FINAL REPORT

MicroClimate

Maintaining Optimal Vapor Pressure Deficit in a Closed Area

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Introduction

MicroClimate is a system that controls the vapor pressure deficit (VPD) of a closed environment using off-the-shelf heaters and humidifiers. VPD is a measure of how much water the air can hold versus how much water the air is actually holding and is crucial for optimizing plant growth. VPD can be calculated from just the temperature and relative humidity of the air; the equation is as follows [1]:

$$VPD = vp_{\text{sat}} \times (1 - \text{relative humidity}/100)$$

Where:

vp_{sat} is the saturation vapor pressure in PSI, $vp_{\text{sat}} = e^{A/T + B + CT + DT^2 + ET^3 + F \ln T}$,

A = – 1.0440397 × 10^4 , B = – 11.29465, C = – 2.7022355 × 10^–2,

D = 1.289036 × 10^–5,E = – 2.4780681 × 10^–9 ,

F = 6.5459673, and T = T[° F] + 459.67.

Just the same way humans have a comfortable temperature and humidity, so do plants. When grown in this window other inputs such as light, water, and nutrients are maximized, creating a healthier and more efficient crop. MicroClimate aims to bring commercial level automation to the hobbyist and scientific grower alike at an affordable cost without much loss in precision. It allows the user to set a target temperature and humidity, polls the environment for its current state, and toggles power to heaters and humidifiers to ensure this target is maintained.

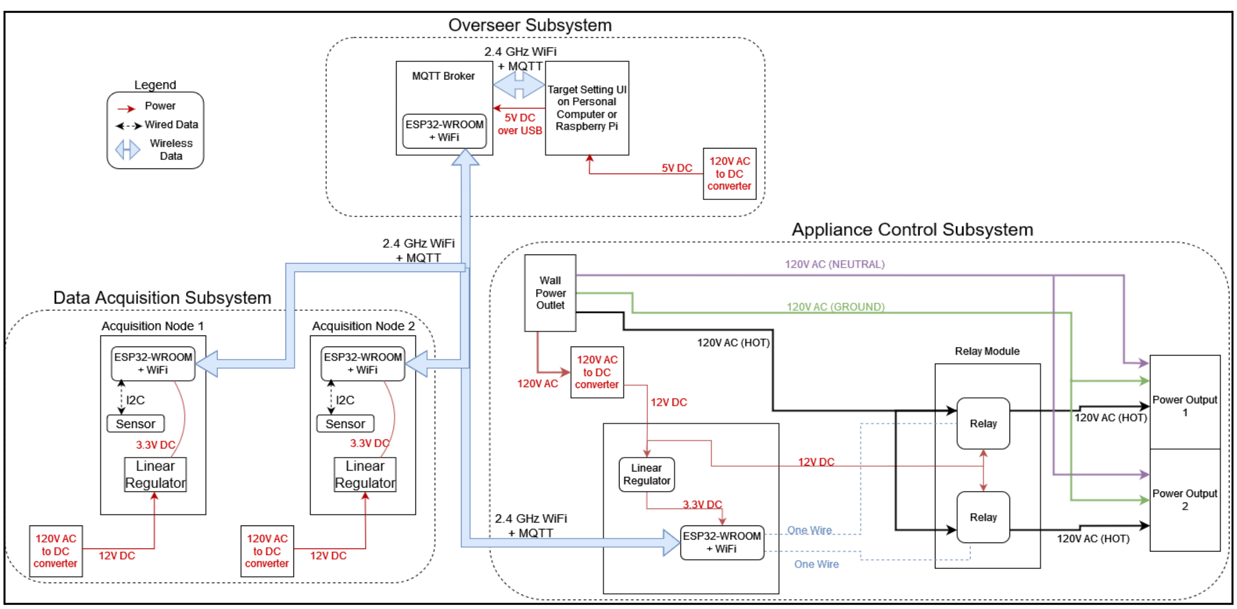

Figure 1: The Block Diagram of MicroClimate

Above is the block diagram of MicroClimate [Figure 1.1]. This system consists of three main subsystems: the Data Acquisition Subsystem, the Overseer Subsystem, and the Appliance Control Subsystem.

Functional Overview

A basic functional overview of the MicroClimate system is as follows:

1. The Data Acquisition node is placed inside the closed growing environment with the sensor at plant canopy level, the height at which most leaves reside. This node senses the temperature and humidity of the environment and communicates this information wirelessly over WiFi + MQTT to the Overseer subsystem.
2. The Overseer, which consists of an MQTT broker/client combination and a network-accessible user interface, records the values it receives from the Data Acquisition subsystem. Using a bang-bang control system, the Overseer compares these sensed values to the target values submitted by the user. There are three cases for this calculation:
   a. If the current values are significantly less than the target values, a control signal “On” is computed for the respective appliance.
   b. Similarly, if the current environment value significantly exceeds the target value, a control signal “Off” is computed.
   c. If the current environment is very similar to the target environment, the previously computed control signal is kept.

   This information is wirelessly submitted to the Appliance Control subsystem using WiFi + MQTT.
3. The Appliance Control subsystem acts as a smart power strip which can enable and disable power to 120V AC outlets using relays and low-voltage logic signals. Each one of these outlets is assigned an actuator, either a heater or humidifier. Depending on the control signals received from the Overseer subsystem, these outlets are either provided or cut off from the wall power, effectively turning the device plugged into them on or off. The power status of these outlets are wirelessly communicated back to the Overseer via WiFi + MQTT.

This system is basic in operation but powerful in control potential. MicroClimate has a robust foundation that is designed to easily be built upon. As climate change drives more and more extreme weather indoor cultivation and its consistency may be increasingly relied on. This system can aid in performing research for indoor cultivation as its small scale allows for many trials to be run in the same footprint as one greenhouse, while also saving energy inputs as less unused air is treated. The block diagrams for each subsystem can be seen in Appendix B.

System Performance Requirements

1. User interface shows the environment's temperature and humidity, and actuators' status. Target values for environment temperature and humidity are able to be set manually through a user interface.
2. After reaching a set environment target, for 95% of the time MicroClimate is running, the temperature and humidity of our closed environment must stay +/- 3 degrees Fahrenheit and +/- 4% relative humidity of our target values.
3. Overall system latency is appropriate for the timescale of cultivation:
    A. The Appliance Control subsystem responds to changes in control information, published by the Overseer subsystem,within 30 seconds 95% of the time.
    B. The Overseer subsystem computes a control systems instruction and publishes it in response to Data Acquisition's published environmental data within 30 seconds 95% of the time.
    C. Overall, the appliances are toggled on or off due to a sensed change in environmental status that is of magnitude to warrant a control change (+/- 3 degrees Fahrenheit and +/- 4% relative humidity) within 60 seconds 95% of the time

Performance Requirements for Data Acquisition Subsystem:

1. Must sample the environment at a rate greater than 3 samples/minute.
2. Must sample the temperature and humidity of the environment with an accuracy within 5% of real values.
3. Must send recorded temperature and humidity data to Overseer Subsystem with MQTT within 60 seconds 95% of the time, and less than 5% of transfers missed.

Performance Requirements for Overseer Subsystem:

1. User Interface on PC sends updates of new user-inputted targets to the broker within 30 seconds 95% of the time.
2. The User Interface receives the correct sensor readings from the Data Acquisition subsystem within 30 seconds of the Data Acquisition publish 95% of the time.
3. The broker computes and publishes the correct control instruction within 60 seconds of the Data Acquisition published topic update.

