The Chemistry Team
PlastiClass-Express

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Capstone Design ECE 4440 / ECE4991

Signatures

Zachary Ross

Eric Powell

Jack Chandler

Statement of work:

Zach:

My main contribution would have to be the work on the mechanical design for the project. This includes designing and printing the cone enclosure and the full system enclosure. The cone enclosure was designed super well for the PCB layout of the emitters and detector, however, the full system enclosure struggled. Given that we obtained our physical PCB pretty late into the semester, there was rather limited time to design the system enclosure perfectly in Solidworks. On top of this, the 3d printers at Clem failed multiple prints, so we were forced to pay to use the printers in the mech building instead, which was not planned. All in all, the system did fit the design after tweaking the plastic of the enclosure, and some areas needed to be taped over to keep everything intact, but the end result was able to house the system successfully.

Secondarily, I worked on parts of the embedded code for the system. Specifically, this included configuring GPIO, the timer and ISR for measuring data, parts of the LCD output, and the data processing algorithm. Having worked on this stuff as early as possible into the project, we had a solid backbone once our hardware was finalized, which made it easier to get to testing later on. After realizing the data processing algorithm wasn't going to work as smoothly as expected, I also contributed to calibrating / fine-tuning the parameters that went into the final algorithm for Demo Day.

Eric:

I worked mainly on the electrical design, including the circuit design of the spectrometry hardware and the PCB layout. This included the overall hardware architecture, component selections for each subsystem (excluding the microprocessor itself), and calculations to optimize system performance. Some of the most important pieces were the design of the infrared emitter driving circuit as well as the photodiode transimpedance amplifier, which included calculations about the gain and bandwidth of the circuit. I was also responsible for the inclusion of design-for-test aspects and the robustness of the PCB.

Following the circuit design phase of the project, I worked on the PCB layout, and the preliminary testing of the amplifier circuit. Once the prototype PCB came in, I assembled it and collaborated with the team on testing the system. I was responsible for adjustments to the hardware and finalizing the PCB design. Throughout the course of the project, I contributed to the organizational side of things by handling part orders, PCB submissions, and budget management.

Jack:

At the start of the project, I worked towards processor selection to satisfy the demand of the project, resulting in the selection of a C2000 TI launchpad, and an LCD. I continued this progress by adding these to the schematic along with the LCD drive circuitry to provide scalable power to the LCD screen. I also contributed to the overall product design in this stage, including the mechanics of the spectrometry capture,

My primary focus was the software development of the project. I developed the communication interfaces for the LCD and ADC for use in the rest of the project. The LCD interface provided functional commands to initialize then display text on the LCD. The ADC required SPI communication, but since launchpad SPI pins were not connected in the layout, I wrote a bit banged SPI controller to communicate with the ADC. I continued this work with the integration of the ADC interface into the timing of the initial capture sequence. In the final stage of the project, I revised the existing code including the main loop functionality, GPIO interrupts, and task scheduler for the timer controlling the capture sequence.

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Abstract

The PlastiClass Express is a portable device that uses near-infrared (NIR) spectrometry to classify the type of polymer in a plastic sample. The device, called the PlastiClass-Express, measures the reflectance of the sample at three discrete wavelengths in the near-infrared region and uses those measurements to differentiate between polyethylene terephthalate (PET), high-density polyethylene (HDPE), and polypropylene (PP) polymers [1], outputting this information to the user through a liquid crystal display (LCD) screen. The reflectance is measured using three sets of three light-emitting diodes (LEDs), each set emitting a different wavelength, and an indium gallium arsenide (InGaAs) photodiode sensing the intensity of light reflected by each LED. A microcontroller conducts the capture sequence on user input and uses a data processing algorithm to produce a definitive classification of the sample. This device functions as a portable solution for plastic identification in the application of recyclable material sorting, as well as demonstrate the capability of affordable spectroscopy.

Background

Every year, tons of recovered waste are found in the form of manufactured plastics that can take between 100-600 years to decompose. If no significant changes are made to reduce waste, the world's oceans may be filled with more plastics than fish by 2050 [2]. With this in mind, we wanted to choose a project that has an obvious environmental impact. We saw potential in working on resin identification in the polymer recycling industry, specifically near-infrared spectroscopy, which has various limitations.

Over the last decade, large conveyor belt implementations as well as cheaper portable alternatives have been created, which utilize the infrared wavelength range from 700nm to 2500nm. Researched applications often utilize mid-infrared frequencies around 1700nm at which the plastics had measurable and identifiable peaks in their reflectance spectrum. However, commercial infrared detecting devices are more expensive above 1700nm than those utilizing lower wavelengths in the range of 700nm to 1200nm, and the plastics of interest demonstrate less significant reflectance peaks within this spectrum [1]. As a tradeoff to clearer and more precise infrared spectroscopy, our product detects and identifies PET, HDPE, and PP polymers using these lower wavelengths, allowing for the use of cheaper hardware. In this regard, the product functions as a proof-of-concept for a more financially favorable resin detection technology. Further development in this scope would include expansion into larger-scale detection, the identification of other materials, and increasing specificity of the properties of the measured object. This project draws primarily from both the ECE Fun and Embedded courses. ECE Fun concepts are used heavily in the circuit schematic and printed circuit board (PCB) layout design. Techniques learned in Embedded courses are employed for the software that will run on the microcontroller, including concepts like interrupt handling. Additionally, concepts from Program and Data Representation are incorporated into the software architecture and the ENGR intro course related to CAD modeling for the mechanical design.

Physical Constraints

Design Constraints

One of the main constraints faced in development was the limited opportunities to manufacture a PCB. This imposed deadlines on when the electrical design and component selection needed to be finished for the first prototype, and limited the amount of full-system testing that could be done prior to manufacturing and assembling that prototype.

A manufacturing constraint faced was the inability to print the electronic enclosure for the system on the Makerbot printers at Clemons library due to the size and shape of the box. This, along with the late acquisition of the final PCB, played a big role in having limited time to really thoroughly design the enclosure, which led to minor design errors in the exact dimensioning of certain parts of the enclosure.

Another constraint was component availability, specifically the availability of an LM317 voltage regulator component [3] used to control the power to the infrared emitters. This component went out of stock between our prototype design and final design, so an adjustment needed to be made by substituting a very similar part with the same key characteristics [4].

Cost Constraints

The intent of this project is to design an affordable system for detecting plastics, compared to researched and current experimental applications [1]. This improvement originates from the $500 budget given for the product's development. The most significant expenses this project has are the microprocessor development board, custom PCB, detector, and emitters for spectrometry. The development board was selected to include a microprocessor functional out-of-the-box with an onboard debugging probe [5]. The custom PCB design contained all relevant circuitry to enable the spectrometry capture, as well as power the device. The total cost per PCB was about $207 as calculated in the appendix.

The product is specialized in its functionality - spectrometry specifically of a few plastic types. However, the application of this function can be applied in multiple ways, including spectrometry research, consumer-level plastic identification tools, and educational use. With respect to the target consumer, the cost of the device may not be purchased in the context of a basic household product but would be financially favorable for those in an academic setting. In general, though, production costs would likely be variable as the components experience price fluctuations.

Tools Employed

The tools used in the electrical design include KiCad [6] for the schematic design and board layout. Using KiCad was a slight adjustment from other circuit design software that we had used in the past. A custom Gerber file renaming utility was used to prepare the files for the class PCB send-out. Websites including Digi-Key Electronics [7] and Mouser Electronics [8] were used for selecting components, and Ultra Librarian [9] was also used to get footprints for some components.

The tools used in the mechanical design include Solidworks [10] and Makerbot Print [11] for designing and slicing CAD models. There was definitely a learning curve for Solidworks, and we haven't done significant CAD modeling ever, and Makerbot Print was entirely new software. But these allowed us to create robust 3d models for both enclosures in the design.

Software development was conducted in Code Composer Studio [12], an IDE developed by Texas Instruments. This IDE directly interfaces with the launchpad used in the design to flash, run, and debug the microcontroller. The team had ample experience with Code Composer Studio from previous embedded projects.

GanttProject [13] is the tool used for project scheduling and time management. This tool was new to us, but provided simple gantt chart creation to schedule the work on the project throughout the semester. NI VirtualBench [14] oscilloscopes measured the analog and digital signals of the project during hardware verification and interface development. The NI VirtualBench was used in previous classes, so we were comfortable using it to debug the analog and digital signals. A disadvantage of this tool was the limit of 2 oscilloscopes because when debugging the timing of the capture sequence, there were instances where 3 or more variables needed to be tracked.

Societal Impact Constraints

Environmental Impact

While the 3D printed components will be made out of renewable and compostable polylactic acid (PLA) [15], PCB manufacturing as a process is extremely wasteful with respect to things such as solder paste waste, solder dross, solvents, volatile organic compounds, and wastewater [16]. Along with this, PCBs are inherently difficult to recycle due to their grouping of hazardous materials. For the scope of this project, it is rather unavoidable to use more environmentally friendly electronics in thinking about the long-term disposal of the product.

Because this product is meant to be re-used though, the only waste involved before long-term disposal should come from the 9V battery. On that note, the device's low-power design should hinder the rate of battery disposal.

Sustainability

The sustainability of this project is relatively replicable. With design files for the PCB and mechanical design, the main consideration becomes part availability. Some relevant components, such as the OPA380AID [17], emitters, and photodiode fluctuate in stock, although replacement components are likely available. The constraint comes from whether replacement emitters of the same wavelengths and similar enough specs otherwise are purchasable. While the launchpad used is not necessarily available, if we were to start reproducing the PlastiClass-Express, we would simply just use the C2000 microcontroller without the launchpad to save space and money, so this is not a sustainability constraint.

Health and Safety

Concerns about consumer safety arise from the NIR emissions during spectrometry. Artificial light emissions may be dangerous to the human eye and skin. These areas are considered separately as the focusing of light in the retina increases the potential for injury [18].

Eye damage results from thermal damage due to sudden intensity or prolonged exposure [19]. Prolonged exposure will not be an issue with the design, as for the application of spectrometry, the emitters will be pulsed during the capture sequence. The sudden intensity would also be a concern, but visible and infrared LED exposure as regulated by the lamps standard (IEC/EN 62471) exposure limits do not directly threaten the safety of an unprotected eye [20].

Skin damage is the last consideration of the spectrometer. The emitters will emit light at a luminous intensity of less than 1 candela per centimeter squared (cd/cm^2), which is below the light and near-infrared threshold limits for occupational use set by the Lawrence Berkeley National Laboratory [19].

Ethical, Social, and Economic Concerns

From an economic standpoint, in particular, our spectrometer is made to serve as a less expensive polymer detection system than most other market spectrometers. Societal impact of this project may include increasing accessibility to spectrometry technology and plastic polymer sorting. Additionally, the PlastiClass Express might demonstrate that industry-standard spectrometers can cut costs by utilizing lower wavelength regions. Increased use of spectrometry in waste management industries automates jobs performed by humans. This may result in more accurate sorting of plastic waste at the cost of jobs in the community. This ethical issue may be furthered by the justification that accurate sorting is beneficial for environmental sustainability because it reduces contamination in the recycling process [21].

External Considerations

External Standards

The product conformed to the international standard for photobiological safety of lamp systems, IEC/EN 62471, by staying within the wavelength range of 200nm - 3000nm with the emitters used. Within these standards, a user's eyes are not directly threatened by sudden intensity or prolonged exposure [22], although the user shouldn't be looking at the emitters while using the device anyway.

NIR-emitting LEDs have an impact when in direct contact with skin. Burns can be caused by the increase of heat in the semiconductor junction when taking measurements. In this regard, we designed the emitter enclosure to prevent users from accidentally touching the LEDs [18]. However, the LEDs will emit at an intensity below the threshold limits set by the Lawrence Berkeley National Laboratory [19].

Another standard that was followed is the NEMA/IEC type 1 standard of protecting users from electrical shock and contact with electronics along with protecting the electronics from external factors such as dirt [23]. This was accomplished by the design of the electronic enclosure.

This device met the international standards for electronic safety set by the IEC (International Electrotechnical Commission), specifically IEC 60950-1:2001 which is for battery-powered electronic devices [24] as well.

