capabilities within the "Setup" tab of the Arduino IoT cloud user interface. This variable was titled "Potentiometer." Within the Arduino IoT sketch editor, code was written to define the variable and associate it with an analog pin on the Nano and write the level of "Potentiometer" to the analog output as a 0-5V value which controlled the output resistance of the digital potentiometer. An Arduino IoT Cloud dashboard 0-255 value slider widget was created and linked to the potentiometer variable to permit control of the variable within the application.

Communication between the Arduino Nano 33 IoT and the Digi-pot was performed with SPI Interface. The SPI Interface allowed the Nano to send the A5162 chip the specified 8-bit value to update the potentiometer resistor value. SPI Interface is implemented with 4 pins: a Clock Signal (SCK), Master Out / Slave In (MOSI), Master In / Slave Out (MISO), and Enable that are located on the Arduino Nano IoT 33 as specified in Table 2.

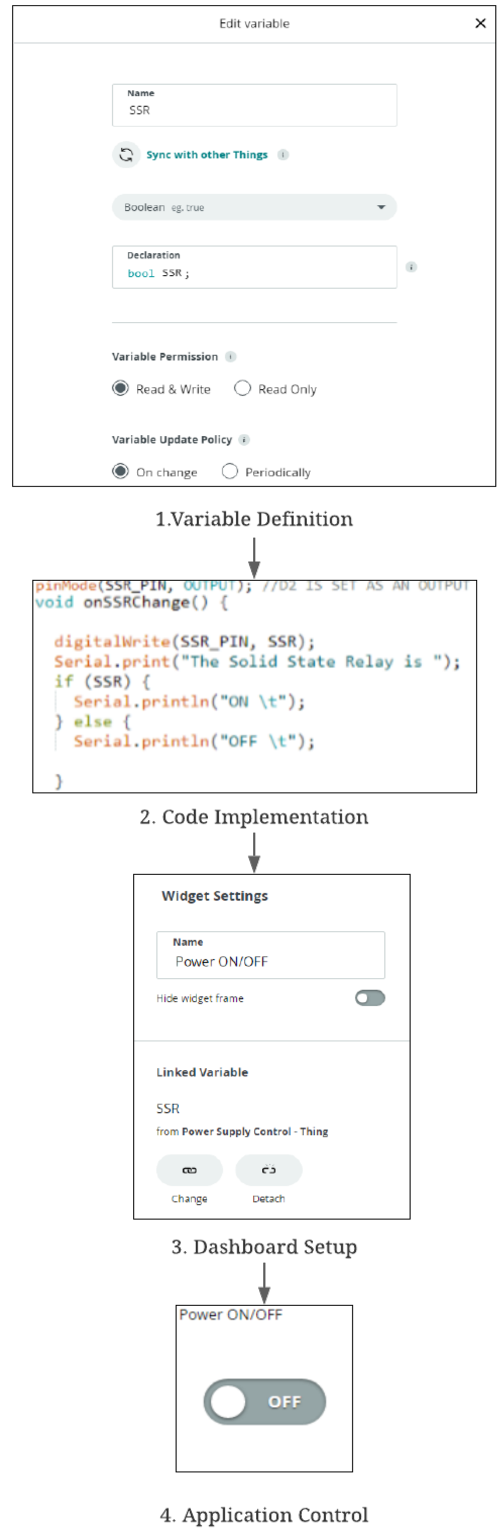

Figure 4 - Variable Setup Process

Arduino pin label	ATSAMD21 pin label	Function
D9	PA20	Enable
D11	PA16	MOSI
D12	PA19	MISO
D13	PA17	SCK

Table 2 Arduino Nano IoT 33 SPI communication pins

Wi-Fi communication is necessary between the Arduino Nano 33 IoT and the "cloud" to allow for updating the Arduino's program when values are changed on the dashboard. This was tested with the use of a digital potentiometer whereby depending on an analog output varying between 0-5V from the Arduino, the potentiometer varies the resistance between its poles. Using the Arduino Cloud App, the On/Off button on the app to turn on and off an output pin which controls a solid state relay, allows for power control. Moreover, a user can turn on the power supply, vary the voltage via the digital potentiometer, and receive voltage feedback via an analog input pin as show in the sample dashboard.

