A Project-Based Printed Circuit Board (PCB) Electronics Course

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Abstract

The economics of electronics and embedded system development have changed significantly over the last decade. Many local industries which do not maintain full-time electronics development staff have demanded that electrical engineering graduates support small-scale custom electronic development efforts, and projects that previously would have been contracted are increasingly handled internally. The same developments that have driven demand for custom electronics in industry have made it flexible and affordable to deliver a project-based PCB design course in a single semester. Grand Valley State University (GVSU) offers an electrical engineering senior elective course covering project specification, software/firmware development, CAD layout, PCB fabrication, surface-mount (SMT) assembly, circuit testing, remediation, integration, and packaging. Over the course of a semester, student teams design, assemble, test, package, and demonstrate unique embedded system projects.

This paper presents the benefits and challenges of teaching and administering a design-build-test embedded system project course in electrical engineering and addresses plans for ongoing improvement. The course instructs students in each element of an electronics development project. This starts with recognizing electronics problems, specifying critical design functionalities, identifying constraints, anticipating risks and failure modes, and designing for test and remediation. During the course, students receive instruction in proper firmware coding techniques, common electronic circuits and practices, component selection, power regulation, data conversion, transmission line theory, signal integrity, layout guidelines, and PCB fabrication techniques each of which the students apply to a semester-spanning project. Student teams order custom PCB boards from commercial vendors, assemble circuits with SMT technology, program, test, and remediate their electronic projects. This paper analyzes the effectiveness of this course, considers feedback, and makes recommendations for future offerings.

Introduction

The School of Engineering at Grand Valley State University (GVSU) has endeavored to create a practical embedded systems electronics class that would train students to develop PCB electronics in industry, including small companies that have little to no history in Surface-Mount Device (SMD) electronics, prototyping, or electronic manufacturing. To this end, EGR436, an embedded interface class, was modified to include a substantial PCB design component and guide students from a problem statement to a fully-realized custom embedded system prototype. The course was offered in Winter 2019 and is currently running in the Winter 2020 semester.

In past years, there have been many impediments to offering an undergraduate design-build-test embedded system PCB electronics course such as this. It requires many tools and services that have not always been widely available to students or were prohibitive in cost or complexity for use in an undergraduate course. The cost of student-grade PCB assembly and rework equipment has come down in price significantly over the last decade, but there has been one substantial change that makes offering custom PCB design courses practical during a single semester.

As little as three years ago, the cost and complexity of purchasing small-scale, multi-project PCBs created as significant burden on the organization of a course. Substantially similar courses in the past have trained students to design PCBs that would not be fabricated [1] or chose to build primitive circuit boards in-house [2]. The option of letting students obtain their own PCBs from discount manufacturers has existed for the last ten years. Discount PCB manufacturers such as Advanced Circuits (Aurora, CO), which has been used in previous PCB-based embedded systems courses [3], offered students two-layer boards at $33 each or four-layer boards at $66 each while charging an extra $50 for “step-and-repeat” that would allow the student to place multiple instances of the same design on a board for them to manually singulate [4]. This student discount remains fundamentally unchanged today [5]. While seemingly, this would

