November 6, 2014

Dr. Andrew Rawicz
School of Engineering Science
Simon Fraser University
Burnaby, British Columbia
V5A 1S6

Re: ENSC 305W/440W Design Specification for the Plantmosphere, an automated greenhouse system

Dear Dr. Rawicz,

The following design specification document outlines our product's design. The Plantmosphere automated greenhouse system controls key elements for plant growth to institute food production in virtually any environment. Our gardening solution requires no prior knowledge or technical experience to operate and has been designed to work in the harsh sub-Saharan Africa climate.

The enclosed document details the low-level design for a prototype model of the Plantmosphere and justifies our chosen parts and their implementation. The document will examine both the hardware and software components of our product and provide a comprehensive test plan for each system. The design specification will serve as reference material for the development of the prototype and outline future considerations for the final product.

Plantmosphere Technologies is a team of six diverse and highly qualified engineers: Faisal Emami, Terry Hannon, Jane Horton, Alex Naylor, Jeffrey Shum, and Mike Thiem. Please feel free to contact me via email at jhorton@sfu.ca with any questions or concerns regarding our functional specification.

Sincerely,

Jane Ashley Horton
Design Engineer
Plantmosphere Technologies

Plantmosphere

Design Specifications Document

Revision: 1.0 Issue Date: 11-06-2014

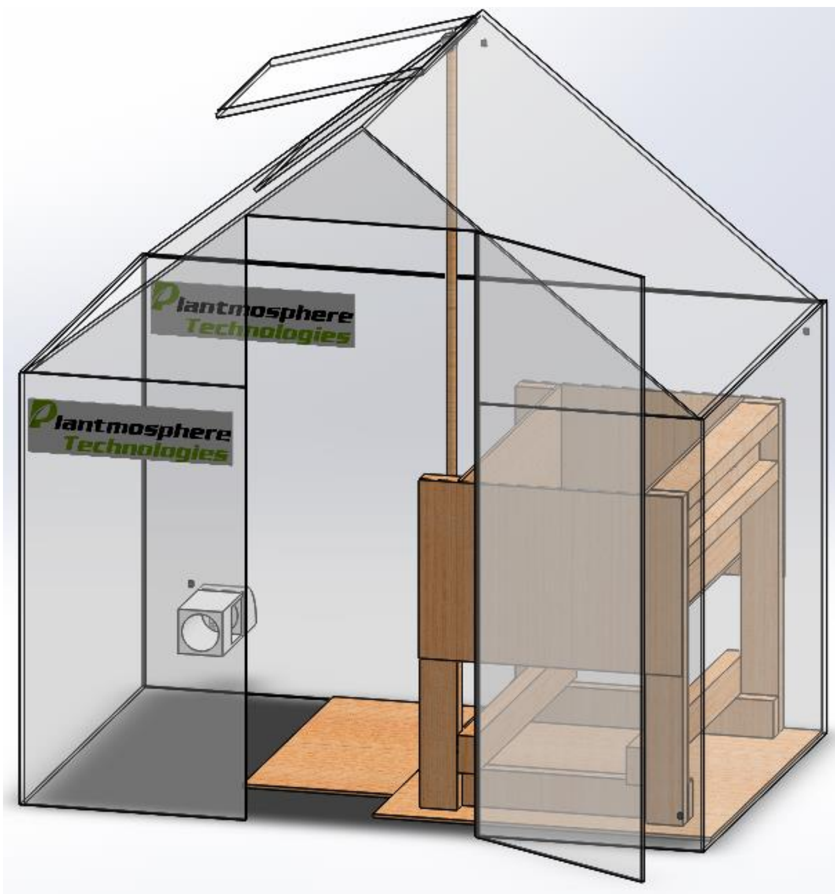

Figure 1: The Greenhouse Structure

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Glossary

Term	Definition
AC	**A**lternating **C**urrent
Air Change	The renewal of the entire volume of air within an enclosure
Allowable Lighting Time	The window of time in which the LEDs are allowed to activate by the lighting control code.
Ampacity	Ampère Capacity determined by the National Electrical Code
Apparent Solar Time	Time derived from the motion of the actual (apparent) sun
AWG	**A**merican **W**ire **G**auge
CFM	**C**ubic **F**eet per **M**inute
Circuit Breaker	Automated electrical switch used to detect and break a circuit in the event of an overload or short circuit
Class 3 Lever	Lever where force applied is between fulcrum and load
CO_2	**C**arbon **D**ioxide
DC	**D**irect **C**urrent
EC	**E**lectrical **C**onductivity at 25 degrees (dS m^{-1})
Equation of Time	The difference between the apparent solar time and mean solar time
Fertigation	The application of fertilizers to the plants through an irrigation system
GFCI	**G**round **F**ault **C**ircuit **I**nterrupt
Handbook of Electronics Tables and Formulas	A technical electronics reference
I2C	**I**nter-**I**ntegrated **C**ircuit
IDE	**I**ntegrated **D**evelopment **E**nvironment
Joule Heating	Heat produced by current moving through a conductor
LCD	**L**iquid **C**rystal **D**isplay
LED	**L**ight Emitting **D**iode
Li-ion	**Li**thium-**ion**
Mean Solar Time	Time derived from the motion of the mean sun, which travels at a constant speed equal to the mean speed of the apparent sun
NPT	**N**ational **P**ipe **T**hread
Opto-isolator	An electronic component that transfers electricity to between two circuits by using light
Photosynthesis	The process plants use to convert sunlight into usable energy
Protoboard	A circuit board for prototyping
PSU	**P**ower **S**upply **U**nit
Reed Switch	Electrical switch activated by an applied magnetic field
Relative Humidity (RH)	The amount of moisture in the air compared to the saturation level for the given air temperature (see Figure 2 for graph)
Residual Salts	When the uptake of salts is less that the addition from fertilizers or irrigation water, salts accumulate in the root zone of soils.
RoHS	**R**eduction **o**f **H**azardous **S**ubstances
RPM	**R**otations **P**er **M**inute
Salinity Threshold	The maximum EC value in the root zone without any plant yield reduction ($dS \cdot m^{-1}$)
Skin Effect	The tendency of high frequency signals to travel on the outer surface of conductors

SMD	**S**urface **M**ount **D**evice
Solar Constant	The constant energy flux density of sun rays incident upon a surface perpendicular to the rays (1.361 $kW \cdot m^{-2}$ minimum, 1.362 $kW \cdot m^{-2}$ maximum)
Stack Effect	Air movement from a temperature difference causing warmer and less dense air to rise
Stomata	Pores in the leaves of plants that allow for the intake of CO_2 and the release of O_2
Sun Declination	Angle between a ray of sunlight traced through the center of the earth and the earth's equatorial plane
Surge Protector	Circuit that absorbs extrinsic voltage spikes
T9	**T**ext on **9** keys
Transpiration	The movement of water though a plant from the uptake into the roots to the evaporation through the leaves, stems, and flowers
Uptake concentration	The ratio between the uptake of a mineral element and the water uptake by the crop ($mol \cdot l^{-1}$)
UTC	**C**oordinated **U**niversal **T**ime
Vapor Pressure Deficit	The difference in vapor pressure between different relative humidity levels at the same temperature. This value increases as temperature increases (see Figure 3 for graph)
VPD	**V**apor **P**ressure **D**eficit (kPa)

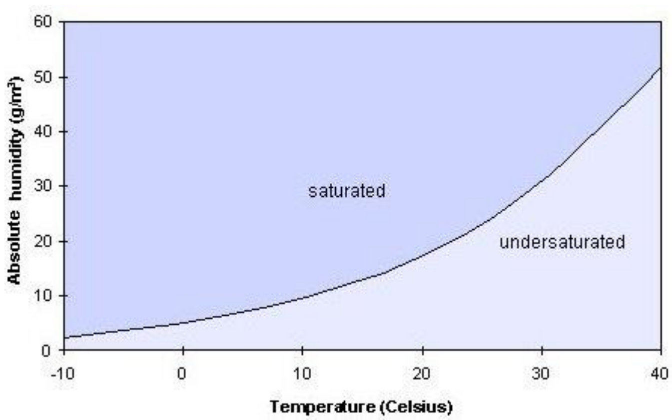


Figure 2: Humidity Saturation at different temperatures

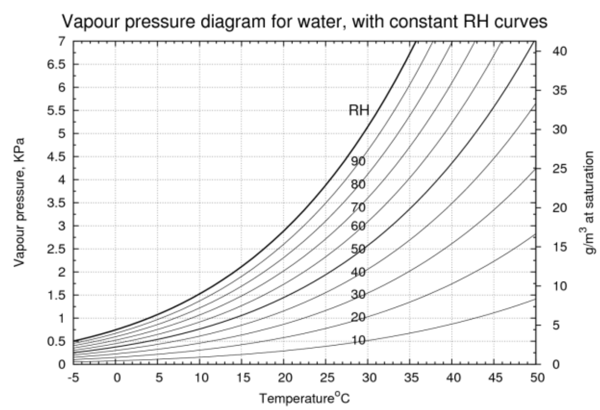


Figure 3: Relative Humidity at different temperatures

Abstract

The Plantmosphere is designed to automate the optimization of the internal greenhouse environment by controlling different factors such as air temperature, air humidity, soil temperature, soil moisture, and lighting, as well as the collection and recycling of water. Air temperature sensor readings determine the ventilation and recirculation system activation in order to optimize internal temperature and ensure proper air mixing. Air humidity sensor readings dictate the need for air misting and recirculation. Soil temperature and soil moisture sensor readings determine when to heat and water the soil respectively. A photoresistor tracks the quantity of light exposure for the plants and determines when to turn on the LEDs. The product will have an LCD along with a touchpad for user interface and control over what they want to plant. This document also contains an extensive test plan that will be applied to each of the subsystems.

1 Introduction

Food shortages are an ever-present problem in Sub-Saharan Africa. Poor agricultural education coupled with decreased productivity due to malnutrition and high imported food prices comprise a vicious cycle that hampers food growth and distribution in the region. To promote food production in Sub-Saharan Africa, Plantmosphere Technologies aims to provide a cheap, user-friendly, and sustainable gardening solution that can operate in any climate.

The Plantmosphere is a user-friendly, automated greenhouse system designed to manage a plant's environment for the duration of its growth cycle, with minimal user input. Our product's durability and focus on water recycling makes it an attractive option for the unpredictable Sub-Saharan Africa climate. The Plantmosphere's modular system design allows users to purchase optional modules that provide additional functionality, enhancing the gardening experience.

The development cycle of this project has been divided into two main phases: the first phase focuses on the critical automation systems to be incorporated in the prototype model, which include:

- Humidification
- Irrigation
- Lighting
- Soil Heating
- Ventilation
- Water Reservoir Control

The second development phase looks into the non-essential automation systems, self-sustainable power sources, and refinements for the final product.

The completion of the first phase will result in the product prototype to be demonstrated at the end of the term. The latter phase focuses heavily on self-sustainability and modularity to improve the Plantmosphere's versatility and allow it to exert more control over its environment. Both development phases will prioritize safety and standard compliance to ensure the well-being of our customers and modular compatibility of our product.

The following document provides detailed design specifications for both the software and hardware of each sub-system relative to the requirements outlined in the Plantmosphere's functional specification. Furthermore, in-depth justification will be provided for all design approaches and testing methods will be developed to analyze the overall and sub-system performance.

1.1 Scope

The following design specification document outlines our design choices, provides justification for each, and explores future product functionality. It explains the theoretical concepts guiding each subsystem's design and uses the requirements laid out in the functional specification as the foundation for meeting our goals. The document is divided into sections based on each subsystem, and examines the purpose and need of the chosen designs therein. Finally, a system test plan has been developed to evaluate the performance of each subsystem and the Plantmosphere as a whole.

1.2 Intended Audience

The audience intended to use this document includes all members of Plantmosphere Technologies and has been created as reference material to be followed during the development phase of our project. The system test plan will be used to demonstrate the product's performance to investors and business stakeholders, while the subsystem details are oriented towards more technically savvy individuals.

1.3 Background

Desertification, erosion, deforestation, and drought are issues that have affected Sub-Saharan Africa for decades, resulting in the reduction of agricultural production. The lack of food is a major cause of malnutrition and decreased productivity, and the education deficit in the region perpetuates the populace's ability to use agricultural tools effectively [1]. Our product has been designed to allow the general population to easily grow plant life in any climate. The Plantmosphere has the potential to alleviate hunger problems in the poorest of the Sub-Saharan Africa nations and promote sustainable future growth.

2 System Overview

The Plantmosphere is comprised of several subsystems which are controlled by an Arduino microcontroller. The subsystems include: irrigation and humidification, lighting, ventilation, and soil heating. The subsystems are controlled with different interconnected devices, which are detailed in Figure 4 below.

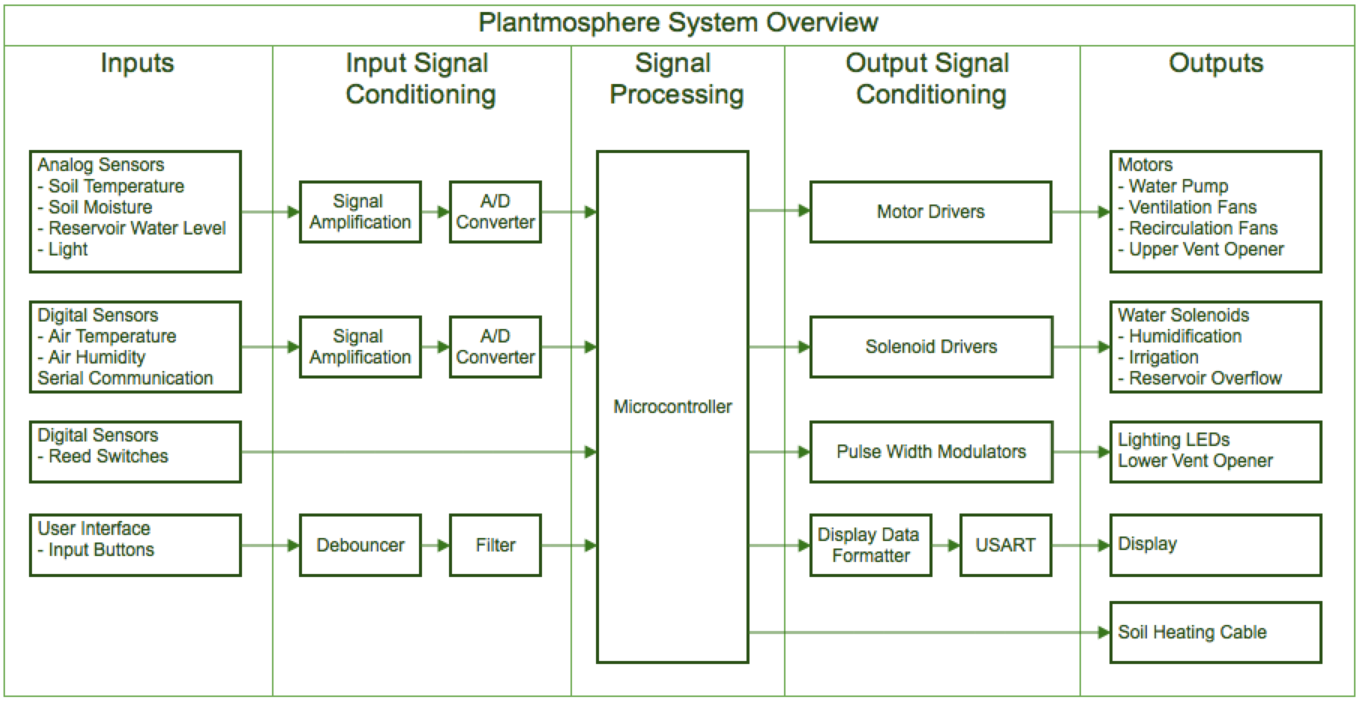


Figure 4: The system diagram and interconnections

Some of the devices are shared between the different subsystems. For example, the air temperature sensors are used by both the irrigation and humidification subsystem and the ventilation subsystem.

2.1 Irrigation and Humidification

The irrigation and humidification subsystem uses multiple sensors to determine when the Plantmosphere requires irrigation, humidification, or both. Figure 5 shows the devices used in this subsystem.

2.2 Lighting

To control the lighting subsystem, light sensors have been employed. Figure 6 presents this subsystem's components.

2.3 Ventilation

Temperature and humidity sensors control the Plantmosphere's ventilation devices. The devices used in this subsystem are presented in Figure 7 below.

2.4 Soil Heating

The soil heating subsystem uses many different sensors to control the soil temperature, as shown in Figure 8 below.

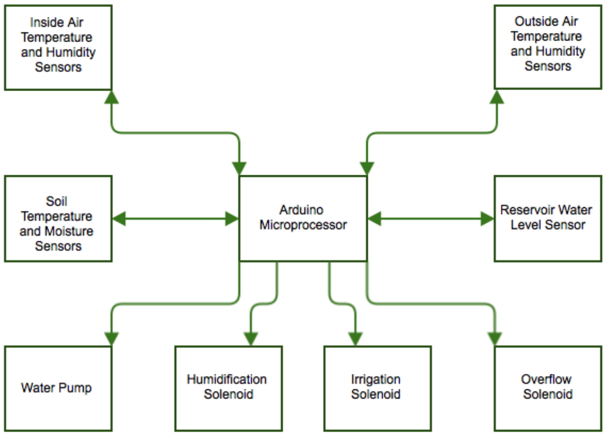


Figure 5: Irrigation and Humidification Subsystem

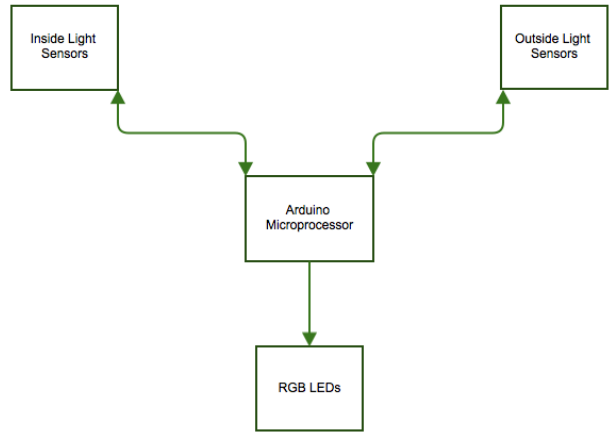


Figure 6: Lighting Subsystem

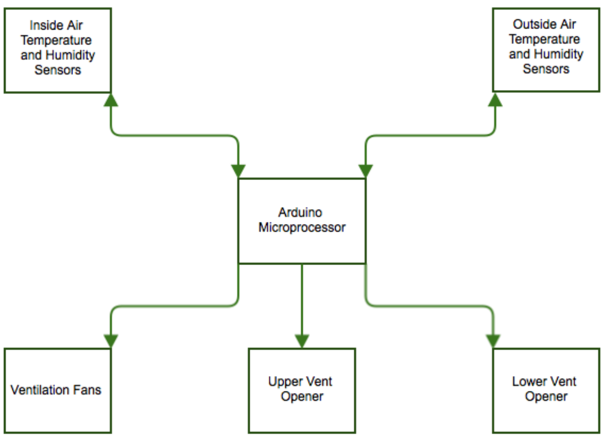


Figure 7: Ventilation Subsystem

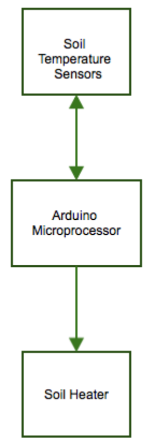


Figure 8: Soil Heating Subsystem

3 Microcontroller

We selected the Arduino Mega 2560 Microcontroller Board as the control unit for the Plantmosphere. Arduino source code is written with Arduino Software: a free, open-source (**R4.1.5**), software package that contains comprehensive libraries well-suited for interfacing with electronics. Since Plantmosphere's software control algorithms do not require heavy processing power or memory, mini-computers such as Raspberry-Pi or Beagle Board were not chosen. Additionally, the Arduino Mega 2560 is less expensive than said mini-computers. The Arduino Mega 2560 was selected above other Arduino models such as Uno or Leonardo due to its compromise between low cost, higher flash memory, additional Analog and Digital I/O pins and shield compatibility. Please refer to Figure 76 in Appendix A for a detailed Arduino model comparison chart.

Figure 9 below depicts the Arduino Mega 2560 Microcontroller Board.

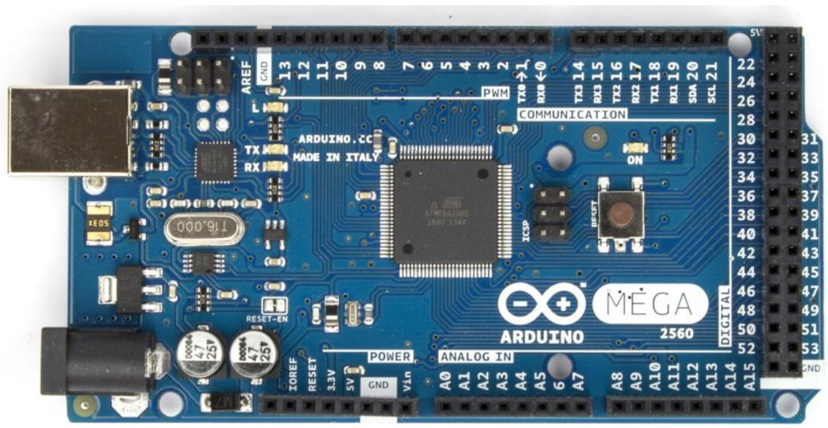


Figure 9: Arduino Mega 2560 Microcontroller

The Arduino Mega 2560 provides an interface with which sensor data can be monitored (**R4.1.2**) and actuators can be controlled (**R4.1.3**). A circuit diagram of the Arduino and its I/O pins is depicted in Figure 10 below.

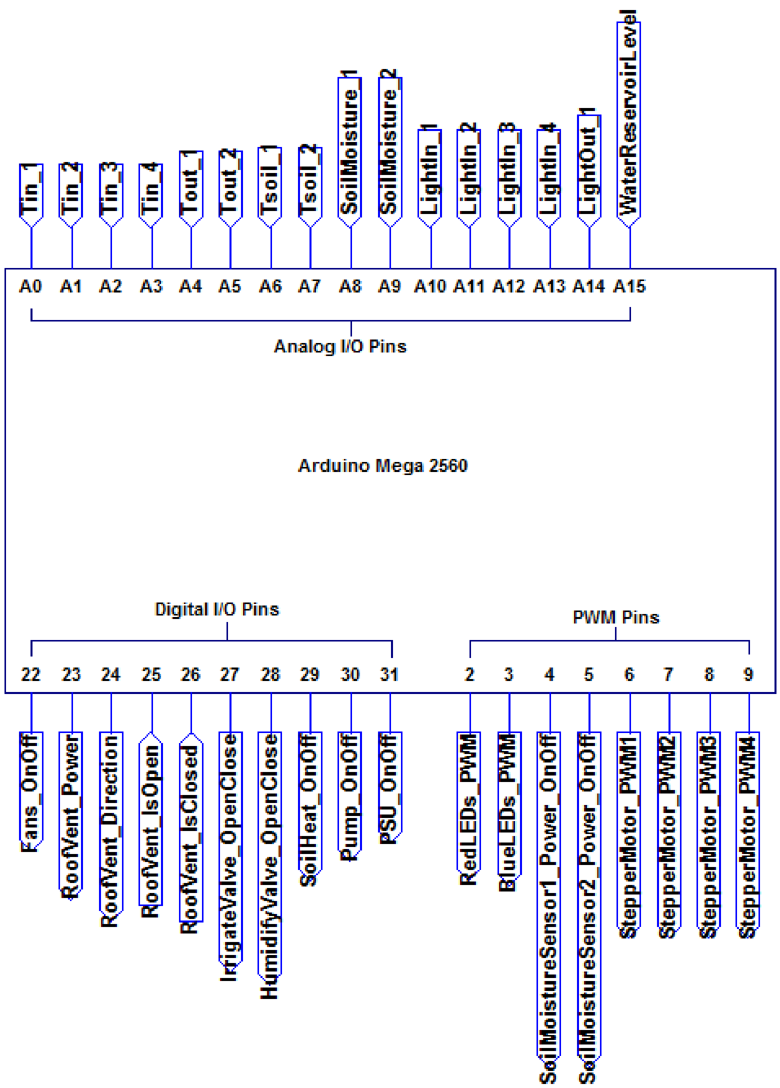


Figure 10: Arduino Pin-Out Circuit Diagram

3.1 Analog Input

The Arduino Mega 2560 is equipped with 16 analog input pins. These pins will read analog voltages from the Plantmosphere's numerous sensors and use analog-to-digital (A/D) converters to convert continuously read analog voltages to discrete digital values with 10-bit resolution. Table 1 below depicts a tentative analog input pin map.

Table 1: Tentative Analog Input Pin Map

Sensor Type	Analog Input Pin Number(s)	Number of Pins
DHT11 Temperature/Humidity Sensor	A0-A7	8
Soil Moisture Sensor	A8-A9	2
PDV-P8104 Photocells	A10-A14	5
Ultrasonic Distance Water Level Sensor	A15	1

3.2 Digital Input/Output (I/O)

The Arduino Mega 2560 is equipped with 54 digital I/O pins. These pins may deliver a digital voltage to an actuator in order to control its operational state. Table 2 below lists a tentative digital pin map to Plantmosphere's actuators.

Table 2: Tentative Digital I/O Map

I/O	Actuator/Sensor Type	Digital Output Pin Number(s)
O	AFB 1212VH-T500 DC Fan	22
O	163899 Push 900 Linear Actuator	23-24
I	30-17154 Reed Switches	25-26
O	997 Solenoid	27-29
O	Gro-Quick Soil Heating Cable	30
O	Bur-Cam 1/3 Hp Noryl Submersible Pump	31

3.3 Pulse Width Modulation (PWM)

15 of the 54 digital I/O pins allow for Pulse Width Modulation with 8-bit resolution. PWM is a method of generating a pseudo-analog output voltage by generating rectangle wave pulses with a digital source. The PWM signal is comprised of a duty cycle and frequency. The frequency defines the length of a cycle, and the duty cycle defines the percentage of the cycle that the pulse is asserted. It can be used in applications that require a finer degree of output control rather than binary control. For example, the light intensity of Plantmosphere's LEDs can be adjusted with PWM. This functionality allows us to satisfy **R3.3.3** and **R3.3.4**. Table 3 lists a tentative digital pin map for actuators that require PWM.