Component Mounting and Enclosure

Assembly was performed in three stages. First, components were soldered to the PCB (Figure 5). During the assembly process of the power supplies, there were some footprint issues among all the teams in class. A mislabeled capacitor polarity in the component library required troubleshooting at this step, but all the power supplies worked as intended after this issue was resolved. Also, discrepancies in voltage rectifier chosen by each team led to an off-board rectifier that could accommodate various pin layouts. This change required additional space inside the enclosures but didn't diminish the performance of the power supplies.

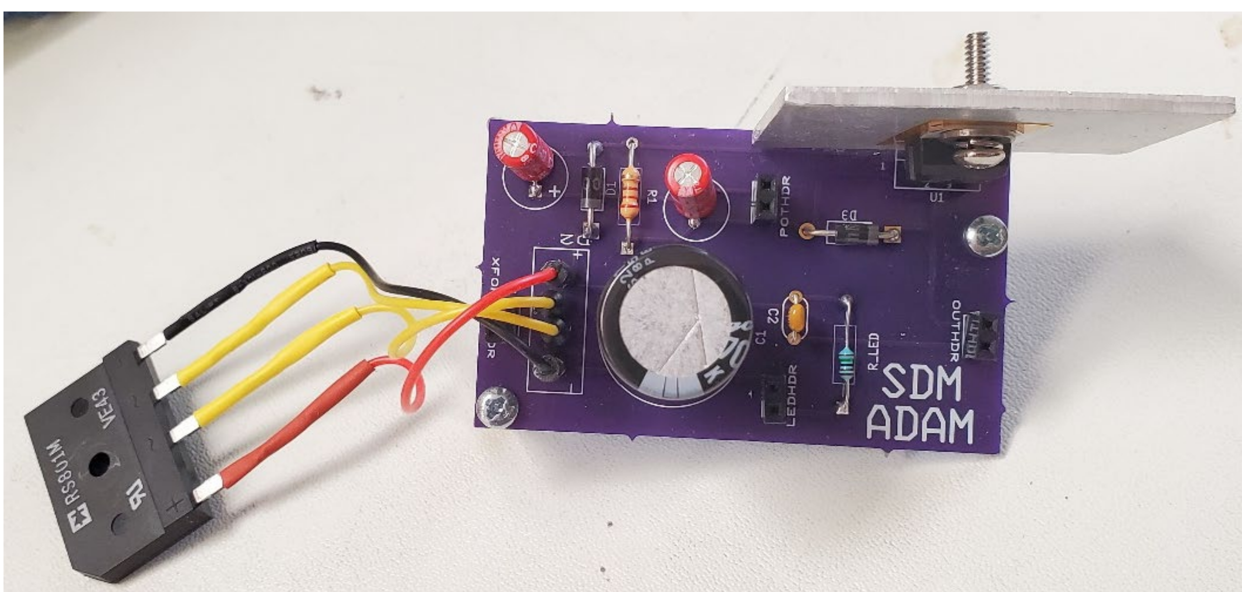

Figure 5 - Assembled power supply circuit

Next, off-board components were added to enhance performance and usability of the power supplies. A heat-sink was added to the LM317 voltage regulator to compensate for the heat generated during operation. The heat-sink used is simply a small 1 inch by 2.5 inches metal sheet attached to the back of the IC package. The voltage output is controlled by a feedback current, which is made variable by including by a 2 kΩ potentiometer in a voltage divider. This potentiometer is mounted externally to allow easy control, though this was later replaced by a digital potentiometer to allow digital wireless control over the circuit. Finally, to show power is being supplied, an LED is mounted externally to shine when the supply is energized. Figure 6 shows an internal layout of the IoT PS with all components assembled.

