Cost-Effective Environmental Control System for a Greenhouse

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Abstract

The project detailed in this report was to create a cost-effective alternative to the commercially accessible, environmentally controlled greenhouses seen on the agricultural market. The objective was to realise an a low-cost environmentally controlled greenhouse by using low-cost components and alternative control methods to reduce certain costs that can autonomously control the growing process of the plant inside. The intent behind the design of this system was to make such a system more financially accessible to growers and remove the complexity to use such a system by making it autonomous. The designed system was able to effectively control the environmental factors inside the greenhouse. However, the automatic irrigations system was not realised due to complications in the hardware. The software for this project can be viewed on my Github page **here**.

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Name: **David Moore**

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Nomenclature

CO_2: carbon dioxide
LED: light emitting diode
HVAC: heating, ventilation, and air conditioning
ADC: Analogue to digital converter
LDR: Light dependant resistor
Relative Humidity: Percentage of water vapour in the environment

Chapter 1: Introduction

1.1 Background to the Study

The agricultural industry is facing several threats such as climate change, especially in the form of drought and water scarcity which has adversely affected agricultural yields in traditional field farms. Coupled with the rising transportation costs and rural-to-urban migration which has left undue pressure on rural field farms with an insufficient number of resources to work the land. All these factors have caused operational costs and food security to become unpredictable for the agricultural industry [1].

1.2 Motivation

All these factors have caused a knock-on effect to the consumer increasing the costs to purchase common food items. As a result many low-income South Africans have been placed in a problematic situation as access to food becomes progressively more difficult. Many individuals that have gardening capacity at their residence have taken the plunge to grow their own food with much difficulty. Local ventures such as GrowBox was founded by Renschia Manuel due to her family being in a similar situation and has grown a local farming community to aid those that struggle to afford food for themselves [2].

As problems have emerged in traditional farming a new frontier in the industry has brought the development of environmentally controlled indoor farms with the goal to produce a greater yield with less land. This has enabled growers to have greater control over their yield as the growing process can be facilitated, to some degree, independently of outdoor environmental conditions. This is achieved by using climate control technology such as sensors, actuators, and controllers that can autonomously monitor and control the indoor environment to optimize plant growth.

However, this paradigm of commercial indoor farming technology has invited valid criticism due to the expertise, high capital and operational costs needed to utilize these efficient systems. Nevertheless, these systems are reliant on these high-cost technologies to produce a satisfactory crop yield [3]. As a result this has barred many potential growers from benefitting from the utility that these technologies offer.

1.3 Problem Statement

While many solutions exist for environmentally controlled greenhouses, the issue of these systems is the reliance of high-cost technologies to achieve an effective crop yield. This is due to the inseparable complications between actuators and environmental factors inside of greenhouses [4]. As a result many of these designed systems in the industry have opted to make use of these high-cost technologies in the pursuit of effectively controlling an indoor environment to match the ideal growing conditions found in nature. While cost-effective solutions have rarely been implemented in the industry.

1.4 Objectives of this Study

The objective of this study is to design and build a cost-effective alternative greenhouse control system to the commercially purchasable environmentally controlled greenhouses and then review the effectiveness of the designed system. This system will have similar functionality that is capable of autonomously monitoring and controlling the greenhouse environment providing ease of use for the grower. This is done through the implementation of low-cost components and alternative methods that produce comparable results to that of its higher cost counterparts.

1.5 Problems to be investigated

These are points of interest that need to be researched from the literature that will form part of the knowledge base in the design process of the cost-effective environmentally controlled greenhouse:

1. What are the important biological needs for plants that need to be considered when designing the controlled greenhouse environment?

2. What are typical sensors that are found in controlled growth environments and their purpose for implementation?

3. What actuators are needed that are fundamental to controlling the greenhouse environment?

4. What are the costs involved when implementing certain environmental control methods and what methods can be used to reduce costs?

1.6 Thesis Contributions

The novel contributions of this low-cost environmentally controlled greenhouse system are as follows:

- A system that can monitor the environmental conditions present in the greenhouse with the use of low-cost sensors.

- A system that can control the greenhouse environment with the use of low-cost actuators.

- A system that can act autonomously which requires minimal user interaction that removes most complications that may arise due to a lack of knowledge on farming.

1.7 Terms of Reference

To meet the objectives of this project, the designed system needs to meet the user requirements detailed in Table 1.1 below:

User Requirement	Description
The system needs to be automated	The system needs to autonomously control the greenhouse environment to reduce the need for expert knowledge on environmental control system
The system needs to be cost-effective	The designed system needs to be financially accessible for growers to gain access to environmental control systems that can aid them to grow crops
The system needs to be small scale	The designed system needs to be portable so that it can be used in residential households

Table 1.1: User requirements for the system

1.8 Scope and Limitations

The goal of this project is to realise a cost-effective solution for an environmentally controlled indoor greenhouse which is accomplished using low-cost components. A few caveats emerge from this aspiration especially in the form of climate control which is a formidable task in of itself to accomplish within indoor farming [4]. A common solution to this is the implementation of HVAC systems that can make use of air conditioning. This provides an effective method to provide heating and cooling to the environment and to manage the internal atmosphere that regulates CO_2 concentrations and relative humidity within the greenhouse [5].

However, these systems are costly to implement and are only effective in large spaces which is not possible since the housing for the designed system is a storage crate. Due to this, the designed system will not be able to provide effective cooling to the growing environment. CO_2 enrichment will not be realised in the designed system as it is also too costly to implement. A common method is to use bottled CO_2 cylinders, but this will incur steep running costs. A low-cost solution to this is to ferment sugar to produce ethyl alcohol and CO_2, but this method cannot be effectively controlled and opposes one of the requirements of minimal user interaction as this needs to be regularly attended to [6].

Due to the time constraints of the project, the report will not be able to detail the plant growing capability of the designed system as this type of experimentation and testing typically takes course over several months, while during the time given, the focus was placed on researching design considerations and the assembly of the low-cost environmentally controlled greenhouse.

1.9 Thesis Outline

The following chapter, **Chapter 2 Literature Review**, details the findings of the investigation from the research literature. The information garnered from the literature will then form the basis of knowledge that will aid in the design process of the project to build a low-cost environmentally controlled greenhouse.

Chapter 3 Methodology will detail the initial design procedures of the project that was inspired from the literature review. This section will the detail the important factors that need to be considered when designing a low-cost environmentally controlled greenhouse. Such as the component selection process in particular what sensors and actuators are needed to monitor and control the greenhouse environment. The section will then end off with what aspects of the design need to be scrutinized which will form the basis of the experimental procedures of the final design. Such as what data is going to be collected and how is that data used and how to test that the design works as intended.

Chapter 4 Design details the design process of how the low-cost environmentally controlled greenhouse was made. The section will begin with the system design which gives a broad overview of how the system should operate. The following section will then take a funnel down approach explaining the hardware that is implemented in the system. Then an explanation of the software that was coded on the controller and how it interacts with the hardware to provide the environmental monitoring and control within the greenhouse system. The chapter will then conclude showing how the system was implemented.

Chapter 5 Results will begin with a preface to the experimentation. The following section will then detail how the different experiments were set up and describe the experimental procedures that were carried out coupled with the results following from each experiment that was done. The chapter will then conclude with a discussion of the results from the different experiments and provide an objective reflection on the performance of the designed system.

Chapter 6 Conclusion will round off the rest of the report. This chapter will detail the accomplishments of the designed system describing the aspects of the project that performed well. The following section will then detail the shortcomings of the designed system and provide some rationale to what limited the intended performance of the system. The chapter will then conclude with reflective remarks on what improvements can be made to the system and provide other design considerations for future iterations of the design.

Chapter 2: Literature Review

2.1 Introduction

The fundamental principles behind environmental control in greenhouses is founded upon a plant's growth cycle found in nature, and as such the goal behind environmental control is to mimic the conditions of nature within an indoor environment. The next section will examine the biological requirements that plants need from the environment. The proceeding section will detail the different environmental control mechanisms that are implemented in controlled greenhouses and explain the functions, purpose and the costs involved. The chapter will then conclude with a discussion highlighting the key points of the literature review that will form the basis of ideas for the design of the cost-effective environmentally controlled greenhouse.

2.2 Biological Requirements Needed for Plant Growth

The control variables that need to be considered when designing an environmentally controlled greenhouse is light, temperature of the air, relative humidity, CO_2 concentration in the air, and water [7]. Collectively these variables induce physiological responses in plants that affect plant growth in some way. This section will detail the important biological needs for plants that will be used as the basis for control within a greenhouse environment.

2.2.1 Light

Light is considered to be the most important environmental variable to control as it impacts several biological processes in plants ranging from photosynthesis, energy balance including transpiration, phase transitions in a plant's life cycle, and affecting the plant's morphology [4].

Plants use light for photosynthesis which converts the light energy in combination with water and CO_2 to produce chemical energy in the form of glucose that stimulates plant growth [8]. This process is enabled due to plants having photoreceptors that absorb wavelengths of light within the polychromatic light spectrum which is between 400nm – 700nm [9].

Most plants require 14 – 16 hours of light to have effective growth during the day [9]. Plants also require rest periods from light exposure akin to the day-night cycle in nature. Any more exposure to light will place detrimental strain on the plant in the form of photo-inhibition which reduces the photosynthetic capacity of a plant [10]. This causes a lack of energy production in a plant that leads to stunted growth and also induces increased transpiration in the plant's leaves which reduces the water content of a plant that results in plant droop [4].

Experiments done by Fu et al.[11] showed the phenomenon known as photomorphogenesis, which is the physiological response a plant has when exposed to specific wavelengths of light that cause changes to a plant's morphology. In the experiment, they exposed a set of lettuce crops to only blue light and another set to only red light. Results showed that blue light produced greener and thinner leaves as it aided in chlorophyll production. While red light produced wider leaves and better root growth as it induced better antioxidant production.

For optimal plant growth, providing a plant with the full spectrum of polychromatic light will guarantee a good yield for a plant. Brodersen & Vogelmann [12] and Gracian [10] notes that if blue light deprivation causes discolouration and accelerates the phase transition of a plant to the reproductive phase. While red light deprivation will cause a plant to have elongated leaves and stem and reduced root growth [12]. Hence why it is important that lighting systems should contain the polychromatic light spectrum to prevent a reduction in crop yield.

2.2.2 Water

Water plays a crucial part within a plant's life cycle as it aids in germinating the seed within the growing medium, photosynthesis, and transpiration. Transpiration is the biological process that is responsible for the transportation of water from the roots to the plant's aerial parts such as the leaves and stems [8].

The Cohesion-Tension theory explains this is possible due to the plant having stomata that can be thought of as valves that open in the presence of CO_2 from the surrounding atmosphere to enter the plant for photosynthesis. In turn, this causes the internal water in the plant to be exposed to the surrounding atmosphere. So, this movement of water within the plant is caused when the surrounding atmospheric pressure is lower than the internal pressure of the plant which causes an upward flow of water from the roots to the aerial parts [13].

Transpiration plays a crucial function in a plant as it is responsible for transporting nutrients collected by the roots to the rest of the plants due to the movement of water. It also acts as a cooling mechanism as the water stored in the stomata can be evaporated when the plant is exposed to high temperatures [13]. This transpiration stream is also responsible for maintaining the rigidity of the plant which is known as turgor pressure. Without the presence of water the plant will become flaccid and wilt [8]. This turgor pressure is important as it allows the plant to respond to external stimuli such as orienting leaves to grow in the direction of light and opening the stomata [13].

2.2.3 Air, Temperature and Relative Humidity

The air within a closed system such as a greenhouse plays an important role that influences the chemical processes of photosynthesis and respiration that use CO2 to produce oxygen and in turn use oxygen to produce CO2 in a cyclical manner [9]. Any changes in the concentration of gasses such as water vapour (relative humidity), oxygen, and CO_2 present in the surrounding atmosphere are affected by the variations in the ambient temperature as it affects the air pressure of the plant's surroundings [8], [14].

Temperature plays an important role as it impacts the timing of growth in plants as it aids in germinating seeds which induces plant growth and affects the speed of its photosynthetic reaction [15]. Typically temperature ranges optimal for plant growth is within 18 – 23°C [9]. Periodic changes in temperature that mimic the temperatures within the day-night cycle found in nature can promote a better growth rate in plants rather than maintaining a steady temperature. Therefore, optimizing temperature in a greenhouse can maximize the growth rate of a plant [1].

Humidity is shown that it does not affect plant growth directly, however it does have a major influence on the processes that do affect plants growth, especially that of transpiration [1], [5]. Relative humidity (RH) describes the amount of water vapour that is saturated in the surrounding atmosphere which affects the air pressure within a greenhouse. With a RH of 0% indicates that there is no water vapour in the air and low air pressure, whilst 100% indicates the air is completely saturated with water vapour and high air pressure which leads to the water vapour to start condensing on surfaces leaving behind traces of water droplets [4], [15].