In terms of PCB design, the PlastiClass-Express followed the IPC-2221A standard that addresses topics like design layout, parts lists, materials, mechanical and physical properties, electrical properties, thermal management, etc. [25].

Finally, all parts sourced for this device are RoHS compliant to ensure that hazardous substances are not present in the device [26].

Intellectual Property Issues

In researching relevant patents to this project, we found a few different spectrometer patents that are quite comparable to what we designed. For starters, a patent already exists with an independent claim for a spectrometer apparatus with a continuous variable wavelength optical filter [27]. This patent focuses a lot on the optical filter and we also used discrete wavelengths, so this might not prevent us from patenting our project. However, another patent exists with a claim for a portable, battery-powered spectrometer [28]. This spectrometer also has a dependent claim that the portable device can connect to a control device through Bluetooth, Wifi, or 4G. A third patent exists as well with dependent claims that the two discrete wavelengths used differ in that one is in the visible wavelength region and the other is in the near-infrared region [29]. All of this is rather similar to our device; however, we might be able to patent the specific use of 3 discrete near-infrared wavelength emitters in conjunction with a complete system that doesn't need to interface with an external device.

Detailed Technical Description of Project

This project uses near-infrared spectrometry to classify the type of resin that a plastic sample consists of. Specifically, a microcontroller uses infrared LEDs of three different wavelengths (870 nm, 1070 nm, and 1200 nm) in conjunction with an indium gallium arsenide (InGaAs) photodiode that measures the reflectance of a sample at each wavelength. The photodiode signal is amplified and converted to a digital value with an analog-to-digital converter, which is then processed by the microcontroller. The microcontroller takes 128 measurements for each of the 3 wavelengths, plus a set of dark measurements (no LED activated), for each sample. It then uses these measurements to determine the type of resin from three options: polyethylene terephthalate (PET), high-density polyethylene (HDPE), and polypropylene (PP). The data processing algorithm uses the relative ratios between different wavelengths, which are a chemical characteristic of the different types of plastic. This process will be described in detail later on. Using three discrete wavelengths at the lower-wavelength end of the near-infrared spectrum allows for less expensive hardware, with the tradeoff of limiting our scope to the three types of resin targeted by this project.

A block diagram of the full system is shown in Figure 1 below. The custom PCB includes the voltage regulators, spectrometry hardware (including the infrared emitters and photodiode detector that are housed in an optical enclosure attached to the PCB), photodiode amplifier, analog-to-digital converter, and user interface (buttons and LCD display). The PCB is connected directly to the headers of the microcontroller launchpad, and both the launchpad and PCB are powered from a single 9V battery.

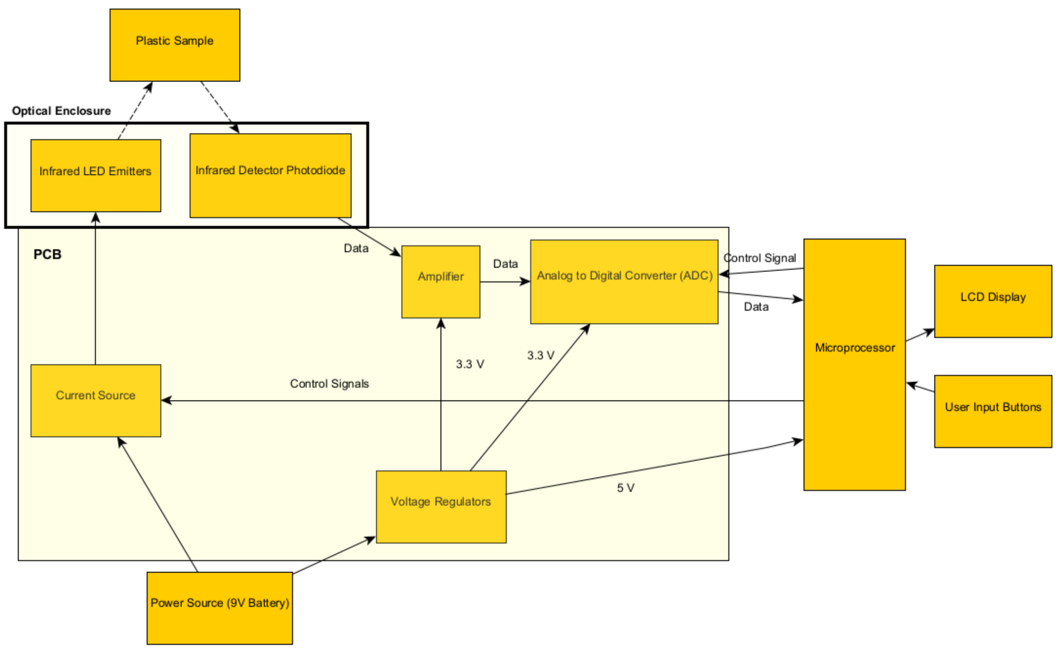

Figure 1: Block Diagram

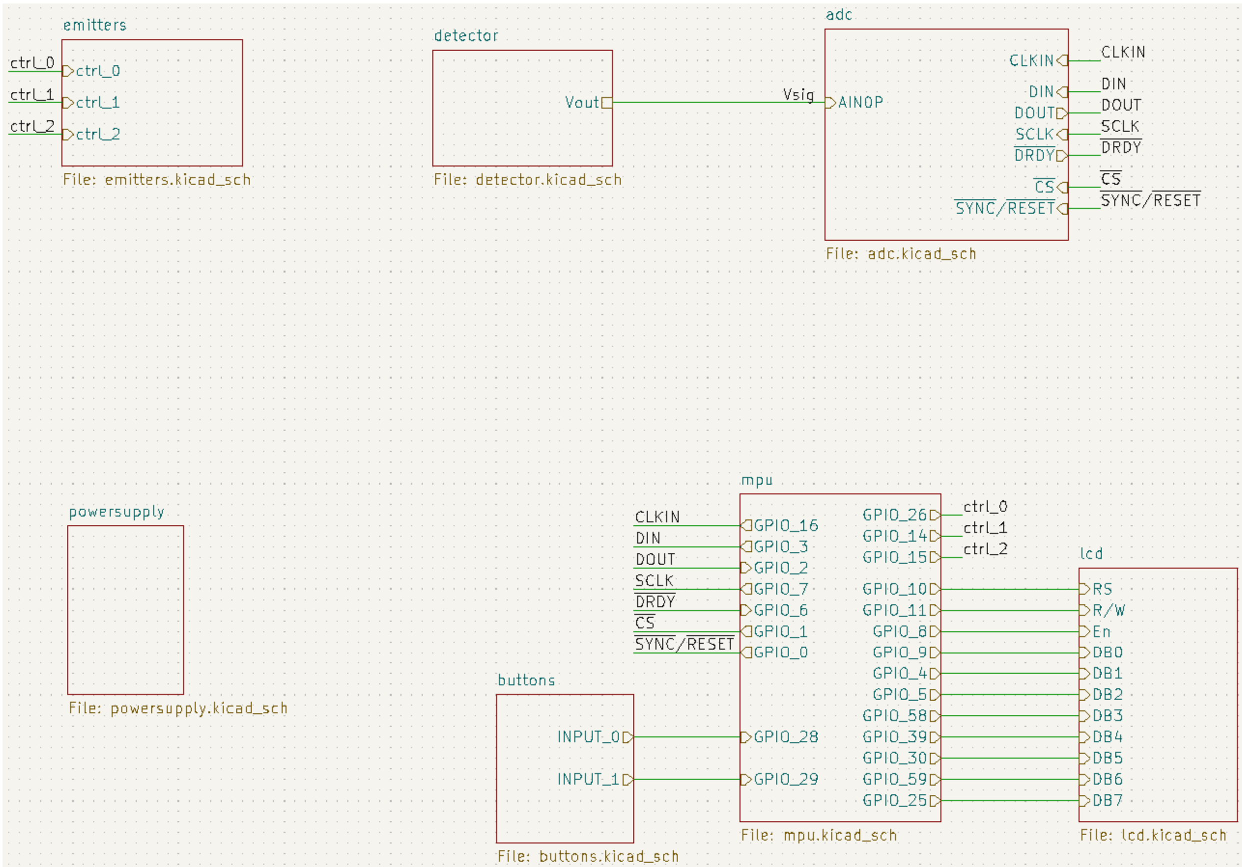

Figure 2: Top Level Schematic

Figure 2 above shows the top-level schematic of the electrical design, including each subsystem from the block diagram in Figure 1. The following section will step through each subsystem and detail the design process and decisions in each.

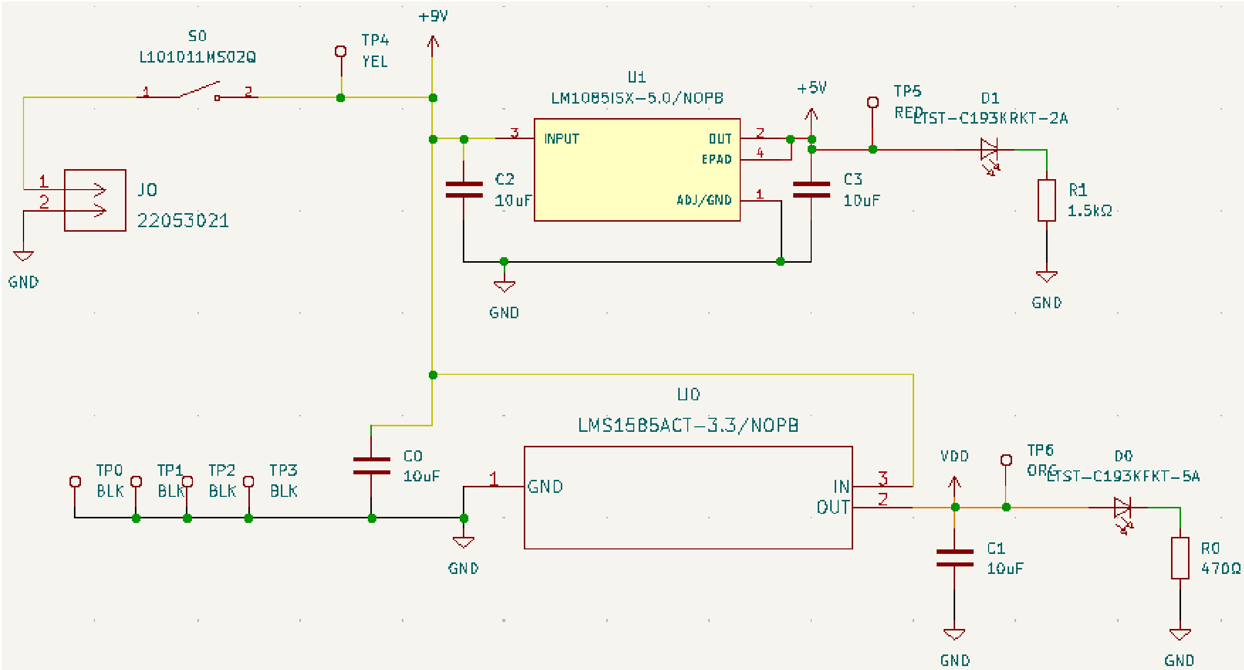

Figure 3: Power Supply Schematic

The power supply schematic shown in Figure 3 includes a power switch, a 3.3V linear voltage regulator [30], a 5V linear voltage regulator [31], and indicator LEDs [32] to easily show that power is present in the system. Both a 3.3V and 5V regulator are necessary, as some components such as the LCD require a 5V supply, while others such as the ADC operate on only 3.3V. Each regulator has the appropriate bypass capacitors, and there are various test points to allow for easier testing and debugging of the physical board (these test points will be seen throughout the subsequent schematics as well). The entire system is powered by a 9V battery that connects to the header J0.

