Watt-Hoo-Wa: Leafy-Link

James Chun, Eric Sheetz, Grayson Deu, Ethan Jenkins

Statement of Work

James Chun - I was first tasked with mainly the PCB design and helping with the microcontroller code at the start of the semester. I selected the microcontroller, sensors and the LCD screen with Eric. Eric and I started coding for the sensors to collect data, and took over so that Eric could start focusing his work on the LCD screen display. I designed the first PCB, and helped Grayson with the final PCB design. Once the sensors were coded, I calibrated the sensors so that it would read appropriate values with the 3.3V power supply. I also designed the LCD screen enclosure using Fusion360, Cura, and the 3D printer.
Grayson Deu - I began this project with the task of designing the power supply system, and gathering the data needed for growing different microgreens. I did the initial design of our power supply circuit, including the AC-DC convertor, buck converter, and relay setup. After ordering the power supply parts, I tested the relays I found in the lab to determine their functionality and use for our project. Throughout the middle of the project time, I helped put together the physical enclosure, did a lot of the wire stripping and connecting, and ordered the parts/material that were necessary for plant growth. I also helped design the final iteration of our PCB, as well as each subsystem that was on our board. Before those parts arrived, I helped create a short term setup to start our microgreen growth. Once the PCB arrived, I soldered and tested it and rewired our project so it was ready to test with the sensors and extra peripherals. Near the end of our project timeline, I tried to help organize the enclosure and wires to set my teammates up for success.
Eric Sheetz - I was the primary agent of the microcontroller development, including configuring the code environment and the timing code and GPIO signalling. I also worked with James on testing and calibrating the sensors. I assisted in the testing of various subsystems and worked to integrate the microcontroller with the power supplies and relays. The UI was also a large focus of mine, and I developed the code which sends all of the sensor data onto the LCD screen so that the user does not need a serial connection to monitor the growth parameters.
Ethan Jenkins - For this project, I was tasked primarily with the water pump and misting system, the grow LED's, and overall physically assembling the project. I selected the grow lights, the misting nozzle, pump, tubing, etc, and ran the testing for each of these subsystems and components. I also worked with Grayson to physically assemble the enclosure, drilling and cutting holes, building the electrical enclosure and installing the pump/LED systems. I also did a lot of wire stripping and electrical connections, and worked with Grayson to test each of the subsystems as we installed them into the enclosure. I also worked to waterproof the enclosure, using epoxy to seal any holes and cracks, and installing the plastic guards to maximize the amount of water the microgreens received and to reduce waste.

On our honor as university students, we have neither given nor received unauthorized aid on this assignment as defined by the Honor Code.

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Abstract

Leafy-Link is an automated hydroponic system designed to simplify the process of growing microgreens. This product is targeted primarily toward restaurants that want locally sourced produce with minimal effort. The system has a number of integrated sensors measuring variables such as temperature, humidity, and pH to ensure continued optimum growing conditions. Leafy-Link also employs the use of a microcontroller to automate the water misting and grow light cycles, aligning them with the ideal conditions of the chosen microgreen. The system includes a number of preset growing options for commonly grown microgreens, allowing users to simply select the corresponding preset for their chosen microgreen. Users will also be informed of the system's water levels, pH levels, and other useful information via the LCD, which also notifies the user when intervention is necessary. By providing its customers with a low-maintenance and efficient system for growing microgreens, Leafy-Link supports the growing trends of environmental sustainability, locally sourced food, and public health improvement.

Background

In an age of technological advancement paired with society's increasing awareness of public health, knowing where and how the food we eat is made has become an important consideration for many Americans regarding their diet. In 2022, 52% of Americans stated they followed a diet or eating pattern, an increase of 23% of the US population from the year prior [1]. Effects of this lifestyle development can be seen in television advertisements and in the trend of businesses and companies having more transparency with their customers on food sourcing. It doesn't take a leap of the imagination to see why this trend has been gaining momentum, as it gives consumers more trust in the systems that bring food to their table, knowing that they can make informed decisions regarding a healthy diet. This demand for transparency extends beyond just knowing where food comes from; it's about witnessing the process firsthand. Enter 'Leafy-Link': an automated microgreen hydroponic system aimed towards restaurants.

The main goal of Leafy-Link is to provide restaurants and culinary professionals the ability to offer customers fresh, high quality microgreens and herbs for their dishes, benefitting both the consumers and the business. Leafy-Link will enable restaurants to grow microgreens with minimum monitoring and without requiring staff to be plant-growing experts. This hydroponic system will also add to the style and decor of the restaurant, enhancing the dining experience for customers.

The food industry is driven by regulations and what consumers are willing to pay for. A study conducted on consumer perception of local and organic foods gathered that 38% of adults said they are more likely to choose a restaurant that offers locally-sourced foods over one that doesn't, with another 30% saying they would prefer organically grown foods [2]. This statistic is even higher among millennials and generation Z [2]. On a similar note, 32% restaurant owners in this study replied that buying local would definitely increase their sales [3]. A similar study concluded that this number could even be close to 66% [3]. These numbers imply that being able to reliably provide customers with healthy, local foods is highly beneficial to sellers. Furthermore, these questionnaires revealed that 43.1% of restaurants frequently buy fresh goods [2]. This highlights a real opportunity for restaurants to increase the quality of their foods and lower their monthly expenses by growing some foods in house. This demand is likely partially responsible for the large, growing market for hydroponics systems and crops, being valued at $12.1 billion and $37.7 billion, respectively, in 2022 [4]. This number is anticipated to grow to $25.1 billion and $2027 by 2027, with respective compound annual growth rates of 15.6% and 7.2% [4].

Not only does Leafy-Link offer direct benefits to its customer base, restaurants, but it also has the potential to diversify the flavor of dishes and provide a wide variety of health benefits. Microgreens have been shown to offer a range of benefits, including immune support, heart health benefits, and even anticarcinogenic effects [4]. Some easy examples of these microgreens and their correlated benefits can be seen in Figure 1 below.

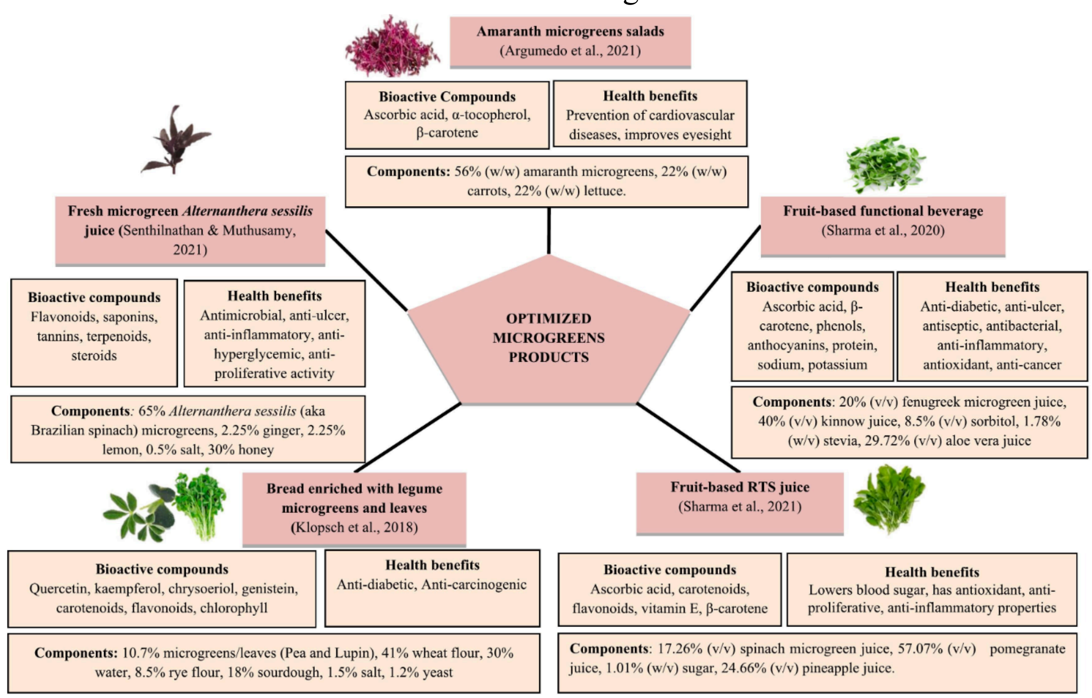

Figure 1. Microgreens and Correlated Health Benefits [4]

Having this mechanism to significantly impact customers' lives is an avenue for restaurants to separate themselves from the competition. It is even easier to bring up nutritional benefits when customers can see where these microgreens are grown while they eat. These health effects are not minute either: a 2020 study by the United States Department of Agriculture supported that microgreens exhibit greater concentrations of vitamins and carotenoids than fruits and vegetables by 30 to 40 times [4]. It should also be noted that the short growth times, low volume requirements, and strong flavor of microgreens make them a very attractive choice for in-house food production and consumption.

Similar Projects and Leafy Link

The idea of automating plant and food growth is not new and has evolved in many ways since the inception of farming. In modern times, however, our ability to monitor and control, along with what is economically feasible to control, has changed drastically. With the dropping price of light emitting diode (LED) technology and sensors becoming more efficient and cheaper, “black box” automated plant growing systems have become a larger slice of the produce production market and of research fields.

An exploration of similar projects is important to understand the niche Leafy-Link will occupy in this developing market, and provided our team with valuable insight as to how to differentiate our product in useful and competitive ways. A hydroponic nutrient film technique system created by a team was designed to provide very precise, real time data for plants [5]. This system consisted of an array of hydroponic plants being monitored by many sensors (pH, Oxygen, Light and Total Dissolved Solids) interfacing to an arduino microcontroller. These sensors provided a feedback loop for the system to monitor important parameters, and make plant height and diameter measurements. This system was focused on the accuracy, precision and frequency of their measurements. A separate group was able to make a hydroponic system more focused on remote control [6]. Their system used similar sensors along with a water level sensor that would interface to the STM32 microcontroller via a PCB. This PCB served as an adapter for the sensors as well as a way to connect a modem to the microcontroller. Their system would collect the data and allow the user to manually change the plant parameters to optimize its growth remotely, via an app. The third project we analyzed was an aeroponic automated system for 6 plants conducted by a separate team [7]. This system consisted of a temperature control with light, temperature, and humidity sensors. These inputs would interface to a microcontroller and drive a fan and mist maker to control and optimize the temperature and humidity of the system. It is important to note that this system relied on direct sunlight for the plants. There are many more similar systems but these three gave us a good idea on how to differentiate our design and target the market. To get a better understanding of how the previously discussed projects operate, Figure 2 through 4 below depict the physical setup and techniques used for automating a microgreen project.

