ENGN2225 Systems Engineering Design

Automated Management of the Climatic Environment within a Domestic Greenhouse

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Automated Management of the Climatic Environment within a Domestic Greenhouse

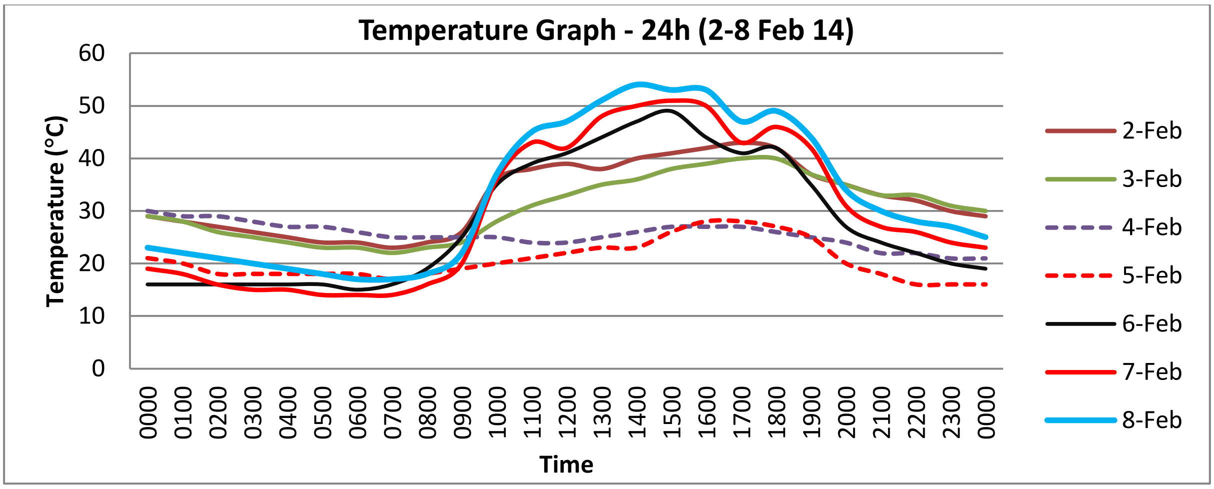
Abstract

A domestic greenhouse can provide the householder with the ability to grow plants for longer periods by maintaining a warmer environment during the cooler months. However, greater growing potential can be achieved by controlling both the temperature and humidity. In general, domestic greenhouses are equipped with manual vents which are set by the user as required. By automating the monitoring of the temperature and humidity (Shamshiri & Wan Ismail, 2013) and adjustment of vents, airflow and moisture levels, the ideal levels can be constantly maintained and optimum growing conditions can be achieved.

Image 1. *Sproutwell Greenhouse: Garden Pro 1800 Model Greenhouse* (Sproutwell Greenhouses, 2015).

1 Background

Domestic greenhouses are generally designed for the household budget and utilise manual vent and louver systems to control the temperature. While these systems are effective, they lack the precision control and feedback to maintain optimum growing conditions.



Graph 1. *Greenhouse temperatures recorded over the period 2-8 February 2014.*[1]

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[1] The temperatures were recorded in Queanbeyan by the author in a 2m x 2.8m domestic greenhouse in 2014.

The results in Graph 1 were recorded in a small domestic greenhouse over a period of seven days during summer in the Canberra region. The greenhouse was fitted with two roof vents, a single floor vent and was shaded with a single layer of shade-cloth (over the roof and two side walls). The vents (fully open) and shade cloth were left in the same position over the period. With the greenhouse unattended, the temperature varied between 14°C and 51°C. As different plants thrive in different environmental conditions, the aim of the project is to design a system to maintain a stable indoor environment with limits determined by the user.

The Client for this project is the average Australian householder with the following requirements:

- Inexpensive (<$500),
- Automated temperature and humidity control,
- Allow the user to define settings,
- Easy to use,
- Not dependent on mains power, and
- Reliable.

2 Aim

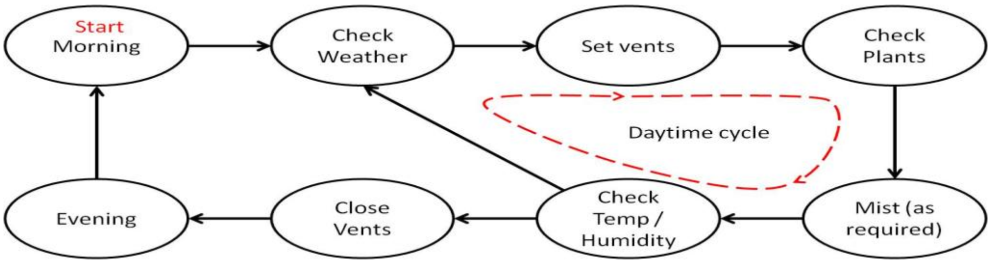
The aim of this project is to apply Engineering Systems Design principles in order to design an automated system which will monitor the greenhouse environment and adjust vents, airflow and moisture levels to maintain a constant growing environment.

3 Greenhouse Environmental Issues

The manual adjustment of temperature and humidity requires an assessment the weather forecast for the day and a decision on how to set the greenhouse vents so that ideal conditions are maintained. The process requires regular assessments of the conditions (both external and internal) and adjusting of the vents to cater to any variations in the temperature and humidity levels. Alternatively, the vents can be set in the morning and closed in the evening, however, this means that any fluctuations during the day are not catered to and the greenhouse environment is not stable. From a cursory examination, the problem appears to relate to the constant monitoring of the environment and adjustment of the greenhouse vents.

3.1 Greenhouse Environmental Management – The Journey

In order to define the scope of the problem, a Journey Map (Image 2) was developed to identify the main steps which contribute to maintaining the greenhouse environment.



[2]

Image 2. *Domestic Greenhouse temperature and humidity adjustment process.*

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[2] Misting is the production of a fine mist of water to cool the environment and increase the relative humidity.