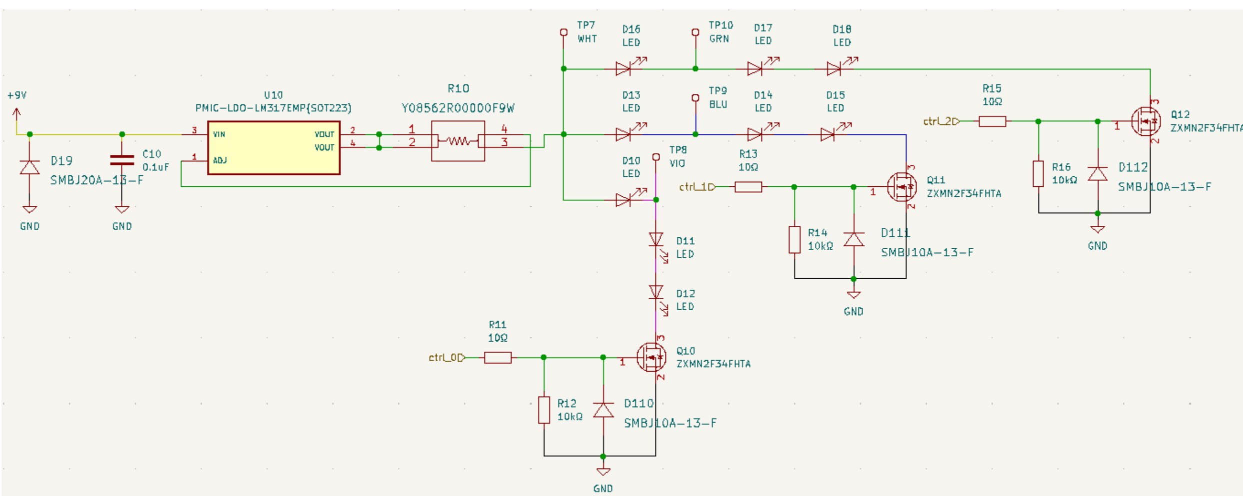

Figure 4: Infrared Emitter Schematic

Figure 4 shows the schematic for the infrared emitter driving circuit. There are 3 wavelengths of emitters, and 3 emitters per wavelength: D10, D11, and D12 emit 870nm [33]; D13, D14, and D15 emit 1070nm [34]; D16, D17, and D18 emit 1200nm [35]. These specific emitter components were chosen in part because of their high power output, narrow spectral output, and narrow viewing angle. The 3 wavelengths were chosen based on preliminary research of the reflectance spectra of PET, HDPE, and PP plastics, as shown in Figure 5 below. In order to stay within our project's budget, we used lower wavelength emitters than prior systems, targeting the significant drop in reflectance of HDPE at around 1200nm, as well as the gradual slope of the PP reflectance as opposed to the near-constant reflectance of PET across that portion of the spectrum. These features allow the device to classify a plastic based on the ratios between the measured reflectance at each wavelength.

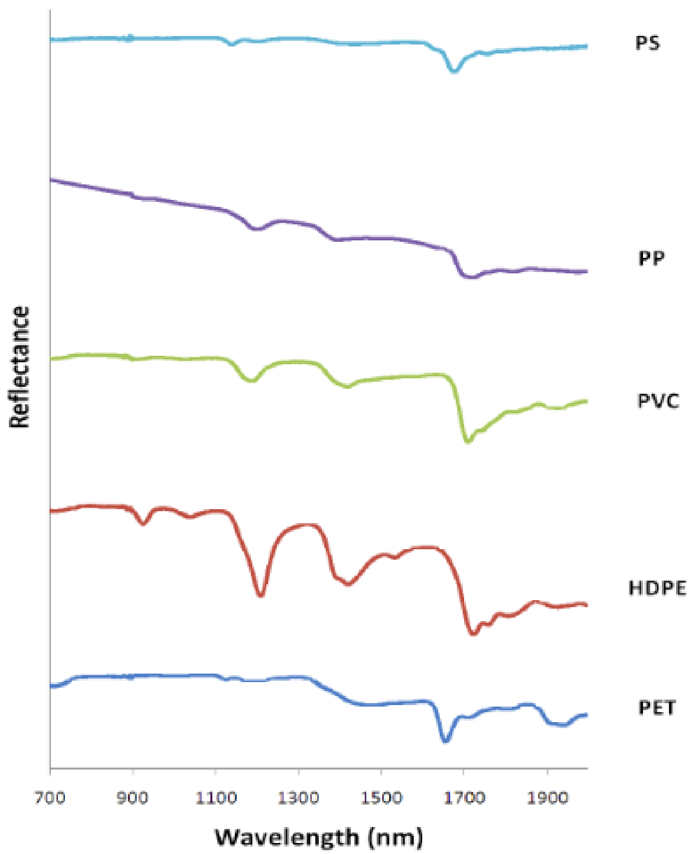

Fig. 3 The reflectance spectra of five resins

Figure 5: Reflectance of Various Plastic Types [1]

Each set of emitters in the circuit is controlled by a MOSFET [36] with a gate-source threshold of about 1.5V, used as a switch by the 3.3V microcontroller GPIO pins. Each MOSFET has a pull-down resistor, input resistor to mitigate ringing, and TVS diode connected to the gate for protection from possible voltage spikes.

An LM317 adjustable voltage regulator [3], with a protection diode and bypass capacitor, is used to power the emitters directly from the 9V supply. The LM317 holds a 1.2V drop between the Vout and Adj pins, so a 2 Ohm current sense resistor [37] is connected between those pins to provide a constant 600mA supply to the circuit.

$$I=V/R=1.2/2=600mA$$

The different wavelengths of emitters have slightly different voltage drops, so controlling the current of the circuit allows for a more constant power output from each set of emitters. Another key part of the design is that the emitters are pulsed for a short period of time at a current higher than they are rated for at DC. This allows there to be higher power output and a more accurate measurement taken in the photodiode subsystem. Only one set of emitters is activated at a time, and never for longer than 100 us at a period of 10 ms, which at 600 mA current falls well within the safe range shown in Figure 6.

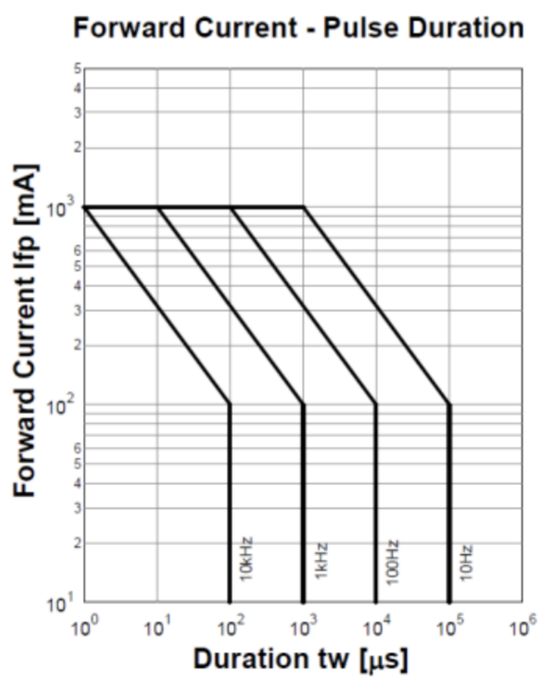

Figure 6: Infrared Emitter Maximum Pulse Duration

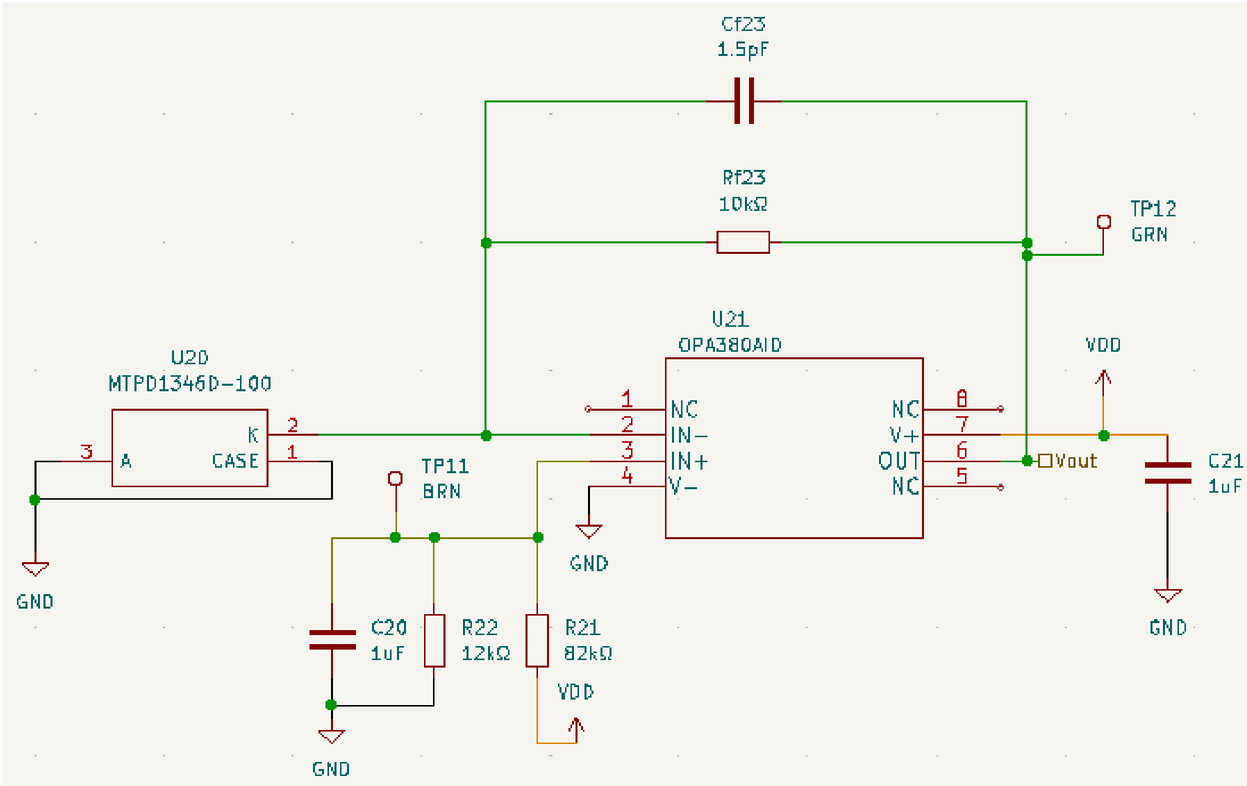

Figure 7: Photodiode Amplifier Schematic

Figure 7 shows the schematic for the photodiode and amplifier subsystem. The photodiode [38], U20, was selected to be an InGaAs photodiode with high speed response covering the full spectral range of our emitter wavelengths, so that it can be used for all measurements taken by the device. The amplifier [17] was chosen due to its optimization for photodiode transimpedance amplifier applications, and a feedback resistor is used to control the gain of the system. There is also a biasing voltage divider connected to the positive input terminal of the amplifier, which holds a constant 0.4V. A capacitor, C20, is also connected to the biasing circuit to filter out any high frequency noise.

Reverse-biasing the photodiode puts it in photoconductive mode, which increases the sensitivity, response time, and dark current by widening the depletion region of the photodiode. The increased dark current is compensated for in software, as the device takes on dark measurement along with each set of infrared wavelength measurements.

The gain required was difficult to estimate without experimental preliminary testing, which was completed using one emitter paired with the photodiode amplifier circuit implemented on a breadboard. This testing led to a targeted gain of about 93dB, though in the final system this ended up being adjusted down to 80dB by replacing the original 100 kOhm feedback resistor, Rf23, with a 10 kOhm resistor. The required bandwidth was determined to be at least 1 MHz for the minimum 10 us pulse duration of the emitters, which the amplifier was able to provide at both gain settings.