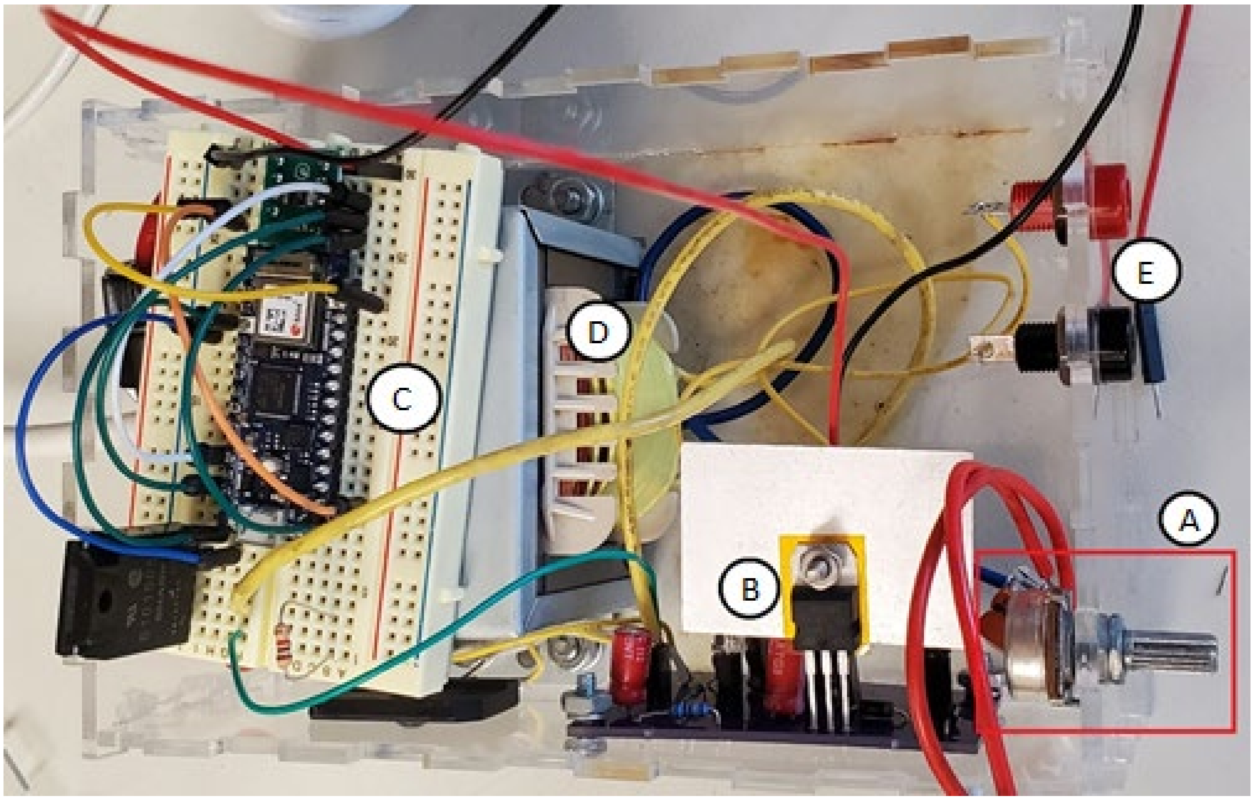

Figure 6 - Assembled IoT PS components which includes the mechanical control potentiometer (a), PCB with Heatsink (b), digital potentiometer (c), 120V transformer (d), and voltage output leads (e)

Finally, vector designs for the project enclosures (Figure 7) were generated with an online tool at makeabox.io given the required length, width, and height of the box. Additionally, openings for components such as output ports, LEDs, and a power cable were added to the design. The resulting schematic was cut out of 1/8" thick wood or acrylic using a Universal PLS6.150D Laser Cutter.

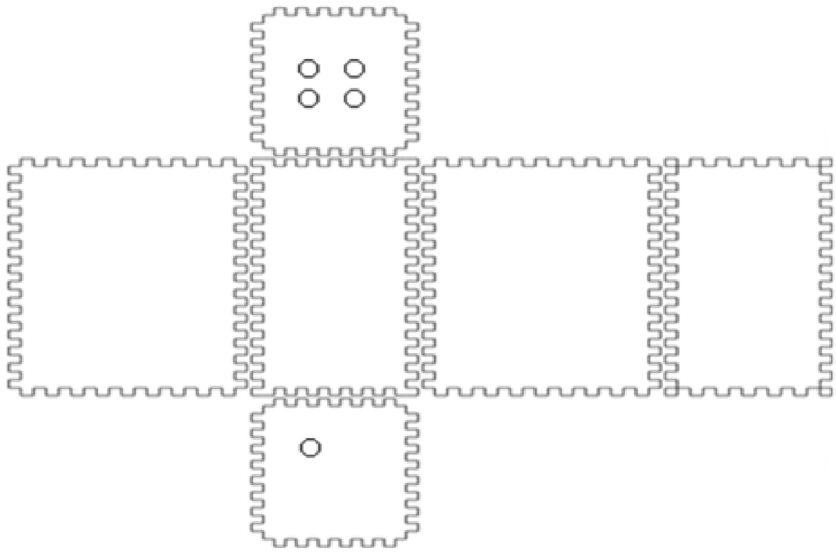

Figure 7 - Example CAD Box Drawing, note that 5 holes will need to be either drilled or added in CAD for the voltage output leads, mechanical control potentiometer, power input and indicator LED.

