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Aeroponic test bed for hypergravity research

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DEPARTMENT of MECHANICAL ENGINEERING

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Shane Brunner, Theron Hawley, Mike Nichols, David Patzelt, and Kurt Sprouse

ENTITLED

Aeroponic Testbed for Hypergravity Research

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

THESIS ADVISOR

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Aeroponic Test Bed for Hypergravity Research

Team Members:

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Senior Design Project Report

Submitted in partial fulfillment of the requirements
for the degree of
Bachelor of Science in Mechanical Engineering
School of Engineering
Santa Clara University

June 12, 2014

Abstract

Taking one pound of food to space costs over $10,000. A plant growth chamber in space would help reduce the cost of transporting food by creating a healthy, long-term source of food that can be used for extended space missions. Currently, there is a lack of knowledge in gravity response mechanisms of plants to facilitate employing such a system. The overarching goal of this project is to add to the current body of knowledge related to growing plants in space by conducting research regarding the effect of hypergravity on cherry belle radish growth. To successfully accomplish this goal, an aeroponic test bed that induces hypergravitational fields ranging from 3gs to 5gs while also providing the nutrients and lighting necessary for growing cherry belle radishes was constructed.

Acknowledgements

We would like to thank the Santa Clara University School of Engineering for their generous project funding, Dr. Marks, Dr. Djordjevic, and Dr. Hight for their continuous project advising, Dr. Bebout and Dr. Hiremath for their input on the background information of our project, Dr. Krishnan and Hugh Eisenman for their electrical assistance, Dr. Conefrey for her help writing and presentation advice, and the v2 Lighting Group for their LED lighting donation.

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Chapter 1

Introduction

1.1 Background

As research in space exploration continues to expand, there is an increasing interest to travel farther than ever before. Unfortunately, the distance of a space mission is majorly limited by lack of access to a sustainable food source. Current space missions rely on dehydrated food that must be sent up with the astronauts for later consumption. At a cost of $10,000 per pound of food just to get the dehydrated food aboard the International Space Station, it is clear that this figure would quickly balloon if applied to space missions of greater distance and duration (Lee). The need to store or continually send up food for these space missions is expensive, bulky, and inefficient. Changes must be made for long term missions to become possible.

One way to eliminate these problems is to provide a sustainable food source to replace some of the prepackaged dehydrated foods that are currently in use. If a reusable garden was available to the astronauts, it would decrease the cost of sending food and extend the limits on survival time in space. In order to accomplish this goal, it is first necessary to have a complete understanding of how plants will behave under conditions they are subjected to during space travel. This includes the effects that long-term exposure to microgravity will have on plant growth. Extensive research has been performed regarding the effects of microgravity on plant growth both here on Earth and aboard the

International Space Station (Morrow). While the effects of microgravity on plant growth have been well documented, the effects of hypergravity on plant growth remain unidentified. After discussing this topic with Dr. Bebout of the NASA Ames Research Center in order to gauge NASAs interest in hypergravity research, we was determined that a hypergravity plant test bed would indeed be beneficial to the greater scientific community. By creating a system that can apply several times the normal gravitational force on vegetation, this project will work to fill in the current gaps in hypergravity plant research and expand the possibilities of future plant studies.

One possible method for inducing hypergravity on plants is to place the plants on the outer edge of a rotating chamber. The rotation of the chamber induces an acceleration and thus a force on the plants. The acceleration created in this manner is a product of the radius and the velocity and can be seen from Equation 1.1 shown below,

$$a = \omega^2 r \tag{1.1}$$

where a is acceleration, ω is angular velocity, and r is the radius of the rotating assembly. For hypergravity systems this equation is important since it is used to determine the exact force that is applied to the plants. Although this project did not test the effect of microgravity, it should be noted that microgravity systems operate by rotating the chamber at extremely slow speeds, of roughly 10 RPH, so that the force applied to the plants in negligible. Furthermore, the purpose of rotating the plants is to neglect the force of earths gravitational field. This is achieved since as the plants rotate, their orientation toward earths gravitational field also rotates, which thus causes the force on the plants to alternate between -1g and 1g. This alternating force ultimately averages out to 0 and thus microgravity is applied to the plants.

1.2 Current Works

As early as 1929, hydroponics has been used to produce commercial crops in an economically feasible fashion (Gericke, pg. 178) . Since then, considerable research has been conducted regarding the use of hydroponics for both commercial use and plant biology testing. With the advent of interest in space-flight, hydroponics was identified as a good candidate for space application(Morrow, pg 1947). Recently, a variety of studies have explored growing plants in simulated microgravity environments.

One of the challenges of growing plants in simulated gravity environment is providing water and nutrients to the plants.A Russian-Bulgarian developed space greenhouse was built to study the full life cycle of plants (Bingham, pg. 839). It was used to grow wheat in 1996 using a substrate water supply which consisted of vitamins and minerals necessary for the plants to thrive. This greenhouse was developed to explore water and oxygen delivery to the roots in a microgravity environment. This hydroponic system grew plants that developed faster and larger than Earth grown plants, showing the applicability and value of hydroponics. This study brought up some of the problems associated with providing water to plants hydroponically. The first problem occurred when particles separated from the substrate when the water began to dry. The second problem occurred when the water created a film around nutrient particles and created a bubble that reduced nutrient dispersion.

More recently, studies aimed at understanding the relationship between fluid mechanics and plant growth in space have been conducted. In 2005, the University of Connecticut explored multiple design solutions for delivering water and nutrients to plants in a microgravity environment in order to optimize liquid and gas fluxes to plant roots under extremely tight volume constraints and reduced gravity conditions (Dani, pg. 12). Students designed a porous media that satisfies plant root metabolic requirements in reduced gravity. Capillarity, substrate water retention, aqueous and gas phase transportation, oxygen concentration, and material selection were aspects of water transportation systems that were each examined in this report. These components established an optimal porous media design, and it was concluded that a great amount of work can be done to improve upon the applicability of the porous media for use in microgravity. This is important to the Aeroponic Test Bed for Hypergravity because it provides analysis of different water distribution methods and many different factors that must be considered for plant growth to be successful in microgravity.

Another important area that requires study is the challenge of providing radiation for photosynthesis in an energy efficient way. A study published by the University of Wisconsin-Madison and the association of Automated Agriculture details the feasibility of using light emitting diodes (LEDs) as a light source (Bula, pg. 36). The useful radiation spectrum is between 400 and 700 nm or roughly the visible light spectrum. Peak absorption of chlorophyll used in photosynthesis occurs at roughly 640nm, a red wavelength. The study found that a combination of red and white LEDs was most effective. LEDs are found to be about twice as efficient as fluorescent light sources for growing plants.

Another study, published by a team at Beihang University in China, has very similar goals to the Aeroponic Test Bed for Hypergravity (Fu, pg. 97). The team created a ground-based prototype of a plant production facility for future space use. Their project was capable of simulating the microgravity effect and the continuous cultivation of leafvegetables on root modules(Fu, pg. 100). The prototype was structured as a cylinder with lettuce planted on a rotating wheel in the center of the cylinder. The roots of the plants were fastened around this wheel, which provided water and nutrients. The rotating plants were surrounded by LEDs on the inside of the cylinder that provided radiation. This project demonstrated that it is possible to create a reliable supply of salad greens in an enclosed source however this project did not take atmospheric concerns into account. It also did not take weight concerns on a spacecraft into account so there are still areas that need to be addressed in our project. This project supplied a reliable method of growing plants in an enclosed space meant to simulate plant growth in various gravitational fields.

Finally, some research on growing plants in space has been done in space itself. Currently, the International Space station has a small hydroponic garden growing a few lettuce plants. A crop of plants has already been harvested and sent to Earth to be tested for toxicity. The purpose of this project is to study the effects of zero gravity and higher radiation on plant growth and to see if it is safe to eat produce grown in space. Clearly, a large amount of research has been done recently on various aspects of the feasibility of growing plants in space. Our project aims to build on this research in an attempt to test plants in a hypergravity field, while utilizing the advances in hydroponic technology that have already been made.

1.3 Objective

The objective of this project is to develop a system for testing the effect of hypergravity on the sprout time of cherry belle radishes in order to provide insight into the feasibility of growing plants in the unchartered waters of extended planetary space missions. The unknowns surrounding the effects of hypergravity on plant growth have made it so any new acquisition of data on plant tendencies in high levels of gravity is useful to solidify the scientific communitys understanding of how plant growth operates.