Performance Requirements for Appliance Control Subsystem:

1. Must be able to enable or disable output power to an outlet, allowing 120VAC +/- 5% VAC to pass through.
2. Must provide power to allow appliances to work at full capacity, output power must be within 5% of full capacity power as measured from the wall.

3. Must use control signals from Overseer subsystem using WiFi and MQTT protocol to set enable or disable outlets. This must occur within 30 seconds of control topic updated with less than 5% of control signals missed.
4. Must send output status signals at a rate greater than 3 times/minute with less than 5% of status signals transfers missed.

Block-Level Changes

The Data Acquisition node went through some changes from design to deployment. The main difference is the number of nodes being used. Originally two nodes were to be assembled for this subsystem and they would collect data independently of each other and relay that information to the Overseer. While our design still allows for two (or even more) nodes, we only implemented one for a few reasons. Time constraints and operational failures that led to the destruction of a Data Acquisition PCB set us back moments before demo and the assembly of only one Data Acquisition node was found to be the best course of action.

Within the user interface, we originally wanted the user to input a VPD target and have the system intelligently choose temperature and humidity targets that best reach the VPD with minimal power consumption. The design condensed and in the final iteration there are just temperature and humidity targets. While this feature is now missing, it can easily be added on top of the current systems as all it would do is choose temperature and humidity targets intelligently, perhaps through a python script on the user interface PC. Keeping room for additional features like this was integral to the system-level design of MicroClimate.

Originally, the Overseer subsystem had a wired design between its two components, the Raspberry Pi and the broker, with communication happening via UART or SPI. We planned on having the Raspberry Pi host a web server that users could connect to to update their environment targets. However, during the development phase, we discovered that utilizing wireless communication would both provide greater convenience and not impact latency significantly enough to justify the use of a wired connection. Thus, we decided that communication within the overseer should be done via MQTT[2].

Design

Design Procedure

Data Acquisition Subsystem

The Data Acquisition subsystem was designed with wired power and wireless communication. This was chosen to allow for flexible placement of the node and sensor probe within the growing tent relative to the Overseer. Most grow tents are under 8’-8’ so a power cord length of 3 feet plus a probe cable length of 3 feet allows for a node to have its power cable reach outside the tent while still allowing for free placement. A 12V power passthrough was also implemented into the design of the Data Acquisition nodes, reducing these spacing constraints even further. There is potential for battery-based nodes as well, but recharging these nodes requires human intervention and is not preferred.

Overseer Subsystem

For the Overseer subsystem, we wanted a microcontroller capable of being an MQTT broker and host, with our subsystems being clients. We chose the ESP32WROOM [3] as our microcontroller for our broker because it included both WiFi and Bluetooth connectivity and we were considering wireless data transfer for our overseer subsystem. Furthermore, the ESP32WROOM is fully compatible with code meant for the ESP32 microcontroller, the more popular microcontroller. This meant we could use the open-source code meant for a more popular microcontroller to aid in wireless data transfer. We also wanted an interface that allowed users to input temperature and humidity targets, view the current temperature and humidity of their environment, and view the status of their appliances. As mentioned prior, we discussed having a Raspberry Pi that hosted a website where users could view their environment data. However, for convenience, we opted to use a Python program that would display a user interface and communicate with our other subsystems via MQTT.

Design Equations and Tools: Control System

A major design equation that we utilized was a control systems algorithm that ran on our broker microcontroller in the overseer subsystem. Specifically, we utilized a simple bang-bang control systems algorithm, where control output is switched from one output to another when the input measurement crosses a predetermined boundary. Given the current temperature(ct), current humidity(ch), temperature target(tt), humidity target(ht), and predetermined thresholds for temperature and humidity(we used tv=1.5℉ and hv=2% rh), the algorithm was implemented as follows:

1. if *ct* < *tt* - *tv*, turn the heater on
2. if *ct* > *tt* - *tv*, turn the heater off
3. otherwise, keep executing previous instruction

This same algorithm was then repeated for the humidity measurements. These instructions were then both sent to our appliance control subsystem.

Design Details

Data Acquisition Subsystem

The Data Acquisition subsystem consists of one or more nodes that sense the environment and relay that information to the Overseer subsystem wirelessly over MQTT+WiFi. We use an ESP32-WROOM-S3 microcontroller with 2 cores, 240 mHz processor frequency, and built-in WiFi antenna. This compact, easy-to-use SoC allows for rapid development of networked technologies at an affordable cost, with a significant amount of power. When bringing up this board, the appropriate passives, programming switches, and debugging headers were added to the schematic, figure x.

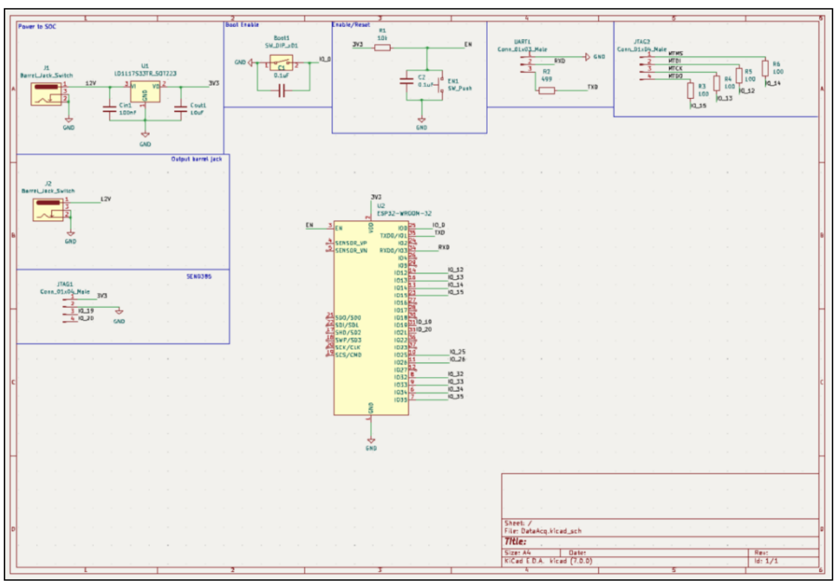

Figure 2: Data Acquisition Schematic.

To power the MCU, a 120VAC to 12VDC wall wart was used in conjunction with a barrel jack. A second barrel jack is connected to the first and acts as a passthrough for 12V power to other nodes, whether it be more Data Acquisition nodes or other future devices. To step down the power from 12V to the MCU's preferred 3.3V a linear regulator with automatic shutdown in the case of extreme temperature was employed. To see how these components were physically laid out on the PCB, see figure x.

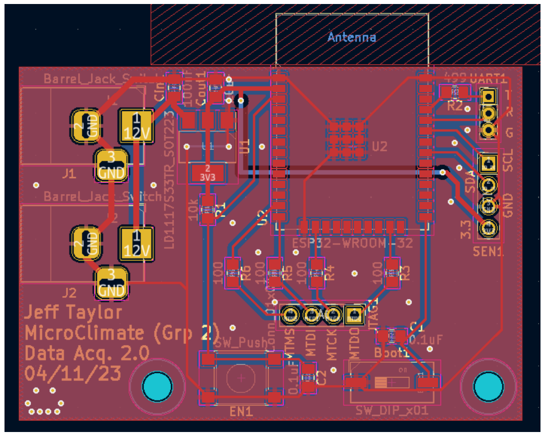

Figure 3: Data Acquisition PCB Layout

The eyes and ears of Data Acquisition nodes is the DFRobot_SHT3x temperature and relative humidity sensor. The sensor itself comes inside an enclosure at the end of a 1 meter long cable, allowing for flexible placement within the growing environment. The SHT3x chip is I2C based [4] and as such SCL and SDA headers were placed on the PCB and routed to the MCU. Configuration of the pins used on the MCU for these two lines occurred via software.