Results and Student Outcomes

Each student created their own power supply by the end of the course. To determine functionality of each design, a 2 kΩ mechanical potentiometer was used as the LM317's V_{out} adjustment. The open circuit voltage of each power supply was then measured. The maximum output voltage achieved using the mechanical potentiometer was 11.8V, and the minimum voltage achieved was 1.27V. The average voltage range achieved was 1.42V - 10.51V. All of the power supplies were tested with the 2 kΩ potentiometers, but only a single power supply was tested using the 2.5 kΩ digipot due to time constraints (Figure 8). It was observed that, while using the digipot, the power supply was able to output a range of between 1.5V - 8.25V.

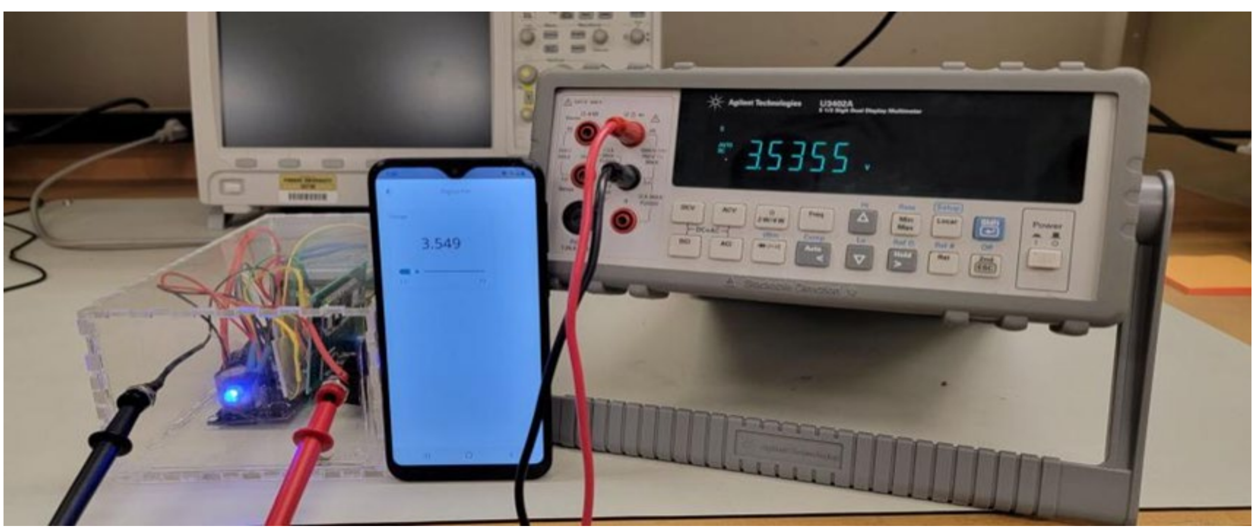

Figure 8 - Final Power Supply with IoT Cloud Application

There were multiple issues that arose during the assembly process that limited the operational range of the final design. There were compatibility issues with some of the components ordered for this project which were immediately problematic upon starting assembly. Both the digital potentiometer and the transistor were not ideal components for their intended use in the system. Error checking of the bill of materials (BOM) would streamline the PCB assembly. Also, the Arduino IoT Cloud service was plagued with connection issues between the various required software components. This is believed to be due in part to using the free version of the service. Using the paid version ($6.99/month) would likely provide better results. However, using another similar service is suggested by the students.

Overall, students suggested the structure of the course could be modified to perform the project design steps sequentially instead of distributed among the general topic lectures and activities. This could eliminate issues such as the students having to relearn the Arduino Cloud Connect software after multiple week spans where it was not required. The PCB design process in UltiBoard also would benefit from more definition. Several board designs had experienced issues with C1 having its polarity labeled backwards on the board. This issue led to several 4700µF capacitors malfunctioning.