Chapter 2

Systems Level

2.1 Overview

The goal of this test bed is to provide a research platform for observing the effects of hypergravity on the growth of cherry belle radishes. Ultimately, this information will be passed along to NASA and various private space companies that are interested in finding a method to sustainably grow food for long-term space missions. There is plenty left to discover regarding how plants grow in space, and researchers are constantly looking to expand their knowledge. This test bed provides a large number of components and subsystems, which are vital to the testing procedures that NASA and various private space companies need. Shown below in Figure 2.1 is a picture of the test bed with labels for each of the major components.

The main structure of the rotating drum was built out of $\frac{1}{8}$ inch acrylic and is not labelled in the diagram since it encapsulates the majority of the space in the diagram and thus can be easily identified without the need for a label. The three main purposes of this structure were to separate the inner lighting from the water that is sprayed onto the outside of the drum, to provide enough space for the radishes to grow, and to ensure that each of the three tiers of the drum induce 3gs, 4gs, and 5gs, respectively, as the drum rotates at 100 RPM. Thirty-six plant modules were attached to the outside of this acrylic structure and Gro Blocks (Mini-Blocks) were placed inside of these modules

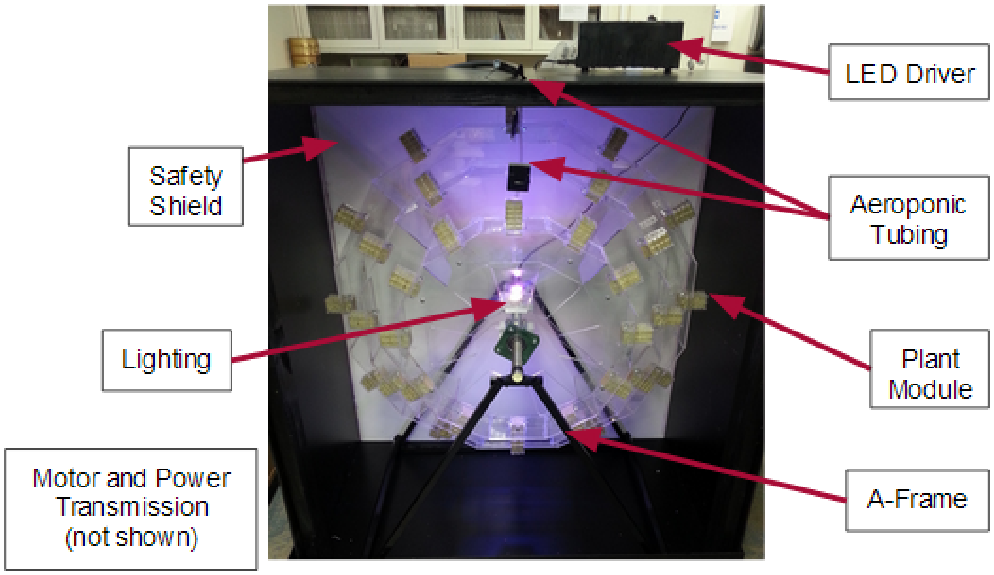


Figure 2.1: Component Photograph of Test Bed

to support cherry belle radish growth. A steel A-frame, in conjunction with a stationary 1 in. diameter galvanized steel pipe were designed to support the acrylic structure and to lift it 6 inches above the ground in order to provide space for the plant modules to rotate. LEDs were attached to the central stationary pipe to provide the proper amount of lighting to the plants. The wires for supplying power to these LEDs were fed through the stationary rod and then connected to the LED driver module, which provides the proper amount of power and is also capable of controlling the brightness of the LEDs. A safety shield built out of PVC surrounds the entire test bed to prevent injury to people near the test bed as it rotates at 100 RPM. One side of this shield was left open so that a removable $\frac{1}{4}$ inch acrylic sheet could be added. This removable sheet was necessary so that the drum is accessible for regular monitoring purposes as well as in case an unanticipated problem occurs that requires tending to. Aeroponic tubing was fed through the top of the safety shield to provide the water and nutrients necessary for plant growth. A bucket full of plant nutrient solution was placed behind the test bed and a submersible pump was placed inside of this bucket. The motor and power transmission are shown below in Figure 2.2 and are discussed in Section 4.3. The motor is located outside of the safety shield and a hole was drilled into the shield so that a shaft can extend from the motor to the inside of the shield. A pulley at the end of this rod was attached to another pulley at a 5:1 ratio using a v-belt.

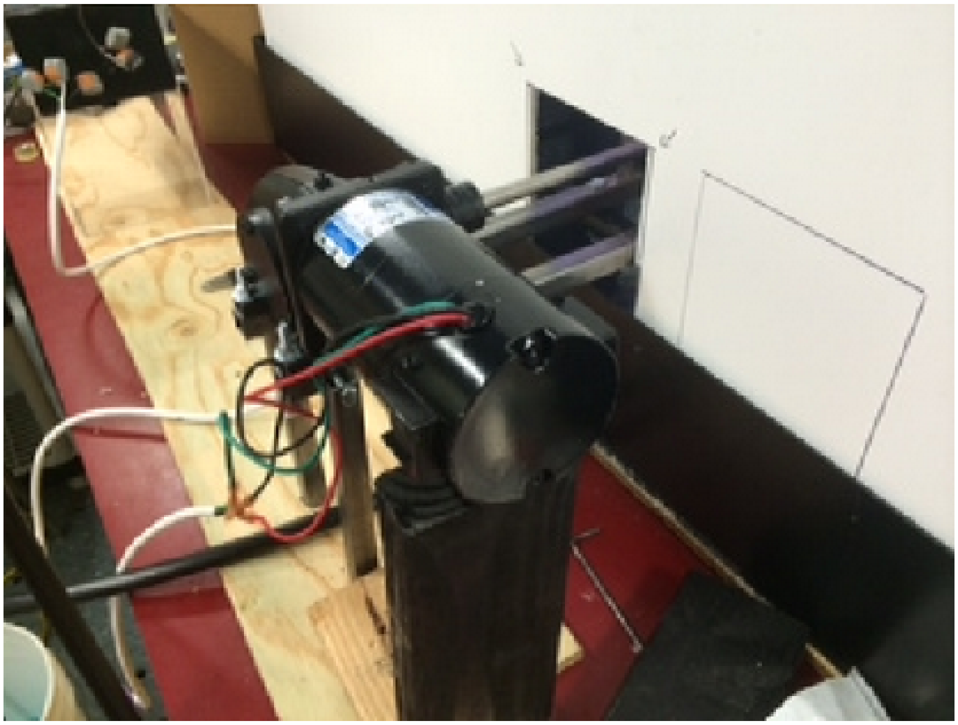


Figure 2.2: Motor and Power Transmission Shaft

2.2 Customer & System level Requirements

In order to receive feedback on the design of the test bed, the test bed team contacted a few professionals who have space research experience. Dr. Hiremath is a dynamics professor at Santa Clara University and works at Space Systems Loral in Palo Alto California, where he has been involved with building and launching multiple satellites. Dr. Bebout is a researcher at NASA

Ames in Mountain View California, with expertise in microbial ecology and how microorganisms thrive in harsh environments such as space. Finally, Dr. Djordjevic is a fluids professor at Santa Clara University and has been involved with hydroponically growing plants in a zero gravity environment at Lockheed Martin in Sunnyvale California.

These professionals provided valuable insight into the design of our test bed and various ways it could be improved. Initially, the test bed was going to be designed so that it could be used in space, but this was unfortunately out of the scope of a 9 month long undergraduate research project. There were numerous specifications that were found to be needed in order for it to be ready for space. Instead of designing something for space, a test bed was designed to test a set of criteria that could be applied in space. One of these criteria was the effect of gravity on plant growth.

This input led to an interest in designing a test bed that can be used to observe the effects of microgravity on a plant, however, this plan was quickly changed. There is already plenty of information regarding the effects of microgravity on plant growth, but very little information regarding the effects of hypergravity on plant growth. Additionally, all of the customers that were interviewed expressed an interest in the effect of hypergravity on plant growth. Hypergravity simply refers to any g force that is greater than the 1g that naturally exists near the surface of the Earth. Knowing how hypergravity impacts plants could be a crucial stepping stone for growing plants in space, depending on what is found through the testing. It could be much easier to grow plants in hypergravity, and provide more food than plants grown in microgravity. However, there are varying magnitudes of hypergravity, and there is no way to know which one would be best to study in a limited amount of time. Both Dr. Bebout and Dr. Djordjevic recommended that the plants be tested under a range of induced forces that would simulate a variety of gravity forces, which is why a three-tiered drum was constructed so that 3 different g forces could be simultaneously tested.