Table 3: Tentative PWM Pin Map

Actuator/Sensor Type	PWM Pin Number(s)
5060BRG LED Strip	2-3
Soil Moisture Sensor	4-5
26M048B2U Stepper Motor	6-9

3.4 Data Logger Shield

A 'shield' is a board that can be mounted onto an Arduino to add features to the Arduino's functionality. The data logging shield displayed in Figure 11 includes an SD card interface, a real time clock (RTC) and a backup battery.

Plantmosphere's prototype and final product design requires an RTC in order to keep track of the time of day. The Arduino Mega 2560 does have a timer built into the chip and timer function called "millis()". The limitation of this timer is that it only keeps track of the time since the Arduino was last powered on. This functionality is not sufficient in the case of Light Emitting Diode (LED) lighting control, where it is imperative to keep track of the daily sunlight delivered to the plants. The backup battery is rated for 7 years, and will ensure that time is kept even if the Arduino is powered off.

The SD card reader provides data storage space for verification testing purposes, in compliance with **R4.1.4**. Signal data storage is required for testing the prototype only, and will not be required for final product revisions. Using this interface we will record and store signal data onto a 2 GB SD card.

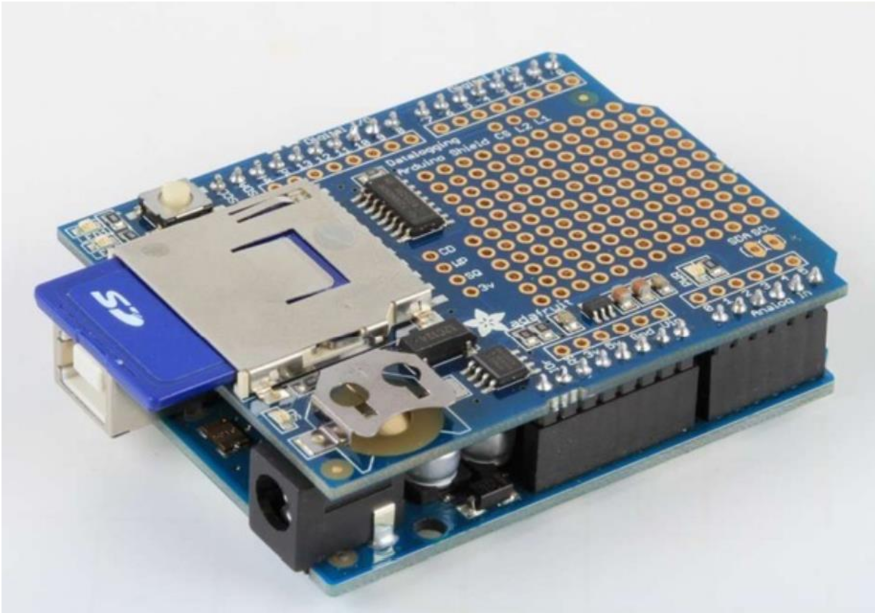


Figure 11: Arduino Mounted with Data Logging Shield

3.5 8-Channel Relay Module

A relay is an electrically operated switch that is controlled by applying a 5 VDC voltage (switch is open) or 0 VDC (switch is closed). Relays are useful for controlling circuits that require much higher currents and voltages than the Arduino is rated for. A relay can be used to isolate the Arduino from higher voltage circuits such as those that require 120 VAC mains electricity to power. Plantmosphere's design incorporates an 8-channel relay module that is depicted in Figure 12 below. Please refer to Figure 77 in Appendix A for a circuit diagram of one channel of the relay module.

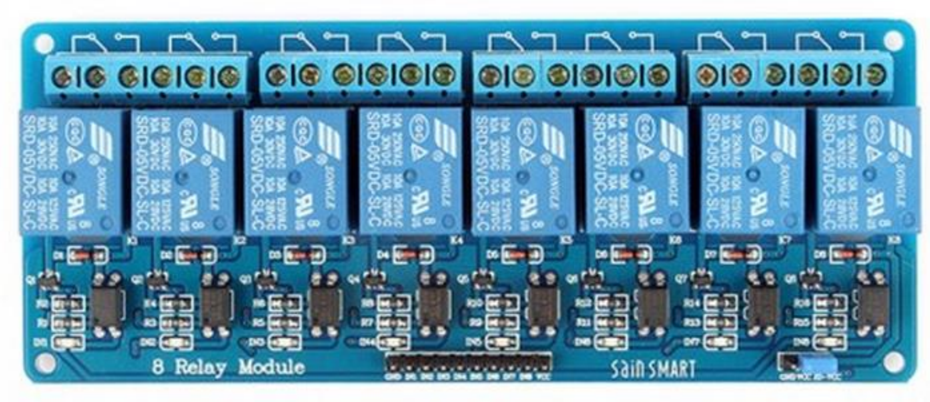


Figure 12: 8-Channel Relay Module

Plantmosphere Technologies decided to purchase the relay module in Figure 12 for several reasons. First, we require a means to control actuators that require high Direct Current (DC) and Alternating Current (AC) to power. Additionally, for our prototype, we wanted to reduce the complexity of labor by eliminating the need to design our own circuit (i.e. using triacs). The 8-Channel relay module is a pre-fabricated component that has already undergone safety and functional testing. Therefore, it is a time-saving, inexpensive, and reliable solution for actuator control. Table 4 below lists the number of relays we are allocating to each actuator within the Plantmosphere system.

Table 4: List of the Number of Relays Required for their Designated Components

Actuator Type	Number of Relays
163899 Push 900 Linear Actuator	2
997 Solenoid	3
Gro-Quick Soil Heating Cable	1
Bur-Cam 1/3 Hp Noryl Submersible Pump	1

Figure 13 below is a circuit diagram of the relay module and the actuators it controls.

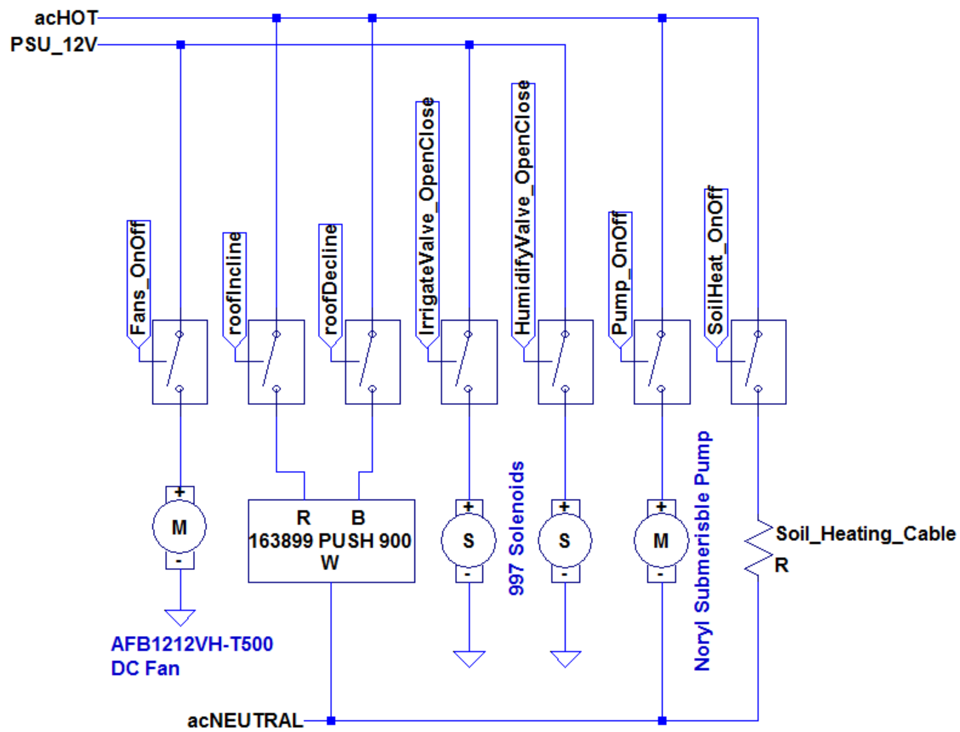


Figure 13: Relay Module Control Circuit Diagram

3.6 Liquid Crystal Display (LCD)

The Plantmosphere prototype will incorporate an LCD module to display the housed plant type, system status, and error messages. It will allow the user to interface with the Plantmosphere. The LCD we chose can display twenty characters on each of its four lines, and uses a standard HD44780U display controller/driver (refer to 18.3 for the HD44780U block diagram).

Figure 14: LCD Module

We selected the LCD module in Figure 14 over other display devices because of its compromise between functionality and cost. Less expensive models only had two lines of twenty characters, whereas we required at least three lines of characters in order to display information to the user as per **R4.2.1** and **R4.2.2**.

Additionally, a touch screen is more expensive and more prone to damage from dirt and weather. The LCD module is compatible with the Arduino, and combined with a keypad, will form an intuitive UI as per **R4.2.4**.

4 User Interface

4.1 Design

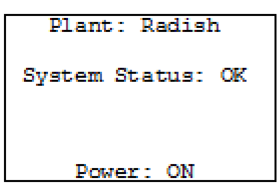
The user interface facilitates communication between the Plantmosphere's systems and the user. It has been designed to use a Liquid Crystal Display (LCD) for visual notifications and a number keypad for user input. The Plantmosphere will have a library of optimal growth conditions for different plants, which allows the user to simply enter the desired plant to grow. The interface will be enclosed inside a weatherproof casing and secured to the greenhouse structure's exterior, granting the user easy access to the interface.

The user is responsible for choosing the plant to be grown and deciding whether or not the Plantmosphere system itself is active. Words can be entered using the "text on 9 keys" (T9) text entry technology. The even numbered keys from 2 to 8 are used for navigation, while key 5 acts an "Enter" key as shown in Figure 15.

Figure 15: The number keypad with navigation arrows and an "Enter" button

The LCD shows the plant type on the first line, the system status on the second, and the power status on the last line. Figure 16 presents a sample of the LCD's output.

A



B

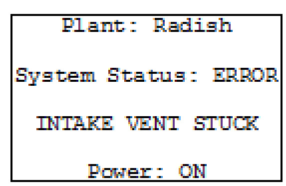


Figure 16: Example of the LCD module display; *A*: the system is operating normally; *B*: the intake vent is stuck

In the event of a system error, the system status Error messages will be presented on the third line, and if more than two subsystem components fail, the second and third lines will cycle through the error messages. The error messages for each subsystem are limited to twenty characters in order to fit the LCD window (Table 5), and are shown in Table 6.

Table 5: The parts used in the user interface system

Part	Model Number	Quantity	Description
LCD Module	SainSmart 20-011-913	1	LCD Module Shield for Arduino 4 lines of 20 characters Supply voltage: 5 VDC
Number Keypad	DSC PC1000	1	10 digit keypad

A

B

Figure 17: User interface part images: *A:* the number keypad [2]; *B*: The LCD module and its pin connections [3]

Table 6: Examples of Potential System Status Errors

Error Message	Description
WATER RESERVOIR LOW	The water level is too low.
WATER PUMP	The pump is not pumping water.
MISTER	The misters not misting.
DRIPPER	The drippers not dripping.
ROOF VENT STUCK	The roof vent is not opening or closing.
INTAKE VENT STUCK	The intake vent is not opening or closing.
FAN #	One of the four fans is not spinning.
LED ARRAY	The LED array is not turning on or off.
SOIL HEATING WIRES	The soil heating wires are not turning on or off.
WATER LEVEL SENSOR	The water level sensor's output is not changing during irrigation or humidification.
INT AIR HUM #	The numbered interior air humidity sensor's output is not changing during ventilation, humidification, or over a period of 30 minutes.
EXT AIR HUM #	The numbered exterior air humidity sensor's output is not changing during ventilation, humidification, or over a period of 30 minutes.
INT AIR TEMP #	The numbered interior air temperature sensor's output is not changing during ventilation, humidification, or over a period of 30 minutes.
EXT AIR TEMP #	The numbered exterior air temperature sensor's output is not changing during ventilation, humidification, or over a period of 30 minutes.
INT LIGHT	The internal light sensor's output is not changing during an LED lighting change, or over a period of 30 minutes.

EXT LIGHT #	The numbered external light sensor's output not changing over a period of 30 minutes
SOIL HUM #	The numbered soil humidity sensor's output is not changing during irrigation or over a period of 30 minutes
SOIL TEMP #	The numbered soil temperature sensor's output is not changing during soil heating or over a period of 30 minutes
AIR TEMP TOO HIGH	The internal air temperature above maximum allowable level over a period of 30 minutes
AIR TEMP TOO LOW	The internal air temperature below minimum allowable level over a period of 30 minutes
AIR HUM TOO HIGH	The internal air humidity above maximum allowable level over a period of 30 minutes
AIR HUM TOO LOW	The internal air humidity below minimum allowable level over a period of 30 minutes
SOIL HUM TOO HIGH	The soil humidity level above maximum allowable level over a period of 30 minutes
SOIL HUM TOO LOW	The soil humidity level below minimum allowable level over a period of 30 minutes
SOIL TEMP TOO HIGH	The soil temperature above maximum allowable level over a period of 30 minutes
SOIL TEMP TOO LOW	The soil temperature below minimum allowable level over a period of 30 minutes
LIGHT TOO HIGH	The light intensity above maximum allowable level for over a period of 30 minutes

The vertical arrow keys are used to navigate through the plant type and system power menus, which blinks the chosen item. The horizontal keys allow the user to scroll through a list of available plants. Furthermore, users may manually enter the plant name by selecting the first line, typing the plant name, and selecting the desired plant. If the plant name selection is idle for more than ten seconds, the display will default back to its previous state. The system power status is toggled by selecting the fourth line, which then displays a confirmation message, requiring a second "select" press.

The SainSmart 20-011-913 LCD (see Figure 17-A) was chosen for its compatibility with the Arduino. The configuration is simple: the pin connections between the LCD and Arduino are pins SDA to A4, SCL to A5, VCC to 5V, and GND to GND, as shown in Figure 17. The initialization of the LCD requires a few simple lines of code requiring the Inter-Integrated Circuit (I2C) address [3]. The DSC PC1000 number keypad will be used as it was salvaged, eliminating the cost towards a new keypad.

Production versions of the Plantmosphere will most likely display the statuses of each subsystem simultaneously, which would warrant either a larger LCD or a more complex display algorithm. In addition to the added notification space, a more complex keypad may be implemented to accommodate further functionality.

5 Humidification and Irrigation System

5.1 Theory

5.1.1 Plant Irrigation

Plants require nutrients and minerals to be absorbed by the roots. Even though mineral absorption is not directly affected by water uptake and water supply, many connections exist between the management of minerals and water [4] (**R2.2.1**).

Some connections include [4]:

- Transportation of minerals by water in the root environment is important
- Water increases the leaching of residual salts and minerals from the root zone deeper into the soil
- Greenhouse plants get most of the needed minerals through fertilization
- Nutrient supply can be developed based on the ratio between the uptake of water and nutrients

Water requirements for a plant are driven by transpiration rate, which can be affected by light radiation, ambient temperature, soil temperature, and relative humidity.

5.1.2 Plant Humidification

Plants respond to the difference in relative humidity between the surrounding air and the stomata. This exchange of gases facilitates photosynthesis. Stomata open and close in response to the vapour pressure deficit. As temperature rises stomata open wider. A vapour pressure deficit range of 8-10 mbar is deemed optimal [4]. As vapour pressure deficit increases evaporation rate also increases. The stomata of most plants close halfway when the vapour pressure deficit reaches 12 mbar to prevent wilting [4]. The reduction in stomata opening size negatively affects gas exchange and therefore photosynthesis.

5.2 Design

The humidification and irrigation system is comprised of: water pump, Gardena control unit, tubing, solenoids, drip nozzles, mist nozzles, relays, air temperature and relative humidity sensors, and soil temperature and moisture sensors (See Table 7 for parts list and description). All of these components are used to help the Plantmosphere provide the best growing environment for plants (**R2.2.1**).

Table 7: The parts used in the Humidification and Irrigation system

Part	Model Number	Quantity	Description
Pump Figure 9-A	BUR-CAM 300500	1	1/3 Hp Submersible Pump Capacity: 3000 GPH/5', 2500 GPH/10', 2000 GPH/15', 1450 GPH/18'. Water-cooled motor for a better performance. 1 1/2” NPT discharge with 1 1/2” reducer.
Control Unit Figure 9-B	Gardena Unit 1000	1	Reduces initial pressure to an operating pressure of 1.5 bar. Water flow is approx. 1000 LPH Filters the water
Tubing Figure 9-C	Gardena Micro-Drip Line	1	15 m Connecting line 13 mm (1/2”) diameter

			10 m Supply line 4.6 mm (3/16") diameter
Drip Nozzles Figure 9-D	Gardena Inline Drip Head	3	2 LPH
Mist Nozzles Figure 9-E	Gardena Micro Mist Nozzles	2	Spray Area: 1 m
Solenoids Figure 9-F	Gardena Irrigation Valve	2	12 VDC 1/2" diameter fitting Minimum Pressure: 3 psi
Relays Figure 9-G	Arduino Relay Shield	1	8 Relays
Humidity and Temperature Sensor Figure 9-H	DHT11	2	Digital Power supply voltage: 5 VDC Temperature range: 0-50 °C Humidity range: 20-90% RH Weight: 4 g

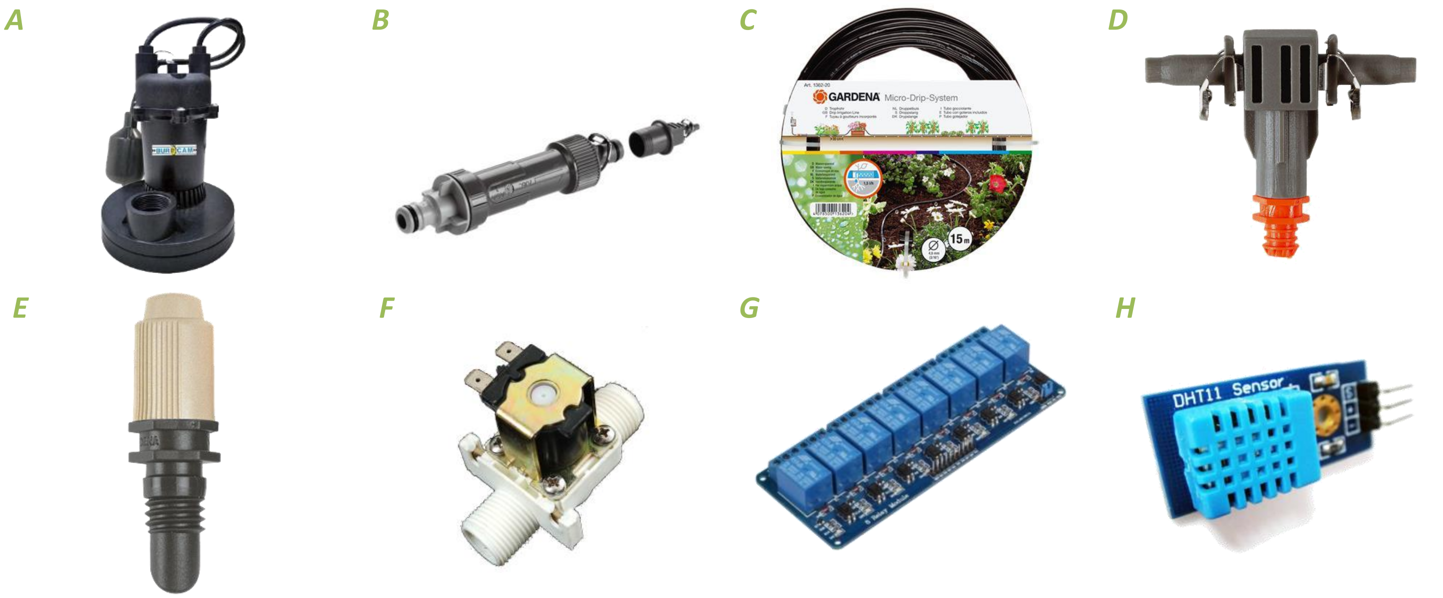


Figure 18: Images of the parts

In order to design the system correctly, we developed a state machine diagram, which is presented in Figure 19 below.

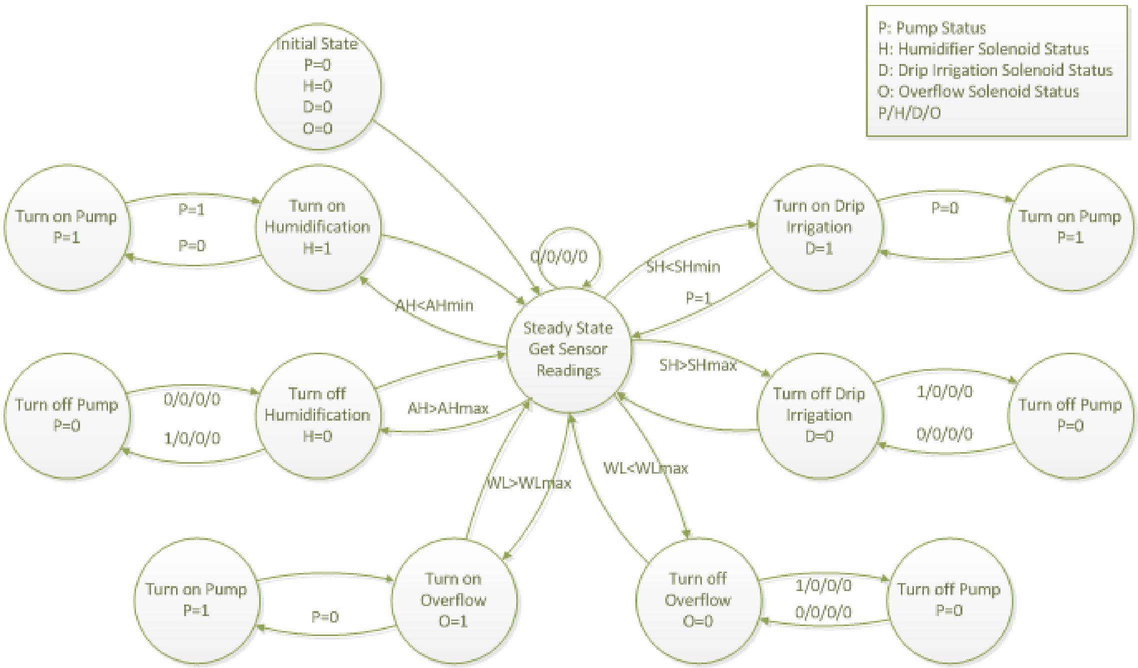


Figure 19: State machine diagram for Irrigation and Humidification System

5.2.1 Control Unit, Tubing, Drip Nozzles and Misters

In order to keep this simple and cost effective we decided to buy an existing system for humidification and irrigation by Gardena (see Figure 20 for the layout). The system will be directed in three different paths: one for the humidification mist nozzles, another for the irrigation drip nozzles, and the third for rain barrel overflow. The addition of solenoids at the beginning of each branch allows the Plantmosphere to control where the water is going. The water can go down any combination of paths just by turning on the solenoids for the given path.

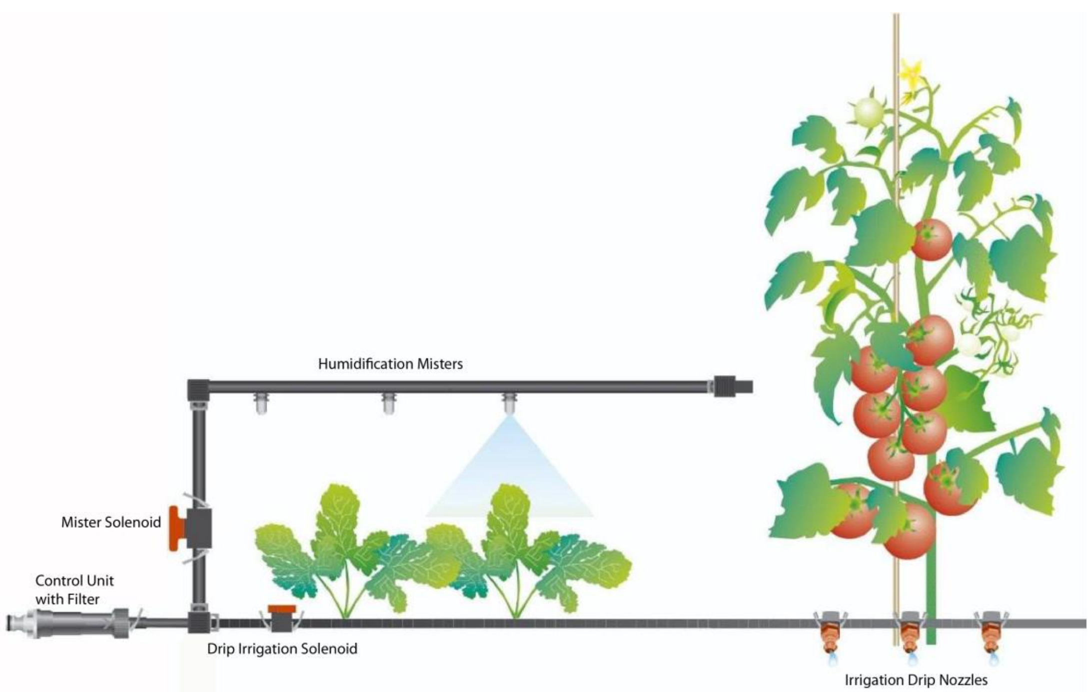


Figure 20: Gardena Micro-Drip System

5.2.2 Water Pump, Solenoids, and Relays

One water pump will be used for humidification and irrigation. The Arduino, using relays, controls the pump and solenoids (see Figure 21 for the circuit layout and Table 8 for the allowable operation combinations). This allows the Plantmosphere to activate the pump only when needed (R3.5.5). The Arduino will not allow the pump to come on if the water level in the water reservoir is too low or if both solenoids are closed, ensuring that the pump does not run dry and damage the motor or build up too much pressure in the tubing that they burst.