The boundary of influence was identified as being the greenhouse structure. Internally, the user has the opportunity to influence all aspects of the environment (leaving cost aside). Externally, however, they are at the mercy of the elements; sun, wind and rain.

3.2 Detailed Examination

For a manual system, the vents are set at the beginning of the day and reset (or closed) at the end of the end of the day. When considering the process flow (Journey Map - Image 2) it can be seen that the in order to maintain a constant environment, the daytime cycle needed to be repeated at regular intervals. Additionally, by designing an automated system, four of the steps (Start, Check Weather, Close Vents and Evening) could be removed from the process.

4 Options for Environmental Management

A number of ideas were examined with regard to managing the environment (temperature and humidity) – not surprisingly, these centred on adjusting watering, airflow and shade. This is supported by del Sagrado, et al., (2015), who summarise the control of the environment as a function of temperature, humidity and CO_2. The role of CO_2 in a greenhouse is to enhance the process of photosynthesis during daylight hours (Ramezani, et al., 2015). However, due to sensor cost (~$150-$200 (Element14, 2016)) and the on-going supply requirements, it is being removed from the scope of this design. It could, however, be incorporated into future designs should it prove to be cost beneficial for the domestic market.

The ideas were mapped into a Concept Classification Tree (Ulrich & Eppinger, 1995) to identify common themes and potential limitations (Image 3). The process identified two main themes; Temperature control and Humidity control. Both of the themes are valid, however, modifying temperature alone (Aldrich & Bartok, 1994) can also be an effective way to adjust humidity. Across these two themes, common controlling systems were identified; shade control, air control, vent control, heat control and water control.

The issue of shade control was considered further, and from the temperature recordings provided in Graph 1, it was considered that a shade system would most likely be a permanent fixture during the warmer months and removed during the cooler months. Therefore, the shade control branch could be removed and the project would focus on air, vent, heating and water control. This resulted in the sub-themes; applying water to cool surfaces to reduce temperature, misting to increase humidity, heating to increase temperature, adjusting vents to regulate airflow and using fans to modify air circulation (to change both temperature and humidity).

The application of water to surfaces to reduce temperature was examined and found to interfere with humidity control; Wraight, et al. (2016) sprayed water on concrete surfaces in greenhouses as a means of maintaining high humidity conditions. Water application was therefore removed from the scope of the project, leaving four main actions; misting, heating, vent control and air circulation.

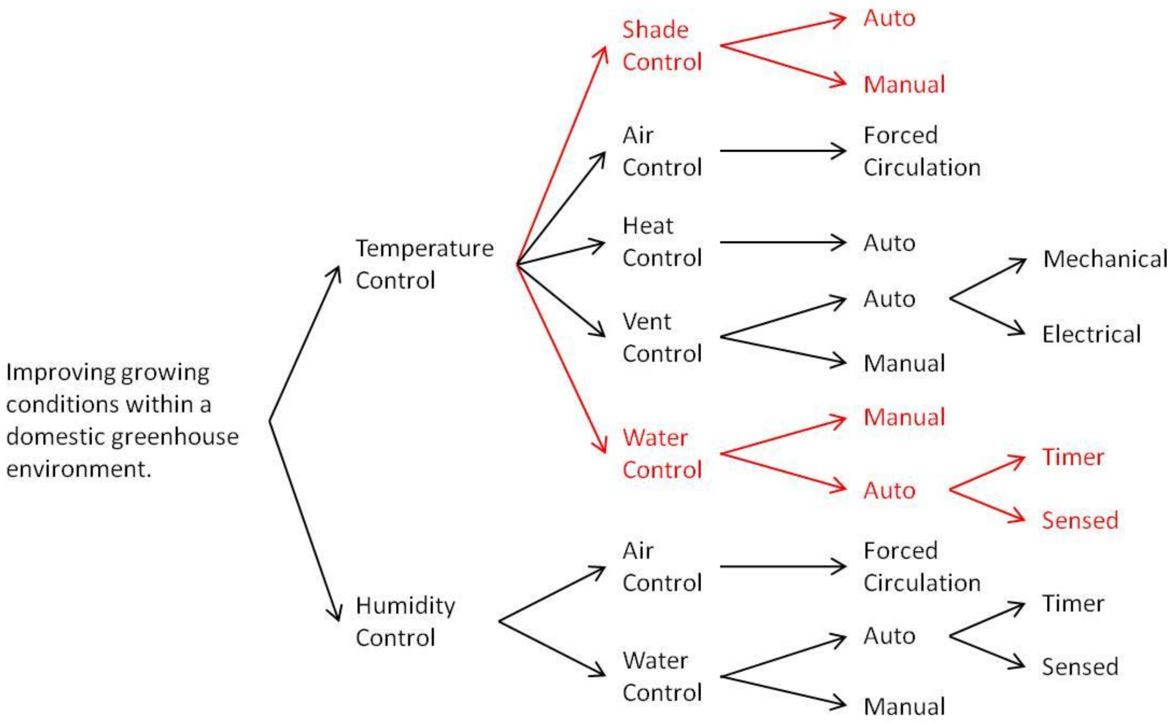

Image 3. *Concept Classification Tree [Note: the branches in red have been discounted from the project]*.

5 User Requirements

A number of available commercial solutions were reviewed, however, these were all designed for the market-garden level / primary producer, rather than the domestic household (FarmTek, 2014). Some solutions were sub-units which still need to be integrated into a main system or supplied with mains power (Sproutwell Greenhouses, 2015), and included systems to retract / open roofs or incorporated industrial fans and heaters. Their price was significantly greater than that desired of the Client or they failed to meet one or more of the Design Requirements. The principles of air circulation, vent control and misting remain the same across both levels of gardening and therefore a bespoke solution was considered.

A pair-wise analysis (Dym, et al., 2008) of the Client's requirements resulted in the top three requirements being identified as being automation, off-mains power and reliability. This was to be expected as these elements are critical to the functionality of the system.