The current research regarding the effects of hypergravity on plant growth is at a very preliminary stage, which explains why information regarding hypergravity systems was not included in Appendix A.4 in Table A.1 and instead microgravity systems were used since they serve as the next most similar device to a hypergravity test bed. Dr. Hiremath even said “It is worthwhile to replicate past studies and reason through them and maybe find some areas of improvement...” There is always more research to be done, and any minor discovery that is made from the experiment could be crucial to future research.

2.3 Benchmarking Results

In order to compare this system to similar products, a number of criteria were compared between each system. This can be seen in Appendix A.4. The main differences in the teams system and the compared systems is that each of the other systems were designed to test microgravity rather than hypergravity. This lead to the teams drum having a much higher rotation speed than the comparable microgravity systems, but other traits such as drum volume, light type, temperature, and diameter were kept similar to the microgravity chambers.

2.4 Key System Level Issues

2.4.1 Rotational Axis

Deciding whether to rotate the drum on a horizontal or vertical axis was the first major system level issue that had to be solved after deciding to induce hypergravity rather than microgravity. The advantage of rotating around a horizontal axis is that as the plants rotate through a single revolution their orientation relative to Earths natural gravitational force also rotates causing the force of Earths gravity to average out to 0. This principle explains why all the microgravity test beds also rotate around a horizontal axis. Whereas, in the vertical orientation Earths gravitational force is perpendicular to the force induced by the rotation of the drum, which thus creates a diagonal resultant force against the plants. The main advantage of rotating around a vertical axis is a constant downward force vector on the plants, while a horizontal axis would have a varying gravity vector on the plants. However, the horizontal orientation is best for the project design because it is more space efficient, and it was determined that the plants would be rotating too quickly for the varying gravity vector to have a significant impact on the plants.

The main critique of rotating around a horizontal axis is that a cyclical stress is induced on the plant since plants at the bottom of the drum are subjected to an extra 2gs of force when compared to plants at the top of the drum. For rotations at lower velocities studies have shown that a rotation of around 4 rpm can approximate microgravity in plant biology and the force of gravity can be effectively ignored. (http://www.plantphysiol.org/content/47/6/756.full.pdf). This has to do with the viscosity of the cytoplasm, which surrounds the cell membrane and thus acts as a buffer between parts of cells. At a certain rotational speed, parts of a cell effectively remain in free fall, giving the cellular structure of the plant the illusion of microgravity. Applying this to hypergravity means that the structure of the plant is constantly shifting slightly. This will mean that the plants will be constantly vibrating slightly. Whether this vibration will significantly affect the test remains to be seen.

2.4.2 Gravitational Variation

In order to simultaneously test several different g forces it was necessary to decide whether to vary the rotational speed or the radius of each of the three drums. These were the two main options since the force applied to the plant depends on the centripetal acceleration, which is equal to the radius times the rotational velocity squared. Having three drums rotating at different speeds would have required a complicated drive-train system so it was decided that varying the radius was a much better solution. It should be noted that building and connecting three drums of varying radii was certainly more difficult than connecting three identical drums, however this added complexity was far less than the complexity that would have been required for the complicated drive-train system.

2.4.3 Inner Support Shaft

There were two options available for enabling the structure to rotate while also providing the necessary support down the central axis of the drum. The structure could either be attached to a stationary rod through the use of bearings that would enable rotation, or the rod could be allowed to rotate which would eliminate the need for bearings since the structure would then just be directly connected to this rotating rod. It was decided that a rotating rod would be impractical since mounting the LEDs to a rotating rod would lead to tangling of the LED wires. The added cost of buying and attaching bearings to the acrylic drum was offset by the fact that it greatly reduced the design complexity of installing the lighting. Therefore, a stationary rod was implemented into the design.

2.5 Team and Project Management

2.5.1 Budget

As can be seen in Appendix B.1, the team exceeded its initial budget by \$738.12. This occurred as a result of two major factors. First, the team was forced to purchase a second motor, driver, and pulleys after the first motor could not be made operational. This cost the team \$453.32. Second, the team had to design and build a safety shield around the drum that was not accounted for in the initial budget. This cost the team an additional \$434.32. These unintended expenses inflated the teams budget by \$887.64 which explains why the the project became so over budget.

2.5.2 Timeline

The timeline for this project can be seen in Gantt Chart form in Appendix B.2. The main timeline issues for this project occurred as a result of complications with the design of the power transmission. Two weeks were spent trying to get the original motor to operate as intended before the group realized that it would have to be replaced with a new, easier to use motor. This set the team back greatly and stalled work on the project while the team waited for the new power transmission parts to arrive. Fortunately, there was still sufficient time to complete the construction of project and perform one complete round of testing before the end of the year.

2.5.3 Design Process

Initially, the plan was to design a test bed that would be durable enough to withstand conditions aboard a spacecraft. However, it was quickly realized that this type of test bed goes far beyond the scope of a senior design project. It was then decided that a microgravity test bed be built for use here on Earth, but through literature review it was discovered that many microgravity test beds already exist, while very few hypergravity testbeds have been created. The team then interviewed several customers who have worked or currently work in the space industry to get a better idea of the interest in hypergravity. It was then possible to design each of the various subsystems that are required in order to successfully grow plants in a hypergravity chamber.

The first stage of designing this test bed involved selecting a plant that does not need to be planted in soil and that could be grown within the tight confines of a rotating chamber. Cherry belle radishes were selected as the best plant because they only take three weeks to become harvestable, their short sprouts enable them to be grown within the confines of our test bed, and they can be grown without soil using hydroponics. Based on a leaf spread of three inches and stem height of 4-6 inches we designed the acrylic structure of the three drums to be as small as possible without over cluttering the radishes. Similarly, based on a radish bulb diameter of $\frac{3}{4}$ in. and a root length of 3 in. we were able to optimize the design of our acrylic plant modules, in which the seeds are planted, to be as small as possible while still having enough space for the radish to reach its full size. A steel A-frame in coalition with a 1 in galvanized steel rod were designed to support the acrylic structure and to maintain it 6 inches above the ground in order to provide space for the modules to rotate. Bearings were attached to both sides of the acrylic drum to enable it to spin around the central stationary rod. Four LEDs were attached to the stationary shaft and wires were sent down the center of the shaft in order to connect the LEDs to the LED driver module, which is used to supply power to the lights and to control the brightness of the lights. A large safety enclosure was constructed out of PVC to ensure that people near the drum do not get injured in case something breaks while the drum is in motion. One side of the enclosure was left open so that a removable $\frac{1}{4}$ in. acrylic sheet could be added to enable access to the drum. We selected transparent acrylic for the removable sheet so that we could observe the drum as it rotates and immediately shut it down if any problems arise. Finally, a pump was submerged in a bucket full of plant nutrients and the hose connected to this pump was attached to the top of the shield and three tubes were connected to this hose and dropped down into the shield in order to deliver water and nutrients to the radishes in each of the three drums.

2.5.4 Risks and Mitigations

One of the main risks involved with this project relates back to the spinning of the drum itself. With a drum of this substantial size and weight rotating at 90 rpm, there is a serious risk of parts along the drum dislodging and causing damage to nearby people or property. There is also a risk of an individual coming into contact with the spinning drum, which could also cause serious bodily harm. In order to combat these risks a $\frac{1}{8}$ inch PVC box was constructed with a $\frac{1}{4}$ inch acrylic access panel latched to one side. It was determined that in order to maintain safety, the motor of the system would remain off until this safety shield was placed around the drum with the access panel latched shut. Likewise, the panel and shield remained in place until the motor is disengaged and the drum comes to a complete stop. By following this protocol, there is no way for the rotation of the drum to cause damage to its surroundings.

Another risk consideration was the existence of water and electronics in close proximity to one another. Getting shocked, or having a short within the system, would each be dangerous situations that could develop with water and electronics so close to one another. Due to this, the water within our system needed to be strictly controlled and all electrical systems waterproofed. Thermal paste and silicon caulk were used as waterproof seals to ensure separation of water and electricity. The safety shield was also useful for its ability to keep the water within a confined space and away from the motor and driver.

