Project Report: **Volume Optimization for Food Production During Deep Space Exploration**

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The Ohio State University Department of Food Agricultural and Biological Engineering

NASA Volume Optimization Capstone Final Design Report

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THE OHIO STATE UNIVERSITY

How Project Subject Was Chosen

This project is sponsored by the eXploration Systems and Habitation (X-Hab) 2020 Academic Innovation Challenge is a university-level challenge designed to develop strategic partnerships and collaborations with universities. NASA has tasked this project to take another step in solving this issue by designing a volume optimized system in which food will be grown for astronauts to consume during long space journeys and to aid in setting up regenerative agriculture production on other terrestrial surfaces.

Abstract

Due to the expense of resupplying personnel in space, approximately $9,100 per pound of supplies, NASA has undertaken a project aimed at creating a sustainable growth habitat for edible plants to reduce the amount of food required to be sent into and beyond orbit during supply missions. The purpose of this project is to develop an expanding, semi-autonomous habitat capable of growing and sustaining a crop of lettuce that can easily be reset to repeat the growth cycle for the next crop with a heavy emphasis on minimizing the amount of space used per pound of usable biomass. The design expands based upon cues from a sensor system monitoring plant growth and health. The design was developed by considering different structural geometries (cubes, spheres, lattice structure etc.) and an accompanying method of expansion (springs, tensioning cables, linear actuators etc.). The different geometries and expansion methods were combined and evaluated for feasibility. This was done by considering how much space each design occupied versus how many plants it could hold and by testing its ability to compress down to a minimum size and then expand to a maximum size in a controlled manner. An expanding sphere design was pursued instead as it is capable of holding several plants and without requiring extra support components compared to cube designs. Research will continue into the development of the supporting systems of the spherical design and feasibility of design variations.

Acknowledgements

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Executive Summary

During extended space travel, resupply for the crew can cost near $9,100 per pound of supplies (Kramer, 2016). Additionally, cost at launch increases exponentially with size. In efforts to cut back on launch and resupply expenses, NASA and the eXploration Systems and Habitation (X-Hab) 2020 Academic Innovation Challenge has worked to create a volume-optimized, semi-autonomous plant growth system to allow for a sustainable food source in space.

The plant habitat was designed based on requirements stipulated by NASA. The system was designed to expand with plant growth, minimizing the amount of required space. The system needed to minimize energy requirements while maintaining a suitable plant growth environment, so a lighting system that minimizes waste was designed. The system needed to be easily maintained and needed to minimize the amount of necessary human interaction, so the system was designed to respond to feedback sensors.

The final design was chosen to be an autonomous expanding sphere utilizing Hoberman's sphere technology. When cued by the plant growth monitoring system developed by a partnering X-Hab team at Ohio State, a step motor would rotate to expand the sphere at a set interval based upon the inner diameter of the sphere and plant size. The sphere housed a central lighting console supported by telescoping arms that utilized adjustable RGBW (red, green, blue, white) LED's to maintain the plant lighting requirement of 250 $\mu mol/m^2s$ even when the plants grew larger and moved further away from the light source. Plants would be grown at select nodes of the sphere utilizing a 3D printed, encased in a polypropylene felt holder. Water and nutrients would be delivered to these nodes to meet the average daily requirement up to 80 mL/day. For lettuce in its youth, only 30 mL/week would be required. A real time clock circuit would control the peristaltic pumps utilized to deliver the nutrient solution. A moisture sensor would also be placed to act as a fail-safe.

The final design was ultimately successful upon testing with all measurable and objective success metrics achieved. A 74% volume reduction was achieved with the system measuring down to be 8 inches at launch and fully expanding to an inner diameter of 30.5 inches. This concept is smaller at launch than current advanced plant habitats that NASA has developed.

A transfer function was developed for the expansion mechanism to allow for adaptation to different plants or expansion mechanisms. Testing with a light meter proved that LED brightness could be increased on a linear scale to meet plant requirements, and the pump system successfully delivered the daily required amount of nutrient solution upon testing.

In future iterations of this design, geometries outside of a sphere such as a cube or half-sphere should be investigated to see if they would interact with the external systems of the space station with more ease. A different geometry could allow for multiple systems to be fit and employed. A linear actuator should be adopted in place of a reel system to expand in space applications, as a reel system relies on gravity.

Introduction

The eXploration Systems and Habitation (X-Hab) 2020 Academic Innovation Challenge is a university-level challenge designed to develop strategic partnerships and collaborations with universities.

It has been organized to help bridge strategic knowledge gaps and increase knowledge in capabilities and technology risk reduction related to the National Aeronautics and Space Administration's vision and missions. In 2016, the X-Hab Challenge scope was formally extended to include other areas of Exploration Systems as well as habitation topics. The competition is intended to link with senior and graduate-level design curricula that emphasize hands-on design, research, development, and manufacturing of functional prototypical subsystems that enable functionality for space habitats and deep space exploration missions. NASA will directly benefit from the challenge by sponsoring the development of innovative concepts and technologies from universities, which will result in novel ideas and solutions that could be applied to exploration (eXploration Systems and Habitation 2020).

For humans to conduct interterrestrial space travel, it will require a sustainable method of replenishing consumable supplies such as water, oxygen, and food. Over the course of the various space programs' histories systems have been developed. Determining a sustainable, efficient, and reliable way to replenish food supplies without requiring a resupply from Earth is an issue that NASA is still exploring. Sending supplies becomes impractical and costly outside of low Earth orbit; resupplying personnel in space costs approximately $9,100 per pound of supplies (Kramer, 2016). NASA has tasked this project to take another step in solving this issue by designing a volume optimized system in which food will be grown for astronauts to consume during long space journeys and to aid in setting up regenerative agriculture production on other terrestrial surfaces.

Background

Alternative Methods of Solving Problem

Given the nature of the project for use in space, research was required to determine best methods and practices to explore during the design of the system. Plant growth in the space environment is little explored, but some research has been done. NASA's existing advanced plant habitats and research projects including the Advanced Plant Habitat (APH), Veggie-PONDS (Passive Orbitat Nutrient Delivery System), and the Vegetable Production System provided the basis for this research project (Johnson, 2018). While not volume-optimized, NASA's International Space Station APH was a primary source of reference featuring autonomy, a variety wavelength LED lighting system, VEGGIE plant growth medium, and adjustable conditions to adapt to each plant attempting to be grown (Johnson, 2018).Volume optimization, minimal yet efficient lighting system and nutrient delivery in zero-gravity environments are all key objectives of the project and were explored in the literature.

Utilization of LED's was an early consideration due to their minimal heat impact and small size (Masa et al., 2008). LED's are also advantageous because of the ability to specify their wavelength and put multiple LED's of different wavelengths together to create the desired lighting for plant growth (Mitchell and Stutte, 2015). While red light has been widely accepted for use in plant growth and photosynthetic stimulation, research shows that other wavelengths should be considered (Masa et al., 2008). Blue light, for example, is notably conducive to growth processes that are typically triggered by light. Some of these include carbon dioxide exchange and stem elongation (Masa et al., 2008). Research also supports the use of far red and green LED's, both of which are notable for being able to pass through the upper canopies of plants as they get thicker and promote growth to the inner canopies (Mitchell and Stutte, 2015). The use of these lights could allow for tighter volume constraints, even when the plant growth becomes increased in diameter.

Targeted, or point lighting, systems were explored as well as central lighting systems to determine the best option to reduce light waste. Further, the research conducted by Poulet et al., (2014) revealed that a non-targeted system of white LEDs also had a 32% reduction in energy use per unit of biomass when compared to the non-targeted system of LEDs with wavelength optimization. This also could help control light exposure time to plants, as too much light exposure could be detrimental to plant health and plant life (Murdoch et al., 2010).

A variety of different nutrient delivery mechanisms have been explored in advanced plant habitats, but not all of them have been explored in microgravity environments. Hydroponics, aeroponics, and substrate based nutrient delivery systems all provide their own advantages in advanced plant habitats. Hydroponics posed risks in mass reduction and nutrient solution temperature control. Substrate in combination with porous tubing appeared to be the least problematic method of nutrient delivery (Monje et al., 2003). Other substrates were explored to fit the needs of our design depending on testing results. One such substrate was a 3D printed, NinjaFlex concept developed by a previous Ohio State X-Hab design team. This substrate featured a flexible material that would easily accommodate root growth while also being adaptable and easy to print in space (Bhutta, et al., 2017). If aeroponics would be applied to our design, a nutrient/water mist would be sprayed on the roots of the plants in the system. In microgravity, the droplets from the mist will stay on the roots to be absorbed (Ling, 2019).

Target Markets or Potential Financial Impact

The primary market for this product consists of government and private entities with an interest in space travel and colonization. Given the extreme costs already associated with such ventures, making the product low cost is far less of a priority compared to making the product highly functional and optimized. According to private space companies, the cost to launch items into space increases with cargo size (Kramer, 2016). High investment at the beginning of this project will be balanced by low launch costs if the advanced plant habitat is small and successful.

This technology could have a secondary market in the home gardening market space, especially for compact living spaces one would find in large cities. According to a recent study conducted by Pulidindi and Chakraborty, this market space is expected to grow by 27.7% between 2018 and 2026 from $3.16 Billion to an estimated $22.07 Billion (Pulidindi & Chakraborty, 2019). This would provide an opening in the emerging market for the system to fill. The technology could be incorporated into urban farming practices where it’s enclosed systems and energy efficient mechanisms could help combat the food safety and high energy consumption that impact urban farms today (Hallet et al., 2016).

External Systems

The solution system needs to interface with the equipment rack system currently used in the International Space Station as well as similar structures on the Lunar Gateway and extraterrestrial stations. Water and power supplies will also be provided by the ISS or Gateway, providing another level of interface.

Constraints and Standards

The system is currently not constrained by any design standard but must meet certain criteria set by the sponsor. The sponsor stated that needs for power and water supply can be set by the design team. The criteria are that the system must be an expandable, autonomous growth module for growing plants in a microgravity environment. The system must grow with the plant and be compact for storage and launch. Additionally, the system should strive to minimize light waste and to be easily maintained and adaptable in design.

The only other existing constraints stem from the requirements to make plant growth successful. In artificial environments, specific lighting and nutrient requirements exist for each individualized plant, and those needs must be met in order to ensure successful plant growth. There are other plant growth standards that will be incorporated into our design such as a light intensity of 250 $\mu mol/m^2 s$ (Brechner and Both, 2012).

Social, Environmental, and Global Issues

The societal issue involved in this project is the advancing of humanity's reach into the solar system beyond low Earth orbit and increasing the viability of long-term, self-sustaining space modules. A volume optimized plant system would allow for sustainable and continuous food production, meaning longer stays in space. Additionally, interactions with plant life could increase astronaut morale during long stays in space by reminding them of home on Earth.

Secondary applications of this technology are volume optimized, or vertical farming on Earth. The world's population is becoming increasingly urban, meaning more people live in cities and closer together. The team's design has the potential to solve problems with growing plants on Earth in confined, unforgiving environments. Urban farming also has the potential to help solve food shortage problems on Earth by mitigating the food desert sprawl (Urban Agriculture, 2012).

Detailed Design Description

Through the course of the project three designs were seriously considered: an expanding lattice structure, a vertically expanding cube constellation structure and an expanding Hoberman sphere. The expanding lattice design consisted of layered, crisscrossed lattice platforms which expanded in the horizontal plane. Each layer was to be raised as the plants grew by a set of linear actuators in order to maintain spacing. The vertically expanding cube constellation consisted of a series of individual growth chambers capable of expanding vertically with the aid of springs. Each growth chamber was to hold a single plant and they could be snapped together to create a custom sized growth system. The Hoberman Sphere design consisted of a commercial off-the-shelf (COTS) Hoberman Sphere device which would hold plants internally at the joint nodes. The sphere would be expanded by a step motor attached to a reel or linear actuator in zero gravity applications to increase the size of the sphere as the plants grow.

The design ultimately pursued was the Hoberman Sphere. The design was selected because of:

1. It is easily accessible COTS supplies
2. The ease at which the design could be expanded
3. The fact it could expand in all directions
4. The simplification of the lighting and expansion mechanism
5. Its ability to hold multiple plants in a single structure

The entire structure could be expanded in gravity environments with the operation of a single step motor attached to a reel adapter. Since the reel attachment used for expansion relies on gravity to work, a linear actuator could be used instead in microgravity. The lighting of the design was simplified from other designs considered as it is able to utilize a single, centralized light source for all plants rather than multiple point light sources for each individual plant as in other design concepts. The existing COTS Hoberman sphere structure also provided mounting and routing for the water and nutrient delivery system.The Hoberman sphere was purchased from a commercial supplier and capable of expanding from an inner diameter of 8 inches, after being loaded with components, and expanding to an inner diameter of up to 30.5 inches as seen in Figures 1 and 2.