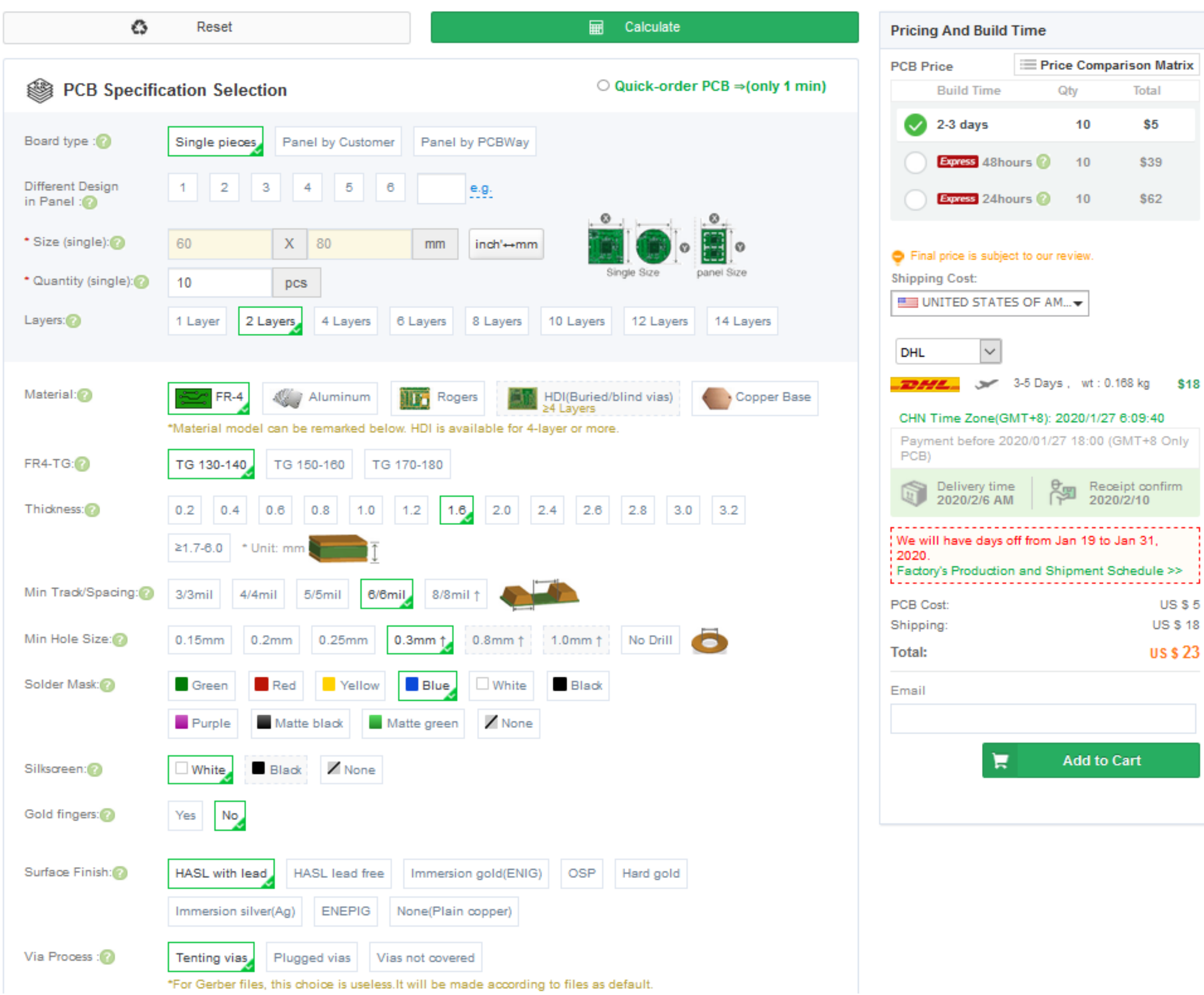

Figure 1 – Screenshot of pcbway.com quoting tool for a two-layer board as of Jan. 2020. PCB Way is one of several Chinese discount manufacturers that provide heavily discounted custom boards available on short notice. In this case, 10 standard 2-layer boards up to 10x10cm (3.9x3.9”) are available for $5 plus $18 shipping from Shenzhen, China.

enable students to independently purchase custom PCBs, various aspects of the interaction made it undesirable. First, most students need more than one PCB board which, if they were to cut the boards themselves, would raise the price to $83 for two-layer and $116 for four-layer boards. Second, the two-layer boards were not of great quality and the discount products tended to be in the 0.031” thickness. Third, even with a stated 5-day lead time, student boards often did not arrive for two-weeks or more.