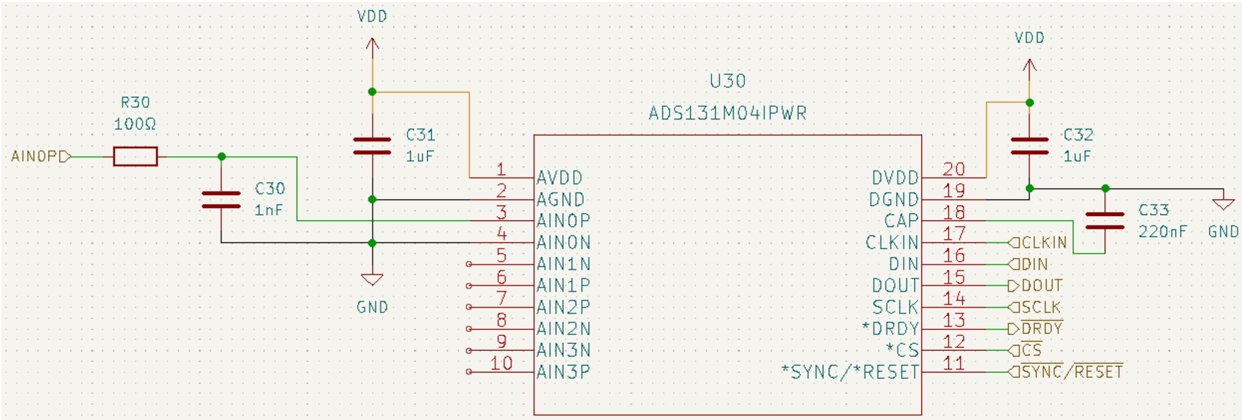

Figure 8: ADC Schematic

Figure 8 shows the schematic for the Analog to Digital Converter (ADC), U30 [39]. Only one of the four available input channels was used, with a low-pass antialiasing filter in front of the input pins. A 220nF capacitor was connected from the “cap” pin to GND as recommended by the ADC datasheet when operating at a supply voltage greater than 2.7 V.

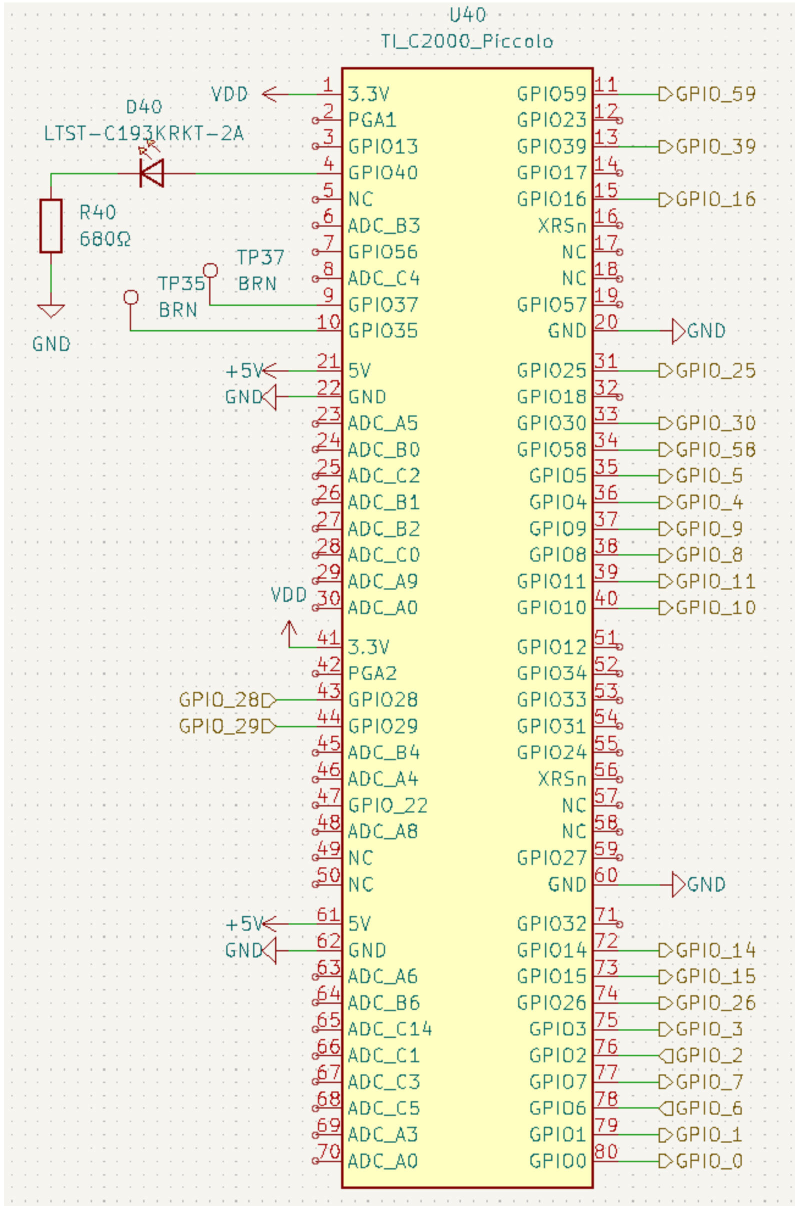

Figure 9: Microcontroller Schematic

Figure 9 shows the schematic for the microcontroller. Relevant GPIO pins are connected directly to the other subsystems, and power is shared from the same supplies as the rest of the board. There is also an indicator LED [32] connected to a spare GPIO pin to function as a heartbeat for debugging purposes.

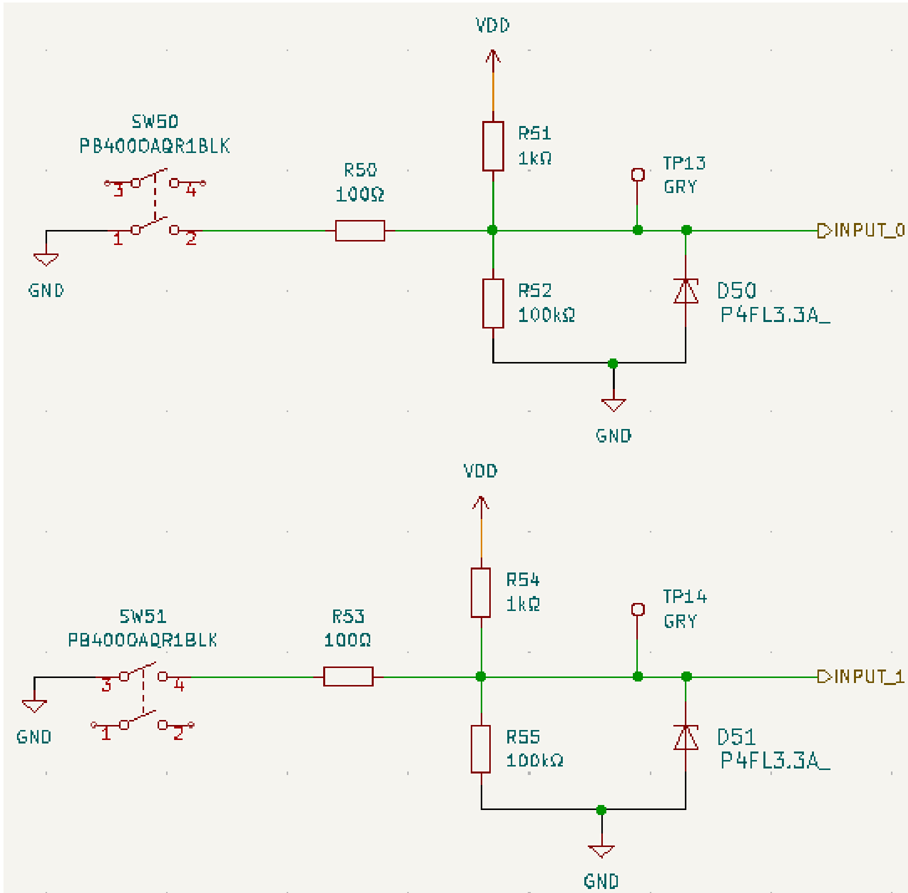

Figure 10: Interface Buttons Schematic

Figure 10 shows the schematic for the user interface buttons. Each is connected to a current protection resistor, pull up resistor network, and a 3.3V TVS diode to protect the GPIO pins from any voltage spikes.

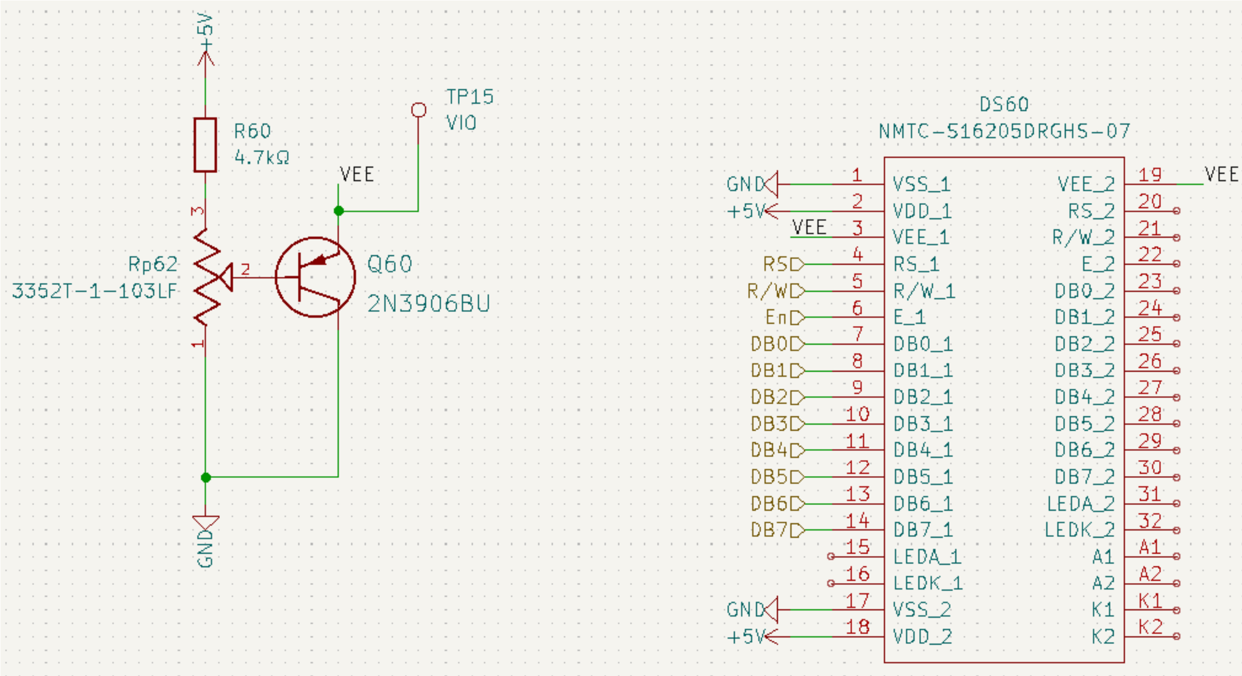

Figure 11: LCD Schematic

Figure 11 shows the schematic for the LCD [40], including a potentiometer [41] connected to the base of a PNP transistor [42]. This allows the contrast of the LCD to be adjusted for optimal viewing.