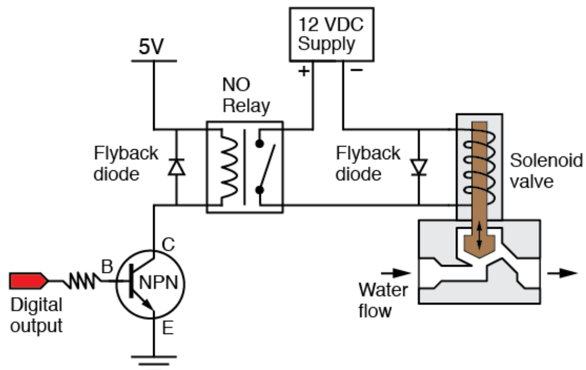


Figure 21: Circuit layout for water solenoid valve control [5]

Table 8: Allowable operation combinations

Operation	Pump Relay	Humidification Relay	Irrigation Relay
Humidification	ON	ON	OFF
Irrigation	ON	OFF	ON
Humidification & Irrigation	ON	ON	ON
Nothing	OFF	OFF	OFF

5.2.3 Air Moisture Sensors

The DHT11 temperature and humidity sensors will be used to determine the Relative Humidity (RH) of the air (**R3.2.1, R3.2.6**). If the humidity levels are too low, the Arduino will activate the relay to turn on the pump and activate the humidity line's solenoid, allowing the water to be dispersed by the misters (**R2.2.2, R3.2.5, R3.5.1**).

The misters will only be turned on when needed and will be turned off when the RH reaches the halfway point between the minimum and maximum thresholds (**R3.5.2, R3.5.3**).

5.2.4 Soil Moisture Sensors

In order to ensure that the plants get the proper amount of water, the Plantmosphere will use soil moisture sensors. The values from the sensors will determine if the soil is too dry, too wet, or within an optimal range. We are using multiple sensors to try to maintain the same moisture level throughout the entire trough (**R2.2.2, R3.2.6**).

If the moisture level is too low the Arduino will turn on the irrigation solenoid. The Arduino will then check to ensure the water pump solenoid is also turned on. When the moisture level gets above the midpoint between the minimum and maximum values the irrigation solenoid will turn off. Because the Irrigation and Humidification systems use the same pump, the Arduino will then check to see if the irrigation solenoid is off. If it is also off the Arduino will also turn off the pump (**R3.2.5, R3.2.6, R3.3.5**).

We will be designing and building our own sensor in order to reduce costs (see Table 9 for price comparison) and increase flexibility by giving us the ability to install the sensor through the back wall of the soil trough. For the sensor, we are going to use two galvanized nails, packing foam, two lead wires, and two resistors. See Figure 22 for a diagram of how the soil moisture sensor will be built. This sensor determines the moisture level using a resistive method. The problem with the resistive method is the resistance of soil changes with temperature. We are using a temperature sensor to correct for this issue. We are putting the temperature sensor close to the soil moisture sensor in order to take into account the heating of the soil from both the sun and the soil heating wire. The Arduino will only turn on the sensor when we need to take a reading. This will help prevent electrolysis, which would slowly eat away the metal nails. Voltage swapping, changing the direction of the current through the sensor is another way was combat electrolysis.

Table 9: Price list comparison for the soil moisture sensor

Sensor	Unit Price	Quantity	Total Price
Homemade	$0.99	2	$1.98
Arduino Moisture Sensor	$8.99	2	$17.98

The sensor will be connected to the Arduino using three pins (two digital outputs and one analog input). Figure 23 shows how the soil moisture sensor will be connected to the Arduino and the location of the resistors.

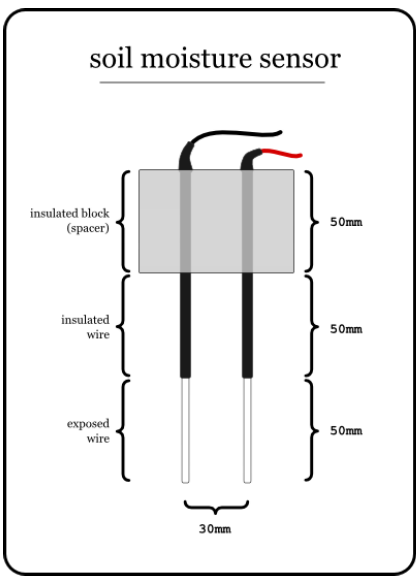


Figure 22: Soil Moisture Sensor [6]

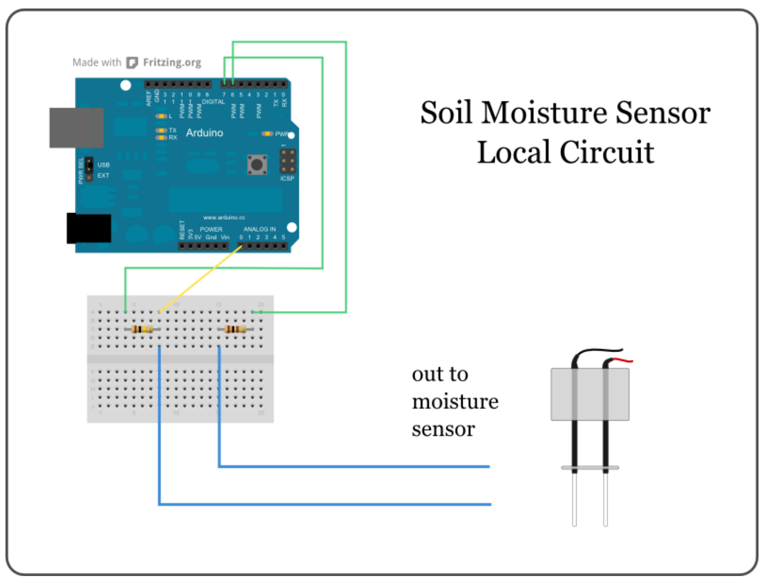


Figure 23: Connecting Sensor to Arduino [6]

Please refer to Figure 45 for an image of the moisture sensor placement within the trough.

5.2.5 Soil Temperature sensor

To ensure that the greenhouse environment maintains a temperature that can promote plant growth, a temperature sensor will be used. The DHT11 is a digital humidity and temperature sensor that measures the surrounding soil. The sensor's low power consumption of 12.5 mW ensures that we minimize our power budget. It will be connected to an Arduino microcontroller, which will receive the data and determine if the soil heating cables need to be turned on or off depending if the temperature of the greenhouse is not optimal for the plants. The soil temperature sensor will also be used to adjust the soil moisture level. As the soil temperature goes up the moister level from the soil moisture sensor goes down. This can give a dry soil false reading turning on the irrigation drip nozzles when they are not needed.

Figure 24 below is a circuit diagram of the soil moisture sensors.

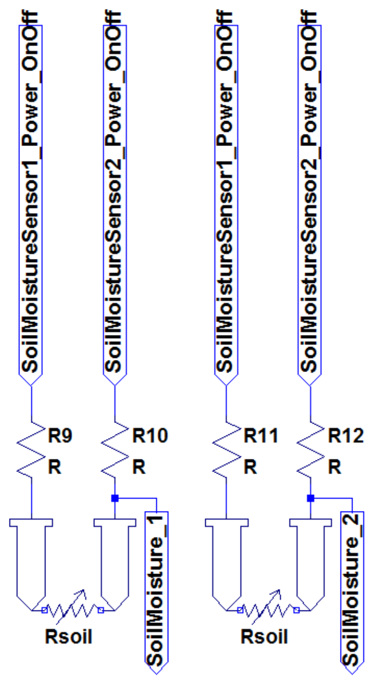


Figure 24: Circuit Diagram for the Soil Moisture Sensors

6 Lighting Design

6.1 Theory

Building and testing our prototype in Vancouver's predominantly cloudy conditions during the winter poses a challenge in lighting. Like other biological organisms, plants have circadian clocks, meaning that their behavior and biology change with the day-night cycle. Plants whose circadian clock periods have been matched to this light cycle have been shown to "contain more chlorophyll, fix more carbon, grow faster, and survive better" than those whose clock periods were out of sync with the same cycle [9].

The test plants (radishes) being cultivated in the prototype require a maximum of six hours of sunlight per day in order to grow and flourish. The maximum light absorption time value is calculated with:

$$Max.Light\ Absorption\ Time = \frac{Max.Light\ Exposure\ Power}{Solar\ Constant} \times Trough\ Area, \quad (2)$$

where the maximum light exposure power is 5 kW·h, the solar constant is 1.362 kW/m^2, and the trough area is 0.555 m^2. The artificial lighting system within the Plantmosphere is a key element in our product that ensures the plants receive the required lighting each day.

The recommended wavelength of light required for plant growth is between 400 and 700nm, with the optimal wavelength being purple light at 470 nm [10]. Using purple light promotes efficient chlorophyll production, encouraging photosynthesis, the process plants use to feed and grow.

Visible light is measured in lumens (lm), which is the total amount of light radiating from a light source. Lumens are based on the human eye's sensitivity to a particular wavelength of light. Moreover, luminous flux (lm·m^{-2}) is the measurement of the total visible light per a unit area, as shown in the following equation:

$$H = \varphi \times q\left(\frac{1.24}{\lambda}\right), \quad (3)$$

where H is the luminous flux in lumens per meter squared, φ is the number of photons per meter squared, q is the electron charge (1.6×10^{-19} C), and λ is the wavelength in micrometers. Note that luminous flux is directly proportional to the amount of light the plants are receiving.

6.2 Design

To ensure that the plants receive enough light, the Plantmosphere will employ an artificial light source. Red/Green/Blue (RGB) LEDs have been chosen for lighting. Their benefits over incandescent light bulbs include a 25000 hour life span, low energy loss through heat dissipation, low power consumption [8]. Furthermore, the use of LEDs minimizes plant transpiration, which conserves water as the plants require less irrigation.

The LEDs themselves will be soldered to a 64P44WE protoboard measuring 2.5 by 0.5 feet, as seen in Figure 25-A below. The entire assembly will be encased in an aluminum surface mount and sealed with silicone to ensure that the electrical connections are protected from water damage. The lighting will be hung from the ceiling of the greenhouse structure ten inches above the cultivated plants, ensuring that the plants receive sufficient high-intensity light when the sun is obstructed. Finally, a photocell will measure the light incident upon the plants and the Arduino will control the lighting system. Table 10 and Figure 25 below summarizes the components used in the lighting system.

Table 10: The parts used for the lighting system

Part	Model Number	Quantity	Description
LED	5050 SMD RGB LED	150	6-pin surface mount RGB LED
Protoboard	64P44WE Protoboard	1	2.5' by 0.5' perforated board RoHS compliancy
Photocell	PDV-P8104 Photocell	5	550nm Peak spectral response Low power dissipation

A *B* *C*

Figure 25: *A*: The 5050 SMD RGB LED; *B*: 64P44WE Protoboard; *C*: The PDV-P8104 Photocell

6.2.1 LED

The lighting system will be built with approximately one hundred and fifty 5050 Surface Mount Device (SMD) RGB LEDs, which are shown in Figure 25-B. Its packaging dimensions are presented in Figure 26 below.

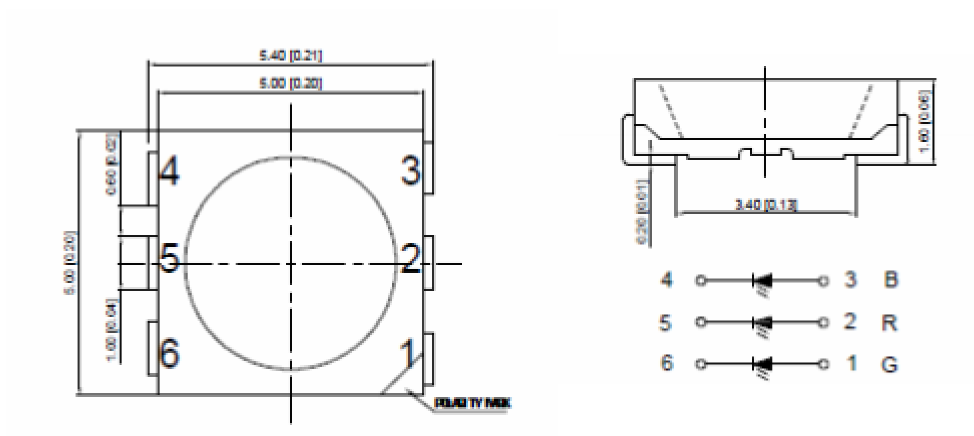


Figure 26: 5050 SMD RGB LED package dimensions

The LEDs are water resistant, which is an imperative feature given the Plantmosphere's humid environment. They are compliant with the Reduction of Hazardous Materials (RoHS) directive, consume low power during operation, and are rated for 500 lumens per 100 LEDs. To obtain purple light at approximately 470 nm, the LEDs will be controlled with a PWM signal so that the intensities of each diode, and subsequently the overall colour, can be varied. The signal will be applied to the base of two TIP41C power transistors that control the red and blue components.

Figure 27 below is a circuit diagram of the LED control unit.

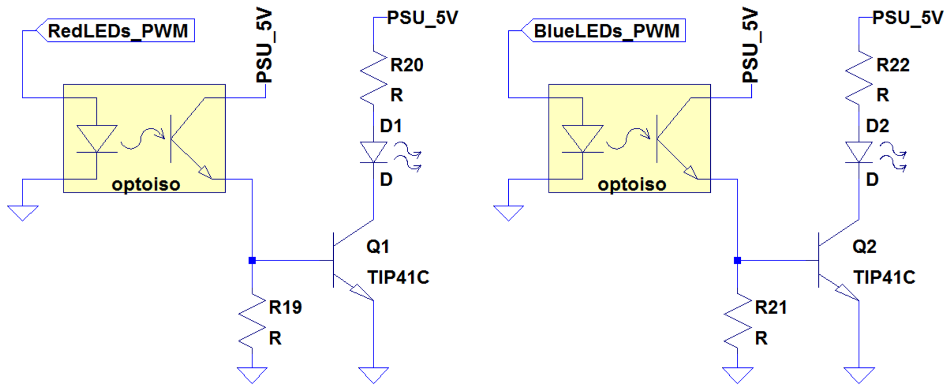


Figure 27: Circuit Diagram for the LEDs

6.2.2 Light sensor

To detect the amount light both inside and outside the greenhouse structure, PDV-P8104 photocells will be used, as seen in Figure 25-C. They will provide light intensity information to the Arduino so it can activate the lighting as needed. The photocell's package dimensions are shown in Figure 28 below.

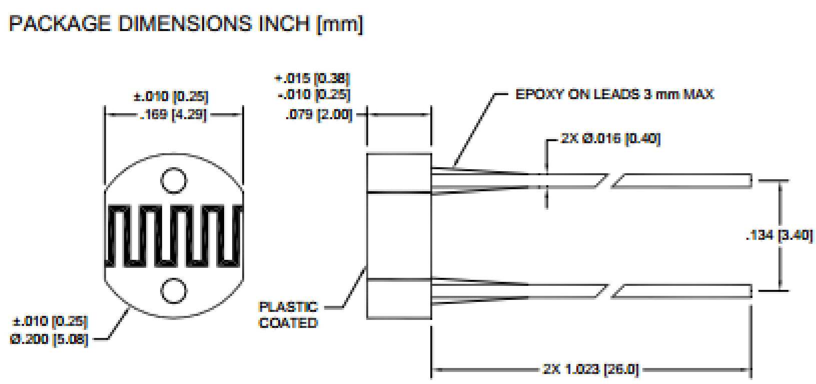


Figure 28: PDV-P8104 package dimensions

Each photocell dissipates a maximum of 60 mW and has a peak spectral response of 550 nm. The Plantmosphere will use five photocells in total, one on each of the four corners of the greenhouse's exterior and one near the plants (see Figure 29). These locations enable us to measure both the light incident upon the plants and the intensity of the sunlight.

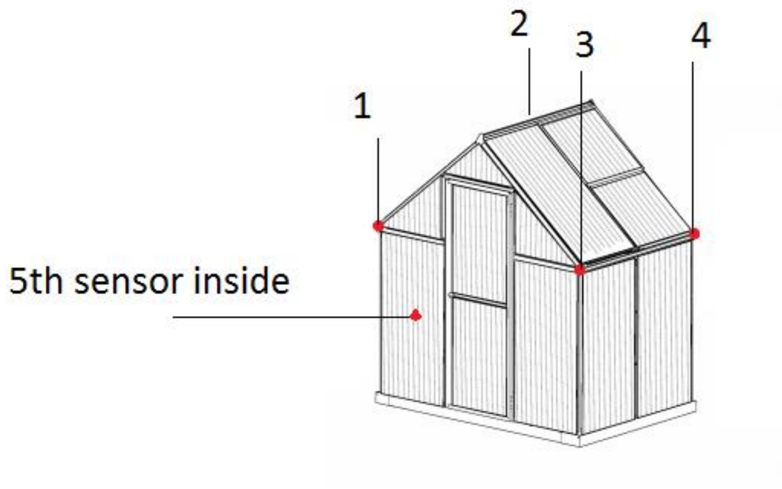


Figure 29: Light sensor location inside and outside the Plantmosphere

Figure 30 below is a circuit diagram of the photocells.

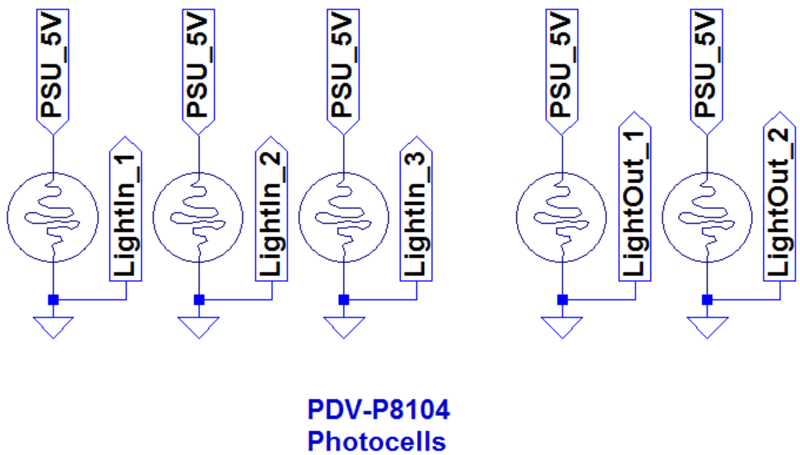


Figure 30: Circuit Diagram for the photocells

7 Ventilation

7.1 Theory

Proper greenhouse ventilation gives impetus for proper plant growth by the prevention of irregular temperature, lack of carbon dioxide (CO_2), pests, and lack of pollination. Excess heat causes more plant deaths than the cold and by allowing fresh air to flow through the greenhouse, the hot air exhausted [11]. Ideally, one air change should take place each minute on a hot day to prevent overheating [12]. Simultaneously, CO_2 is replenished, allowing proper photosynthesis to take place. Healthy plant growth stems not only from the sugars produced and used as food, but the moving air blows around the leaves, forcing the plants to grow studier stems and roots, improving CO_2 diffusion into the leaves, and keeping pests from settling on the plants. Some plants are dependent on air movement for self-pollination before they bear fruit [11].

Ventilation is classified into two types, active and natural. Active ventilation is where a moving part, such as a fan, is required to induce air movement. Natural ventilation is where air movement occurs without the use of a moving part, and can be further classified into wind-driven and buoyancy-driven natural ventilation. Wind-driven ventilation occurs when wind creates pockets of high and low pressure after colliding into an object or structure. As a result, air is forced into any gaps at high pressure areas and draws air out of gaps at low pressure areas. Buoyancy-driven ventilation is when there is a temperature difference in the air. Warmer air is less dense and rises, while cooler air is denser and falls. In architecture, buildings are designed to make use of buoyancy-driven ventilation through chimney stacks, which coins this ventilation as the stack effect [13].

7.2 Design

The ventilation system is responsible for the intake of fresh air, recirculation of air, and exhaust of stale air. The system uses active ventilation and circulation, but is also designed to make the most of natural buoyancy-driven ventilation with the stack effect [14]. The main sub-systems include the floor vent, recirculation fans, and roof vent, which are Arduino controlled based on readings from the temperature and humidity sensors.

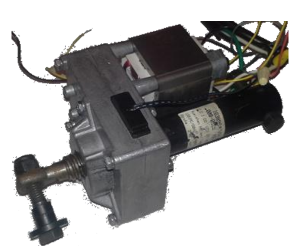
Table 11: The parts used in the ventilation system

Part	Model Number	Quantity	Description
Intake and Recirculation Fans	Delta Electronics AFB1212VH-T500	4	RoHS compliant 12VDC 103.7 CFM IP55 – dust protected, water resistant 120mm x 120mm x 25.4mm
DC Motor	Portescap 26M048B1B	1	RoHS compliant 5VDC 7.5° step angle
AC Motor	163899 PUSH 900	1	Salvaged treadmill motor Linear actuator
Humidity and Temperature Sensor	DHT11	6	Digital Power supply voltage: 5V Temperature error: 0-50°C Humidity range: 20-90%RH Weight: 4g

A

B

C



D

Figure 31: *A*: The Delta Electronics AFB1212VH-T500; *B*: Portescap 26M048B1B; *C*: 163899 PUSH 900; *D*: DHT11

7.2.1 Recirculation Fans

The four recirculation fans are situated 6 inches off the ground in the bottom corners of the greenhouse, and angled upwards at 30°. One fan is secured along each wall, with six inches of space behind each fan, and pointing counter clockwise around the greenhouse (see Figure 32). They are responsible for circulating air around the greenhouse to evenly distribute the CO_2 as per **R3.4.2**, and their low placement ensures adequate airflow to cause plant movement as per **R3.4.3**. The helical flow ensures movement of all air in the greenhouse, eliminating dead spots in the corners of the greenhouse where air of different temperature or CO_2 concentrations may stagnate. The air flows directly out of the roof vent because of its orientation. Note that the final choice of fan placements and orientations are dependent on the results of further testing.

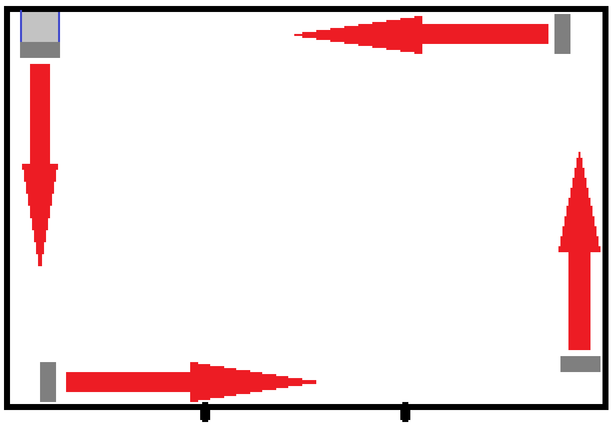


Figure 32: The fan placement for counterclockwise airflow (top view)

The ventilation system will make use of four Delta Electronics AFB1212VH-T500 (Figure 31-A) in order to exceed the suggested minimum CFM of one air movement per minute, and its compact size (Table 11). It was tested against other high-powered fans which ran on AC power, but were too large to fit in the greenhouse. Salvaged fans of equal size were also tested, but did not have sufficient CFM. None of the previously tested fans were guaranteed to be RoHS compliant nor able to withstand humid conditions, whereas the AFB1212VH-T500 is both RoHS compliant and IP55 protected against dust and water jets [13].

The aforementioned fan placement is for the prototype version. Referring to the ventilation test plan, further testing of optimal fan placement will benefit the development of this prototype. Production versions may require more than four ground-level fans depending on the greenhouse size.

7.2.2 Floor Vent

The initially proposed design of the intake vent mimicked a ridge vent (Figure 33). The goal was to create an air pressure difference at a small opening by creating high velocity airflow over the gap in the wall, which would draw in fresh air. However, the fans under test did not generate enough velocity, and the attempt to funnel the airflow of a larger and higher CFM fan was space inefficient.

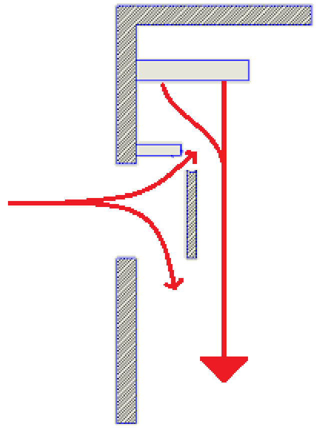


Figure 33: The initial intake vent design (top view)

The revised design of the floor vent allows fresh air to be drawn into the greenhouse through an intake vent manifold by one of the four recirculation fans. The vent manifold will allow air to be exchanged between the greenhouse and its surroundings, while preventing rainwater and small animals from entering through the opening. Placing the vent near the bottom of the greenhouse wall maximizes the vertical distance to the roof vent, which allows us to take advantage of the stack effect as per **R3.4.10**. The floor vent is installed six inches above the ground in order to prevent water ingress due to flooding as per **R3.4.11.**

The intake manifold (depicted in Figure 34) provides an unobstructed path for incoming air, while preventing rainwater from entering the greenhouse structure via an undesired route.

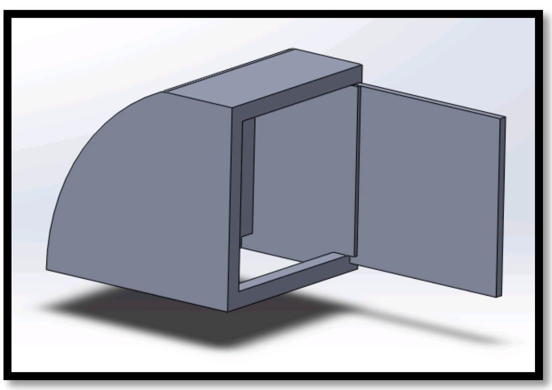


Figure 34: The intake vent manifold with open door (3D view)

Air is required to pass into the greenhouse through the intake vent manifold before the intake fan, and still function during recirculation. The vent enclosure is constructed from wood in order to guarantee a tight fit around the fan. As per **R3.4.7,** A stepper motor controlled hinged door is the mechanism that determines the function of the intake fan. When the door closes off the vent from allowing fresh air into the greenhouse, it leaves an opening in the vent enclosure, exposing the back of the fan, and allowing it to recirculate air within the greenhouse (Figure 35-A). When the door opens to allow fresh air into the greenhouse, it simultaneously blocks the opening in the side of the vent enclosure, allowing the intake fan to draw solely fresh air (Figure 35-B). The stepper motor axle is attached at the end of the vent door as a hinge, and rotates in either direction to swing the door into its intake or recirculation states. The motor rests and is encased on top of the vent enclosure. A 3D model of the vent without the hinged door and fan can be seen in Figure 35-C.