Temperature has an inversely proportional relationship with relative humidity. Higher temperatures lower RH and decreases the air pressure, while lower temperatures increase RH and increases air pressure [7]. Low humidity induces higher transpiration rates in plants due to the low air pressure. It has been shown in fruiting plants like tomatoes that there is an increase in the fruit growth; however, if left unchecked it will cause the plant to wilt as it can deplete a plant's water reserves. High humidity hinders transpiration in plants which leads to rot and a loss of turgor in plants that causes it to droop [5], [7], [8].

Maintaining a RH of 50% - 70% is an optimal range to promote plant growth [16]. Having a RH of more than 90% or sudden changes in temperature that induces drastic changes in RH will cause the water vapour in the air to condense and leave behind water droplets. This increases the likelihood of fungus growth as fungal spores thrive in damp and humid environments which causes various crop diseases to emerge [4]. Therefore, it is important to have dehumidifying elements within a greenhouse such as ventilation to induce steady changes to the relative humidity in the surrounding environment [1].

Enriching CO_2 concentration within a greenhouse environment has a profound effect on plant growth and yield [4], [5] This is due to plants naturally using CO_2 to construct the organic tissue that make up its body which is predominantly made of carbon compounds and increases the rate of the photosynthetic reaction [4], [14].

2.3 A Review on Environmental Control Methods in Greenhouses

The implementation of controlled-environment agricultural systems is used in modern greenhouse farms as a means of improving the development of plants by aiding in its growth and improving the quality of the cultivated crops. This is possible with automatic control systems that are capable of conditioning indoor environments that make it suitable for plant growth. The objective of these approaches aims to create a suitable growing environment for plants to produce the optimal crop yield [17].

This section will examine the different environmental control methods used in controlled greenhouses, highlighting the different sensors and actuators used while describing the effectiveness and costs involved.

2.3.1 Heating, Ventilation and Air Conditioning (HVAC) Control

2.3.1.1 Heating

Heating systems are implemented to recover the heat energy lost in a greenhouse system due to external temperatures being lower than the internal temperature. Controlled greenhouse systems traditionally have been fitted with thermostats to control the ventilation and heating system for manual control. However, this has fallen out of favour in modern controlled environments with the implementation of controllers in combination with temperature and humidity sensors that automate the control process. The implementation of a heating system is dependent on the heat energy losses is greenhouse systems which is determined by these 3 factors [18]:

1. The physical size of the greenhouse affects the heat transfer in the system as it is proportional to the surface area of the greenhouse.

2. The geographical location of the greenhouse. Regions where temperatures are consistent such as locations situated near the equator will maintain minimal heat losses and won't require a heating system, whereas regions where temperatures fluctuate regularly will require a heating system.

3. The plant housing material that makes up the greenhouse affects that rate of heat loss of the system as due to the different heat transfer coefficients that are inherent to these materials. Plastic housing have relatively low heat transfer rates compared to that of glass housing due the difference in heat transfer coefficients, as glass conducts heat more efficiently than plastic.

Classical heating systems in greenhouses made use of boilers to generate steam or hot water that is circulated via a piping system throughout the greenhouse as a source of heat within the environment [18]. However, this method has lost popularity due to the complexity of setting up such a system due to the boilers needing a separate storage area, a demanding installation process, and running fuel costs needed to purchase coal or wood [15].

Hot-air heating system such gas fired heating units have become are a more popular alternative to boiler-based heating systems due to its ease of implementation and is comparatively lower in cost. However, it is less efficient at heating the environment than the hot water heating system as air doesn't conduct heat as well as water [18]. These systems also benefit at enriching the environment with CO_2 by siphoning small traces of the exhaust emissions from the process into the greenhouse [15]. It should be noted that these emissions contain traces of sulphur and ethylene which can be damaging to plants and people, therefore this emission should only be added to the environment for short periods of time [18].

Lighting systems in modern controlled greenhouses have been adopted as primary heat sources and have seen widespread popularity as it reduces implementation costs of HVAC system by removing the need for heating control. This due to it being the most cost-effective option in comparison to the other heating systems mentioned above as it has a 2-for-1 purchasing benefit as it can provide lighting and heating to the greenhouse environment. The drawback to this option is that the heating supplied is not easily controllable and needs to be combined with a cooling system to prevent overheating the crops. The heating supplied also only affect the lighting area, whereas other heating systems can provide controllable uniform heating to the greenhouse environment [19].

2.3.1.2 Ventilation

Ventilation plays an important role in a greenhouse as it is a method used to limit the internal temperature and humidity within the greenhouse. Ventilation can decrease the internal temperature but cannot decrease it beyond the temperature outside the greenhouse as the temperature inside the greenhouse will always be higher than the external temperature. Ventilation is also used to regulate the humidity by interchanging the humid internal air for the drier external air [5].

Natural ventilation such as permeable plant housing or windows is the most cost-effective means of ventilation as the air inside the greenhouse can move naturally due to the pressure difference induced by the temperature differences between the hotter inside and the colder outside environment. However, problems emerge when cooling is needed as heat transfer due to natural airflow is gradual when internal and external temperature differences are minute. Natural ventilation is only beneficial in locations where breezes occur occasionally [7], [18].

Mechanical ventilation such as fans are regarded as the most reliable method of ventilation due to its ease at inducing airflow within a greenhouse thereby effectively regulating the atmospheric conditions in combination with temperature, relative humidity, and CO_2 concentration sensors. This is possible through inducing air movement by siphoning air through controllable openings. This is the most expensive method of ventilation; however, it is dependent on the scale of the greenhouse where it is installed. Noise levels, installation and operational costs need to be considered when fans are being implemented [18].

2.3.1.3 Air Conditioning used for Cooling

Air conditioning is used for the purpose of cooling the greenhouse environment and is used in combination with ventilation. Evaporative cooling is considered the most cost-effective option of air conditioning. It is implemented by using pads that are kept damp by having water flowed onto it and is placed in an area of low pressure near the ventilation inlet. Incoming air will flow into the wet pad and evaporate the water on the pad which will then in turn cool the air as it flows into the greenhouse. This method requires frequent maintenance of replacing the water to reduce salt build up on the pads [18]. This cooling system is only effective in geographical locations of low humidity and causes temperature gradients in sizable greenhouses which makes temperature control problematic [8].

High-pressure fog systems are also effective at cooling the greenhouse environment and regulates the relative humidity in the system. This method makes use of high-pressure pumps fitted with fog nozzles to produce a fog of water droplets into the air and cools the environment as the hot air will evaporate the water droplets like the wet pads used in evaporative cooling. This method can be costly due to the number of nozzles and high-pressure pumps needed [18].

Reverse cycle air conditioning is the most effective at cooling the environment but is the most expensive option to implement due to the cost of the equipment needed. This method draws in incoming external air and siphons it over a coil filled with a liquid refrigerant. The heat from the air is then transferred to the refrigerant which cools the air. The cold air is then directed into the greenhouse via the ventilation system. The warm refrigerant is then sent to the compressor which converts the liquid into a hot gas. The gas is then directed outside the greenhouse via the ventilation system where it can cool down and condense back into a liquid. The liquid then flows into an expansion valve that absorbs the remaining heat and siphons the liquid back to the coil to begin the cooling cycle once again [20].

2.3.2 Lighting Control

Natural and artificial light should be considered as light sources upon planning [21]. Lighting systems have a significant impact on the costs involved for greenhouses. Lighting systems account for 20% - 50% of the initial investment costs and 70% - 80% of the recurring electrical costs in controlled greenhouse systems [22]. These costs are dependent on the type of plants that are being cultivated. Plants that are not sensitive to the quality of light received can make use cost-effective lighting equipment, while on the other hand when quality of light is a factor additional costs may occur but is recommended for desired results [22].

Plant housing that is made of transparent material and is in a location that receives moderate weather can make use of natural lighting. During the day, the sunlight can permeate through housing and deliver the solar energy to the plants to undergo photosynthesis [21]. This helps alleviate the dependence of artificial lighting and save costs on electrical utility costs. Attempts have been made to implement semi-transparent solar cells as part of the greenhouse structure to create a self-sustaining energy model. It has been shown to be effective at reducing electrical utility costs, however it isn’t widely adopted due to the high cost of implementation [21].

Light Emitting Diodes (LEDs) have seen widespread adoption for lighting systems in modern greenhouses. This is due to advances in LED manufacturing that has led to the technology being moderately affordable in comparison to other lighting systems. Their advantages ranges from having long lifespans, energy efficiency, and the capability of being able output preferable light wavelengths to support a plant’s morphology during the photoperiod [15][21].

Typical sensors used in lighting systems are photoconductive cells such as light dependent resistors (LDR) and Photosynthetic Active Radiation (PAR) sensors. LDRs are used to detect the light intensity in lighting systems and are the most cost-effective option to implement. Incoming light hitting an LDR changes its electrical resistance from a few hundred Ohms(Ω) in the presence of light to several thousands of Ohms(Ω) in the dark. In combination with an analogue-to-digital (ADC) converter to measure the voltage across the sensor, it can relay information of the light intensity of the environment. This sensor is typically used in applications to determine whether the lighting system should be turn on/ off which can reduce electrical utility costs [23].

PAR sensors are used to measure the photon flux density of incoming light sources within the polychromatic light spectrum. It outperforms the LDR in light sensing as it can relay information of the light intensity of the environment and is used to measure the distribution of the different wavelengths of light within the lighting system [24]. This is often used in combination with lighting systems that can output specific wavelengths of light to manipulate the morphogenic properties of plants to get a desired quality for certain crops [4]. However, the application of these sensors is the most expensive to implement as the PAR sensors alone cost more than R7 000 [24].

2.3.3 Irrigation Control

Irrigation control makes use of soil moisture sensors to determine whether the crop needs to be watered by quantifying the water content in the soil. The sensor determines soil moisture by measuring by the electrical resistance of the soil. When the soil is damp a low resistance is measures, and a high resistance is measured when the soil is dry [25].

An irrigation system is controlled through the use water pumps that influence the flow of water by inducing pressure differences in the pipes and water valves that dictate the flow of water by blocking or permitting water flow within in a pipe [17]. The costs of water pumps are based on the pressure it needs to output which is determined by volume of water that needs to be circulated within the system, whereas water valves are comparatively low-cost. A low-cost irrigation method is to remove the need for a water pump by placing the water storage tank above the growing environment. The water will then flow by using gravity to induce a pressure difference in the pipes and its flow can then be controlled using only water valves [21].

2.4.4 Carbon Dioxide Enrichment

CO2 enrichment systems are costly to implement due the equipment needed and running costs involved. NDIR CO2 sensors are commonly used and functions by emitting a unique wavelength of infrared light within the sensor housing and measures how much of that light is absorbed by a photoelectric detector. When CO2 enters this housing, it absorbs some of the emitted light and reduces the amount of light that hits the detector. The CO2 concentration of the environment can then be calculated based on how much of this light hits the detector [26].

As mentioned before, the emissions produced by gas fired heating can be used to enrich the greenhouse environment with CO2. The most common method used is the use of pressurized CO2 canisters. These canisters are periodically purchased and are generally coupled with pressure regulators, gas flow meters, valves, fittings, and tubing. This can then be combined with a NDIR CO2 sensor and a controller to autonomously enrich the greenhouse environment to the desired CO2 concentration. A low-cost method for CO2 enrichment is to ferment sugar which then produces alcohol and CO2. However, this method is laborious to implement and lacks any effective means of control [6].

Chapter 3: Methodology

The purpose of the investigation conducted in the literature review was to find solutions to the problems listed in **Chapter 1**. Section 3.1 details the solutions to the problems derived from the literature review. Section 3.2 details the subsystems needed to implement the solutions. Section 3.3 details the experimental process, the data that needs to be collected and how that data will be analysed.

3.1 Outcomes of the Literature Review

To determine the components that need to be used in the design, the findings in the literature review show what environmental factors need to be monitored and low-cost methods used to control them. These findings are listed in Table 3.1 below:

Environmental Factor	**Control Methods**
Light	LED lighting systems in combination with LDRs can provide sufficient lighting to crops and LDRs can be used to control the activation of these systems.
Temperature	LED lighting systems can be used as heat sources for the greenhouse environment. Ventilation systems can be used as a cooling method in greenhouses in environments.
Relative Humidity	Ventilation systems can regulate the humidity by exchanging the dry air from the outside into the greenhouse.
CO_2 Concentration	Fermenting sugar can supply CO_2 to the greenhouse system and can be monitored using NDIR CO_2 sensors.
Water	Irrigation systems can use water reservoirs placed above the greenhouse in combination with water valves can be used as the irrigation system, and the water content of the soil can be monitored using analogue soil moisture sensors.