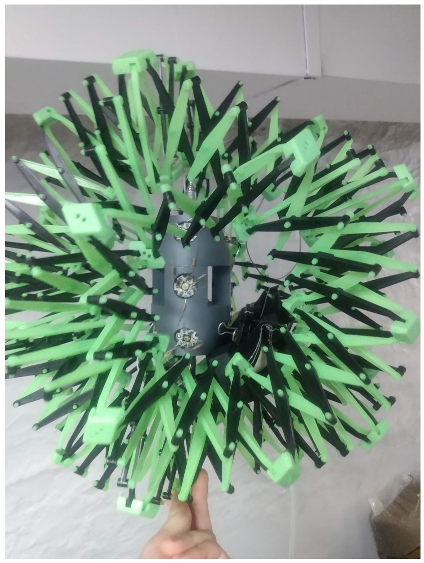

Figure 1: Fully compressed system (8”)

Figure 2: System at maximum expansion (30.5")

This sphere serves as the primary structure for housing the plants and the design components of the system. The design consisted of 9 RGBW LED chips used to provide the required photon flux to the plants for growth. These LED chips are controlled by an Arduino microcontroller that controls the light intensity based upon plant growing area information from the Bio-Sensing team. To hold the LED chips and image processing equipment within the sphere a custom cylindrical structure, diameter of 3 inches and height of 4 inches, was designed to be placed in the center of the sphere as the center console. The structure is held in place by a set of telescoping arms capable of extending and contracting with the sphere as seen in figure 3.

Figure 3: Center console lighting structure

An additional Arduino microcontroller is used to operate the water and nutrient delivery system which consist of a peristaltic pump, tubing and a NinjaFlex substrate developed by a previous Ohio State X-Hab team which is capable of holding water in reserve for the plants. One block of NinjaFlex substrate is used for each plant and is wrapped in a polypropylene felt bag to prevent leakage. These bags are held in place via custom holders which attach to the sphere nodes and measure 4.5" x 2.0" x 3.3" (see Figure 4). The current design is suited to hold 4 of these substrate holders and subsequently 4 lettuce plants. If the design was adapted for other types of plants, more could be grown.

Figure 4: Plant growth pillow pack attached to a sphere node

Elements of this project which were manipulated to test and improve design reliability and efficiency include: water/nutrient solution volume delivery, tube sizing, lighting intensity, reflective material, and coding redundancies. The volume of water and nutrient delivery can be varied to supply the appropriate amount of nutrient solution to the plant substrate in order to facilitate optimum growth (Table 5 Appendix II). Tubing size has been evaluated and optimized in order to facilitate adequate flow to the plant substrate and to also prevent kinking in the lines as the sphere expands and contracts. The light intensity was designed to be adjustable to achieve proper photon flux values for growing plants within the structure. Furthermore, the addition of a reflective material in “dead spaces” of the structure has been considered to help improve the lighting efficiency and reduce wasted energy. Coding redundancies have also been implemented within the control codes to prevent the structure from damaging itself during operation. For example, the number of stepper motor rotations is counted in order to prevent the system from over expanding and causing damage to the joints of the structure.

Design Evaluation

Methods

For evaluation of the design, the following method of measurable success metrics were: utilized:

1. Does the system supply a regenerative, volume-efficient food source?
2. Does the mechanism properly expand and contract?
3. Does the mechanism produce sufficient lighting for plant viability?
4. Does the mechanism deliver sufficient water and nutrients for plant viability?
5. Does the mechanism optimize the volume of the plant environment?
6. Is the mechanism volume-optimized to the smallest possible size for pre-launch?
7. Is the design intuitive and easy to use?
8. Is the device maintainable, easy to repair, and easy to clean for reuse?
9. Can the device be easily built and manufactured?

10. Is the design cost efficient for the reproduction of several units and is it adaptable to different plant types?

Data Collected

The expansion device is intended to be used in a continuous batch process. Several units can be implemented for the desired amount of food production, supplying a regenerative and volume-efficient source of food. Basic trial and error tests were run between the Bio-Sensing and mechatronic teams to determine proper trigger-expansion communication. An image of lettuce growth overlap was sent to the Bio-Sensing team's Raspberry Pi microcontroller which sent a signal to the volume team's arduino microcontroller to trigger the step motor for sphere expansion. Once fully expanded, the batch is ready for harvest and the sphere is ready for reset, cleaning, and contracting to original size for reuse or storage.

The central console was determined to produce sufficient lighting for plant viability by testing. It was also determined that light emission could be adjusted linearly in increments. Figure 5 below shows the data from the test where a light meter was used to measure the light intensity of a single LED chip at incremental, 8-bit power values supplied by the Arduino for various distances.

Table 1: Distance from light source data collection

4"			6"			8"		
Arduino 8-bit	Lux	PPFD	Arduino 8-bit	Lux	PPFD	Arduino 8-bit	Lux	PPFD
250	292	8	250	125	3	250	66	2
225	267	7	225	114	3	225	60	2
200	236	6	200	99	3	200	53	1
175	211	5	175	86	2	175	46	1
150	184	5	150	74	2	150	39	1
125	150	4	125	60	2	125	32	1
100	120	3	100	47	1	100	25	1
75	90	2	75	35	1	75	18	0
50	60	2	50	23	1	50	11	0
25	29	1	25	10	0	25	4	0

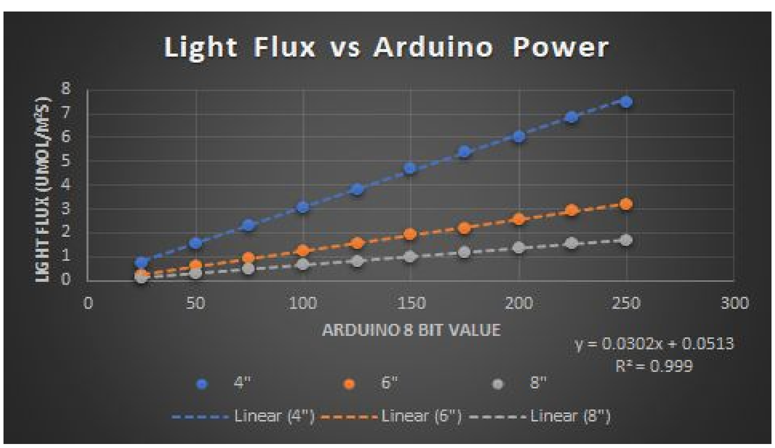

Figure 5: The linear relationship between light flux and Arduino power

The design supplies sufficient water and nutrients to the plants for viability via a simple two-pump system configuration.

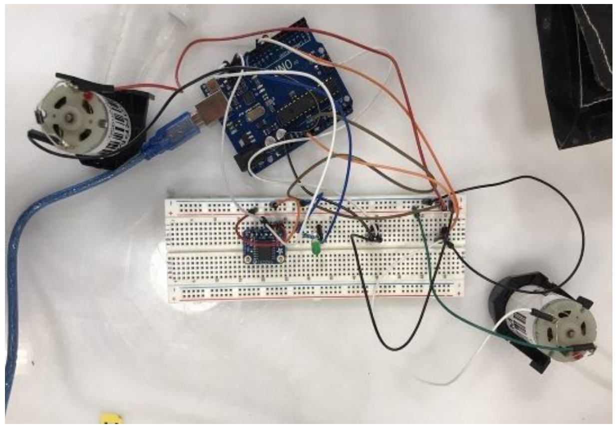

Figure 6: Two-pump system configuration with Arduino

The following general schematic was modified for two pumps functioning in series.

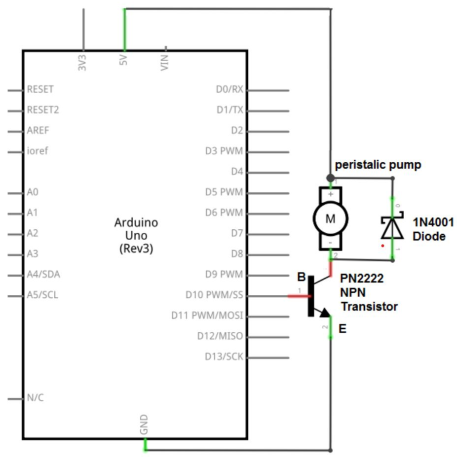

Figure 7: Pump system schematic retrieved from: http://www.learningaboutelectronics.com/Articles/Peristaltic-pump-circuit-with-an-arduino-microcontroller.php

Each node containing the plant, substrate, substrate containment, and holder will have an inlet and outlet line. The outlet line will utilize suction from the second pump to remove any excess water in the substrate. Code was developed in Arduino and adjusted based on water needs. Inlet lines that will pump, on average, 80 mL to each adult plant. This value was determined from the average amount of the recommended water range of 60mL to 100mL per day (Massa, 2020). The following tests were conducted with this configuration to ensure test code accurately delivers 80 mL/day as well as tests to optimize the pump selection for head loss.

The volume and plant environment are both optimized by maximizing growth space, optimizing water delivery and lighting, and minimizing total volume of the unit. Calculations and tests were completed by the unit containing four lettuce plants on their own nodes. By use of the plant growth information from the plant sensing imaging system, this unit design can be adapted to any plant type given that at least one plant at maturation will fit within the maximally expanded unit.

The design was tested and found to be intuitive and easy to use. As plants grow, the sphere grows. The sphere can also be fully expanded for maintenance or repairs throughout the growth cycle. There is sufficient space for two sets of hands to reach into the sphere whilst fully expanded.

All components of the mechanism are either snap-fittings, removable screws, or zip-tied components. Everything can be assembled and disassembled aboard spacecraft. The 3D printed substrate was chosen as it was proven by the 2017-2018 OSU NASA team that it is capable of growing lettuce plants from germination (Bhutta, et al., 2017). This substrate is also easy to clean and reuse. Substrate holders were specifically designed to allow for easy removal of each plant for harvest and cleaning.

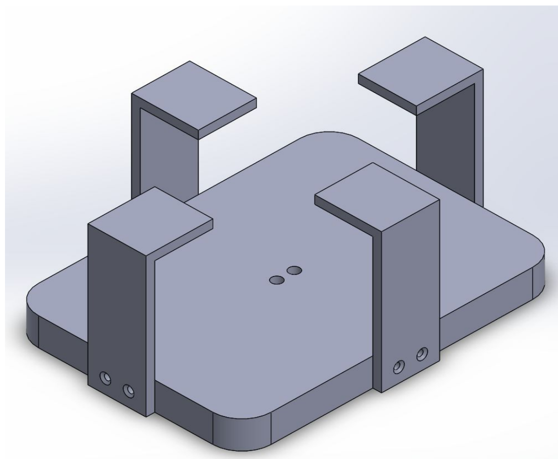

Figure 8: 3D printed substrate holder design for easy maintenance

This design is cost-effective for both Earth and space usage. All components were either readily available for purchase or able to be 3D printed. For durability, higher quality, and precise unit production, a larger funding budget could be implemented. By this design, the ratio of sphere pre-launch volume to complete expansion volume was reduced to 26%, from a 30.5" maximum inner diameter to a 8" minimum inner diameter sphere containing all internal components (74% total volume reduction).

This minimum size of this growth structure is smaller than both the Advanced Plant Habitat and VEGGIE system currently being used by NASA upon launch. The initial and final values were used to calculate the change in inner diameter with each rotation of the step motor: approximately 1.0714 inches per rotation. Knowing this, a transfer function was developed to track sphere size as the system expands where 8 inches is the initial diameter and x is the number of rotations of the motor.

$$Inner\ Diameter\ (inches) = 1.0714x + 8$$

Results

Assembly of the expansion arms, lighting, and water delivery components were evaluated for the effectiveness of the system as a whole. The step motor rotates 21 times for complete sphere expansion. A trigger signal comes from the plant sensing imaging system that tells the motor to expand at set but adjustable intervals. Four lettuce plants used in testing can fit in the designed sphere. For other types of plants with different size and shape characteristics (such as taproot vegetables) the design is adaptable for more or less plants. This satisfies the principle requirement that the mechanism optimizes the volume of the plant environment.The ratio of sphere pre-launch volume to complete expansion volume was reduced to 26%, from a 30.5" maximum inner diameter to an 8" minimum inner diameter sphere containing all internal components (74% total volume reduction). ennoLogic light meter tests showed that the Arduino power can control the LED brightness and can be adjusted on a linear scale for plant viability. LED brightness depends on the expansion size of the sphere, since lighting needs change when the plants are at different growth stages and distances from the light source. The pump delivers up to 80 mL/day to mature lettuce plants. The Hoberman sphere design and prototype was evaluated by NASA engineers at Kennedy Space Center on Tuesday, March 10th, 2020. All measurable success metrics were thus met by this design.