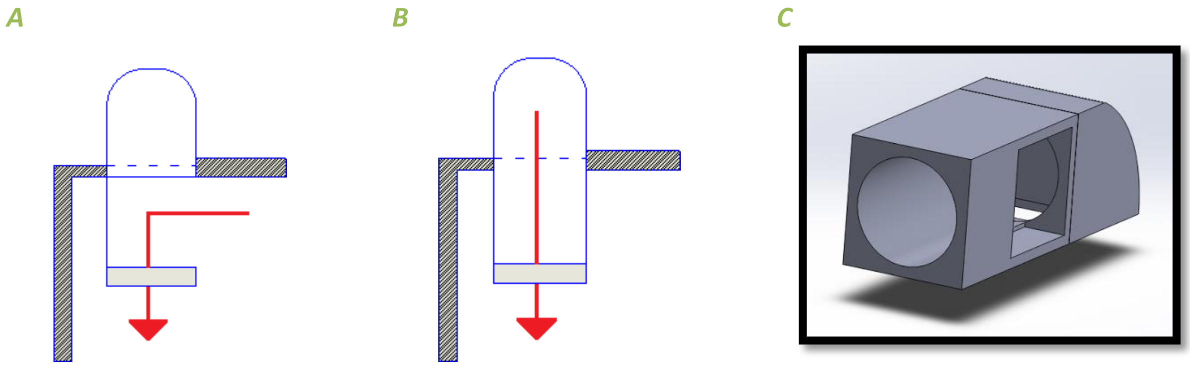


Figure 35: The intake vent configuration: *A*: the recirculation configuration (top view); *B*: the intake configuration (top view); *C*: the 3D view excluding hinged door and fan

The door's dimensions are slightly smaller than the vent enclosure to allow free motion within the enclosure, but the openings the door seals off are slightly smaller than the door and lined with weather strip at the point of door contact for air tightness (**R3.4.8)** (see Figure 36).

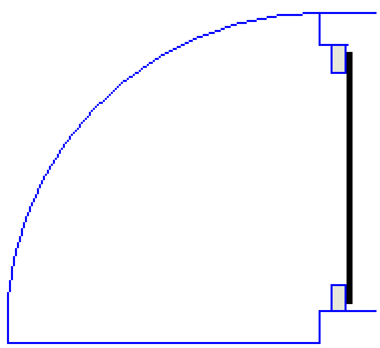


Figure 36: The intake vent opening with airtight door (side view)

The chosen motor is Portescap 26M048B1B (Figure 31-B) for its RoHS compliance, DC rating, and stepping controllability [15]. Using the motor to step in increments of 7.5° will open and close the vent door in a precise and controlled fashion. The motor is simple to control using digital input pulses, and is excellent in responding to starting, stopping, and reversing [16]. Using a continuous RPM motor would require a gear system to reduce the RPM acting on the door. A small motor gear would need to act on a large door gear, which would be space inefficient. Monitoring the amount an RPM motor has rotated would also require additional sensors, making the stepper motor a superior choice. Figure 37 is the control circuit diagram for the stepper motor.

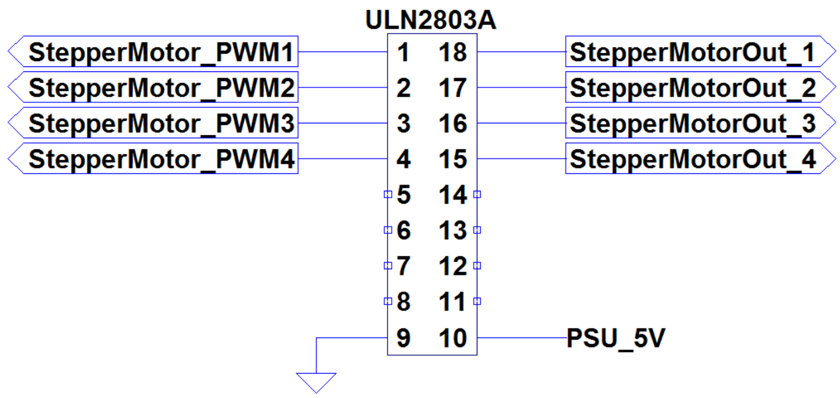


Figure 37: Stepper Motor Circuit Diagram

The current designs and materials for the vent enclosure and opening are for the prototype version; they make use of salvaged and budget materials. Production versions will likely use non-biodegradable and rust resistant material. Future versions may also forgo this budget design completely and contain multiple intake-specific fans with louvered vents, depending on the greenhouse size.

7.2.3 Roof Vent

The roof vent is the hinged roof panel already built into the greenhouse structure. It is tasked with exhausting warmer and less dense air for temperature regulation to maximize the natural airflow in the stack effect.

To control the upper vent, a linear actuator is connected to a beam, acting as an extension, which then is connected to the vent. The actuator drives the push and pull action to respectively open and close the vent **(R3.4.7)**. The beam will be attached close to the fulcrum of the vent using a hinge, acting as a class 3 lever to maximize the amount the vent is opened. The actuator is located on the ground to maximize stability, and directly beneath the roof vent's fulcrum (Figure 38). In addition to the actuator itself, reed switches will be used to determine when the vent is either open or closed. As seen in (Figure 38), a magnet will be attached at the beam with one reed switch mounted at two locations on an adjacent beam. When the magnet passes over one of the switches, it will open the control circuit, and the motor will stop running.

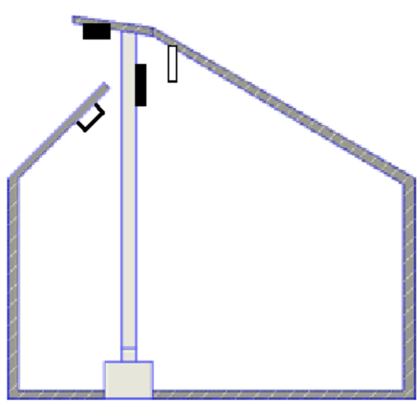


Figure 38: The linear actuator, magnet, and reed switch placement within the greenhouse (front view)

Despite the difference between the floor and roof vents, there will still be a balance between intake and exhaust. This is due to the intake fan, as any additional air drawn into the greenhouse will create a pressure difference, driving air out through the only other opening, the roof vent, and eliminating the need for an exhaust fan.

The current roof vent is for the prototype version only, as it is built into the greenhouse structure. Production versions may use exhaust-specific fans built into the roof for active ventilation, or use ridge vents to take advantage of natural wind-driven ventilation. Motor placement and roof vent opening mechanism could be optimized for space efficiency by securely supporting and fastening it under the bottom right side of the roof, with the beam running parallel to the underside of the roof.

The 163899 PUSH 900 linear actuator (Figure 31-C) is used because is it a salvaged motor. The linear motion simplifies the opening and closing configuration for the roof vent, eliminating the need to install a rotating motor.

Figure 39 depicts roof ventilation control circuit.

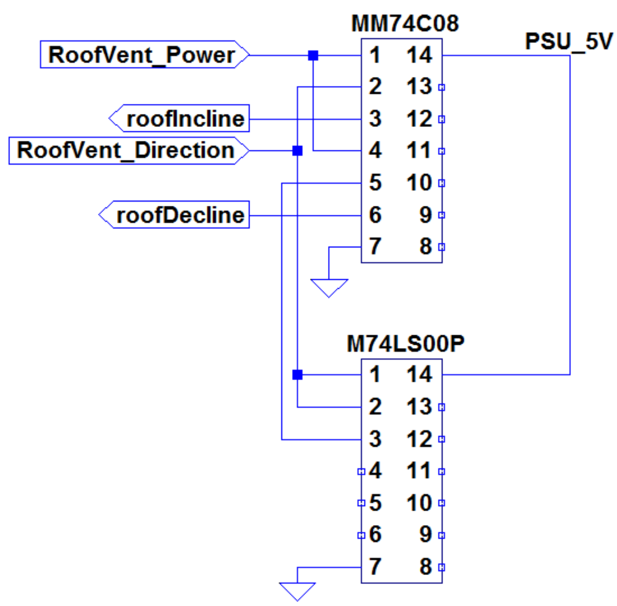


Figure 39: Circuit Diagram for Roof Ventilation Control

7.2.4 Temperature and Humidity Sensors

The air temperature and air humidification sensor readings are used to determine the state of the ventilation system. Two sensors will be secured on the outside of the greenhouse to measure the external environment temperature. By placing them on opposite walls of the greenhouse, the two readings will attempt to obtain an accurate average temperature in the case that one side of the greenhouse becomes shaded. Four sensors will be secured inside to measure the internal greenhouse temperature and humidity. They are secured at different heights on different walls, and not in the direct line of flow of any recirculation fan: on the underside of the roof peak, low in the back left corner beside the intake vent, low in the front right corner below the trough’s level, and high in the back right corner above the trough’s level (Figure 40). This placement ensures accurate temperature readings and an indication of air mixing. Referring to the ventilation test plan, exact sensor placement will be optimized with further testing.

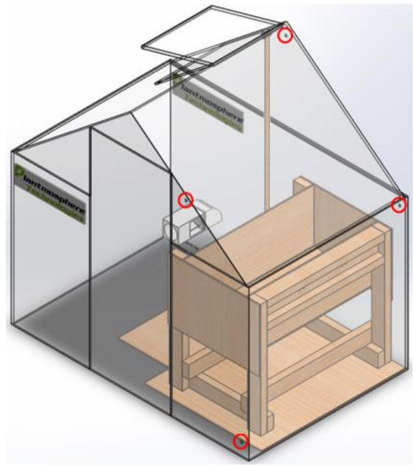


Figure 40: Internal Air and Humidity Sensor Placement

When the greenhouse air temperature is too high and the environment temperature is cooler, or the converse, the intake and exhaust vents will open, and the four fans will activate. This draws in external air, while expelling internal air, which equalizes the greenhouse’s air temperature. The vents will close when the internal temperature meets or adjusts as closely as possible to the optimal growing temperature.

The DHT11 temperature and humidity sensor (Figure 31-C) was chosen for its RoHS compliance, temperature and humidity reading ranges, low cost, compact size, and ability to read both temperature and humidity [17]. The DHT11 eliminates the need for wiring separate sensors for air temperature and air humidity, and instead outputs digital signals from one small and compact sensor. It is also a lot cost option, which has been proven to work well in other greenhouse projects seen on YouTube [18].

The DHT11 sensors are for the prototype version, but can also be used in production versions. The DHT22 is an upgraded version of the DHT11 sensor that provides more precise, accurate readings and a wider range of both temperature and humidity detection.

Figure 41 below is a circuit diagram of the soil temperature sensors.

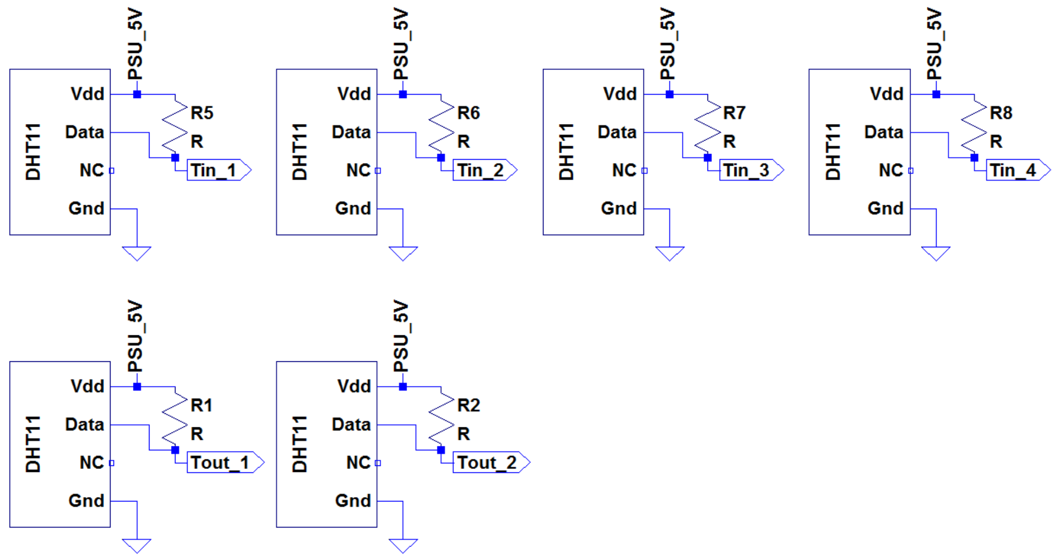


Figure 41: Circuit Diagram for Ambient Temperature Sensors

8 Soil Heating System

8.1 Theory

Germination is the active growth of a seed embryo, which is generally characterized by the sprouting or emergence of a plant from a seed [19]. The temperature of a seed's environment is a strong factor in facilitating seed germination and preventing seed dormancy. Dormant seeds will not germinate due to unstable and non-optimal environmental conditions. Soil temperature can be manipulated more quickly and with less energy expenditure than air temperature can be, by the use of a soil heating cable. Therefore, the Plantmosphere will use soil heating cables to best control the seed's local temperature.

Each seed type has its own optimal germination temperature. One study compared the germination percentages of two seed types. As depicted in Figure 42 below, one seed was more likely to germinate under cooler temperatures (~20 ˚C or 68 ˚F), whereas the other thrived under warmer conditions (~30 ˚C or 86 ˚F).

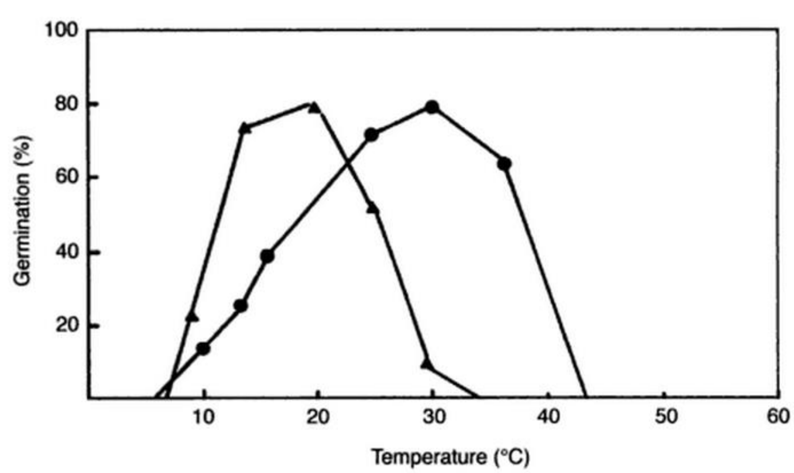


Figure 42: A Comparison of Germination Temperature Ranges for a Summer Plant (●) and Winter Plant (▲) [19]

Note that for our prototype we will be planting radishes. The ideal germination temperature range for a radish is 13-30 ˚C (55-85 ˚F) [20].

8.2 Design

8.2.1 Soil Warming Cable

The Gro-Quick electric soil warming cable is 24' in length, and generates heat at 3.5 W per linear foot (84 W in total).

The cable is equipped with a thermostat which activates the cable when it senses temperatures below 24 ˚C (74 ˚F). In future product revisions, the thermostat will be removed or replaced so as to support plants that have optimal germination temperatures which exceed 24 ˚C (74 ˚F). For the Plantmosphere prototype, the thermostat will not be the primary controller of the soil heating cable. Two DHT11 temperature sensors will control when the cable will be powered in order to prevent the soil from overheating as per **R3.7.2**.

The cable will be installed into the plant trough as per the layout depicted in Figure 43 below.

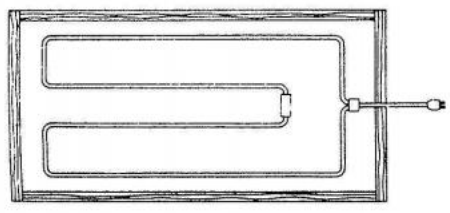


Figure 43: Soil Heating Cable Configuration [21]

The soil heating cable will be installed 3 inches from the surface of the soil (~2.5 inches from the seeds). It will be fastened to 0.5 inch steel hardware cloth with string every 6-9 inches.

The hardware cloth will protect the cable from being moved or damaged by gardening tools. Additionally, the cloth will facilitate even thermal distribution as per **R3.7.3**. Figure 44 demonstrates how the heating cable will be fastened to the hardware cloth.

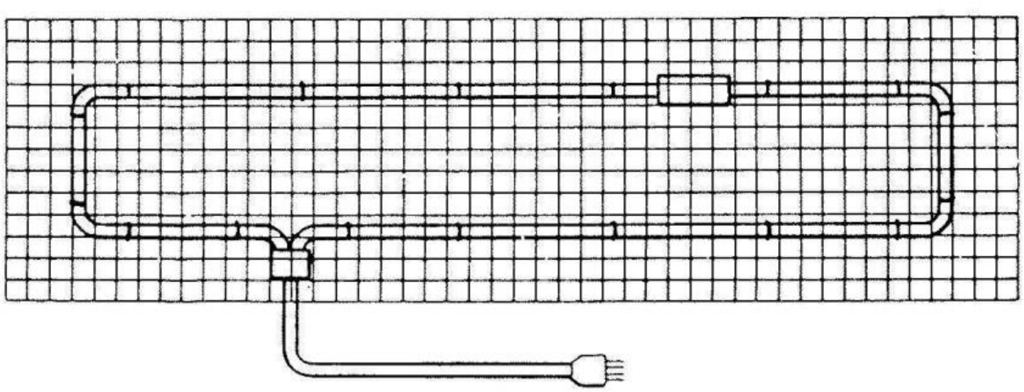


Figure 44: Soil Heating Cable Installation with Hardware Cloth [21]

Note that the cable configurations in Figure 43 and Figure 44 are recommended by the heating cable's datasheet. For our prototype, adjustments to these configurations are subject to change in order to satisfy requirements **R3.7.2** and **R3.7.3**. The degree to which these requirements are satisfied will be evaluated during test plan execution (refer to Section 15.7).

A soil heating cable is a simple solution that facilitates seed germination and plant growth by controlling soil temperature. We decided to select a soil heating cable instead of a soil heating mat due cost and power consumption. Additionally, soil heating mats are not completely waterproof. Table 12 below compares a soil heating mat versus a soil heating cable of approximately equal planting area coverage.

Table 12: Comparison Chart of Soil Heating Cable versus Soil Heating Mat [22] [23]

Item	Gro-Quick Soil Heating Cable	Warm Seedling Heat Warming Mat
Price (USD)	$34.66	$69.98
Power Consumption	84 W	127 W

Table 12 shows that the soil heating mat is approximately twice the price, and consumes 1.5 times as much power as the cable.

8.2.2 Soil Temperature Sensors

Two DHT11 temperature sensors will have two functions – to correct for the effect of temperature on the resistive soil moisture sensors, and to directly measure the temperature of the soil in order to control the soil heating cable. The sensors will be placed proximal to the soil moisture sensors as depicted in Figure 45. The left DHT11 is 12 inches from the left edge of the trough, and the right DHT11 will be placed 12 inches from the right edge of the trough. The sensors will be placed approximately 3 inches from the top of the trough so as to measure the soil temperature close to the heating cables.

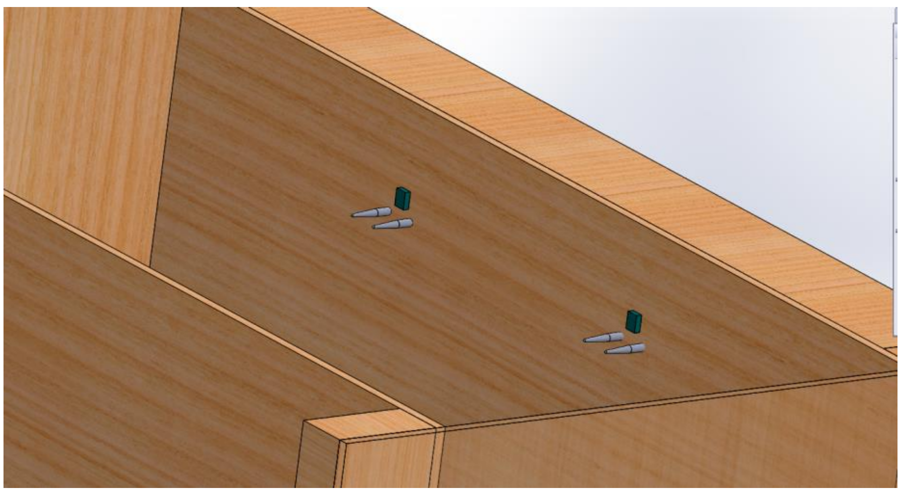


Figure 45: Soil Temperature Sensors Positions Relative to Soil Moisture Probes

Figure 46 below is a circuit diagram of the soil temperature sensors.

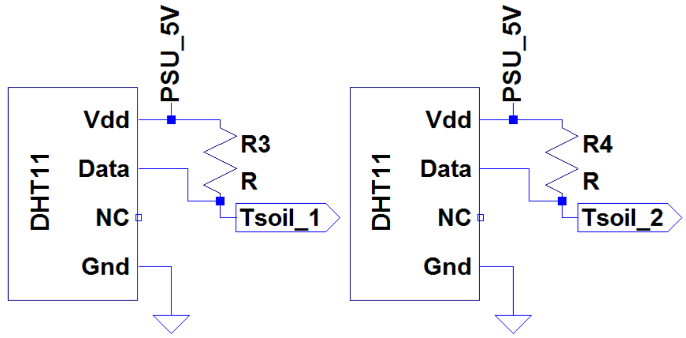


Figure 46: Circuit Diagram for Soil Temperature Sensors

9 Structure

The greenhouse structure houses the plants and automating system components, serving as the barrier to isolate the external and internal environments. Its floor area is 6 feet by 4 feet, large enough to house all components and accommodate at least one user **(R2.3.9)**. The structure contains a lockable door to ensure a secure seal **(R2.3.2)**. Its roof vent is utilized as an exhaust vent, with an attached beam down to the vent motor. An intake vent is designed and installed into a wall cutout in the greenhouse structure. A raised trough contains the soil and plants and is situated on a plywood board, which is also the foundation for the bolted down roof vent motor (refer to Figure 47).

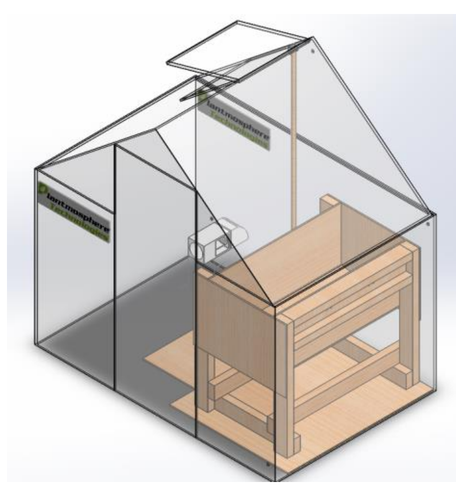


Figure 47: Greenhouse Structure with Trough and Fan

The greenhouse structure chosen is the Palram Mythos 701636 (described in Table 13) for its construction materials, rigid structure, built in roof vent, and low cost. Other greenhouse start-up kits used a pop-up set up, and offered no sturdiness. The Palram Mythos offers a rigid structure built with corrosion resistant galvanized steel frame, and polycarbonate walls for both thermal insulation and UV protection **(R2.3.8)**. The structure is waterproof, and holds built in gutters along the outside, which accommodate hoses for a convenient water collection system **(R2.3.5)** [1]. The rigidity of the structure allows a vent to be installed by cutting into the wall, without having the structure collapse. This start-up was also cost effective, and eliminated the need to design or build a greenhouse structure from scratch.

Table 13: Greenhouse Description

Part	Model Number	Quantity	Description
Greenhouse Structure	Palram Mythos 701636	1	82in x 72.8in x 51.1in 100% UV protected Rust-resistant, corrosion-free Roof vent Gutter

The Palram's small dimensions are acceptable for the Plantmosphere's prototype version, but production versions will likely be larger to sustain larger scale food growth.

The trough will be constructed from wood. The bottom of the trough will be sloped towards the middle and perforated with ¼ inch holes on 2 inch centers to allow water to drain out of the soil into a water collection pipe. (refer to Figure 51 and Figure 49). This water drips into a collection pipe, which runs the length of the trough, and is funneled into the water reservoir. The trough itself is secured on a plywood board, raised to provide space for the water recollection pipe, and to elevate the soil level to an ergonomic height of thirty-five inches **(R2.3.7)**. It is placed on the right side of the greenhouse to prevent rainwater from falling through the roof vent directly into the trough, preventing over watering and protecting the LED array (Figure 50). Soil moisture and temperature sensors are attached directly onto the inside wall of the trough (Figure 51).