2.5.5 Team Management

For the management of this project, the team decided to assign one or two team members to each of the subsystems in order to ensure that each subsystem would effectively have a manager ensuring that everything would be completed on time and according to plan. While each subsystem did have a manager in charge, the work done on each subsystem was by no means restricted to the manager of each project alone. In this way, the team was able to collaborate to get each pressing aspect of the project complete while each manager was able to keep his own subsystem in mind. This system proved to be effective, however it did occasionally become an issue when work needed to be done on a subsystem without that subsystems manager present. This problem did not occur frequently, but in the future it would be a good idea to ensure at least two members of the group have a full understanding of each separate subsystem.

The biggest issue this team had was coordinating times to meet together with the entire group. Managing the work, school, and social schedules of 5 individuals proved exceedingly difficult, and often led to the team meeting in groups of 3-4 at a time. This made communication more difficult than anticipated and occasionally stalled our project more than the team desired. The team tried to combat this issue by ensuring that missing members of the group would supply all necessary information to the rest of the group prior to meeting, however there were still occasions where work had to be stalled just to coordinate with the missing team member.

While this group never designated a team leader, it most likely would have been preferable if we had. Having a specific group member be responsible for organizing the group and keeping us on track would have helped us with our coordination and efficiency. While the group would often alternate taking charge and leading at different points throughout the project, the steady hand of a single leader would have been a valuable asset to have.

Chapter 3

Structure

3.1 Role and Requirements

The role of the structure is to provide a means of simulating an increased gravitational field on radish plants. To this end, it involves a rotating assembly, which is meant to hold the plant modules. It also involves a steel truss frame that is used to support the rotating assembly. While the primary purpose of the structure is to provide a way to rotate the plants, another essential function is to integrate with all the other subsystems. The structure is housed in a PVC shield that forms a box around the rest of the structure in order to prevent people from accidentally coming in contact with the spinning drum.

Detailed System Requirements:

1. Provide rotation up to 100 RPM
2. Couple with 36 plant modules
3. Fit within a 3ft x 4ft x 5 ft volume
4. Position plant modules at three different radii of:
    (a) 0.3 meters
    (b) 0.4 meters
    (c) 0.5 meters

5. Allow for airflow
6. Fully contain water
7. Allow easy access to inside the dodecagon
8. Be structurally sound
9. Manufacturable by a student in the Santa Clara University Mech labs
10. Within budget
11. Integrate with aeroponic, lighting, and power transmission
12. Operate safely

3.2 Options and Trade Summary

One important decision was how to vary the gravity felt by the plants. One option would be to have multiple rotating assemblies each spinning at a different speeds. The main advantage of this system is that each plant could be grown at the maximum possible radius. This is advantageous because as the plant grows towards the center of the drum the change in gradient of gravity felt across the plant is smaller the larger the radius of the plant location. Another option would be to vary the radius. This was chosen because of the expense and challenge of making three separate rotating assemblies that are all spin at different speeds.

Another important decision was what material to make the structure out of. Wood, steel, aluminum, wood, and acrylic where all options. Acrylic was chosen because it was easy to manufacture through laser cutting. This allowed for many identical pieces to be cut quickly from acrylic sheets. The same laser cutting technique could have been used for wood, however wood is not naturally waterproof and was hence discarded.

For the support structure, a bolted steel frame was selected for its strength and limited expense. A steel tube frame is easy to manufacture since cutting the steel tubing and then drilling holes is the only required manufacturing. Wood could have been used, but it is less strong and not waterproof.

The shield PVC was selected because it is waterproof and relatively inexpensive. It is less expensive than acrylic, which would have allowed the structure to be viewed from all angles.

3.3 Detailed Design Description

The structure consists of a three tiered dodecagon made of acrylic plastic that rotates around a steel shaft. This shaft is fixed along a horizontal axis, which is connected to the rotating assembly through bearings. The shaft is supported by a steel truss frame. This truss frame also supports the power transmission system. The three tiers of the dodecagon couple with plant modules so that each module faces towards the central shaft. Twelve plant modules are held at a distance of 0.3, 0.4, & 0.5m from the rotational axis; for a total of 36 plant modules. The central shaft provides mounting for the lights and heat sinks. The sides of the drum support the three tiers, while also being removable to allow access of the plant models. One side of the dodecagon also mounts a pulley, which drives the rotation. The complete structure can be seen in Figure 3.1.

3.4 Design Analysis, Test, And Verification

3.4.1 Finite Element Analysis

Finite element analysis (FEA) was undertaken in order to validate the design of the rotating assembly. Structural stability is extremely important in this design because the horizontal rotation will cause a cyclical fatigue stress that could cause components to fail over time. At the same time, it is also ideal to use as little material as possible in the design in order to remain low weight and within budget. Lower weight allows the motor to need less power- saving money and electrical consumption. It also allows for the assembly to be moved

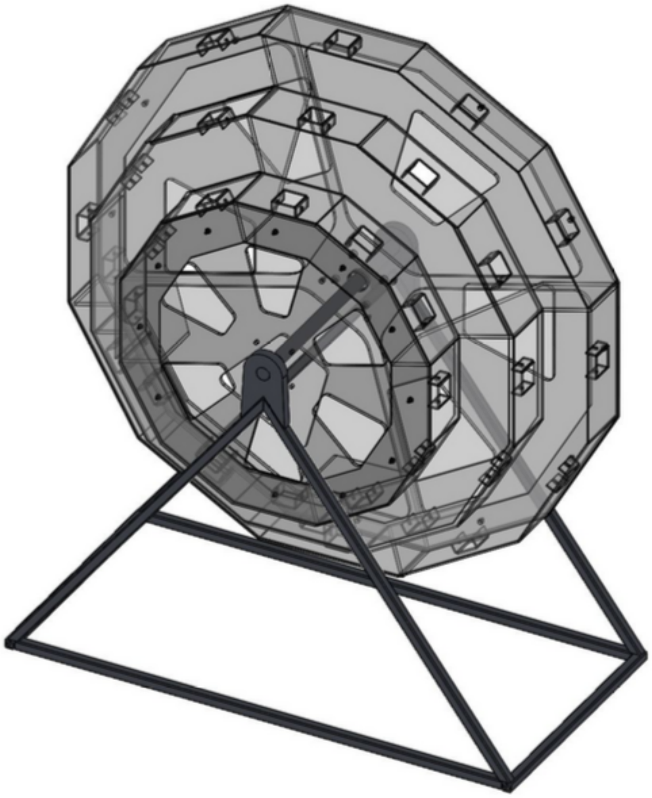


Figure 3.1: Isometric view of a CAD model of the structure.

easily by hand. It was also important to attempt to purchase as little material as possible to allow for money to be spent on other subsystems. FEA analysis was used to balance these considerations. The inputs used, and results of these analyses can be seen in the table below.

Table 3.1: FEA Model Inputs

Inputs		
Orientation	**Force**	**Purpose**
Away from axis	15 N	Module & plant weight
Tangent to axis	60 N	Forces acting when moving assembly

Table 3.2: FEA Model Results

Results	
Max Stress	**Max Bending**
3.35 MPa	2 mm

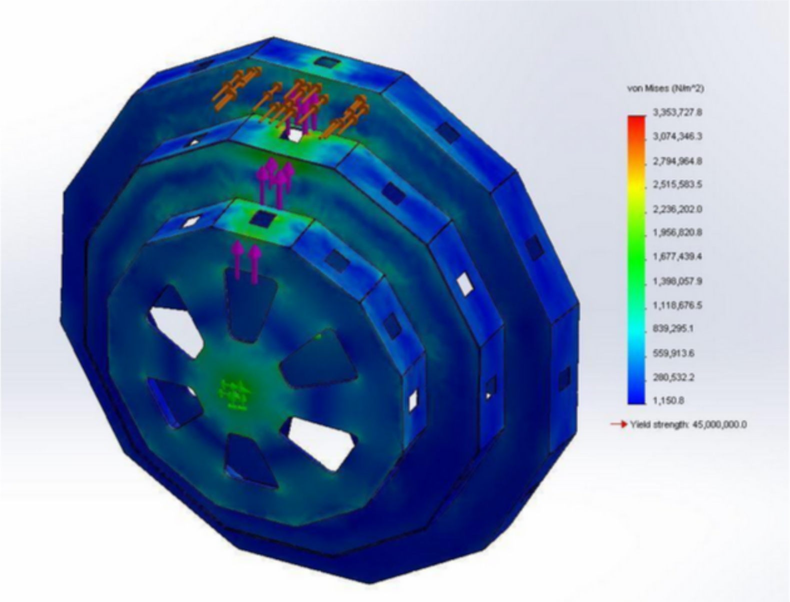


Figure 3.2: FEA Results for Stress

Based on the results of the FEA analysis, the average maximum stress was found. Using this maximum stress, the current design was shown to be safe with a factor of Safety of 3.7. This is based on the average glue strength, found from tensile testing to be 12.32 MPa. This analysis does not take into account fatigue, which is accounted for in section 3.4.3.