The Design Requirements were further examined to identify the associated Engineering Characteristics and Performance Metrics and tabulated in Table 1 (Blanchard & Fabrycky, 2011). Based on the top three requirements identified by the pair-wise analysis, the focus of the Design Requirements was on sensor accuracy, maximising (or optimising) output / response, power generation / storage and minimal power consumption. These metrics provide a solid basis for the performance of the individual sensors and actuators. They also provide a common baseline for comparison, and when combined, provide an overall understanding of the system performance and interactions between each of the Design Requirements. For example, it would be expected that DR02-06 *Applies Heat* will have a direct affect on DR05-02 *Power Storage* – it is clear that there will be trade-offs at the final design stage.

The issue of reliability is addressed during the Testing and Evaluation phase as part of the Test Regime where components are subjected to a number of testing cycles.

A number of the Engineering Characteristics did not have formal metrics; namely Control(s) and Display which are represented by Identifiers DR03 and DR04. During the Test and Evaluation process a simple ranking of 1-5 will be applied to these Engineering Characteristics, with the higher the value indicating a more optimised function. While this is somewhat subjective, the general process would be as follows:

- An interface which requires less than three levels of navigation to enter a temperature or humidity level will score 5.
- An interface which requires between three and five levels of navigation to enter a temperature or humidity level will score 3.
- An interface which requires more than five levels of navigation to enter a temperature or humidity level will score 1.

The metrics for these Engineering Characteristics will need to be evaluated when prototypes are made available so that systems are judged on an even basis.

Importance	Customer Requirement	ID	Design Requirement	Engineering Characteristics	Metric (TPM)
1	Automated temperature control	DR02-01	Senses temperature	+ sensing	±°C (accuracy)
		DR02-02	Adjusts vents	• control	s (Time) W (Power)
		DR02-03	Fan output	• flow	l/min (vol/min) W (Power)
		DR02-04	Senses humidity	+ sensing	±% RH (accuracy)
		DR02-05	Applies water	• flow	l/min (vol/min) W (Power)
		DR02-06	Applies Heat	+ temperature	W (Power)
2	Not dependent on mains power	DR05-01	Renewable energy	• energy capture	W (power)
		DR05-02	Power storage	+ battery life	Ah (Amp hrs)
3	Reliable	DR06-01	Accurate sensing / response	+ sensing	±°C (accuracy)
		DR06-02	Temperature range	+ temp range	°C (range)
		DR06-03	Humidity range	+ humidity range	RH (Rel Humidity)
4	Inexpensive	DR01-01	Less than $500	- cost	$ (cost)
5	User defined settings	DR03-01	User interface Input	• controls	0-5 Score W (power)
		DR03-02	User interface Display	• display	0-5 Score W (power)
6	Easy to use	DR04-01	Simple controls	• controls	0-5 Score
		DR04-02	Simple display	• display	0-5 Score

Table 1. *Engineering Characteristics and Performance Metrics.*

It is worth noting that the Engineering Characteristic 'Flow' (associated with DR02-03 and DR02-05) has been given an optimised characteristic rather than an increase. This is to prevent the design from incorporating a fan or misting unit which is too powerful (or not powerful enough). This metric can be refined to include a maximum / minimum vol/min. In this case, multiple systems under test which fall within the maximum / minimum window will be further assessed against power consumption.

6 Logic and Function

The initial Journey Map identified that during daylight hours the greenhouse environment required continual monitoring and adjusting of vents to maintain ideal temperature and humidity – this was further supported by the temperature readings shown in Graph 1.

The outcomes from the Journey Map and the Concept Classification Tree were translated into a Functional Flow Block Diagram (FFBD) which outlined five main steps (Image 4).

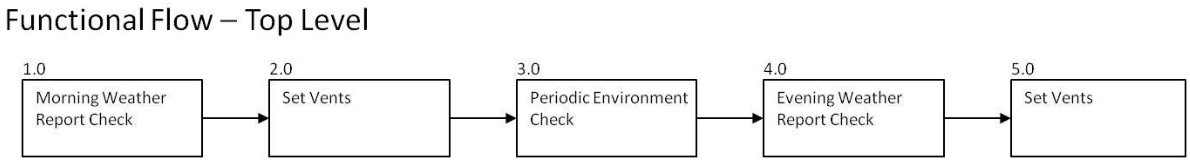

Image 4. *Top Level FFBD for domestic greenhouse environmental control.*

However, this FFBD requires continual user interaction with the system. Further consideration and incorporation of an automated capability reduced this to a two-step process. The first step is where the user sets the environment limits. The second step is a repeated cycle which addresses monitoring and adjustment of the environment. The amended FFBD is outlined in Image 5.

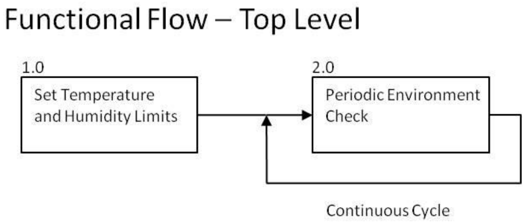

Image 5. Amended *Top Level FFBD for domestic greenhouse environmental control.*

Function 1.0 is a simple user interface function and provides the user with the ability to set temperature and humidity levels. As it is a simple data entry process, it will not be addressed further in this paper.

Function 2.0 is the main operating system which manages the sensors and determines the status of the environment before applying adjustments to the actuators. The decomposition of Function 2.0 into the subordinate levels is shown in Image 6. The first subordinate functions, 2.1 *Check Temperature* and 2.2 *Check Humidity*, do not have multiple sub-functions assigned to them, as these are functions which are designed to read (or sense) and record data. The remaining functions can be seen to have a number of OR sub-functions to enable the adjustment and control of the environment.

It is evident that the introduction of an automated system has significantly reduced the number of functions within the initial FFBD. While this may appear as a reduction in effort, those functions have been absorbed into subordinate functions within the new Function 2.0 of the amended FFBD.