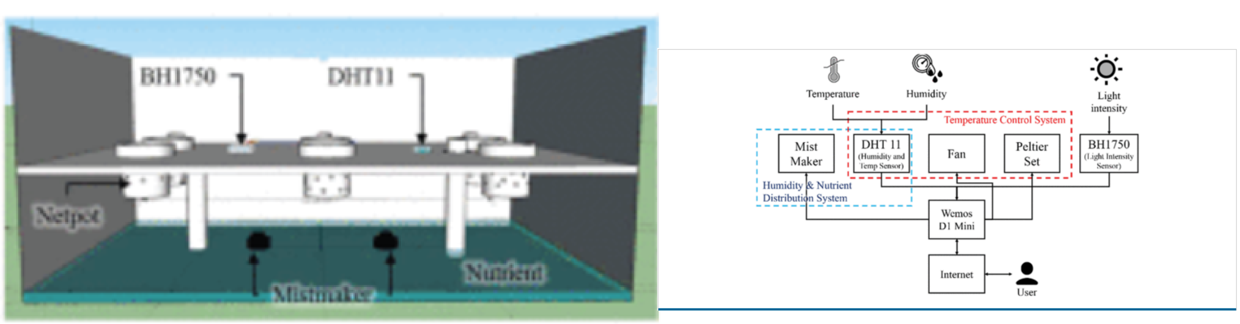

Figure 2. Similar Project Setup [5]

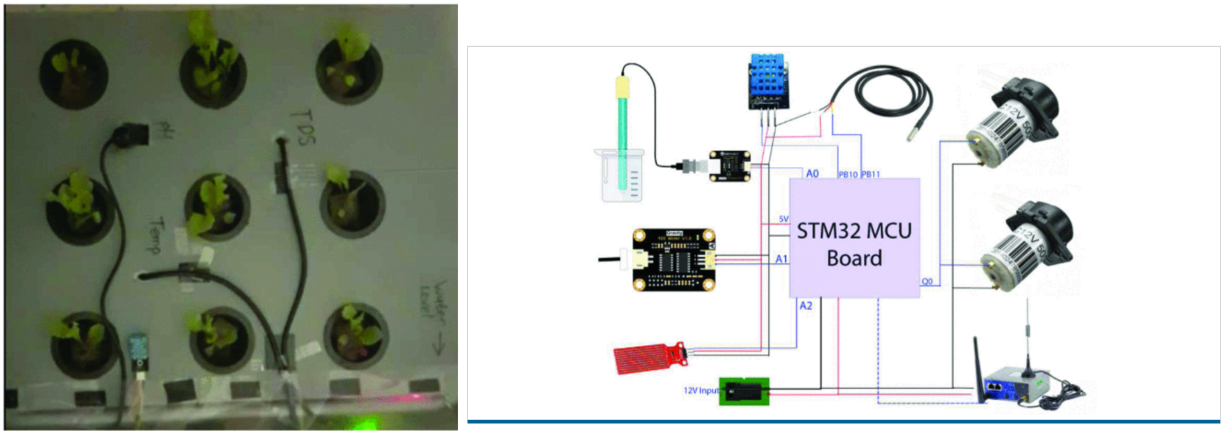

Figure 3. Similar Project Setup [6]

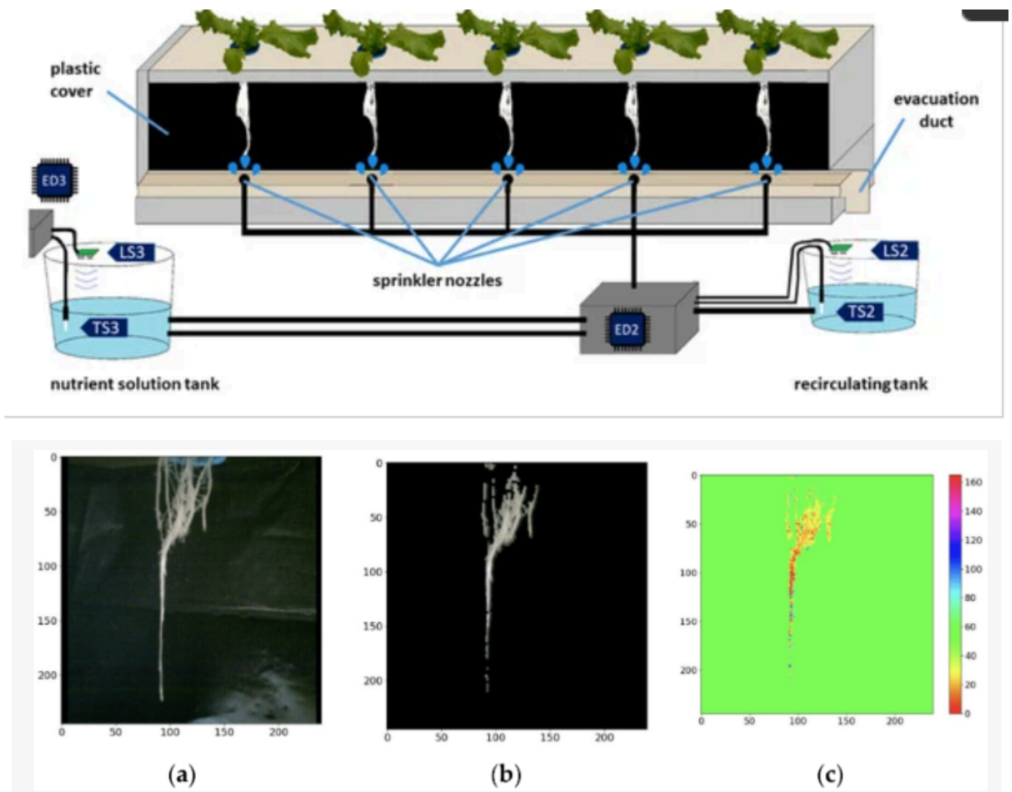

Figure 4. Similar Project Setup [7]

Leafy-Link is a minifridge sized solution that only requires the user to know the name of the microgreen they want to grow to see results. All they will need to do is place the seeds into the enclosure, fill up a tank with nutrient water, plug up the device, and watch their healthy food grow. Our system is as automated as possible, allowing the experience to be largely hands off, besides infrequent water refills, microgreen procurement, and harvesting. It includes internally stored presets for common microgreens, allowing for users to grow superfoods with no expertise.

Not only does it provide an easy way for restaurants to grow their own greens, but it also has been designed with aesthetics in mind, adding to the ambiance of restaurants. We have designed our system enclosure in a way that shows potential customers the natural growth of the plants, as well as the interesting automated design of our system. Our solution is compact and relatively inexpensive compared to higher end products in this market. It is especially important that we have designed the enclosure to be largely modular, to accommodate for the differing needs across restaurants. The enclosure of our system can be seen below in Figure 5, depicting how Leafy-Link is a relatively aesthetic solution for a modern or conservative restaurant environment. Leafy-Link distinguishes itself from similar projects with its “plug and play” solution to this market idea, a solution that is both aesthetic and effective for all users.

Figure 5. Leafy-Link Enclosure

Related Coursework

Our team's coursework in electronics, embedded systems, and signal and systems at the University of Virginia provided us with the expertise and perspective to have completed this project in the 12 week timeline. The courses in the three-part Fundamentals of Electronics curriculum (ECE2630, ECE2660, ECE3750) have provided us with the circuit design, signal processing, and debugging skills that were necessary for this project. Intro to Embedded Systems (ECE3430) has provided us with the coding experience and program design that helped us design the simple and complicated components of this system. Electromagnetic Energy Conversion (ECE3250) provided us with more experience with higher voltage systems and motors, which were required for this project. Beyond these specific courses, individuals of our group have completed a number of other electrical engineering and computer science courses that aided in the development and integration of both the software and hardware which comprised the technical elements of our project. The completion of many hardware and software projects throughout our electrical and computer engineering programs has sharpened our abilities for design, time management, and teamwork, which was integral to the success of Leafy-Link.

Project Description

Performance Objectives and Specifications

The Leafy-Link project is an automated hydroponic plant irrigation system for restaurants or individuals looking to grow their own microgreens. The system has internal sensors to measure humidity, temperature, pH, and water reservoir level. In addition, total dissolved solids (TDS) are measured periodically as a proxy for determining the nutrient solution concentration in the water reservoir. The user has preset options for specific plants and the ability to set custom settings for controlling the lighting and humidity levels via the LCD touchscreen. The system will notify the user through the user interface (UI) when maintenance is required, i.e. when the nutrient or water reservoir levels are low. Additional notifications such as pH range warnings and estimated growth cycle completion were also implemented. We define a growth cycle as a run where the LEDs and pump are toggled to provide light, water and nutrients for the plant. This project allows nearly anyone to grow a plant of their choosing with minimum upkeep. This automated system was designed with the capability to help users save time and resources on plant maintenance and preliminary research while providing visual appeal and entertainment.

How it works

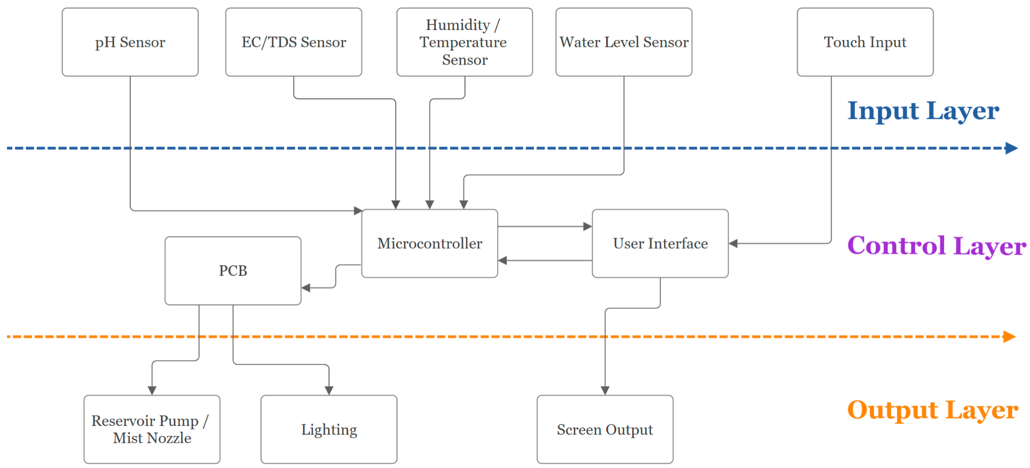

Figure 6. Block Diagram of the System Process

Figure 6 above shows the block diagram of the device. Microgreens of the user's choosing are placed in a tray above the water reservoir, which is located at the bottom of the enclosure. The microcontroller queries the sensors at regular intervals to measure the humidity, temperature, ph-level, and TDS-level of the water. For given thresholds, if the humidity level is out of the optimal range, the microcontroller detects this from the sensor and triggers a relay which operates the pump. The pump takes the water through tubing from the reservoir up to the top of the enclosure and out through the misting nozzle assembly onto the plant tray below. This allows for the microgreens to capture water from the mist through the hemp mat they are rooted to. The water eventually flows through the mat and tray back into the water reservoir below. If the water level of the reservoir becomes low, the water level sensor output will allow the microcontroller to detect this and display water deficiency on the LCD screen to notify the user to fill up the water reservoir. In fact, the pH and TDS sensors are used similarly: each of these sensor's outputs are queried by the microcontroller at given intervals, allowing the microcontroller to display a time-variant median value of the readings. Additionally, if the pH or TDS is out of range, a notification will appear, just as it does for the low water condition, identifying the specific system deficiency. The LEDs are controlled by the microcontroller using another relay, and the microcontroller's LED output control pin is toggled using a timer. The user selects the desired hourly duration of the light/dark periods by either custom selection or the ideal conditions embedded into the microcontroller for the selected plant, and the timer duration is automatically updated during each interrupt request to facilitate variable lighting conditions.

The system is powered by a PCB, which attaches to an AC-DC power supply that is plugged into a receptacle via a 10 foot cable. This setup allows for constant, reliable power and enough length to allow for many connection locations in an indoor facility. Our AC-DC power supply handles all short circuit and overcurrent conditions that could potentially happen as a result of the enclosure environment. The PCB acts as a docking station for all electrical components, providing 24V, 5V, and 3.3V direct current voltage sources (and ground connections) for all electrical components used in this project.

Technical Details

The microcontroller used for this project is the ESP32-S2-DEVKITM-1 (DevkitM-1). It is compatible with many arduino-style peripherals and is a low-power, single core device [8]. The DevkitM-1 model of the ESP32-S2 microcontroller line is an entry level development board made by Espressif that has I/O pins configured conveniently for entry level users. Since the microcontroller's task in this project is to take data from the sensors, control the relays, and display the collected data on a LCD display, an overspec microcontroller was not required. The microcontroller's built-in wifi feature allows for the project to potentially be further developed to display the system information on an app or webpage, allowing the user to access, control, and be aware of the status of the system remotely. The low power usage and competitively low price of the microcontroller assist in lowering the final cost and power usage of the project.