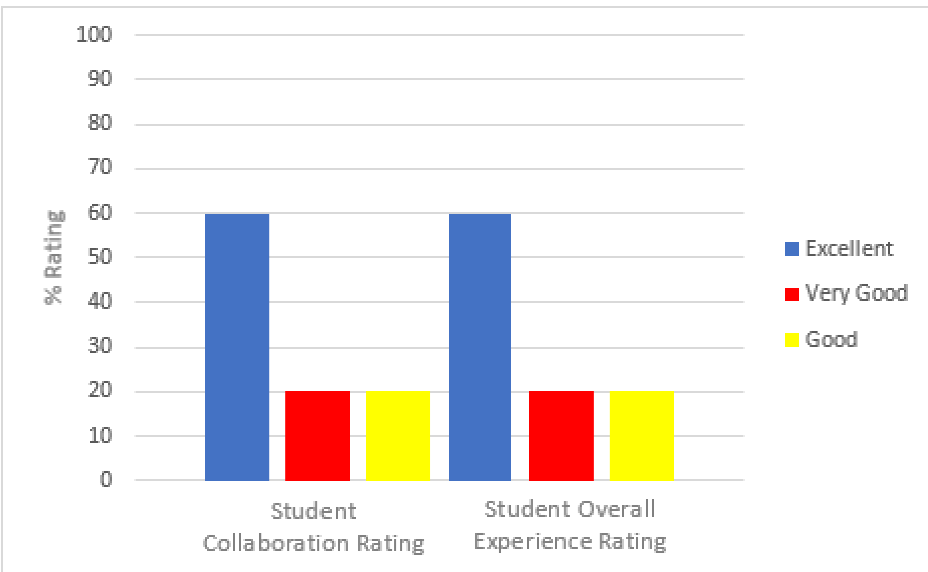

Figure 9 - Student Collaboration and Overall Experience Ratings

Despite these challenges and failures to reach target performance, feedback data (Figure 9) from the students shows that 60% of the class felt that the collaboration elements and overall experience of the project was excellent. Future iterations of this project will seek to address the concerns noted earlier to improve the student experience and increase the likelihood of a successful product at the end of the process. It is worth noting that the feedback was not negative, and the numerous issues encountered did serve as valuable learning experiences and lessons that can be applied by the students in their capstone courses and future industry work.

Conclusion

The IoT Power Supply project was an attempt to expose students to design considerations in many topic areas outside of their core competencies and to eliminate the silo style of thinking traditionally associated with engineering education. Students were asked to experiment with topics outside of their immediate expertise such as IoT connectivity, heatsinking, and the design and manufacturing of a project enclosure. Even selecting and ordering components from online vendors was a different approach than the fixed-supplies lab activities that they experience in many courses. Overall, this project helped the students gain experience working on a problem that requires them to execute both design and fabrication of a system and immersed them in a robust troubleshooting process.

There were a number of positive elements to the students' experience that were observed. As broadly noted in past works, project-based learning gives students exposure to many "real-world" issues that arise when working in engineering design [2]. The troubleshooting involved is a valuable learning experience with industry relevance [3]. There is also a collaborative component to this open style of project that further prepares students for future success [4]. The feedback from the students and instructor observations will be used to improve future iterations of this project to improve project outcomes while maintaining the educational outcomes.

References

[1] "Arduino Nano 33 IoT." @arduino. http://store.arduino.cc/products/arduino-nano-33-iot (accessed 1/20/2022).

[2] W. Ju, L. Oehlberg, and L. Leifer, "Project-based learning for experimental design research," in *DS 33: Proceedings of E&PDE 2004, the 7th International Conference on Engineering and Product Design Education, Delft, the Netherlands, 02.-03.09. 2004*, 2004.

[3] P. Rivera-Reyes and R. E. Boyles, "Training in Troubleshooting Problem-Solving: Preparing Undergraduate Engineering Students for Industry," in *2013 ASEE Annual Conference & Exposition*, 2022, pp. 23.1261.1-23.1261.16. [Online]. Available: https://peer.asee.org/22646.pdf[Online]. Available: https://peer.asee.org/training-in-troubleshooting-problem-solving-preparing-undergraduate-engineering-students-for-industry.pdf

[4] K. A. Smith, "Cooperative learning: effective teamwork for engineering classrooms," in *Proceedings Frontiers in Education 1995 25th Annual Conference. Engineering Education for the 21st Century*, 1-4 Nov. 1995 1995, vol. 1, pp. 2b5.13-2b5.18 vol.1, doi: 10.1109/FIE.1995.483059.

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