Table 3.1: Cost-effective control methods for essential environmental factors

3.2 Controlled Greenhouse Subsystems

Based on these control methods in Table3.1 these are the necessary subsystems that need to be assembled to implemented it which is expressed in Table 3.2:

Lighting		Ventilation		Irrigation	
Sensors	***Hardware***	***Sensors***	***Hardware***	***Sensors***	***Hardware***
Light dependant resistors	LED Lights	Humidity sensor	Fans	Soil moisture sensor	Piping
		Temperature sensor			Valves

Table 3.2: Subsystems of an environmentally controlled greenhouse

3.3 Experimentation, Data collection and analysis

In order to determine if the designed system works as intended, the subsystems of the environmentally controlled greenhouse needs to be tested. The control procedure of each subsystem needs to collect the environmental data from the sensors and use it to determine the activation of the control hardware. The system can then be considered to work as intended if it is able to do that. Table 3.3 below details how the data is used for each subsystem:

Collected data	How data is collected	How the data is used once analysed
Ambient lighting	Light sensor using an LDR	The ambient lighting data is used to determine the activation of the lighting system
Temperature	Temperature sensor	The temperature data inside the greenhouse can be used in the ventilation system to provide cooling to the greenhouse environment. Temperature data can be used in the lighting system to deactivate the lights to stop it from producing more heat.
Humidity	Humidity sensor	The humidity data is used to determine the activation of the ventilation system. If the relative humidity inside the greenhouse is too high, the water vapour can condense which will increase the likelihood of fungal diseases forming.

Soil moisture	Soil moisture sensor	Data of the soil moisture can be used to determine the activation of the irrigation system. If the soil is dry then the irrigation system can turned on and water the plant.

Table 3.3: Data collection and analysis of the environmental data

Chapter 4: Preface to the Design

This chapter serves as a preface to the design process. The following section details the system requirements. The proceeding section then details the component selection and calculates the cost of the designed environmentally controlled greenhouse. The chapter will then conclude with the testing procedures of the designed system.

4.1 System Requirements

Table 4.1 below details the system requirements for the environmentally controlled greenhouse:

ID	Requirement	Description
SR01	Lighting	The system needs to provide artificial lighting to the greenhouse to supplement the lighting requirements of the plant when ambient lighting is too low
SR02	Ventilation	The system needs to be able to provide ventilation to the greenhouse. This is to regulate the humidity and to a degree, the temperature of the greenhouse.
SR03	Irrigation	The system needs to be able to autonomously water the plant inside the greenhouse.

Table 4.1: System requirements

4.2 Component Selection

Table 4.2 below shows the chosen components that are to be implemented in the designed system and the costs to procure it:

Component Name	**Price (ZAR)**	**Quantity**
Sensors:		
DHT11 Temperature and Humidity sensor	45	3
MH-Z19 NDIR CO2 Sensor	630	1
Velleman VMA303 IO Arduino Moisture Sensor	220	1
Light dependant resistor	13	1
Actuators:		
12V DC Fan	83	2
12V DC Normally Open Solenoid Water Flow Valve	95	1
Hardware:		
MCP3008 ADC	75	1
basic Slim LED Floodlight	110	1
4 Channel 5V Relay Board	69	1
Controller:		
Raspberry Pi 3B+	790	1
Power Supplies:		
12V Power Supply	160	1
5V Power Supply	160	1
Other:		
70*l* Sealable Plastic Storage Crate	290	1
Cabling and connectors	100	N/A
Total:	R3 013	

Table 4.2: Chosen components for design

4.3 Testing Procedures

In order to determine if the system functions as intended tests need to be performed to verify it. Table 4.3 below shows the testing procedures for the design system:

ID	**Test**	**Description**
TR01	Lighting activation	This is to test if the lighting subsystem works as intended. The subsystem must activate the lighting system when the ambient lighting is low and switch the lighting off when the ambient lighting is sufficient.
TR02	Environmental cooling	This is to test if the system can determine when the system needs to be cooled down based on the temperature data from the sensors. When the internal temperature of the greenhouse becomes too warm, the fans need to be activated and the lighting system needs to be deactivated.
TR03	Ventilation activation	This is to test if the system can determine when the humidity of the system is too high based on the sensor data. The system needs to turn on the ventilation system when the relative humidity is too high to reduce the water vapour in the greenhouse environment.
TR04	Irrigation activation	This is to test if the system can determine when the plant's soil is dry and needs to be watered.

Table 4.3: Testing Procedures for the designed system

Chapter 5: Design

This chapter details the design process of the cost-effective environmental control system for a greenhouse. The chapter will begin with the system design which provides an overview of the entire greenhouse system illustrating the overall functionality of the system and showing how the different system components interact with each other. The following section then details the hardware design which delves into the different components used and the accompanying circuitry involved. The proceeding section details the design of the software that is coded onto the Raspberry Pi controller, how code interacts with the hardware, and the coding libraries used. The chapter will then conclude showing how the greenhouse system was assembled.

5.1 System Design

In order to demonstrate how the system operates, this section will provide an explanation of each functional block within the system as seen in figure 5.1 below:

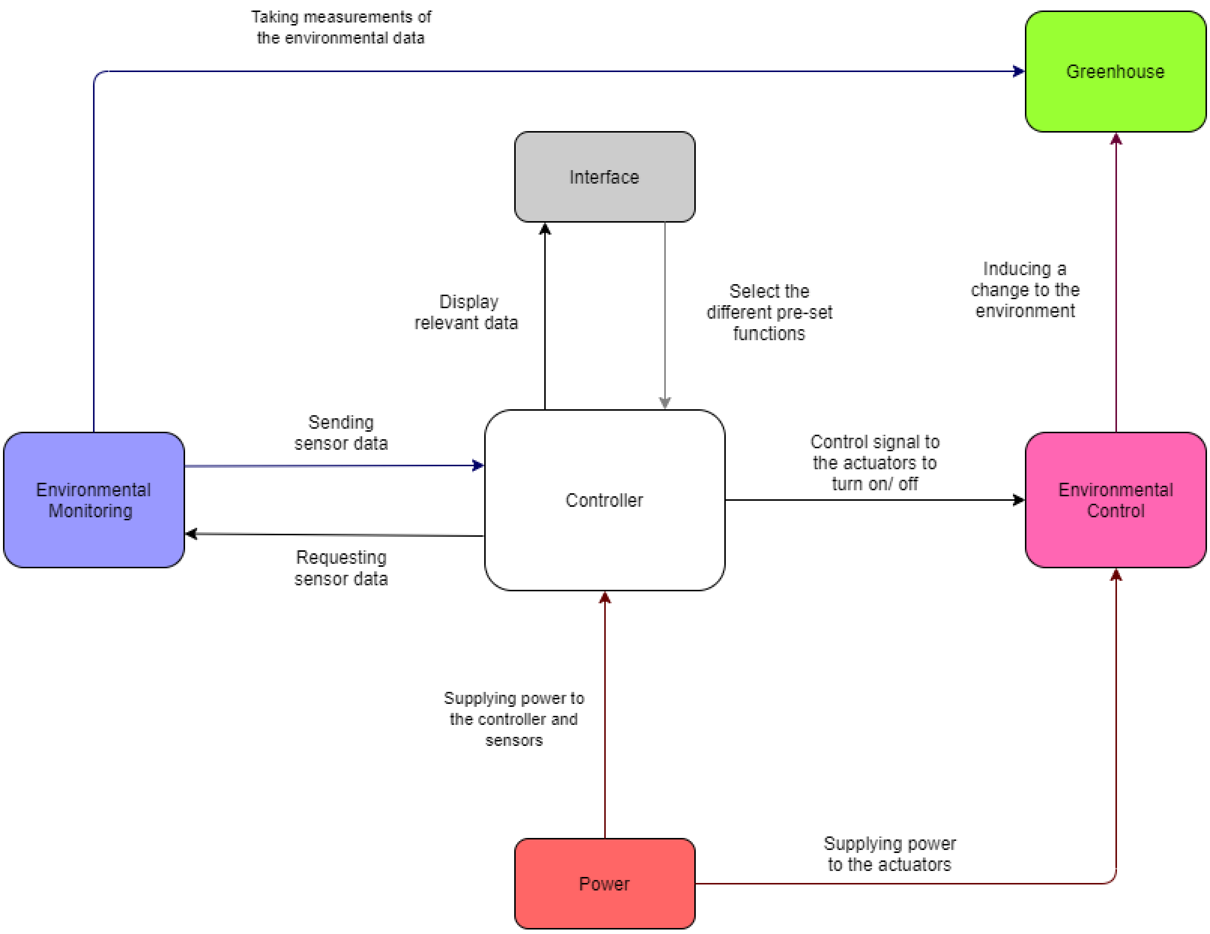


Figure 5.1: Functional block diagram of the controlled greenhouse system

Greenhouse represents the physical growing environment that houses the plant which is the subject of control in this system.

Environmental Control refers to the components that are responsible for inducing a change of state within the greenhouse when the environmental variables deviate from its equilibrium point. The components that included in this functional block are:

- The LED lamp responsible for providing light and heating to the system
- The 2 DC fans that are the intake and an extractor fan which is responsible for providing ventilation to the system
- The solenoid valve that forms part of the irrigation system that permits the water to flow from the water tank through the tubing to the soil of the plant

Environmental Monitoring refers to the various sensors within the system that measures the different environmental variables of the system. The sensors that are included in the functional block are:

- 3 x DHT11 sensors that are responsible for measuring the temperature and humidity of the environment. 1 sensor is placed on the outside to measure the external temperature, and the other 2 are placed on the inside to measure the internal temperature and relative humidity.

- MH-Z19 NDIR CO2 sensor responsible for measuring the CO_2 concentration within the greenhouse.

- Velleman VMA303 analogue soil moisture sensor, this is used to measure the water content present in the soil.

- Light dependent resistor which acts an as analogue light sensor that responsible for measuring the intensity of the ambient lighting of the environment.

Controller refers to the Raspberry Pi that forms the interface between the hardware and the software of the system. This functional block is responsible for controlling the greenhouse environment by running the environmental control program that is coded onto the device. The program operates by reading the environmental data from the various sensors then determines the state of the greenhouse environment. It then decides if any of the environmental control components need to be activated in order to regulate the system and bring it back to a state of equilibrium.

Interface refers to the pre-set command line inputs that can be typed in when executing the program on the Raspberry Pi controller. The pre-set inputs will either run the environmental control algorithm, the different testing procedures, display the current environmental data, or individually activated the different environmental control components.

Power refers to the power supplies responsible for operating the electronics of the system:

- 5V supply that powers the Raspberry Pi and the sensors
- 12V supply that powers the DC fans and the solenoid water valve
- 220V AC supply that powers the LED lamp

5.2 Hardware Design

The procured hardware mentioned in (insert section here) needs to perform a set of actions specified in the system requirements (seen in Table 4.1) that facilitate the operation of the environmentally controlled greenhouse. Table 5.1 expresses the hardware requirements that is needed for the operation of the environmental control system.

ID	Requirement	Description
HR01	Measure temperature	The system must have sensors capable of measuring the temperature present in the environment
HR02	Measure relative humidity	The system must have sensors capable of measuring the relative humidity in the greenhouse's atmosphere
HR03	Measure soil moisture	The system must have sensors capable of measuring the water content present in the soil
HR04	Measure ambient lighting	The system must have sensors capable of measuring the light intensity of the environment
HR05	Monitor CO_2 concentration	The system must be able to monitor the concentration of CO_2 in the greenhouse's atmosphere
HR06	Ventilate the greenhouse	The system must be able to ventilate the system by exchanging the air from inside the greenhouse with the air outside of the greenhouse
HR07	Provide artificial lighting to the greenhouse	The system must be able to provide lighting to the greenhouse when ambient lighting is too low
HR08	Crop irrigation	The system must be able to water the crop autonomously
HR09	Provide power to the system	The system must be able to power all of it components to facilitate its operation
HR10	The controller must be able to interact with all the essential hardware components of the system	The controller must be able be interface between the hardware and the software, and as such it must be able to connect and interact with the hardware of the system.
HR11	Hardware interface for controller	A hardware interface is needed when the controller unable to interact with an essential hardware component of the system.

Table 5.1: Table expressing the hardware requirements of the environmental control system of the greenhouse

5.2.1 Raspberry Pi 3B+ Controller

The Raspberry Pi will act as the controller for this environmentally controlled greenhouse system. It can power all the sensors and the ADC via the 3,3V and 5V pins. The controller can interface with all the digital sensors using Serial and PWM communication. It is also able to interface with the analogue sensors using the ADC via SPI communication. The controller is able activate the actuators, and the LED lamp via the use of a 5V relay module. Thereby satisfying the requirements for HR10.

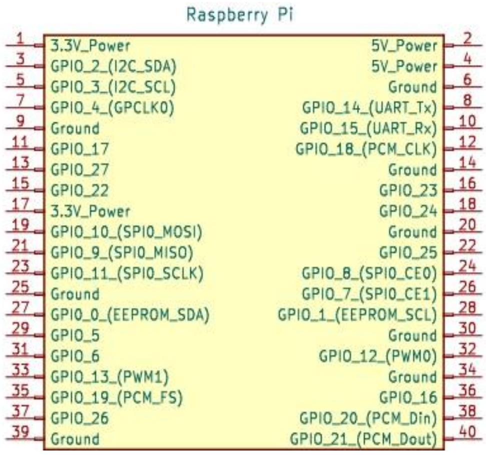


Figure 5.2: Raspberry Pi Pinout

5.2.2 DHT11 Temperature and Humidity Sensor

The DHT11 sensors measure the temperature and relative humidity of the environment. The DHT11 sends the recorded data to the controller via Serial communication. Thereby satisfying the requirements for HR01 and HR02.