Cost Analysis

Below is the cost budget for the project. This budget includes all the materials the team purchased to create and prototype the design. The total budget for the project totals to $.

Table 2: Project budget

Item	Cost USD
Springs	
Prototyping supplies, light meter, plant food, tubing, Hoberman sphere	
Valve Fittings	
Pumps	
Electrical Supplies	
Initial Prototyping Supplies	
RGBW Grow LED’s	
Lenses	
Springs, Tension Cables	
Total	

Below is the estimated cost budget for the team’s final design. This includes estimations of costs for materials, labor involved to implement design, and maintenance if relevant for a single unit. If the client wanted to build the design themselves, the total cost to implement the design is $. The team estimates about 2 hours for maintenance and 2 hours of build time. Possible maintenance on the system would be cleaning the plant nodes after harvest, replacing any broken pieces, or replacing broken LED’s. Servicing the system will not take long because the parts are simple and easy to reproduce. A basic 3D printer onboard the space vessel could print out replacement parts in a matter of hours. Operating costs would be low because the system only needs electricity and the plant support systems to be activated. The system runs autonomously with minimal astronaut intervention needed.

Table 3: Design implementation costs

Item	Cost USD
3D Printed body	
3D Printed center console	
Valve Fittings	
Pump	
Electrical Supplies	
RGBW Grow LED’s	
Maintenance Labor ($/hour)	
Building Labor ($/hour)	
Total	

The benefit to an expandable design is that it uses only the amount of space vessel volume needed at the time of plant life cycle. The team estimates a significant savings in payload launch with this design because its volume is only a diameter of 8 inches when it’s compressed.

Future Design Considerations

Environmental & Sustainability

For future interactions the system can be designed for environmental and sustainable use. With the current design, the system can be implemented for other types of vegetables beside leafy greens, which will make the system more versatile. The system can be used commercially on Earth and be used in small spaces. Using this for indoor use, like urban gardening and vertical gardening, will reduce the need of farmland and to be used for all seasons. Restaurants and grocery stores will be able to replenish out of season vegetables year round.

Power efficiency can be optimized in the system, lighting, and water/nutrient delivery, which will make the system more sustainable with further testing. Further research will be needed for other vegetables types for optimized growth and integration with the system. For reusability and durability purposes, a hard plastic box-like structure instead of the pillow can be implemented in the hydroponic design as a plant mount. This will be easier to maintain and clean compared to the polypropylene felt pillow design. Having the lights attached to the system itself and facing towards the plants will lead to less light waste and be able to efficiently light the plants under the leaf canopy without extra heat generation.

Manufacturability

Having the parts easy to 3D print and snap together will help the system be easily manufacturable. Using 3D printed plastic parts that can be assembled together with simple tools will help the user to easily assemble and disassemble the product. Having the system disassembled at launch and assembled at the final location will reduce launch mass and space for other systems or supplies.

Ethics, Health & Safety

For future design, the system can be improved with health and safety in mind. Easy maintenance will help improve the safety of design and reduce hazards. Having snap fittings and implementing a hinged opening to the design will help create an opening for the user to easily access to harvest plants and to troubleshoot any problems with the central console. This design will lead to less injury that resulted from entanglement and pinching from the system or nutrient tubing. A fail safe code will be implemented to prevent the stepper motor from rotating too far that will cause the Hoberman sphere to break from the tension cable. This fail safe code will allow the stepper motor to rotate in the opposite direction to reduce expansion.

Social & Political

With the ability to grow food in space, this can potentially lead to longer space travel that could have political and social impacts depending on future outreach and programs. Growth of sustainable food in space can potentially lead to life in space as well, which can affect society socially and economically. Psychological wellbeing is important for astronauts for any travel in space. On the spaceship, visualizing growth of plants can affect the mental health of astronauts positively by providing greenery and resemblance to life on Earth. This can be achieved by placing lights on the system members to face inward, which will help reduce the amount of light waste seen.

Conclusions & Recommendations

Conclusions

A functional, volume efficient unit was designed for use in microgravity environments. The system can read inputs from the camera monitoring system and expand its interior volume to provide proportional space for the plants to thrive within. The lighting system was designed to be highly optimized, minimizing waste light by utilizing LED's in a central light configuration. LED's provide the plants with the proper wavelengths to promote growth, and generate less heat and energy consumption than high pressure sodium bulbs. The LED's that provide point lighting can be replaced with different light units and lenses suited to a variety of plant species (the system is currently optimized for lettuce). Though optimized for lettuce, a large variety of leafy plants can be grown within the current unit configuration providing nutritious treats for the astronauts. Plants need nutrients to grow, and the delivery system was designed to work in conjunction with the NinjaFlex pillow system that ensures all the plants' nutritional needs are accounted for. The peristaltic pumps provide a clean flow of water that is free from contact with the pump's internal mechanism. Ease of maintenance was achieved through design simplification, and additively manufactured parts. The system is modular, allowing for installation of different LED's and growing pillows on different nodes to allow for a variety of non-root type plants to be grown within. The structure can also be exchanged for another of a different size to provide a better form factor for various plant architectures, while maintaining the same base unit for control and mechatronics.

Recommendations

For future work, three areas are recommended for further consideration:

Alteration of design configuration from full sphere to a half sphere

By transitioning to a semi-sphere design, the unit will be less intrusive giving it the ability to be mounted in more locations within the spacecraft than the full sphere.

Placing lighting systems on the structural members facing inwards

One of the major design considerations that emerged throughout the project was supporting the astronauts mental health. In a spacecraft with limited windows and an aluminum and white color pallet, seeing a vibrant green growing plant is a reminder of life on earth. Mounting lights on the structure to provide point lighting directed only at the plants and create less light spillage from the unit, this would allow astronauts to gaze into the unit and enjoy the plant life.

White light for astronauts

Astronauts working within the International Space Station have reported that the colored lighting systems on veggie units provided a distraction in their peripheral vision. It is recommended to provide light color similar to the one present on the spacecraft so that the astronauts can enjoy observing the plants grow.

Due to COVID-19, a pause in testing limited making any further recommendations at this time.

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Appendix

I. Qualifications of Personnel

Angelina Sorice

Chris Tkach

Quincey Patterson

Samantha Patrick

Jane Petrie

Taylor Daniel

II. Design Details and Test Data

Table 4a: Volumetric flow rate of pump

	Trial 1	Trial 2	Average
Water (mL)	29.57	29.57	x
Flow Rate (mL/sec)	0.293	0.284	0.29

Table 4b: Amount of time pump will run to meet requirements for Black-seeded Simpson Lettuce

	Time pump will run for (sec)	Comments
About 30 mL/week	103.991	First week and growing
About 80 mL/day	277.308	Last two weeks of Lettuce life

Table 5a: Pump optimization constants and information used

Constants and Information	
Coefficient of Friction (silicone)	1.000
Earth gravity (m/s^2)	9.810
density of water (kg/m^3)	1000.000
Number of Plant Nodes:	4
Number of Systems:	1
dynamic viscosity of water (Pa*s)	0.001
1 Pa*s = 1 kg*s	1.000
Diameter of Hoberman sphere, fully expanded (30 in),	0.762
cicumference of Hoberman sphere (m)	2.394
Area of Hoberman sphere (m^2)	1.824
0 g accelertion constant m/s^2	9.81E-06

Table 5b: Tubing specifications for pump optimization calculations

Tubing specifications	
Material	silicone
Inner Diameter (m)	0.002
roughness (m)	1.50E-06

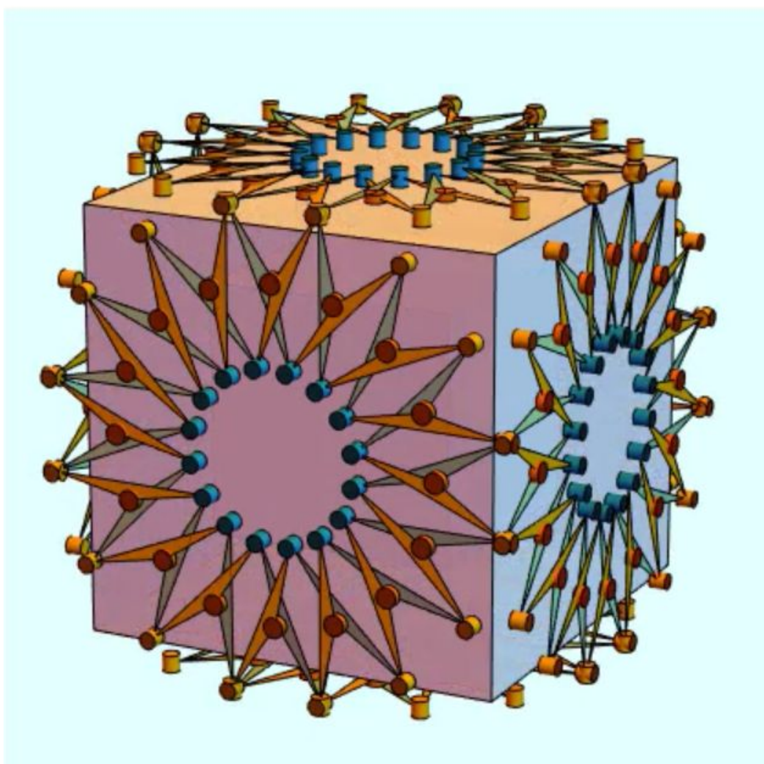
Table 5c: Fitting specifications for pump optimization calculations

Fitting specifications	QTY	Type	Friction Factor for each	Location
Plastic One way check valve	2	diaphragm check valve	2.3	Between lines on each end of pump to prevent backflow

Table 5d: Pump matching process calculations and assumptions made

Calculations Needed:		Comments
Avg flow rate (mL/sec):	1.000E-03	
Avg. flow rate (m^3/sec)	1.000E-09	
Average fluid velocity (m/sec)	3.183E-04	By slowing the rate of the fluid, we are able to reduce the head loss of the pump and reduce energy
Reynolds Number (Re) - Turbulent Flow	0.610	Laminar Flow
Friction Factor	104.844	
H (head loss) or Darcy's Eqn (m)	6.872	Head loss from straight pipe; can be applied because in microgravity
Cross sect-area of pipe for 2mm (m^2)	3.142E-06	
Length of line [pump to node] (m)	3.197	
Head of pump location relative to node (m)	0.381	
Head loss on Earth (m)	4.600	

Appendix II, Figure 9: Semi-sphere Hoberman sphere designs retrieved from
https://buildingdynamics.org/chuck-hoberman/.



Appx II, Figure 10: Hoberman Cube design retrieved from:
https://demonstrations.wolfram.com/HobermanCube/

Remote Sensing for Assessing Plant Growth and Biomass Optimization

The Ohio State University

Department of Food, Agricultural and Biological Engineering

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Student Branch Faculty Advisor: Dr. Jane Fife *Jane Fife* 05/14/2020

May 15, 2020

Problem Statement

NASA needs an automated system to grow plants in space because astronauts require plants for nutrition and improved mental health, but cannot afford putting time towards growing and maintaining plants themselves.

Abstract

NASA is interested in growing plants in space and is looking for efficient methods that utilize the least space and labor. The aim of this project is to develop a sensing system to monitor environmental conditions surrounding the plants and images of the plant canopy area. This system is to be integrated with an expanding volume mechanism to efficiently grow lettuce in space. The objective of the integrated system is to remotely provide data encompassing water usage, water stress, and plant biomass, in addition to triggering the volume mechanism to expand once the sensing system detects that plants are overlapping.

Acknowledgements

Thank you to the following people for support and contributions throughout the project:

Dr. Peter Ling, The Ohio State University

Dr. Jane Fife, The Ohio State University

Engineers and Scientists at NASA Kennedy Space Center

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Tables and Figures

Executive Summary

NASA is interested in growing plants in space and is looking for more efficient methods that have a low equivalent system mass (ESM) and are not labor intensive to the astronauts. While in space, astronauts need fresh food for nutritional and mental health benefits, but cannot afford the time needed to monitor and harvest plants manually. The objective of this project was to develop a sensing system to monitor environmental conditions surrounding the plants and take images of the plant top canopy area in order to provide data encompassing water usage, water stress, and plant biomass, in addition to triggering a volume mechanism to expand once the sensing system detects plant overlap. The project aims to serve a dual purpose by its applicability in space as well as provides insights on its automation capabilities for terrestrial applications such as vertical farming.