More frequently, a PCB class would purchase a complete 18x24” panel from a PCB manufacturer. This was available from many custom manufactures and it was possible to purchase the first two-layer panel at around $400 with each subsequent panel around $50, or purchase a 4-layer panel at around $550 with each subsequent panel costing around $75. This was an economical model since at 20 4x4” board per panel, each student could get four two-layer boards for approximately $27.50, or four four-layer boards at $38.75. The difficulties were that the instructor needed to enforce a hard deadline for all boards to send out on a common panel, that any error on any board in the panel would be flagged by the manufacturer, that panelization was easiest and cheapest if all students submitted boards of identical size, and there were few remedies for the students who discovered that they had designed inoperative boards.

In both cases, it was very difficult to obtain surface mount stencils for the PCB, which would require anywhere from $60 to $130 per design and tended to be prohibitive to the students or course budget.

Starting around 2017, several international discount PCB manufacturers began to appear online and market their services to English-speaking customers. Some of these include:

- PCBWay (Shenzhen, China): 10 two-layer boards for a total of $5, 10 four-layer boards for $44 total, $18 four-day shipping, framework stencils for $15 [6].
- AllPCB (Hangzhou, China) offering 10 two-layer boards for a total of $7, 10 four-layer boards for $33, $18 four-day shipping, framework stencils available for $20 [7].
- FirstPCB (Hangzhou, China) offering 5 two-layer boards for a total of $2, 10 four-layer boards for $11 total, standard DHL shipping rates, no stencils [8].

This list is by no means exhaustive and does not include the numerous PCB brokers that will negotiate discounts with international manufacturers. These manufacturers provide a greater number of choices and options than previous discount PCB manufacturers. At their discount price, they include several options of soldermask color, board thicknesses, and silk screen color, while providing standard manufacturing capabilities and tolerances. Stainless steel stencils are available at a fraction of the domestic costs, making SMT assembly reasonable in an undergraduate course. Additionally, these services provide an online quotation feature that allows students to quickly determine how different design choices will affect the overall price of a board, especially of smaller vias or smaller trace widths. Figure 1 shows the screenshot of the PCBWay.com quoting tool for a two-layer printed circuit board.

Course Description

EGR436 is offered as a four-credit lab-and-lecture course once per year. It is advertised as an electronics course covering electronic interfaces between a microcontroller, sensors, actuators, and other interfaces to the environment. During the semester, students will program microcontrollers to communicate with external peripherals, sensors, and wireless communication interfaces. The class focuses on developing a complete embedded system prototype, ready for testing and refinement. All students will have completed at least one semester of microelectronics and one semester of embedded programming. The course requires the students to have a prerequisite knowledge of embedded programming, since the project requires that they build a battery-operated embedded system in which a microcontroller interfaces to a PC through a USB connection, to external memory through SPI, and with the student's phone through Bluetooth 4.0 (BLE), among several other sensors and peripherals. The class is aimed primarily at electrical engineering undergraduate seniors.

Some of the objectives for the class are as follows:

- The student will be able to identify a problem, interrogate a customer, specify the problem, identify critical functionalities, write requirements, identify likely failure modes, write a test plan, and design for test and remediation.
- The student will be conversant in the language of electronics and familiar with common circuits, circuit techniques, and their principles of operation.
- The student will be able to identify good from bad PCB design practices and component selection based upon considerations such as signal integrity, EMC, and assembly yield.
- The student will be able to design to the constraints of external manufacturers, commercial components, and budget.

The class does not require the student to purchase a textbook. All required materials would have been purchased for previous coursework, particularly the MSP432 Launchpad (approximately $20 available at several online retailers). Suggested materials include a MSP432 programming guide and a solderless breadboard for circuit prototyping, both of which were required for previous coursework. Because there is no required textbook purchase for the class, students are informed at the start of class that they will be purchasing the custom PCBs and components for their project.