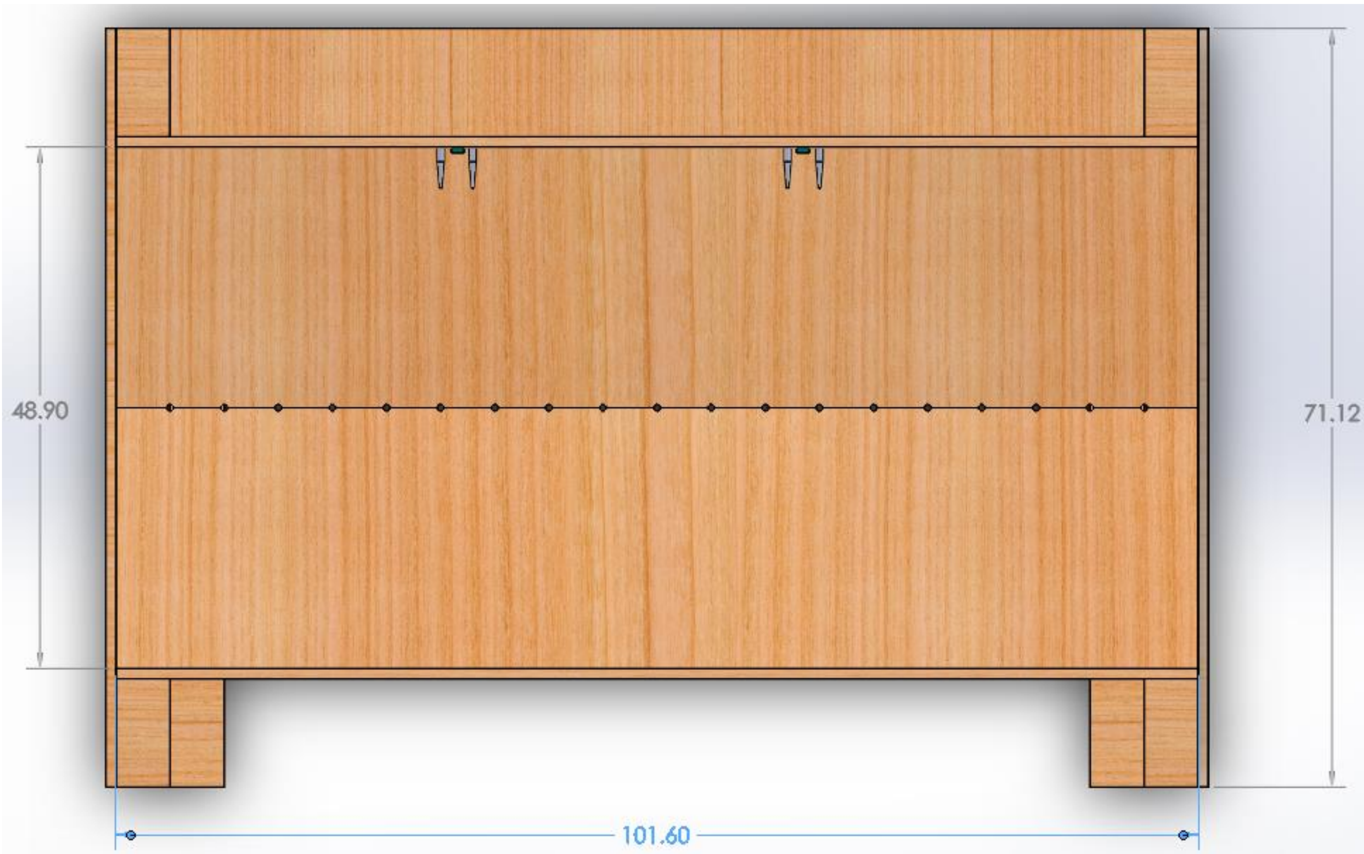


Figure 48: Perforated and Tapered Base (top view)

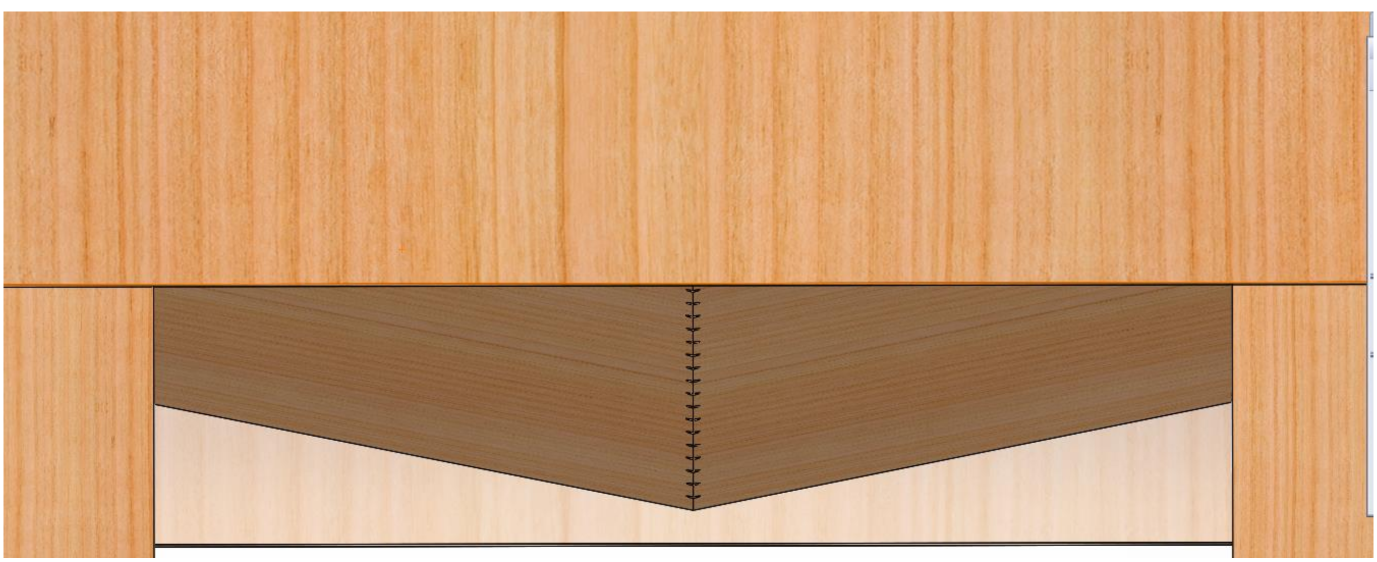


Figure 49: Perforated and Tapered Base (looking from below)

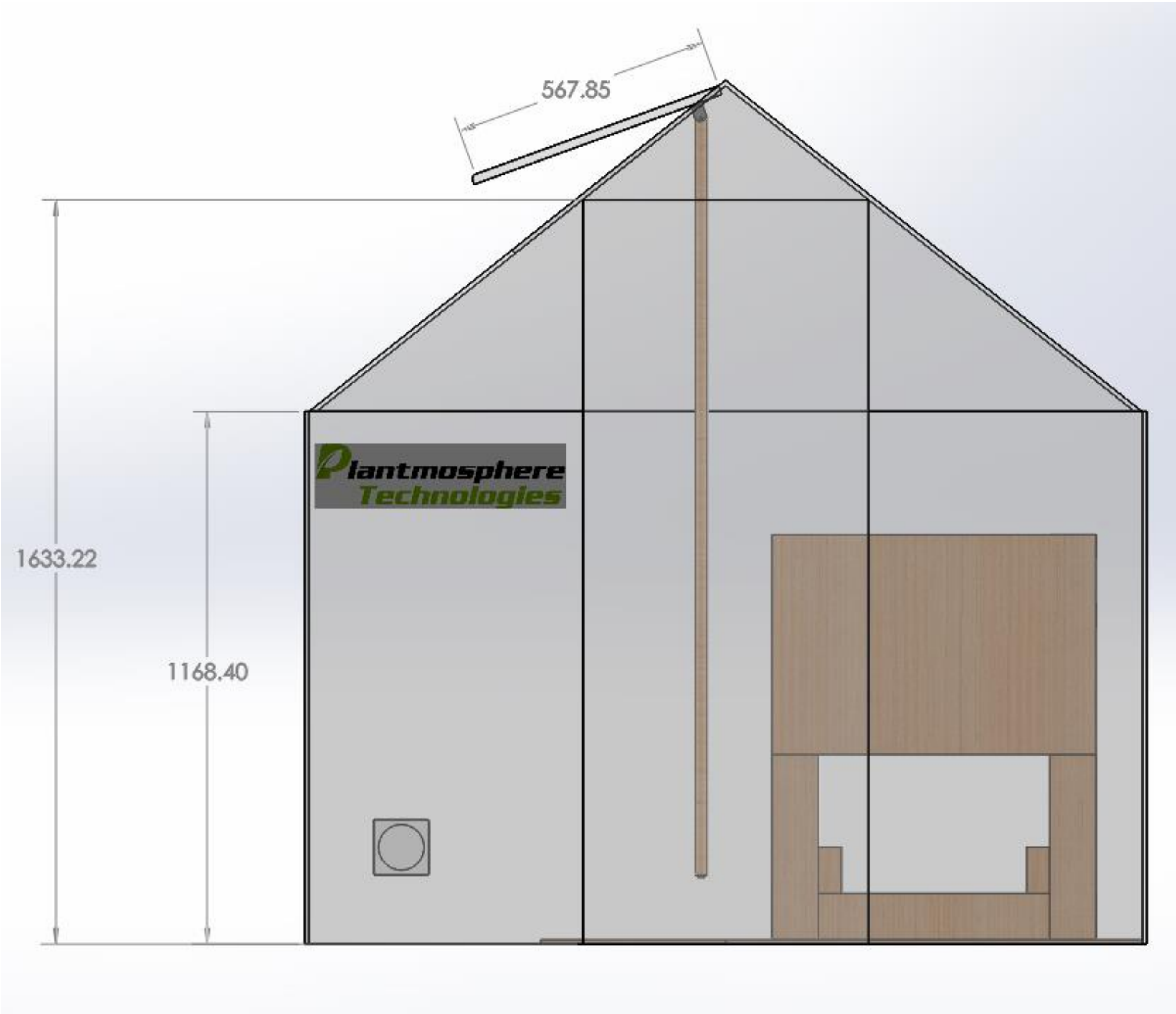


Figure 50: Trough Placement (front view)

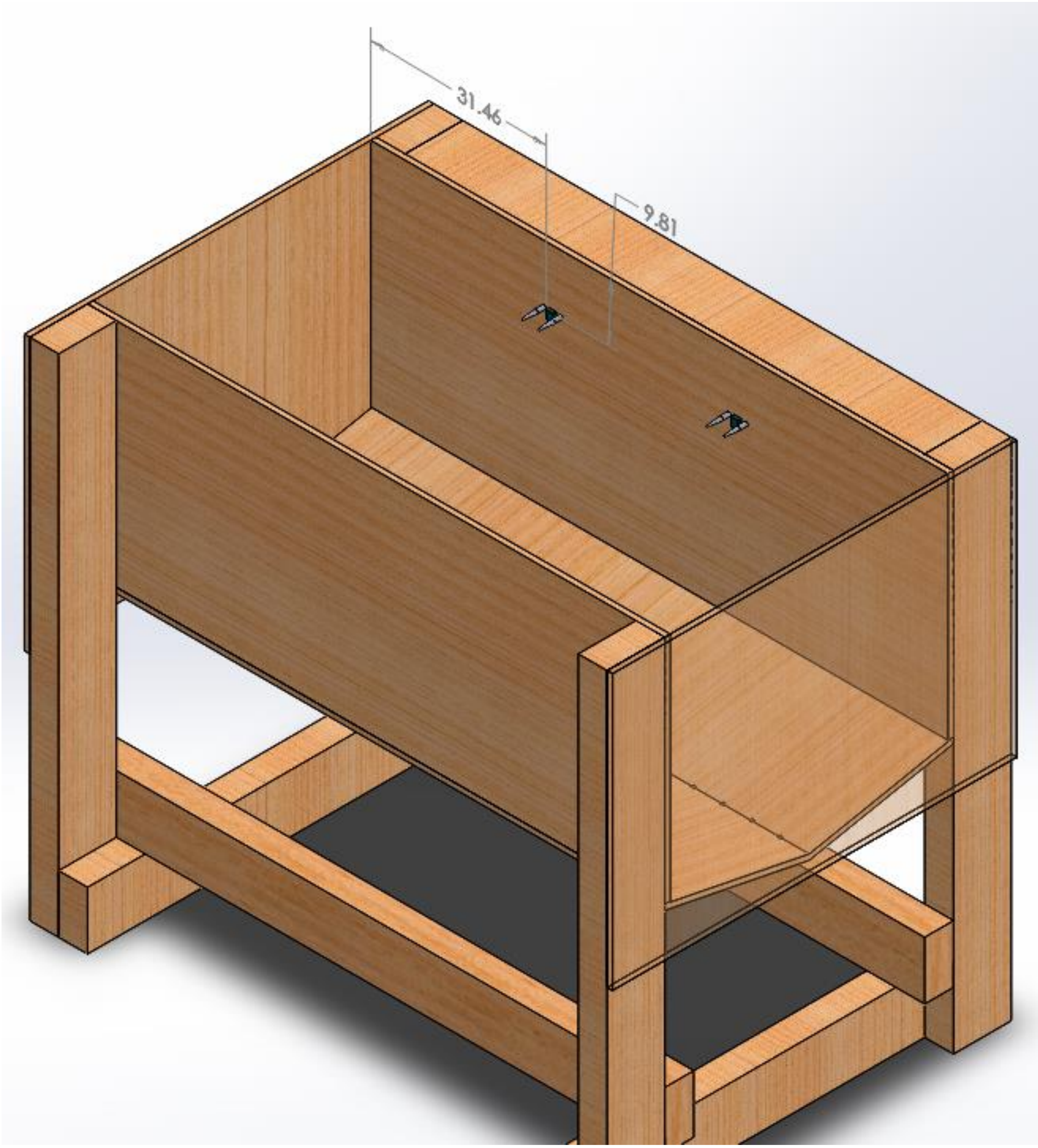


Figure 51: Raised Trough (3D view)

10 Water Reservoir

10.1 Design

The water reservoir will hold water retrieved by the rainwater capture system. The reservoir itself will be a 55 gallon food-grade plastic barrel, similar to the one depicted in Figure 52. The collected rainwater will flow from the gutters, through a tubing system, and into the barrel. In order to distribute the water to the humidification and irrigation systems, a submersible pump will be placed at the bottom of the barrel.

Figure 52: A 55 gal food-grade plastic barrel for use as a water reservoir [25]

The lid of the reservoir will be sealed to prevent users from accessing the water (**R2.5.10**). The other openings in the reservoir body will be small in diameter to minimize the diffusion rate of water vapour out of the reservoir. The connections between the reservoir and all tubing will be made by drilling and tapping holes in the lid and installing 3/8 inch male National Pipe Thread (NPT) to female 1/4 inch outer diameter tube quick connect fittings, as shown in Figure 53. These fittings will allow users to quickly and easily replace damaged tubing, or to disconnect the reservoir for transportation.

Figure 53: A 3/8" male NPT to female 1/4" OD quick connect fitting [26]

In the event that the water reservoir is already full and continues to receive more water, it needs to be able to safely overflow. The diagram shown in Figure 54 below outlines a method for overflow protection. When the water level in the reservoir rises above the top of the overflow pipe, any additional water will flow into the overflow pipe and out of the reservoir, being safely guided towards an exterior drainage site.

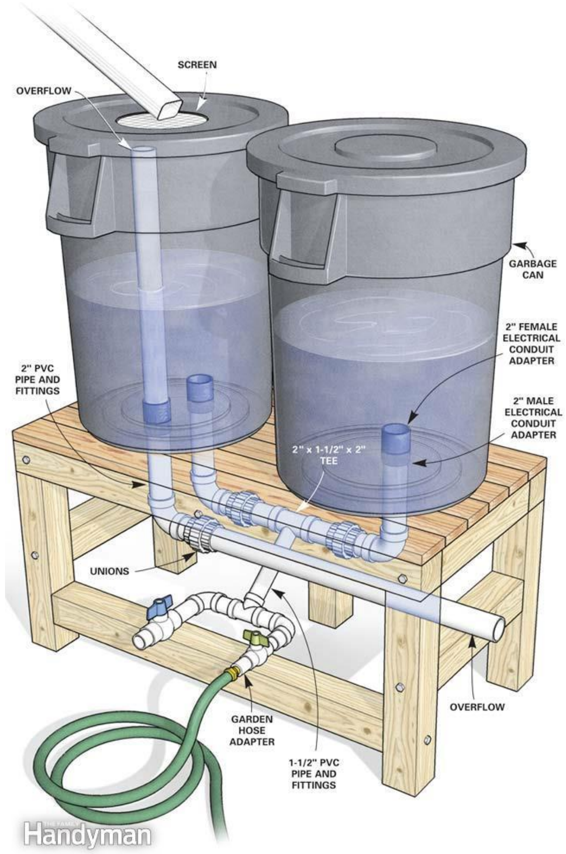


Figure 54: The overflow plumbing configuration [27]

10.1.1 Water Level Sensor

To monitor the reservoir's water level, a waterproof ultrasonic distance measuring module will be used, as seen in Figure 55 (**R3.6.11**). The module will be installed in the lid of the reservoir to monitor the amount of remaining water, and if the level becomes too low, the Arduino will disallow pump activation in order to protect it from being damaged.

Figure 55: A waterproof ultrasonic distance measuring module for water level monitoring [28]

The sensor has a range of 4 m and dissipates 75 mW when in operation. It measures the distance from the bottom of the tank by sending a pulse, receiving the reflection, and measuring the elapsed time.

10.1.2 Water Level Sensor

The Plantmosphere will use an ultrasonic distance water level sensor (Figure 55) to be placed in the reservoir (**R3.6.11**). The sensor uses a high frequency, has a distance range of 400 cm, and low power consumption dissipating 75 mW when in operation. Placing this just outside the tank, it measures the distance from the bottom of the tank and back by sending a pulse transmission and receiving the reflection of that pulse. If the water level in the tank is low, the sensor will communicate with the Arduino to ensure that the water pump cannot turn on for there is not enough water.

11 Software

11.1 Arduino

Once written, the Arduino program (known as a “sketch”) will be loaded onto the Arduino with the Arduino Integrated Development Environment (IDE). The Arduino code will be comprised of two primary functions. The **setup()** function executes at the time the Arduino is powered on. Initialization of I/O pins will occur during **setup()** execution. The second primary function is **loop()**, which executes after **setup()** completes, and continuously iterates until the Arduino is powered off. The **setup()** function will serially execute blocks of code that correspond to sensor-actuator pairs. For example, in one block of code, light will be sampled from the photo-resistors and LED light intensity will be adjusted accordingly (refer to Section 12.6). The next block of code will correspond only to ventilation and then the next block to soil heating etc. until every electronic component of the Plantmosphere has been monitored and/or controlled as per **R4.1.2** and **R4.1.3**. This program infrastructure is ideal because it prevents more than one Arduino I/O pin from being accessed at the same time, which the Arduino Mega 2560 is not equipped to do without port registers. Port manipulation is unnecessary for Plantmosphere’s functionality, and makes code difficult to debug and maintain. Therefore, the Arduino code used to control the Plantmosphere system will be implemented using the simple processes depicted in Figure 56 and Figure 57 below.

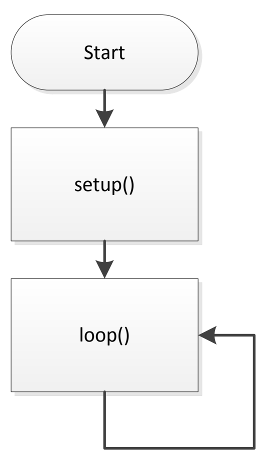


Figure 56: Flow Chart of Arduino Code Execution

Thus far in the prototype design process, no particular order of execution has been deemed more beneficial than any other. Therefore, the implementation flow chart in Figure 57 below depicts an arbitrarily selected order of execution for individual system code blocks.

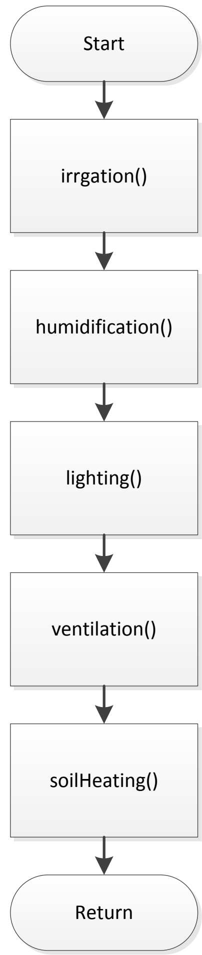


Figure 57: *loop()* Implementation Flow Chart

`loop()` executes additional code that is not depicted in Figure 57. The water level sensor will be checked to ensure that there is still a sufficient volume remaining in the trough (**R3.6.12**). All of the measurements sampled by the Arduino will be stored (**R4.1.4**) in a microSD card via the data logging shield. The sensor measurement values will be acquired at the beginning of `loop()`.

In order to avoid introducing any delays in `loop()`, the ventilation code will not issue any commands to actuators, or use any explicit delay commands. Each sub-system will analyze the latest set of sensor measurements, make decisions based on this information, and request actions for the actuators in order to best control that system's control variables. These flags will be inspected at the beginning of the next iteration of the `loop()`, function. If any sub-systems have requested conflicting commands for a given actuator then the microcontroller will decide which sub-system should get priority control over the actuator. For example, if `ventilation()`, wants to open the vents in order to warm up the greenhouse, but `humidification()`, wants the vents to remain closed because the exterior humidity is higher than its threshold value, then the Arduino will do whatever is necessary to keep both control variables (tempIn and rhIn) as close to their target values as possible.

By structuring our algorithm in this client-server model, we allow the Arduino to arbitrate disputes that may arise between the different sub-systems with different needs. This helps in finding the most optimal solution in a way that is intuitive to implement in code. Additionally, structuring each sub-system's code to introduce no delays of their own allows the Arduino to sample the sensors at the highest possible rate, ensuring that information about transient behavior (of light intensity, for example) will not be lost due to under-sampling.

11.2 System Variables

Table 14: Lighting System Variables

Variable Name	Variable Description
timeNew	Current time of day as measured by the Real Time Clock (RTC)
timeOld	Temporary variable containing the time of day from the previous code block execution
timeSunrise	Time of sunrise
timeSunset	Time of sunset
timeQuota	Time of light exposure quota for housed plant
dayBegin	Flag indicating that daytime has been detected: 1: Day has begun 0: Day hasn't begun yet
lightpowerIn	Amount of light measured inside the greenhouse
lightpowerOut	Amount of light measured outside of the greenhouse
energyAccu	Current energy accumulated by the plant
energyQuota	Daily light exposure quota for housed plant

Table 15: Ventilation System Variables

Variable Name	Variable Description
tempInStdDev	Standard deviation across multiple samples of temperature within the greenhouse
tempInStdDevMax	Maximum acceptable standard deviation across multiple samples of temperature within the greenhouse
tempOutStdDev	Standard deviation across multiple samples of temperature outside the greenhouse
tempOutStdDevMax	Maximum acceptable standard deviation across multiple samples of temperature outside the greenhouse
tempIn	Temperature within the greenhouse
tempOut	Temperature outside the greenhouse
tempMin	Minimum acceptable greenhouse temperature
timeMax	This is the longest consecutive amount of time that it is acceptable for the specified plants to spend outside of their temperature range: [Tmin, Tmax]
timeOK	This is the amount of time it will take for the internal temperature to return to the acceptable range, specifically, to become equal to the average of Tmin and Tmax
fanStateReq_V	Request flag from the Ventilation system: 'ON' is a request to turn the fans on, 'OFF' is a request to turn the fans off, and 'OK' indcates that the Ventilation system doesn't care about the fan's state
ventStateReq_V	Request flag from the Ventilation system: OPEN' is a request to open the vent, 'OFF' is a request to close the vent, and 'OK' indcates that the Ventilation system doesn't care about the vent's state

Table 16: Irrigation System Variables

Variable Name	Variable Description
moistureSoil	Moisture level of the soil as measured by the soil moisture sensors
moistureSoilMin	Minimum acceptable soil moisture level
moistureSoilMid	Soil moisture level that is the midpoint between moistureSoilMin and moistureSoilMax
moistureSoilMax	Maximum acceptable soil moisture level
pumpStateReq_I	Request flag from the Irrigation system: 'ON' is a request to turn the pump on, 'OFF' is a request to turn the pump off
ventStateReq_I	Request flag from the Irrigation system: 'OPEN' is a request to open the vent, 'CLOSED' is a request to close the vent
misterSolenoidStateReq_I	Request flag from the Irrigation system: 'OPEN' is a request to open the mister solenoid, 'CLOSED' is a request to close the mister solenoid
dripSolenoidStateReq_I	Request flag from the Irrigation system: 'OPEN' is a request to open the drip solenoid, 'CLOSED' is a request to close the drip solenoid

Table 17: Humidification System Variables

Variable Name	Variable Description
rhIn	Relative Humidity within the greenhouse as measured by the humidity sensors
rhOut	Relative Humidity outside of the greenhouse as measured by the humidity sensors
rhMin	Minimum acceptable Relative Humidity level
rhMid	Relative Humidity level that is the midpoint between rhMin and rhMax
rhMax	Maximum acceptable Relative Humidity level
pumpStateReq_H	Request flag from the Irrigation system: 'ON' is a request to turn the pump on, 'OFF' is a request to turn the pump off
ventStateReq_H	Request flag from the Irrigation system: 'OPEN' is a request to open the vent, 'CLOSED' is a request to close the vent
misterSolenoidStateReq_H	Request flag from the Irrigation system: 'OPEN' is a request to open the mister solenoid, 'CLOSED' is a request to close the mister solenoid
dripSolenoidStateReq_H	Request flag from the Irrigation system: 'OPEN' is a request to open the drip solenoid, 'CLOSED' is a request to close the drip solenoid

Table 18: Soil Heating System Variables

Variable Name	Variable Description
tempSoil	Temperature of the soil as measured by the soil temperature sensors
tempSoilMin	Minimum acceptable soil temperature
tempSoilMid	Temperature of the soil that is the midpoint between tempSoilMin and tempSoilMax
tempSoilMax	Maximum acceptable soil temperature
heatcableStateReq_S	Request flag from the Soil Heating system: 'ON' is a request to turn the soil heating cable on, 'OFF' is a request to turn the soil heating cable off

11.3 Humidification Control

Internal humidity levels within the greenhouse will be controlled with threshold detection. The Arduino will monitor the humidity with the DHT11 sensor. If humidity levels fall outside of the configured ideal threshold range configured for the housed plant, the Arduino will assert a request flag to activate the misters. In order for the misters to activate, the pump must be on and the mister solenoid must be open. An overview of the humidification control algorithm to be implemented in Arduino code is depicted in Figure 58 below.