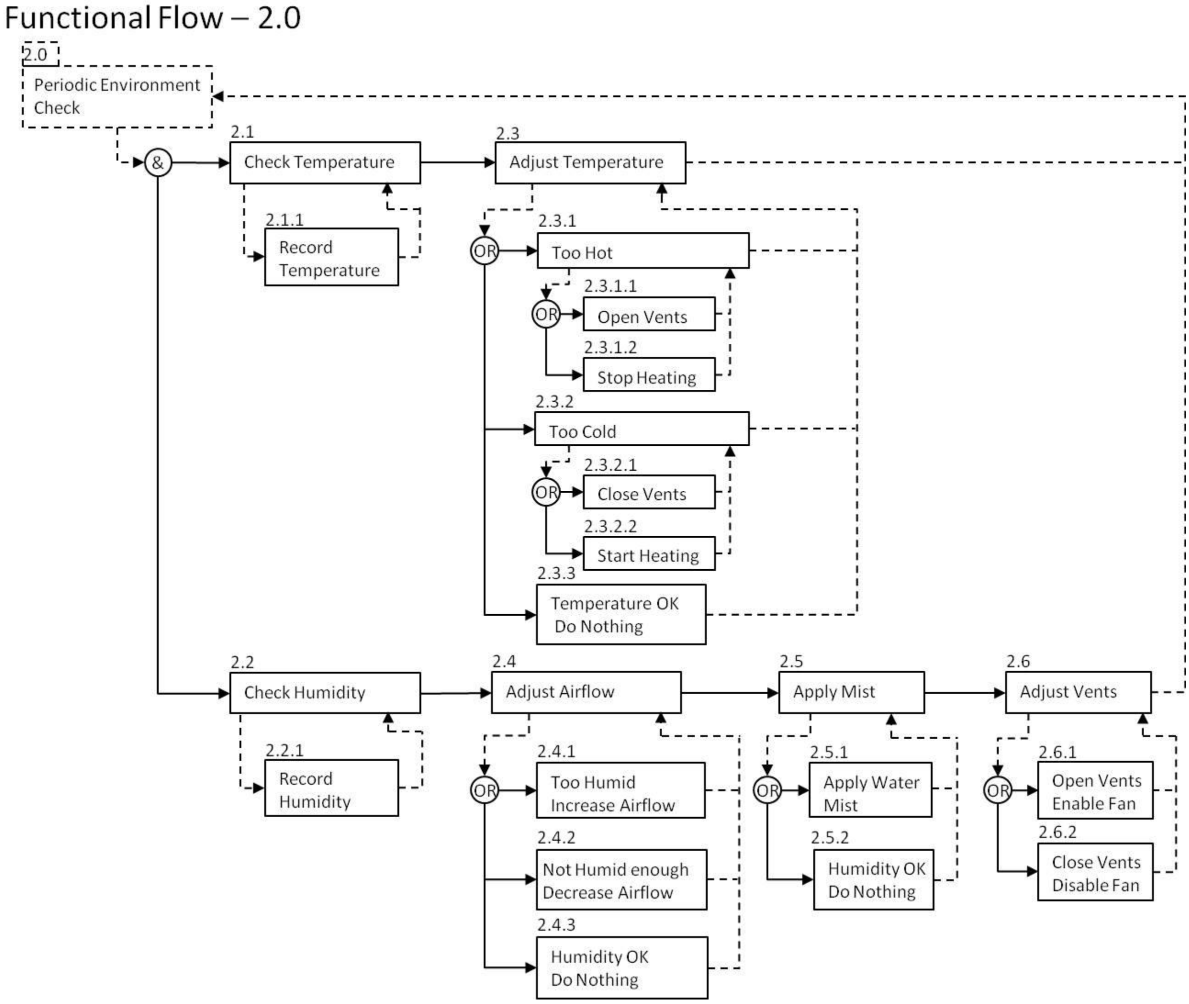

Image 6. *Periodic Environment Check FFBD for greenhouse environmental control.*

A review of the sub-functions identified that control of the vents was being influenced by two different functions – temperature control and humidity control (Functions 2.3 and 2.6). These two aspects will need to be examined under Logic Control so that they do not adversely affect the output from each other. For example, if the two functions continue to adjust the vents independent of each other, they could cause an endless loop of feedback and continual adjustment which would increase power consumption and reduce efficiency (in addition to wear and tear on the system). This needs to be considered when coding the micro-controller so that after an adjustment is made, a period of settling is enforced to allow the environment to stabilise.

Two additional tools were used to examine the relationships. An N^2 Diagram was used to highlight the close relationship between the vent actuator and both the Humidity and Temperature sensors, and a Timing Map was used to present a solution to allow the environment to stabilise before making additional adjustments (National Aeronautics and Space Administration, 2007).

6.1 N^2 Diagram

The N^2 Diagram shown in Image 7 outlines the interaction between each of the elements within the system. In this case, a Direct Interaction is defined by either an electrical connection or a mechanical connection. A Logic Interaction is defined by one element being able to influence another element indirectly (i.e. through another element such as the microprocessor), and Feedback is defined as elements which provide data to another element. As can be seen, both the Relative Humidity (RH) Sensor and the Temperature Sensor have the ability to interact with the vents. As outlined previously under Logic and Function, these two sensors and their influence on the vents will need to be monitored during the development of the micro-controller coding phase.