While the tools and facilities necessary to support PCB assembly and testing are inexpensive, most serve a multipurpose role and support graduate research, capstone projects, and other electronics exercises as well. These include:

- Professional ECAD Software: This course uses Altium Design Workbench as the PCB design software. This software was chosen because it is a powerful professional tool commonly used in local industry and, after 2018, Altium reestablished very reasonable rates for university licenses.
- Assembly tools: Good stencil printers, either accepting standard framed stencils or universal frames, can be purchased in the range of $900 - $4000 depending upon the features desired [9].

- A reflow oven: Several options can be obtained for a few hundred dollars, or if budget does not permit, a $60 toaster oven that can reach 215ºC (425ºF).
- Several boom-arm mounted microscopes: approximately $500 each to support assembly and troubleshooting [10].
- Several solder rework stations: Rework stations with soldering iron and hot air are available for approximately $80 each.
- Custom enclosures or housings: Provided at low-cost through on-site 3D printing services.

Course Topics

The lecture component of EGR436 meets for two 1-hour 15-minutes sessions per week. Lectures are delivered using PowerPoint and examples on the board. A rough breakdown of the topics presented are:

- The electronics development cycle (1 lecture): A discussion about the project management tools for interacting with a customer, identifying the problem, specifying a solution, writing requirements, and developing a preliminary test plan.

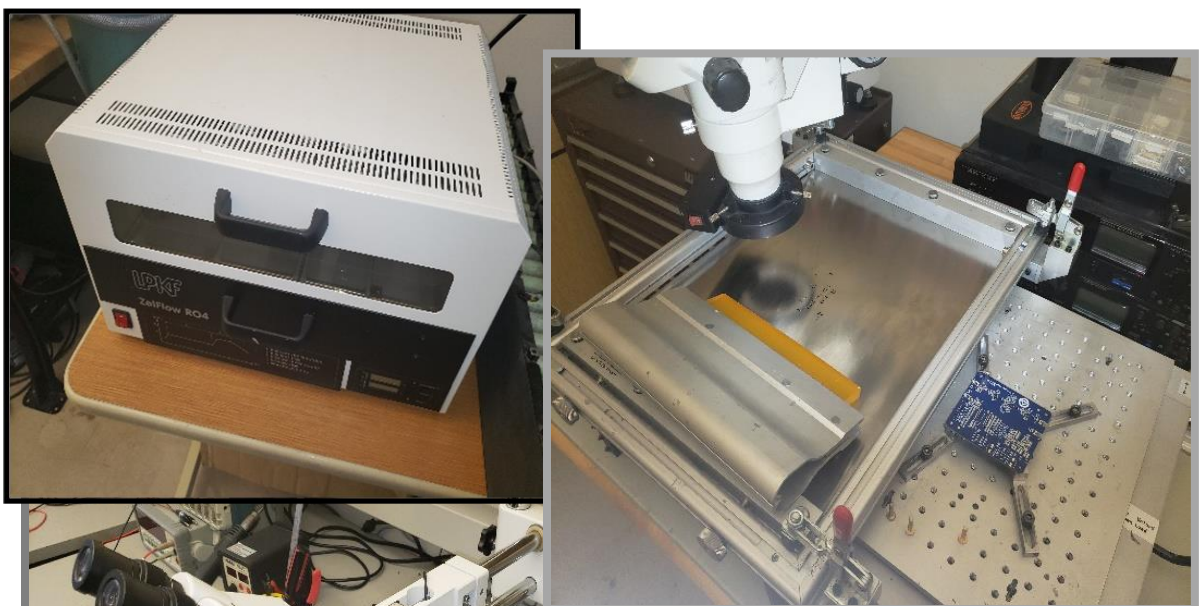

Figure 2 – Some of the laboratory equipment necessary to operating the course. (Top left) A PCB reflow oven. A toaster oven will suffice if not reflow oven is available. (Top right) A stencil printer with plan view microscope. (Bottom left) Rework station with microscope. If these facilities are not already available, they can be established starting at around $2000 investment.