The architecture of the sensing system consists of three camera modules and six environmental sensors. The sensors include CO_2, radiation, temperature, relative humidity, wind speed, and soil moisture. These sensors and cameras were integrated into an expanding volume mechanism developed by a collaborating team. The data collected from these sensors will be input into an altered Penman-Monteith evapotranspiration model to estimate plant water usage. The images were processed and determined plant canopy area and height for more accurate modeling. The image processing also determined overlapping of plants and triggered a volume mechanism to expand.

The team was unable to perform physical data collection due to unforeseen COVID-19 circumstances. Instead, theoretical values were input into the evapotranspiration model to simulate average growing conditions on Earth. This allowed the team to estimate the water needed to provide design recommendations for a water tank reservoir, approximately 2,500 g/day for eight lettuce plants. The image processing component of the system was tested and validated to estimate plant area with 97% accuracy. Stereo vision was used with image processing to determine the height of the plants. Using stereo vision to compare the distance of the plant from the camera to the change in percentage of screen the plant occupied, an R^2 value of 0.914 was achieved. The image processing also correctly expanded the volume mechanism and validated the triggering signal. This same signal also triggered lights in the volume mechanism to shine brighter, ensuring even lighting conditions throughout the growth of the plant as it moves farther from the light source as the volume mechanism expands.

Further recommendations for this project include calibrating the evapotranspiration model with experimental data to gain accurate water usage data. Future research should also look into techniques that can determine water stress of plants based on the movement of the leaves through image processing.

1. Introduction

The Exploration Habitat project (X-HAB) is sponsored by the National Aeronautics and Space Administration (NASA). NASA is a U.S. government agency responsible for science and technology related to air and space. Their mission is to discover and expand knowledge of space for the benefit of humanity. Each year, NASA hosts the X-HAB capstone project to give senior engineering students the chance to work on real-world applications while also providing the engineers at NASA with new ideas. The overall objective of the project this year is to use the engineering design process to create an automated system for monitoring and growing plants in a microgravity environment. Astronauts will not only be provided with fresh food using the proposed system, but also eating and viewing fresh plants can improve their mental health and wellbeing. NASA will work to implement this system on the Lunar Gateway station; a space station that will serve as a “rest stop” for astronauts on their way to the moon and beyond. Astronauts must be conservative with their time and energy; therefore, one of the most important aspects of the project is that the design is completely autonomous, allowing astronauts to grow food crops more easily during long term space missions.

2. Background Information

2.1 Project Background

2.1.1 Definition, Scope, and Problem Statement

NASA seeks an improved method to provide astronauts nutrition in space as the current method of sending ready-to-eat meals does not provide optimal nutrition and the method of delivery is rather expensive. Equivalent System Mass (ESM) is to be considered as well, as these ready-to-eat meals take up space that could be used for other cargo. This is a problem that affects astronauts who reside in space stations. The ready-to-eat meals provide them suboptimal levels of nutrition and negatively impact their mental health. A financial strain is also put on NASA as they have to ship these meals into space via rocket ships. Providing fresh plants would not only improve the overall health of the astronauts but also improve their mental health viewing the plants. Growing plants on a space station will be self-sustaining and cheaper for NASA as it would allow the space station to provide some of its own food and oxygen.

From considerations from the initial research, a fishbone diagram was used to complete a root cause analysis for the project. The diagram (Figure 1) shows the causes and effects for potential problems in the system. The goal of this chart was to find the cause of some potential problems and trace it back to the source. Further research on plant growth in space needs to be done due to the limitation of resources, harsh growing environments, and needs of the astronauts. Finally, the systems used by NASA are constrained heavily by space and need to minimize their Equivalent System Mass (ESM).

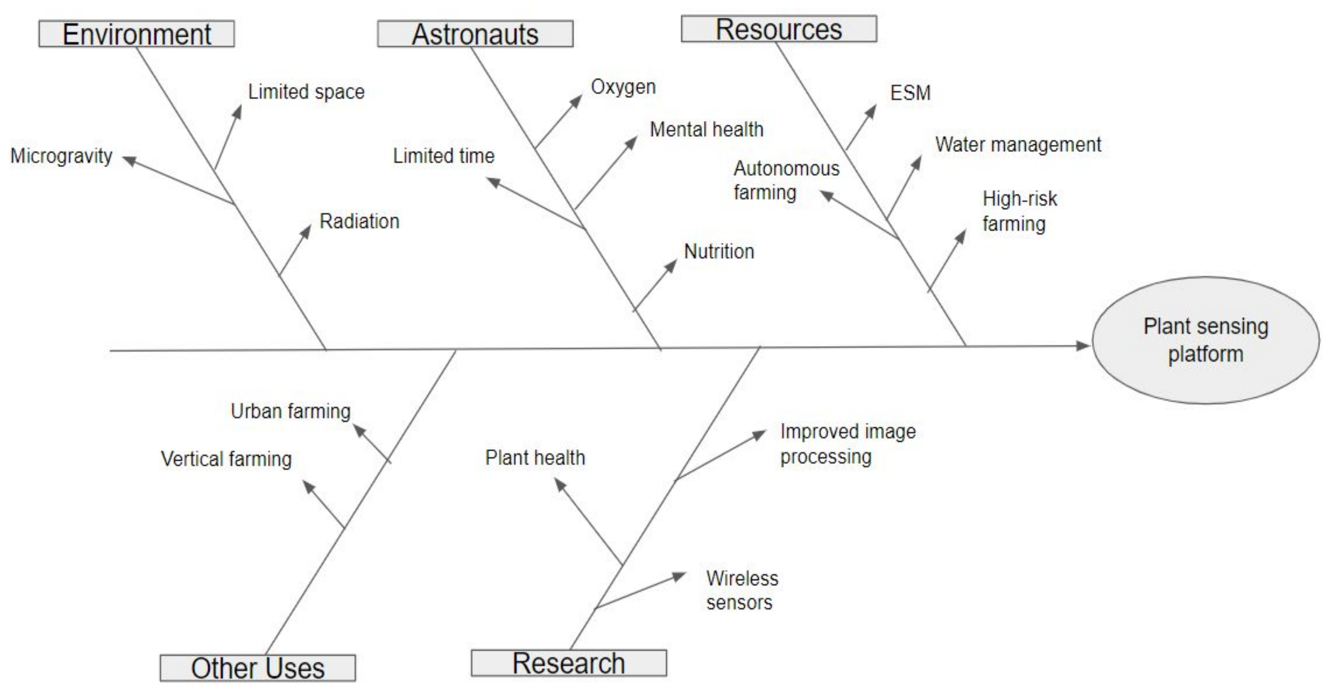

Figure 1: Fishbone Diagram for Root-Cause Analysis

After the root cause analysis was done and background research was conducted, a problem statement for the project was formed. The problem to be solved is that NASA needs an automated system to grow plants in space because astronauts require plants for nutrition and improved mental health, but cannot afford putting time towards growing and maintaining plants themselves. The overarching goal of these experiments is to support NASA's overall research on the growth of plants in space, ideally improving upon the automation aspect of the plant growth systems for space as well as terrestrial applications such as vertical farms. Past studies of plant growth in space, studies on using image processing for plant growth, studies on plant health monitoring, and data obtained from last year's X-HAB team are all sources of background information for this project.

2.1.2 Technical Aspects and Literature Review

Multiple projects have been completed on automated plant growth in space through NASA X-HAB at The Ohio State University. In the 2018-2019 academic year, the biological impact portion of the project focused on two aspects: evapotranspiration (ET) modeling and image processing. Modeling was done with data collected from a sensing platform (Figure 2). The platform consists of multiple sensors, including a temperature and relative humidity sensor, carbon dioxide sensor, pyranometer, quantum sensor, and wind speed sensor, that were operated via an ARDUINO processor. The data collected from these sensors were used in an altered version of the Penman-Monteith Model to calculate the evapotranspiration rate of the lettuce plants (Figure 2). The second aspect of the project involved using image processing to determine the top canopy leaf area. The images were taken using a single overhead camera mounted on a robot (FarmBot, Department of Food, Agricultural, and Biological Engineering (FABE) at The Ohio State University) and the area and volume of the plants were analyzed using image processing tools programmed in MATLAB.

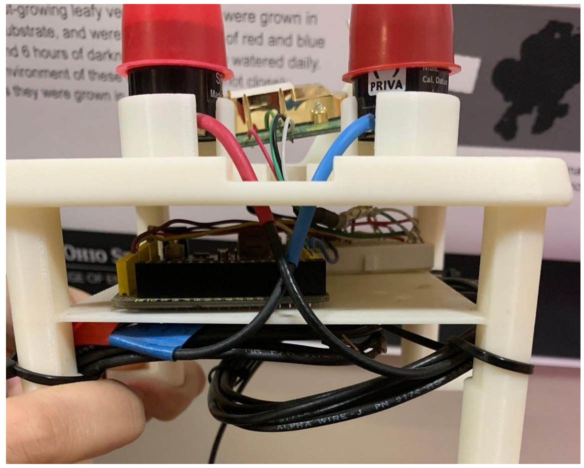

Figure 2: Sensing platform from 2018-2019 X-HAB team

$$ET_0 = \frac{0.408\Delta R_n + \gamma \frac{37.5}{T+273} u_2(e_2 - e_a)}{\Delta + \gamma(1 + \frac{0.34u_2}{fCO_2})} * 0.002TCA^{0.65}$$

Figure 3: Altered Penman-Monteith Evapotranspiration Model Used to Calculate ET Values from Sensor Data

This year, the team has the task of working towards improving the sensing platform and image processing of the previous year's team. In order to improve upon the sensing platform, the team was focused on getting the wind speed and quantum sensors to perform by developing functioning codes. For the improved image processing aspect of the project, the team sought to improve the accuracy and computing power of the image processing system by incorporating an image processing program in Python through a Raspberry Pi processor. In addition to the tasks of improving the sensing platform and the image processing aspects, the team also worked with another OSU X-HAB team (Volume Optimization team) to use the team's improved image processing program to trigger an automated expansion mechanism of a growing system. The volume expansion mechanism was a growing container in which the lettuce would be supplied with light, nutrients, and water in a volume-efficient, autonomous method. As the lettuce grows, the leaves of the plants begin to overlap, which is when the mechanism is signaled to expand based on a signal that is sent from the image processing software used to monitor the evapotranspiration rates and biomass of the lettuce. In addition to this, the team incorporated a soil moisture sensor to validate that the plants in the system are being supplied with an appropriate amount of water.

Many of the assumptions used by the previous year's X-HAB team were used this year in regards to the sensing platform, evapotranspiration model used, and type of plants grown. The same sensors and microcontroller used by the previous year's team were used for the calculation of the evapotranspiration model due to the high accuracy of the sensors. The altered Penman-Monteith Model for Evapotranspiration was selected because the ambient CO_2 concentrations are much higher on the space station, and this model accounts for that. Lettuce was again selected as the plant to grow because it is a fast-growing, leafy crop that has been widely studied.

One important design criterion is that the design adheres to Equivalent System Mass (ESM) guidelines. ESM is a tool used by NASA to interpret options in the ALS (Advanced Life Support) program that meet all requirements for the lowest possible launch cost while considering the mass, volume, power, cooling and crew time needs [9]. In the interest of keeping impact on ESM low, appropriate sensor selection meeting the requirements for a low-cost launch is desired. Therefore, the best performing sensors with relatively low mass, volume, and power consumption were selected. In conjunction with keeping the ESM low, NASA is also concerned with water consumption. A study focused on irrigation management concluded the fundamental principle of adequate irrigation management is to satisfy the water requirements by crops with the lowest possible consumption of water [2]. In space, water is even more valuable, and this principle holds very true.