Overseer Subsystem

The overseer subsystem sits at the heart of MicroClimate and consists of the broker and a user interface. Since it is an MQTT broker, the broker is responsible for facilitating the wireless data transfer among the three subsystems. It is also responsible for computing a control systems algorithm with data it receives and sending an instruction to the appliances. The overseer subsystem also consists of a user interface, which was discussed previously.

Since the overseer subsystem did not require a PCB, we will use this opportunity to go more in depth about the software that brings the overseer subsystem to life. To start, we initialize an MQTT host on the ESP32WROOM microcontroller that we call the broker. We utilized a software library called TinyMQTT [5] to initialize the broker as an MQTT broker or host. All other microcontrollers for the other subsystems were initialized as clients to this host.

MQTT works on a publish/subscribe basis. Once connected to the broker, nodes on the broker's network write to topics(publish), and recipient nodes read from those topics(subscribe). To facilitate communication, we created topics based on the data we wanted to communicate, and had one subsystem publish and another subscribe to those topics. For example, when we were working on sending sensor data from data acquisition nodes to the broker, we had data acquisition publish to the following topics every 10 seconds: :"*data_acq/node0/temp*" "*data_acq/node0/rh*", "*data_acq/node1/temp*", and so on. We then subscribed the broker to these topics and populated local variables when new data was sent. We followed something similar for any other data transfer we did. Ultimately, this created a network of communication through the broker via MQTT.

Appliance Control Subsystem

The Appliance Control subsystem enables/disables output power to our outlets and appliances, which it does by toggling on relays that allow current to flow through on an enable signal. These control signals are sent by the Overseer subsystem over MQTT + WiFi. The appliance control node runs off of a PCB that has a ESP32-WROOM-S3 SOC, which has an ESP32-WROOM chip along with built-in networking compatibility. This allowed us to develop our code in a simpler fashion on a more compact and lower energy board. The PCB had two functions: route 12VDC power to the relays and retrieve control signals from the Overseer over WiFi (and send the low-voltage enable signal to the relays). The specific passives, headers required for power transfer, programming peripherals, and other parts required for the PCB can be found in the schematic in figure x and the pcb design in figure y.

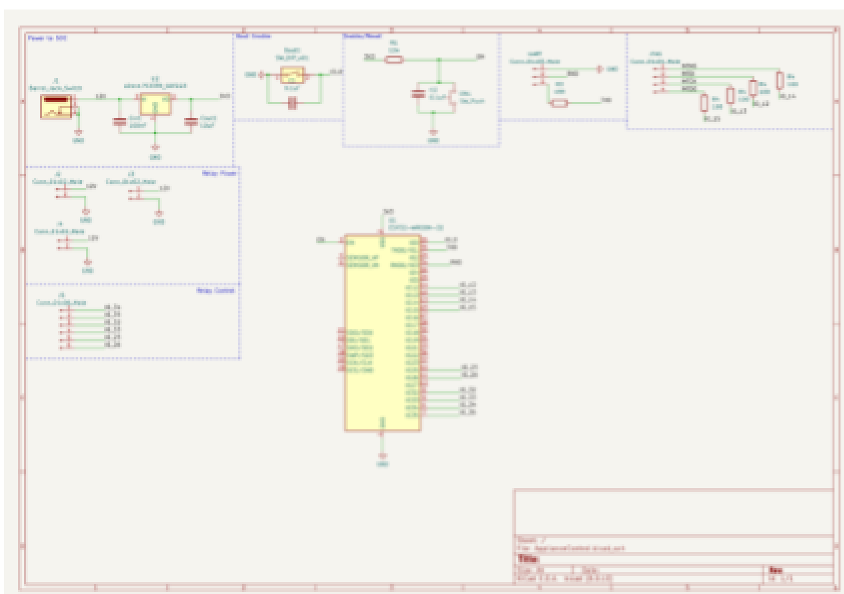

Figure 4: Appliance Control Schematic

For our relays we chose the Omron G5LE [7] and a Pololu Basic 2-Channel SPDT Relay Carrier [8] to place the relays on. We chose the Omron G5LE as it had an operating power of 12V, which is what our PCB took in as power, and provided a maximum switching voltage of 250 VAC, more than enough for dealing with wall power. These relays also switched with 3.3VDC which is the output voltage on the pins of the SOC. We also chose to have a purchased PCB for the relays to sit on for an added safety feature since we are not experienced with dealing with high voltage. These relays switched the HOT wire of the input power with the enable signal from the ESP32-WROOM-S3.

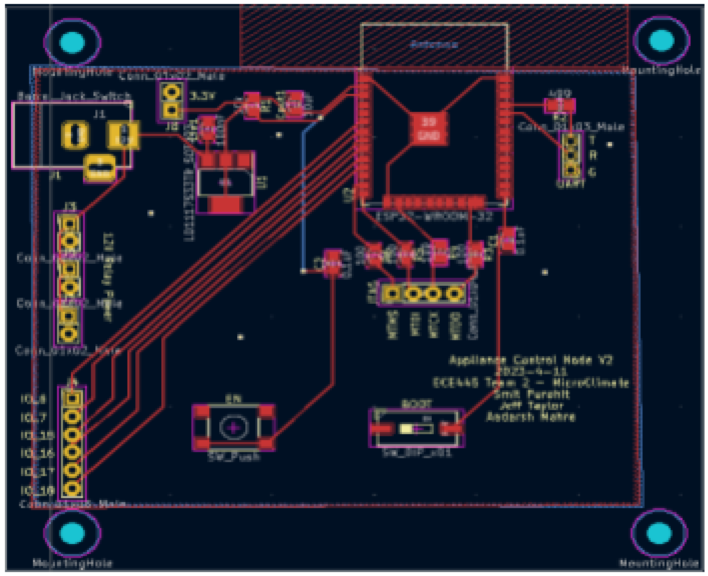

Figure 5: Appliance Control PCB

Power to the node for the relays and the board came from a AC-12VDC converter that plugged into a barrel jack and provided power to the relays in addition to power to the SOC after being stepped down using a linear regulator. The ESP32-WROOM-S3 requires 3.3V for power so the LD1117S33CTR [6] linear regulator was used, which turned the 12VAC to 3.3VDC while maintaining the current necessary for the SOC.

Verification

Verification of High Level Requirements

High Level Requirement 1

User interface shows the environment's temperature and humidity, and actuators' status. Target values for environment temperature and humidity are able to be set manually through a user interface.

This high-level requirement is qualitative in nature and describes the basic user functionality of MicroClimate. As seen in the image below, the user interface can receive updates on current sensed environmental conditions at the same frequency as the rest of the system and receives status information from the appliances. There are UI elements for setting temperature and humidity setpoints, and when updated, will modify the heating and humidifying outputs of the system to best meet the environment targets.