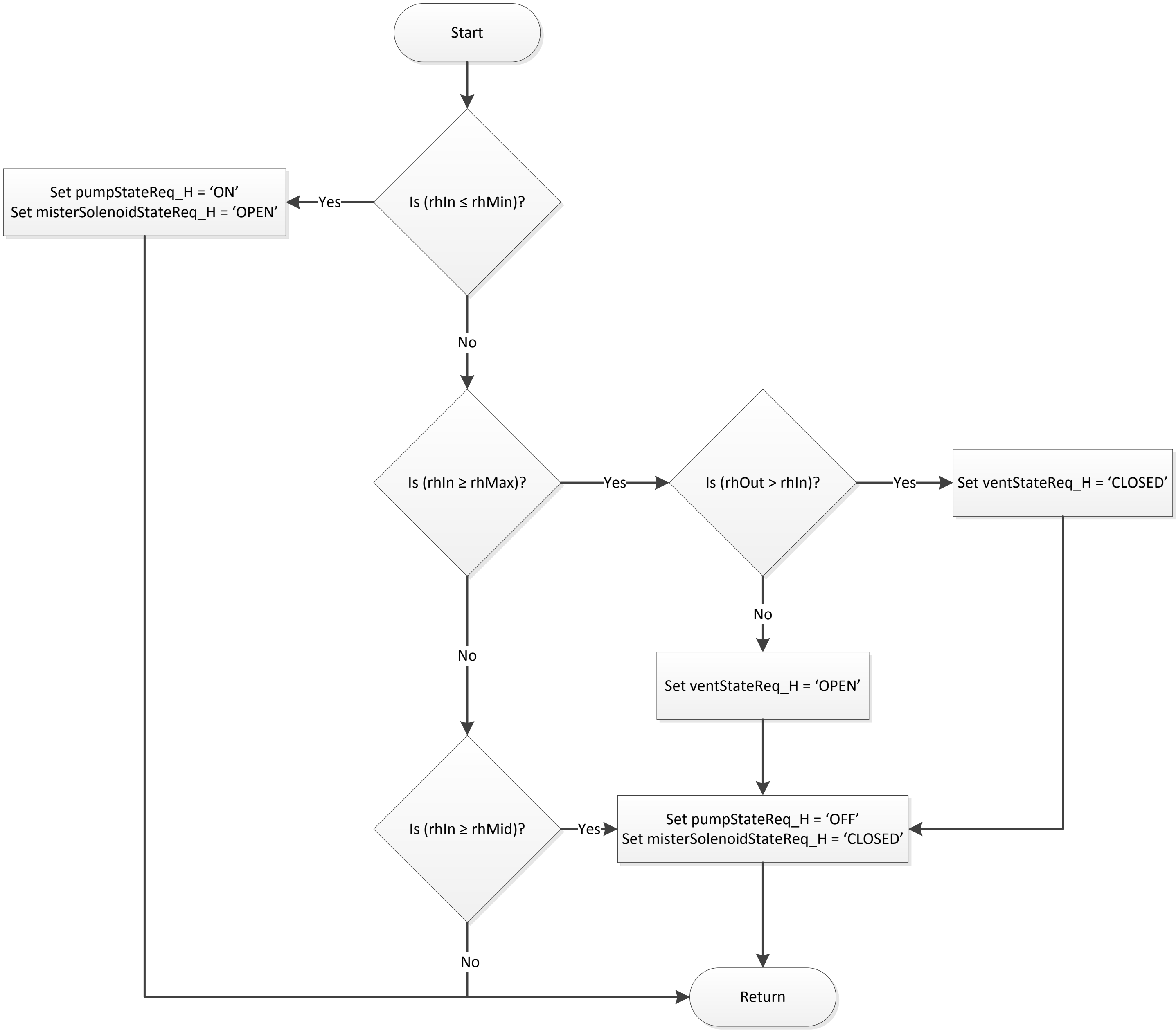


Figure 58: ***humidification()*** **Implementation Flow Chart**

11.4 Irrigation Control

The position of the irrigation solenoid is controlled by the soil moisture level. When soil moisture is low, the irrigation control function will send a request to the main loop for the water pump to turn on and the drip irrigation solenoid to open. When the moisture level reaches an acceptable value, the irrigation system will request for the drip irrigation solenoid to close. Since the irrigation and humidification systems use the same pump, the program will then check to see if the mister solenoid is closed. If the mister solenoid and the irrigation solenoid are both closed, the program will turn off the pump as well. An overview of the humidification control algorithm to be implemented in Arduino code is depicted in Figure 59 below.

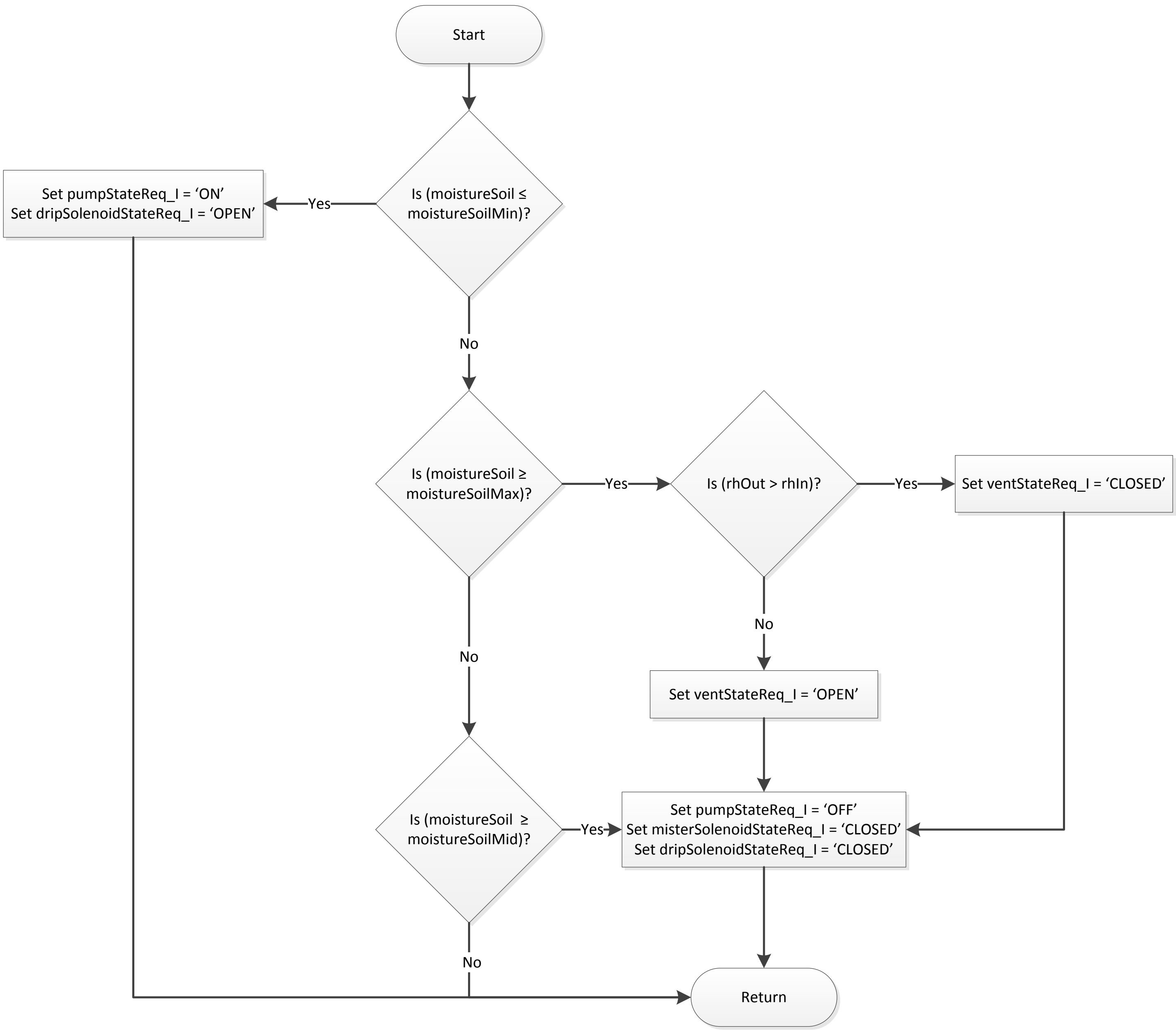


Figure 59: `irrigation()` Implementation Flow Chart

11.5 Ventilation Control

The ventilation system is responsible for maintaining the appropriate internal air temperature. This code will monitor the internal and external temperatures, and then compare these values to plant-specific target values, taking appropriate actions to control the temperature, as shown in Figure 60 below. Instead, `ventilation()` will set global variables requesting particular actions for the fans and vents: `fanStateReq_V` and `ventState_Req_V` respectively. These two flags are string variables that indicate what the vents and fans should be doing in order to optimize the interior air temperature exclusively.

One energy-saving technique that Ventilation employs is to look at temperature *trends*, as well as the instantaneous value. When the interior air temperature (`tempIn`) goes out of range, the Arduino will look at the previous several minutes of logged temperature data, and determine whether the trend is continuing, or if it is turning around. If it looks as though the temperature will soon return to its desired range naturally, then it will be allowed to do so naturally, without expending any electrical energy on the actuators. If instead the microcontroller finds that `tempIn` is drifting even farther from the desired value, it will attempt to use the vents and vans to correct this imbalance, if possible, by exchanging air with the outside.

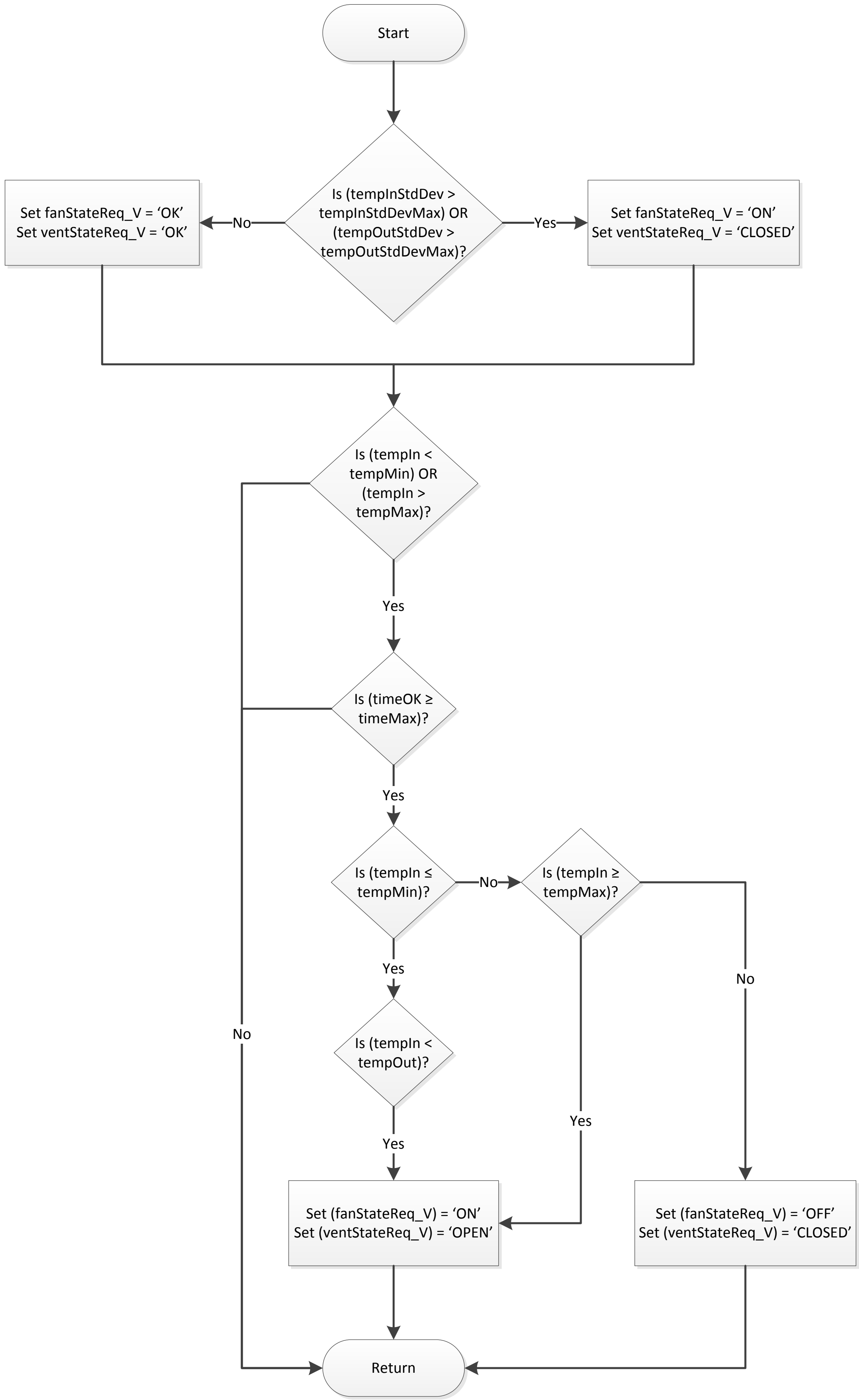


Figure 60: *`ventilation()`* Implementation Flow Chart

11.6 Lighting Control

To control the lighting system, photocells will be used to monitor light intensity both inside and outside the greenhouse. Subsequently, the need for additional lighting will be determined based on a number of factors including total accumulated light energy exposure, approximate time of sunset and sunrise, and the daily light exposure quota. Figure 61 below depicts an overview of the implementation of *`lighting().`*

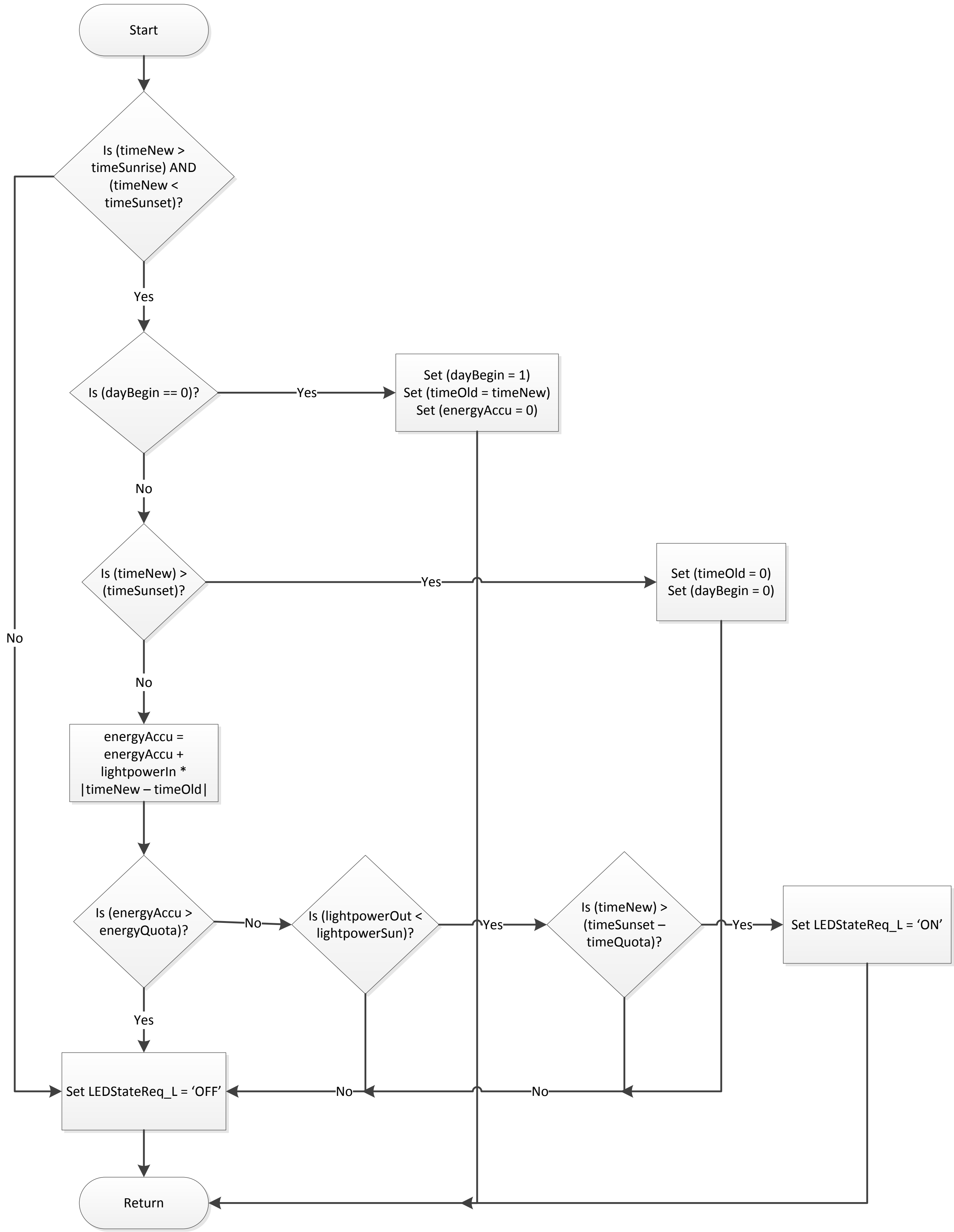


Figure 61: *lighting()* Implementation Flow Chart

Note that the time exposure quota is defined as 6.58 hours, while the energy exposure quota is a maximum of 5.0 kW·h as outlined in Section 7.1. Exposing the plants to further lighting could cause them harm, so the LEDs are only allowed to be activated when the current time of day is greater than the difference between the approximate sunset time and the daily light exposure quota. Furthermore, the sunset time has been approximated to be at 5 P.M. as the product demonstration will take place in winter in Vancouver.

Future product revisions will be able to determine a more accurate sunset time using the sunrise equation seen below:

$$sunrise\ time = 720 + 4\left[lon - \cos^{-1}\left(\frac{\cos(90.833)}{\cos(lat)\cos(decl)} - \tan(lat)\tan(decl)\right)\right] - eqtime, \quad (2)$$

where lon is the longitude, lat is the observer's latitude, $decl$ is the sun declination, and $eqtime$ is the equation of time [28]. Note that this equation is used to determine both the Coordinated Universal Time (UTC) sunrise and sunset times [28].

11.7 Soil Heating Control

Soil heating control will be performed by monitoring the temperature sensed by the DHT11 sensor, and turning the soil heating cable on and off based on the temperature value. Our control algorithm is based on a threshold range of acceptable temperature values. If the soil temperature falls outside of this range, the Arduino will signal the cable to activate or deactivate as necessary. An overview soil heating control to be implemented with Arduino code is depicted in Figure 62 below.

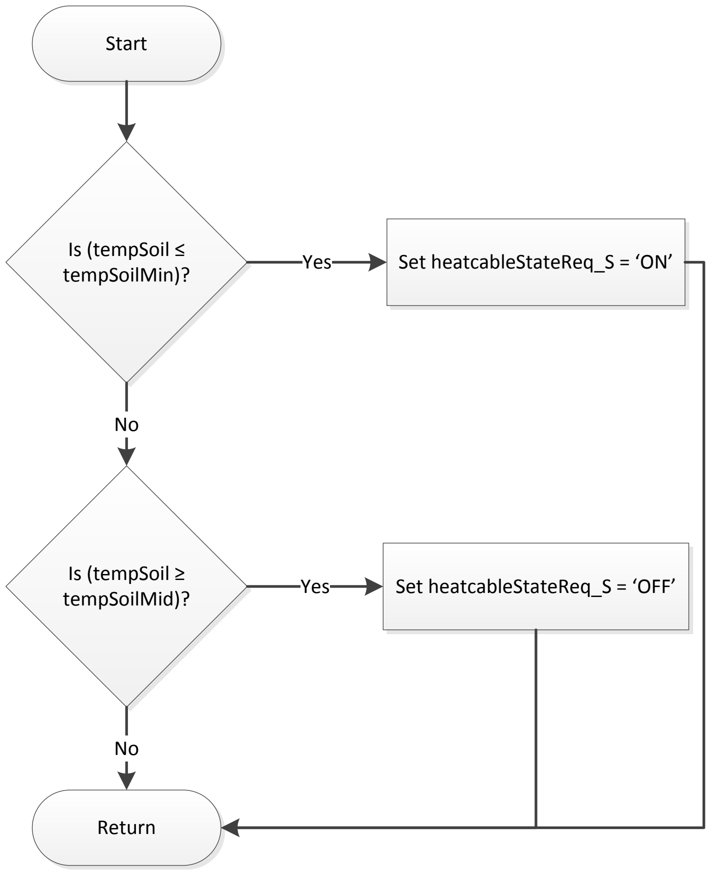


Figure 62: *`soilHeating()`* Implementation Flow Chart

Note that the program will bring soil temperature into the acceptable temperature range (`tempSoilMid`). This is to prevent cycling between turning the cables on and off in the case where soil temperature is straddling the upper or lower threshold value.

12 Power

12.1 Design

12.1.1 Power Supply

Power for the Plantmosphere must to come in the form of both Alternating Current (AC) and Direct Current (DC). To satisfy this need, we will use mains electricity in accordance with **R2.4.3**. A power strip with a Ground Fault Circuit Interrupt (GFCI) breaker will be used to divide power among the devices, as seen in Figure 63 below. Components requiring AC power will get their power directly from the power strip, while those requiring DC power need a dedicated power supply. The projected worst case power consumption for AC devices can be found in Table 10 below.

Figure 63: The TLM609GF power strip with a GFCI breaker [29]

Table 10: Summary of the worst case power requirements for all AC components at 120 V

Component	Quantity	Unit Power Consumption (W)	Total Component Power Consumption (W)
TLM609GF Power strip	1	5.22	5.22
163899 PUSH 900 Linear Actuator	1	50	50
Gro-Quick 24' Electric Soil Warming Cable	1	84	84
Bur-Cam 1/3 Hp Noryl Submersible Pump	1	150	150
Total			**284**

In order to conform with **R3.2.3**, we will be using the LOGISYS PS480D-BK 480 W ATX (Advanced Technology eXtended) form factor Power Supply Unit (PSU) (see Figure 64) for all DC devices. The components we've chosen in each sub-system follow this standard, ensuring that they are operating in their rated voltage ranges. Additionally, the selected PSU has a multitude of outputs at common voltages. The PSU's electrical specifications can be found in Table 11 below:

Figure 64: LOGISYS PS480D-BK 480 W ATX form factor PSU [30]

Table 11: Electrical specifications for the 480 W ATX form factor PSU

Parameter	Value
AC Input Voltage	110-120/200-240 VAC

DC Output Voltage	+3.3 V @ 28 A	+5 V @ 36 A	+12 V @ 16 A	-12 V @ 0.8 A
Maximum Power	92.4 W	180 W	192	9.6
Number of Outputs	6	11	11	1

To ensure that the power limit is not exceeded, our components have been selected such that they use minimal current at low voltages. Table 12 and Table 13 below summarize the power requirements of all DC components in the worst case scenario:

Table 21: Summary of the worst case power requirements for all 5 VDC components

Component	Quantity	Unit Power Consumption (mW)	Total Component Power Consumption (mW)
2N4401 NPN Transistor	4	0.0005	0.002
M74LS00P NAND Gate Array	1	0.1	0.2
PDV-P8104 Photocell	5	0.42	2.1
DHT11 Temperature & Humidity Sensor	8	12.5	100
MM74C08 AND Gate Array	1	7.5	30
Soil Moisture Sensor	2	250	500
SainSmart 8 Channel Relay	1	600	600
ULN2803A NPN Darlington Transistor Array	1	700	700
TIP41C NPN Power Transistor	3	315	945
Arduino Mega 2560 Microcontroller	1	1000	1000
5060BRG LED Strip	50	215	10750
Total			**14627.3**

Table 22: Summary of the worst case power requirements for all 12 VDC components

Component	Quantity	Unit Power Consumption (W)	Total Component Power Consumption (W)
LOGISYS PS480D-BK Power Supply Fan	1	1.8	1.8
26M048B2U DC Stepper Motor	1	6	6
997 Solenoid	3	3.84	11.52
AFB1212VH-T500 DC Fan	4	4.8	19.2
Total			**38.52**

The aforementioned power method has been chosen due to its simplicity, high reliability, and safety features. Using a pre-fabricated solution permits us to focus on other sub-systems which are not off-the-shelf products and require more in-depth design and testing. The PSU is well-suited for our power requirements and uses standardized connectors and voltage levels. When not in use, the PSU can be powered down by the Arduino to conserve energy.

Initially, AC/DC wall adapters were considered, but their size, lack of ground connector, and cost lead us to consider alternative options. Moreover, the PSU was donated by a group member, allowing us to allocate our financial resources to other systems.

In later product revisions, we aim to power the Plantmosphere with a self-sustainable power source, which will require a means to store energy. To evaluate storage needs, Table 23 below presents approximations for power consumption in an average day.

Table 23: Approximate power consumption in an average day

Component	Approximate Uptime (hrs.)	Total Watt-hours (W·h)	Supply Voltage	Total Amp-hours (A·h)
2N4401 NPN Transistor	6	0.000012	5 VDC	0.0000024
M74LS00P NAND Gate Array	0.25	0.000125	5 VDC	0.000025
MM74C08 AND Gate Array	0.25	0.0075	5 VDC	0.0015
PDV-P8104 Photocell	12	0.0252	5 VDC	0.00504
DHT11 Temperature & Humidity Sensor	6	0.45	5 VDC	0.09
ULN2803A NPN Darlington Transistor Array	0.25	0.175	5 VDC	0.035
163899 PUSH 900 Linear Actuator	0.25	12.5	120 VAC	0.1042
SainSmart 8 Channel Relay	2	1.2	5 VDC	0.24
26M048B2U DC Stepper Motor	0.25	6	12 VDC	0.5
Soil Moisture Sensor	6	3	5 VDC	0.6
Gro-Quick 24' Electric Soil Warming Cable	1	84	120 VAC	0.7
997 Solenoid	1	11.52	12 VDC	0.96
TLM609GF Power strip	24	125.28	120 VAC	1.044
Bur-Cam 1/3 Hp Noryl Submersible Pump	1	150	120 VAC	1.25
Power Supply Fan	10	18	12 VDC	1.5
TIP41C NPN Power Transistor	8	7.56	5 VDC	1.51
AFB1212VH-T500 DC Fan	1	19.2	12 VDC	1.6
Arduino Mega 2560 Microcontroller	24	57.6	12 VDC	4.8
5060BRG LED Strip	8	86	5 VDC	17.2
Total				**32.07**

Taking into consideration the fact that we must comply with **R2.5.5** (note, however, that RoHS does not cover batteries [31]), it would be wise to use Lithium-ion (Li-ion) batteries despite their premium cost and rapid aging [32].

To choose a storage capacity, we must first regard the charging limitations of Li-ion batteries. As seen in Figure 65 below, the battery charges with a constant current (Stage 1) until it saturates (Stage 2). Once the current reaches a pre-determined level, which is typically about three percent of the rated current, current stops flowing (Stage 3) until the stored charge is approximately five percent of the rated current (Stage 4). Applying voltage to the battery past the last two stages risks stressing and damaging the battery.

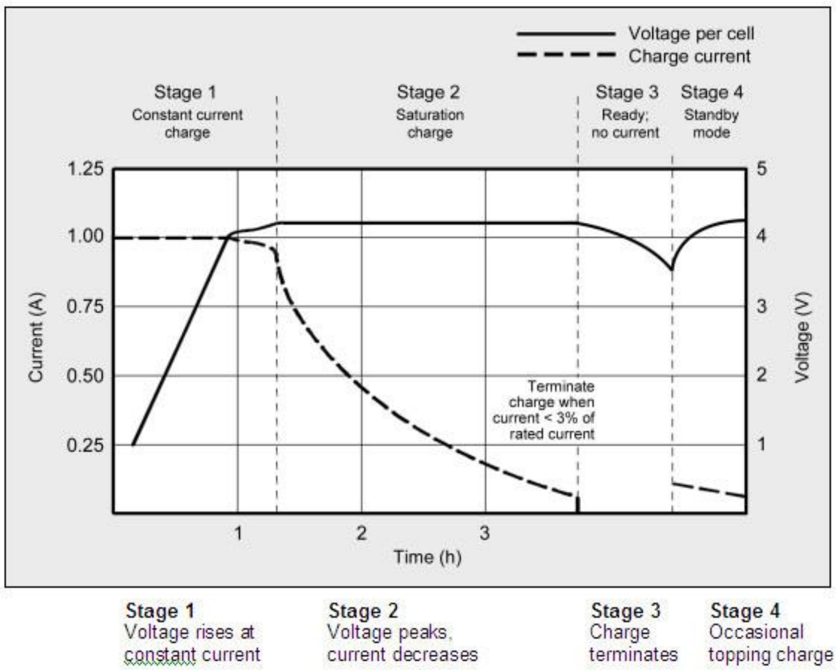


Figure 65: The charging stages of Li-ion batteries [33]

Furthermore, over-discharging these batteries can also increase aging. To maximize the life of any Li-ion battery, then, it is paramount that their storage capacity be based on power generation and dissipation rates.