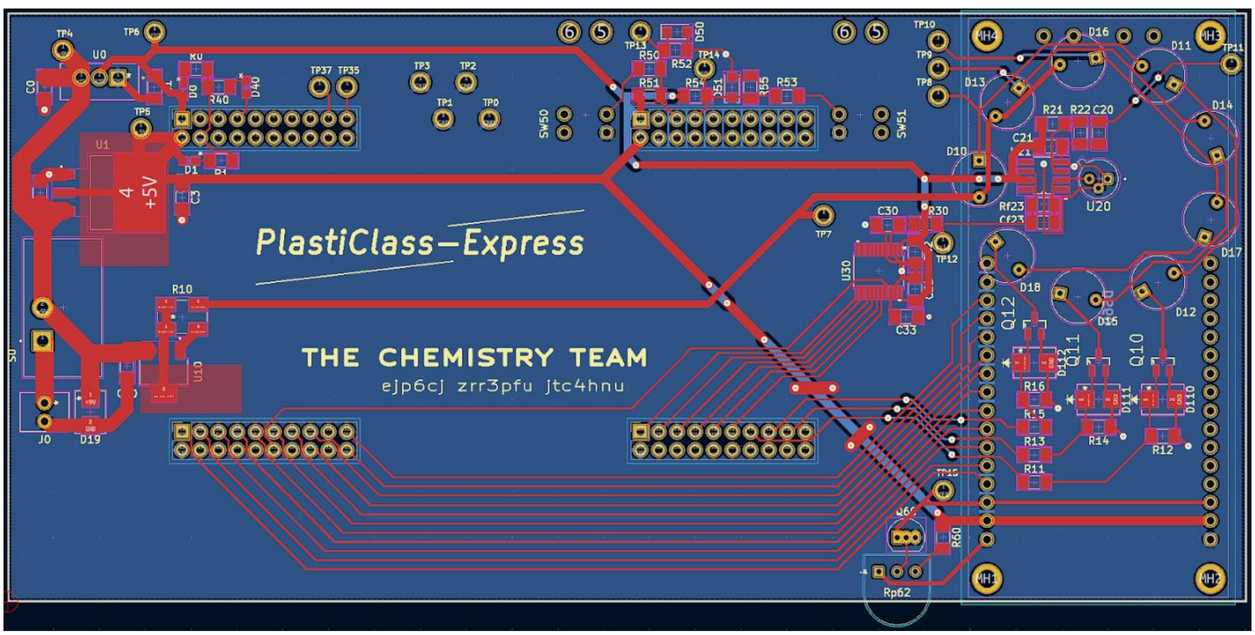

Figure 12: PCB Layout

The final PCB layout is shown in Figure 12. This includes headers for the microcontroller launchpad and LCD to connect directly to the board. Heatsink copper pours are used under the 5V voltage regulator and LM317 emitter power source. Ground plane stitches were used in areas where traces needed to be routed on the bottom of the board, for example as shown in Figure 13. A guard trace was also routed around the photodiode signal trace to reduce parasitic noise in the measurements, as shown in Figure 14.

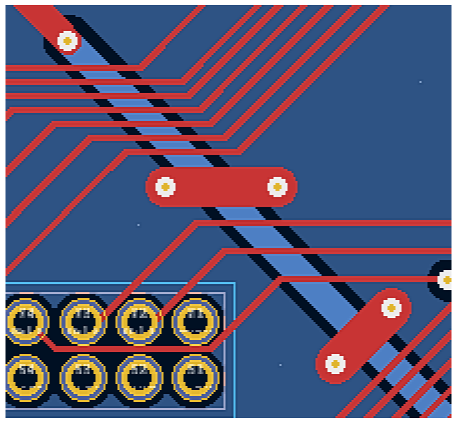

Figure 13: Ground Plane Stitches

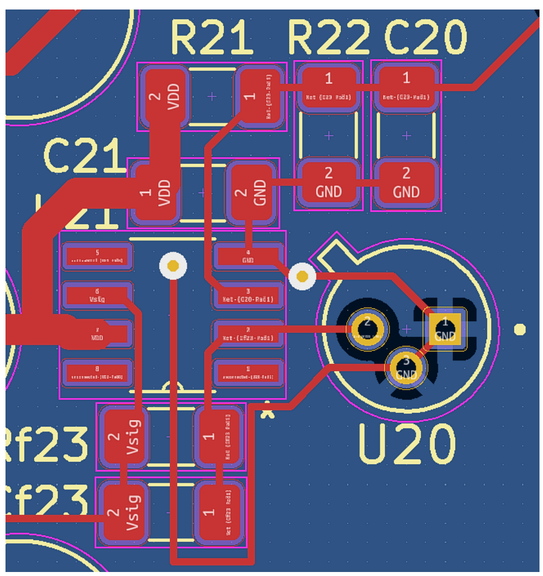

Figure 14: Photodiode and Amplifier Layout

Several design modifications had to be made following the first prototype of the device. This included changing multiple GPIO pin connections due to reserved functionality of those pins that was originally overlooked. The gain of the amplifier system was also adjusted to better fit the measurements within the available dynamic range of the device. The LM317 also had to be substituted for a very similar part with the same key properties [4] in the final board due to part availability issues with the original component. There were also several changes to the software design and measurement-taking process, as the emitter pulse lengths had to be increased in order to function with the timing constraints of the ADC.

The software for this project was written to a C2000 microcontroller housed on an F280049C launchpad. It handles the flow from the button press for measurements to the output display on the LCD. Upon the user starting the system, the LCD will display the name of the system: PlastiClass-Express, followed by a message stating that the user should press the middle button to identify their resin. With the press of this button, a GPIO interrupt will trigger a boolean used in the main method to set to 1, which will cause the capture timer to start running with interrupts occurring every 5 microseconds. A timer task written in main is called on every interrupt, and the timer will continue to run until all measurements have been recorded by the timer task. All in all, the timer interrupts 307200 times in conjunction with the timer task. The task scheduler increments a counter to track the current step in the measurement processes. At key elements in the capture sequence (synchronizing the ADC, turning the LEDs on/off, and reading the ADC), the task scheduler will make appropriate hardware GPIO changes. The ADC read function was bit banged to produce SPI communication with the ADC pins. The duration of this read process is in the order of 100 microseconds, so this was integrated into the main processes with control flags to adjust the timing of the read to the ADC pulse. A GPIO interrupt on the data ready output of the ADC would set the flag to read the ADC, and when the task scheduler sets the respective flag to enable reading, the main processes will read the value from the ADC. At a fixed increment, the counter in the task scheduler will reset to 0, and increment the index of the LEDs used to continue the capture sequence on the next wavelength.

When the measurements have finally been recorded by the ADC, the data processing algorithm begins. The flow is shown below in Figure 15.

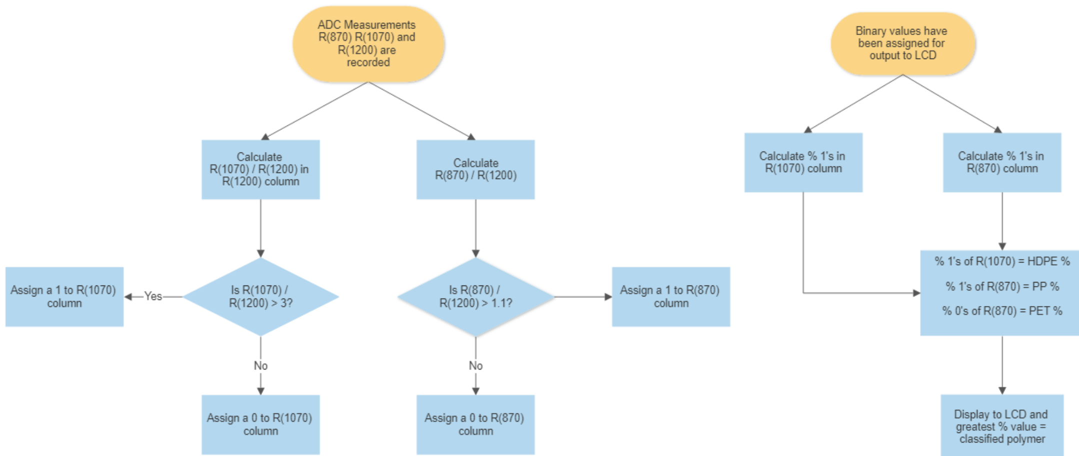

Figure 15: Data Processing Flow

Calibration of the measurements was required to consistently process the capture results. Initial ADC readings of the collected samples are plotted in Figure 16 at frequencies 870nm, 1070nm, 1200nm, and with no LED pulse, respectively. These measurements demonstrate a consistent ambient light level as well as variation in ratios of the three frequencies that produces the unique characteristics of each polymer for identification.

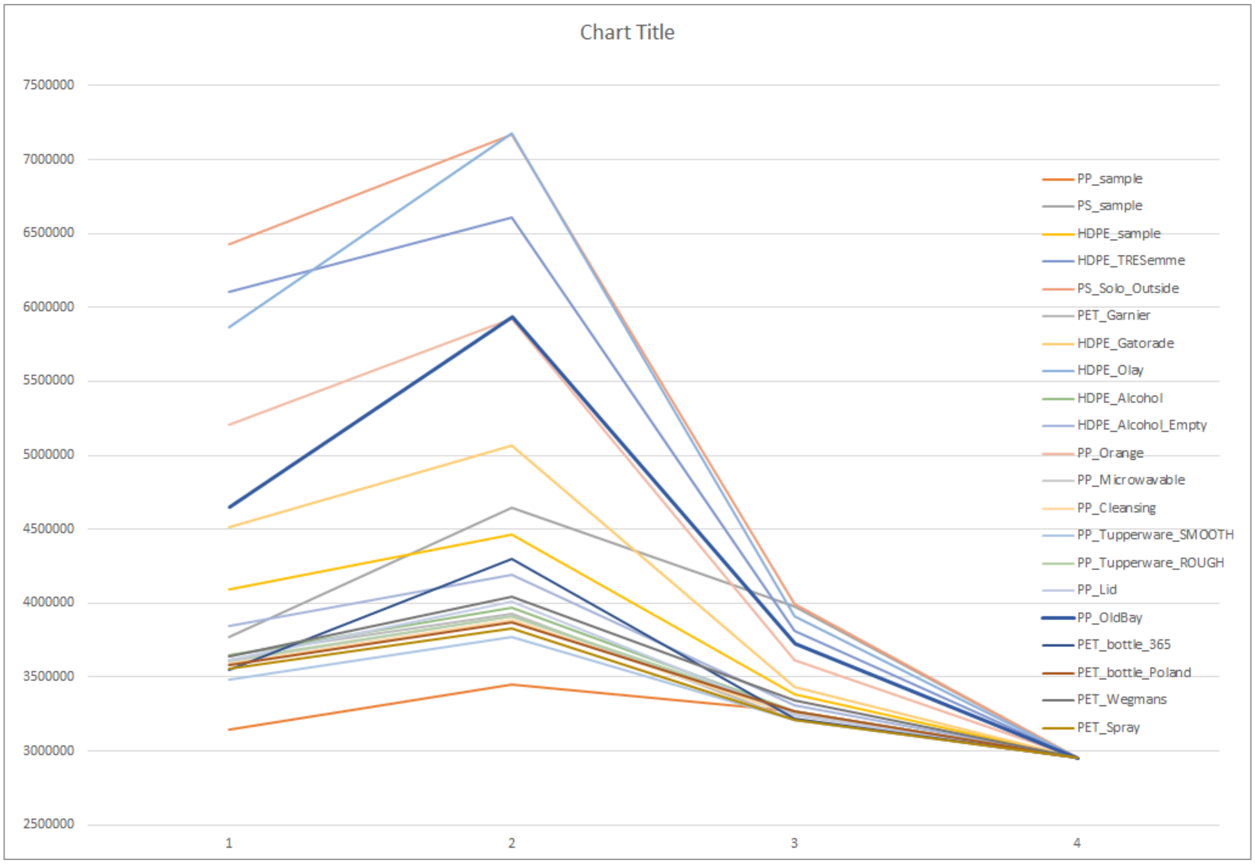

Figure 16: Sample ADC Readings

Ratios were extracted directly from these ADC readings. Without further processing, HDPE was concluded to be able to be identified by a ratio of the 1070nm and 1200nm pulses. This calculation is plotted in Figure 17. The second measurement theoretically identifies the PP and PET polymers, but as shown, were not far enough to be distinguishable.

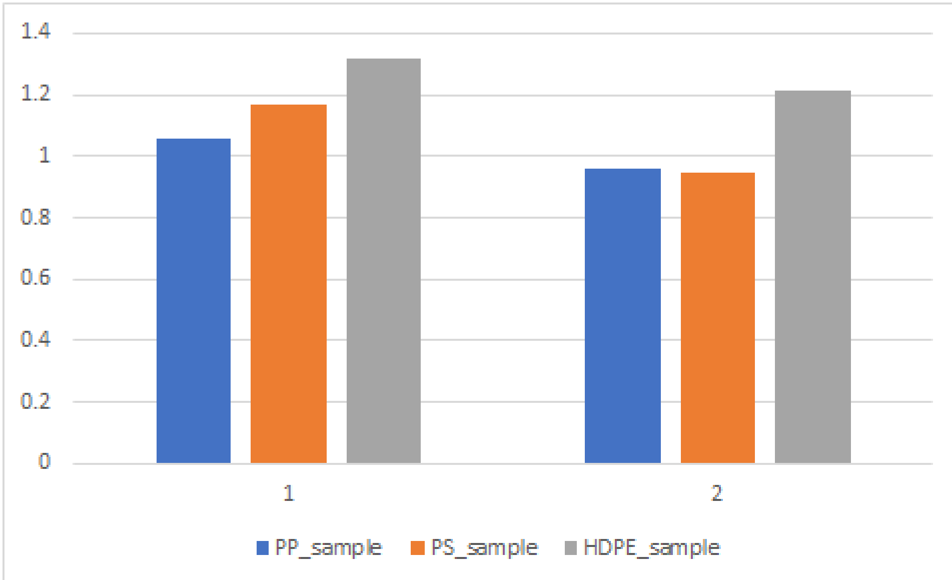

Figure 17: Sample Ratios (1070nm/1200nm and 870nm/1200nm)

To identify between PP and PET, a new calculation was used to scale the recorded measurements to better match the theoretical reflectance. This operation scaled each wavelength measurement differently, resulting in the amplitude difference shown in Figure 18. When applied to the collected plastics, the new values were shown to produce a close limit between the plastics reflectances, as shown in Figure 19.