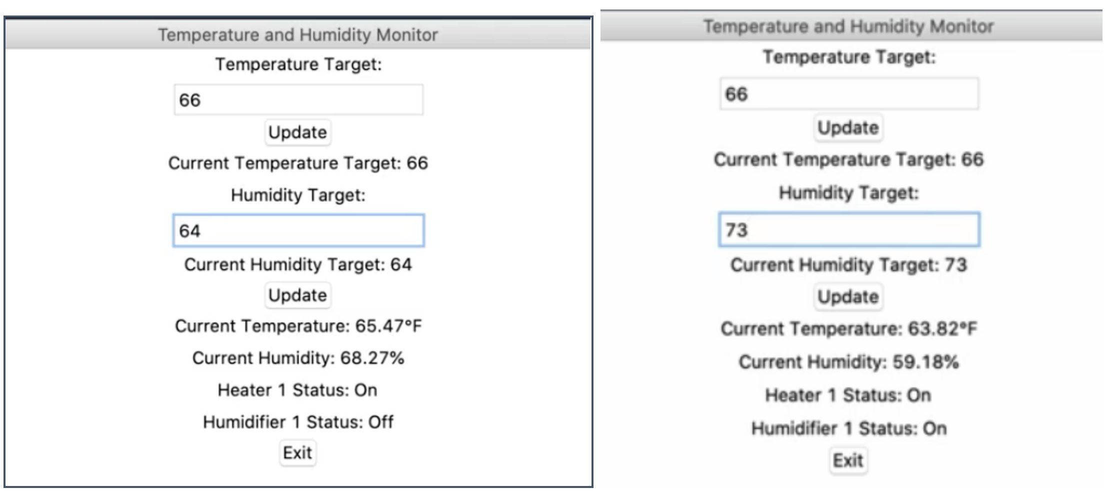

Figure 6: UI state at 2 different points in operation.

When looking at Figure 6, note the changing temperature and humidity targets that are dependent on user input. Also, comparing the current humidity and humidity targets between the two, it is apparent that the system disables power to the humidifier if the current humidity exceeds the humidity target by a fixed amount.

High Level Requirement 2

After reaching a set environment target, for 95% of the time MicroClimate is running, the temperature and humidity of our closed environment must stay +/- 3 degrees Fahrenheit and +/- 4% relative humidity of our target values.

This requirement is a core pillar of MicroClimate as the system as a whole aims to to maintain a set environment. To verify that we met this requirement, we used the UI to set target values for the temperature and humidity and measured the internal conditions in the grow tent using an off-the-shelf hygrometer. Figure x demonstrates these condition measurements when the temperature target is set to 62° F and the Relative Humidity target is set to 64%. The blue line is the measured temperature and humidity while the red lines represent the thresholds or the "error" that the system must maintain within. Both the graphs have a small moment of time where the target variable is outside the threshold which fits the requirement of the system maintaining an environment for 95% of operation time. The exact measured values can be seen in Appendix A, Section I.B.

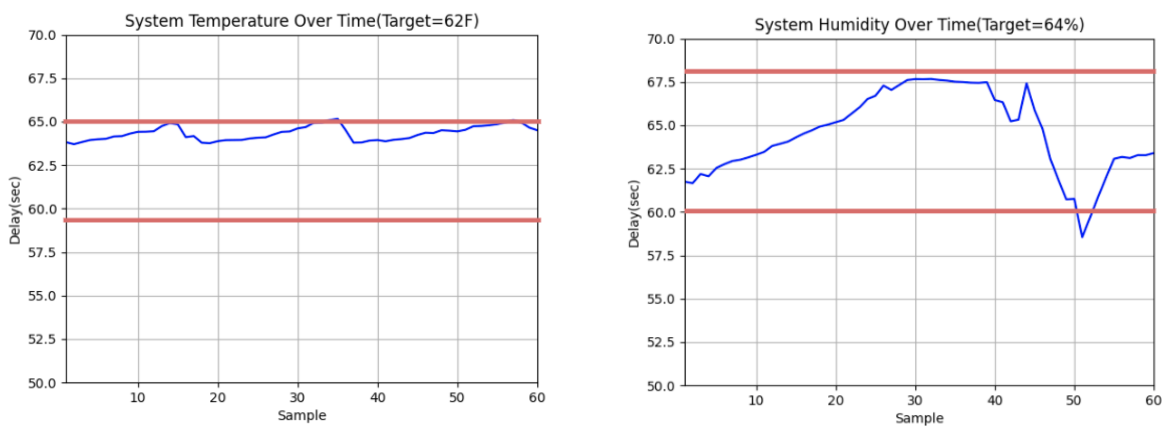

Figure 7: System Temperature and Humidity Over Time

High Level Requirement 3

Overall system latency is appropriate for the timescale of cultivation:

A. *The Appliance Control subsystem responds to changes in control information, published by the Overseer subsystem,within 30 seconds 95% of the time.*

This requirement was verified by determining the time of new target values being published from the user interface and the time of these values being received by the appliance control subsystem. The difference was then calculated as the total delay. This was repeated for a total of 10 samples, as seen in the below figure.

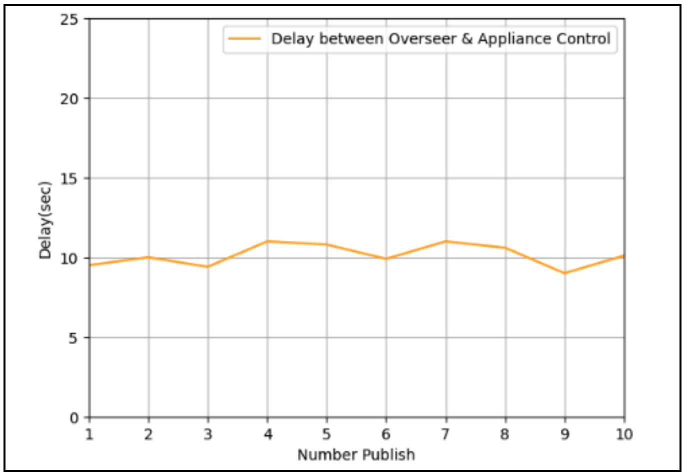

Figure 8: Publish to Receipt Delay between Overseer and Appliance Control Subsystems

B. *The Overseer subsystem computes a control systems instruction and publishes it in response to Data Acquisition's published environmental data within 30 seconds 95% of the time.*

This requirement was verified by determining the time of new sensor readings being published from the data acquisition subsystem and the time of these values being received by the overseer subsystem. The difference was then calculated as the total delay. This was repeated for a total of 10 samples, as seen in the below figure.

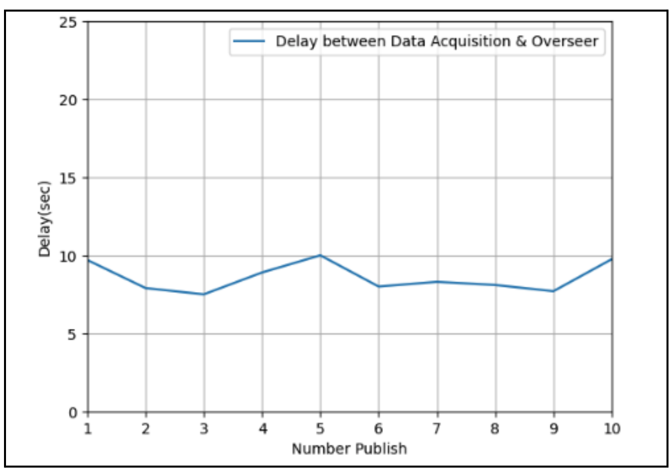

Figure 9: Publish to Receipt Delay between Data Acquisition and Overseer Subsystems

C. *Overall, the appliances are toggled on or off due to a sensed change in environmental status that is of magnitude to warrant a control change (+/- 3 degrees Fahrenheit and +/- 4% relative humidity) within 60 seconds 95% of the time.*

This requirement was verified by adding the time of new sensor readings being published from the data acquisition subsystem and the time of these values being received by the overseer subsystem and the time of new target values being published from the user interface and the time of these values being received by the appliance control subsystem . This was repeated for a total of 10 samples, as seen in the below figure.