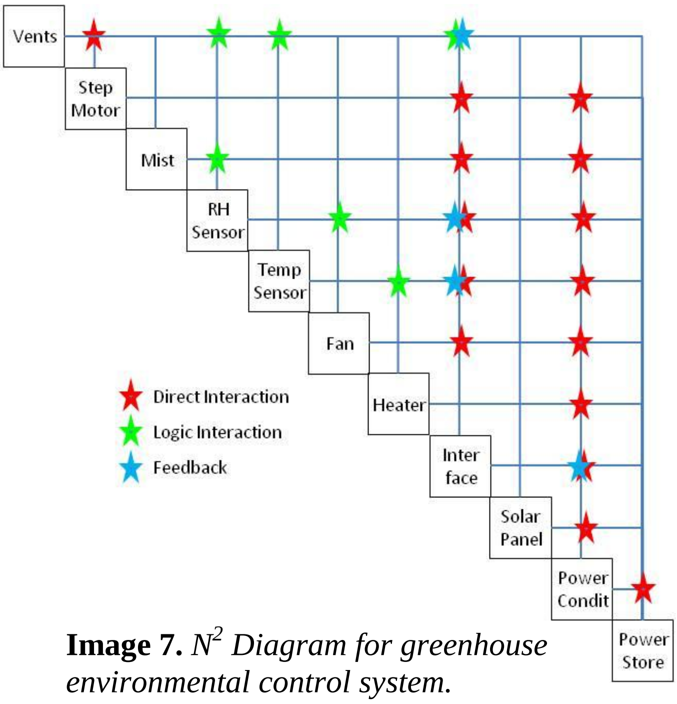

Image 7. *N^2 Diagram for greenhouse environmental control system.*

It should be noted that the N^2 Diagram does not provide a solution to the potential conflicting feedback loop, but rather highlights (visually) that both the Temperature and Relative Humidity sensors drive the vent actuators and may provide conflicting signals. The solution to the issue is provided in the Timing Map (Image 8), where a settling time is enforced to provide time for the environment to stabilise.

6.2 Timing Map

The Timing Map further defines the relationship, timing sequences and interactions between the temperature adjustment function and the humidity adjustment function. As can be seen, a settling time is required to be upheld between the adjustment of the vents (due to temperature changes) and the commencement of the humidity calculations. This will allow the environment to stabilise before additional changes are made.

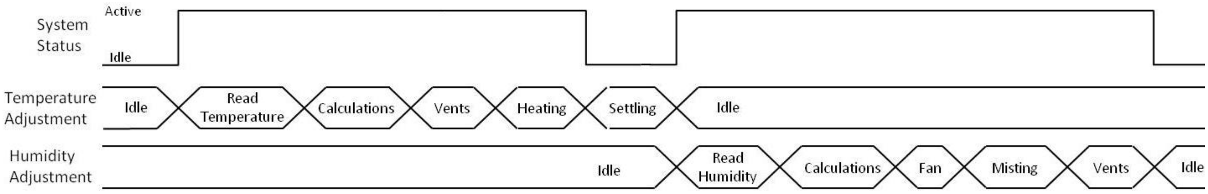

Image 8. *Timing Map for greenhouse environmental control system.*

7 System and Interface

A System Interface Map was used to outline the interfaces between the functions as identified through the previous process of Functional Allocation. The system was broken into five subsystems:

- **Power Subsystem.** Generates green energy and maintains a store of energy for the whole system. It undertakes power generation, storage and monitoring.
- **User Interface.** Accepts the user input and displays system outputs.
- **Logic Board.** Provides the driver for the User Interface and system control.
- **Sensor Subsystem.** Controls the sensors and their feedback.
- **Actuator Subsystem.** Controls the actuators and their feedback.

The System Interface Map (Image 9) was based around a single micro-controller which provides a single 'logic hub' for the system with the other subsystems feeding into it. This provides a modular system which allows for future improvements. For example, the temperature / humidity / misting calculations (undertaken by the Control Board) may be changed on future versions which would allow for the same User Interface, Power, Sensor and Actuator subsystems to be used, but with an improved Control Board. In a similar manner, any failures of the Sensor or Actuator subsystems can be repaired by simple plug-in system replacement. The design also enables consideration for future improvements, such as more efficient actuators or an increased number of actuators and / or sensors (for expansion).