Previously, the 2018-2019 OSU X-HAB team developed a sensing platform to collect the necessary data needed to estimate water usage and evapotranspiration, while also providing a method of non-destructive crop yield measurement, as detailed in their report [4]. The platform contained five sensors: solar radiation, photosynthetically active radiation, wind speed, CO_2 levels, and temperature and relative humidity. The five sensors used were commercially available. The sensors were wired, and the platform required an outlet to operate. Kacira et al. [5] designed a sensor platform with wired sensors and found that the wires prevented full mobility of the system. Commercially available wireless sensors can produce the same accuracy as wired sensors with added freedom and mobility. A study conducted with tomato plants using temperature, humidity, light, and carbon dioxide sensors achieved a 10-meter communication range with a 5% data loss due to inclement weather and high humidity [1]. However, using wireless sensing capabilities comes with challenges. Wilson et al. [11] mentions wireless sensing networks for space applications require frequent replacement of batteries for power, small volume and mass due to high costs associated with launching items to space. Moreover, electromagnetic interference in space compromises the wireless sensing abilities. Keeping the low ESM requirement in mind and other challenges with wireless sensing networks, ultimately, the idea was discarded and it was decided that the sensors would best be integrated directly into the volume expansion mechanism to conserve space and reduce ESM.

The first step in the image processing portion of the project is to improve upon the MATLAB code from last year's team and create a new python code with faster and more efficient image processing capabilities. PlantCV, a Python based image processing software package similar to OpenCV , is a good source of open source codes previously made for automated farming and also has a wide variety of built-in functions for synthesizing a new image processing program [3]. Making a new code in Python and improving upon the image processing capabilities is one objective of the current team. The data collected using image processing was used to determine mathematical relationships between different physical properties of the lettuce plants. For example, the canopy area of the lettuce plants was determined using the PlantCV program. From there, the volume of the plant, and by extension the biomass, can be calculated. Once biomass data is acquired, it can then be analyzed in comparison to another variable, such as the amount of oxygen generated through photosynthetic processes or root moisture level as affected by evaporation demand. An example of the use of image processing in this manner is the mathematical function found with the help of PlantCV that relates side view plant area with fresh biomass for Setaria plants [3]. This study found wild plants are more efficient at utilizing all available water for biomass growth than domesticated plants of the same species, which is an example of a correlation between biomass and water efficiency. Further analysis can be done in a similar style to find correlations for O_2 and water vapor production as related to plant coloration, top canopy area, and side view area.

2.2 Patent Landscape

Code for image processing and evapotranspiration modeling will build upon existing programs and algorithms. There are several codes and softwares (Section 4.1) that have image processing capabilities. The codes that will be used for reference will be open source codes. Open source means it is available to the public and can be modified and shared (Open Source Resources, 2019). There are different licenses depending on the developer of the code as well as the source from which the code is downloaded from. There are some licenses which dictate if an open source code is modified and released, the original open source code must be released alongside it (Open Source Resources, 2019). The team will be diligent in identifying which codes can and cannot be used and will adhere to any stipulations and/or licenses that come with such code.

As for the sensors put onto the sensing platform, attention will be given to the patents put on each type of product. Some of the components of the platform will likely be open source hardware. Open source hardware enables any person to study and modify the hardware, and also sell any designs made with testing of systems including the hardware [7]. This would mean the hardware may be tested in any way the team chooses. However, there will also be sensors which will be patented and therefore will have specific guidelines to follow to ensure research on the platform is being done according to legal standards.

3. Detailed Design Description

3.1 Proposed Designs

NASA has identified equivalent system mass (ESM) as one of the most important criteria for the team. ESM represents the sum of the system mass and an appropriate fraction of the supporting system masses. ESM is used to quantify the expense of shipping and operating something into space based on its mass, volume, power consumption, crewtime used, and its overall usability. NASA wants a modular ESM efficient sensing platform that can be deployed in tight or enclosed environments. NASA also wants a non-destructive plant monitoring methodology that can provide real-time estimates of biomass, oxygen, and water vapor produced from the plant production system. Finally, NASA expressed interest in implementing a way to evaluate plant production performance and implement adjustments to the system based on the data that is collected from the sensing platform.

To develop a more efficient method for measuring the water usage and biomass of the lettuce in an ESM efficient manner, a system architecture was developed, and several solutions were considered within its framework. The basic input involves the use of a central control program that measures the evapotranspiration rate of the lettuce from sensor data and the top canopy area of the plants from an image processing program. The output of the model is the estimated plant water usage, plant mass estimates, and a triggering point for the volume expansion mechanism. The developed system architecture is shown in Appendix B.

3.1.1 Camera Selection

Three key aspects of the project relied on using the camera for image capturing: the evapotranspiration model, the image processing software, and the volume expansion mechanism. It was important that the camera was able to effectively capture the canopy area of multiple plants so that all of these aspects of the project worked properly. The Dorhea Raspberry Pi 4B 3B+ Camera Module (Figure 4) was the device selected to do the image capturing for all three aspects of the project.

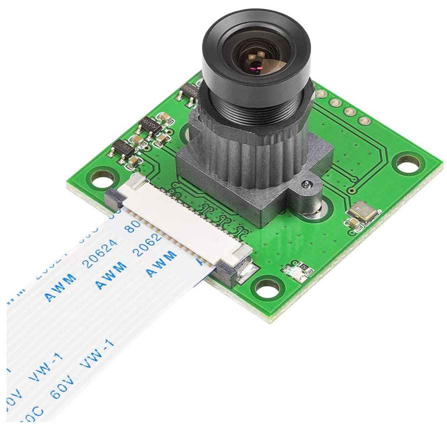

Figure 4: Dorhea Raspberry Pi 4 B 3 B+ Camera Module

The team evaluated five different concepts for the camera which consisted of either different types of cameras or different combinations of cameras. The goal of the camera concept matrix was for the team to gain a better understanding of the criteria of the project and the different camera options available. The most important criteria considered for the camera were ESM, power consumption, data usability, and system integration. The Dorhea camera was ultimately selected as the best option as it was designed to be used with Raspberry Pi, which was the microcontroller used for image processing. On top of this, it was lightweight, small, and had low power needs making it both ESM and energy efficient. There were a wide variety of lenses available for testing for it as well, which is why it was selected as the optimal device to use.

3.1.2 Soil Moisture Sensor Selection

The soil moisture sensor was used to measure the moisture present in the solution the lettuce was being grown in. Moisture data was primarily necessary for the Volume

Optimization team so they would know when it was necessary to water the lettuce being grown. As the system was desired to be as autonomous as possible, when thinking of ideas, the requirement of the system being low maintenance was highly stressed. Keeping in mind the different requirements of the project, possible ideas for the soil moisture sensor such as a wired sensor, a wireless sensor, an active RFID sensor, and a passive RFID sensor were considered to weigh out different options.

The full soil-moisture sensor Pugh decision matrix is shown in Table 1 . The selected concepts for the soil moisture sensor varied based on different types of sensors. The goal of the matrix was for the team to gain a better understanding of the criteria of the project and the different types of soil moisture sensors available. The most important concepts for this matrix were maintenance, mass, and system integration.

Table 1: Soil Moisture Sensor Pugh Decision Matrix

			Active RFID		Passive RFID		Wireless Soil Moisture Sensor	
Evaluation Criteria	Weightfactor	Baseline	Rating	Weighted	Rating	Weighted	Rating	Weighted
Mass	5	0	1	5	1	5	-1	-5
Volume	4	0	1	4	1	4	1	4
Power	2	0	-1	-2	1	2	0	0
Maintenance	5	0	-1	-5	1	5	0	0
Totals:	-	0	-	2	-	16	-	-1

There are two key factors for the soil moisture sensor to have, it must be ESM efficient and autonomous. Ideally, a passive RFID soil moisture should be used since it is relatively low mass and can autonomously transmit data wirelessly. On top of this, a passive RFID sensor would require no power to be input from the system. However, the team was unable to acquire this sensor, so a wired capacitive soil moisture sensor (Figure 5) was used instead. This sensor was able to be wired directly into the system to transmit data. Due to the issues in obtaining the passive RFID sensor and the sensor’s ease of direct integration with the system through wired data transmission, the team deemed the capacitive soil moisture sensor as a suitable replacement.

Figure 5: Capacitive Wired Soil Moisture Sensor

3.1.3 Microcontroller Selection

A microcontroller was necessary to control the sensors that were being used to validate the evapotranspiration model used by last year’s team. An emphasis was put on selecting a microcontroller with high processing power, as an objective for the team was to improve upon the image processing capabilities from last year’s team project. Two possible microcontrollers were examined as possible candidates, an Arduino Mega, which was used by last year's team, and a Raspberry Pi 3B+ (Figure 6).

Figure 6: Two Microcontrollers: ARDUINO (left), Raspberry Pi (right)

The full microcontroller Pugh decision matrix is shown in Table 2. The selected concepts varied based on the different types of microcontrollers available. The goal of this matrix was to gain a better understanding of the criteria of the project and to compare the specifications of the different types of microcontrollers available. The most important criterion of a microcontroller matrix was processing power.

Table 2: Microcontroller Pugh Decision Matrix

			Raspberry Pi 3B+	
Evaluation Criteria	Weight Factor	Baseline	Rating	Weighted
Analog Inputs	1	0	-1	-1
Digital Inputs	2	0	-1	-2
Size	1	0	1	1
Mass	1	0	-1	-1
Processing Power	5	0	1	5
Power Consumption	1	0	-1	-1
Python Compatibility	4	0	0	0
Totals	-	0	-	1

For the microcontroller, the goal was to improve upon the existing models. In the end, the best way to do this was to use both the microcontrollers. The Raspberry Pi 3B+ was considered for its better data processing capabilities like image processing and Arduino was considered for its better data acquisition capabilities with the sensor interface.The Raspberry Pi 3B+ was found to have a much higher processing power and was Python compatible. Moreover, custom image processing tools written in Python performed better than available functions in Matlab. The Raspberry Pi would also receive and process all the data for the biomass calculation and be used to trigger the volume expansion mechanism. The Arduino was used as a microcontroller for the sensors used in the evapotranspiration model due to the fact that the Arduino had analog inputs and had a much higher degree of compatibility with the sensors used. The Arduino was connected to the Raspberry Pi and the data from the sensors was fed into the Pi for the evapotranspiration model calculation.

3.1.4 Image Processing Software Selection

The research performed by last year's NASA capstone team produced a preliminary code for automated top canopy area calculation [4]. This code transformed the image from the RGB color space to the HSV color space, and then utilized k-means clustering to identify the pixels for the plants, the size reference, and the background. There however exists additional methods of image processing for identifying objects in a captured picture. Finding methods to improve upon the accuracy of image processing will enable more accurate evapotranspiration sensing and potentially lead to the ability to assess leaf turgor pressure.

For the image processing development of the project, coloration analysis and Canny edge detection were two additional methods considered. Coloration analysis is a technique where pixels of a certain color are selectively found and either removed from the image or changed to another color. Canny edge detection is an algorithm which identifies sharp contrasts within an image, enabling the ability to find the edges between captured objects.

To begin, an analysis with the LAB color space was added upon the end of last year's code. And then a new code for Canny edge detection was made. And lastly an analysis with the RGB colorspace was added to the Canny edge detection code. Area of the canopy was found by dividing the number of pixels for the plant with the number of pixels in the reference square (that has a physical size of 1 in^2). The output of each algorithm is shown in Figure 7.

Figure 7 illustrates the output of the code combining all of the different approaches to image processing for top canopy area. For this experiment, output values of canopy areas were produced for the intention of using the values in the ET model during future testing. Also, having the area allows for the ability in the future to compare the calculated areas with a reference.

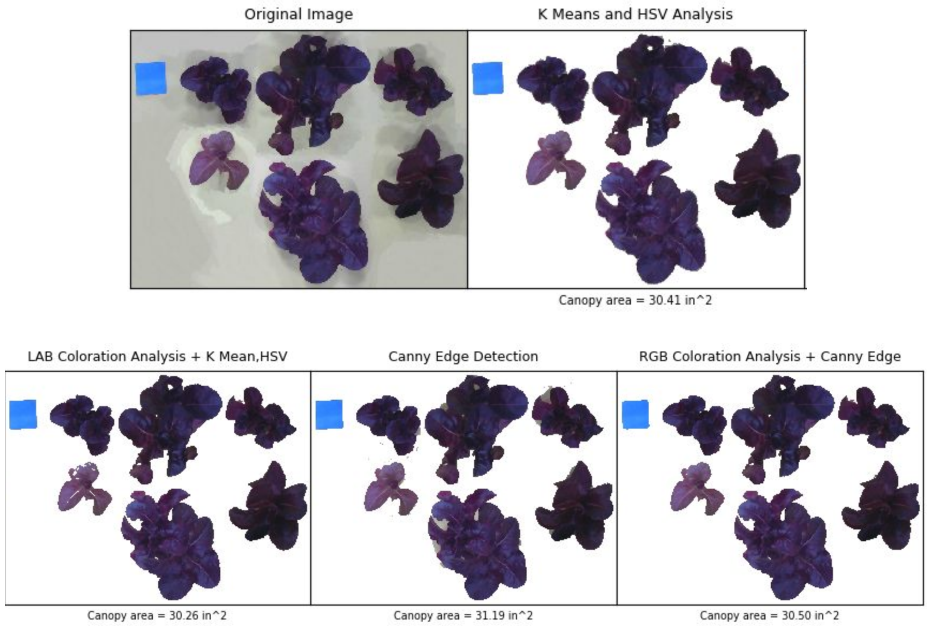

Figure 7: Comparison of Various Algorithms for Plant Canopy Area Detection

3.1.5 Lens Selection

In order to reduce ESM and the number of cameras needed in the system, the possibilities of using wide angle lenses were explored. To test the effectiveness of wide- angle lenses compared to normal lenses, an experiment was designed. For this experiment, the metrics that were focused on were the angle of the lens and the camera distance from the plant canopy. Figure 8 shows how increasing the angle of the lens allows the camera to be closer to the object it is capturing. Having the capability to reduce the space needed for proper image capture allows the plant growth system to not have to occupy as much space.