1 sensor is placed on the outside of the greenhouse to measure external temperature while the other 2 sensors are placed on the inside of the greenhouse environment to measure the internal temperature and relative humidity. 2 sensors are place inside to maintain data accuracy by taking the averaged readings between the 2 sensors.

The placement of these sensor plays an important role for the ventilation of the system. This is to stop the fans from activating in an attempt to cool down the greenhouse environment when the internal temperature matches the external temperature as it will be ineffective [4].

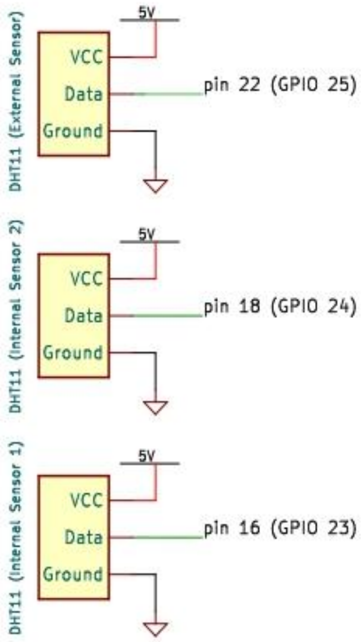


Figure 5.3: DHT11 sensors circuit diagram

5.2.3 MH-Z19 NDIR CO_2 Sensor

The MH-Z19 NDIR CO_2 sensor measures the CO_2 concentration with the environment's atmosphere. Thereby satisfying the requirement for HR05.

The typical communication protocol of this device is via UART. However, PWM communication was used due to the ease of implementation due to a quirk of the Raspbian operating system (OS) of the Raspberry Pi controller. The OS only permits administrative access to make use of the UART communication protocol as it prioritizes it for Bluetooth communication and other security reasons.

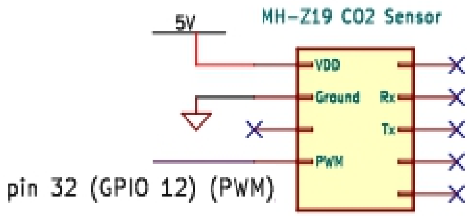


Figure 5.4: MH-Z19 NDIR CO_2 sensor circuit diagram

5.2.4 MCP3008 ADC, Velleman VMA303 Soil Moisture Sensor, and a LDR Light Intensity Sensor

The MCP3008 is an analogue-to-digital converter (ADC) that converts the variable voltages outputs of analogue devices to digital values. This is useful as the Raspberry Pi's GPIO pins can only interpret digital signals. Thereby fulfilling one half of the requirement for HR11.

The Velleman VMA303 Soil Moisture Sensor is an analogue device that measures the water content within the soil. Thereby satisfying the requirement for HR03.

The sensor outputs a variable voltage depending on the soil moisture. This is because the resistance is low when the soil is moist as it is more conductive thereby outputting a low voltage. Conversely the resistance is high when the soil is dry, thereby outputting a high voltage.

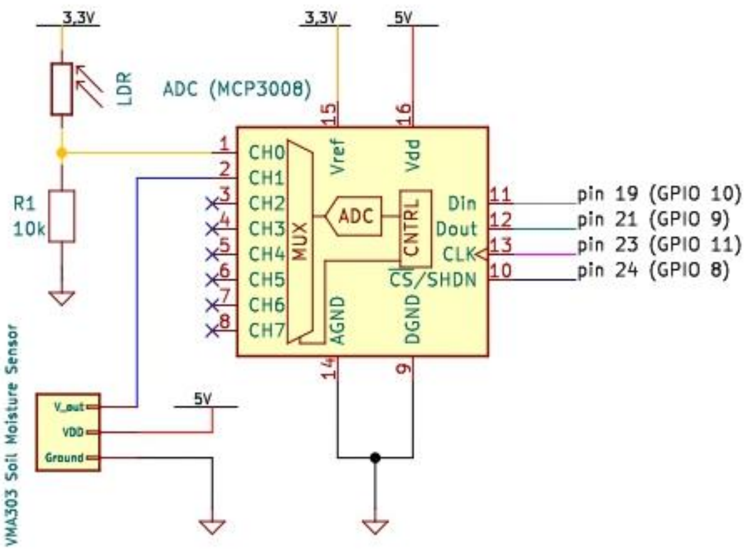


Figure 5.5: Circuit diagram for LDR light sensor, VMA303 Soil Moisture sensor, and MCP3008 ADC

The light dependent resistor (LDR) acts as a light intensity analogue sensor which is used to measure the ambient lighting of the environment by outputting a variable voltage. Thereby fulfilling the requirement for HR04.

The LDR's resistance changes depending on the lighting of the environment, thereby outputting a variable output voltage when wired in a voltage divider configuration as seen in figure 5.5. The sensor's resistance decreases in a bright environment, thereby outputting a high voltage. Conversely, the sensor's resistance drastically increases in a dark environment, which outputs a low voltage.

During the implementation and testing of the system, I accidently burnt out the ADC and broke it. To circumvent this setback I devised this LDR configuration to make a digital light sensor as seen in figure 5.6 which outputs a binary value describing the state of the ambient lighting.

The LDR is wired in a voltage divider configuration in series with a 10 kΩ trimmer potentiometer. The GPIO pins when set to input mode only reads a 'high' value when an electrical signal is above 2V. So, the potentiometer is used to adjust the sensitivity of the data readout of this 'light sensor'. The sensor will output a voltage higher than 2V when the ambient lighting is considered bright. Conversely, the voltage output when the environment is considered too dark will output a voltage lower than 2V.

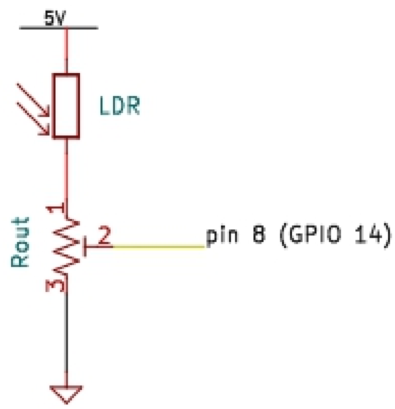


Figure 5.6: LDR configuration for a digital light sensor circuit diagram

5.2.5 HUIKE 4-Channel 5V DC Relay Module

The HUIKE 4-channel 5V relay module acts as a switch that allows the Raspberry Pi to activate the actuators and LED lamp via a control signal sent from the GPIO pins. Thereby satisfying the other half of the requirement for HR11.

The relay module is capable of handling 10A worth of current, 30V for DC and 220V AC. Which makes it suitable to operate as relays for the actuators and the LED Lamp. The LED lamp and the actuators are all connected to the normally close (NC) terminals so that they only turn on when the control signal is received from the controller.

Figure 5.7: HUIKE 4-channel 5V relay module

Source: Adapted from [27]

5.2.6 LED Lamp

The lighting used in this system is a 50W LED lamp that outputs 3300 lumens that needs a 220V AC power source. Thereby satisfying the requirement for HR07.

The LED lamp supplies the necessary heating and light requirements for plant growth within the greenhouse environment. However, this heating is not properly controlled.

The LED Lamp will only turn on when the control signal is sent to the relay by the controller.

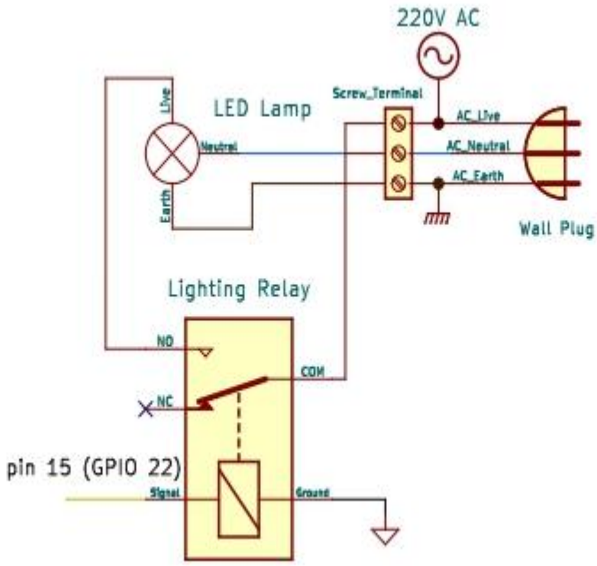


Figure 5.8: LED Lamp connected to relay circuit diagram

5.2.7 Normally Open 12V Solenoid Water Valve

The solenoid valve is an actuator that forms part of the irrigation system that is responsible for watering the plant within the greenhouse. Thereby fulfilling the requirements for HR08.

The valve is normally open which causes the water not to flow through the tubing unless it is powered, which only occurs when the relay is activated by the controller.

Unfortunately the irrigation system doesn't operate as the valve cannot open. The valve needs to be powered and pass a water pressure threshold to open. However, the water pressure within the tubing isn't nearly enough to open the valve.

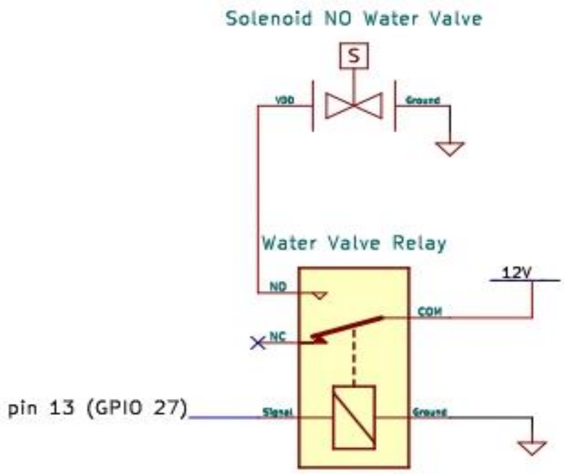


Figure 5.9: Solenoid Water Valve connected to relay circuit diagram

5.2.8 12V Intake and Extractor Fans

There are two 12V DC fans that are the actuators for the ventilation system for the greenhouse environment. Thereby satisfying the requirement for HR06.

One of the fans will be used as an intake fan which is responsible for siphoning the external air into the greenhouse, while the other fan acts as the extractor fans which siphons the internal air of the greenhouse to the external environment.

When these fans are activated in tandem, it induces an air current within the greenhouse. This aids in regulating the humidity and the internal temperature to an extent.

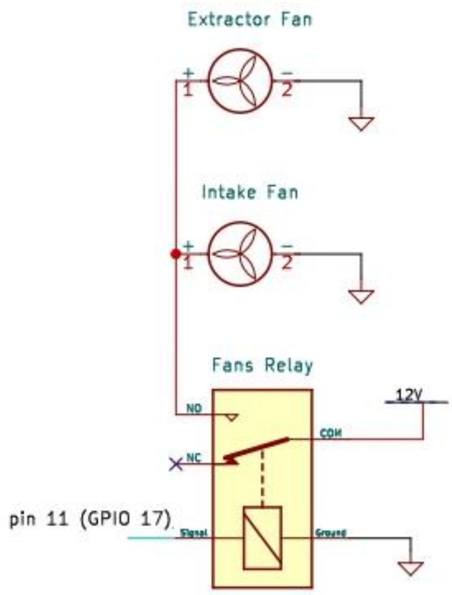


Figure 5.10: 12V intake and extractor fans connected to relay circuit diagram

5.2.9 Power Supplies

The Raspberry Pi controller and the sensors (which is powered through GPIO pins) is connected to a 5V power supply with a maximum output current of 2A. The Raspberry Pi rarely exceeds a current draw of 0,5A during its operation. The actuators are powered by a 12V power supply with a maximum output current of 1,5A. The water valve draws 1A of current when activated and the fans only draw 0,095A of current. The LED Lamp is an AC voltage device which is powered through a wall plug. Both the 5V and 12V power supplies are suitable to power the DC devices during operation. Thereby fulfilling the requirement for HR09.