- Electronic vocabulary, communication protocols, and common commercial off-the-shelf (COTS) ICs: (3 lectures): An indoctrination in the names of common circuits and signals, such as decoupling capacitors, pi-filters, CMOS, LVDS, linear regulators, level shifters, capacitor types, and the different packages.
- Layout do's and don'ts (2 lectures): A discussion of design rules, a look at some bad designs, the resulting failures, and how they can be improved.
- PCB fabrication techniques, and assembly failure modes (2 lectures): A discussion of the tools that PCB manufactures use to construct different stack-ups, and identifying common failure modes in PCB electronic assembly.
- Low-power design (1 lecture): A presentation of low-power system concepts, programming and circuit techniques to reduce current consumption and increase battery life.
- Substrates, materials, transmission lines, and high-speed circuits (3 lectures): An analysis of fields and radiation in a circuit, calculating transmission line loss, coupling, and mismatches, and their effect in high-speed digital and analog interfaces.
- Digital-to-analog conversion (DAC) and analog-to-digital conversion (ADC) circuits (3 lectures): A discussion of data conversion performance and different DAC and ADC circuit techniques.
- Voltage regulation, voltage reference circuits, and energy harvesting (3 lectures): A discussion of performance specifications of voltage reference and voltage regulators, thermally compensated Zener diode reference circuits, Bandgap reference circuits, linear voltage regulator circuits, different switch regulator circuits, and how to use these circuits in the application of energy harvesting, specifically solar energy harvesting.
- Feedback circuits (1 lecture): A discussion of effects of feedback on the gain, distortion, noise, and input/output impedance and a presentation of different types of feedback circuits.
- Wave-shaping and signal generation (3 lectures): A discussion of voltage comparator, Schmitt trigger, multivibrator, peak detector, and sample-and-hold amplifier circuits; circuit techniques of oscillators including sinusoidal oscillators and relaxation oscillators.
- Phase locked loop (PLL): An analysis of PLL circuits including the transfer function, phase detection, low pass filter, and voltage-controlled oscillators; applications of PLL in frequency multiplier, frequency synthesis, and frequency demodulation.

The associated laboratory meets once per week for three hours. Approximately half of the laboratory session are dedicated to lab exercises, while the other half are set aside for project work to discuss challenges, perform design reviews, and solve problems. The students are given seven weeks to complete six laboratory exercises. These include:

- External UART/USB Interfaces: Students interface a microcontroller through a USB-to-TTL converter. The students must program the interface on the microcontroller and the PC.
- Communicating with Memory/SPI: Students must establish an automatically defragmented file storage in SPI memory. The microcontroller will store files, retrieve entries, or delete entries via commands and file from the PC.

- Bluetooth Interfacing: Students will interface a microcontroller to a Bluetooth 4.0 (BLE) module to store, retrieve, or delete files stored in SPI via commands from the student's phone.
- ECAD Basics: Students will generate one complete PCB fabrication packet of a simple evaluation board.
- SMD assembly and testing: Students will paste, populate, reflow, and test a DC-to-DC solar power battery-charging board.
- Low-power modes and peripheral management: Students will identify the current consumption associated with different operating modes of the microcontroller and use the microcontroller to enable and disable external peripherals and limit current draw.

Project

The class was divided into teams of two with an odd member set into a team of three. Each team was tasked to identify a problem that could be addressed with a system that met the following requirements:

- Operates on solar-power and solar rechargeable batteries
- Monitors the current and voltage of the solar panel and battery
- Uses a microcontroller
- Uses at least one environmental sensor
- Logs data
- Communicates over Bluetooth Low Energy (BLE)
- Communicates through USB
- Charges batteries through both the solar panel and the USB port.
- Uses a custom fabricated PCB board and populated by your team
- Packaged and installed for use in the application.