The sensors that were implemented for this project include a humidity/temperature sensor, a pH sensor, a TDS sensor, and a water level sensor**.** The humidity/temperature sensor measures the humidity and temperature of the growth environment, allowing the user to check the status of these variables on the LCD display. The DHT11 (humidity and temperature sensor) was selected to collect and display humidity and temperature data [9]. The pH sensor lies in the water reservoir, allowing the user to be assured the water stays at an acceptable pH for the chosen plant [10]. A TDS sensor is used to detect the total amount of nutrients added to the water reservoir and ensure the water supply has enough nutrients throughout the watering cycles [11]. The water level sensor drops its signal output voltage when it stops being exposed to water, allowing monitoring of the quantity of water left and subsequent notifying through the LCD display when the water supply goes low [12]. Sensors were chosen based on price and their connectivity to arduino-platform devices since our ESP32 microcontroller has very similar hardware connections.

To provide our system with constant and reliable power, we chose the PMT-24V150W2BA AC-DC power supply module that also has built-in safety features to protect our load circuitry [13]. This power supply has a 150W power capacity, and can convert either 240V or 120V three phase inputs to a 24V DC power supply that is accessible through 2 pairs of terminal block connectors. We went with this particular device because its physical dimensions were a perfect fit for our exterior power supply enclosure design and its 150W capacity exceeded our maximum power demands (with plenty of room for future expansions). Our main loads, which we will go into further depth on later, had an estimated power draw of around 100 Watts total (in practice, the average power draw is much lower). This was determined through the datasheets and under the assumption that our sensors and microcontroller power draws were negligible compared to our other loads. Although having every device draw maximum power at once is an unlikely situation, it was important to take this into consideration, and it did not cost us much more to purchase a power supply that exceeded our maximum requirements. It was also beneficial that the power supply had a DC output of 24V because our largest load operated at maximum efficiency when run off of a 24V power supply. Below you can see a simplified version of our design calculations that verified the use of our chosen power supply. Figures 7 and 8 show the system schematic and physical design of the PMT-24V150W2BA.

$$P_{required-max} = \sum P_{loads} \simeq 100\ W$$

$$P_{supply} = 150\ W > 100\ W$$

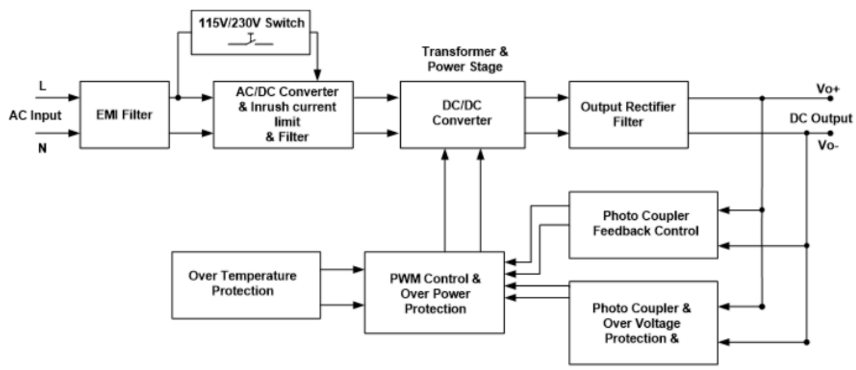

Figure 7. PMT-24V150W2BA System Design [13]

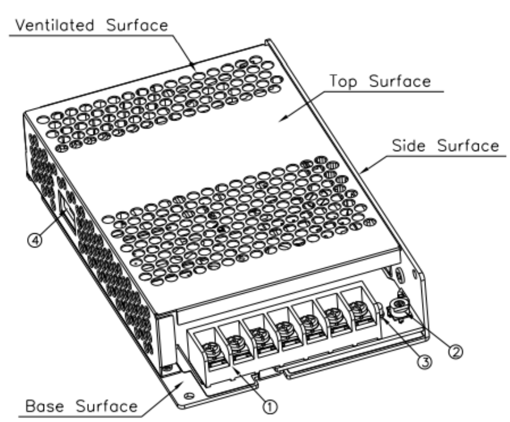

Figure 8. PMT-24V150W2BA Physical Design [13]

We designed our PCB to use the 24V DC power from the mounted power supply as the input and transform it into usable power for all of our attached electrical devices. This includes the 24V power that our pump requires to run, the 5V power that our LEDs, microcontroller, and screen use, as well as a 3.3V power for the sensors and relays. The first decision was choosing a buck converter that had the ability to provide enough current for the 5V loads, which we estimated to be about 4 Amps for a 20W load capacity. We chose the FEWS-2405A20T, DC-DC converter due to its power capabilities and isolation properties [14]. The DC-DC converter is pictured in figure 9 below.

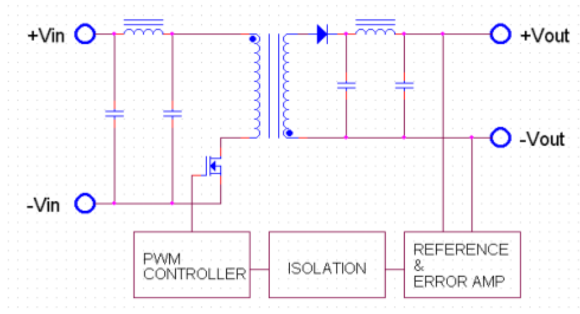

Figure 9. FEWS-2405A20T Simplified Device Schematic [14]

We then designed a non integrated DC-DC convertor based on the SY8113I step down regulator [15]. Based on the application schematic from the datasheet, which can be seen below in Figure 15, we used components [16] through [20] to implement the DC-DC converter from 5V to 3.3V. The passive components were mainly chosen based on reliability, precision, PCB footprint size, and cost.

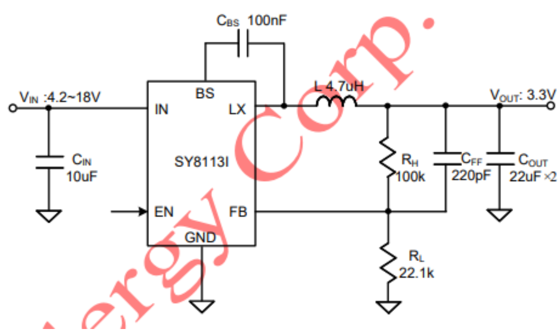

Figure 10. SY8113I Step Down Regulator Application Schematic (3.3 Vout) [15]

In order to use the 24V, 5V, and 3.3V power supplies, our PCB needed a dynamic way to connect all sorts of electrical components to itself. To do this, we selected jumper pins [21], screw connectors [22], and a USB-A connector [23] so that we could connect standard 2.54mm wires as well as larger wires to the PCB. Once we chose all of these components, we used the EasyEDA software to design our PCB. For our design, we had to create a custom footprint for the buck convertor in Figure 9, based on the datasheet recommendations. It was also important to note how we took the trace widths into account, and made our traces 100 mils, 70 mils, and 30 mils across for our 24V, 5V and 3.3V traces respectively. This will lower the thermal losses from the traces and help our board stay cool under constant operating conditions. Our PCB layout can be seen in Figure 11 below.

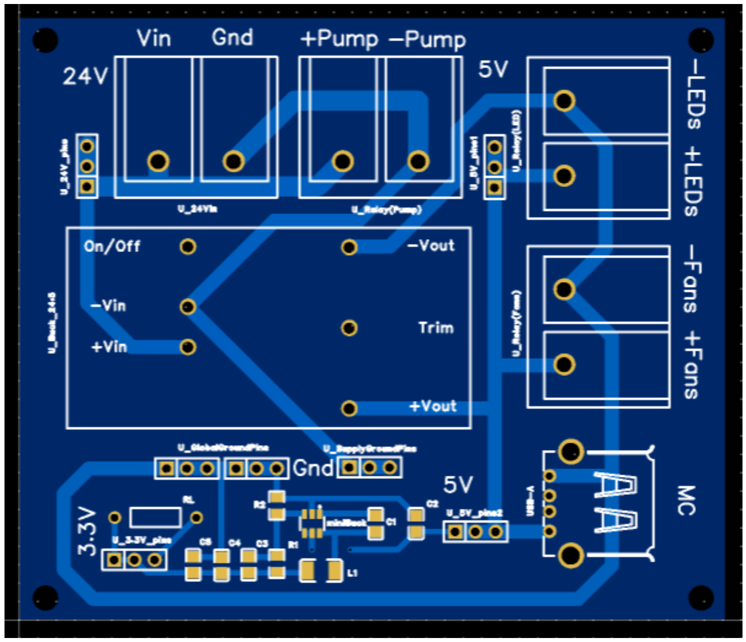

Figure 11. PCB Layout via EasyEDA

After verifying that our circuit worked via FreeDFM, we ordered our designed PCB through JLCPCB by sending the design gerber files generated by the EasyEDA software to JLCPCB. Once our PCB arrived, we soldered all of the electrical components onto the board, and did a connectivity check using a multimeter to ensure all of our connections were at an electrical node. The resulting PCB, our final version, can be seen below in Figure 12.

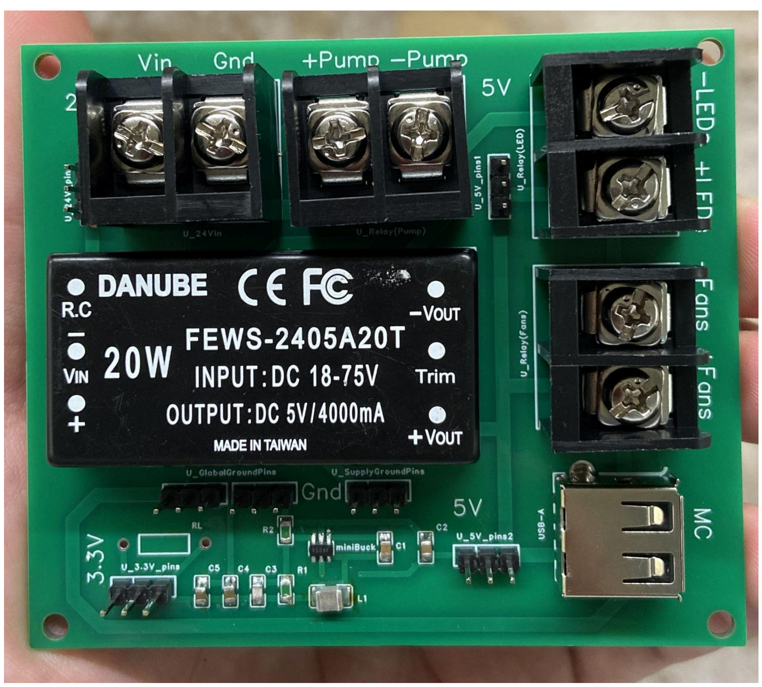

Figure 12. Final PCB used in Leafy-Link

To water the plants in our enclosure, a pump [24] and a mist nozzle [25] were used to draw water from the reservoir and spray/mist the water onto the plants and hemp mat. A 12-24V DC pump was used with an adjustable pressure between 17 psi and 65 psi. In our design we chose to run the pump at 24V, which allowed it to run more efficiently by drawing less current. We designed the system to run the pump at around 20 psi to protect the microgreens from any damage that could have been caused by excessive pressure. We used a 4-point nozzle to ensure the entire microgreen tray received water, and adjusted the nozzle to the softest spray setting. Additionally, we designed plastic guards to limit water leakage and ensure the maximum amount of water ended up in the microgreen tray. These rails were installed on the sides of the inside of the enclosure and epoxy was used to make them water tight. Whenever the humidity level becomes too low, the microcontroller activates a relay to pump a given amount of water from the water reservoir to the nozzle at the top, spraying water onto the plants. The sprayed water will keep the humidity level appropriate for the plants, and the water will be absorbed by the plants through the roots in the hemp mats. Any water that is not absorbed will flow through the porous tray below the mats and reach the water reservoir for reuse.

LED lights [26] were used for the project to illuminate the plants, and offer different lighting time lengths depending on the optimal growth conditions.. The LEDs will turn on and off at specific time intervals which are either determined by user input, or the predefined optimal values stored in the microcontroller.

To use the low power GPIO pins on the ESP32-S2-DEVKITM-1 to control the high powered pump and LEDs, we needed to make use of relays to easily control and protect these devices. We managed to find a package of relays in the NI Lounge, and after lots of testing, decided that they fit our specifications. The relay boards, based on the Songle SRD-12VDC-SL-C Relay [27], required ~3 Volts to throw the inductor used for the switch. The microcontroller can throw the relay with only one GPIO pin, which aided in our design.