5.2.10 Circuit implementation

After analysing the functionality of all the individual hardware components it is apparent that the hardware requirements for the system have been realized, the overall circuit can be seen in in figure 5.11 below:

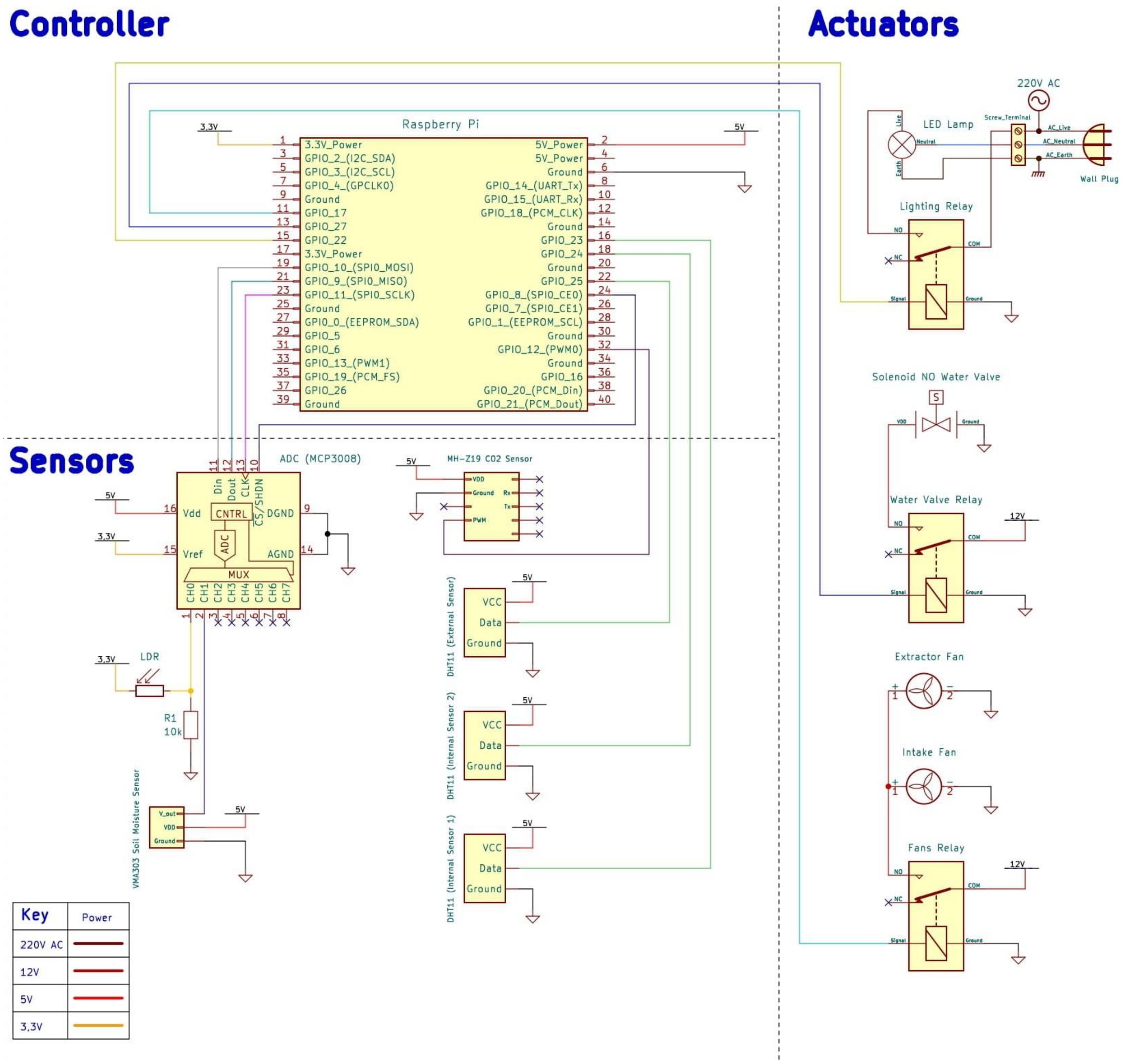


Figure 5.11: Overall circuit diagram for the hardware

5.3 Software Design

This section details the software that is implemented on the Raspberry Pi controller. The repository of the code can be found on my Github page here. This section will explain how the different classes works and the libraries used. The environmental control program is comprised of the 2 python classes, *main.py* and *hardware_interface.py*. The control program launches through *main.py* where a command line argument must be supplied. The functionality of this class will be explained in the following section. *hardware_interface.py*, as the name implies, acts as the interface for the hardware of the system and provides functionality to the GPIO pins of the controller. The functionality of the *hardware_interface.py* will be explained in the proceeding section.

5.3.1 *main.py*

This class acts as the entry point of the environmental control program and the interface for the user. The class takes in 8 different command line arguments. These arguments provide various functions, namely, running the environmental control algorithm, or running the various test procedures which records the testing data into a .csv file, or displays the current environmental data from the sensors, or to individually activate the actuators and LED lamp.

```
david@raspberrypi:~/Desktop/Greenhouse $ python main.py -h
Hardware interface is initialized
usage: main.py [-h] [-r] [-ct] [-ht] [-vt] [-d] [-l] [-w] [-f]

Run the default greenhouse control algorithm or run the different testing
procedures for the greehouse or test the sensors and actuators by using the
commandline arguments shown below:

optional arguments:
  -h, --help          show this help message and exit
  -r, --run           Greenhouse environmental control operation
  -ct, --control      Tests the environmental control capability of the
                      greenhouse
  -ht, --heating      Tests the heating capability of the LED lamp
  -vt, --ventilation  Tests how the ventilation of the greenhouse influences
                      the environment
  -d, --display       Displays the current sensor data of the greenhouse
                      environment
  -l, --lights        Turns the LED lamp on then off after 10 seconds
  -w, --water         Opens the water valve for 2 seconds
  -f, --fans          Turns the fans on then off after 10 seconds
```

Figure 5.12: Command line arguments for *main.py*

External library imports

argparse – Provides the functionality of taking in command line arguments

numpy [28] – Provides data handling functionality

When *main.py* is executed and provided with a valid argument, the first thing the program does is to instantiate an object of the *hardware_interface.py* class to make use its functions and initialize the GPIO pins of the controller.

Functions

The functions are called upon depending on the command line argument supplied.

run: This is the intended environmental control algorithm for the system. It is set to run for 12 hours (this serves to act as the day cycle for the plant), where the system will ensure that the plant:

- Has adequate lighting
- The internal greenhouse atmosphere is safe for the, ensuring that the internal humidity and temperature isn't too high.
- Remains hydrated

The system is then set to go on standby for 12 hours (this serves to acts as the night cycle for the plant), this is to save electrical costs and ensures that the plant is not subjected to too much lighting.

Figure 5.13 visualizes the control loop for this algorithm. The other control algorithms shown in the figure will be detailed in the following section as they are functions within the *hardware_interface.py* class.

It should be noted that a delay after the control loop is necessary due to the refractory period needed form the sensors, namely the LDR light sensor and the DHT11 sensor. The LDR has a relatively slow response time when lighting conditions change and taking samples from it too quickly will relay inaccurate ambient lighting data. The DHT11 don't operate on the Raspberry Pi that well and tend to time out when a request for data occurs to frequently.

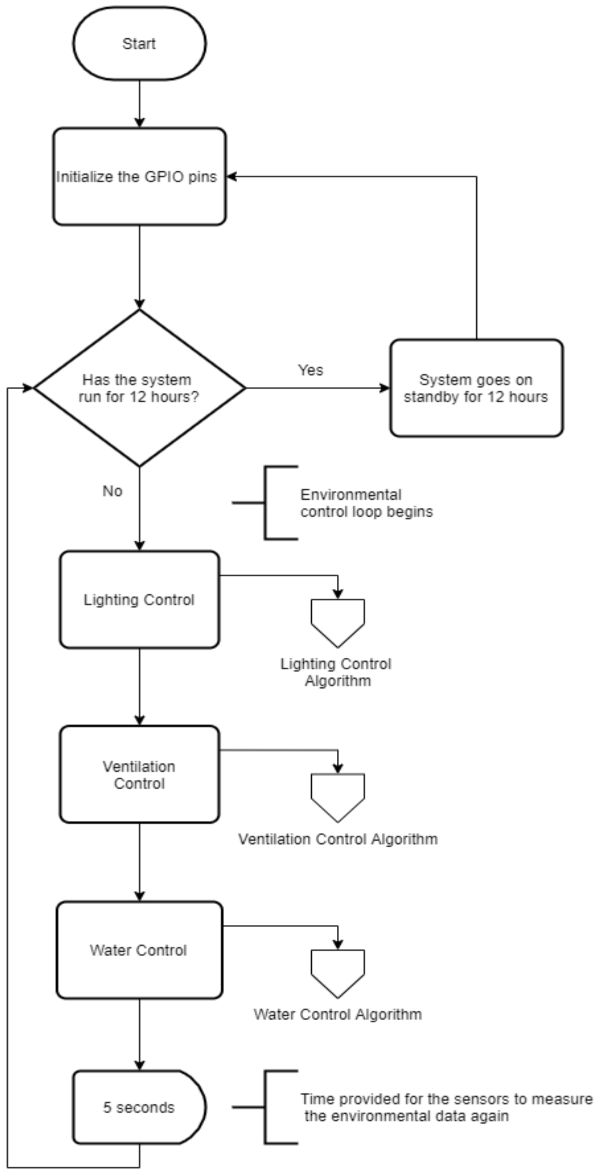


Figure 5.13: Flowchart visualizing the environmental control algorithm

control: This runs the environmental control test. It runs for 30 minutes and records the sensor data and the activation of the actuators and LED Lamp into the *environmental_control_log.csv* file

heating: This tests the heating capability of the LED lamp. It runs for 30 minutes and records the internal temperature of the greenhouse from the DHT11 sensors *into the lamp_heating_log.csv* file

ventilation: This tests the ventilation capability of the intake and extractor fans. The fans turn on for the duration of the test, then is switched off. The test runs for 30 minutes and records the external and internal temperature of the environment from the DHT11 sensors, the relative humidity inside the greenhouse from the DHT11 sensors, and the CO_2 concentration inside the greenhouse from the MH-Z19 sensor. The sensor data is the stored into the *ventilation_log.csv* file

display: This displays the current environmental data from the sensors in the terminal.

lights: This sends a command to turn the LED lamp on for 10 seconds.

water: This sends a command to open the valve for 2 seconds to water the plant.

fans: This sends a command to turn the fans on for 10 seconds.

5.3.2 *hardware_interface.py*

This class houses the various functions that allow the controller to interface with the hardware of the greenhouse system such as initializing the GPIO pins, reading the data from the sensors, the activation of the actuators and the LED lamp, and the control algorithms responsible for regulating the greenhouse environment.

External library imports

board [29] – Adafruit circuitpython library that configures the GPIO pins

digitalio [29] – Adafruit circuitpython library that initializes input/ output functionality of the GPIO pins

adafruit_dht [29] – Adafruit circuitpython library that interfaces with the DHT11 sensors

mh_z19 [30] – Interfaces with the MH-Z19 NDIR CO_2 sensor
MCP3008 [31] – Interfaces with the MCP3008 ADC

Constants

DHT_External: Instantiated object from the *adafruit_dht* library that references the DHT11 sensor placed outside of the greenhouse

DHT_Internal1: Instantiated object from the *adafruit_dht* library that references one of the DHT11 sensors placed on the inside of the greenhouse

DHT_Internal2: Instantiated object from the *adafruit_dht* library that references the other DHT11 sensors placed on the inside of the greenhouse

Light_Sensing: References the GPIO pin connected to the digital light intensity sensor

Fans: References the GPIO pin connected to channel 1 of the relay that activates the intake and extractor fans

Water_Valve: References the GPIO pin connected to channel 2 of the relay that activates the solenoid water valve

Lights: References the GPIO pin connected to channel 3 of the relay that activates the LED lamp

ADC: Instantiated object from the *MCP3008* library that references the ADC. This enables SPI communication between the ADC and the Raspberry Pi and initializes the necessary GPIO pins

Light_Channel: References the ADC channel that the analogue light intensity sensor is connected to

Soil_Moisture: References the ADC channel that the analogue soil moisture sensor is connected to

Threshold: A dictionary storing the values that are considered to the equilibrium conditions of the greenhouse environment. These act threshold values to activate/ deactivate actuators or LED Lamp. The values stored are:

"Light_Threshold": 512,
"Moisture_Threshold": 512,
"Humidity_Threshold": 70.0,
"Temp_Threshold": 24.0

Variables:

Light_state: A Boolean value reference the state of the LED lamp. 1 = on, 0 = off

Fan_state: A Boolean value reference the state of the fans. 1 = on, 0 = off

Functions

initialize_GPIO:	Initializes the relevant GPIO pins for input or output mode
get_external_temp:	Gets the measured temperature from outside the greenhouse from the external DHT11
get_internal_temp:	Gets the measured temperature from of the two DHT11 sensors from inside the greenhouse and returns the averaged data of the 2 sensors
get_humidity:	Gets the relative humidity from of the two DHT11 sensors from inside the greenhouse and returns the averaged data of the 2 sensors
get_CO2:	Gets the measured CO2 concentration inside the greenhouse. The value returned is in PPM (parts per million)
get_light_reading:	Gets the state of the ambient lighting of the environment. Returns 1 if it is too dark and returns 0 if it is bright enough. (Deprecated function due to ADC breaking) The LDR light sensor data is read from the ADC 10 times, returns then averaged result to avoid inaccurate readings. The returned value would range from 0 – 1024
get_soil_moisture:	The soil moisture data is read from the ADC 10 times, returns then averaged result to avoid inaccurate readings. The returned value would range from 0 – 1024
turn_light_on:	Sends signal to the relay channel 3 to turn of the LED lamp by setting the GPIO pin output voltage to high
turn_light_off:	The output voltage of the GPIO pin that is connected to the relay channel 3 is set to low, which will turn the LED Lamp off
set_lighting_state (state):	Sets the *Light_state* Boolean variable to the input value *state*
get_lighting_state:	Returns the value of the *Light_state* variable
turn_fans_on:	Sends signal to the relay channel 1 to turn of the fans on by setting the GPIO pin output voltage to high
turn_fans_off:	The output voltage of the GPIO pin that is connected to the relay channel 1 is set to low, which will turn the fans off
set_fan_state (state):	Sets the *Fan_state* Boolean variable to the input value *state*
get_fan_state:	Returns the value of the *Fan_state* variable

light_control: Function calls are made to get the sensor data for the ambient lighting and the internal temperature of the greenhouse.