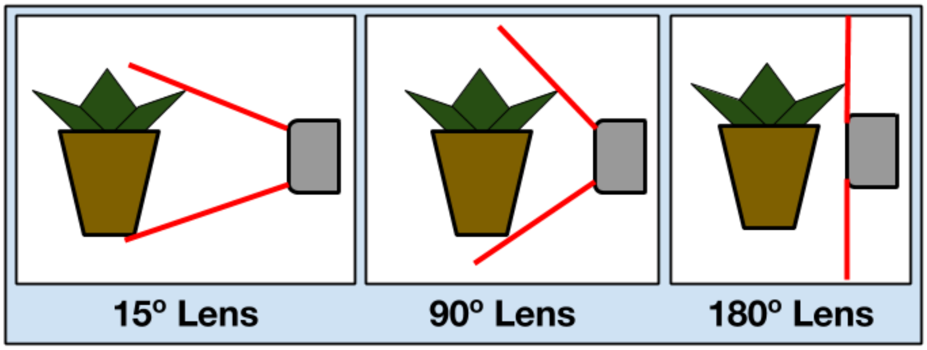

Figure 8: Effect of Increasing the Angle of the Camera Lens (Angles Not to Scale)

For the specific set up of the experiment, four Purple Waffle plants were used as a model for dark colored lettuce plants. A 120° angle lens was used along with a smartphone camera (with a ~60° lens). The smartphone camera was used as a reference and will be further referred to as the “normal” camera configuration. The camera and lens were positioned above the plants just enough for all plants to be in the view of the frame (Figure 9). The height of the camera above the foreground was recorded, as well as an estimate of the average plant canopy height.

From the ground reference, the average canopy height was estimated to be 8 inches. For the height of the camera for each image, the camera was 26 inches above ground reference for the normal image, and 19 inches above for the 120° wide angle lens attachment.

The wide-angle lens proved to effectively capture all plants while being at a lower height than with the normal camera. Relative to the plant canopy, the wide-angle camera had to be only 11 inches above compared to 18 inches for the normal lenses. This gives a 38.9% reduction in the necessary vertical height of the camera relative to the plants. With the system, it would give a 26.9% reduction in the total height from the ground reference.

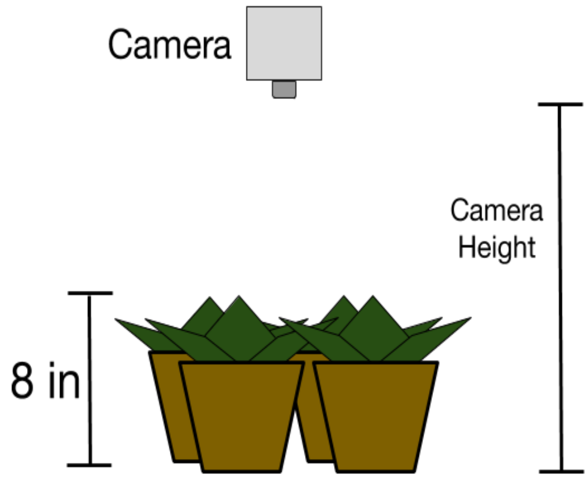

Figure 9: Experimental Setup for Analyzing Wide Angle Lens Camera Height

3.2 Selected Design & Rationale

Although the Dorhea camera and infrared camera were selected as the best options from the decision matrix, the team decided not to use the infrared camera due to a wide-angle infrared lens not being available. The results from the wide-angle lens experiment indicated that a wide-angle camera is successfully able to reduce the needed height of the system while still giving useful and accurate data. Thus, the final design the team selected was the use of three Dorhea cameras for image processing, with the cameras all mounted in the center of the volume expansion mechanism. The team decided to use three Dorhea cameras due to their precision and compatibility with a wide variety of lenses. The center mount design was selected due to the fact that the center of the mechanism is the only place that each of the cameras could be mounted to get a full view of all the plants. Attaching a 140° lens to each camera allowed a complete 360° view of the expansion mechanism.

Python programming with OpenCV commands was chosen for this project over the use of MATLAB, which was used for last year's project. The reason for this change was because Python is a much better source of open-source codes, and OpenCV has more image analysis commands compared to MATLAB. Therefore, finding previously-made codes to improve upon was easier. There was also a larger selection of image analysis tools, which could be used to produce an algorithm with higher accuracy and shorter run time. Lastly, the LAB Coloration Analysis followed by K Means clustering in the HSV colorspace gave results closest to the actual canopy area in a short period of time. Overall, the higher image processing capabilities of the Python program was the primary reason that it was selected.

A Raspberry Pi model 3B+ was chosen over an Arduino Mega for the image processing because Raspberry Pi has more processing power than the Arduino, which outweighs the greater amount of analog inputs that the Arduino has for the image processing and computing aspect. The sensors that were selected by the previous years' team for the evapotranspiration model were shown to be more compatible with Arduino than Raspberry Pi. A voltage regulator for the wind-speed sensor was used to maintain a stable output voltage of 0.4-2 V. A new, calibrated pyranometer with a millivolt adaptor was obtained so that useful data could be obtained. A table of selected sensors to be used with the Raspberry Pi to validate the evapotranspiration model can be found in Appendix A.

Another concept the team was tasked with was the implementation of a soil moisture sensor. The team decided that a wireless soil moisture sensor was highly desirable because an important deliverable of the project was that the sensing platform be easily deployable at any point in the system. All the other sensors besides the soil moisture sensor would take similar measurements, regardless of where they were deployed in the system. However, if the sensor was wired, it would restrict the placement of the sensor to a location that was within the immediate proximity of the soil. With this in mind, the team decided that the optimal choice was the implementation of a wireless soil moisture sensor that would wirelessly transmit data to a relay. However, the team was unable to procure such a sensor, so a wired capacitive soil moisture sensor that was accurate and ESM efficient was used instead. It was wired directly into the microcontroller and one sensor was used to ensure adequate water delivery throughout the system.

Initially a wireless sensing platform was desired to fit NASA's requirement of easy system integration. However, it was decided the sensors would be implemented directly into the volume expansion mechanism to eliminate the need for a sensing platform. Direct implementation of the sensors into the volume expansion mechanism also eliminated the need for wireless sensors. The cameras would be plugged into the Raspberry Pi and the sensors would be directly plugged into the Arduino, which would also be connected to the Pi. The biomass, water usage, and trigger for the volume expansion would all be performed by the Pi. The Pi can transmit its results by being directly plugged into an on-board computer to download the results in real time. The system also has the benefit of not having to deal with bandwidth issues in space, which can cause issues in data transmission.

3.3 Design Components

The design of the volume expansion mechanism is what dictated many of the final design decisions for the system. The final design of the volume expansion was a Hoberman sphere (figure 10), which limited both the location and number of cameras in the system. The sphere used was made of plastic and has a 9.5 inch diameter when fully compressed and a 30.0 inch diameter when fully expanded.

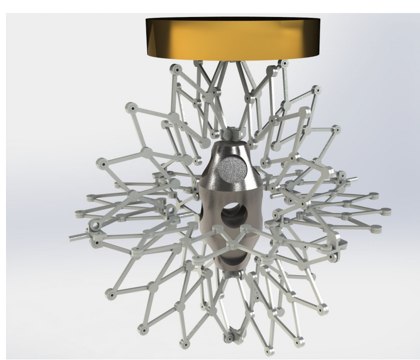

Figure 10: Hoberman Sphere

The sphere had a restrictive design with respect to camera placement, the only feasible way to get all of the plants in view of the cameras and to achieve optimal compressibility of the sphere was to mount them in the center of the sphere. Each of the cameras was 2.1” x 1.6” x 1.6” and weighed 0.8 oz. Therefore, an apparatus was designed by the volume optimization team to hold the three cameras in a way where the canopies of all the plants in the system could be viewed. The center apparatus was designed in Solidworks and then 3-D printed (figure 11). It was directly attached to the top and bottom nodes of the sphere and connected to extendable stainless-steel rods that held it and the cameras in place.

Figure 11: Apparatus to Hold the Cameras

The Raspberry Pi 3B+ was 3.4” x 2.3” x 0.7” and weighed 1.8 oz. The Arduino Mega used was 4.4” x 2.7” x 1.3” and weighed 1.6 oz. Both of the microcontrollers would be secured on the bottom of the Hoberman sphere. The Pi would be connected to the cameras via extension cables and the Arduino would be directly wired into all of the sensors. Information on the mass and volume of the sensors used in the sensing platform can be found in Appendix A. All of the sensors will be directly attached to the Hoberman sphere centered around a bottom node. The conditions around that node will be used to represent the conditions present in the sphere.

3.4 Design Variables

The location and combination of the cameras for image processing were important throughout the project, the idea went through many renditions until the final design was reached. Initially, estimates for the biomass were going to be obtained using a top-view camera and a side-view camera to obtain plant height. However, this design was not feasible in a sphere given that the system needed to be ESM-efficient and it would not be possible to get height estimates of the plants without more cameras. Therefore, instead of using multiple cameras to estimate height, stereo vision was used to estimate plant height instead.

Throughout the experiment, multiple types of lenses were examined to find the best fit for the camera. After the wide-angle lens experiments were conducted, it was determined that the team could use either a 120°, 140°, or 160° wide-angle lens. After the final configuration of the cameras was determined, it was observed that if the 160° degree lenses were used, then there would be a significant amount of potential overlap between plants. This overlap is where the multiple cameras would capture the same plant since the camera's field of view extended into each other. This would potentially cause the system to read more plants than there actually are in the system. This would cause issues in the biomass estimation program as well as the expansion triggering mechanism. Therefore, 120° and 140° lenses were examined as the best potential fit for the system. If 120° lenses were used, then there were potential blind spots in the system that the camera was not able to cover. The 140° wide angle lens was selected as the best potential option since the amount of overlap between the plants would be minimal compared to the 160° lens and there wouldn’t be any spots the cameras would not be able to cover like the 120° lens.

3.5 Success Metrics

The overall goals for this project were to use the evapotranspiration model to estimate the water usage of plants, use image processing to accurately estimate plant biomass, and trigger the image processing system under proper stimuli. Table 3 describes the developed success metrics for proper system function.

Table 3: System Variables and Success Metrics

Need	Metric	Unit	Acceptable Range	Perferred Target
Top Camera Placement	Distance from Lens to Top Plant Canopy	Inches	6 inches - 12 inches	6 inches
	Amount of Plants Captured	% of Total Plants	90 % - 100 %	100 %
Camera Lens (Both for Top and Side)	Angle of Lens	Degrees	100 - 180 degrees	180 degrees
	Effect of Lens Distortion	% Error from Normal Camera Calculated Canopy Area	0 % - 10 %	0 %
Sensing Platform	Individual Sensor Accruracy	% Error from Standard	0 % - 15 %	0 %
	Comparison to Last Year's Platform	% Difference of ET Calculation	0 % - 15 %	0 %
	ESM	Grams and cubic centimeters	10-100 g, 10-150 cm^3	65 g, 80 cm^3 (~80% of Last Year's Platform)
Power Supply	Average Voltage	Volts	4.9 V - 5.1 V	5 V
	Largest Deviation from Average	Volts	-0.5 V - 0.5 V	0 V
	Battery Life (If Not Self-Charging)	Days	7-14 days	14 days
Image Processing Code (Biomass, System Expansion)	Run Time	Seconds	4 seconds - 15 seconds	4 seconds
	Accuracy	% Error from By-Hand Estimation in ImageJ	0 % - 15 %	0 %
ET Model Rapsberry Pi Code	Run Time	Seconds	4 seconds - 15 seconds	4 seconds
	Accuracy	% Error when Comparing Model to Water Input and Biomass	0 % - 25 %	0 %

The goal set when testing this platform was to get the evapotranspiration model to be 75% - 100% accurate to the actual plant evapotranspiration and get all of the sensors in the platform working. Last year's team had issues getting the wind speed sensor and the pyranometer to work properly, however this year, the team got all of the sensors on the sensing platform to work properly. If the team got similar results to accuracy that last year's team had with the model, then it would have been considered successful. To validate the sample calculations performed, the team compared the conditions and data collected from previous studies to outputs from the model to ensure the sample calculations are accurate.