The touchscreen LCD display is the method of input and output for the UI. It displays necessary information collected by the sensors, allowing the user to view such information at any given moment, as it is mounted on top of our enclosure. The LCD screen we use is the HiLetgo ILI9341 [28]. It is a touchscreen LCD display that will display all the sensor information and have screen sensitivity which allows the user to manually control the system outside the preset if they wish. Some of the controls include turning on and off the water and lights and starting a new cycle when the user puts in a new plant. It also shows the user the sensor readings obtained from buffers. The buffers are size 9 for each sensor except for the water level sensor, which has a size 5 buffer. These buffers are used so that the median value is taken to display to the user and for the microcontroller's logical decisions such as when to run the pump. This approach was used to avoid any transient inconsistencies in the sensors and ensure the system operated as expected.

The system physically operates as a hydroponic system where the plants are placed in a porous container that allows for the applied water to filter back down into a water reservoir. This reservoir feeds the pump via tubing that runs from the reservoir bottom all the way back up to the nozzles. When the microcontroller throws the relay to start a spray cycle, water will spay out of the nozzles, onto the plants, and back into the reservoir. The LEDs also toggle on/off in the system via the relays and microcontroller. The sensors were placed in various locations (water level, pH, and TDS sensors in the reservoir, DHT sensor on the right upper side of the enclosure). As an important side note, we made sure to include small holes for airflow in our system since these plants would not be able to properly grow in a fully closed system. Refer to Figure 5 for a better understanding of our physical setup.

Test Plans

The test plan for this system was split into two parts: individual component testing and system integration testing. By dividing the testing into two parts, the functionality of each subsystem was verified before they were integrated into the larger system. A microgreen mix with well-known growth requirements was used for testing throughout our system fabrication process and helped to provide an effective evaluation of sensor accuracy and system functionality. We used the Mild Micro Mix from Johnny's Selected Seeds, which contains mizuna, cabbage, kale, and kohlrabi [29].

In the first phase, individual component testing began with the microcontroller (DevkitM-1). The microcontroller was tested to ensure it would properly interface with all of the other components (pH sensor, humidity sensor, etc). Using platformIO on visual studio code, the sensors were tested and calibrated to make sure that they are displaying the correct values. To ensure that sensor data and user alerts are shown correctly, the microcontroller's connectivity with the LCD display was tested.

Each sensor is connected individually to the microcontroller and tested independently to verify basic functionality. In order to ensure accuracy, the temperature and humidity sensor were placed in controlled surroundings, and the temperature and humidity recorded. To make sure the pH sensor gave accurate readings, it was placed in tap water for calibration. When the pH sensor was tested in tap water, it was measuring in the range of 7-7.4, which ensured that the pH sensor accurately read the pH level of the liquid. The TDS sensor was separately tested in tap water, and calibrated where the value was reading around 350 ppm. Each sensor works correctly when tested in isolation.

Next, we tested the water pump and mist nozzle to ensure adequate pressure and water delivery without damaging the microgreens. We ran the pump at various PSI levels to find the ideal pressure for the misting nozzle we had selected. We also calibrated each misting nozzle by adjusting each of the nozzle openings to find the ideal misting settings. In order to make sure the LED grow lights supply the plants with adequate light at predetermined intervals, we then tested the LED grow lights first with an external power supply, before integrating them with the system power supply and testing this larger system. We found that each LED uses around 3 watts of power, requiring 5 volts at around 0.6 amps. This power draw was well within the designed value for the power supply and verified the LED's could be adequately powered in our system. We tested to ensure correct timing and adequate brightness to allow for optimal microgreen growth.

Testing the power supply, hardware, and load functionalities was integral before the system integration is possible. Because of this, we started off with the testing of our power supply. By connecting our power supply to a receptacle via our power cable [30], we were able to test the voltage pins with a multimeter, and then test our 5V buck converter by connecting the leads to the supply. These tests worked on the first try, an image of this testing can be seen below in Figure 13.

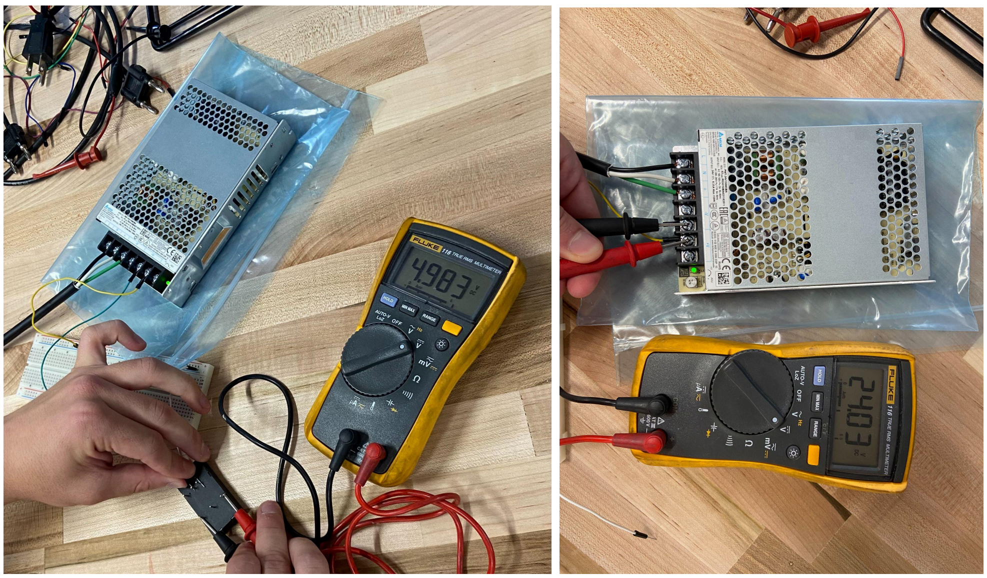

Figure 13. Power Supply Test

Next, it was time to test the relays that we found in the NI Lounge. To begin our test, we needed to figure out how they worked. We used a beep test on the multimeter to determine which ports were normally open (NO) and normally closed (NC). Then we used an AD2 to try different voltages on the control pins to determine the voltage magnitude and polarity that will throw the inductor and switch the relay. After testing a few voltages, we determined that the relay requires a voltage equal to ground on the control pins to throw the relay and approximately 3V to close the relay back. This is likely due to an optical isolator circuit that precedes the relay, however without the datasheet, we moved on knowing how to use it. If left unconnected, the relay will stay closed. This was ideal, since our microcontroller has the capability to output 3.3V or more at its GPIO pins, making it capable of controlling the relay(s) without intervention. We then tested the active power consumption of the relays to take their power draw into consideration, determining it to be approximately 0.165W per relay when using a 3.3V control voltage. This testisting can be seen in Figure 14 below. We also tested to ensure that the relays were rated for the load currents that were required for our project. Although unpictured, we tested and verified the relays were specified for a much higher current than we needed, which matched up to the SRD-12VDC-SL-C datasheet.

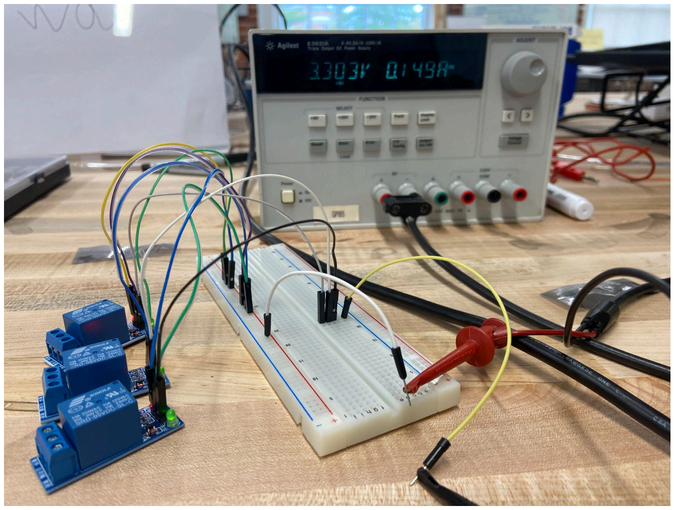

Figure 14. Relay Testing, Power Consumption

After testing the relays, we used the AD2 to do a test run using the relays to switch on and off the LEDs and Pump, while we waited on the microcontroller programming to progress. This test was successful, so we were confident to move onto the PCB design and testing.

Before the PCB arrived and could be integrated into our system, we created a short term setup for a growth cycle, by connecting our power supply and buck convertor to our relays and microcontroller via the setup that can be seen in Figure 22 in the Appendix. We ran an incomplete version of our program that would keep the lights and pump on a preset timer in order for the plants to grow. The most relevant code file regarding this test program was the "timer.cpp" file (shown in the appendix in Figure 21), as it operated the timers which turned on/off the lights and pump. This setup was successful, as we were able to get our microgreen mix growing two weeks before the demo day after they had germinated for a couple days first.

As previously discussed, we began our PCB tests by verifying the connection for all nodes and making sure the solder joints were solid. Next, we connected the PCB to the power supply via the "Vin" and "Gnd" pins, depicted in Figure 12. Then we used a multimeter to determine the correct voltages were present at each screw and jumper pin. The voltages were all within our tolerance range, so with no loads our PCB was verified to be fully functional. This concludes the majority of our subsystem and component testing.

System integration began after each component was confirmed to function independently. In order to make sure that the sensors, microcontroller, pump, mist nozzle, and LED light functioned harmoniously together, they had to be connected and tested as a whole system. After troubleshooting all connections made for all components attached, we aimed to verify our sensor data via the LCD screen. Likewise, we aimed to do a test run for our growth cycle to confirm there were no power issues.

As can be seen below in Figures 15 and 16, by testing different water levels for our reservoir and monitoring the values through our LCD display, we were able to confirm the functionality of our LCD screen and sensors.

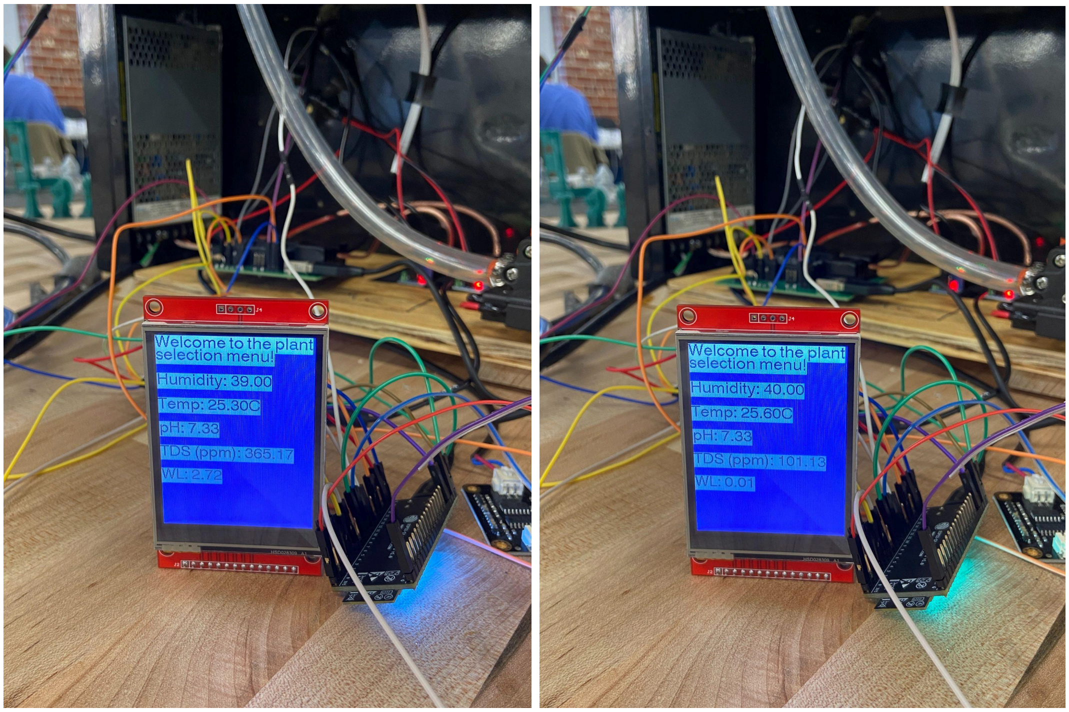

Figure 15. Full Sensor Integration Results on LCD Display

Figure 16. Full Sensor Integration Test Setup

One important thing that we discovered with the sensor integration test is the stability of our TDS sensor. When the TDS sensor was tested with all other components in the system, its readings spiked unexpectedly. After numerous attempts to recalibrate the sensor in tandem with the system, the TDS sensor readings still spiked when mixed in the environment or with level changes in our water reservoir. We are confident this is caused by the voltage reading on the TDS sensor probes being shifted by the other sensor voltages being applied to the water. However, once the system was fully built, the TDS sensor's readings were constant, which meant that we could recalibrate the sensor for the end product under the assumption that the user will keep the setup the same as our final version. Finally, to make sure the system recognizes when the water level is too low and notifies the user, the water level sensor was tested by filling the reservoir to various levels and recording its response. The water level sensor, when fully submerged, gives readings of 2.72V, and the voltage value decreases whenever the amount of water touching the sensor decreases, eventually reaching near 0V when fully out of the water and isolated in a dry environment. This allowed us to set a certain voltage level of the water sensor, which would alert the microcontroller if the voltage level dropped below that threshold, signifying that the water level is too low.