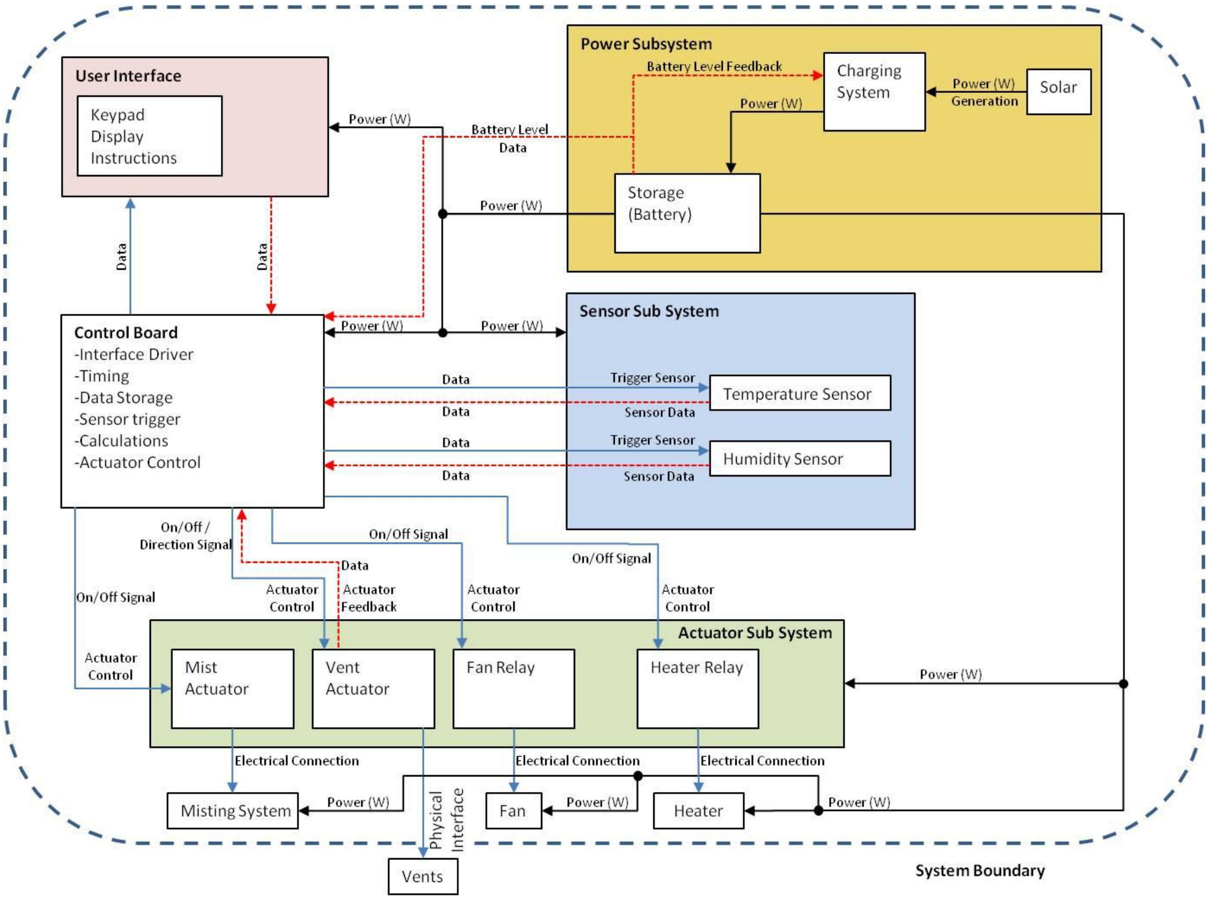

Image 9. *System Interface Map for greenhouse environmental control system.*

It is important to note that external to the system are the greenhouse structure and the vents which are manipulated by the Vent Actuator.

8 Testing and Evaluation

8.1 Design Requirements and Test Regime

As the system is designed to use modular components, a number of tests were designed to assess the individual modules in isolation. This ensures that any failure of one module does not affect the results of other modules being tested. As the majority of the modules use electronic components, a number of the tests involve assessing the accuracy, speed and power consumption of the modules.

As a prototype has not yet been developed, the most suitable Test and Evaluation methods to be used are Type 1 and Type 2 Testing (Blanchard & Fabrycky, 2011). The outcomes of these tests will lead into the most suitable modules being selected for prototyping the final design.

In order to design suitable tests, the Design Requirements and Performance Metrics from Table 1 were used. Metrics such as cost and ease of use will not be assessed until a working prototype is produced. This reduced the initial testing process to the three main design requirements of automation, off-mains power and reliability. An overview of the Test Regime is shown at Table 2 (with the detailed testing outlined at Appendix 1).

ID	Design Requirement	Test Regime
DR02-01	Senses temperature	Temperature readings are taken over a defined period and assessed for accuracy.
DR02-02	Adjusts vents	Vent actuators are operated and the time taken to open and close a vent is recorded, in addition to power consumption.
DR02-03	Fan output	The fan is operated for a defined period with the volume of airflow and power consumption recorded.
DR02-04	Senses humidity	Humidity readings are taken over a defined period and assessed for accuracy.
DR02-05	Applies water	Water application is assessed over a defined period with water volume and power consumption being recorded.
DR02-06	Applies heat	Heating capability is assessed over a defined period and power consumption recorded.
DR05-01	Renewable energy	Power generation is measured under varying conditions and assessed against a minimum rating.
DR05-02	Power Storage	The battery under test is subjected to diurnal temperature cycling and its output assessed against a minimum rating.
System Control Board	Logic Control	The System Control Board is cycled through a number of preset stimuli (changes in temperature and humidity) to validate the control logic and power consumption.
Complete System Test	Test Structure	A Test Structure and Control Structure are monitored over a set period to confirm functionality of the system.

Table 2. *Test Regime for Automated Environmental Control System.*

Due to the modularity of the system, Type 1 Testing (Blanchard & Fabrycky, 2011) is being used to assess the individual modules in a controlled environment. Each individual test will confirm whether the modules function as required (across the range of variables and with the desired accuracy) and also provide a performance evaluation for later consideration. The evaluation data will be useful should consideration be given to expansion or changes to the design through the life cycle of the finished product.

The first two elements of Type 2 Testing (Performance Tests and Environmental Qualification) (Blanchard & Fabrycky, 2011) have also been incorporated into the test regime. To confirm capability and performance, the testing will be performed over a number of iterations and environmental ranges (temperature and humidity). The combining of these tests will reduce costs associated with the testing process in addition to identifying modules which may fail early and therefore not require future effort (saving time and resources).

It should also be noted that while tests are being undertaken to assess individual modules, a test of the System Control Board has also been designed so that the integrated system can be tested. This will ensure that there are no data conflicts or adverse interactions across the whole system. It will also highlight any timing issues which may arise between sensing and actuator control.

Finally, a Complete System Test to assess a Test Structure against a Control Structure should be conducted over a six month period. This will confirm functional operation of the system in addition to providing a comparison of automated versus non-automated systems.

8.2 Standardised Testing – Scissor Mechanism

In order to adjust the greenhouse vents, there needed to be a physical interaction between the controlling system and the structure. To cater to the possibility of testing partial systems (e.g stepper motors as a single entity) or whole systems which included a structural interface, a standard mechanical interface was designed to enable standardised testing.

A simple scissor action mechanism was designed (Image 10) to provide a standard test mechanism for different motors or actuators.