One cause for concern was the maximum bending deflection of 2mm. Although relatively insignificant, this could lead to fatigue stress in the glue joints over time. This bending occured in the outer sides of the rotating assembly. This led to the addition of cross braces to reduce shear forces within the assembly. These can be seen in the figure below.

The results of the FEA analysis were also used to justify the design decision to assemble the bulk of the rotating assembly from $\frac{1}{8}$in acrylic, with the sides made from $\frac{1}{8}$ inch acrylic.

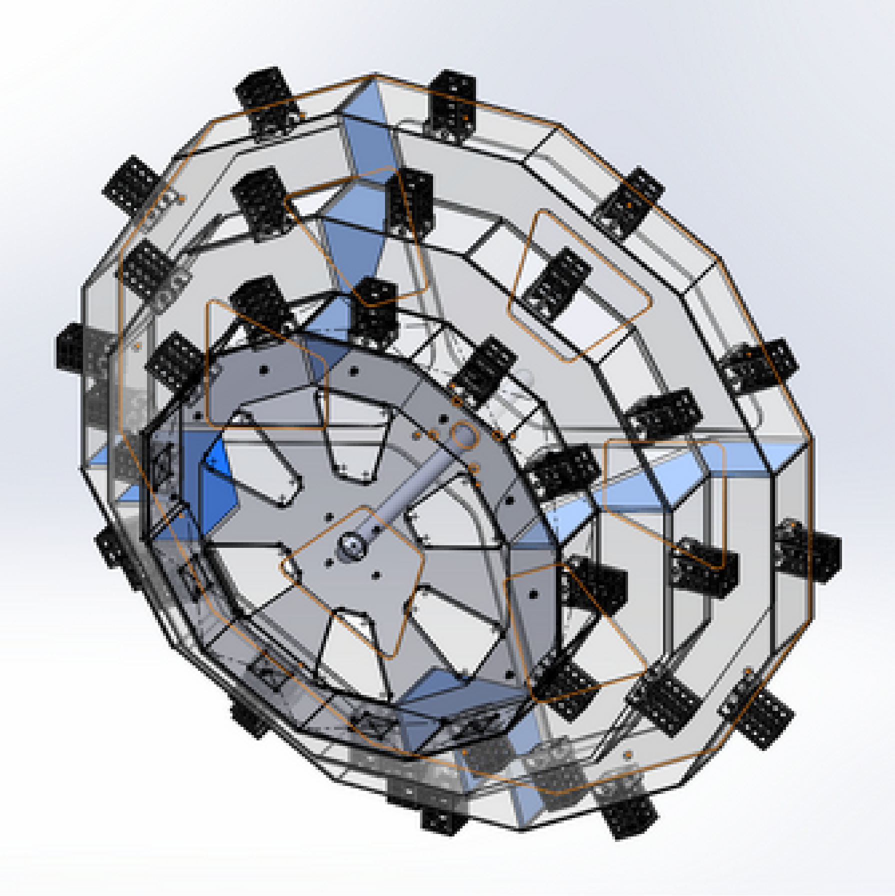


Figure 3.3: Cross Braces added after FEA Results

3.4.2 Acrylic Tensile Testing

In order to test the integrity of the rotating assembly, tensile tests were run on samples of the acrylic. These samples were cut into pieces with cross sections of 20mm by 3.17mm and had an original length of 36mm. These samples are meant to test the integrity of the $\frac{1}{8}$ inch acrylic that is used for most of the rotating assembly. These samples were placed into an Instron tensile testing machine, and were slowly pulled apart until the sample fractured. From figure 3.4, the samples failed at an average stress of 32.8 MPa. The samples were also able to elongate approximately 2.3mm. Both of these fall well within the standards required for the rotating assembly, and provide a factor of safety which is approximately 11.5. The stress-strain curve of the samples show that the acrylic is a brittle material, but this is acceptable since the acrylic will not be under compression. Tension is going to occur throughout the structure with the induced forces on the assembly. Compression should not occur when the structure is rotating, and the compression on the structure when it is stationary is negligible for the integrity of the acrylic.

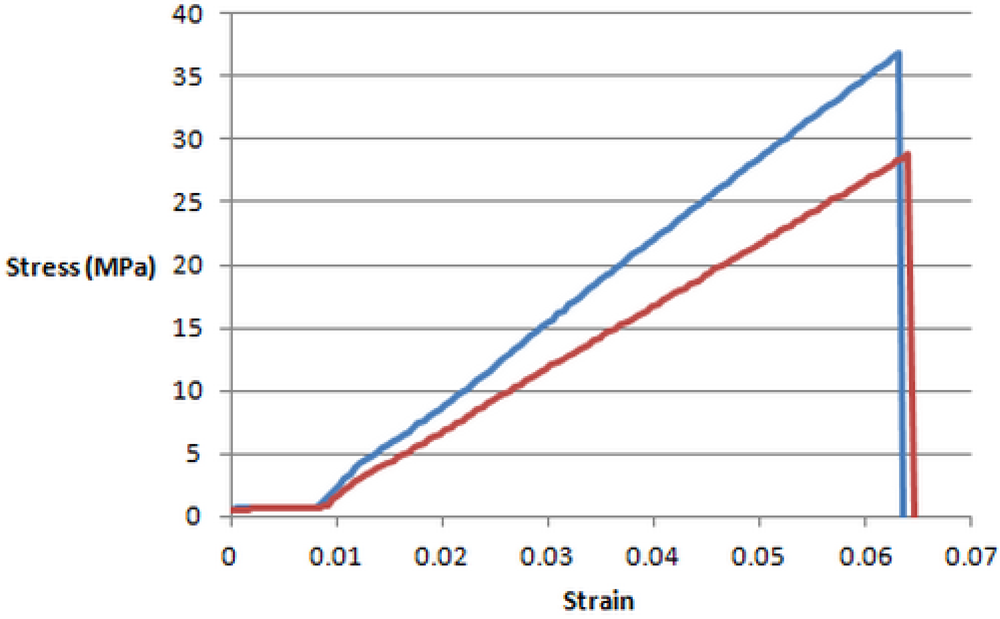


Figure 3.4: Stress-Strain Curve of solid acrylic plastic

Since the glue was what held the acrylic plastic together, this had to be tested as well. Samples of the same dimensions as the solid acrylic pieces were cut in half with a laser cutter, and glued together to dry overnight. The results of the stress-strain graph can be seen below in figure 3.5. The results were more varied than the solid acrylic pieces, likely due to inconsistencies with the gluing process. It is incredibly difficult to be consistent with gluing the plastic together, and this is accounted for through more tests. The average maximum stress for the glue was 11.8 MPa, which is still much larger than the 3.35 MPa of stress seen on the finite element analysis. Even the weakest sample failed at 7.66 MPa which still gives a factor of safety of 2 for the rotating assembly. Strain is not nearly as important for the glue because it is meant to hold sides together, and will not be stretching or elongating itself. Overall, the structure is very sound and designed to hold up with the rigorous requirements needed in order to properly run the experiment over long periods of time.