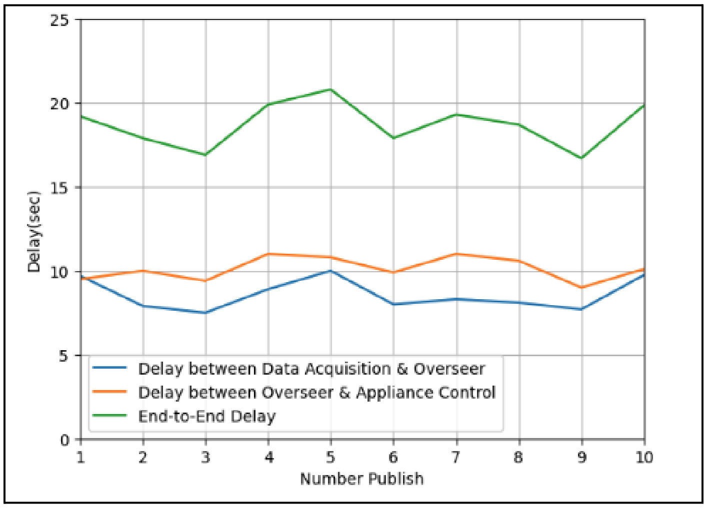

Figure 10: End-to-End Publish to Receipt Delay Subsystems

Table is shown for all delay values in Appendix A.I.

Verification of Subsystem Requirements

See Appendix A for copies of all requirements and verification tables. Below, the methodology and reasoning behind the requirements and verifications will be discussed per subsystem.

Data Acquisition R&V

There are two main pillars of the Data Acquisition subsystem that are required for a functional system: accuracy and latency. The sensor must gather quality, accurate data so we can know that when the system reports a certain temperature it is actually the temperature being experienced. To satisfy this requirement, the temperature/humidity probe was placed in a sealed tupperware container with a hygrometer, a device that simply measures temperature and relative humidity. The tupperware was left covered for 24 hours, during which time I would take periodic samples of the probe recorded values and hygrometer recorded values.

The Data Acquisition nodes must relay current information to the Overseer in a timely manner and at a consistent rate. The faster this rate is, the more data the system and user will have to analyze in the future. As plants generally take longer to respond to changes in environment conditions than humans, a minimum required period of information communication is once every 20 seconds, with sent values being received within 30 seconds of delivery. To test this, the max rate of the DFRobot_SHT3x sensor was determined to be 1 second, which exceeds requirements. To test the latency, we measured the difference in the time that the Data Acquisition node sent information and the time the Overseer received it. This had an average of under 10 seconds.

Overseer R&V

For the overseer subsystem, latency was a priority. The accuracy and timing of messages sent and received between subsystems could make or break our system. Our requirements and verification for this subsystem reflected this emphasis on latency. These requirements and verification can be seen on Appendix II.

Appliance Control R&V

The appliance control node must have the ability to (a) enable/disable output power based on control signals received from the Overseer and (b) ensure the output power, current, and voltage are all the same as if the appliance was plugged into the wall. When a control signal is sent to enable or disable a specific outlet, the appliance control node must send the low-voltage control signal to the relays within 30 seconds while missing no less than 5% of messages. In order to test this and ensure the requirement is fulfilled, we sent multiple on/off signals to the appliance control node every 10 seconds and measured the output using a Kill-A-Watt [9] to see if it matched with the expected status of the output.

Verifying that the node was able to output the correct amount of voltage, current, and power was quite straight forward. Essentially, we want to verify that from the perspective of the appliance, there is no difference whether it is plugged into the wall or the appliance control node. We first plugged each appliance into our Kill-A-Watt and plugged the Kill-A-Watt into the wall. After turning on the appliance and waiting ~5 minutes to make sure they get warmed up, we measured the current draw, voltage, and power draw using the Kill-A-Watt. We then set both outlets to be enabled and followed the same methodology to verify that the values are within 5% of the values measured from the wall. Data for verifying the Appliance Control requirements can be found in Appendix A, Section 4.A.

Costs

Labor Costs

($/hour) x 2.5 x hours to complete = TOTAL
90k/year -> $43.27/hr
Aadarsh Mahra: $43.27/hr x 2.5 x 50 hours = $5,408.75
Jeffrey Taylor: $43.27/hr x 2.5 x 50 hours = $5,408.75
Smit Purohit: $43.27/hr x 2.5 x 50 hours = $5,408.75

TOTAL COST OF LABOR = $16,226.25

Component Costs

Table 4: Component Description and Cost

Item	Manufacturer	Quantity	Cost
ESP32-S3-WROOM-1-N4R8	Espressif	6	$3.69
SEN0385	DFRobot	2	$19.90
2-Channel Relay Carrier with 12VDC Relays	Pololu	2	$9.49
Raspberry Pi 3	Raspberry Pi	1	$35.00
CP2102 Programmer	IZOKEE	1	$8.99
LD1117S33CTR Voltage Regulator	STM	6	$0.66
VEL12US120-US-JA DC power supply	XP Power	2	$12.71
54-00166 2.1mm barrel jack	Tensility International Corporation	6	$0.74
10-03921 Plug to Plug cable	Tensility International Corporation	2	$6.79
Commercial Grade Tamper-Resistant	Pass & Seymour	4	$3.48

Single Outlet			
20-Amp Self-Test GFCI Outlet Ivory	Smart Electrician	1	$14.99
7301K113 Electronics Washdown Enclosure	McMaster-Carr	2	$9.90
PCB Components (Capacitors, resistors, headers, cables/wires)	n/a	n/a	$35.00
Extension Cord	Menards	1	$24.99
Appliance Control Enclosure	Menards	1	$7.89

Total Cost of Components = $ 278.9

Total Costs:

Grand Total = Cost of Labor + Cost of Components = $16,226.25 + $278.9 = **$16,505.15**

Conclusions

MicroClimate has proven to be successful in managing the temperature and humidity of a closed growing environment for extended periods of time. This system appropriately and speedily monitors, calculates, and reacts to changes in conditions to assure crops are experiencing the desired VPD to either grow optimally or endure experimentally.

This project can be extended upon by us as individuals and the community alike to feature even more data collection apparatuses or actuators to automate small-scale cultivation even further. The precision found in MicroClimate can help scientists explore how global warming will impact the crops our nation depends on to survive, and can even serve as a growing environment to test the crops of the future. As outdoor weather becomes more extreme and sustainability becomes culturally popular, MicroClimate can be a means for gardeners to bring their harvest indoors, preserving their hobby despite the conditions that exist outdoors.

Our design is fully and totally compliant with the IEEE [10] and ACM Code of Ethics [11]. Ethical, safe, and sustainable practices were put at the forefront of MicroClimate, and we ensured that each of us upheld and practiced our ethics guidelines. Per the IEEE Code of Ethics, our design is lawful and does not incorporate work by other people without proper credit. In addition, during our design process, we made sure that any decisions we made are fully and unambiguously lawful and safe. A primary ethical concern in relation to MicroClimate specifically is the possibility of harm that can come to our users or to us as a result of handling wall power. As a result, we ensured the utmost care was taken when designing our system, which included multiple safeguards such as a GFCI outlet. In order to uphold the code of ethics and ensure no harm comes to users of MicroClimate or to us, we followed all OSHA guidelines [12] for electrical safety. To further promote safety in our design, we wrote a Standard Operating Procedure which can be found in Appendix C.