A check is then made to determine if the the ambient lighting is dark and that the internal temperature of the of the greenhouse doesn't exceed the threshold value. If the check passes the controller will then send a signal to the relays to turn the LED lamp on

If the previous check fails, then another one is made to determine is the ambient lighting is bright or if the internal temperature of the greenhouse exceeds the threshold value. If this check passes, the LED lamp will be turned off

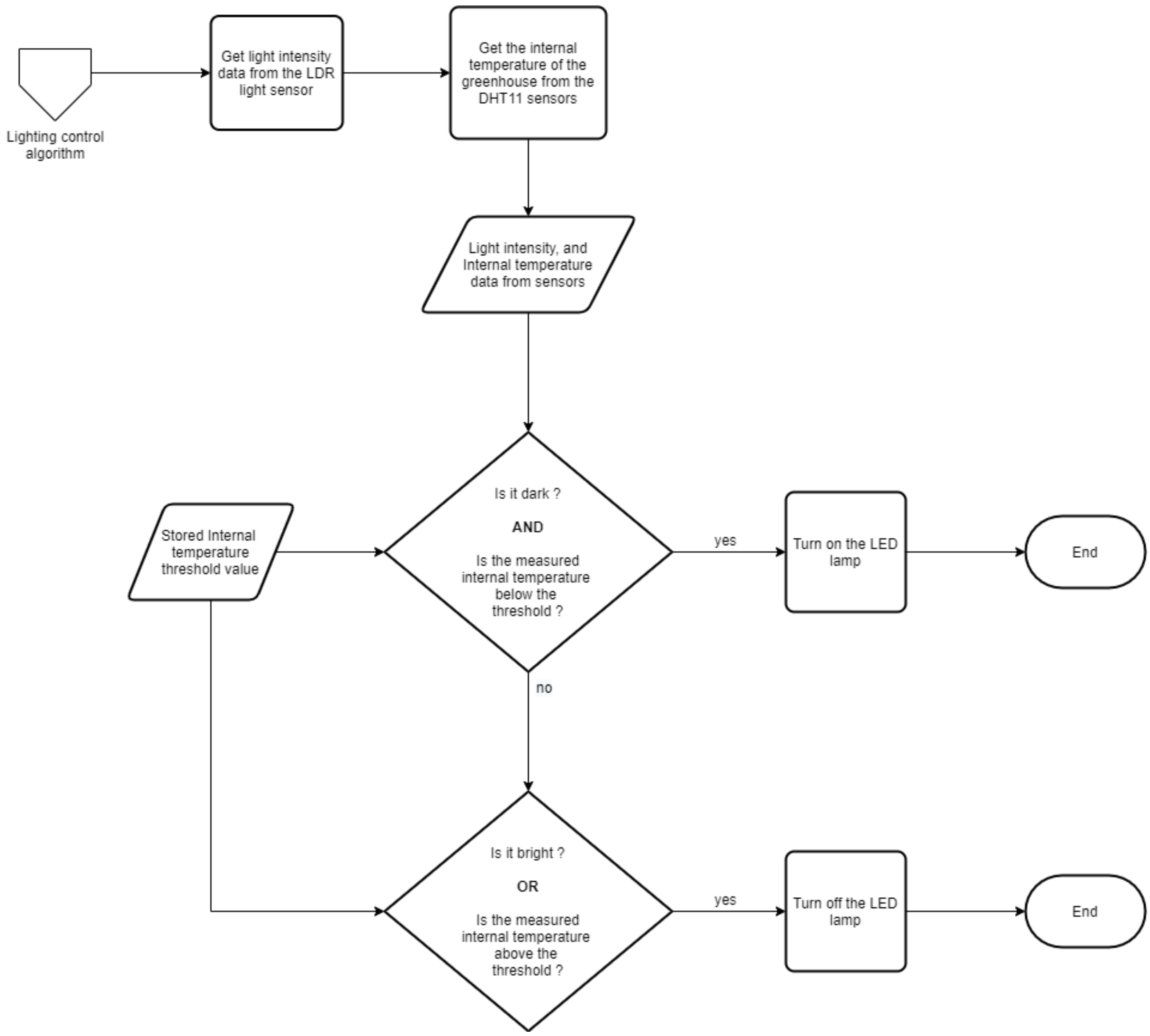


Figure 5.14: Flowchart visualizing the lighting control algorithm

ventilation: Function calls are made to get the environmental data from the DHT11 sensors to get the for the external temperature, the internal temperature, and the relative humidity of the greenhouse environment.

A check is then made to determine if the relative humidity exceeds the threshold. If the check passes the controller will then send a signal to the relays to turn the fans on. This is to reduce the water vapour present in the environment.

If the previous check fails, then another one is made to determine if the internal temperature is higher than the external temperature. If this check passes, the fans will be turned on. This is to cool down the environment, but it will be ineffective if the external and internal temperatures are the same.

If all the previous checks fail, then the fans will be turned off.

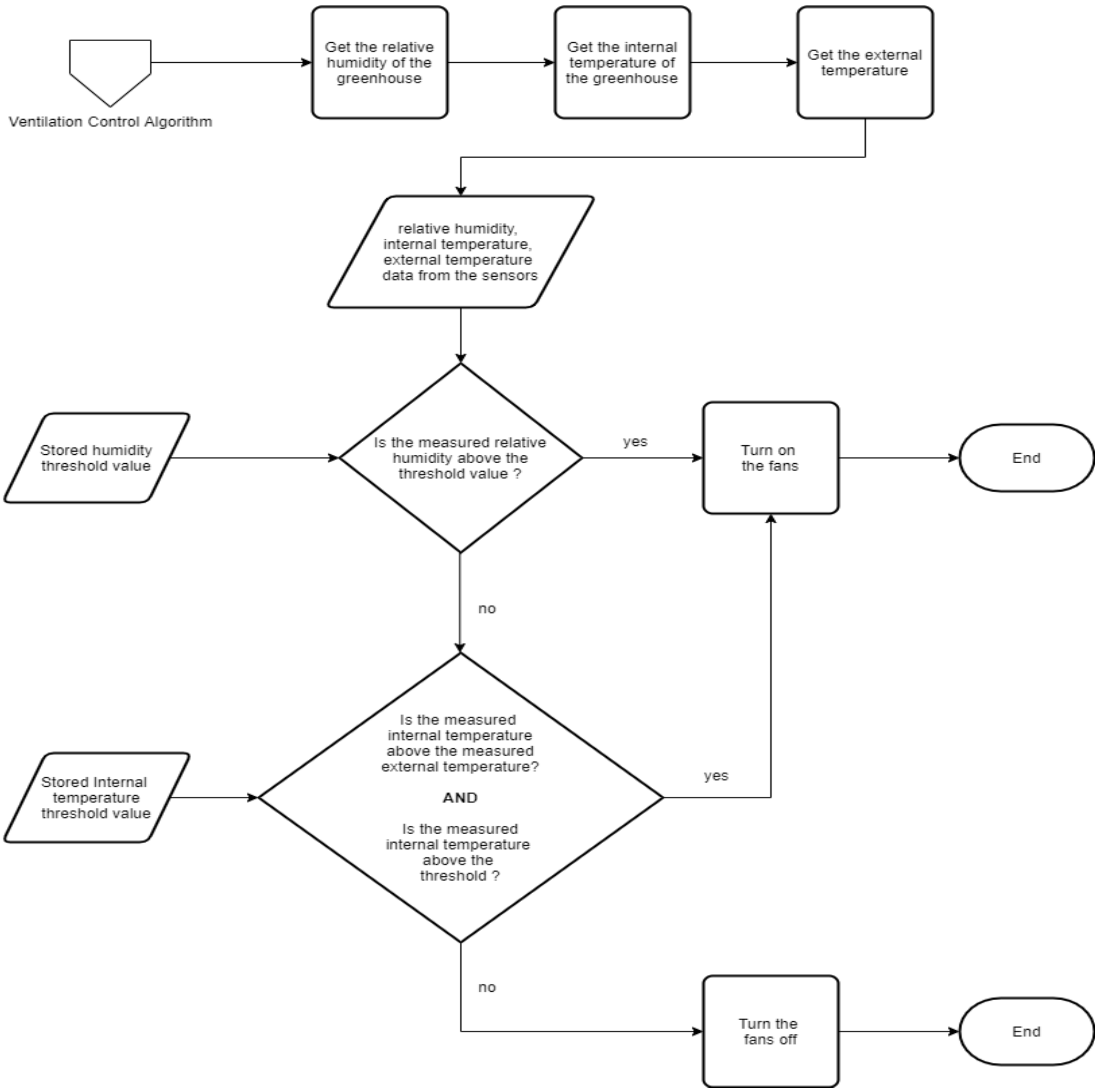


Figure 5.15: Flowchart visualizing ventilation control algorithm

water_control: A function call is made to get the soil moisture data the ADC.

A check is then made to determine if the measured soil moisture exceeds the threshold. If the check passes the controller will then send a signal to the relays to open the solenoid valve. This will allow the water from the reservoir to flow through the tubing and water the plant.

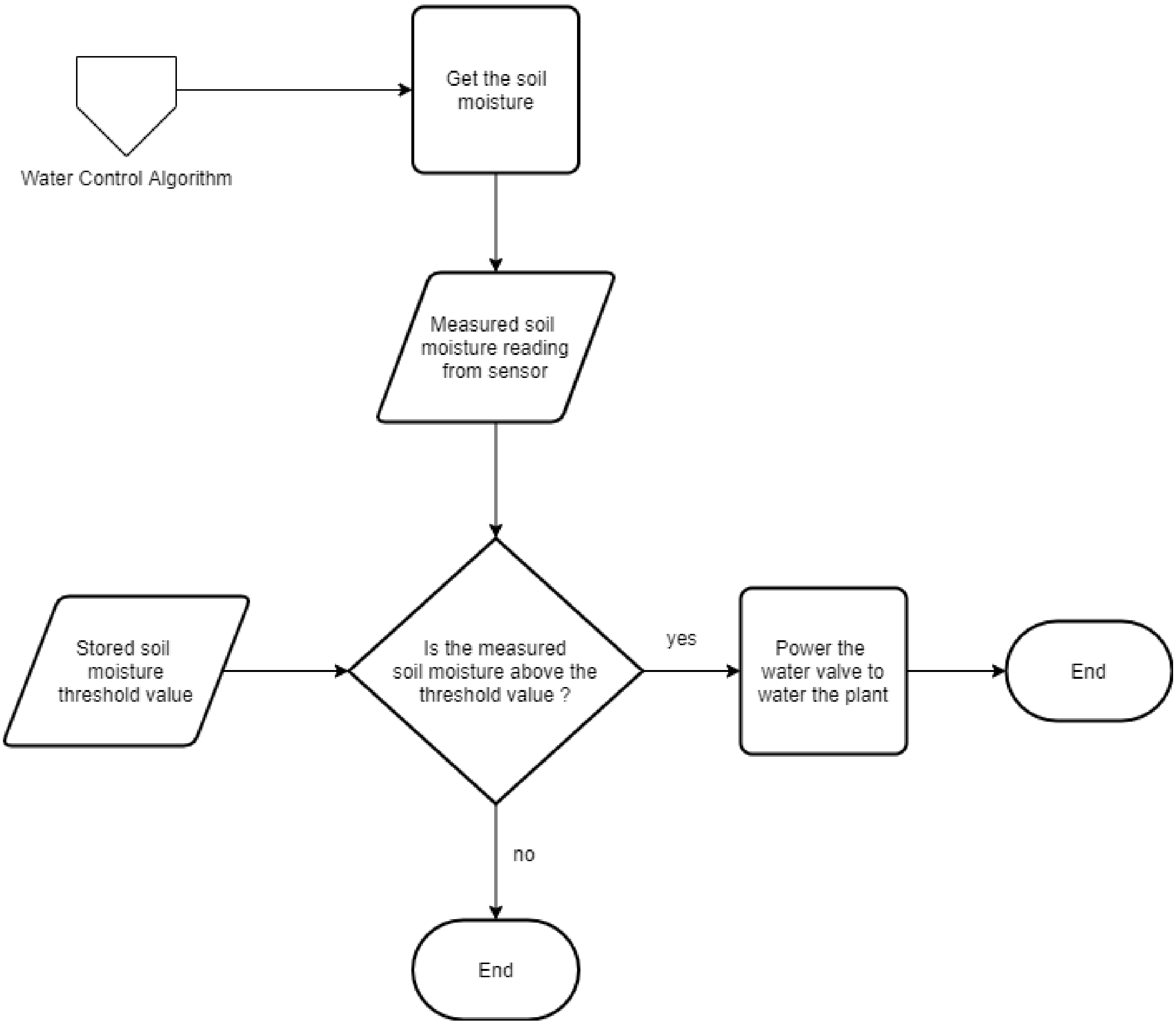


Figure 5.16: Flowchart visualizing water control algorithm

5.4 Implementation

5.4.1 Greenhouse

The system's greenhouse is a 70*l* transparent plastic storage container. The following modifications were made to improve its functionality as a greenhouse and aid in setting up the other subsystems:

- A thin wooden board was bolted down to the bottom and a piece of the board extends the container which is where the electronics can be placed.