Since our temporary program successfully ran a growth cycle for our microgreens, we were positive we would be able to run a growth cycle with our current program version. After watching a short cycle run with our current program version, we were confident in the functionality of Leafy-Link as a whole.

Physical Constraints

The success of this project was reliant on a number of variables outside the scope of its design. One of the first constraints was designing our system with components that are easily available. Failure to account for this factor could have resulted in a subsystem that underperforms due to the use of a part we had not specifically designed for. Our plan to greatly minimize this problem was to use parts available in our lab, such as passive elements and transistors, as well as making sure to order our parts early to allow for prototyping. By completing our prototype early we were able to figure out what components we could keep and got insight for ordering the components that could present inconsistencies. This also gave us a more firm understanding of which subsystems would be more costly in our planning of our final budget.

With these components and parts in mind, costs were also a huge constraint. We were provided a budget of $500 USD and as we worked through the design, we compiled an itemized bill of materials which we continuously updated as we moved further along in the process. In our design, we were able to save a considerable amount of money by repurposing an old wine cooler for our enclosure. This trend of cost friendly decisions continued throughout the physical design of our enclosure, as we designed for functionality while keeping prices to a minimum. This allowed us to balance the costs associated with the manufacturing of our system, and will provide users of the technology a simple and aesthetically pleasing product. The biggest mistake we made for costs was failing to realize the last day for bulk class orders. By having to personally purchase our final PCB, along with the components that were required to complete the PCB, we ended up paying much more in shipping costs than we would have if we had done this sooner. The extra shipping costs made up about $60 USD for our last 3 purchases on parts worth approximately $20 total. Although this was not ideal, and makes our budget management seem worse, time was our biggest constraint near the end of our project, so the orders were well worth the extra shipping costs. Another consideration is that our project build cost does not reflect what the cost of this system would be on the market. Very often (basically always), the cost to design and build a system for the first time is much higher than the expected retail cost. We have many leftover components, partly due to the fact that electronic components are often sold in bulk so we had to order more than we needed for many items.

To make the management of our project easier, we broke it up into more logical subcomponents. This allowed us to more effectively consider and purchase the necessary equipment (some items may be repeated as they fall into more than one category). The core skeleton of this project is a physical enclosure that consists of a thermally insulated housing, a plant medium to place the seeds in, a container for the plant medium, electrical housing and conduit, a water containment system, and a place to house the LEDs. Most of these parts were widely available and purchased through amazon, local hardware stores, while others had to be hand built using the available power tools. The enclosure we chose already had effective insulation and was largely watertight, meeting many of the requirements for our design.

The next system was the control and information system that used sensors and a microcontroller to make decisions for our system. Major components for the control system involved a number of sensors, a PCB, a microcontroller, a pump, mist nozzles, an LCD screen, and electrical components that were soldered onto our PCB. Many of these components had already been decided upon (as seen in Table 2) and were relatively inexpensive. Many electrical components were purchased through Digikey/LCSC Electronics or acquired through our engineering lab/workspace.

The moving parts of this system required higher power and more costly components. Some of these components included a power supply circuit, a motor, a pump, and electrical connection devices that were soldered onto the PCB. These circuits were among the first designed and were the first purchased and tested, ensuring success in case of part availability issues. Our initial design left plenty of room for more expensive power components in case we needed to pivot. Finally, water was required for the growth of our microgreens and system operation. Our system cost did not take into account this water due to its ubiquitousness compared to the other resources used.

It was also our plan to find free access to the tools that would be needed for testing and verification of our product. Many power tools were necessary for the enclosure, and many members of our team had the required tools or access to university substitutes. We used drills, dremals, screw drivers, table saws, and other rotating machinery to remove and attach many components for our enclosure. The use of wire strippers allowed us to manually alter each wire and cable to fit our connectivity and size needs, while using electrical tape to safely secure each connection. A team member brought their own electrical tape, which was used throughout all intermediate phases of the project, and used to organize and manage a lot of our wires/cables for concision and safety.

Likewise, electrical testing equipment such as oscilloscopes and multimeters were integral. We had access to all of these tools and many more in the electrical and computer engineering department. We also needed simulation software that would be used prior to building our circuits, which we had acquired throughout our electrical and computer engineering curriculum. Some of these software tools included Multisim, Ultiboard, the PlatformIO environment on VSCode, and Waveforms. Multiple team members had access to and experience with these software tools making their usage effective and easy.

Arguably the most important and most challenging constraint of our project was time. Our project has so many different subsystems that rely on each other, that in the cases of setbacks, many team members also dealt with delays due to propagation of the initial delay. We organized each team member's work so that we could work in parallel as much as possible, but as we approached the project end, it became difficult to test the entire system functionality exhaustively. To combat this, we had to compromise many tests and some functionality by proving capability instead of fully fleshing out the functions. The most important example of this was our LCD touchscreen capability. Once we completed our full system integration, all that remained to be completed was the UI input for the user to select the plant they want to grow. When testing this function, we discovered that the wiring connecting the touchscreen layer on the screen to the XPT2046 driver was damaged, and thus the touch response/capabilities were almost nil. We are hoping to have another screen by demo day so that we can show the ability of the system to respond to user input. However, if this does not occur, then a small adaptation of the software will be done in order to make the plant selection process as straightforward as possible through flashing the microcontroller. Using a header file with commented out lines for each plant selection, the user can simply uncomment the line for their chosen plant. Thankfully, VSCode and PlatformIO are free applications, and the "platformio.ini" project file sets all of the necessary configurations. So, all the user would need to do is download the software and project files, remove the comment on the line for the plant they want in the "user.h" file, and run the build/flash commands provided by PlatformIO.

Societal Impact

The societal impacts of this automated plant care system stretch across a variety of sectors including public health, environmental sustainability, and the economy.

Public Health, Safety, and Welfare

This system offers a number of clear benefits to public health. By allowing restaurants to grow their own in-house microgreens, this system promotes the consumption of fresh, locally sourced produce. Additionally, microgreens are known for their particularly high nutrient content, with high levels of minerals, vitamins, and antioxidants [31]. By simplifying through automation the process by which one can grow microgreens, this system will increase access to said microgreens and the numerous health benefits that come with them. This system will be particularly useful in urban areas and/or food deserts, where locally sourced produce is scarcer, and will provide nutritional opportunities that may otherwise be nonexistent. Furthermore, since the system is automated, there is essentially no need for manual intervention and therefore, a lower chance of human error, which can result in problems like over- or underwatering or improper nutrient levels. This contributes to the safety of food production by ensuring a safer, more reliable yield of healthy plants.

Cultural and Social Factors

There is a growing cultural awareness and social desire, particularly in the United States, for sustainable, locally sourced food. The more these sentiments continue to intensify, the more this system serves the social will of the population, aligning very closely with the concepts of urban farming and sustainability movements. Urban farming has been proven to improve food security and incubate stronger community ties [32]. The project facilitates access to microgreen cultivation for restaurants mainly, but also individuals, consequently supporting societal tendencies towards sustainability and food independence. Additionally, it supports social awareness about hydroponics, plant maintenance, and the advantages of eating food that is locally sourced.

Environmental Impacts

Hydroponic systems, like the one employed in this design, use water much more efficiently than traditional agricultural techniques. This increased efficiency results in a reduced strain on the environment, particularly for water resources. Research indicates that hydroponic farming systems on average use up to 90% less water to produce the same amount of produce compared to standard soil-based systems [33]. As many parts of the world are facing droughts and issues with water scarcity, this system plays a beneficial role in water conservation efforts. Moreover, because this system allows customers to grow their desired microgreen nearly anywhere, it will effectively reduce the carbon footprint typically associated with both the transportation and distribution of produce from rural areas to urban centers. Research concludes that by growing produce locally, people can significantly reduce transportation-related carbon emissions [34]. This system also works to somewhat decentralize food production, consequently creating more reliable and sustainable food supply chains.

However, despite these environmental benefits, this system's use of electrical components like the motor and microcontroller do carry potential environmental costs as they do require power to operate and resources to be created. The eventual disposal of the electrical components and circuitry pose an environmental risk if handled improperly, which is why it is crucial for future customers to properly dispose of this system when they choose to stop using it [35].

Economic Impact

This system can have a significant economic impact, especially for restaurants and even individuals looking to grow microgreens at a lower cost. The automated approach eliminates a lot of the guesswork and labor necessary in daily plant care, but traditional farming methods still require a significant amount of labor and skill to control plant growth conditions. This effectiveness can lower operating expenses, improve production stability, and give customers a consistent supply of microgreens [36]. Establishing a dependable internal supply for fresh microgreens might be especially advantageous for restaurants since it decreases their dependency on outside, potentially costly vendors. This is especially true for less common microgreens, as restaurants that need them can have a consistent in house supply, without having to worry about buying from a vendor in large quantities, potentially leading to waste. It also provides flexibility in menu-planning as the restaurant can choose which microgreens they want to grow. In a similar vein, individuals using the system at home will save money by growing their own microgreens over buying them, which may not even be an option if stores do not carry them.

Ethical Considerations

Looking at this system from an ethical perspective, it is clear that the design aligns with our goal of providing increased access to healthy food with a minimal environmental impact. However, since incorrect disposal of e-waste can have detrimental effects on the environment and human health, it is imperative to take into consideration the responsible disposal of the system's electrical components at the end of its life cycle [37]. Furthermore, there are worries regarding possible job displacement in the agricultural industry due to automation in farming. Although this method is designed for small-scale use (individuals and restaurants) rather than large-scale agricultural enterprises, it's crucial to think about how automation may affect jobs in farming communities in the long run, even though this specific system is unlikely to noticeably contribute to this phenomenon.

External Standards

Compliance with external federal and industry standards was a crucial consideration throughout the development of our design to ensure reliability, safety, and functionality. These standards informed the decision making of our design, the component selection, and the testing procedure, in an effort to guarantee the system met established engineering practices and aligned with future scalability and commercialization requirements.

IEEE Std 1100-2005 (IEEE Recommended Practice for Powering and Grounding Electronic Equipment) was adhered to during the design and testing of the project's power and grounding systems. In order to prevent power surges and short circuits, this standard provided guidance for the appropriate grounding and shielding of the AC-DC power supply. Furthermore, shielded connections were employed to reduce electromagnetic interference (EMI), which was particularly crucial considering the enclosure's sensitive sensors and microcontroller functions [41]. The IEEE 802.11 standards were also followed by the Wi-Fi-enabled ESP32-S2 microcontroller to guarantee dependable and strong wireless connectivity, setting the stage for future remote monitoring features [42].