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Appendix A

Tables

I. System Verification Results

A. Overall Latency Table

Data Acq -> Overseer (sec)	Overseer -> App. Control (sec)	End-to-End (sec)
9.7	9.5	19.2
7.9	10.0	17.9
7.5	9.4	16.9
8.9	11.0	19.9
10.0	10.8	20.8
8.0	9.9	17.9
8.3	11.0	19.3
8.1	10.6	18.7
7.7	9.0	16.7
9.7	10.1	19.85
Average = 7.80 sec	**Average = 9.21 sec**	**Average = 17.01 sec**

B. Environment Variables Values during System Operation

	Target	Avg. Error	% Time within 3°F, 4% RH
Temperature	62°F	3.746%	95.24%
Humidity	64 %RH	3.138%	96.83%

II. Data Acquisition Requirements and Verification Table

Requirements	Verification
1. Must sample the environment at a rate greater than 3 samples/minute. 2. Must sample the temperature and humidity of the environment with an accuracy within 5% of real values. 3. Must send recorded temperature and humidity data to Overseer Subsystem with MQTT within 60 seconds 95% of the time, and less than 5% of transfers missed.	1. Determine available sampling rates from DFRobot_SHT3x library. Measure period of sampling and ensure it is less than 20 seconds. 2. Take 10 measurements of temperature and relative humidity with the sensor and compare to off-the-shelf hygrometer sensed values. 3. Begin periodic publishing of Data Acquisition node. Send 20 environmental data measurements over MQTT to Overseer subsystem, measure the time between sent and received, and ensure sent values are the same as received values for greater than 19 of the 20 occurrences.

III. Overseer Requirements and Verification Table

Requirements	Verification
4. User interface on the PC publishes updates to the target topic(s) when users set new targets. The broker should receive these messages within 30 seconds of the publish time.	4. Publish to new targets using the user interface. Record the time at which these publishes occur. Record the time at which the broker receives the publishes to the same topics. The difference in these times should be under 60 seconds.
5. The Overseer receives the correct sensor readings from the Data Acquisition subsystem within 30 seconds of the Data Acquisition publish 95% of the time.	5. Publish fake data from the Data Acquisition MCU and record the time of publish. Then, record when the User Interface receives this data as a subscriber. The difference in these times should be under 30 seconds.
6. The Overseer computes and publishes the correct control instruction within 60 seconds of the Data Acquisition published topic update.	6. Publish fake data from the Data Acquisition MCU and record the time of publish. Then, record when the Overseer publishes an instruction to the Appliance Control subsystem. The difference between these times should be under 60 seconds.

IV. Appliance Control Requirements and Verification Table

Requirements	Verification
1. Must convert 12VDC to 3.3 VDC for powering the microcontroller within 5% of 3.3VDC. 2. Must output 12VDC at power out header, must be within 5% of 12VDC. 3. Must set 3.3VDC +/- 5% VDC and 0VDC +/- .1 VDC output signals based on received control information. 4. Each relay in the Relay Module is switched on/off within 5 seconds of receiving the respective control signal. Each relay enables and disables outlet voltage. When enabled, the voltage must be within +/- 5% of measured wall-provided VAC. When disabled the voltage must be 0 +/- 0.1 VAC.	1: Measure the voltage before and after the linear regulator, voltage output must be in the range 3.135-3.465 VDC. 2: Measure voltage at all power out headers, voltage output must be in the range 11.4-12.6 VDC. 3: Set a sample variable to 'ON' or 'OFF' on the broker and measure the voltage output at the associated GPIO pin on the microcontroller. The voltage output should be in the range 3.135- 3.465 VDC for signal 'ON' and -0.1 - 0.1 VDC for signal 'OFF'. 4A: Set the enable pin of each relay in the module to HIGH and measure time to relay switching through a continuity test of the NO (Normally Open) and COM (Common) output pins. Continuity should be achieved. Set the enable pin of each relay in the module to LOW and test the continuity of the same output pins. There should be no continuity. 4B: Using a Kill A Watt, measure the voltage present at each outlet. Toggle the enable pin to HIGH and ensure the voltage present is in the range of 114-126 VAC. Toggle the enable pin to LOW and ensure the voltage present is in the range -0.1 - 0.1 VAC.

A. Appliance Control Node data

Measured Reference Values (Measured with Kill-A-Watt)				
Wall voltage (VAC)	124.3			
Heater Power Consumption in Wall (measured after 5 min on) (W)	1333			
Humidifier Power Consumption in Wall (W)	22.2			
Measured Verifcation Values (Measured with Kill-A-Watt)				

	Expected Value	**Average Measured Value**	Deviation from Expected	**MicroClimate Acceptable Threshold**
Voltage Out from Linear Regulators (VDC)	3.3	3.322	0.67%	5%
Voltage Out at Power Headers (VDC)	12	11.898	-0.85%	5%
Voltage Out at Control Headers (VDC)	3.3	3.274	-0.79%	5%
Time to Toggle Outlet 0 after On signal sent (s)	30	1.769	-28.23	< 30
Time to Toggle Outlet 1 after On signal sent (s)	30	1.698	-28.30	< 30
Outlet 0 Voltage when Relay 0 Enable is On (VAC)	124.3	124.44	0.11%	5%
Outlet 0 Voltage when Relay 0 Enable is Off (VAC)	0	0	0.00%	5%
Outlet 1 Voltage when Relay 1 Enable is On (VAC)	124.3	124.29	-0.01%	5%
Outlet 1 Voltage when Relay 1 Enable is Off (VAC)	0	0	0.00%	5%
Heater Power Consumption in Appliance Control Node (measured after 5 min on) (W)	1333	1325	-0.60%	5%
Humidifier Power Consumption in Appliance Control Node (W)	22.2	22.3	0.45%	5%
Status Signal Misses (Control Sent, No Status received)	0	0	0.00%	5%

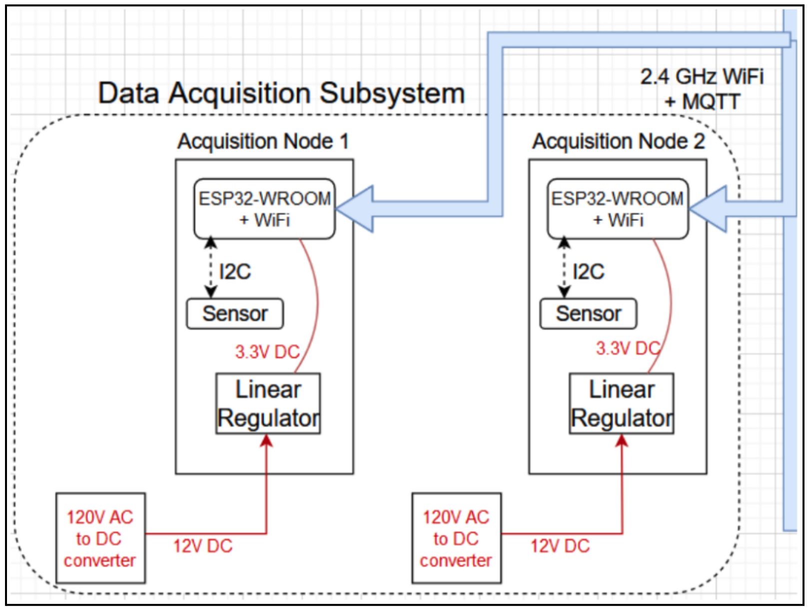
V. Low-Level Requirements and Verification Table

Component	Requirements	Verification
Enclosure	1: Prevent enclosure interior humidity from exceeding 60% at and above 70° F	1: Take internal humidity readings with a hygrometer when the enclosure is placed in a high-humidity environment.
AC/DC Adapter, Jacks, and Cord	1: Be able to provide a voltage >= 5V DC at a distance of 20 feet from 120V AC 2: Must handle maximum 1A across jacks and cord	1: Use a voltmeter to check if output voltage exceeds 5V DC over 25 feet run of wire. 2: Put a small resistive load (100mA) at the end of the circuit to test continuity and heat. Step up resistive load until target is met.