The first step in the project was to identify a problem. Project teams were given some latitude in the requirements for solving existing problems for parties willing to sponsor the team's project. This was followed by developing a requirements document and test plan for the system. Time was provided in lab for students to perform breadboard testing of their projects, assembly, and design remediation. The students were required to meet several milestones throughout the semester to guide their progress. These were:

1. Produce a brief problem statement and a description of the solution. Produce a document and discuss this with the professor during laboratory (5% project grade, due week 4).
2. Produce a requirements document for the system (5% project grade, due week 5).
3. Breadboard demonstration of critical features (10% project grade, due week 7).
4. PCB design review in lab of schematics and layout (30% project grade, due week 9). Examples are shown in Figures 3 and 4.
5. Submission of PCB design files for fabrication.
6. PCB population, testing, and remediation.

7. Demonstration of completed system (50% project grade + 20% for being voted best project, week 14). Examples are shown in Figures 5 and 6.

Among the projects that students submitted were a capacitive soil moisture detector for alerting a user to water the plants (Figures 3 and 5), a presence detector to log activity near entryways, a bee counter to measure and record the passage of bees in a commercial beehive, a piggy bank that keeps and reports an accurate account of its contents (Figures 4 and 6), a Bluetooth logger that logs the history of nearby Bluetooth identities for surveillance purposes, a beer cooler monitor lid and temperature monitor, a digital camera trigger and wireless photo transmitter for ski slopes, a pool water temperature monitor, and a self-aligning solar panel gimbal and energy logger.

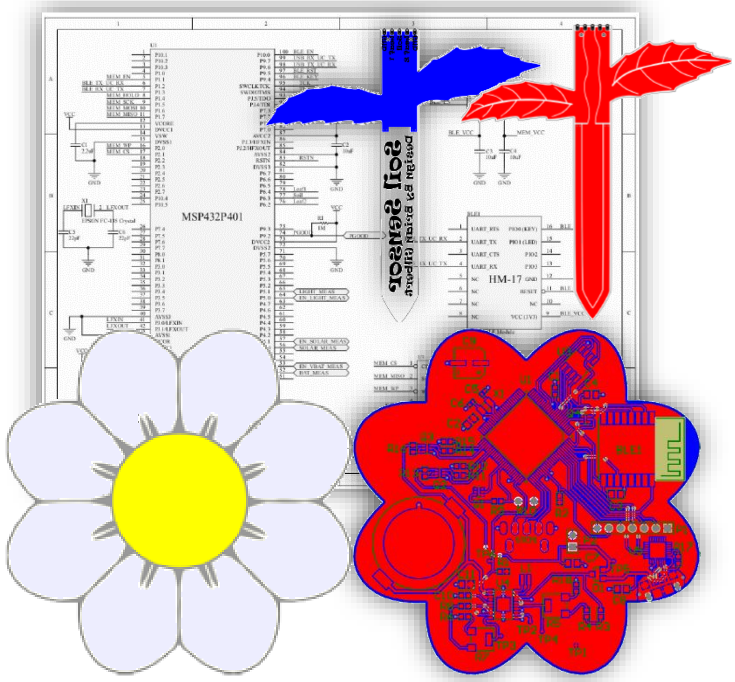

Figure 3 – Example of the design materials for a student project making a plant monitoring system which informs the user through Bluetooth communication of improper lighting or soil moisture conditions for a range of common houseplants. The flower is composed of two PCB boards, where the flower head holds most of the circuitry and the stem composes the capacitive pads to measure soil moisture. (Final implementation below.)

Course Assessments

In the first offering of EGR436, students produced projects of variable quality. The three best projects were functional, well-designed, and attractive like those shown in Figures 5 and 6. The three worst projects managed to demonstrate all the critical functionalities but were not able to integrate all aspects of the design prior to the due date. The five middle projects managed to integrate their project, achieve their objectives, but could clearly benefit