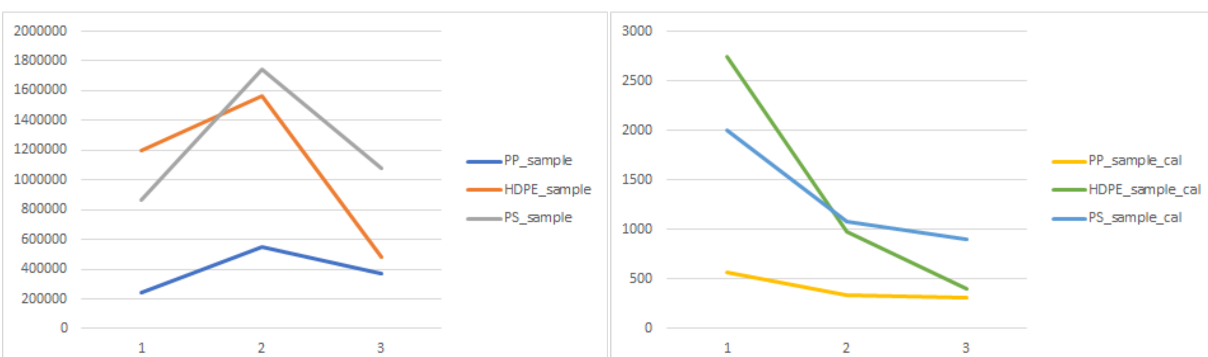

Figure 18: Sample Reflectance Before and After Calibration

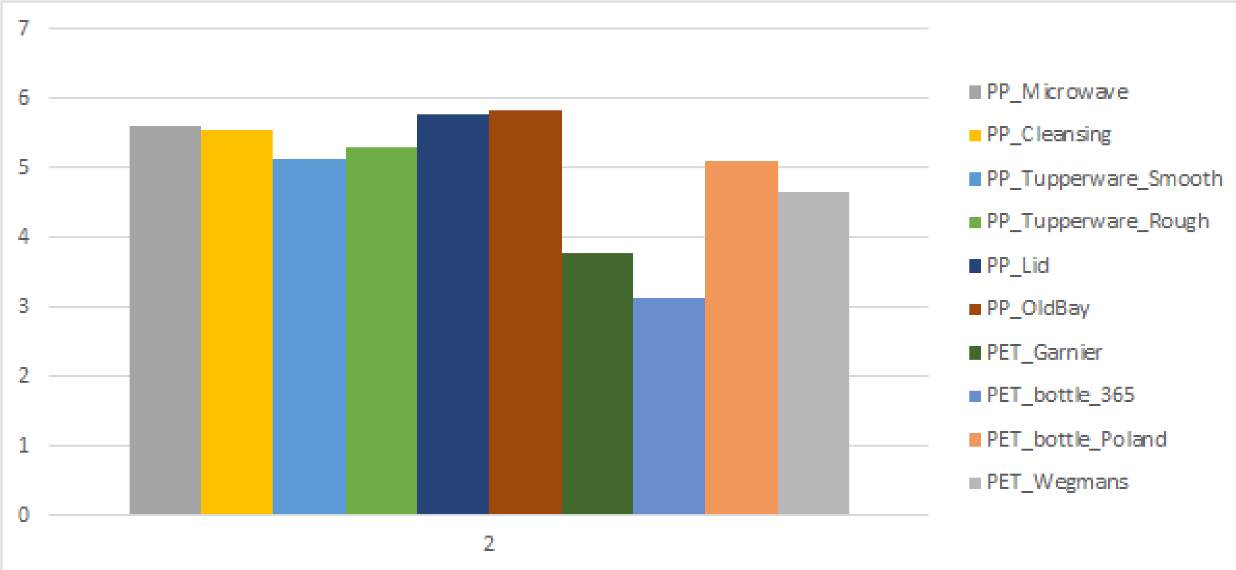

Figure 19: PP and PET Reflectance Ratio (870nm/1200nm) After Calibration

The LED emitters and photodiode detector housed on the PCB required a special enclosure to mitigate ambient light interference as well as angle specular reflectance away from the photodiode. The final design is shown in Figure 16. By angling each of the 9 LEDs between the purple baselines, facing up towards the top of the cone, deterministic specular reflectance is directed away from the photodiode detector, which is located in the central purple cone. Furthermore, the cone is clear for viewing purposes, but the actual design is an opaque gray, keeping the LEDs from being exposed to ambient light.

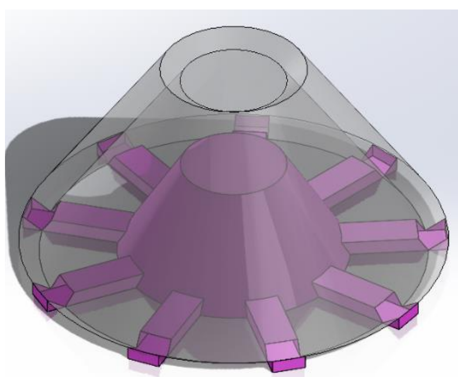

Figure 20: Emitter and Detector Enclosure

The full system enclosure is shown below in Figure 17. The outer shell uses a snap-on feature such that screws did not have to be a part of the final design. The standoff and the cone enclosure were used as the base for the PCB, with the two circular openings on the back face being available for the system's two buttons. The top opening is for the LCD display and the small front flap functions as access to the system's power switch.

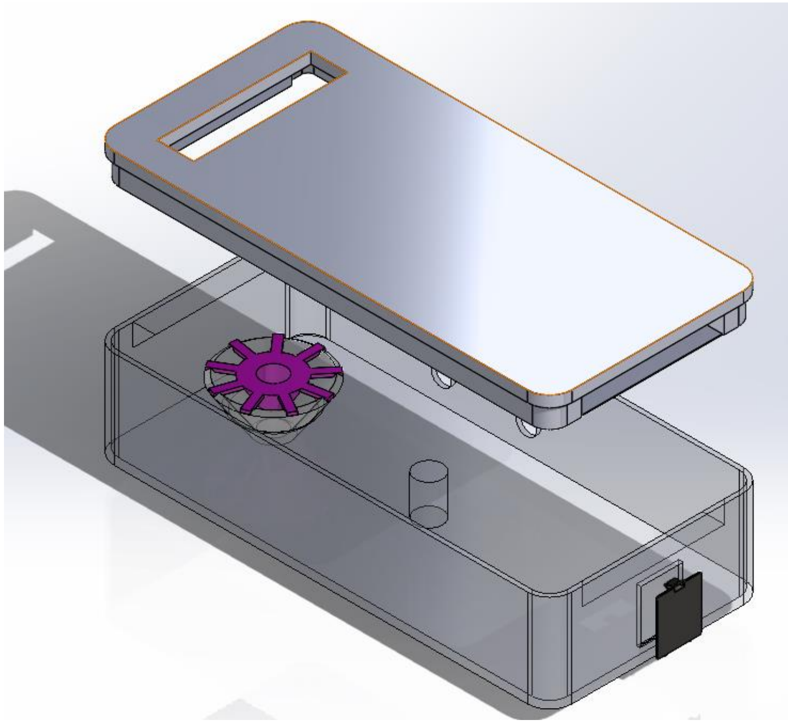

Figure 21: Full System Enclosure

A variety of minor issues came about with this design when everything was finally printed with about a week left in the project. For one, the holes for the cone and buttons were slightly off in their dimensions, and the snap feature was almost impossible to get off after getting on. The flap for the power switch was smaller than anticipated, and the plastic broke with minimal force. Finally, the case as a whole was a bit too small in its length, width, and height, causing components to have to slightly cram to get everything into the shell. All in all, with minor cutting adjustments to the print as well as some applied tape, everything was able to fit in the end, although tweaks to the design would've been made with more time to work on the project.

Project Time Line

Our initial Gantt chart, shown below in Figure 18, ended up being a relatively poor model of when time was spent on different tasks. Mechanical design began much earlier in the semester because the emitter enclosure was needed for initial testing. Circuit design was mostly on target, with a few delays in regards to actually acquiring the ordered PCBs. This also delayed most of our verification tasks all across the board, with final design verification mostly taking place in the final days of the project.

In terms of the separation of tasks, we were able to follow our original plan for parallelizing work on the software, electrical design, and physical design. Eric worked mostly on the electrical design as his primary task, especially at the beginning of the semester to ensure we would make the PCB sendoff deadline. This was a mostly serial job that Jack secondarily helped with, while Zach began designing the software architecture. Once parts started to come in and circuit design was getting close to being finalized, we pivoted and had Zach focus on mechanical design. At the same time, Jack took over the primary load of the later stages of software development. Some aspects of the design were not completely fleshed out according to the schedule and had to be revised later in the design, including the data processing algorithm and hardware design revision. While we were cognizant of deadlines for the project, delays to PCB and part acquisition hindered sections of development and led to a not insignificant amount of work being left to the last couple weeks of the project. The updated timeline of the project is accurately depicted in figure 19, the final gantt chart.