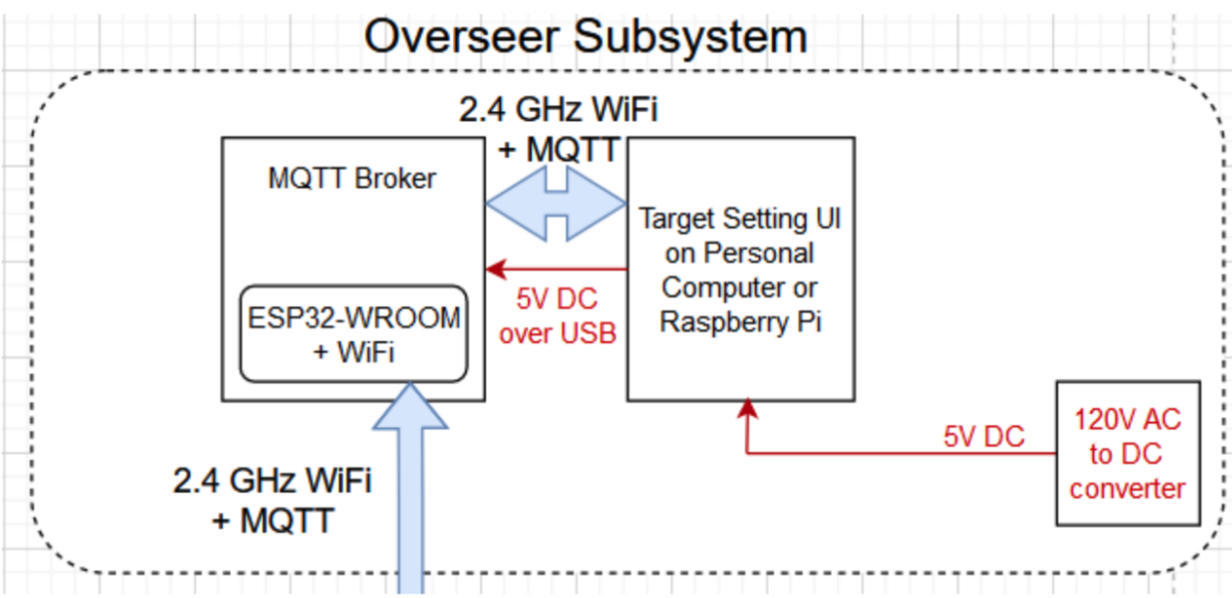
Component	Requirements	Verification
Temperature and Humidity Sensor	1: Must poll environment with accuracy of +/- 5% 2: Probes are resistant to high humidity (>85% RH) environment	1: Take 10 measurements with sensor and compare to hygrometer reading. 2: Place probes in consistent, high humidity environment for 24 hours and take periodic readings.
Microcontroller	1: Must be able to transmit data over WiFi from within tent at over 1 Mbits/S 2: Must operate on and be able to set GPIO at 3.3V +/- 5% DC	1: Send fixed size files at max speed between 2 ESP32's for 10 seconds. Measure files transmitted and divide. 2: Use a multimeter to measure GPIO outputs with logic high (3.3V) and logic low (0V) set.
Linear Regulator	1: Provide 3.3V +/- 1% from a 12V source 2: Can operate within 0-300mA 3: Maintain stability below 250° F	1: Measure the output voltage using a multimeter. 2: Use a resistive load to deliver at most 300mA through the linear regulator, and measure the output current and voltage using a multimeter. 3: During verification for requirement 1, use an IR thermometer to ensure IC stays below 250° F.

Appendix B: Subsystem Diagrams

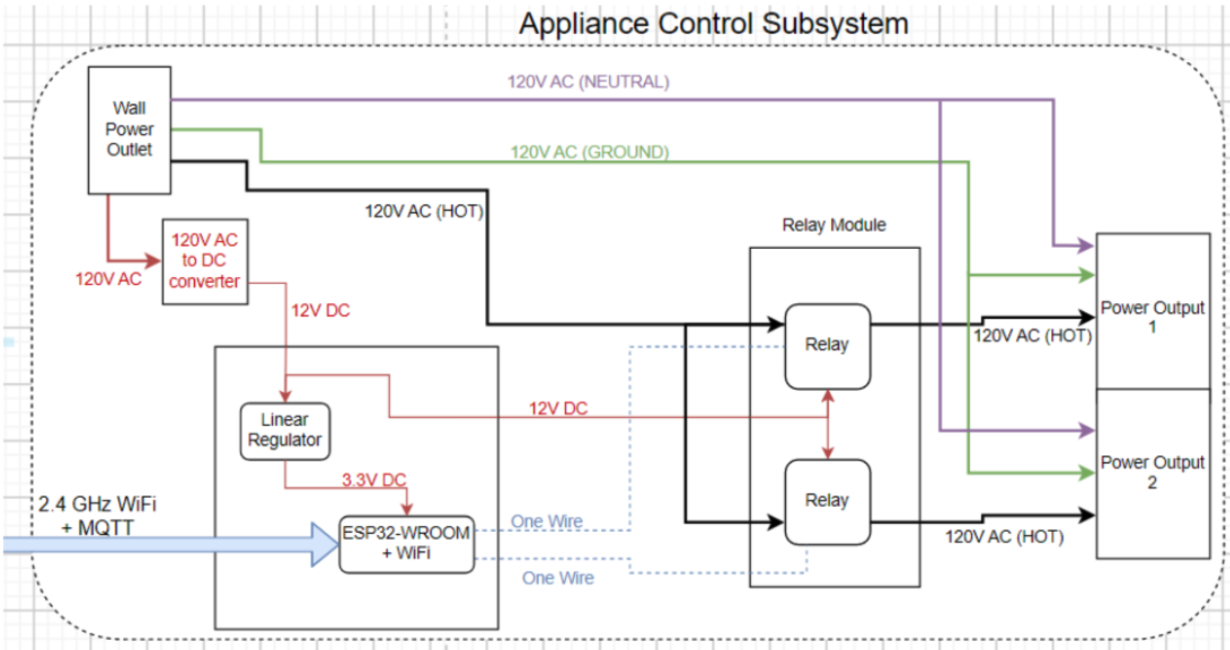
I. Data Acquisition Subsystem Block Diagram