Leafy-Link's printed circuit board (PCB) was designed and manufactured in accordance with IPC-2221 (Generic Standard on Printed Board Design). In order to maximize both performance and long-term endurance, this standard specified crucial design components including: trace widths, trace spacing, and thermal management. To manage their individual current demands while reducing thermal losses, the 24V, 5V, and 3.3V traces were specifically dimensioned, ensuring optimal functionality. To assure additional standard compliance and lower the possibility of assembly errors, the PCB board was checked using FreeDFM prior to manufacturing [43].

Given that the design involves the movement of water through the water pump and misting system, we ensured that the power supply and other electrical circuitry adhered to NEMA (National Electrical Manufacturers Association) standards. These standards require that electrical system enclosures be insulated from any water, to prevent moisture ingress and to protect the electrical components from issues associated with contact with water. Adhering to this standard significantly improved the overall safety and reliability of Leafy-Link by significantly reducing the likelihood of malfunction due to water leakage [44].

The software used in the design for Leafy-Link adhered to the guidelines of ISO/IEC 62304 (Medical Device Software – Software Life Cycle Processes). Though this is not specifically a medical device, by complying with these standards we ensured additional safety for users of the design [45]. To accomplish this, we took additional documentation to aid in troubleshooting and future improvements and methodically tested the sensor data collection, user interface interactions, and relay controls. Furthermore, the LCD touchscreen display, DHT11 temperature and humidity sensor, and other peripherals all followed industry-standard communication protocols, guaranteeing a smooth integration with the ESP32 microprocessor.

The FDA's Standards for the Growing, Harvesting, Packing, and Holding of Produce for Human Consumption were followed in the selection of the water and nutrient delivery components, such as the pump, water reservoir, and misting nozzles. In order to ensure that the system complied with safety regulations for agricultural applications, these standards required that all components in contact with water and nutrients be made of food-safe materials. This was particularly crucial for Leafy-Link's main application in eateries, where patrons would eat the microgreens [46]. The design also complied with the RoHS (Restriction of Hazardous Substances Directive), which places limits on the usage of dangerous material components, like lead and mercury, in order to limit its harmful effects on the environment. The PCB, sensors, and microcontroller that were used in the final design, were all ensured to be RoHS-compliant components, to guarantee system safety. This made sure the system was in line with international initiatives to lessen environmental contamination and electronic waste [47].

Following these guidelines allowed Leafy-Link to create a reliable and effective design that guarantees user-friendliness, agricultural effectiveness, and safety. These factors not only improved the system's quality but also established it as a scalable option for future usage in actual restaurants.

Intellectual Property Issues

The patentability of our design, Leafy-Link, is reliant on its ability to demonstrate novelty, utility, and not have obviousness likeness when compared to prior art. To analyze the patentability of Leafy-Link, we have compared our system to three similar patents, two existing and one in the process of approval: U.S. Patent No. 11,452,270 B2, U.S. Patent No. 11,304,391 B1, and U.S. Patent Application No. 2022/0369582 A1. Each of these patents outlines systems with similar features to Leafy-Link, centered around automated hydroponic or aeroponic cultivation, environmental control, and microgreen growth. Though other systems have related features and target audiences, Leafy-Links unique design and additional features make it a patentable innovation.

U.S. Patent No. 11,452,270 B2 was granted in September of 2022 and describes, "Automatic system for control and management of hydroponic and aeroponic cultivation of plants." [48]. The 1st Independent Claim describes a system that integrates a sensor module to monitor parameters like pH and electrical conductivity, as well as an injection module for nutrient delivery. Dependent Claim 2 specifies the use of probes for pH and conductivity, while Dependent Claim 6 describes feedback loops for real-time adjustments. This design integrates a sensor module, nutrient injection module, and an additive control module. Its claims of novelty broadly cover systems that monitor and manage environmental parameters such as pH and nutrient levels, positioning the system as a versatile plant cultivation solution. The focus of this system is specifically on ensuring precision and efficiency in environmental control and nutrient delivery for a wide range of plant types and growth conditions. Although Leafy-Link includes similar features, like the pH sensor, our system diverges considerably from this existing system through its concentration on the user experience. Leafy-Link includes preset growing options for specific microgreens, integrates an LCD user interface, and has a compact and aesthetic design tailored specifically for restaurant environments. These distinctions provide a novel and specialized application, one not covered by the dependent, setting Leafy-Link apart from the scope of this patent.

U.S. Patent No. 11,304,391 B1 was granted in April of 2022 to Eddie James DeJong. This patent describes a "Microgreens Grower" which includes "a chamber; a seed support disposed above the chamber, the seed support having a structure which is configured to prevent seeds of a predetermined size from falling through, but is permeable to water; a mist generator disposed below the seed support and in communication with a water reservoir; at least one grow light disposed above the seed support; and an electronic controller operable to selectively provide electrical power to the mist generator and the at least one grow light." [49]. The Independent Claim 1 of this patent outlines the structural components of the grower: a seed support, mist generator, grow lights, and an electronic controller for automation. Building on the Independent Claim, Dependent Claim 5 expands on the structure of the grower by specifying a programmable timer used to control the misting and lighting cycles. Furthermore, Dependent Claim 7 discusses how the system controls the misting frequency based on changing environmental needs. While Leafy-Link shares a number of the features discussed in this patent, primarily the automated grow light and misting cycles, it far surpasses the simplicity of this existing design through its integration of numerous sensors, used to monitor real-time changes in humidity, temperature, and water levels. Additionally, the use of a programmable microcontroller and inclusion of preset growth settings optimized for specific microgreens, enhances user convenience and goes beyond the scope of functionality described in the Dependent Claims described in U.S. Patent No. 11,304,391 B1.

U.S. Patent Application No. 2022/0369582 A1 was first filed by Focus Universal Inc in May of 2022 and is currently in the process of achieving patent approval. This patent describes a "a system and method for a smart hydroponic system. The system includes a central controller and one or more smart hydroponic system modules . . . [which] automate a number of tasks required to maintain hydroponic agriculture. Further, these tasks are localized to provide greater precision to the agriculture." [50]. Independent Claim 1, of this design, highlights its modular hydroponic system structure, utilizing a central controller to automate tasks like nutrient delivery. Dependent Claim 3 specifies the systems ability to monitor environmental parameters such as temperature, pH, and conductivity, while Dependent Claim 8 focuses on the systems modular scalability for different agricultural setups. This system was designed in a modular fashion, allowing for simple and efficient scalability, and enabling users to automate a wider range of agricultural tasks. Its independence claims are largely grounded in the system's modular adaptivity, good for both small and large scale use, and its wide range of applications. In contrast, Leafy-Link has a far more narrow scope, specifically targeting restaurants and urban growers, offering a compact and affordable design tailored for microgreen cultivation. While the system described in the patent champions versatility, Leafy-Link is concentrated on simplifying the user experience and maximizing efficiency for growing specific microgreens. By having a more well defined client base, and focusing on automation and ease of use, Leafy-Link is able to distinguish itself beyond the Dependent Claims discussed in this patent, and offer a novel solution likely to receive patent protection.

After comparing Leafy-Link to U.S. Patent No. 11,452,270 B2, U.S. Patent No. 11,304,391 B1, and U.S. Patent Application No. 2022/0369582 A1, it is evident that while Leafy-Link shares some features with these existing systems, it introduces unique innovations that set it apart. The combination of preset growing options, real-time sensor integration, a compact and aesthetic design for restaurant use, with an emphasis on user-friendliness demonstrates a novel and non-obvious approach to automated hydroponics. These distinctions meet the requirements for patentability, showing that Leafy-Link is not only innovative but also provides a targeted solution that fills a specific market gap, making it a strong candidate for patent approval.

Timeline

At the beginning of the semester, we developed a Gantt chart to organize the necessary tasks for full system development, including relevant deadlines/events. This initial chart is shown below in Figure 17. As the semester progressed, we were able to stay relatively within the task completion deadlines set by the Gantt chart. However, once our system started coming together, we faced issues with integration which significantly slowed our progress, causing us to fall behind. The difficulties in sensor calibration, the PCB redesign, and the UI integration were the primary tasks which gave us trouble and failed to complete on time (the initial PCB was completed on time, but it needed to be updated). These issues would have been easier to avoid if we had been more specific by providing subtasks for the major tasks. The final Gantt chart, shown in Figure 18, reflects the actual time it took to complete the specified tasks by including black borders around the days in which the tasks were worked on until completion.

Figure 17. Initial Gantt Chart

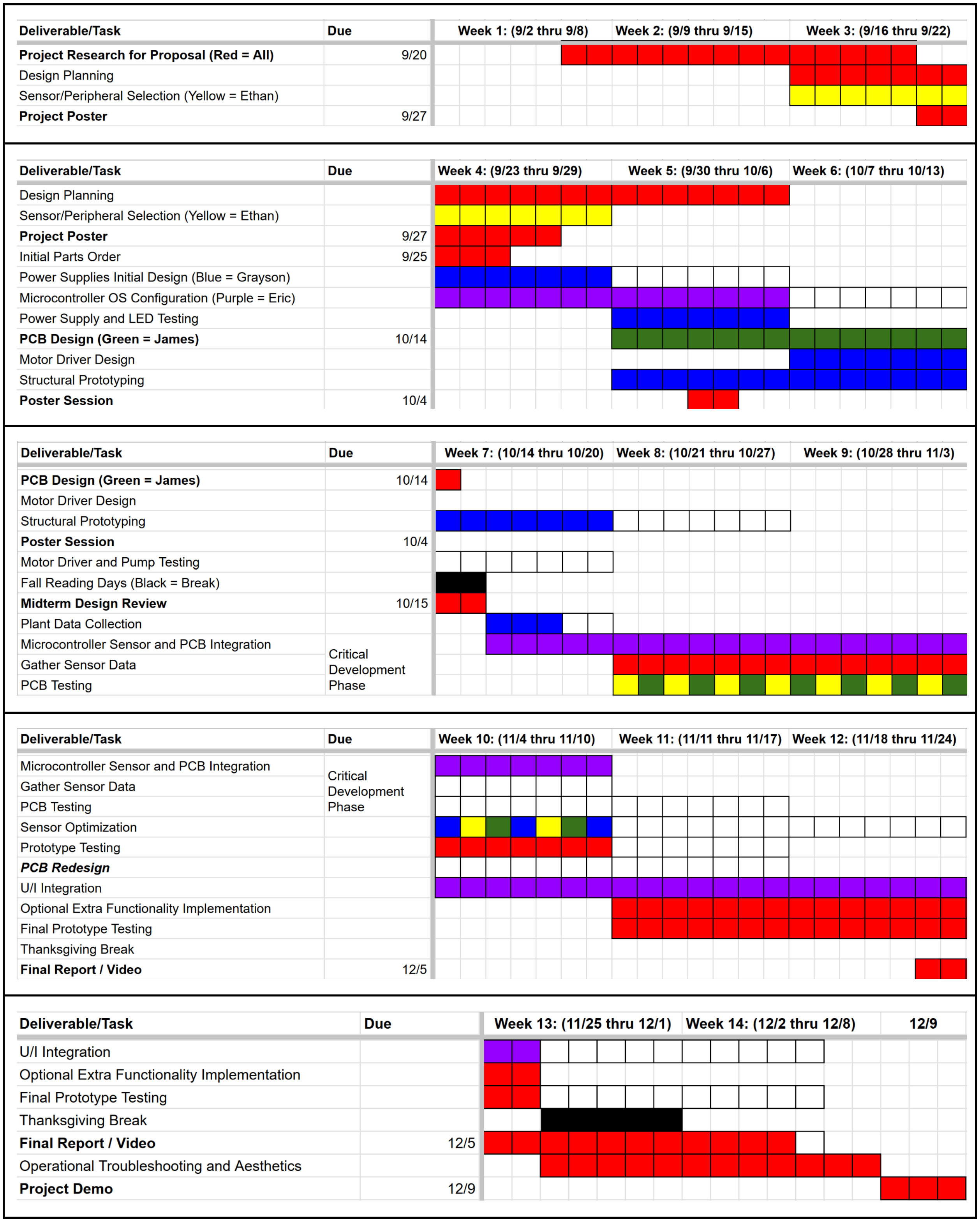

Figure 18. Final Gantt Chart

Costs

The detailed costs and list of materials purchased are in Table 1 in the appendix. The total cost of the project came down to be 466.61 dollars, with 33.39 dollars remaining from the budget. While the project was able to be finished within the given budget, the final cost of the project more than doubled from our preliminary cost estimate. These additional costs have come from multiple different sources such as additional material being purchased: i.e. fans, plant trays, etc.. More components had been added to the project to ensure that the system worked seamlessly and some parts had to be replaced with the new PCB functions. The actual cost of the project would be lower considering the fact that additional parts were purchased for the PCB as we had to redesign our PCB, and some parts were ordered more than the necessary amount to be used as a backup component if any of them failed when testing the system. Since we had multiple different delivery orders throughout the semester, the additional delivery cost would also have to be taken into consideration, which would be lower if the product were to be produced in bulk, since all the components would be ordered at the same time now that the product is fully assembled and we have knowledge of the parts that are needed for the product and what parts we do not need.