- Two hooks were placed on the front and left side, respectively, to aid in mounting the irrigation system. The front hook is mounted with 2 screws and the other one is mounted using glue pads.

- holes were drilled in the lid which allowed the LED lamp's cabling to pass through

- 4 holes were then cut out of the container:

    1. <u>Front - bottom-right</u>: Used to allow cables to pass through, used to connect the sensors inside to the electronics.

    2. <u>Right – bottom-right</u>: Used as the intake opening where one of the 12V DC fans is fitted.

    3. <u>Left – top-left</u>: Used as the extractor opening where the other 12V DC fan is fitted.

    4. <u>Left – middle-left</u>: Allows the plastic tubing to enter the greenhouse

5.4.2 Ventilation

The fans are mounted to the container using the glue pads and placed by ventilation openings. The cabling is then extended and guided to the electronics area by using the glue pads to stick it onto the container.

5.4.3 Irrigation system

A small plastic bottle is used as a water reservoir and is kept in place by the front hook. The bottle is situated above the soil bed which allows the water to flow down due to gravity. This was done to reduce the need for a water pump.

The solenoid valve is mounted to a small wooden block which is then mounted to the front of the container using a glue gun. Wiring was then made and attached to the power terminal using a spade connector.

The irrigation system set up is then completed by attaching the plastic tubing to the bottle and the input opening of the valve. Tubing is then attached to the output of the valve and guided through the opening on the side of the container and is placed above the soil bed. The hook is used to support the tubing and keeps it above the soil bed.

5.4.4 Lighting System

The LED lamp is mounted to the lid of the container using nuts and bolts. The cabling is then guided through the opening on the lid. Two connectors are placed on the lid which will be used to guide the wiring for the LED lamp. A wired 3-point plug was made and is then attached to the LED lamp using the connectors. The live wire from the plug and the power wire of the LED lamp is then guided through to the electronics area and connected to the relay module.

5.4.5 Fully Assembled Greenhouse

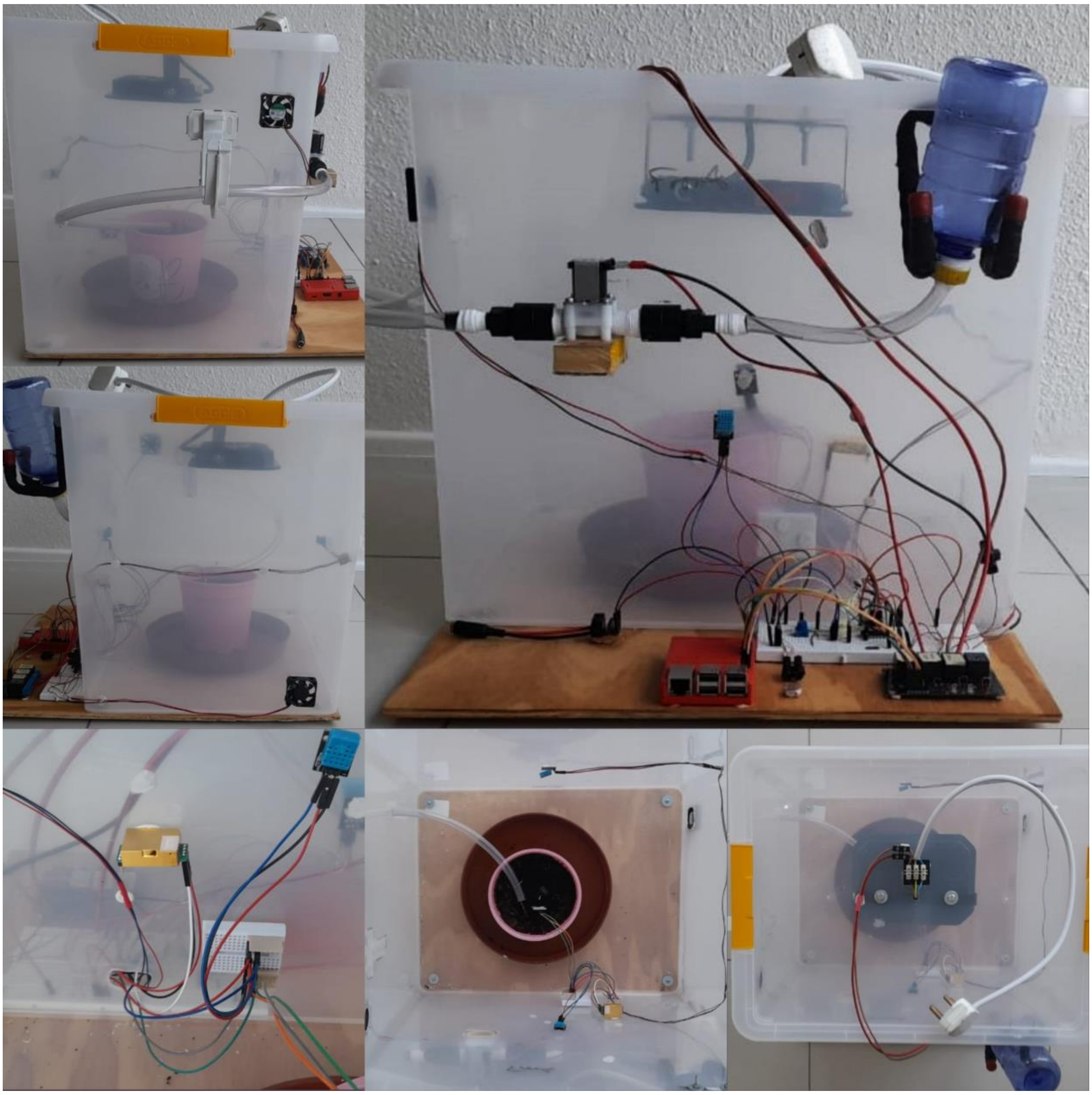


Figure 5.17: Fully assembled greenhouse in a collage format

Chapter 6: Results

Three experiments were organized with the purpose of verifying that the designed environmental control system functions as planned based on the testing procedures seen in **Table 4.3**, and to gain insight to the characteristics of the system. The following section will explain how each of the experiments were set up and the results of each experiment. The chapter will end with a discussion of the experimental results provide an objective reflection on the performance of the designed system and verifying that the system have passed the test procedures.

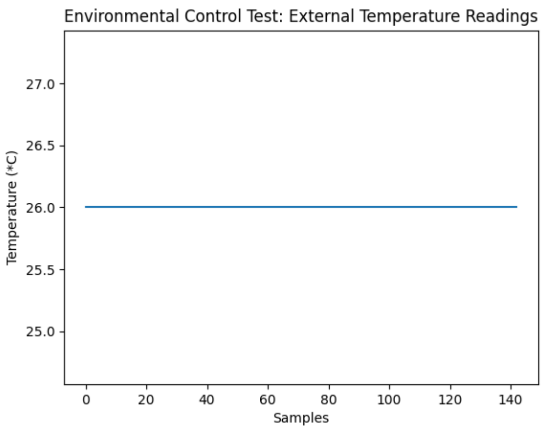
Unfortunately, the irrigation subsystem could not be tested. As mentioned in the previous section, the solenoid water valve would not open due to a lack of water pressure in the tubing, and the ADC broke before the experiments could be performed, so the system would not be able obtain data of the water content of the soil to effectively control the irrigation system.

6.1 Experiments

6.1.1 Environmental Control Test

The aim of the experiment was to determine that the environmental control system functions as intended. The system can be considered to function correctly by obtaining sensor data and activating the actuators to back to a state of environmental equilibrium when the environment is in an unstable state.

As described in section 5.3.1, the environmental control algorithm will run for 30 minutes. In that time sensor data and the activation state of the actuators will be recorded. The test was performed in a dark environment so that the LED lamp would be turned on as a means of heating the system. A small pool of water is also in the planting tray to increase the humidity of the system. This was done to induce a change in the environmental conditions that would cause the system to activate the actuators giving the recorded data more depth. The figures below display the results of the experiment:



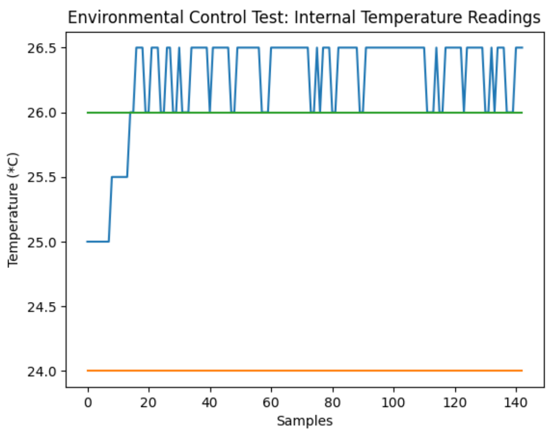


Figure 6.1: External and Internal Temperature data for Environmental Control Test

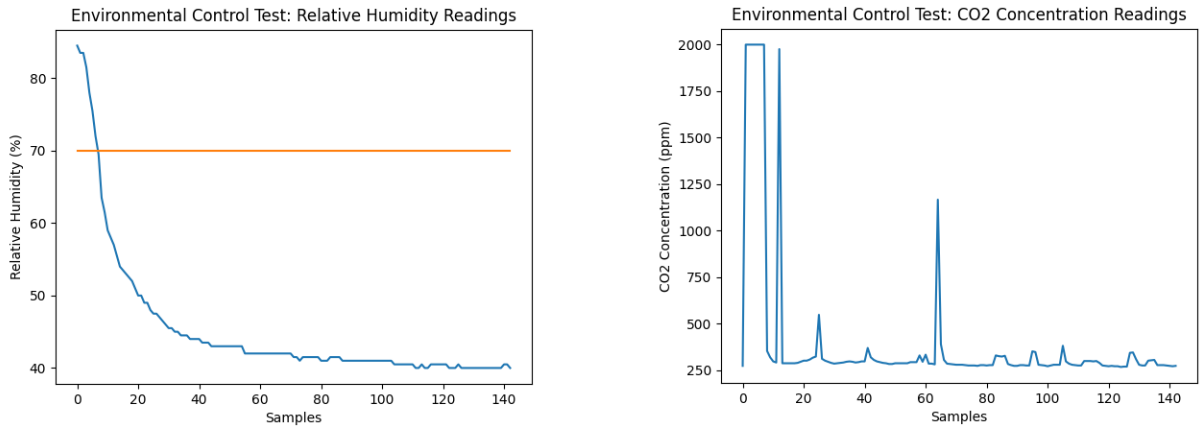


Figure 6.2: Relative humidity and CO2 concentration data for Environmental Control Test

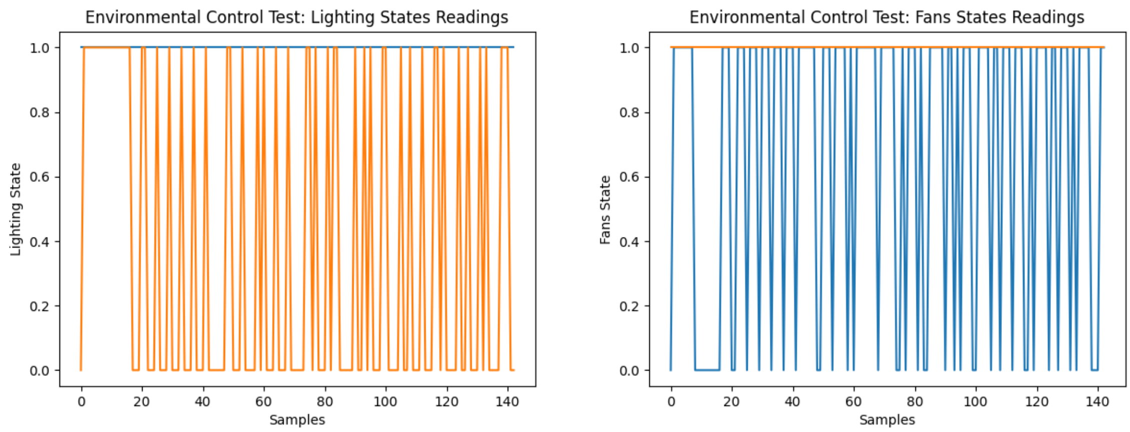


Figure 6.3: Activation state for the LED Lamp and Fans for Environmental Control Test

6.1.2 LED Lamp Heating Test

The aim of this experiment was to test the heating capability of the LED lamp by measuring how much heat it produced. This was done by turning the LED Lamp on for 30 minutes and recording the temperature data inside of the greenhouse. Figure 5.4 below shows the recorded experimental data.