II. Overseer Subsystem Block Diagram



III. Appliance Control Subsystem Block Diagram



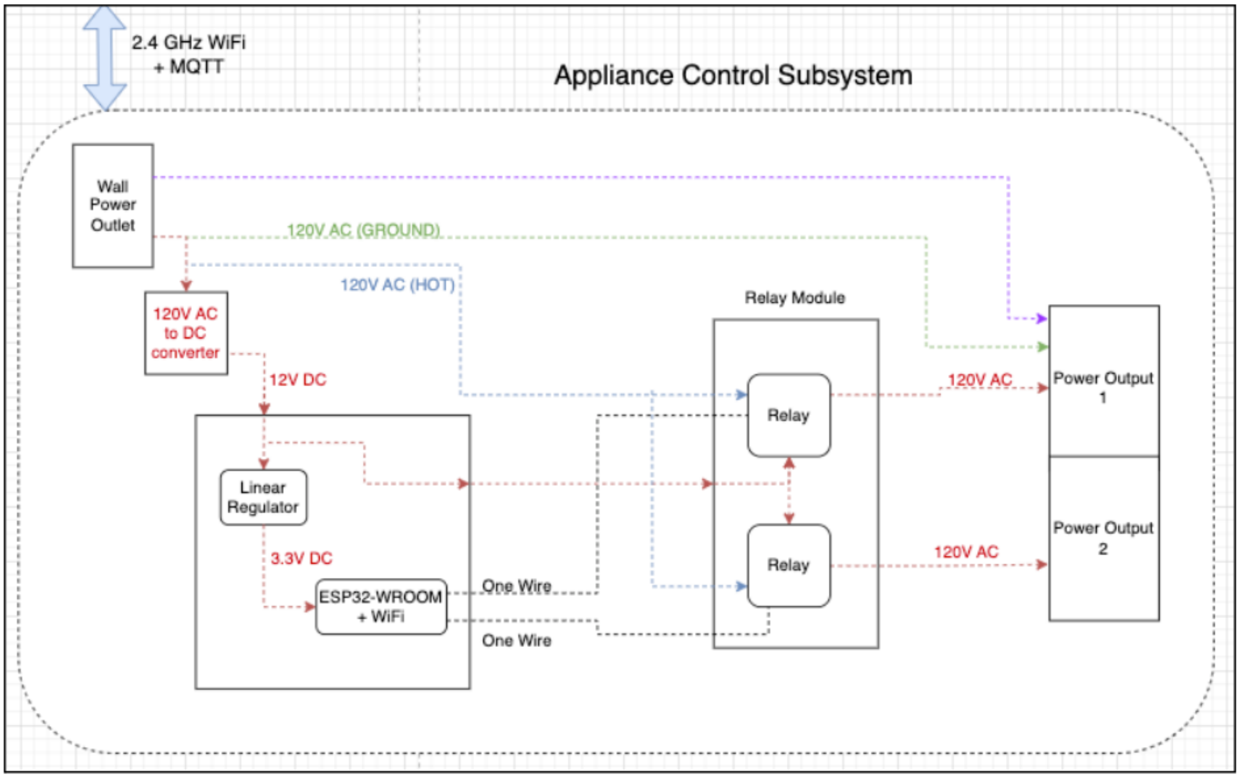
Appendix C

Standard Operating Procedure for Hazardous Electrical Procedures and/or Equipment

I. Briefly describe the project, equipment involved, and expected results of normal operation.

MicroClimate is a Vapor Pressure Deficit (VPD) management system that monitors and controls environmental variables such as temperature and humidity to maintain a certain VPD range. The Appliance Control Subsystem is of particular interest, as it interacts with 120VAC from the wall. The Appliance Control Node serves to provide controllable power to each individual appliance used to control the VPD. This node will use a microcontroller to send control signals to relays, allowing power from the wall to flow through or not flow through to the output outlet. The equipment involved are relays and the appliances we are using. In normal operation, the subsystem should send control signals to the relays and they should allow/disallow current to flow through, powering the appliances.

II. Sketch a single-line diagram of the experiment or equipment which illustrates the primary function(s) and component(s) of the system. Include text where helpful.



III. Electrical Hazard Recognition:

Provide the operating parameters of your equipment or those used during the procedure described above (under normal operation conditions).

Electrical Parameters (General):

Parameter	LOWEST	HIGHEST
VOLTAGE [V]	0	120V
CURRENT [A]	0	15A
POWER [W]	0	1500W
FREQUENCY [Hz]	0	60 Hz

Does this experiment use any custom or home-built equipment?

YES NO

Is testing (e.g., with a multimeter) performed above 50 V or 5 mA?

YES NO

Is Lockout/Tagout required for this experiment or equipment?

YES NO

UIUC Electrical Hazard Classification: Medium Risk

IV. Electrical Hazard Mitigation:

For each hazard identified on the previous page, provide steps for how the risk will be reduced. If not possible to reduce risk, explain how the risk will be managed.

HAZARD	RISK MITIGATION
120 VAC - Shock Hazard	The risk will be reduced by ensuring that when working with the components that relate to the 120 VAC, we ensure that we have tested the circuit first with lower and safer voltages. In addition, we will ensure that the component has been discharged and not plugged in for at least 5 minutes. There must be no current flowing through the system. Finally, in our design, we have incorporated safety components such as a GFCI. Since a critical part of our project relies on the 120VAC, we will be unable to fully reduce the risk but through these measures, it will be managed.

V. Additional Hazard Recognition and Mitigation:

Include pertinent information regarding additional (non-electrical) hazards associated with this procedure. Refer to the American Chemical Society's tools for hazard assessment as needed.

Chemical:

REAGENT	CONCENTRATION	QUANTITY	GHS HAZARDS

Physical / Mechanical:

HAZARD	LOCATION	MITIGATION	NECESSARY PPE

ADDITIONAL RISK MITIGATION:

For each hazard identified above, provide a narrative of how the risk will be minimized. If not possible to reduce risk, explain how the risk will be managed.

HAZARD	RISK MITIGATION

VI. Electrical Personal Protective Equipment

Is PPE required? YES NO

Required PPE**; circle all that apply:**

Eye protection

Gloves, disposable

Gloves, leather

Lab coat

Flame-resistant (blue) lab coat

Face shield

Hearing protection

Hard hat

Grounding stick/wand (negligible resistance; “soft” grounding)

Discharge stick/wand (some resistance; “hard” grounding)

VII. Other

PROCEDURAL DETAILS: Provide a specific and detailed process description. If appropriate, refer to instrument operating instructions.

Safe assembly and operation of the Appliance Control Subsystem starts with wires connecting the wall power to each relay. These wires will have the appropriate AWG per the voltage, current, and length specifications. In attaching the wires to the relays, we will ensure all power is off and there is no current flowing through the circuit. Once the relays are connected, we will test the circuit for any problems with a lower and safer voltage. After this has been checked and approved, we will only then test with the high voltage. In safe operation, the system will provide current to the relays at all times but the relays will only pass that current to the appliances when the control signal is sent. In addition, there must be no risk of fire through our design.

OUT-OF-NORMAL EVENTS: Provide a list of several points or types of failures associated with this procedure or equipment. Also include any emergency shutdown procedures.

There are several points of failure in this system. One main point of failure is the relays. If the relays stop operating at a safe level, we may get fluctuations in the switch, causing voltage swings and a possible fire and shock hazard. Another point of failure is the wiring. While all steps will be taken to ensure safe and proper wiring, the wires may come loose or become frayed. In this case, not only will the subsystem be in danger of not working, but there is a danger of shock and fire. A final point of failure is a surge from the wall outlet. This can be fixed with an emergency shutdown procedure, such as implementing a circuit breaker and a GFCI outlet.

TRAINING: Enumerate and explain the training requirements for a researcher to undertake this procedure.

1. The only training required for this procedure is the following courses on https://ovcrportal.research.illinois.edu/Training/: Laboratory Safety Training, Electrical Safety: Risk Assessment, Electrical Safety: Recommended Practices, and Electrical Safety: Fundamentals.
2. There should be no training required to operate the device

Appendix D

Abbreviations

ACM - Association for Computing Machinery

AP - Access Point

COMM - Common, in the context of a relay

I2C - Inter-Integrated Circuit; Communication Protocol

IC - Integrated Circuit

IEEE - Institute of Electrical and Electronics Engineers

MCU - Microcontroller Unit

MQTT - Message Queuing Telemetry Transport

NO - Normally Open, in the context of a relay

RH - Relative Humidity

RPI - Raspberry Pi

SOC - System on Chip

SPDT - Single Pole Double Throw

UART - Universal Asynchronous Receiver-Transmitter

VPD - Vapor Pressure Deficit

MCU - MicroController Unit