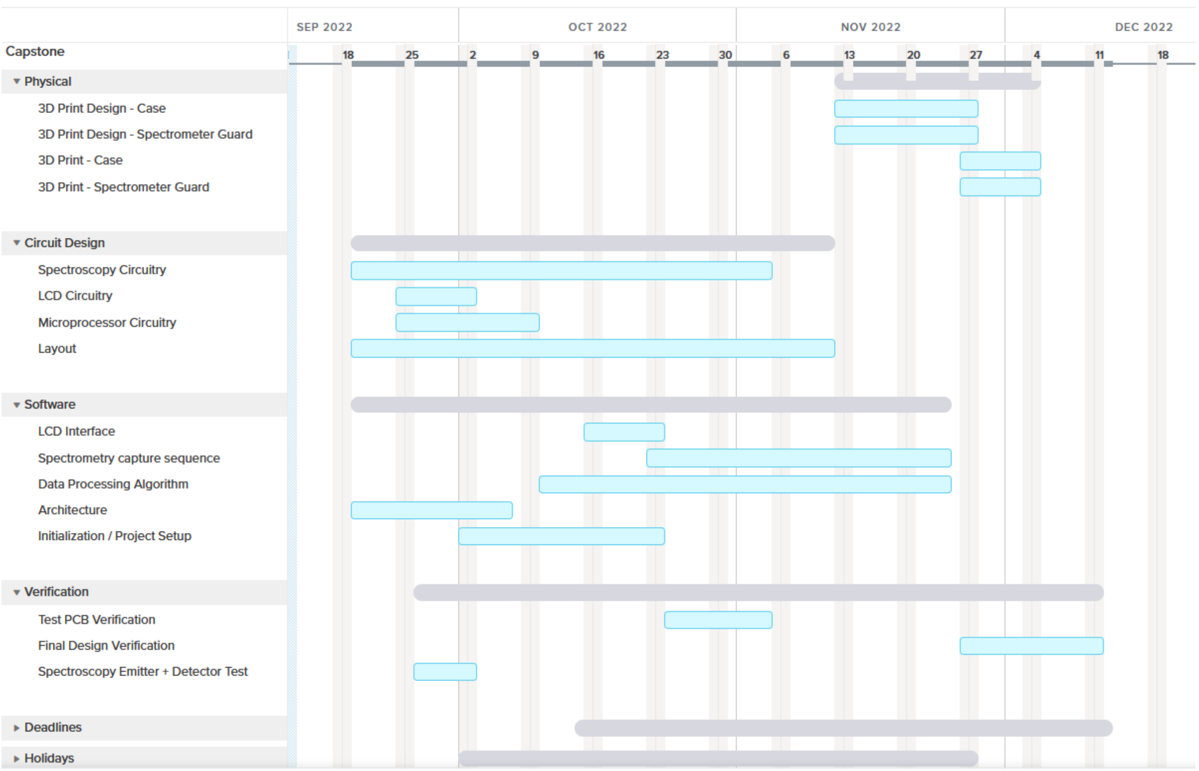

Figure 22: Initial Gantt Chart

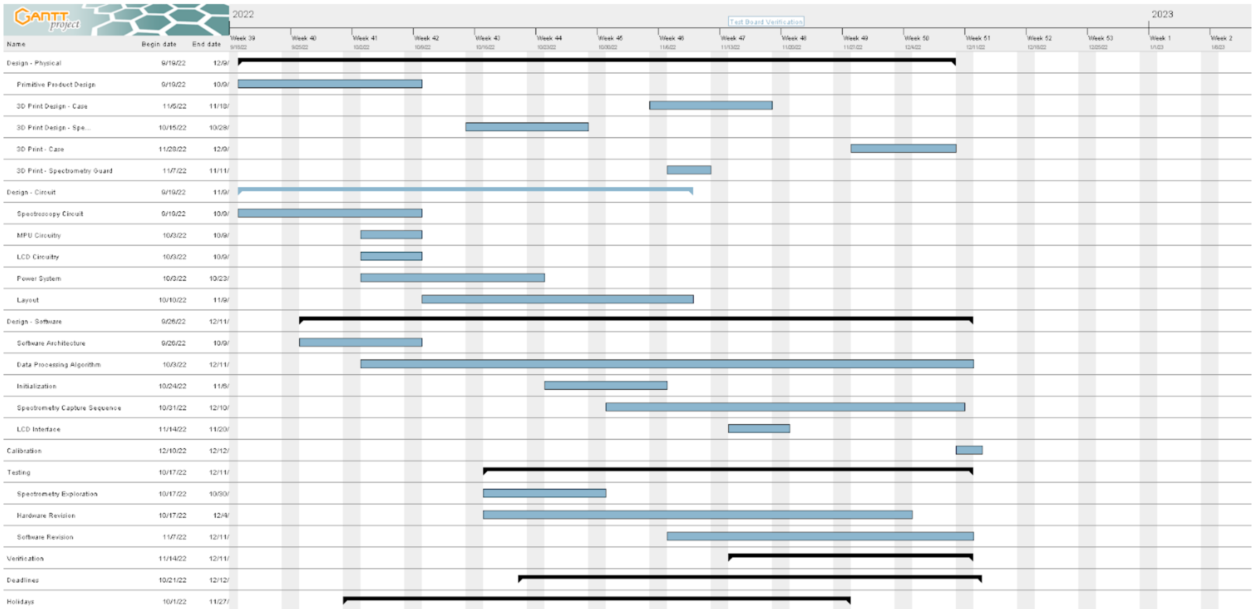

Figure 23: Final Gantt Chart

Test Plan

A test plan was created to model the testing procedure of the device. This test plan follows the linear sequence of the spectrometry capture, and is abstracted so that it may be followed in hardware and software. The plan is portrayed as a decision tree in Figure 20.

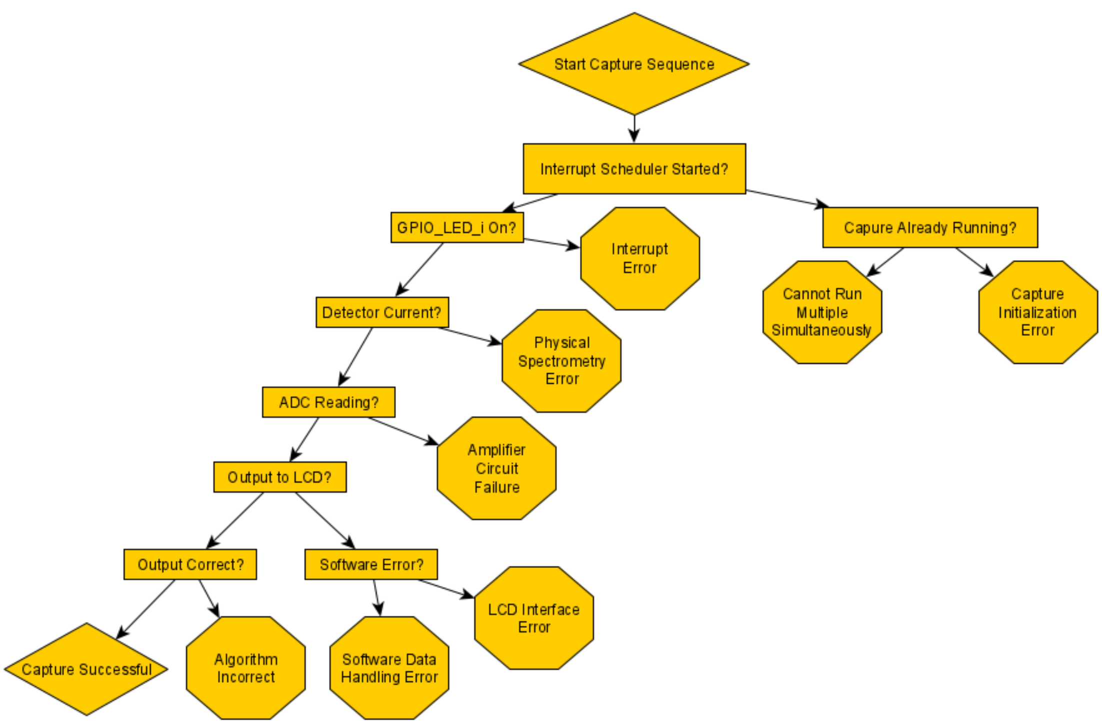

Figure 24: Device Test Plan Decision Tree

The test plan was able to be followed at all points of the development process by simulating the components that are not used in the test. The first testing conducted was a verification of the hardware emitter/detector setup, featuring one LED and the photodiode detector on a breadboard. By driving the LED at a small DC signal, we confirmed that the photodiode responds to the infrared LED, and also estimated the effect of ambient light. From this testing, it was concluded that distance of the sample must be standardized for consistent results and that ambient light does drive a significant output on the photodiode, both of which were integrated into the design in the spectrometry enclosure cone.

Once the launchpad arrived, the initial software architecture was verified through the same test plan. Without switches, emitters, or the detector, the capture sequence was able to be tested using other GPIO on the board. We were able to determine that the timer was behaving as intended and the timer task ran smoothly using test data.

The next step in verification was the entire spectrometry circuit. Another breadboard circuit was created using a single LED, the photodiode, and the relevant circuitry for the biasing and amplification of the photodiode output. In this case, a DC drive on the LED was shown to be correctly amplified, and the gain of the circuit was selected to appropriately match the ADC input.

This process was then embedded into the prototype board. This board contained the same amplification tested before, and the launchpad was able to be connected to headers. With this prototype, the launchpad software was used to drive the actual LED emission circuit. From this testing, it was demonstrated that the photodiode amplification was successful when driven by the launchpad.

At the same time, an interface for LCD communication was completed. This was tested in a separate program to display data to the LCD. The LCD was connected on a breadboard to the launchpad, and driven with a simple potentiometer circuit. Once the interface was refined, this was transferred to the prototype board. At this point, it was observed that the recommended power drive circuit in the LCD datasheet was not able to supply enough power on the board [39], so the circuit was reconfigured with spare resistors. By reducing the resistance from the source to the LCD drive, the LCD had enough power to display and the potentiometer control was preserved.

The final step on the prototype board was developing an interface for the ADC. The ADC SPI communication was not connected to the integrated SPI pins of the launchpad, but it was too late to fix for the final board send out. Instead, the communication was bit banged, after which the timing of the ADC read was integrated into the spectrometry capture sequence. At this point, the launchpad was transferred to the final PCB. By following the test plan up to the reading of the ADC, it was observed that the 1.2V reference voltage of the ADC was the maximum voltage it could read, so the amplification circuit was modified with a smaller resistor to reduce the gain such that the maximum output voltage was around 1.1V.

Finally, once ADC testing was completed, full system testing was performed. Having gathered about 20 plastic samples, each one was run multiple times to get an idea of how the data processing algorithm was performing. Once it became clear that an extra layer of calibration would be necessary, rather than just calculating reflectance ratios, weights were added to each wavelength's measurements to scale the algorithm for better performance.

Final Results

The project proposal submitted at the start of the capstone project listed the intended requirements for the design.

- The device detects between all 3 tested plastic types
- The device detects between at least 2 plastic types
- The device can be calibrated to adjust for variation in emitter intensity
- The device displays measured data to the user
- A fresh battery lasts at least 40 measurements
- The device responds to user input

Starting at the simpler requirements, user input was successfully achieved. The device accepts input in both buttons exposed on the side of the case. The center button generates a GPIO interrupt that will start the spectrometry capture sequence. This is easily verifiable as the LCD screen updates once the capture is complete with the relevant information about the sample.

A requirement for battery life was included to ensure that the device is practically useful for its intended function. A 9V battery is used to supply all power to the device. If the battery were to drain quickly either from high power consumption or over drawing the battery, then the device would not function long enough for convenient use. Over the course of testing, it was demonstrated that the device lasts more than 100 measurements, and also sustains the device when not taking measurements for at least 6 hours. We conclude that the device battery life is appropriate, although some small improvements may be able to extend the lifespan further, such as reducing the length of the LED pulse, which currently is longer than required for the ADC.

The requirement of displaying data to the user is a requirement that the LCD successfully displays the classification of the current sample. The original idea of displaying actual data to the user was decided to be flawed, given that the extracted reflectance data is arbitrary on a user-level and the implemented data processing algorithm produces definitive results without a measurement of confidence or accuracy. The finalized LCD display output has three basic screens: a welcome page, usage instructions, and recent results. When starting the device, the LCD is updated with the welcome page while the device initializes. After a delay, the instruction will prompt the user to press the center button to measure a sample. When the capture sequence is completed, the LCD is then updated to indicate that the capture is completed and which of the 3 polymers the algorithm concluded the sample to be. This fulfills the requirement of displaying to the user.

Calibration is required to ensure the spectrometry returns accurate reflectances from the sample. Initial measurements of the plastic samples were sampled and compared to the theoretical reflectance shown in Figure 5. Using the expected results, a divisor was assigned to each wavelength, which is then used in data processing to extract more unique characteristics. Dynamic calibration was integrated into the second button. This button will store the ambient light reading into a calibration offset value used in the data processing algorithm. Both of these techniques constitute a capable system of adjusting the measurement values to the expected reflectance ratios used and thereby predict the polymer of the sample.

Plastic detection performance was tested by using the device on an assortment of salvaged plastic samples. By the design of the data processing algorithm, HDPE was detected with almost 100% accuracy. This demonstrates that the product is capable of detection between 2 plastic types with a high degree of accuracy. Expanding the data processing algorithm to the next plastic type was more difficult due to the similarity in measured reflectance. For this reason, the calibration was expanded to scale the measured reflectances at wavelengths. Once this was achieved, the device could also differentiate between PET and PP polymers. However, an unresolved bug in either hardware or software resulted in the loss of reflectance readings over time, potentially related to a loss of power supply in the 9V battery. The device is concluded to be able to differentiate all 3 types of plastics under the assumption of a consistent battery level and calibration. However, large variations in samples such as surface texture and thickness were shown to significantly influence the spectrometry and therefore the classification results.

Costs

The overall cost of this project was $489.07. This was within the $500 project budget.

The total cost of the final device is $293.59. Key expenses include the PCB, launchpad, and 3D prints. The cost to create one PCB, including a $33 manufacturing cost and all soldered components, is $206.79. Costs of external devices include the launchpad ($46.8), a 3D printed case ($40), and a 9V battery. The launchpad, LCD, and optical enclosure were reused from the prototype to the final product.