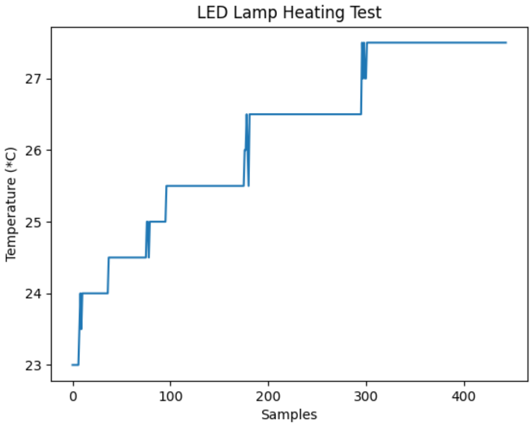


Figure 5.4: Heating data for LED Lamp Heating test

6.1.3 Ventilation Test

The objective of this experiment was to gauge the effectiveness of the ventilation system by testing its capability of regulating the humidity inside the greenhouse. The test is done by turning the fans on for 30 minutes and recording the relative humidity data of the greenhouse. The test was performed by placing a 500 *ml* container of boiling water inside of the greenhouse 5 minutes before the fans were turned on. This was done to drastically increase the relative humidity inside of the greenhouse in order to determine the rate of water vapour extraction that the fans are capable of. The results of this test can be seen in Figure 5.6 below.

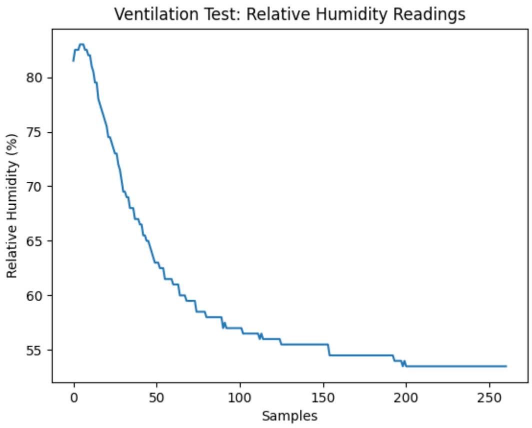


Figure 5.6: Relative humidity data for Ventilation test

6.2 Discussion

The results of the Environmental Control test shows that the system can control the environment by activating the actuators by using the data from the sensors. The temperature of the system was controlled as this can be seen that the lights switch off when the internal temperature exceeds the threshold and turns itself back on when the conditions are stable. Also the fans activate when the internal temperature is unstable and is turned off when it is. The system is also capable of controlling the humidity inside of the system, as the fans are seen to activate in the beginning when the initial humidity conditions exceeded the threshold.

The results of the LED Lamp Heating Test show that the lamp can be used as a heating source for the greenhouse as the temperature steadily climbs over the duration of the test. If time permitting, I would have like to run a test subjecting the greenhouse to a cold environment and seeing if the control system can maintain the internal temperature using the LED lamp.

The results of the ventilation test show that the system is very effective of reducing the humidity inside the system, the log data shows that the relative humidity was reduced by over 40% within the 30 minutes time frame.

Based on the results observed from these experiments, the designed system has passed 3 out of the 4 testing procedures and could not perform the test procedure TR04 to test the irrigation system.

Chapter 7: Conclusion

The objective of this project was to design and assemble a cost-effective environmental control system that can be used inside of greenhouses. The intent was to design a system that is financially accessible to potential growers and to automate the growing process which removes the need for expert knowledge on farming.

The results have shown that the system is capable of effectively monitoring the essential environmental variables by using low-cost sensors. It is also seen that the system is certainly capable of regulating the lighting and humidity within the greenhouse environment and can regulate the temperature to an extent.

Unfortunately due to the ADC breaking and solenoid water valve not working as intended, the automatic irrigation of the system could not be realised. Important factors that the designed system could not control is enriching the environment with CO_2, nor can it effectively provide cooling to the greenhouse environment due to the costs of implementing the equipment needed to facilitate these processes.

The calculated costs of the designed system amounted to approximately R3 000. Which isn't exactly low-cost. It should be mentioned that many of the components were freely procured from UCT's White Lab and the components that were already at my disposal, and luckily enough the soil moisture sensor was freely given to me by the Yebo Electronics in Boston, Cape Town, when I was buying some cables. The only items that had to be procured was the 12V DC fans, the water valve, tubing, plastic storage create and the LED Lamp.

Components that can be cut is the MH-Z19 NDIR CO2 sensor that amounts to R600, as it isn't not used to facilitate any control mechanisms in the designed system. The Raspberry Pi can be replaced with a micro-controller such as a STM32 controller. A potential R1 000 can be reduced from the overall costs of the designed system.

For future work that would improve these different iterations of this design, I recommend the use of a small-scale water pump. This would be able to facilitate the necessary water pressure needed to drive the water valve and decrease the complications of creating an automated irrigation system where the water reservoir needs to be placed above the soil bed of the plant. A microcontroller could also be used to replace the Raspberry Pi to decrease the costs for the controller. It would also avoid complications of facilitating the communication between the sensors and the controller, as the operating system made the implementation difficult on several occasions.

References

[1] D. H. Park *et al.*, “A study on greenhouse automatic control system based on wireless sensor network,” *Wirel Pers Commun*, vol. 56, no. 1, pp. 117–130, 2011, doi: 10.1007/s11277-009-9881-2.

[2] “GrowBox.” [Online]. Available: https://growboxnursery.co.za/

[3] F. J. Baumont de Oliveira, S. Ferson, R. A. D. Dyer, J. M. H. Thomas, P. D. Myers, and N. G. Gray, “How High Is High Enough? Assessing Financial Risk for Vertical Farms Using Imprecise Probability,” *Sustainability*, vol. 14, no. 9, p. 5676, 2022, doi: 10.3390/su14095676.

[4] J. C. Bakker, “Greenhouse Climate Control: Constraints and Limitations,” *Acta Horticulturae*, no. 399. pp. 25–36, 1995. doi: 10.17660/actahortic.1995.399.2.

[5] B. J. Bailey, “Greenhouse Climate Control - New Challenges,” *Acta Horticulturae*, no. 399. pp. 13–24, 1995. doi: 10.17660/actahortic.1995.399.1.

[6] R. H. Thayer, “Carbon Dioxide Enrichment Methods.” [Online]. Available: https://www.hydrofarm.com/carbon-dioxide-enrichment-methods

[7] J. R. Rath *et al.*, “A Review of Greenhouse Climate Control and Automation Systems in Tropical Regions,” *Acta Hortic*, vol. 8, no. 1, p. 5676, 2020, doi: 10.2139/ssrn.3749031.

[8] A. Muhr, “Creating a Cost-Efficient Controlled Growth Environment Prototype Combatting Food Insecurity in South Africa,” 2018.

[9] B. Min and S. J. Park, “A smart indoor gardening system using IoT technology,” *Lecture Notes in Electrical Engineering*, vol. 474, pp. 683–687, 2018, doi: 10.1007/978-981-10-7605-3_110.

[10] A. Gracian, “Red & Blue LEDs But No Green?,” 2017. [Online]. Available: https://albopepper.com/red-blue-LED-grow-lights-with-no-green-spectrum.php

[11] W. Fu, P. Li, Y. Wu, and J. Tang, “Effects of different light intensities on anti-oxidative enzyme activity, quality and biomass in lettuce,” *Horticultural Science*, vol. 39, no. 3, pp. 129–134, 2012, doi: 10.17221/192/2011-hortsci.

[12] C. R. Brodersen and T. C. Vogelmann, “Do changes in light direction affect absorption profiles in leaves?,” *Functional Plant Biology*, vol. 37, no. 5, pp. 403–412, 2010, doi: 10.1071/FP09262.

[13] S. Trimble, “Transpiration in Plants: Its Importance and Applicationsitle,” *October 7, 2021*. https://cid-inc.com/blog/transpiration-in-plants-its-importance-and-applications/

[14] P. R. P, P. C, M. R. Williams M, N. R, and M. Ariffuddeen M, “Case Study on Performing Indoor Gardening with New Technology Implication to Overcome the Gaps in the Existing Solutions,” *International Research Journal on Advanced Science Hub*, vol. 2, no. 8, pp. 19–22, 2020, doi: 10.47392/irjash.2020.85.

[15] D. Brenchley, “Cost - Effective Controlled Environment Agriculture,” no. October, 2019.

[16] J. R. Rath and M. Ghosal, “Studies on environmental control of greenhouse for crop production,” *Int J Chem Stud*, vol. 8, no. 5, pp. 674–676, 2020, doi: 10.22271/chemi.2020.v8.i5j.10377.

[17] R. L. Sumalan *et al.*, “A Cost-effective embedded platform for greenhouse environment control and remote monitoring,” *Agronomy*, vol. 10, no. 7, 2020, doi: 10.3390/agronomy10070936.

[18] H. Considerations, “ENVIRONMENTAL CONTROL OF GREENHOUSES,” no. June 1997, pp. 1–19, 2005.

[19] S. C. Technologies, "Lighting and HVAC – Are They Friend or Foe?" [Online]. Available: https://surna.com/lighting-and-hvac/
[20] "How Does Reverse Cycle Air Conditioning Work?" https://hellobreeze.com.au/how-does-reverse-cycle-air-conditioning-work/
[21] F. Kalantari, O. Mohd Tahir, A. Mahmoudi Lahijani, and S. Kalantari, "A Review of Vertical Farming Technology: A Guide for Implementation of Building Integrated Agriculture in Cities," *Advanced Engineering Forum*, vol. 24, pp. 76–91, 2017, doi: 10.4028/www.scientific.net/aef.24.76.
[22] K. Kele, "Indoor Farming : Fancy Concept or Environmental Breakthrough ?," 2018.
[23] E. Mahjoub, "Optimization of Light Conditions in a Greenhouse Environment," 2022.
[24] J. D. Stevens, D. Murray, D. Diepeveen, and D. Toohey, "Adaptalight: An Inexpensive PAR Sensor System for Daylight Harvesting in a Micro Indoor Smart Hydroponic System," *Horticulturae*, vol. 8, no. 2, 2022, doi: 10.3390/horticulturae8020105.
[25] A. Z. Mohd Zaki *et al.*, "Building a Smart Gardening System and Plant Monitoring Using IoT," *Journal of Sustainable Natural Resources*, vol. 02, no. 01, pp. 1–6, 2021, doi: 10.30880/jsunr.2021.02.01.001.
[26] "How Do CO2 Sensors Work?" https://www.processsensing.com/en-us/blog/how-CO2-sensors-work.htm
[27] "HUIKE 4-Channel-5V-Relay-Module Picture." [Online]. Available: https://www.bananarobotics.com/shop/image/cache/data/sku/BR/0/1/0/1/3/BR010135-4-Channel-5V-Relay-Module/4-Channel-5V-Relay-Module-600x600.jpg
[28] Numpy, "numpy." [Online]. Available: https://github.com/numpy/numpy
[29] Adafruit, "circuitpython." [Online]. Available: https://github.com/adafruit/circuitpython
[30] UedaTakeyuki, "mh-z19." [Online]. Available: https://github.com/UedaTakeyuki/mh-z19
[31] Luxedo, "RPi_mcp3008." [Online]. Available: https://github.com/luxedo/RPi_mcp3008

Appendix

Ethics Form:

ETHICS APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		David Moore
Department		EBE - Electrical Engineering
Preferred email address of applicant:		mrxdav015@myuct.ac.za
If Student	Your Degree: e.g., MSc, PhD, etc.	BSc Electrical and Computer Engineering
	Credit Value of Research: e.g., 60/120/180/360 etc.	40
	Name of Supervisor (if supervised):	Justin Pead
If this is a researchcontract, indicate the source of funding/sponsorship		N/A
Project Title		Low-cost Environmental Control Indoor Greenhouse

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

APPLICATION BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	David Moore		08/18/2022
SUPPORTED BY	**Full name**	**Signature**	**Date**
Supervisor (where applicable)	Justin Pead		22/08/2022

APPROVED BY	Full name	Signature	Date
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).			
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the questions in Section 1.			