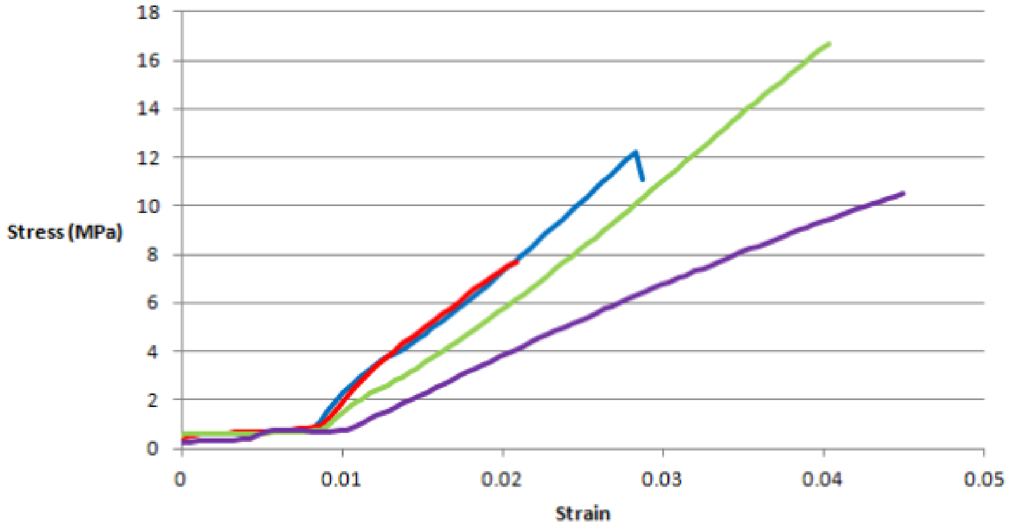


Figure 3.5: Stress-Strain Curve of Adhesive Bonded Acrylic Plastic

3.4.3 Fatigue Analysis

Because the rotating assembly of the drum is continually rotating, all parts of the design are subjected to a cyclical loading. This fatigue can cause hairline cracks to form over time, lowering the yield strength and eventually causing failure by fracture(Spotts, 152). In order to prevent this failure mode it is necessary to keep the maximum stress felt by a material below what is known as the fatigue limit. Using the Goodman failure theory outlined in Design of Machine Elements it is possible to find the maximum safe stress(Spotts, 157). In the following equation Savg is the average stress, Sr is the range stress, Kf is the concentration factor and Syp/N is the yield stress divided by the factor of safety.

$$S_{avg} + S_r K_f \leq \frac{S_{yp}}{N_{fs}} \tag{3.1}$$

Because of the presence of multiple types of stress concentrations present on the design, a very conservative stress concentration factor of 2.5 was assumed. The range stress was found to be .5 MPa. Using the Goodman equation the maximum allowable stress was found to be 4.6MPa. This gives a factor of safety of 2.68. Based on this result there should be little wear due to fatigue. This analysis validated the design of the rotating assembly.

3.4.4 Detailed Design Solutions

One important consideration was how to couple the 36 plant modules with the rest of the assembly. In order to make each module removable, each plant module was bolted on to the frame as shown in Figure 3.6. Each plant module was bolted in such a way that even if a nut came loose or a plastic mounting piece came unglued, the module would not fly out of the assembly. This was a very important safety concern; to have no parts that could possibly break and fly off the rotating assembly.

Another consideration is allowing working access to the center of the rotating assembly. This was accomplished by bolting the sides of the assembly on so that they could be removed. The sides of the dodecagons also had large holes cut in them to allow both airflow and access to inside the drum if necessary.

3.4.5 Requirement Validation

Running the structure for an extended test has shown that, overall, the rotating assembly is structurally sound. One failure is that one of the outside panels of the rotating assembly fell off while the assembly was rotating. The safety shield prevented it from flying into the lab space. This failure was most likely due to improper glueing. It was replaced and no further problems

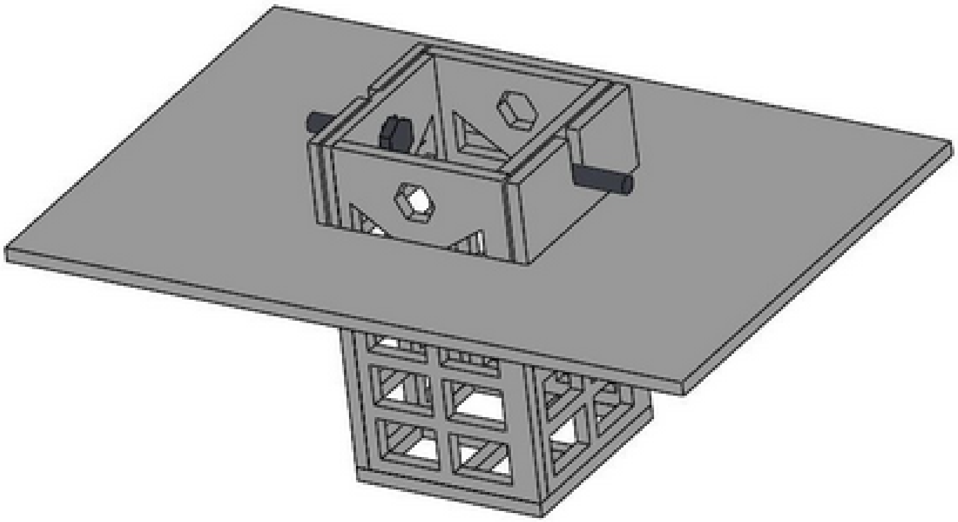


Figure 3.6: Plant Module Bolted to Inward Face of Acrylic Drum

have been encountered. This was also a validation of the safety shield, which functions to prevent any moving parts from coming in contact with a person.

One other design requirement that was not met to complete satisfaction was waterproofing. The steel square tubes that make up the stand and motor mount, as well as the steel shaft, are showing patches of surface rust. The spray paint that was used to waterproof them has not held up to testing. For the duration of the tests in question no significant weakening of the structure will could occur from rust. However, it is unsightly and could cause problems if the design is used for future testing.

All the other design requirements were met. Namely the structure positions the modules at a radius of 0.3m, 0.4m and 0.5m, while integrating with lighting, power transmission and aeroponics. It also allowed the modules to be accessed easily and allowed for airflow to the modules.

Chapter 4

Motor and Power Transmission

4.1 Role and Requirements

The power transmission subsystem is the driving force behind the rotation of the assembly. This is one of the most crucial components of the overall system. The assembly must rotate at an approximate speed between 90 and 100 RPM in order to achieve the desired induced forces. When the rotating assembly spins at the required speed, this is going to induce accelerations ranging from 3 to 5 Gs. A Direct Current (DC) motor powers the rotating assembly, and its torque will be transmitted through a pulley system with A type v-belts in a 5:1 ratio. This ratio will reduce the speed to the desired output, and increase the torque exerted on the rotating assembly. Since the rotating assembly needs to run for long periods of time, a chassis will convert a standard 115 volt Alternating Current (AC) signal into the 90 volt DC signal required for the motor. This chassis will also act as a speed control in case there are future complications or the rotational speed of the assembly needs to be adjusted. It will also act as an emergency shut-off, so if the current becomes too much for the motor to handle, fuses on the chassis will blow to ensure the safety of the motor.

4.2 Options and Trades Summary

The two major challenges facing the power transmission involved the signal type of the motor and the method of power transmission. In order to transmit the torque from the motor safely, v-belts were chosen over chains and gears. V-belts are designed for low torque and low speed loads. Compared to many mechanical systems, a 60 pound load is incredibly insignificant. Chain and gear drives are typically used in higher torque systems such as bicycles (chains drives) and car transmissions (gear trains). V-belts also allow for a considerable amount of tolerance in the design. This is perfect for the Aeroponic Test Bed since it has a very flexible design, and will be moved out of position in order to measure various facets of the growth process. V-belts are also much less expensive than its counterparts, and easier to maintain and replace incase it fails (Shoup). They are also quiet, which works if it is going to run in a lab where undergraduate classes will be held.

The motor could have been either AC input or DC input. Initially, an AC motor seemed to be the obvious choice as there would be a simple solution to powering the motor, as it could be plugged straight into a standard wall outlet. However, there were further complications that prevented our acquired AC motor from being implemented into the design. Initially, a replacement Whirlpool dryer motor was going to be used to power the drum. Logically, a dryer motor rotates about 100 RPM and carries a significant load, so it was believed to be a simple solution. However, the particular motor that was used was difficult to implement into any design other than a dryer. The motor was a three phase motor, and had two-speed control. A three phase motor means there are three sensors located around the coils to ensure a constant power output. Since it was an AC motor, this meant two coils must be powered with current running in opposite directions in order for the motor to run properly. This became difficult to wire as most dryers are designed with preset drivers built inside. This means that replacing a dryer motor is simple since it plugs into to the driver since that is specifically what it is designed for. The motor also rotated at a minimum speed of 1200 RPM without a speed controlled driver. This would ultimately not work with our v-belt design choice because v-belts are designed for a maximum of 12:1 speed ratio. This was cutting it too close to the factor of safety in order for the drum to run safely over a long period of time.