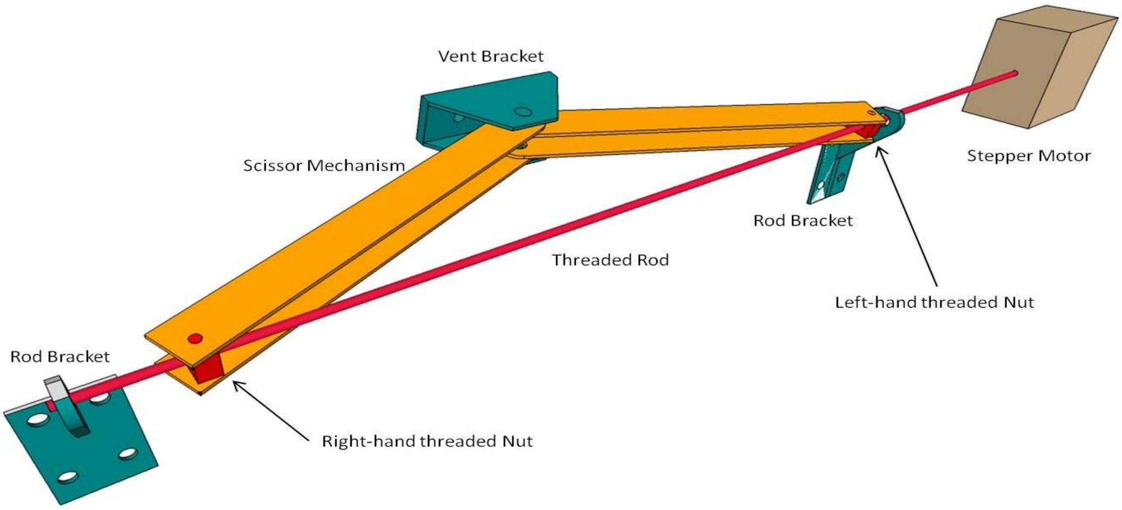

Image 10. *Hinge Opening system.*

As the stepper motor turns in a clockwise direction, the two nuts are drawn together, forcing the scissor mechanism to close, this action moves the vent bracket outwards, causing the vent (similar to a window which is hinged along the top edge) to open. Driving the stepper motor in the counter-clockwise direction causes the scissor mechanism to open and closes the vent.

8.3 Repeatability

The Test Regime has been designed to provide a standard set of repeatable tests for competing modules and can be used at later stages to conduct fault finding. Each of the tests is conducted a number of times to provide an average performance for assessment and confirm reliability of the sub-elements and the system as a whole.

9 Conclusion

Over the process of Systems Engineering Design, the final design focussed on a modular system which monitored both temperature and humidity and provided for the adjustment of vents, forced air circulation, heating and misting.

The use of a modular system provides a number of benefits for the design, particularly in the testing, manufacture and ongoing life-cycle of the project. In the testing phase, the modularisation of the system allows for subsystems to be tested in isolation from each other. This ensures that the module performance is not influenced by other systems and also allows for consistent and repeatable testing. Additionally, it allows for different modules to be tested concurrently – potentially reducing evaluation time. During the manufacturing phase, modularisation allows for different manufacturers to be engaged to supply different modules; and during the project life-cycle, allows for ease in maintenance and upgrades.

9.1 Design Communication

The illustrations at Images 11 and 12 give an idea of the final system. The solar panel on the rear right roof provides the power for the system via the white power conditioning unit. Power storage is located beneath it, and provides power to the remaining system components (Interface Unit- grey/red, Sensor Unit – green, Misting Unit – blue, Vent Actuators and Scissor Hinge – yellow, Heating Pad – red and Fan – white).

It is anticipated that the misting unit would be similar to a small fish pond pump (with spray nozzles) and that each of the sensors (possibly multiple sensors located throughout the environment to provide an average value) would be self contained modules wired directly back to the Controller Board. Both the Heating Pad and pump for the Misting Unit would driven by a simple on/off relay system.

The integrated system will allow the user to define the environmental requirements in a “set and forget” manner. A short video outlining the functionality of the system is available from the author on request.

9.2 Future Options

Modular systems also provide the option for through-life upgrades and easier repair / maintenance, by enabling a repair at the subsystem level rather than the system level. It also introduces some flexibility to the system design by allowing for subsystem upgrades during the design process (provided the interface and data requirements etc remain unchanged). As indicated in Section 4 (Options for Environmental Management), future developments could include a system for sensing and releasing of CO_2 to assist in plant growth. This would likely be a simple upgrade which incorporates a CO_2 sensor and relay actuated gassing system.

Image 11. *Sectioned View.*

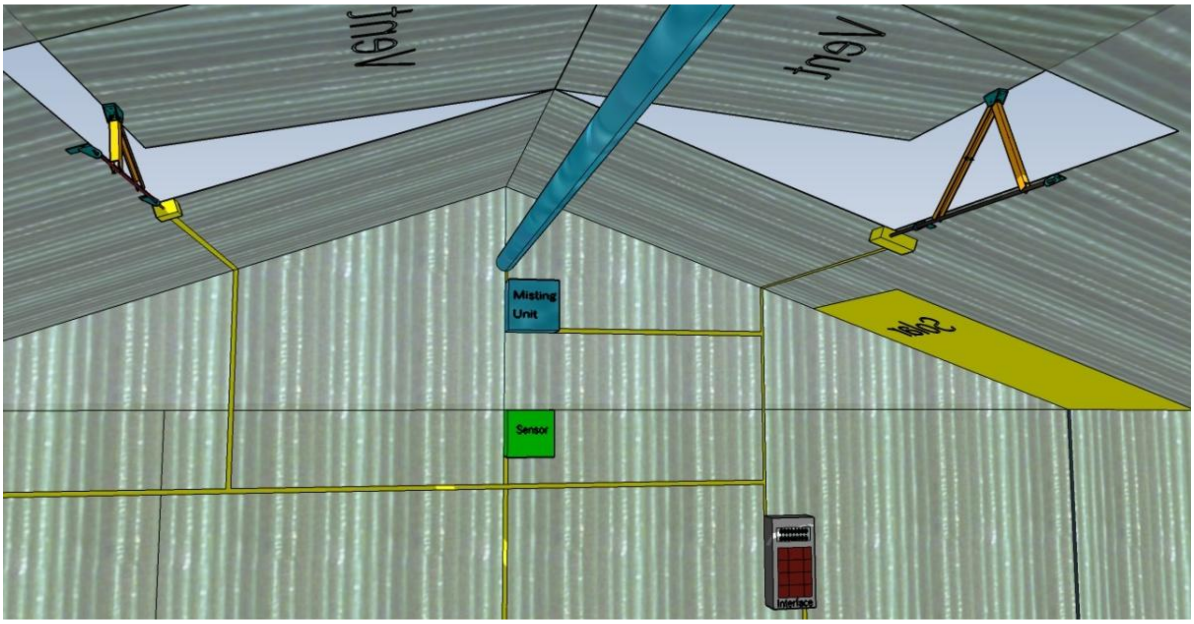

Image 12. *View of Misting Unit, Sensor Unit, User Interface, Vent Actuators and Solar Panel.*