Particularly, when ordering the final PCB iteration and its associated parts, we spent much more on shipping than the components themselves. This was due to a previously discussed issue where we had to order parts after the last day to "class order" parts. This was done due to time constraints, but paid off in the end because the PCB simplified our wiring greatly. The good news is that we still managed to stay under budget, and if we were to create a copy of the final version of this project, it would cost us much less. Part of the process of designing a new product includes making modifications and pivoting mid-project. This has an associated cost, which would be removed if future copies were made.

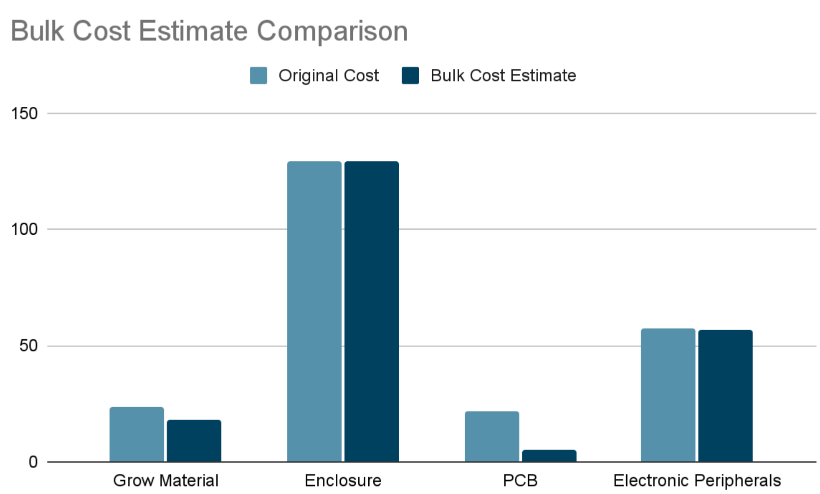

Figure 19. Original Cost vs Bulk Component Cost Estimate Breakdown

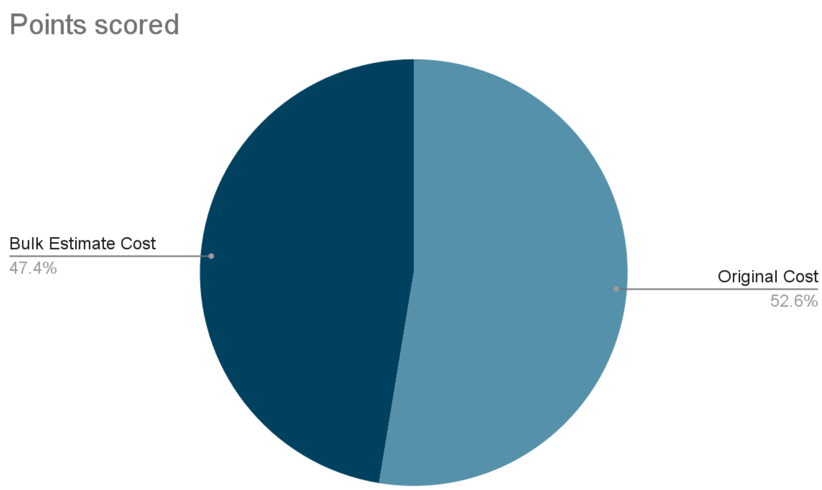

Figure 20. Original vs Bulk Cost Comparison

Figure 19 and Figure 20 depict the cost comparison of the actual project cost as opposed to the project if it were mass produced. That is to say, if we ordered parts on the magnitude of 10,000 parts an order. A lot of the materials such as the sensors, LCD screen, and components involved with the enclosure system do not clearly sell in bulk on their websites, and do not offer much advantage to the price if it is to be mass produced. However, some of the materials such as PCB components from Digikey/LCSC and grow materials did offer an advantage in price when being bought in bulk. Since these parts made up a small percentage of the total cost necessary for product development, the savings for these parts were only about 5.2%. If we were to automate this product, we would try to search for more parts that could be bought in bulk to increase these savings.

Likewise, along with the per item savings that could occur due to bulk purchases, the savings due to shipping would be our main benefit. We experienced this truth with our PCB shipping costs resulting in more than the total component costs near the end of our project. Although an in-depth analysis would be necessary to calculate the savings due to bulk purchasing, we are confident that shipping costs would be the biggest benefit to buying our components in bulk. This is of course assuming that we would be manufacturing a significant number of our products.

As far as manufacturing this product, this could be automated. The way we have our product put together right now, it would not be ideal to automate. This is because most of the solutions to our wiring and setup was hand created, which is difficult to replicate in an automated environment. Things like screw pins and unsoldered connections would be downright cost ineffective for automation. With this in mind, if we were to mass produce this product we would re-design it with more soldered components to increase the amount of the product that could be fully automated. The PCB and enclosure alterations could however be fully automated how they currently are designed. On another note, it would be interesting to try and create a modular system if mass production was the goal. By creating a system where the user could store

Leafy-Link's next to each other and monitor the plant environments from one UI, it would be much more enticing for larger consumer bases.

Final Results

The system was fully built and tested to ensure its functionality. The water nozzle and lights turn on at a given preset determined in the microcontroller code, with the water nozzle spraying water pumped from the container to the plants, and any excess water that is not absorbed drains back down to the water container with all the sensors. The LCD screen was able to properly read in the sensor information, display, and update the readings. All the sensors are connected simultaneously to the PCB and the microcontroller for power supply and relaying the sensor readings, which are then fed to the LCD screen to display. The wiring for all electrical not located on the inside of the enclosure can be seen in Figure 21 below. We will try to clean up the wiring and have better organization and cable management for our demonstration.

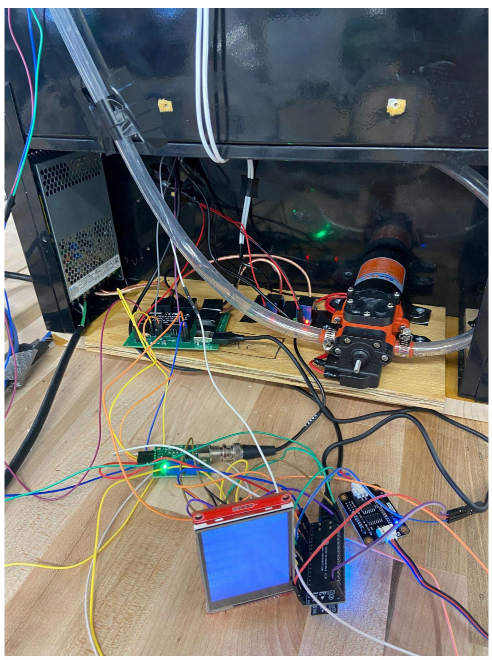

Figure 21. Leafy-Link Prototype Wiring

One concern, which was previously mentioned, is the TDS sensor reading, which seems to vary when any other electrical component is in the water reservoir. However, it is also promising that the TDS sensor reading is stable when everything is stable. This means that as long as nothing new is introduced to the environment that may disrupt its readings through the electrical nodes of the sensor, the TDS sensor will be able to provide a stable reading to the user. On the same note, as of this report, we have yet to incorporate touch screen functionality to the LCD screen. As discussed this was due to a hardware failure which likely occurred during transportation of the screen to/from the lab. We have a workaround planned for our demonstration if we do not have it working by then. Although this is unfortunate, it does not eliminate the functionality of Leafy-Link after startup, and only changes the way in which the user must input the plan they want to grow.

With the current status of Leafy-Link, it is capable of providing the intended functionality to a user; automating the growth of microgreens for a restaurant. However, some of the components did not function as seamlessly as we aimed for. Our project proposal specifications were met except for the screen touch input, which somewhat lowers the setup ease-of-use. These project specifications can be referenced in Table 1 in the Appendix. We have not received significant feedback yet on the final design, so that is also unclear. Overall, we rate ourselves a "B" since we were not able to get all initially expected systems functioning properly by the writing of this report.

Engineering Insights

Developing a project from scratch using teamwork, time management and the engineering skills we have gained at UVA gave us insight for what to expect in a real world engineering project. From creating a Gantt chart to planning out every part of the project, coming up with our own task list and splitting up the work proved more difficult than previous projects we worked on in the FUN series.

With the preliminary cost estimate, the project seemed to be extremely cheap compared to other similar products that already exist in the market, but the final product almost doubled from the initial estimates. Gantt chart timeline proved helpful for some planning and splitting up the work in terms of making progress, but there were numerous occasions when we finished certain parts early, and had certain work take longer than expected. For example, assembling parts did not take as long as expected, while coding the microcontroller, calibrating the sensor, testing plant growth in the system took longer than what we had planned for in the initial Gantt chart. With these timeline issues, time management was a challenge where some weeks we would only need to spend 2-3 hours a week to fulfill the expected progress while some weeks we had to put in 10 or more hours a person to keep pace with the project expectations.

Having a weekly meeting scheduled for everyone to meet and check the progress on the project was immensely beneficial, allowing everyone to gather at least once a week and evaluate what needs to be done next, and splitting up the work weekly.

Future Work

One of the biggest challenges we faced had to do with the software part of the project. The microcontroller was the main component of the project, connecting the sensors, lights, water pump, and the LCD screen. Calibrating the sensors and designing the LCD screen to fit our specific goal took up a considerable amount of our time, going into the last week. While writing some of the code was simple, making sure to use the same platform, merging all the code, and dealing with power supply issues with the microcontroller originally supplying power to all the sensors and the LCD screen proved to be more challenging than expected. Much of the other hardware that was purchased such as the sensors have a lot of online resources available to understand how it works, how to calibrate, etc., which helped save a lot of time with the project.

If we were to give advice to a future capstone team who decided to continue this project, it would be to spend more money on the important parts of the project and worry about the budget more when choosing peripherals. By designing our integral systems first, we often purchased cheap but usable components. If we were to have purchased a microcontroller that we were more familiar with, we could have saved lots of time and effort. Likewise, if we would have purchased higher end sensors, there is a chance we would not have dealt with as many calibration issues. This is arguably unavoidable for a project with as short a timeline as capstone, where it is easy to overdesign some subsystems and underdesign others. If we made design decisions earlier, we could have potentially avoided some of these issues; however, there is always a tradeoff between time spent designing and testing in a project. Another pitfall we encountered was something as simple as cable management. Our PCB only had the necessary amount of pins for our project to work, and if we were to have given ourselves extra connection pins, it could have simplified our wiring further. We also did not take into account the access (or lack thereof) for multipurpose wires, jumpers, and cables in the NI Lounge. We assumed these inexpensive and common parts would be widely available in the lounge, however we ended up using wires that were often the wrong length for our ideal usage. Since these parts are so cheap, we should have purchased more wire initially to simplify our wiring and cable management.