This meant a DC motor was a much easier option. DC motors are typically easier to work with, and are highly adaptable to a wide variety of situations. A DC motors speed can be controlled by its current, where an AC motors speed is controlled by the frequency of its signal. A DC motor requires a power supply, which is easily solved by a chassis that converts an AC signal into a DC signal. The DC motor that was ultimately decided upon also had a much better speed and torque match for the needs of our test bed.

4.3 Design Description

The DC motor was a right angle shaft gear motor from McMaster-Carr (part number 59825K49). This required a 90 volt DC signal, and had a max current flow of 1.4 amps. This meant it uses 126 Watts at maximum power which is 42.336 kWh per each test cycle of two weeks. More importantly, the motor was $\frac{1}{8}$ HP at 500 RPM and 13 in-lbs of torque. Most DC motors have high speeds and low torque, which is the exact opposite of what is needed for the Aeroponic Test Bed. A gear motor has a small gear train built inside the motor in order to reduce the speed and increase the torque output on the shaft. However, the speed needed to be reduced further, which is done with a simple pulley system using v-belts.

An AC-to-DC converter (KBIC 120) was the best option to power the motor for an extended period of time. A DC drive chassis from KB Electronics was able to successfully convert a standard 115 volt AC signal to a 90 volt DC signal required for the motor. This chassis is designed for motors between $\frac{1}{100}$ of a HP, all the way to $\frac{1}{2}$ of a HP. The chassis fits well within the standards for the motor, so there is no heatsink required. Fuses were also built into the circuitry of the driver to act as a failsafe, to ensure the motor does not overheat and break. There is also a potentiometer which acts as a speed controller in case there are future researchers who wish to change the induced forces on the plants.

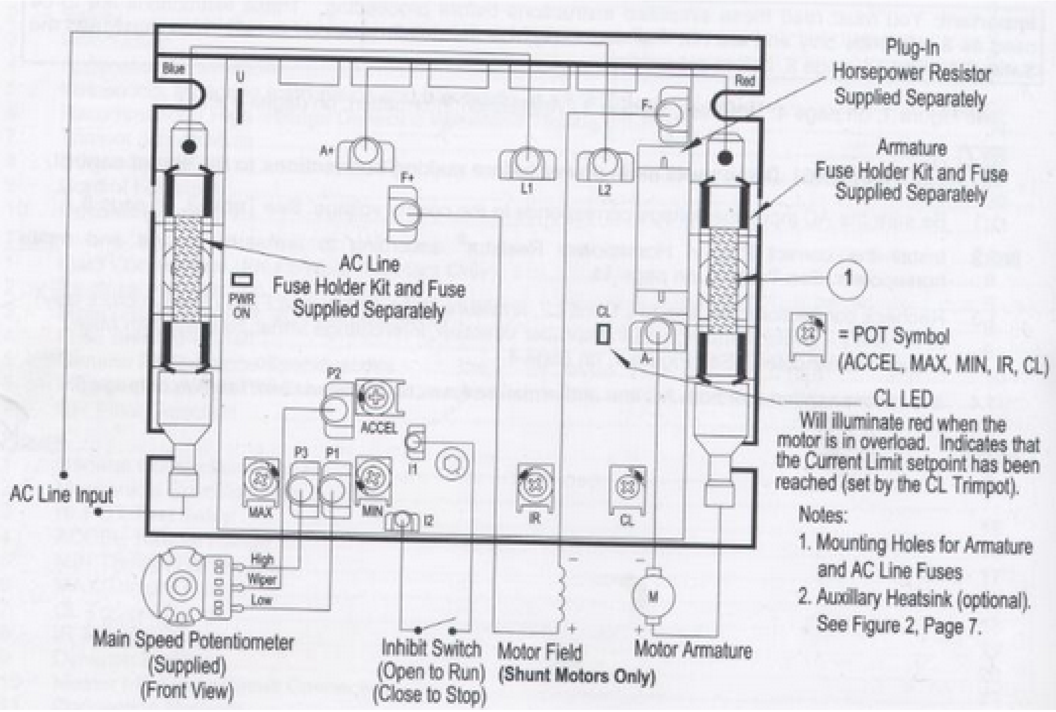


Figure 4.1: Circuit Diagram for the AC-DC Chassis

The power from the gear motor was transmitted through a simple pulley system involving a v-belt and a steel shaft. The motor was placed behind the safety shield, and its shaft extends by using a coupler to attach the $\frac{5}{8}$ output shaft to a $\frac{1}{2}$ steel shaft that extends into the safety shield. The steel shaft was supported by a steel-flanged ball bearing that was reinforced to a stand for the motor. A small pulley with a pitch diameter of 2 was placed on the end of the shaft. A 50 v-belt was attached to the small shaft, and transmits the power to a larger pulley located on the back of the drum. The larger pulley was located to the side of the drum with the smallest radius. This allows for easy access to the plants by removing the larger shield located on the opposite side of the drum. The larger pulley has a pitch diameter of 10 which gives a pulley ratio of 5:1. This means the drum should rotate at a speed of 100

RPM, and receives a torque of 65 in-lbs from the motor. Although 65 in-lbs of torque is fairly small, this will not affect the growth of the plants. According to calculations, it should take the drum approximately 20 minutes to reach its full speed of at least 90 RPM. Although the plants would not be feeling the fully induced forces desired, this start-up period is negligible since the drum will be running over days or weeks at a time. Torque is important in order to maintain the speed of the drum. This means the torque has to counteract the friction felt from the bearings of the drum, as well as the v-belts. Both the v-belts and bearings are very high quality and provide minimal friction, so this was not considered a problem for the drum.

4.4 Requirement Validation

In order to ensure the rotating assembly would reach the appropriate speed, a red marker was placed inside the drum and used a stopwatch to time 10 rotations. At full speed, the assembly was rotating too quickly to count, and greater than the desired 100 RPM. Fortunately, a speed controller could be wired into the chassis, and the speed of the motor was adjusted accordingly. In order to reach 90 RPM, the rotating assembly had to reach 10 revolutions within 6.67 seconds. Once the aeroponic test bed hypergravity team felt the rotating assembly reached the approximate speed, trials were taken to ensure consistency. The assembly completed 10 revolutions in 6.62, 6.58, and 6.73 seconds. This ensured that the rotating assembly fell between 90-100 RPM during the testing process. Once the appropriate motor speed was found, it was marked on the controller to ensure consistent testing.

Table 4.1: Drum Rotational Velocities by Trial

Time for 10 Revolutions	**RPM**
6.62	90.6
6.58	91.2
6.73	89.2

The rotating assembly got up to speed well within 20 minutes. The test bed team overestimated the amount of torque needed, and the rotating assemble easy got to its desired speed with 5 seconds of turning on the motor. The motor was also able to run for upwards of a week without any visible problems. The motors temperature would reach steady state after 6 hours, and be able to run for days at a time with no interruption.

Chapter 5

Lighting

5.1 Role and Requirements

The lighting subsystem plays a crucial role in the overarching goal of the Aeroponic Test Bed to test the effects of hypergravity on the sprout time and final mass of Cherry Belle Radishes. In order to fulfill this role, the requirements of the lighting system were broken down into plant requirements and electrical requirements. Plants require some amount of light in order to go through the process of photosynthesis and turn that light into energy for growth. The plants, therefore, must be delivered full and even coverage in order to ensure control of the lighting variable on plant growth. Along with this basic knowledge that plants need light, research has been conducted regarding the peak absorption regions of chlorophyll, so the lighting system should mimic the spectral absorption of plants for the best results.

Once the Xicato LED modules were chosen as the light delivery method, a few more requirements arose which were taken into consideration in the design process. The first of these requirements was finding the proper power delivery device for the LEDs since these modules require a driver (or ballast) in order for them to run. The test bed team also required dimming capabilities in order to run tests at varied levels of light output. The third requirement for the lights was that the modules had to remain below 90 degrees Celsius in order to fall within their operating temperature. Finally, the wiring of the system had to remain watertight to ensure the safety and operability of the whole test bed system.

5.2 Options and Trades Summary

In order to induce the photosynthesis process in a controlled way the aeroponic test bed team looked into some of the most commonly used lights in current hydroponic growing settings. The three that were most often used were compact florescent lights (CFLs), Halogens, and light emitting diodes. For each of these lights the test bed team was able to compare the start time, the dimmability, the lifespan compared to incandescent bulbs, and the energy used as compared to incandescent bulbs.