Appendix 1 – Detailed Test Regime

ID	Design Requirement	Test Regime
DR02-01	Senses temperature **Measurable:** ±°C (accuracy)	In a closed environment, vary the temperature from -10°C to 90°C to -10°C (cycling 100 times). Each cycle to take 1 hour with measurements taken every minute by the sensor under test. Results to be compared with a calibrated test system.
DR02-02	Adjusts vents **Measurable:** - Power consumption - time	A horizontal hinged vent is to be opened and closed by the actuator under test. The vent is considered open when the free edge has moved 20cm from the closed position. Voltage and current are to be measured every 100ms during the process and the total power consumption for an opening and closing cycle is to be calculated. The vent must achieve the fully open position (from closed) within 15 seconds and must achieve the closed position (from fully open) within 15 seconds. Cycle repeated 100 times.
DR02-03	Fan output **Measurable:** - Power consumption - l/min (vol /min)	The fan under test is to be placed in an environment where the airflow can be measured. The fan is to be run for 1 minute intervals (with a 1 minute rest period) for 100 intervals. During each interval, the following are to be measured: - Velocity of air drawn into the environment. - Volume of air drawn into the environment. - Voltage and current are to be measured every 100ms to determine the total power consumption for an interval.
DR02-04	Senses humidity **Measurable:** ±% RH (Rel Humidity)	In a closed environment, vary the humidity from 10% to 80% to 10% (cycling 100 times). Each cycle to take 1 hour with measurements taken every minute by the sensor under test.
DR02-05	Applies water **Measurable:** - Power consumption - l (vol)	In a closed environment, apply misting to vary the humidity from 10% to 80% in 10% steps. Each 10% interval is to be maintained for 1 hour; voltage and current are to be measured every 100ms to determine the total power consumption for an interval and for a cycle (cycling 100 times).
DR02-06	Applies heat **Measurable:** - Power consumption	In a closed environment with the temperature starting at 10°C, apply heating to increase the temperature to 20°C. Voltage and current are to be measured every 100ms to determine the total power consumption. Cycle 50 times.
DR05-01	Renewable energy (Solar) **Measurable:** - Power generation	In a closed environment, vary lighting (to simulate the sun) to represent full sun, 50% sun (cloud) and 25% sun (overcast). Panels are to be subject to each level of lighting for 30 minutes and the total power generated for each period is to be recorded. The test is to be conducted 100 times.
DR05-02	Power Storage **Measurable:** - Ah (Amp hours)	The battery under test is to be held in a closed environment at -5°C for a period of 14 hours, after which the battery must be capable of providing a minimum of 12V @ 1A for 2 minutes. The battery is then raised to 22°C for 2 hours, recharged fully and the cycle repeated. The cycle is to be repeated 100 times.
System Control Board	Logic Control **Measurable:** - Manage actuators - Pass / Fail	In a Test Bench environment, the control board is to be connected to two input modules (representing temperature and humidity). The board is also to be connected to four output modules (representing each of the relay / actuators – vent, fan, heating pad relay and misting pump relay). The System Control Board is to be cycled through a number of preset stimuli (changes in temperature and humidity) to validate the control logic and power consumption.
Complete System Test	Test Structure **Measurable:** Stable Environment	Over a six month period, the system is monitored in an existing greenhouse (Test Structure) adjacent to a one without the system (Control Structure) and the temperatures in both structures compared to confirm the system function.

Table 3. *Detailed Testing Regime for Automated Environmental Control System for a Domestic Greenhouse.*

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Process Reflection and Peer Review

Design Evolution. I found that my initial thoughts on what the end product would look like were close, but not identical to the final design. Some aspects I had considered were outside of the scope and would have led to "scope creep" where the project would have become unmanageable. The continual review of the Requirements Map helped to keep the project aim in focus and to stop me wandering off track.

Subject Matter Expertise. This aspect cannot be understated. As I read more about control systems and the relationship between temperature, humidity, and plant growth, I began to refine my concept and the design of the final product. This involved the exclusion of watering for cooling, a moisture sensor and CO_2 delivery as these do not assist in controlling the environment. It also excluded identifying a specific temperature and humidity range, as these requires differed from plant to plant (tropical vs temperate environments).

"When is enough, enough?". I found that the continuous reassessment could potentially be a resource trap which led me to this question. For me, this to be the biggest hurdle of the process. As the cycle continually spirals inwards, I found there was always something to tweak, which then cascaded to cause another review and so on. Sooner or later the effort outweighs the benefit. I think that the answer to "When is enough, enough?" is driven by finances and time – these two factors are the driving forces in all businesses and would be prevalent in the design cycle of any product.

Peer Review

I found the Peer Review to be both challenging and beneficial as I see this as not just a process to receive comments on my Portfolio, but an additional opportunity to 'rate myself' against others and possibly learn from other writing, research and presentation styles.

Peer Review on My Portfolio. Even after the Portfolio had been submitted I was still making changes (When is Enough, Enough?). This included removing tables from the document to place in an Appendix. I had previously incorporated the Testing table in the main text, but felt that due to its size and content it was better to be located in an Appendix. This is because I see it as a supporting element – to me the issue of a comprehensive testing regime is the key rather than the outlined testing process. Including a condensed version (as recommended in one of the peer reviews) in addition to the detailed table provides the initial demonstration of the testing concept with the detail available for reference if required. I also had considered moving the Design Requirements and Engineering Characteristics tables to an Appendix, but originally settled on only moving the Engineering Requirements. I had considered that the Design Requirements table was more important in the text to support design analysis process. After reading through one of the peer reviews, it was pointed out that the Engineering Characteristics table covered both areas and was more suited to the main body of the text – I have modified the document accordingly.

My Peer Review on Other Portfolios. I found this to be both rewarding and challenging as it caused me to examine and interpret work from someone else, and at the same time reflect upon what I had produced (almost in a comparison mode – e.g. did I think my description of a particular process / element better, worse or the same). The most challenging part was to provide tempered feedback on a topic which I felt was not well researched or having no scientific basis. Finding a balance between honesty and being supportive was difficult – it also resulted in significant time being spent validating the concept.