To improve upon Leafy-Link's current version, we would recommend making it modular, and adding more control to the system. By making the system modular, it would be able to better fit varying needs for potential consumers. This would likely require or simply work better with wifi connectivity and server management, but is definitely possible and very applicable. Also, by potentially adding fans and thermal control, you would be able to provide an even more optimal environment for plant growth. This would give future teams much more opportunity to explore control systems, and likely require lots of testing since there are often more variables than accounted for in design. Lastly, it is difficult to promote a healthy growing environment for microgreens in the NI Lounge, where other teams are using power tools and soldering, resulting in unideal plant conditions. Although it would be hard to find a place where the team could meet to work on the project and where the plant has optimal conditions, it is something to consider when bringing this project to fruition.

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Appendix

Grade	Description
A	**Microgreens Growth:** Successfully grows proper yields of at least three different types of microgreens from seed to harvest with minimal intervention. **Automation:** All sensors are integrated and functioning flawlessly, with proper control of the lights and water pump/sprinkler system. **User Interface:** The LCD screen provides all necessary data clearly, with intuitive controls and accurate alerts. **Durability:** Operates without failure or need for repairs through multiple growth cycles. **Ease of Use:** Setup and operation are straightforward, requiring minimal instruction. **Aesthetics:** Visually integrates well into its intended environment, enhancing appeal. **Documentation:** Comprehensive guide provides straightforward direction for all user needs. **Feedback:** Very positive from users regarding usability, reliability, and produce quality.
B	**Growth:** Grows multiple types of microgreens; minor adjustments or troubleshooting may be needed. **Automation:** Most sensors work with minor issues; some manual adjustments might be necessary. **UI:** Functional but could benefit from enhancements in user interface clarity or functionality. **Durability:** Generally reliable but might need occasional maintenance or recalibration. **Ease of Use:** Mostly user-friendly but requires more setup or troubleshooting than expected/intended. **Aesthetics:** Adequate but could be more visually integrated or appealing. **Documentation:** Sufficient guide; lacks depth or clarity in some areas. **Feedback:** Positive overall, with constructive criticism on usability or efficiency.

C	**Growth:** One type of microgreen grows but requires significant manual intervention. **Automation:** Basic automation works, but significant components of the system (e.g., sensors or controls) are not fully operational. **UI:** Displays necessary data but lacks clarity or has functionality issues. **Durability:** Frequent operational disruptions or need for repairs. **Ease of Use:** Complex setup or operation; detailed instructions are needed. **Aesthetics:** Functional design but not attractive or well-integrated. **Documentation:** Basic information provided; guide lacks depth or polish. **Feedback:** Mixed, with clear opportunities for improvement identified.
D	**Growth:** Minimal growth success, with extensive manual intervention required. **Automation:** Automation attempts are mostly unsuccessful; many components fail or require constant manual control. **UI:** Barely functional, with significant usability issues. **Durability:** Frequent breakdowns or non-functional components. **Ease of Use:** Very difficult to operate or set up without expert guidance. **Aesthetics:** No consideration for visual appeal or integration. **Documentation:** Poorly documented; guide is unsatisfactory or missing. **Feedback:** Negative, with users noting significant operational and usability issues.
F	**Growth:** No successful growth of microgreens. **Automation:** Complete failure or absence of automation features. **UI:** Non-functional or missing user interface. **Durability:** System is not operational or breaks down immediately. **Ease of Use:** Impossible to use without complete redesign or overhaul. **Aesthetics:** No effort towards design aesthetics. **Documentation:** Nonexistent or completely inadequate. **Feedback:** Users find it unusable or non-functional.

Table 1. Initial Expectations Specifications

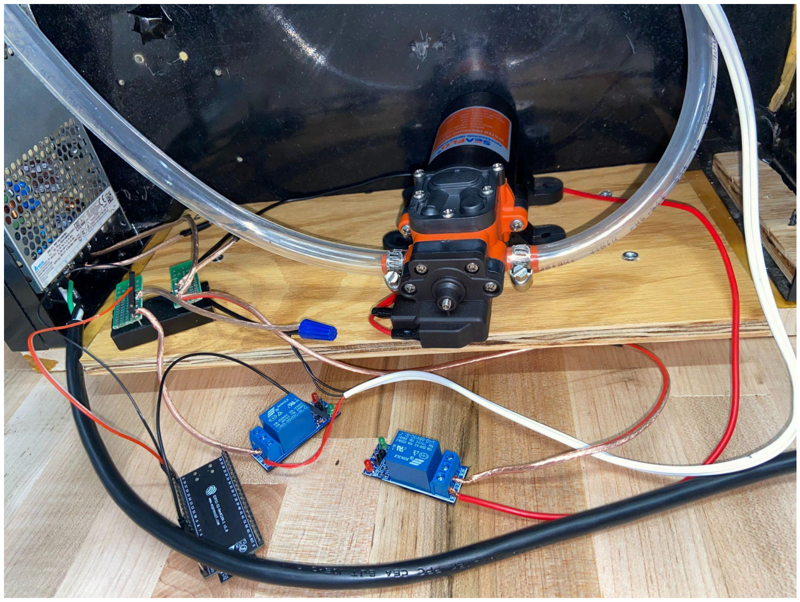

Figure22. Short Term System Setup for Microgreen Growth Cycles

```
#include "timer.h"
#include <Arduino.h>\
static int lightState = LOW;
static int pumpState = LOW;
void IRAM_ATTR timer_group0_isr(void *param) {
  uint32_t int_st_timers = TIMERG0.int_st_timers.val; // Check which timer interrupt occured
  if (int_st_timers & TIMG_T0_INT_ST) {
    timer_group_clr_intr_status_in_isr(TIMER_GROUP_0, TIMER_0); // Clear interrupt
    digitalWrite(LIGHTING_PIN, (lightState = !lightState));
    if (lightState = LOW){
      updateTimer(TIMER_0, 10*60*60); // Off duration, set at 10 hrs
    }else{
      updateTimer(TIMER_0, 14*60*60); // On duration
    }
    timer_group_enable_alarm_in_isr(TIMER_GROUP_0, TIMER_0);
  }
  if (int_st_timers & TIMG_T1_INT_ST) {
    timer_group_clr_intr_status_in_isr(TIMER_GROUP_0, TIMER_1); // Clear interrupt
    digitalWrite(PUMP_PIN, (pumpState = !pumpState));
    //digitalWrite(FAN_PIN, pumpState);
    if (pumpState == LOW){
      updateTimer(TIMER_1, 20*60); // Off duration
    }else if(lightState = HIGH){
      updateTimer(TIMER_1, 2*60); // On duration when lights are on
    }else{
      updateTimer(TIMER_1, 1*60); // On duration when lights are off
```

```
        }
        timer_group_enable_alarm_in_isr(TIMER_GROUP_0, TIMER_1);
    }
}
void setup_timer(timer_idx_t timer_num, int seconds) {
    timer_config_t config = {
        .alarm_en = TIMER_ALARM_EN,
        .counter_en = TIMER_PAUSE,
        .intr_type = TIMER_INTR_LEVEL,
        .counter_dir = TIMER_COUNT_UP,
        .auto_reload = TIMER_AUTORELOAD_EN,
        .divider = 80 // 80 MHz / 80 = 1 MHz, i.e. 1 tick per microsecond
    };
    timer_init(TIMER_GROUP_0, timer_num, &config);
    // Set alarm value for 4 hours (14400000 milliseconds) = 14400000000ULL
    // 15 seconds = 15000000ULL
    timer_set_alarm_value(TIMER_GROUP_0, timer_num, seconds*1000000ULL);
    timer_enable_intr(TIMER_GROUP_0, timer_num);
    timer_isr_register(TIMER_GROUP_0, timer_num, timer_group0_isr, NULL,
ESP_INTR_FLAG_IRAM, NULL);
    timer_start(TIMER_GROUP_0, timer_num);
}
void updateTimer(timer_idx_t timer_num, int seconds) {
  // Ensure minutes > 0 && minutes < 1440
  // Assuming your timer counts in microseconds
  uint64_t alarmValue = (uint64_t)seconds * 1000000;
  timer_pause(TIMER_GROUP_0, timer_num);
  timer_disable_intr(TIMER_GROUP_0, timer_num);
  timer_set_alarm_value(TIMER_GROUP_0, timer_num, alarmValue);
  timer_enable_intr(TIMER_GROUP_0, timer_num);
  timer_start(TIMER_GROUP_0, timer_num);
}
```

Figure21. Initial System Test “timer.cpp” Code

Name/part	Cost ($)
Wine Cooler	50
Microcontroller	16
PH sensor	16.88
Humidity/Temperature Sensor	6
Water Level Sensor	5.85
TDS sensor	11.8

LCD Screen	16.39
LED Strips	17.99
Pump	27.99
AC-DC Convertor	27.37
Power Cord	10.23
Buck Convertor	14.19
Buck Convertor 2	7.98
USB A Pin	2.13
Small DC Fans	8.38
Water Reservoir Tub	15
Clamps	11
Adapters	20.5
Tubing	11
Nozzle	15
Microgreens	15.03
Plant Tray	19.99
Hemp Mats	15.99
Maxi Grow	14.99
Breadboard	1.4
1st PCB	10.59
M-F Jumper Wires	3.99
PCB 2.0 Digikey Parts	21.53
PCB 2.0 LCSC Parts	30.3
PCB 2.0	21.12
Total Cost	$ 466.61
Remaining Budget	$ 33.39

Table 2. Project Total Cost

Item(s):	**Unit Price**	**Bulk Price**	**% Saved**	**Type**
Microgreens	$8.40/ounce	$4.01/ounce	52.26	Grow Material
Maxi Grow	$10.42/lb	$10.42/lb	0	Grow Material
Hemp Mats	$0.54/mat	$0.38/mat	29.63	Grow Material

Plant Trays	$4.00/tray	$3.00/tray	25.00	Grow Material
Water Reservoir	$15.00/tub	$15.00/tub	0	Enclosure Sys
Tubing	$11/set	$11/set	0	Enclosure Sys
Clamps	$11/box	$11/box	0	Enclosure Sys
Nozzle	$4.67/each	$4.67/each	0	Enclosure Sys
Enclosure	$50.00/each	$50.00/each	0	Enclosure Sys
Pump	$32.99/pump	$32.99/pump	0	Enclosure Sys
LED	$4.75/LED	$4.75/LED	0	Enclosure Sys
PCB	$0.40/each	$0.65/each	-38.46	PCB
Screw Pins	$0.21/each	$0.11/each	47.62	LCSC
Jumper Pins	$0.02/each	$0.01/each	50.00	LCSC
Mini Buck	$0.14/each	$0.07/each	50.00	LCSC
TDS	$11.8/each	$11.8/each	0	Digikey
Microcontroller	$8.00/each	$8.00/each	0	Digikey
Water sensor	$1.95/each	$1.56/each	20	Adafruit
Temp/humidity	$2.00/each	$2.00/each	0	Sensor
Ph-sensor	$16.88/each	$16.88/each	0	Sensor
LCD Screen	$16.39/each	$16.39/each	0	Display screen
PCB Components	$21.53	$4.52	79	PCB

Table 2. Unit vs Bulk Price for Project Items

Simplified User Manual for Leafy-Link:

1) Place the Leafy-Link enclosure in your desired location near an outlet.
2) Place hemp mats onto growth tray, and put desired microgreens onto the medium.
3) Fill up water reservoir halfway with water and mix in the specified amount of nutrients.
4) Place sensors on the bottom rack of the enclosure inside the water reservoir.
5) Shut the enclosure door and plug in the cord to the nearest GFCI receptacle.
6) Use the LCD touchscreen to select microgreen or custom settings.
    a) Alternatively use “user.h” file to select plant
7) Check on Leafy-Link once a week for notifications
    - Water level notification: refill water reservoir with proper solution
    - TDS/pH notification: check water reservoir and refill if solution seems off
    - Estimated Maturity Notification: remove microgreens and enjoy
    - If other errors arise contact Leafy-Link supplier
8) Start a new cycle by returning to step 2.