Using the results from Table 23, it is apparent that about 33 A·h flows within the circuit in a given day. To keep the battery from discharging below twenty percent or charging above ninety seven percent, this value represents about eighty percent of the total battery capacity. Therefore, the storage capacity should be approximately 42 A·h, but to allow a larger window for error, we will use a 50 A·h battery. A potential candidate can be seen in Figure 66 below.

Figure 66: The 50 A•h Li-ion battery [34]

The main technology we will examine is solar power generation. Based on the previous analysis and assuming five hours of peak sunlight, we would require a solar panel capable of producing about 16 W in the same amount of time. We are then forced to use a 3 W solar panel at the minimum, which can be found in Figure 49 below.

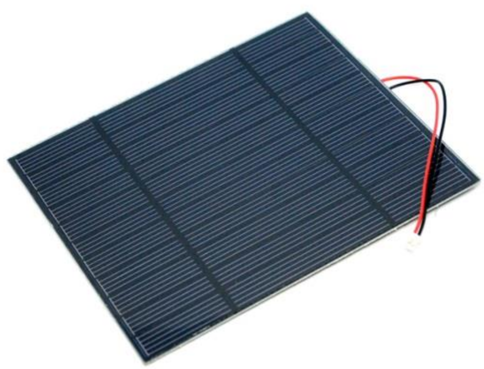


Figure 67: The 3 W solar panel [35]

With our abundant use of digital logic, it would be ideal to exclusively use DC devices in future product versions. Solar power facilitates this transition as it produces DC power.

Alternatively, wind power could be used to sustain the Plantmosphere's systems. Both wind and solar power could also be supplemented by manual power generation in case the user wants to charge the battery when other sources are insufficient.

12.1.2 Hook-up Wire

12.1.2.1 Power

The possibility of high current flow in our product's sub-systems amplifies the importance of choosing appropriate power wiring. For our purposes, we will consider both the wire gauge and type. It is important to note that current flow determines wire gauge rather than voltage, so the same wire can be used for both our AC and DC signals.

The Plantmosphere's sub-systems are close in proximity, meaning that wire gauge should be chosen based on its maximum ampacity for chassis wiring rather than for power transmission. Dedicated 12 VDC, 5 VDC, and ground busses will be fastened to the upper rim of the greenhouse to supply components mounted far from the trough. Furthermore, another 5 VDC and ground bus will power components located near the trough. To determine the maximum current rating, we must then evaluate the bus that draws the most current in the worst case. The upper current limit is defined by the bus that draws the most current draw under full load, which corresponds to the 5 VDC through bus at 2.25 A. Based on the *Handbook of Electronic Tables and Formulas*, an American Wire Gauge (AWG) of at least 26 will suffice, but to err on the side of caution, 24 AWG will be used [36].

Wire type is tied to frequency: high frequency signals require stranded wire due to the skin effect, while solid wire is used at low frequencies. In our case, solid wire is sufficient as we are working with DC and mains electricity, which propagates at a low frequency.

To distinguish between the 12 VDC, 5 VDC and ground lines, blue, red, and black wires will be used. The chosen wires can be seen in Figure 47-A-C below.

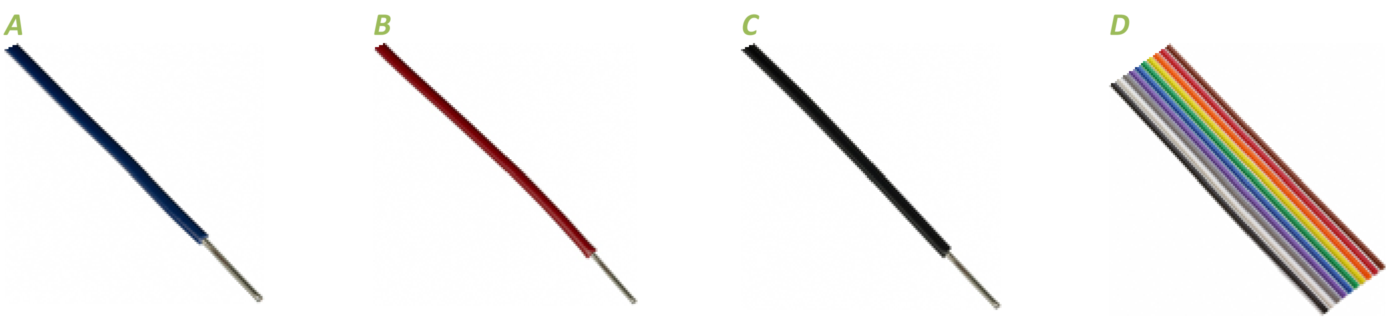


Figure 68: *A*: The blue 24 AWG Wire [37]; *B*: The red 24 AWG Wire [38]; *C*: The black 24 AWG Wire [39], *D*: The rainbow ribbon cable [40]

12.1.2.2 Data

The current that runs through our sub-systems' data lines is small compared to that of the power lines, meaning that we can choose a lower gauge of wire. Rainbow ribbon cables will be used due to their multiple colours and lower cost per foot per conductor. The cable can be seen in Figure 68-D.

13 Electrical Safety

Given the humidity of our product's internal environment and its use of high power components, extra precautions must be made to ensure the safety of our customers and the reliability of our components. To address these issues, multiple layers of protection have been considered for implementation into both the prototype and the final product in accordance with the electrical and safety requirements.

13.1 General Electrical Protection

To supply mains electricity to the Plantmosphere, we require a robust and reliable electrical protection. Additionally, six outlets are needed to power all of our components.

Circuit breakers represent an easy and reusable way to control the current being drawn from the Plantmosphere system in the event of a short or overload. To protect the system from extrinsic power surges, a surge protector can be employed to absorb any voltage spikes seen at the outlet.

Another important aspect to consider is eliminating the risk of electrical shock considering the humidity of the environment. To rectify unwanted electrical conduction, a Ground Fault Circuit Interrupt (GFCI) breaker can be used. GFCI breakers monitor the balance of current between the live and neutral wires of mains electricity, as seen in Figure 69 below.

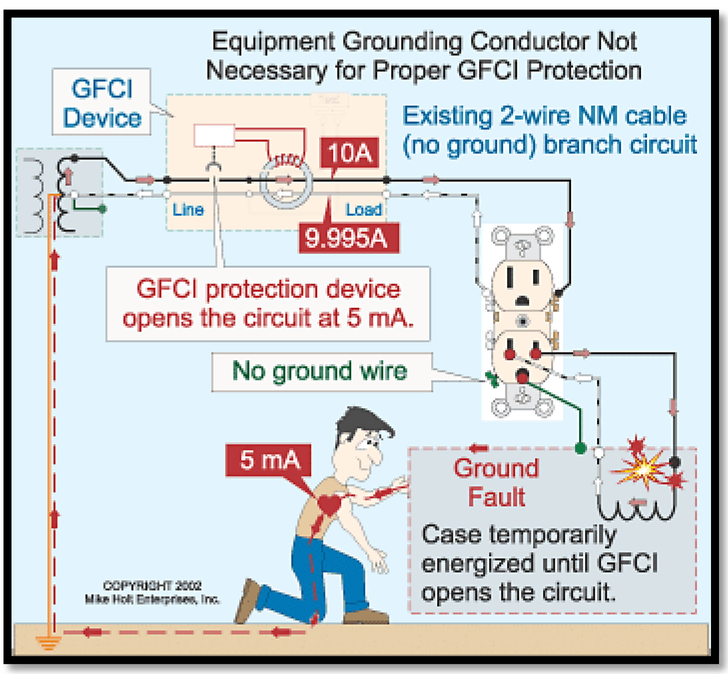


Figure 69: The operation of a GFCI breaker during electrical shock [41]

When current is lost due to electrical shock, there will be a difference in the current supplied to and leaving the circuit. Both Alternating Current (AC) lines flow through a solenoid. If the current difference exceeds five milliamps, a magnetic field is induced, which in turn triggers the GFCI device to open the circuit. It is also important to note that GFCI works for any both grounded and ungrounded plugs.

As a consequence of these needs, we have elected to use the TLM609GF power strip and the Staples® 3-outlet surge protector, seen in Figure 70 below.

A

B

Figure 70: *A*: The TLM609GF power strip with GFCI plug [29]; *B*: The Staples® 3-outlet surge protector [42]

Despite the TLM609GF's cost, its numerous safety features make it an obvious choice for a humid environment. Not only does it have a GFCI plug, but it also contains a circuit breaker that trips when more than fifteen amps are drawn. In addition, its rugged design lends itself for outdoor use. The Staples® 3-outlet surge protector is a cheap and highly rated surge protector. Its 1200 J rating ensures that it can protect electrical equipment from extreme power surges. Both components have grounding pins, ensuring that we conform with **R2.4.8**.

Alternatively, a combination of a surge protector power strip and portable GFCI plug would be cheaper. The drawback to this combination is that in the event of a surge, both the components would need to be replaced since the large influx of power passes through the GFCI plug before it reaches the surge protector. On the other hand, the current proposed configuration would stop the surge before it reaches the more expensive component.

13.2 Circuit Breakers

To ensure the safety of our devices and comply with **R2.4.7,** circuit breakers will be used to regulate current flow in high power circuits. These reusable elements break circuit connections once the current has risen beyond the component's rated value. Figure 71 below shows a cross-sectional view of a typical mechanical circuit breaker.

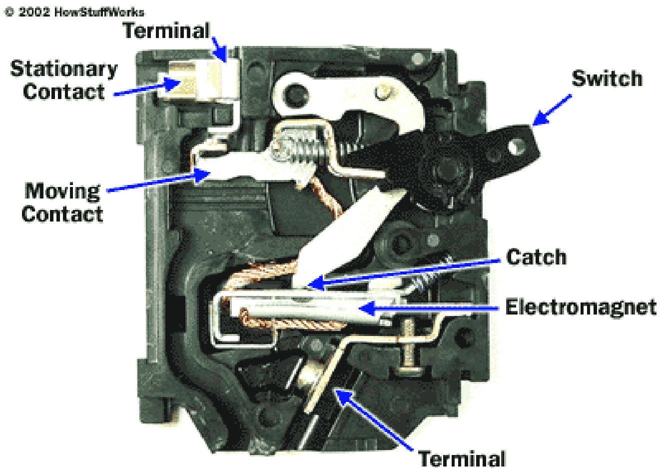


Figure 71: A cross-sectional view of a mechanical circuit breaker [43]

During normal device operation, the stationary contact completes the circuit and allows current to flow. When the current draw becomes too large, the electromagnet pulls the switch downwards, which forces the moving contact to break the circuit connection.

Circuit breakers will both allow us to prevent our components from drawing too much current and not require us to replace the device in this event. Alternatively, fuses perform an identical function, but they must be replaced after they have been used.

13.3 Opto-isolators

To protect the Arduino from any high power devices it controls, opto-isolators provide ample circuit isolation as per **R2.4.7**. Figure 72 below depicts a cross-sectional view of two configurations for transistor opto-isolators.

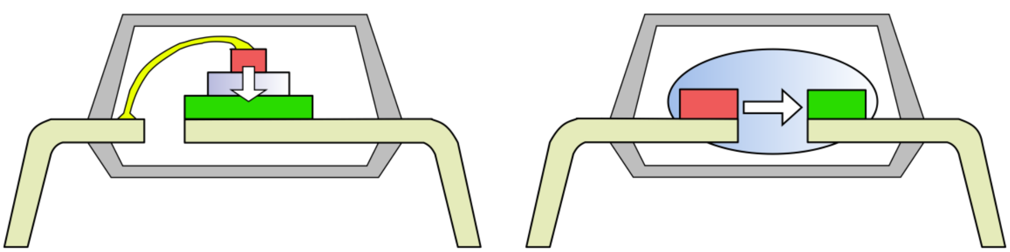


Figure 72: A cross-sectional view of a two transistor opto-isolators configurations; the red and green blocks correspond to a Light Emitting Diode (LED) and phototransistor, respectively, separated by a blue dielectric [44]

The component itself offers nearly complete circuit isolation with the use of an LED and a light detector. Light is emitted by the LED while a current flows through it, which is subsequently coupled to the adjacent circuit with a phototransistor. The dielectric material between these two elements prevents current flow, which leads to isolation in the kilovolt range.

For our application, opto-isolators are an ideal choice as they are cheap, readily available, and allow enough isolation to guarantee the Arduino's safety.

Alternatively, digital isolators have much better performance, reliability, and integration, but these enhancements also increase the price [45]. Moreover, digital isolators are designed for complex AC signals rather than simple DC ones. These factors make opto-isolators the optimal choice for Arduino protection.

13.4 Electrical Enclosures

To protect the numerous systems from damage and humans from electrical shock, all components will be encased in order to conform with **R2.5.3**, **R2.5.4**, **R2.5.6**, and **R2.5.7**

The component dimensions and their suggested enclosure sizes are outlined in Table 24 through Table 29 below.

Table 24: Component and suggested enclosure sizes for power components

Component	LxWxH (cm)
LOGISYS PS480D-BK Power Supply	14.5×14.5×8
TLM609GF power strip	41.07×18.03×6.86
Suggested Enclosure Size	**45×40×10**

Table 25: Component and suggested enclosure sizes for stepper motor

Component	LxWxH (cm)
26M048B2U DC Stepper Motor	4.29×2.616×2.502
Suggested Enclosure Size	**4×6×2.7**

Table 26: Component and suggested enclosure sizes for linear actuator

Component	LxWxH (cm)
163899 PUSH 900 Linear Actuator (fully declined)	10.5×7.5×20
Suggested Enclosure Size	**12×10×20**

Table 27: Component and suggested enclosure sizes for the Arduino and its controlled components

Component	LxWxH (cm)
Arduino ATMega 2560	10×5.5×1
SainSmart 8 Channel Relay	14×5.5×1.5
Various control circuits	4×5.5×1
Suggested Enclosure Size	**16×15×4**

Table 28: Component and suggested enclosure sizes for the LED board

Component	LxWxH (cm)
LED board	77×16×2.54
Suggested Enclosure Size	**80×18×3**

Table 29: Enclosure size for the LCD module

Component	LxWxH (cm)
Enclosure Size	25.4×20.32×7.62

Any sensors that require exposure to the Plantmosphere environment will be wrapped in heat shrink tubing to protect their leads from both electric shorts and corrosion. Furthermore, electrical wires and connections will also be wrapped in heat shrink tubing and terminated in standardized headers to facilitate reliable contact. Any gaps in either the greenhouse structure or the enclosures will be filled with silicone paste in order to create a watertight seal.

14 Calibration

14.1 Soil moisture sensor

The homemade soil moisture sensor will be calibrated using a professional soil moisture sensor. For this calibration we will use a device like the "WaterStick" Moisture sensor (refer to Figure 73).

Figure 73: The WaterStick from RONA [46]

14.2 DHT11 Digital Humidity Temperature Sensor

The DHT11 digital humidity temperature sensor will be calibrated using a standalone device like the indoor digital hygrometer (refer to Figure 74). The humidity of the environment will be measured at different relative humidity values with the hygrometer, and the DHT11’s measured output will be compared against the hygrometer’s.

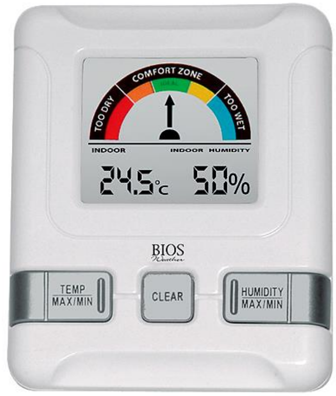


Figure 74: An indoor digital hygrometer [47]

14.3 Light Sensor

To calibrate the photocell, we intend to use a digital photometer (see Figure 75). In a dark room or enclosure, the LED brightness will be varied and measured by both the photometer and the photocell. This will ensure that the Plantmosphere will be able to accurately determine the intensity of sunlight.

Figure 75: A digital photometer [48]

14.4 RGB LED Output

The RGB LED output will be measured using a spectrometer. Different voltage levels will be mapped to different wavelengths and stored in a table. This table will be referenced by the Arduino to produce the proper colours for plant illumination.

14.5 Water Level Sensor

This sensor will be calibrated manually. The water reservoir will be filled to a specific height, and the sensor's output value will be checked against the actual measured height. This will be completed at different water levels to ensure the water level sensor is accurate.

15 Test Plan

Testing of the Plantmosphere will be comprised of verification and validation of individual system components, and the system as a unit to ensure performance, reliability, and safety. Test suites will be executed on hardware and software components. Sensor signals will be obtained with data logging shield and exported to a micro SD card in order to monitor communication between software inputs and system outputs. Electrical equipment functionality and safety will be verified with a comprehensive testing procedure. Each of our team members are equipped with an Arduino UNO in order to test sub-systems in parallel prior to integration testing.

15.1 Humidification

Table 30: Humidification Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.1-T1	R3.5.1	Assess the humidification system's ability to regulate the RH level of the interior air when the temperature is optimal.	1. Add water to the reservoir above the minimum level. 2. Set the test level for optimal RH at 85%. 3. Set the test level for optimal temperature above the current temperature for the test. 4. Execute the humidification control algorithm.	The misters should turn on, thereby increasing the interior air's RH until it reaches 85%.
15.1-T2	R3.5.1	Assess the humidification system's ability to regulate the RH level of the interior air when the temperature is not optimal.	1. Add water to the reservoir above the minimum level. 2. Set the test level for optimal RH at 85%. 3. Set the test level for optimal temperature below the current temperature for the test. 4. Execute the humidification control algorithm.	The misters should only turn on once the ventilation system is deactivated, and if the RH is still below optimal level.
15.1-T3	R3.5.1	Verify that the humidification system deactivates when the RH level and temperature of the internal air is optimal.	1. Add water to the reservoir above the minimum level 2. Set the test level for optimal RH above the	The humidification system deactivates or remains inactive.

			current RH for the test. 3. Set test level for optimal temperature above the current temperature for the test. 4. Execute the humidification control code.	

15.2 Ventilation

Table 31: Ventilation Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.2-T1	R3.4.2 R3.4.3	Assess the functionality and electrical efficiency of the fans' arrangement to influence the fan configuration decision.	1. With the vents closed, monitor the inner temperature with multiple sensors until the difference between the highest and lowest internal air temperatures is greater than some 5 degrees Celsius. 2. Leaving the vents closed, turn on the fans until the difference between the highest and lowest internal air temperature is less than 1 degree Celsius. 3. Record elapsed time and consumed energy. 4. Repeat steps 1-3 for various fan configurations and internal temperature gradients.	When fans are activated, a successful ventilation system will mix the interior air, re-establishing thermal uniformity sufficiently quickly, and will not deprive the plants' leaves of airflow.
15.2-T2	R3.4.5	Assess the effectiveness and efficiency of the ventilation system when attempting to establish thermal uniformity between the greenhouse interior and exterior.	1. With the vents closed, monitor internal temperature with multiple sensors until the difference between the inside and outside temperatures is at least	When vents are opened and fans are activated, a successful ventilation system will equalize the internal and external air temperatures sufficiently quickly, and will not

			5 degrees Celsius. 2. Open the vents, and activate the fans until the difference between inside and outside temperatures is less than 1 degree Celsius. 3. Record time elapsed and consumed energy over the duration of the test. 4. Repeat steps 1-3 for various combinations of differences between inside and outside temperature.	deprive the plants' leaves of airflow.

15.3 Irrigation

Table 32: Irrigation Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.3-T1	R3.6.3	Verify irrigation system can direct water from the reservoir to the trough.	1. Add water to the reservoir. 2. Program the Arduino to turn on the water reservoir pump.	The pump should be able to supply enough pressure such that all water in the reservoir can be delivered to the trough.
15.3-T2	R3.6.3	Verify irrigation system can provide sufficiently distributed moisture across the soil.	1. Distribute multiple soil moisture sensors across the soil. 2. Read the moisture level from all sensors with the Arduino. 3. Calculate the moisture difference between all sensors. 4. Adjust the irrigation tubes, pump pressure and/or Arduino control code and repeat Steps 1 to 3 until the difference between sensor moisture values is sufficiently small.	The moisture sensors should read sufficiently similar moisture values.
15.3-T3	R3.6.7	Verify that the water reservoir and its	1. Add water to eaves troughs.	No water should leak from the reservoir, tubes

		connections do not leak.	2. Check reservoir connections.	connecting to the reservoir, and tube connection joints.
15.3-T4	R3.6.9	Verify the functionality of the water overflow pipe.	1. Fill reservoir with water to a level exceeding the top of the overflow pipe.	Overflow pipe should direct excess water to a drain.
15.3-T5	R3.6.14	Verify that the runoff pipe delivers water to the reservoir.	1. Pour water into empty plant trough.	Poured water should be collected by the runoff pipe without significant pooling within the trough. Runoff pipe should direct all water into the reservoir.

15.4 Lighting

Table 33: Lighting Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.4-T1	R3.3.2	Verify that the lighting system will not block natural sunlight.	1. Mount the lighting at its required height above the trough. 2. Monitor the natural sunlight exposure at multiple points between sunrise and sunset.	The natural sunlight will be able to illuminate the plants.
15.4-T3	N/A	Verify that the lights only activate once the sun is obstructed, the allowable lighting time is surpassed, and the plants' daily light exposure quota has not been met.	1. Obstruct the outer photocells after the allowable lighting time. 2. Execute the lighting control code.	The lights will activate.
15.4-T4	N/A	Verify that the lights will deactivate once the plants' daily light exposure quota has been filled.	1. Shine light onto the inner photocell until their daily light exposure quota has been filled. 2. Execute the lighting control code.	The lights will deactivate.
15.4-T5	N/A	Verify that the lights will deactivate when sunlight is unobstructed.	1. Shine light onto the outer photocell that is ≥ the solar constant. 2. Execute the lighting control code.	The lights will deactivate.

15.4-T6	N/A	Verify that the lights cannot turn on past sunset.	1. Obstruct the outer photocell and allow the lights to turn on. 2. Leave the photocells obstructed until the current time passes the time of sunset.	The lights will deactivate.

15.5 Power

Table 34: Power Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.5-T1	R2.4.5	Verify that the PSU can enter a standby mode.	1. Deactivate the DC sub-systems. 2. Set the power supply's standby control pin high. 3. Turn on the DC sub-systems.	The sub-systems should not turn on.
15.5-T2	N/A	Assess the PSU's ability to simultaneously supply all sub-systems with the power they require.	1. Turn on all of the DC sub-systems at maximum load.	The sub-systems should operate as expected.

15.6 Safety

Table 35: Safety Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.6-T1	R2.5.3	Assess the hermiticity of the electrical enclosures.	1. Spray water onto the enclosure. 2. Open the enclosure. 3. Inspect the inside of the enclosure for water.	There will be no water inside the electrical enclosure.
15.6-T2	R2.5.3	Assess the heat dissipation capabilities of the electrical enclosures.	1. Turn on the sub-systems with enclosures. 2. Check the enclosures' temperatures.	The electrical enclosures will not be excessively hot.
15.6-T3	R2.5.6	Assess the hermiticity of the electrical insulation.	1. Spray water onto the insulation. 2. Probe the insulated wire and the sprayed area. 3. Find the resulting	The resistivity should be high.

			resistivity.	
15.6-T4	R2.5.7	Assess the performance of the LEDs while enclosed.	1. Measure the light output of an LED. 2. Put the LED into the enclosure. 3. Measure the light output of the enclosed LED.	The light output should be similar.
15.6-T5	R2.5.7	Assess the performance of the photocells, the temperature and humidity sensors, and the soil moisture sensors while enclosed.	1. Measure the output of each sensor in its environment. 2. Put each sensor into their respective enclosure. 3. Measure the output of each of the enclosed sensors.	The sensor output should be similar.
15.6-T6	R2.5.10	Assess the hermiticity of the water reservoir.	1. Spray water onto the water reservoir's lid. 2. Open the lid. 3. Inspect the inside of the water reservoir for water.	There will be no water inside the water reservoir.
15.6-T7	R2.5.12	Assess the strength of mounted components.	1. Mount the component. 2. Apply force with a force gauge. 3. Measure the force required to move the mounted component.	The force required to move the mounted component should be high.

15.7 Soil Heating

Table 36: Soil Heating Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.7-T1	R3.7.2	Assess the soil heating cable's ability to heat the soil.	1. Distribute multiple soil temperature sensors across soil. 2. Program the Arduino to power the soil heating cable when the average temperature across the sensors is ≤ 74˚F. 3. Read the temperature from all sensors with the Arduino.	The soil heating cable should be able to heat the soil to temperatures above 74˚F.

15.7-T2	R3.7.3	Assess the plant trough's temperature distribution.	1. Distribute multiple soil temperature sensors across the soil. 2. Read the temperature from all sensors with the Arduino. 3. Calculate the temperature difference between all sensors. 4. Adjust the soil heating cable configuration and repeat steps 1 to 3 until the difference between the sensor temperature values is sufficiently small.	The soil temperature should be sufficiently distributed throughout the trough.

15.8 Integration Testing

Table 37: System Integration Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.8-T1	R4.2.1	Assess the integration of the Plantmosphere's sub-systems.	1. Run all modules simultaneously with the Arduino. 2. Acquire continuous data of all obtainable signals.	All measured environmental parameters should reach and remain stable at the configured inputs. Output signal data should present expected values.

15.9 User Interface (UI) Testing

Table 38: User Interface Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.9-T1	R4.2.1	Asses the functionality of the user interface display module and keypad.	1. Run Plantmosphere system. 2. Press the up, down, left, right, and enter keys in various combinations.	Pressing a direction key should highlight the field on the LCD module corresponding to the arrow direction relative to the previously highlighted field. Pressing the enter key should select the highlighted option in such a way that the action results in visible feedback (de-

				highlighting the selected field). If the Power option is selected, the system should respond by turning the power off (if the power is on) or on (if the power is off).
15.9-T2	R4.2.2	Asses the ability of the UI to update the System Status field upon detection of an error by the system.	1. Induce an error, i.e. empty the water reservoir completely.	The LCD module should display the error corresponding to the user-induced error.