For bulk production of the device, the microcontroller launchpad would most likely be replaced by a less expensive microcontroller, exchanging debugging capability and unused features for a lower cost. The cost of components for the PCB would also be significantly lower if parts were ordered in bulk quantities, e.g. 10000 units. We estimate that the bulk cost of a single PCB, again including a $33 manufacturing cost, would be $122.47.

Future Work

This project has room for improvement in both the performance of the device and the scope of its functionality. Pitfalls in development include reserved GPIO pin usage and ADC internal processing.

The spectrometry scheme was successful in measuring reflectance of plastic samples. Data from different samples had consistent magnitudes and characteristics. However, improvements to the spectrometry process could be made. The optical enclosure was designed to limit ambient light and correctly angle the LED emitters to reduce specular light reflection. The mechanical design did not enforce a consistent LED angle, so the LEDs had to be manually aligned. Also, in order to accurately account for variation in the surface of the plastic, an unused idea of polarizing filters might be implemented. This idea would use parallel and perpendicular filters to block reflected specular light, which was concluded to be a potential issue in samples with rough surface textures.

The design targets identification of 3 polymers, which is a tradeoff of number of classifiable polymers for affordability. Advancement of the project scope could entail increasing the number of measured wavelengths and expanding the data processing algorithm. Measuring at more or different wavelengths would change the observed reflectance spectrum of the samples. This could be utilized to target different characteristics of the reflectance spectrum to improve classification accuracy, or expand the classification to identify a larger set of polymers as well as non-plastic objects. The data processing algorithm used limited calculations in a tree-based decision model to make a definitive classification. While effective for the target polymers, this process limits the output of the device to a discrete class. This could be changed to a different model or incorporate elements of machine learning to also present error of the measurement, and confidence of the result, while also identifying a larger or dynamic set of polymers.

The launchpad has abundant GPIO pins available, which were assigned based on physical location to reduce layout complexity. A hidden pitfall here was the reservation of GPIO functionality on the launchpad. Some GPIO pins were used within the launchpad, such as the boot drive selection pins. The initial design had connected one of these pins to analog circuitry that drove the pin to ground, and prevented the device from booting from flash. An after-the-fact solution is to connect the circuitry to a different pin, but it may have been better to identify potential issues with reserved GPIO use beforehand within the datasheet.

The ADC gave trouble when programming the capture sequence. The selected ADC only operated in a continuous conversion mode. The datasheet indicated that a synchronization pulse would realign the ADC capture with the pulse, which is critical in this design to synchronize the ADC reading to the pulse of the LED emitters. An important discovery we made about synchronization was that it flushes the internal ADC buffer, generating erroneous output until the

ADC has had time to read multiple new values. This functionality was not mentioned in the references, so the proposed capture sequence failed to return meaningful data.

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Appendix

Bill of Materials:

Part	Manufacturer	Manufacturer Part #	Vendor	Vendor Part #	Qty Per PCB	Qty	Per Unit Price	Cost
Microprocessor Launchpad	Texas Instruments	LAUNCHXL-F280049C	Digikey	296-53092-ND	0	1	46.8	46.8
Amplifier	Texas Instruments	OPA380AID	Texas Instruments	OPA380AID	1	3	2.27	6.81
Liquid Crystal Display (LCD)	Microtips Technology	NMTC-S16205DRGHS-07	Mouser	668-NC-S16205DRGHS	1	1	7.96	7.96
Headers for LCD	Adam Tech	PH1-16-UA	Digikey	2057-PH1-16-UA-ND	2	2	0.27	0.27
Photodiode	Marktech Optoelectronics	MTPD1346D-100	Mouser	193-MTPD1346D-100	1	3	16.56	16.56
870nm Infrared Emitter	Marktech Optoelectronics	MTE8760N5	Digikey	1125-1090-ND	3	9	3.1	27.9
1070nm Infrared Emitter	Marktech Optoelectronics	MTE7110N5	Digikey	1125-MTE7110N5-ND	3	6	12.76	76.56
1200nm Infrared Emitter	Marktech Optoelectronics	MTE1200N5	Digikey	1125-MTE1200N5-ND	3	6	12.76	76.56
LM317 Emitter Current Source	Texas Instruments	LM317EMP	Digikey	LM317EMPCT-ND	1	2	2.56	5.12
Current Sense 2Ω Resistor	Vishay Foil Resistors	Y08562R00000F9W	Digikey	Y0856-2.0A-ND	1	2	11.6	23.2
Enhancement MOSFET	Diodes Incorporated	ZXMN2F34FHTA	Digikey	ZXMN2F34FHCT-ND	3	6	0.51	3.06
Analog to Digital Converter	Texas Instruments	ADS131M04IPWR	Digikey	296-ADS131M04IPWRCT-ND	1	2	6.12	12.24
3.3V Voltage Regulator	Texas Instruments	LMS1585ACT-3.3/NOPB	Digikey	LMS1585ACT-3.3/NOPB-ND	1	2	2.99	5.98
5V Voltage Regulator	Texas Instruments	LM1085ISX-5.0/NOPB	Digikey	296-35391-1-ND	1	2	2.09	4.18
Button	E-Switch	PB400OAQR1BLK	Digikey	EG5548-ND	2	4	2.12	8.48
3.3V TVS Diode	Panjit International Inc.	P4FL3.3A_R1_00001	Digikey	3757-P4FL3.3A_R1_00001CT-NI	2	4	0.51	2.04
10V TVS Diode	Diodes Incorporated	SMBJ10A-13-F	Digikey	SMBJ10A-FDICT-ND	3	6	0.46	2.76
20V TVS Diode	Diodes Incorporated	SMBJ20A-13-F	Digikey	SMBJ20A-FDICT-ND	1	2	0.48	0.96
Power Switch	C&K	L101011MS02Q	Digikey	CKC5106-ND	1	2	2.79	5.58
Red LED Indicator	Lite-On Inc.	LTST-C193KRKT-2A	Digikey	160-1909-1-ND	2	4	0.27	1.08
Orange LED Indicator	Lite-On Inc.	LTST-C193KFKT-5A	Digikey	160-1829-1-ND	1	2	0.39	0.78
PNP Transistor	onsemi	2N3906BU	Digikey	2N3906FS-ND	1	2	0.39	0.78
Potentiometer	Bourns Inc.	3352T-1-103LF	Digikey	3352T-103LF-ND	1	2	2.5	5
9V Battery Connector	SparkFun Electronics	PRT-00091	Digikey	1568-1366-ND	1	2	1.6	3.2
Header for Battery Connector	Molex	0022053021	Digikey	900-0022053021-ND	1	2	0.41	0.82
Header Socket for LCD	Sullins Connector Solutions	PPTC161LFBN-RC	Digikey	S7014-ND	2	4	0.98	3.92
Headers for Launchpad	Adam Tech	PH2-20-UA	Digikey	2057-PH2-20-UA-ND	4	8	0.29	2.32
Test Point BLK	Keystone Electronics	5011	Digikey	36-5011-ND	4	8	0.42	3.36
Test Point RED	Keystone Electronics	5010	Digikey	36-5010-ND	1	2	0.42	0.84
Test Point ORG	Keystone Electronics	5013	Digikey	36-5013-ND	1	2	0.42	0.84
Test Point YEL	Keystone Electronics	5014	Digikey	36-5014-ND	1	2	0.42	0.84
Test Point WHT	Keystone Electronics	5012	Digikey	36-5012-ND	1	2	0.42	0.84
Test Point GRN	Keystone Electronics	5126	Digikey	36-5126-ND	2	4	0.42	1.68
Test Point BLU	Keystone Electronics	5127	Digikey	36-5127-ND	1	2	0.42	0.84
Test Point VIO	Keystone Electronics	5129	Digikey	36-5129-ND	2	4	0.42	1.68
Test Point BRN	Keystone Electronics	5125	Digikey	36-5125-ND	3	6	0.42	2.52
Test Point GRY	Keystone Electronics	5128	Digikey	36-5128-ND	2	4	0.42	1.68
Capacitor, 220nF	YAGEO	CC1206JKX7R9BB224	Digikey	311-4386-1-ND	1	2	0.28	0.56
Capacitor, 1nF	YAGEO	CC1206GRNPO9BN102	Digikey	311-4372-1-ND	1	2	0.3	0.6
Capacitor, 1uF	YAGEO	CC1206JKX7R7BB105	Digikey	311-1924-1-ND	4	8	0.37	2.96
Capacitor, 1.5pF	YAGEO	CC1206CRNPO9BN1R5	Digikey	311-1214-1-ND	1	2	0.27	0.54
Capacitor, 0.1uF	YAGEO	CC1206JKX7R0BB104	Digikey	311-3557-1-ND	1	2	0.27	0.54
Capacitor, 10uF	YAGEO	CC1206KKX5R8BB106	Digikey	311-1466-1-ND	4	8	0.56	4.48
Resistor, 100Ω	Bourns Inc.	CRM1206-FX-1000ELF	Digikey	CRM1206-FX-1000ELFCT-ND	3	6	0.17	1.02
Resistor, 100kΩ	Rohm Semiconductor	ESR18EZPF1003	Digikey	RHM100KAFCT-ND	2	6	0.17	1.02
Resistor, 12kΩ	Bourns Inc.	CR1206-FX-1202ELF	Digikey	CR1206-FX-1202ELFCT-ND	1	2	0.1	0.2
Resistor, 82kΩ	Bourns Inc.	CR1206-FX-8202ELF	Digikey	118-CR1206-FX-8202ELFCT-ND	1	2	0.1	0.2
Resistor, 10kΩ	Stackpole Electronics Inc	RMCF1206JT10K0	Digikey	RMCF1206JT10K0CT-ND	4	8	0.1	0.8
Resistor, 10Ω	Stackpole Electronics Inc	RMCF1206FT10R0	Digikey	RMCF1206FT10R0CT-ND	3	6	0.1	0.6
Resistor, 1.5kΩ	YAGEO	RC1206FR-071K5L	Digikey	311-1.50KFRCT-ND	1	2	0.1	0.2
Resistor, 470Ω	Stackpole Electronics Inc	RMCF1206FT470R	Digikey	RMCF1206FT470RCT-ND	1	2	0.1	0.2
Resistor, 1kΩ	Stackpole Electronics Inc	RMCF1206FT1K00	Digikey	RMCF1206FT1K00CT-ND	2	6	0.1	0.6
Resistor, 680Ω	Stackpole Electronics Inc	RMCF1206FT680R	Digikey	RMCF1206FT680RCT-ND	1	2	0.1	0.2
Resistor, 4.7kΩ	Stackpole Electronics Inc	RMCF1206FT4K70	Digikey	RMCF1206FT4K70CT-ND	2	4	0.1	0.4
Capacitor, 1pF	YAGEO	CC1206JRNPO9BN270	Digikey	311-1155-1-ND	0	1	0.24	0.24
Capacitor, 4.7pF	YAGEO	CC1206JRNPO9BN200	Digikey	311-1153-1-ND	0	1	0.25	0.25
Capacitor, 10pF	YAGEO	CC1206JRNPO9BN150	Digikey	311-1151-1-ND	0	1	0.24	0.24
Capacitor, 15pF	YAGEO	CC1206JRNPO9BN100	Digikey	311-1150-1-ND	0	1	0.24	0.24
Capacitor, 20pF	YAGEO	CC1206CRNPO9BN4R7	Digikey	311-1218-1-ND	0	1	0.27	0.27
Capacitor, 27pF	YAGEO	CC1206CRNPO9BN1R0	Digikey	311-1212-1-ND	0	1	0.27	0.27
Resistor, 0Ω	Stackpole Electronics Inc	RMCF0603ZT0R00	Digikey	RMCF0603ZT0R00CT-ND	0	2	0.1	0.2
Resistor, 0Ω	Stackpole Electronics Inc	RMCF0402ZT0R00	Digikey	RMCF0402ZT0R00CT-ND	0	2	0.1	0.2
							PCBs:	66
							3d Prints:	40
							Cost per PCB:	206.79
							Total Cost:	489.07