The goal for image processing was to develop a program that would be able to estimate the biomass of the lettuce based on the height and canopy area. For the experiment to be considered successful, the canopy height estimation must be at least 85% accurate, while the plant height estimation using stereo vision must be at least 90% accurate. The differences in accuracies is due to the limited resources in working with estimating the plant height using stereo vision. The overall biomass of the plant should be able to be estimated from these parameters with at least 85% accuracy.

The volume expansion triggering mechanism does not have a threshold that it needs to reach in order to be deemed successful. It needs to be able to expand the amount it is told to and only expand under proper stimuli. If the expansion mechanism only triggers when the image processing software detects less lettuce plants than were in the system before and the mechanism by only two turns then the system will be considered successful.

4. Design Evaluation

4.1 Data Collection

4.1.1 Evapotranspiration Model

Although all the environmental sensors of the sensing platform were calibrated and functioning, due to the campus closure, physical data collection was not able to occur. In place of experimental data, the team used values from literature to simulate an ideal growing environment for the plants. These assumed values were then input into the altered Penman-Monteith evapotranspiration model to estimate the water usage of the plants, as correlated with plant top canopy area. The parameters used for the ET model would then be used to estimate water usage data in order to provide recommendations to design a water tank reservoir, a desired end goal of the ET Modelling system. The parameters that were used simulated a growing environment on Earth and are summarized in Table 4.

Table 4: Theoretical Data Collection Values

Parameter	Units	Value
Temperature	°C	25
Radiation	MJ m^{-2} day^{-1}	15
Relative Humidity	%	60
Wind Speed	m/s	1.5
CO_2 Concentration	ppm	400

4.1.2 Image Processing

Image Processing data collection was done by taking photos of single or multiple lettuce plants. These plants were placed on top of various backgrounds which were a consistent non-green color. The use of these backgrounds enabled proper image segmentation through algorithms involving finding the plant canopies by categorizing pixels within a certain color range. This method of data collection for images was done specifically for experiments dealing with finding top canopy area and perimeter. This includes comparing different segmentation techniques, testing the use of stereo vision for finding plant height, and for creating input images for verifying the triggering mechanism algorithm. Stereo Vision traditionally uses two cameras to see the same object and the baseline distance between the two cameras can be determined accurately [10]. Although in this method, a single camera stereo vision approach is used to get the two images of the plants by taking a picture at a certain location and then moving the camera one inch forward towards the plants after the first image. Beyond collecting data for area and perimeter measurements, Section 3.1.5 describes the process for data collection when experimenting with using a wide angle lens to reduce the needed distance between the camera and the plant. This shortening of the distance between the camera and the plants contributes to volume optimization of the integrated growth structure as the overall growth volume is reduced.

4.1.3 Volume Expansion Mechanism

When determining how the volume mechanism was going to expand, there were two options. The first of these options was to have the mechanism expand a set amount each time the sensing system detected overlapping plants. The second option was for the volume mechanism to continually expand and re-check for overlap until the plants no longer overlapped. The former option offered simpler communication between the sensing system and the volume mechanism, while the latter option offered a more space efficient process for growing plants.

Another consideration for the volume expansion was communication between the sensing system and the volume mechanism. Ultimately, it was decided that the sensing system's Raspberry Pi would communicate with the volume mechanism's Arduino. Upon research, the team determined that serial communication between the boards would serve as a sufficient channel for the signals to send and be read by the Raspberry Pi and Arduino.

4.2 Data Analysis

4.2.1 Evapotranspiration Model

Due to the COVID-19 pandemic, the team could not get environmental data using the functioning sensors and had to resort to some of the values provided by the last year's OSU X-HAB team to account for values that were not obtainable. These standard values generated by the environmental sensors were then imported into an Excel file to model the evapotranspiration mechanism by performing step by step calculations based on the procedure outlined by Zotarelli et al. [12]. As the team was not able to get actual environmental data from the sensors in the lab, a flat rate of 15 MJ/m^2/day for estimation of total radiation and 400 ppm for CO_2 level were used. The radiation value and a standard CO_2 level were considered assuming plants were studied under indoor lab conditions with blue and red lights. Also for the radiation and temperature values, the procedure outlined in Zotarelli et al. [12] recommends using daily average values for total radiation and temperatures, therefore the above stated total radiation value and an average daily temperature of 25℃ were considered.

Due to COVID-19 constraints, the team was not able to collect lab data. Therefore, standard values of sensors working in different systems from literature and last year's reported values were assumed by the team. This constraint creates possible sources of error for the environmental data obtained as the team was not certain if all the assumptions made for the parameters were accurate as the team had no means to test and verify the parameters using the functioning and calibrated sensors in lab settings.

Originally, the evapotranspiration model was going to be validated for plants at different stages of growth. However, the team was unable to test this with live plants due COVID-19 caused campus closure. Instead, the team varied the canopy area in an evapotranspiration model calculation and then compared the values obtained from literature with those obtained from the model to estimate the system's maximum water requirements.

Ideally, if data were able to be collected for the evapotranspiration model the team would have also varied the conditions of the system in order to test the validity of the model in non-optimal systems. This would be a good study to see how effective that the model would be if used on other plants and not just lettuce.

4.2.2 Image Processing

Images taken of lettuce plants were input into the codes shown in Appendix C. Section 3.1.5 details the use of the following calibration and correction codes used when utilizing a wide angle lens attachment to the camera(s). Section 3.1.4 then describes the analysis done through the code for comparing different image segmentation techniques. As done with code for comparing image segmentation, the final code used for determining plant top canopy area and perimeter was analyzed by statistically comparing the output data with manual image segmentation results through ImageJ. For the multiple camera code, analysis of the functioning of the code was done by ensuring proper image file outputs are achieved from each camera being operated. Lastly, for studying the capability of stereo vision to find the distance between the plant and the camera, a graph was made for the percentage of the image taken up by the plant for each height. The data was graphed and a power series regression was done to model the capabilities of the camera used in the experiment.

4.2.3 Volume Expansion Mechanism

Of the two methods for the volume mechanism to expand, the option of the mechanism expanding a set amount was selected based on the ease of translating a set signal to the volume mechanism's Arduino microcontroller. The set amount was determined to be three expansions using a linear actuator motor, which was decided by the volume optimization team. The decision to expand the volume mechanism the same amount each time simplified the code used to communicate between the sensing system and volume mechanism.

Boolean logic was used to signal whether the volume mechanism should expand or not. This process used a user-input value of the number of plants that were supposed to be in the growth module. The image processing program then determined the number of plants using edge detection. If the number of plants detected by the sensing system was fewer than the number of plants input by the user, the sensing system would send a "1" signal to the volume mechanism, signifying a "yes" that the volume mechanism should expand. If the number of plants detected by the sensing system was more than or equal to the number of plants input by the user, the sensing system would send a "0" signal to the volume mechanism, signifying a "no" the volume mechanism should not expand. The code accounted for possible errors in plant detection by dedicating an option for the sensing system to detect more plants than there are in the growth module. This code can be seen in Appendix D.

Another check that was built in the code was the volume mechanism sending the signal received from the growth module expansion controlling Arduino back to the image processing Raspberry Pi. This served two purposes: to ensure the correct signal was received and to end the communication between the two microcontrollers until the next image reading. Evaluation of the triggering mechanism was done on a trial and error basis.

5. Results

5.1 Evapotranspiration Model Results

The plant water usage is to be estimated by the evapotranspiration model results. However, the correlation between the actual water usage and the estimated usage was unable to be verified since experimental data could not be collected in the lab due to unforeseen COVID-19 circumstances. In the context of the design, this means that further testing and validation is required. The experimental calculations were performed using an altered Penman-Monteith evapotranspiration (ET) model to estimate the system water usage needs in a 24 hour time period. The sensor environmental values were input to the ET model excel sheet programmed to perform the step by step calculations outlined by Zotarelli et al. [12]. As a result, for eight fully grown lettuce plants under optimal growing conditions, the water usage is calculated to be approximately 2500 grams of water per day as shown in Appendix F.

5.2 Image Processing Data Results

The image processing program was able to use LAB color space along with Canny Edge Detection to estimate the overall canopy area of the plants with 97% accuracy. Stereo Vision was used to determine the overall plant height by finding a correlation of 0.914 between the distance of the camera to the plant and the percentage of screen taken up by the plant when the camera was moved one inch closer to the plant (Figure 12). Plant height can be determined with one camera taking two images at two distances from the plant. The single camera stereo vision approach along with the use of wide angle lenses is a beneficiary ESM improvement as it reduces the use of multiple cameras as well as contributes to the volume optimization of the integrated growth structure. From accurate measurements of plant canopy size and plant height, one can use the data for a multitude of purposes such as biomass determination, water usage estimation, gas exchange estimations (including oxygen, CO_2, and water vapor), plant water status monitoring (i.e using dynamic canopy area information to detect plant wilt), lighting control to adjust light intensity at canopy level as the growth volume expands, growth volume expansion control of the integrated growth structure. In addition to this, there is a known correlation between the plant's biomass and its overall oxygen output. Based on this correlation, the approximate oxygen output of each plant was able to be estimated as shown in Appendix E.

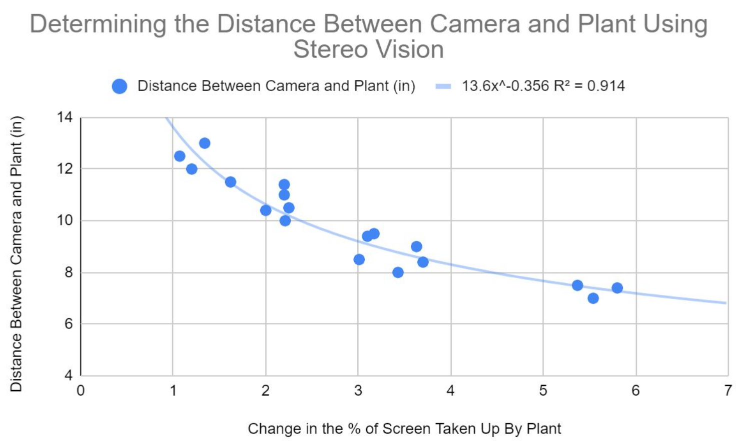

Figure 12: Strong Correlation between Percentages of Plant Pixels and the Distance between the Camera and Plants.

5.3 Volume Expansion Results

The triggering mechanism accurately triggers the volume expansion mechanism to expand when the cameras used in image processing detect less individual plant canopies than were put initially in the growing system. The triggering mechanism code is designed to output an expansion signal only when the individual plant canopies are touching or overlapping. As a result, the expansion mechanism continues to expand until it detects an appropriate number of canopies or when the expansion mechanism reaches a specified expansion limit.

6. Cost Analysis

Implementing this sensing device, as it was designed by the team, would be relatively inexpensive, as the sensors and processors are readily available and easy to assemble (Table 5). However, this design is still in the prototype phase of development, and further design improvements could add to the cost of implementing the design. For example, more accurate sensors will be more expensive.

Table 5: Breakdown of project expenses

Concept	Item	Cost
Image Processing	Lens Board and Raspberry Pi Camera X 3	
	M12 Lens Set, Arducam for Raspberry Pi Camera	
Temperature & Relative Humidity Sensor	HDC 2010 EVM	
CO_2 Sensor	Telaire 6613 CO_2 Module	
Pyranometer	Li-Cor (LI-200R) with Signal Amp.	
Wind Sensor	Wind Sensor Rev. C, MD0550	
Power Supply	TalentCell Rechargeable Battery Pack	
	ADC Transistor	
Data Acquisition	Raspberry Pi 3B+	
	Arduino	
Signal Processing, Wiring	Miscellaneous	

7. Further Design Considerations

The sensing and volume expansion device is designed to limit the amount of power consumed, while still providing accurate data results. To achieve this, the Raspberry Pi and Arduino boards are programmed to enter sleep mode between data measurements. To keep the impact on ESM low, previous studies using compact sensing devices to monitor environmental data in greenhouses were investigated as a starting point for sensor selection by last year's team [4]. The sensing device was designed to be ESM-efficient as it was built upon the already compact system designed by the previous year's team with limited excess or non-reusable material. Therefore this design is highly sustainable and ideal for environments with limited space.