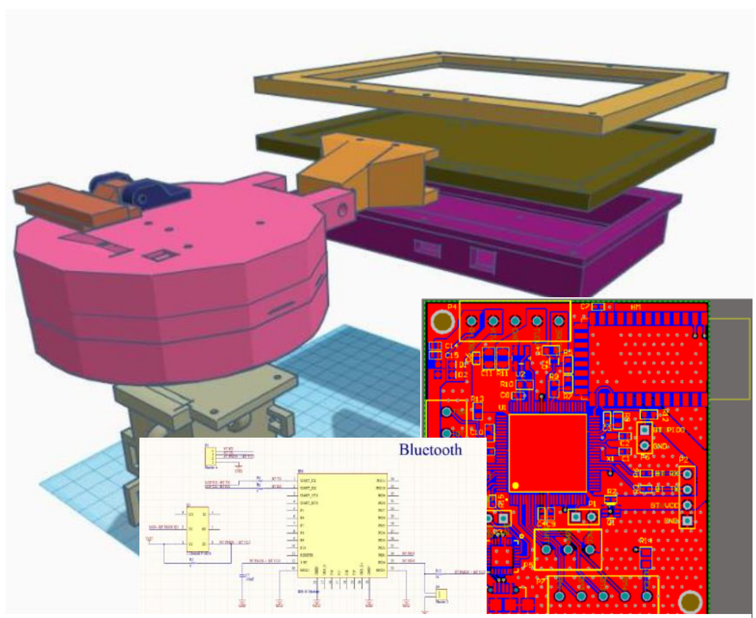

Figure 4 – Example of the design materials for a solar-powered piggy-band accountant when maintains an accurate balance of the coins in the bank and communicates the balance and any activity to the user's phone through Bluetooth. (Final implementation shown below.)

from additional time. All students demonstrated an ability to select components, design PCBs, and assemble circuits. The principle deficiencies we observed were in battery management, as several students who predicted weeks of battery life exhausted their battery cells within hours or were unable to operate with the solar panel they had selected. Some of the difficulties could be attributed to a rushed project schedule toward the end of the semester, which we have attempted to relieve in the second offering of the course. For example, Winter 2019 was interrupted by a week of snow days (the so called "Snowpocalypse") which is one factor that delayed the implementation of PCB designs.

Figure 5 – Implementation of the plant monitoring system. The team took advantage of the low-cost features offered by PCBWay to make an artistic and functional product.

The evaluations for the first offering of the course were mixed. On the one hand, students described the course as "…stimulating and relevant" while the PCB topics were" …interesting and useful…", and that the "…class was very challenging, but I did learn a lot from it." Two students identified this course as their favorite course in the curriculum in their senior exit surveys. Some students did not enjoy the experience. "It at the very least showed me I didn't want to be a hardware engineer." "It didn't stretch my thinking very much because I was already familiar with a large portion of the content…" Some criticisms of the class centered around its lack of focus. "The course was not a continuous progression through a discipline. Often, each lecture was an entirely new topic…"

Figure 6 – Photograph of the solar-powered piggy bank accountant. This project had more mechanical design than many as the different size coin are diverted to different sensors for counting when they are inserted.

The course is being offered again in a substantially similar format in Winter 2020. The 2020 offering has been further disrupted by university-wide shutdowns due to the COVID-19 pandemic. Present plans are to allow the project to proceed after the end of the Winter 2020 semester. The results of the latest semester will be presented.

Conclusion

This course demonstrates the possibility of offering a senior embedded-systems prototyping course in which students design, build, and test a system in both its hardware and software aspects. This course was made possible by embedded system programming prerequires in GVSU electrical engineering program, a modest investment in PCB assembly technology and tools, and the plummeting cost of rapid PCB fabrication. These factors could be replicated at other universities which have not traditionally supported electronics fabrication or cannot draw upon a deep research-oriented infrastructure.

The quality of the student projects was an encouraging indication that the objectives of the class were achieved. All student teams were able to demonstrate a proficiency of the subdisciplines necessary to develop an embedded system prototype while the less successful teams failed primarily at integrating all parts of design prior to the project deadline. The course is being offered again in 2020 and the results will be presented.

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