15.10 Validation Testing

Table 39: System Validation Test Plan

Test Case	Applicable Requirement(s)	Objective	Steps	Expected Outcome
15.10-T1	R2.2.1	Verify that the system promotes the healthy growth of plants	1. Plant a case group of radish seeds and partially grown radishes in the trough. 2. Plant a control group of radish seeds and partially grown radishes outside of the greenhouse. 3. Run the Plantmosphere system for several days or weeks. 4. Harvest the control and case plants and compare their size and assess their relative health.	Case group of radishes should show significantly better health than control group. Seeds should be germinated and partially grown radishes should have increased in size.

16 Conclusion

The Plantmosphere is an automated greenhouse system that will give anyone, even non-gardeners, the ability to grow plants easily. The automated systems include: irrigation and humidification, lighting, ventilation, soil heating, and rain water capture. The system will be controlled by an Arduino microcontroller making it easy to configure and customize. The system will be as water friendly as possible allowing it to be used in parts of the world where water is scarce. Water conservation is accomplished with two methods; ensuring the system only uses the water it needs without and waste, and sealing the water reservoir to prevent evaporation. The system will maintain the proper atmosphere for any plant that is selected through an integrated user interface.

This design specification document is written to highlight and explain the design decisions made for the Plantmosphere. The design specification uses the requirements outlined in the function specifications document in order to further detail design rationale. Both documents will be used by the Plantmosphere Technologies team as a reference to facilitate a smooth development process. Using the comprehensive information provided by this document, Plantmosphere Technologies is confident that completion of our working prototype will be delivered by December 3rd, 2014.

17 Works Cited

[1] R. F.-N. S. L. P. Conceição, “Africa Human Development Report 2012: Towards a Food Secure Future,” United Nations Development Programme, 15 May 2009. [Online]. Available: http://www.undp.org/content/undp/en/home/librarypage/hdr/africa-human-development-report-2012/.

[2] DSC, "PC1000," [Online]. Available: http://www.dsc.com/index.php?n=products&o=view&id=1083. [Accessed 5 November 2014].

[3] SainSmart, "SainSmart IIC/I2C/TWI Serial 2004 20x4 LCD Module Shield for Arduino Raspberry Pi," [Online]. Available: http://www.sainsmart.com/sainsmart-iic-i2c-twi-serial-2004-20x4-lcd-module-shield-for-arduino-uno-mega-r3.html. [Accessed 5 November 2014].

[4] W. V. C Sonneveld, “Water Uptake and Water Supply,” in *Plan Nutrition of Greenhouse Crops*, the Netherlands, Springer, 2009, pp. 103-123.

[5] G. Recktenwald, “Wiring of Solenoid Valves,” Louisiana Tech University, 2013. [Online]. Available: http://web.cecs.pdx.edu/~eas199/B/howto/fishtank/wiring/solenoid_wiring.html. [Accessed 04 11 2014].

[6] GardenBot, "The Soil Moisture Sensor," [Online]. Available: http://gardenbot.org/howTo/soilMoisture/. [Accessed 5 November 2014].

[7] Popular Science, “Do Plants Sleep?,” 10 03 2014. [Online]. Available: http://www.popsci.com/blog-network/our-modern-plagues/do-plants-sleep. [Accessed 03 11 2014].

[8] Dreamland, "SMD 5050 RGB," [Online]. Available: http://www.tweaking4all.com/wp-content/uploads/2014/01/5050LED.pdf. [Accessed 04 11 2014].

[9] A. N. Dodd, N. Salathia, A. Hall, E. Kevei, R. Toth, F. Nagy, J. M. Hibberd, A. J. Millar and A. A. R. Webb, "Plant Circadian Clocks Increase Photosynthesis, Growth, Survival, and Competitive Advantage," vol. 309, no. 5734, pp. 630-633, 22 July 2005.

[10] Advanced Photonix, Inc., "CdS Photoconductive Photocells," 30 03 2006. [Online]. Available: http://advancedphotonix.com/wp-content/uploads/PDV-P8103.pdf. [Accessed 04 11 2014].

[11] Greenhouse Catalog, "Greenhouse Ventilation," [Online]. Available: http://www.greenhousecatalog.com/greenhouse-ventilation. [Accessed 5 November 2014].

[12] NSW Department of Primary Industries, "Ventilation in greenhouses," [Online]. Available: http://www.dpi.nsw.gov.au/agriculture/horticulture/greenhouse/structures/ventilation. [Accessed 5 November 2014].

[13] Digi-Key, "AFB1212VH-T500," [Online]. Available: http://www.digikey.ca/product-

search/en?KeyWords=603-1202-ND&WT.z_header=search_go. [Accessed 03 11 2014].

[14] Green Building Tech, "Natural Ventilation," 2007. [Online]. Available: http://gbtech.emsd.gov.hk/english/utilize/natural.html. [Accessed 03 11 2014].

[15] Digi-Key, "Stepper Motor - 26M048B1B," [Online]. Available: http://www.digikey.ca/product-detail/en/26M048B1B/403-1005-ND/417812. [Accessed 03 11 2014].

[16] Solarbotics, "Stepper Motor Basics," [Online]. Available: http://library.solarbotics.net/pdflib/pdf/motorbas.pdf. [Accessed 2 November 2014].

[17] adafruit, "DHT11 basic temperature-humidity sensor," [Online]. Available: http://www.adafruit.com/product/386. [Accessed 03 11 2014].

[18] instrumentek, "Arduino Greenhouse mrk 2," 18 07 2012. [Online]. Available: https://www.youtube.com/watch?v=qmSyfodR7E8. [Accessed 03 11 2014].

[19] R. J. Probert, "The Role of Temperature in the Regulation of Seed Dormancy and Gernination," in *Seeds: The Ecology of Regeneration in Plant Communities*, CABI Publishing, 2001, pp. 261-289.

[20] Cornell University, "Radishes," 2006. [Online]. Available: http://www.gardening.cornell.edu/homegardening/scene341b.html#profile. [Accessed 02 11 2014].

[21] Wrap-On Co. Inc., *Gro-Quick Soil Heating Cable Datasheet*, Bedford Park, 2002.

[22] Amazon, "Gro Quick Electric Soil Heating/Warming Cable-ea 24 Ft," [Online]. Available: http://www.amazon.com/Quick-Electric-Heating-Warming-Cable-ea/dp/B00HWA21XU/ref=pd_sim_lg_3?ie=UTF8&refRID=01XDNFYD2FT79DBPKT34. [Accessed 2014].

[23] Amazon, "NEW Dirt Genius DGHT40 Warm Seedling Heat Warming Mat Hydroponics 20.5" x 48"," [Online]. Available: http://www.amazon.com/Dirt-Genius-DGHT40-Seedling-Hydroponics/dp/B00CTWBK9W/ref=sr_1_1?s=lawn-garden&ie=UTF8&qid=1415261708&sr=1-1&keywords=Dirt+Genius+DGHT40. [Accessed 2014].

[24] Home Depot, “Palram DeluxeTwin Wall Greenhouse - Silver - 6 Feet x 4 Feet,” [Online]. Available: http://www.homedepot.ca/product/deluxetwin-wall-greenhouse-silver-6-feet-x-4-feet/863825. [Accessed 9 October 2014].

[25] Lexington Container Company, "Welcome to USA Emergency Supply," [Online]. Available: https://www.usaemergencysupply.com/images/md/water_barrel_30_gallons.jpg. [Accessed 6 November 2014].

[26] WIC Valve, "Male Straight Connector Tube OD 1/4 X NPT 3/8 Air Hose Fitting," [Online]. Available: http://www.wicvalve.com/Male-Straight-Connector-Tube-OD-1-4-X-NPT-3-8-Air-Hose-Fitting-PMC-T1-

4-N3-8.htm. [Accessed 5 November 2014].

[27] The Family Handyman, "How to Build a Rain Barrel," [Online]. Available: http://www.familyhandyman.com/smart-homeowner/how-to-build-a-rain-barrel/view-all. [Accessed 5 Novmber 2014].

[28] Amazon.com, "Waterproof Ultrasonic Distance Measuring Module," [Online]. Available: http://www.amazon.com/Waterproof-Ultrasonic-Distance-Measuring-Module/dp/B008EOETME. [Accessed 6 November 2014].

[29] National Oceanographic and Atmospheric Administration, "General Solar Position Calculations," [Online]. Available: http://www.esrl.noaa.gov/gmd/grad/solcalc/solareqns.PDF. [Accessed 3 November 2014].

[30] Digi-key, "C2003A.12.03," [Online]. Available: http://www.digikey.ca/product-detail/en/C2003A.12.03/C2003R-100-ND/57457. [Accessed 3 November 2014].

[31] Newegg.com, "LOGISYS Computer PS480D-BK 480W ATX12V Power Supply," [Online]. Available: http://www.newegg.com/Product/Product.aspx?Item=N82E16817170012. [Accessed 1 11 2014].

[32] Digi-key, "RoHS FAQ's," [Online]. Available: http://www.digikey.com/ca/en/environmental/rohs-faq.html. [Accessed 1 11 2014].

[33] Cadex Electronics, "Is Lithium-ion the Ideal Battery?," 2014. [Online]. Available: http://batteryuniversity.com/learn/article/is_lithium_ion_the_ideal_battery. [Accessed 1 11 2014].

[34] Cadex Electronics, "BU-409: Charging Lithium-ion," 2014. [Online]. Available: http://batteryuniversity.com/learn/article/charging_lithium_ion_batteries. [Accessed 1 11 2014].

[35] SMART BATTERY, "SMART BATTERY® 12V 50AH DEEP CYCLE LITHIUM ION BATTERY," [Online]. Available: http://www.lithiumion-batteries.com/products/12v-50ah-lithium-ion-battery/. [Accessed 1 11 2014].

[36] Seeed Studio, "3W Solar Panel 138X160," [Online]. Available: http://www.seeedstudio.com/depot/3W-Solar-Panel-138X160-p-954.html. [Accessed 1 11 2014].

[37] Power Stream, "Wire Gauge and Current Limits Including Skin Depth and Strength," 29 September 2014. [Online]. Available: http://www.powerstream.com/Wire_Size.htm. [Accessed 3 November 2014].

[38] Digi-key, "C2003A.12.07," [Online]. Available: http://www.digikey.ca/product-detail/en/C2003A.12.07/C2003L-100-ND/122013. [Accessed 5 November 2014].

[39] Digi-key, "C2003A.12.03," [Online]. Available: http://www.digikey.ca/product-detail/en/C2003A.12.03/C2003R-5-ND/4455016. [Accessed 3 November 2014].

[40] Digi-key, "C2003A.12.01," [Online]. Available: http://www.digikey.ca/product-

detail/en/C2003A.12.01/C2003B-100-ND/39831. [Accessed 3 November 2014].

[41] Digi-key, "3811/10 300," [Online]. Available: http://www.digikey.ca/product-detail/en/3811%2F10%20300/MC010M-50-ND/3878630. [Accessed 5 November 2014].

[42] Electrical Construction & Maintenance, "How GFCIs Work," 1 3 2002. [Online]. Available: http://ecmweb.com/content/how-gfcis-work. [Accessed 1 11 2014].

[43] Staples, "Staples® 3-Outlet 1200 Joule Wall Mount Surge Protector, White," [Online]. Available: http://www.staples.ca/en/Staples-3-Outlet-1200-Joule-Wall-Mount-Surge-Protector-White/product_199689_2-CA_1_20001#revs_content. [Accessed 3 11 2014].

[44] howstuffworks, "How Circuit Breakers Work," [Online]. Available: http://electronics.howstuffworks.com/circuit-breaker2.htm. [Accessed 1 11 2014].

[45] Wikipedia.org, "Opto-Isolator," [Online]. Available: http://en.wikipedia.org/wiki/Opto-isolator. [Accessed 1 11 2014].

[46] Silicon Labs, "Isolator vs. Optocoupler Technology," [Online]. Available: http://www.silabs.com/products/power/isolators/Pages/isolator-vs-optocoupler-technology.aspx. [Accessed 1 11 2014].

[47] RONA, ""Waterstick" Moisture sensor," [Online]. Available: http://www.rona.ca/en/waterstick-moisture-sensor-03985006. [Accessed 6 November 2014].

[48] RONA, "Hygrometer - Indoor Digital Hygrometer," [Online]. Available: http://www.rona.ca/en/hygrometer---indoor-digital-hygrometer. [Accessed 6 November 2014].

[49] Sale Stores, "Extech LT300 Light Meter," [Online]. Available: http://salestores.com/extechlt.html. [Accessed 6 November 2014].

[50] National Fire Protection Association, "NFPA 70: National Electrical Code," 2014.

[51] British Standard, "BS 7671: The Institution of Engineering and Technology Wiring Regulations," 2008.

[52] International Electrotechnical Committee, "IEC 61558-1: Safety of power transformers, power supplies, reactors, and similar products," 07 04 2009. [Online]. Available: http://webstore.iec.ch/preview/info_iec61558-1%7Bed2.1%7Db.pdf. [Accessed 11 10 2014].

[53] International Electrotechnical Committee, "IEC 60634-1: Low-voltage electrical installations," 29 11 2005. [Online]. Available: http://webstore.iec.ch/preview/info_iec60364-1%7Bed5.0%7Db.pdf. [Accessed 11 10 2014].

[54] Canadian Standards Association, "CSA C22.1-12: Canadian electrical code," 2012.

[55] McDonough Braungart Design Chemistry (MBDC), LLC., "Cradle to Cradle® Certification Program Banned Substances," 2009.

[56] Arduino, "Arduino Mega 2560," [Online]. Available: http://arduino.cc/en/Main/ArduinoBoardMega2560. [Accessed 1 October 2014].

[57] Digi-key, "TLM609GF," [Online]. Available: http://www.digikey.ca/product-detail/en/TLM609GF/TLM609GF-ND/1765462. [Accessed 1 11 2014].

[58] Adafruit, "DHT11 basic temperature-humidity sensor + extras," [Online]. Available: http://www.adafruit.com/product/386. [Accessed 1 November 2014].

[59] YouTube, "Arduino Greenhouse mrk 2," [Online]. Available: https://www.youtube.com/watch?v=qmSyfodR7E8. [Accessed 1 November 2014].

[60] Lexington Container Company, "Your One Stop Container Shop & Survival Supplies Store!," [Online]. Available: http://www.lexingtoncontainercompany.com/New-Drums.html. [Accessed 5 November 2014].

[61] RP Electronics, "Ultrasonic Distance Sensor Module," [Online]. Available: http://www.rpelectronics.com/sen136b5b-ultrasonic-distance-sensor-module.html. [Accessed 5 November 2014].

18 Appendix A

18.1 Arduino Model Comparison Chart

	Processor	Processor Voltage	Supply Voltage	Flash	SRAM	Digital I/O Pins	PWM Pins	Analog Inputs	Hardware Serial Ports	Dimensions	Shield Compatibility	Notes and Special Features
Uno	16MHz Atmega 328	5v	7-12v	32Kb	2Kb	14	6	6	1	2.1"x2.7" 53x75mm	Excellent (most will work)	
Uno Ethernet	16MHz Atmega 328	5v	7-12v	32Kb	2Kb	14	6	6	1	2.1"x2.7" 53x75mm	Very Good (some pin conflicts)	Has Ethernet Port. Requires FTDI cable to program.
Mega	16MHz Atmega 2560	5v	7-12v	256Kb	8Kb	54	14	16	4	2.1"x4" 53x102mm	Good (some pinout differences)	
Mega ADK	16MHz Atmega 2560	5v	7-12v	256Kb	8Kb	54	14	16	4	2.1"x4" 53x102mm	Good (some pinout differences)	Works with Android Development Kit.
Leonardo	16MHz Atmega 32U4	5v	7-12v	32Kb	2.5Kb	20*	7	12*	1	2.1"x2.7" 53x75mm	Fair (many Pinout Differences)	Native USB capabilities. USB Micro B programming port.
Due	84MHz ARM SAM3X8E	3.3v	7-12v	512Kb	96Kb	54	12	12	4	2.1"x4" 53x102mm	Poor (voltage and pinout differences)	Fastest processor. Most memory. 2-channel DAC. USB micro B programming port. Native micro AB port.
Micro	16MHz Atmega 32U4	5v	5v	32Kb	2.5Kb	20*	7	12*	1	0.7"x1.9" 18x49mm	N/A	Smallest board size. Native USB capabilities
Flora	8MHz Atmega 32U4	3.3v	3.5-16v	32Kb	2.5Kb	8*	4	4*	1	1.75" dia 44.5mm dia	N/A	Sewable Pads. Fabric-friendly design. Native USB Capabilities
DC Boarduino	16MHz Atmega 328	5v	7-12v	32Kb	2Kb	14	6	6	1	0.8"x3" 20.5x76mm	N/A	Can build without headers or sockets for smaller size. Requires FTDI cable for programming
USB Boarduino	16MHz Atmega 328	5v	5v (USB)	32Kb	2Kb	14	6	6	1	0.8"x3" 20.5x76mm	N/A	Can build without headers or sockets for smaller size. USB Mini B programming port.
Menta	16MHz Atmega 328	5v	7-12v	32Kb	2Kb	14	6	6	1	0.8"x3" 20.5x76mm	Excellent (most will work)	Mint-Tin Size and Prototyping Area. Requires FTDI cable for programming.

Figure 76: Arduino Model Comparison Chart

18.2 Circuit Diagram of One Channel of the 8-Channel Relay Module

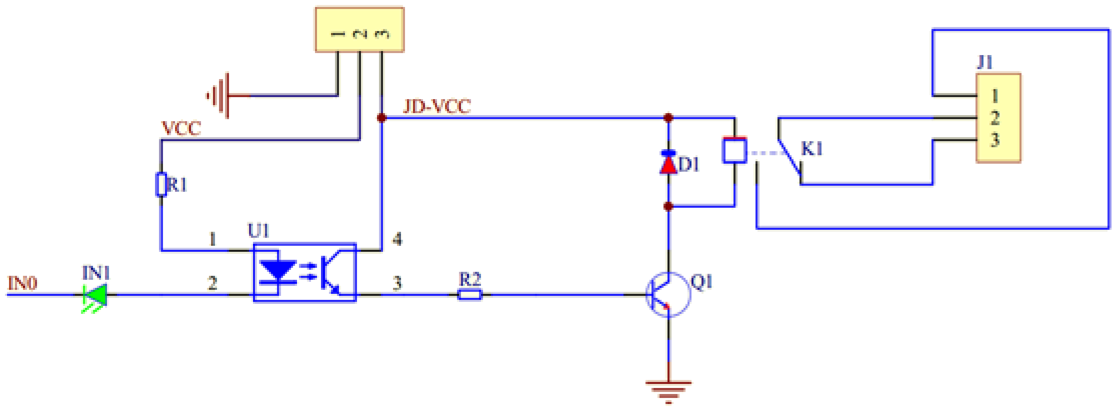


Figure 77: Relay Module Channel Circuit Diagram

18.3 HD44780U LCD Module Block Diagram

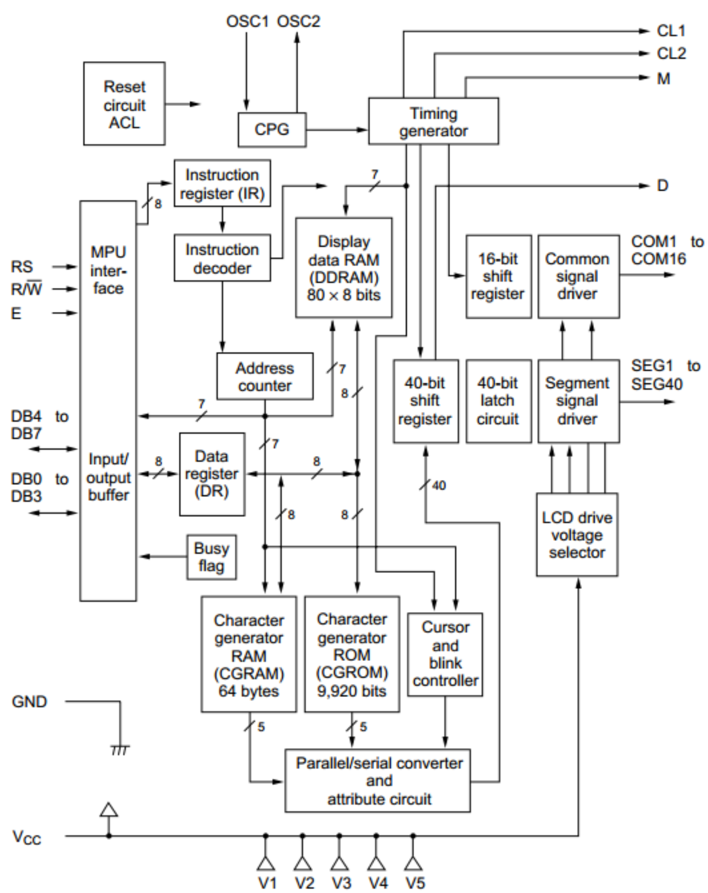


Figure 78: HD44780U Controller/Driver Block Diagram

18.4 Wiring Bill of Materials

Table 40: Wiring BOM

Source	Sink	Power Length (ft.)	# Power Wires	Power +20% (ft)	Item Power Length (ft.)	Data length (ft)	# Data Wires	Data +20% (ft)	Item Data Length (ft.)	Total Length
Arduino	Tin/RHin Top Left Back	1	2	1.2	2.4	5	1	6	6	8.4
Arduino	Tin/RHin Bottom Right Back	1	2	1.2	2.4	7	1	8.4	8.4	10.8
Arduino	Tin/RHin Top Right Front	1	2	1.2	2.4	9	1	10.8	10.8	13.2
Arduino	Tin/RHin Bottom Left Front	1	2	1.2	2.4	11	1	13.2	13.2	15.6
Arduino	Tout/RHin Top Left Back	1	2	1.2	2.4	5	1	6	6	8.4
Arduino	Tout/RHin Bottom Right Back	1	2	1.2	2.4	7	1	8.4	8.4	10.8
Arduino	Linear Motor's TTL Circuit	1	2	1.2	2.4	2	2	2.4	4.8	7.2
Arduino	Tout/RHout Roof Peak Left	2	2	2.4	4.8	4	1	4.8	4.8	9.6
Arduino	Tout/RHout Power Box	1	2	1.2	2.4	1	1	1.2	1.2	3.6
Arduino	Tin Trough	1	2	1.2	2.4	2	1	2.4	2.4	4.8
Arduino	Relay Control (x5)	1	2	1.2	2.4	1	5	1.2	6	8.4
Arduino	Lout Top Right Front	1	2	1.2	2.4	0	0	0	0	2.4
Arduino	Lout Top Left Front	1	2	1.2	2.4	9	0	10.8	0	2.4
Arduino	Lout Top Right Back	1	2	1.2	2.4	5	1	6	6	8.4
Arduino	Lout Top Left Back	1	2	1.2	2.4	5	1	6	6	8.4
Arduino	Lin Trough	1	2	1.2	2.4	4	1	4.8	4.8	7.2
Arduino	Soil Moisture Sensors (x2)	7.5	4	9	36	7.5	2	9	18	54
Arduino	Darlington NPN Array	1	2	1.2	2.4	1	4	1.2	4.8	7.2
Arduino	NPN Power Transistors (x3)	1	2	1.2	2.4	1	3	1.2	3.6	6
Arduino	Red LED Control	0	0	0	0	5	1	6	6	6
Arduino	Blue LED Control	0	0	0	0	5	1	6	6	6
Arduino	Water Level Sensor	1	1	1.2	1.2	1	4	1.2	4.8	6
Arduino	Reed Switch 1	1	2	1.2	2.4	2.5	2	3	6	8.4
Arduino	Reed Switch 2	3	2	3.6	7.2	2.5	2	3	6	13.2
Arduino	Stepper Motor	8	1	9.6	9.6	9	4	10.8	43.2	52.8
DC Fan 1	Fan Negative Bus	5	1	6	6	0	0	0	0	6
DC Fan 2	Fan Negative Bus	5	1	6	6	0	0	0	0	6
DC Fan 3	Fan Negative Bus	3	1	3.6	3.6	0	0	0	0	3.6
DC Fan 4	Fan Negative Bus	1	1	1.2	1.2	0	0	0	0	1.2
Fan 12 V Bus	DC Fan 1	6	1	7.2	7.2	7	1	8.4	8.4	15.6
Fan 12 V Bus	DC Fan 2	6	1	7.2	7.2	11	1	13.2	13.2	20.4

Fan 12 V Bus	DC Fan 3	4	1	4.8	4.8	5	1	6	6	10.8
Fan 12 V Bus	DC Fan 4	1	1	1.2	1.2	12	1	14.4	14.4	15.6
Fan Negative Bus	NPN Power Transistor (x1)	1	1	1.2	1.2	0	0	0	0	1.2
LED Array	NPN Power Transistors (x2)	3	2	3.6	7.2	0	0	0	0	7.2
LED Trough 5 V Bus	LED Array	1	1	1.2	1.2	0	0	0	0	1.2
Linear Motor's TTL	Relay Control	0	0	0	0	1	2	1.2	2.4	2.4
PSU	Upper 5 V Bus	19	1	22.8	22.8	0	0	0	0	22.8
PSU	Fan 12 V Bus	16	1	19.2	19.2	0	0	0	0	19.2
PSU	Upper GND Bus	19	1	22.8	22.8	0	0	0	0	22.8
PSU	Trough 5 V Bus	7	1	8.4	8.4	0	0	0	0	8.4
PSU	Trough GND Bus	7	1	8.4	8.4	0	0	0	0	8.4
PSU	LED Trough 5 V Bus	7	1	8.4	8.4	0	0	0	0	8.4
PSU/Mains	Relay (x6)	1	12	1.2	14.4	0	0	0	0	14.4
Relay	Linear Motor	5	3	6	18	0	0	0	0	18
Relay	Pump	3	2	3.6	7.2	0	0	0	0	7.2
Relay	Solenoids (x2)	3	4	3.6	14.4	0	0	0	0	14.4
Relay	Soil Heating Cable	3	2	3.6	7.2	0	0	0	0	7.2
TOTAL POWER (ft.)	**300**	**TOTAL DATA (ft.)**	**231.6**							