In its current state, this design would be relatively easy to manufacture. All sensors and cameras are readily available and easy to connect to the Raspberry Pi and Arduino processors. However, this design is still in the prototype phase, and therefore the ease of manufacturing may differ as the design becomes more sophisticated.

With regards to the health and safety of astronauts, several factors were taken into consideration. In order to avoid heat buildup from the Raspberry Pi or Arduino, the devices will remain in sleep mode between data measurements. Another consideration was anomalies in the data, which could lead to a false triggering of the expansion mechanism. To avoid this, built-in "checks" were programmed into the code that would display an error message if a data value is outside of the expected range.

A social implication of this device is its alternate application for indoor or vertical farming. This device could potentially make growing and maintaining indoor gardens easier for people in urban areas or food deserts, which would provide fresh produce to people who otherwise may not have access to it.

8. Conclusions & Recommendations

The goal of this project was to design a modular, ESM-efficient sensing device to trigger a volume expansion mechanism that could be deployed by NASA in microgravity environments for monitoring plant health and growth. The team was successfully able to program all sensors required for data collection and use image processing to trigger an expansion signal to the volume expansion device designed by a collaborating Ohio State NASA X-Hab team. Unfortunately, the team was unable to collect real-time sensor data for the evapotranspiration and biomass models due to COVID-19 constraints.

One consideration for future work is to use the completed sensor system to obtain growth data from lettuce plants grown in the lab. This data could then be compared to lettuce plant data obtained from calibrated devices, such as a Velocicalc meter, and a statistical analysis could be performed to verify the accuracy and calibration of the programmed sensors.

Once it is verified that the sensors are calibrated, the sensing device could then be used to collect real-time lettuce plant data to be used to validate the altered Penman-Monteith evapotranspiration model (Figure 2) as well as the biomass model. This could be done using a statistical analysis comparing theoretical values for the models and the actual values obtained using the sensors.

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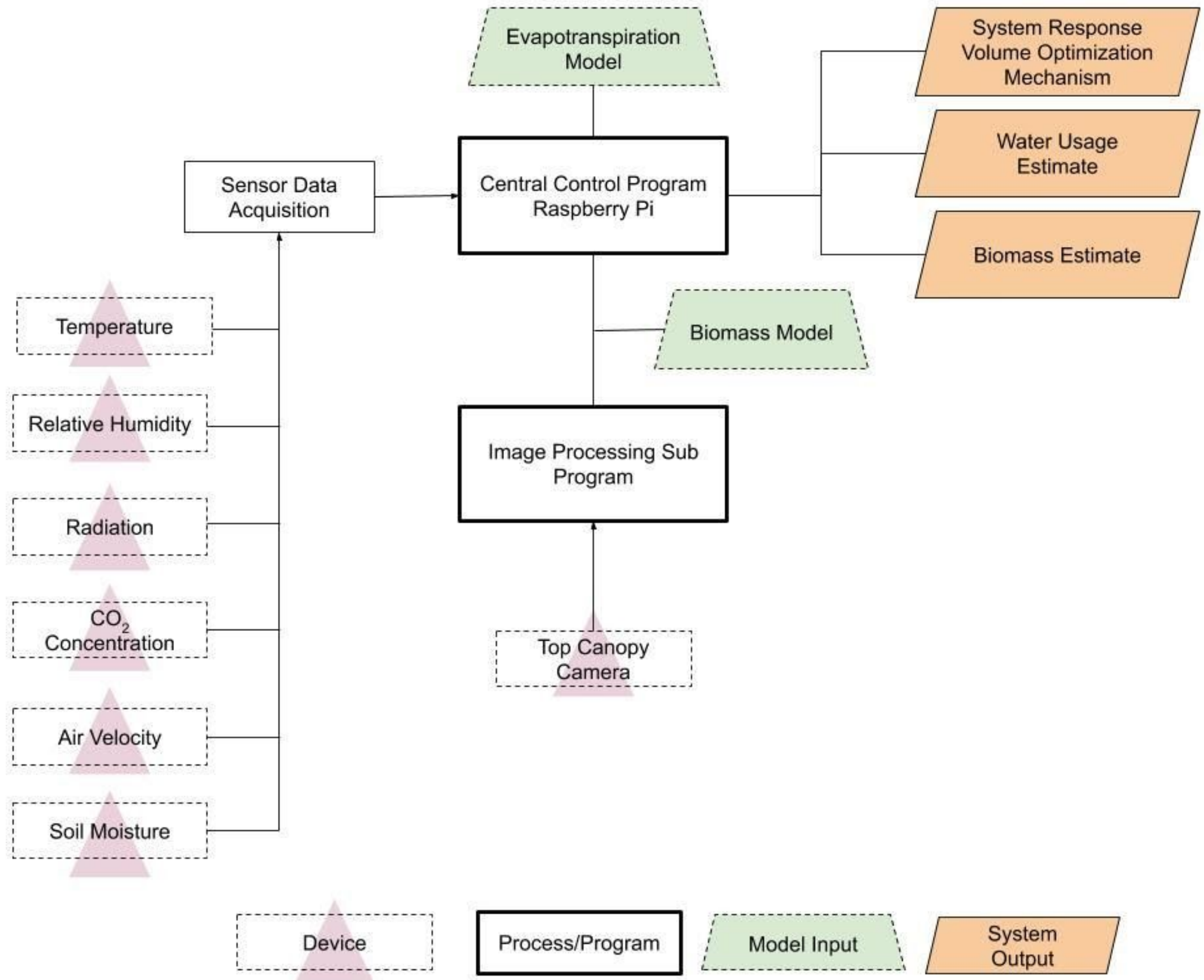
Appendix A

Summary of Selected Sensors:

Criteria	Device	Accuracy	Mass (kg)	Volume (m3)	Power (W)
Temperature	TI HDC2010	±0.2°C	0.0001	1.52E-09	1.08E-06
RH	±2%	-	-	-	-
CO_2 Concentration	Telaire 6613 CO_2 Module	3% or 5% of reading	0.015	3.00E-05	9.00E-01
Wind Speed	Wind Sensor Rev. C	Unavailable	0.0012	4.43E-06	2.00E-01
Total Radiation (Pyranometer)	Li-Cor 190R	±3%	0.029	1.59E-05	5.00E-08
Data Acquisition	Raspberry Pi Model 3B	64 bit CPU	0.05	9.66E-05	1.70E+00
Totals:	-	-	0.0953	1.47E-04	2.80E+00

Appendix B

System Architecture of Remote Sensing Platform



Appendix C

Image Processing Codes

Appendix D

Wind Speed Sensor

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/* Modern Device Wind Sensor Sketch for Rev C Wind Sensor
 This sketch is only valid if the wind sensor if powered from
 a regulated 5 volt supply. An Arduino or Modern Device BBB, RBBB
 powered from an external power supply should work fine. Powering from
 USB will also work but will be slightly less accurate in our experience.
When using an Arduino to power the sensor, an external power supply is better. Most Arduinos have a
 polyfuse which protects the USB line. This fuse has enough resistance to reduce the voltage
 available to around 4.7 to 4.85 volts, depending on the current draw.
 The sketch uses the on-chip temperature sensing thermistor to compensate the sensor
 for changes in ambient temperature. Because the thermistor is just configured as a
 voltage divider, the voltage will change with supply voltage. This is why the
 sketch depends upon a regulated five volt supply.
 Other calibrations could be developed for different sensor supply voltages, but would require
 gathering data for those alternate voltages, or compensating the ratio.
 Hardware Setup:
 Wind Sensor Signals    Arduino
```

Appendix E

Calculation of oxygen output of the lettuce from its biomass:

Given that fresh weight, dry weight, C% of dry weight were all obtained from a previously made biomass model for Cogollo lettuce, had a sampling size of 15 plants.

Equation of photosynthesis: $6CO_2 + 6H_2O \Rightarrow C_6H_{12}O_6 + 6O_2$

Humidity (%) = (Fresh Weight(g) - Dry Weight(g)) / Fresh Weight(g)

Carbon weight (g) = C% of Dry Weight(%) * Dry Weight(g)

O_2 Output (g) = (Molecular Weight O_2 / Molecular Weight Carbon) * Carbon Weight

Lettuce Part	Fresh Weight (g)	Dry Weight (g)	Humidity (%)	C % of Dry Weight (%)	Carbon Weight (g)	O2 Output (g)
Root	56.6	12.8	77.44	39.9	5.1072	13.6192
Stalk	96.6	6.1	93.7	36.75	2.24175	5.978
Leaves	430.2	22.3	94.81	35.08	7.82284	20.8609066
Total	583.4	41.2	-	-	15.17179	40.4581066

Appendix F

Variables for evapotranspiration model:

Variable	**Definition**	**Required Data/Sensor**
Rn	Net radiation at the crop surface[MJ m^-2 day^-1	Radiation sensor
G	Soil heat flux density[MJ m^-2 day^-1]	Small, negligible
T	Air temperature at 2 meter height[C]	Temperature sensor
u2	Wind speed at 2 meter height[m s^-1]	Wind speed sensor
es	Saturation vapor pressure [kPa]	Relative humidity sensor
ea	Actual vapor pressure[kPa]	Relative humidity sensor
es-ea	Saturation vapor pressure deficit[kPa]	Calculation
delta	Slope of vapour pressure curve[kPa C^-1]	Average temperature(daily)
gamma	Psychrometric constant[kPa C^-1]	Atmospheric pressure
fCO2	CO2 factor	CO2 Sensor
TCA	Top canopy area	Area(image processing)

Calculation for evapotranspiration model:

Step	Term	Calculation
1	Temperature	T_avg
2	Rs	Rs=Radiation*0.0864
3	u2	u2=h*4.87/(LN(67.8*h-5.42)
4	Slope of saturation vapor pressure curve	D=(4098*(0.6108^((17.27*T _avg)/(T_avg+237.3))))/((T+ 237.3)^2)
5	Pressure based on meters above sea level	P=101.3*((293-(0.0065*226))/293)^5.26
6	Gamma: psychrometric constant	Ga=(0.001013*P)/(0.622* 2.45)
7	Soil Heat Flux:G	Ignored due to small value
7	etmax	etmax=0.6108^((17.27* T_max)/(T_max+237.3))
8	etmin	etmin=0.6108^((17.27* T_min)/(T_min+237.3))
9	es	es=(etmax+etmin)/2
10	Actual vapor pressure	ea=6.11*10^((7.5*T)/273.3 +T)
11	capD=delta term(inverse relation to earth)	J=number of day in the year I=(2*Pi()/365)*J dr=1+I capD=0.409*sin(((2*Pi())/ 365)*J-1.39)
12	rad(convert latitude from degrees to radians)	rad=(40.005529*Pi())/180
13	Sunset hour angle	ws=ACOS(-TAN(rad)* TAN(capD))

14	Extraterrestrial Radiation(Ra)	c=COS(rad)*COS(capD)*SIN(ws) Ra=(1440/Pi())*0.082*dr*(ws*SIN(rad)*SIN(capD)+c
15	Clear sky solar radiation(Rso)	Rso=(0.75+0.00002*226)*D25
16	Net solar or net shortwave radiation(Rns)	Rns=(1-0.23)*Ga
17	Net outgoing longwave solar radiation	Rnl=4.903*10^-9*((T_max+273.16)^4/2)*0.34-0.14*SQRT(ea)*(1.35*(Rs/Rso)-0.35)
18	Net radiation	Rn=Rns-Rnl
19	CO2 factor	g=0.0485-7*10^-5*CO2+3.4*10^-8*CO2^2 gCO2=D30*(1.4-0.4*(CO2/330)) fCO2=gCO2/330
20	Final ET Calculation	ET=(0.408*Rn+Ga*(900/(T+273))*u2*(es-ea))/(D+Ga*(1+(0.34*u2)/fCO2))
21	Water usage[m^3/ha/day]	ET*10
22	Water usage[m^3/in^2/day]	Water usage[m3/ha/day]*0.0000812902
23	Water usage[m^3/day]	Water usage[m^3/in^2/day]*TCA(in^2)
24	Water usage[grams/day]	Water usage[m^3day]*1000000

Appendix G: Qualifications and Contact Information of Personnel

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