The dimmability of a light ensures a range of luminous output without the requirement of changing bulbs. This was a necessary requirement for the aeroponic testbed in order to provide the proper amount of heat and light for the cherry belle radishes. The CFLs were the only lights in this category that were non dimmable, with the LEDs and halogens having a 10 to 100% dimming curve. The LEDs and the halogens also had an instantaneous start time that would be necessary for the experiment. Due to these two factors the CFLs were ruled out from the final design of the lights.

The next two important factors in the lighting selection were the lifespan of the lights and the energy usage of the lights. While the energy usage of the lights was an important factor in choosing the lights, it was not crucial that the test bed team minimize the energy usage. The reason for this was that the Aeroponic test bed team was seeking to create a test bed that would be able to ensure accurate results of experiments by ensuring consistent and constant variables. Therefore, the energy usage of the lighting was not as important as the radiation the lights were to emit onto the plants. With this being said, the LEDs used about 75 % less energy than an incandescent light bulb would, and the halogens only used 10 to 20 % less energy. The lifespan of these lights was another crucial characteristic of the lighting that had to be observed due to the lengthy nature of the experiments. The LEDs far outweighed the halogens in this category with 25 times the average life of halogens. This sealed the LEDs in as the lighting selection of choice for the Aeroponic Test Bed. These tradeoffs can be clearly seen in Table 5.1 below.

Table 5.1: Lighting Selection Trade-Offs

LED	CFL	Halogen
Instant Start	Delayed Start	Instant Start
Dimmable	Non Dimmable	Dimmable
25X longer Lifespan	8X longer lifespan	Incandescent Lifespan
75% less energy	75% less energy	10-20% Less energy

5.3 Design Description

The design of the lighting system is crucial to the overall function of the test bed, but was not able to be fully implemented until the lighting type had been chosen by the process described above. Once the LEDs were chosen as the lighting selection the design process for the actual subsystem began. This process was broken down into five separate areas consisting of Spectral output, Electrical Management, Thermal Management, Structural Incorporation, and Safety.

Along with the selection of type of lights the test bed was going to use, it was important to ensure the lights would provide the proper spectral output for the plants. In order to do this, figure 5.1 shown below was obtained from NASA.gov. This figure depicts the spectral absorption of certain items on earth. By looking at this graph, and knowing that state of the art spectral imaging machines would not be available to the team, it was gathered that the most important spectral absorptions for the plants would be the local minima in the graph of around 500 nm and 650 nm. With these two peaks in mind the test bed team knew that the lights had to have spectral output in the same ranges, so based on the spectral outputs shown on the datasheets provided by xicato, we decided to use 4 separate 1000 lumen modules. These modules have the spectral output shown in Figure 5.2 which lined up enough for sufficient reason to believe the lights would induce photosynthesis.

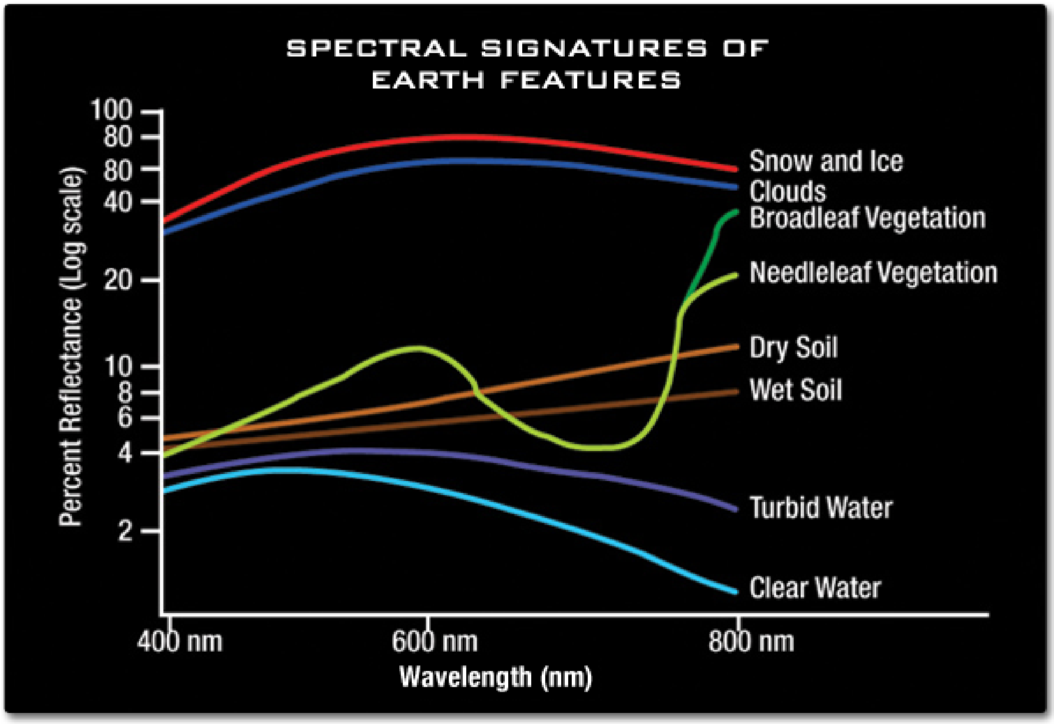


Figure 5.1: Spectral absorption of Earth as Given by NASA

After the spectral power of the lights was used to find the specific module, the first component of the lighting design was the management of the electrical components and what was required to make the lights function properly. The electrical components that mattered were the wire management, the power supply, and the dimming capabilities and on/off switch. The power dissipation of the LEDs was used to calculate the requirement for a power supply. This was done by putting the constant current LEDs in series and using the range of voltages given in the LED datasheets to find the total minimum and maximum power required for the LEDs to operate. Once the driver was selected a simple single pole single throw switch was connected to the power supply to turn it on or off and a potentiometer was connect to the 0 to 10 volt dimming wires

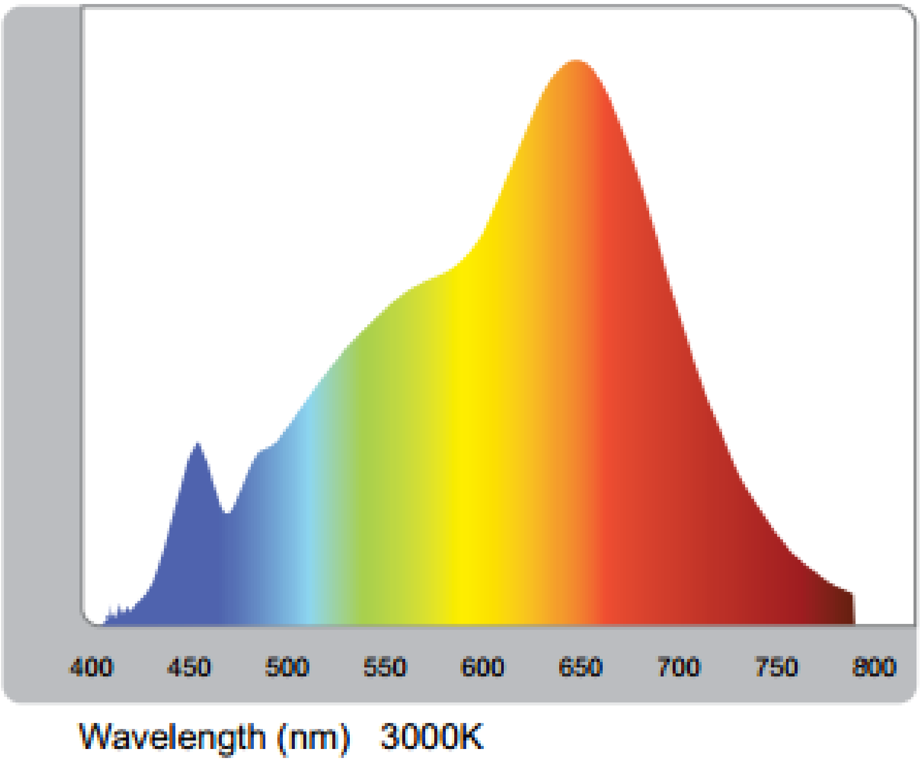


Figure 5.2: Spectral Power Distribution of LED Module

of the driver to allow for variation in lumen output.

The next design component was the thermal management of the LED modules due to the high temperatures of the individual modules. The modules had to remain below 100 degrees C and without any form of heat sink they would exceed this temperature within 2 hours. In order to fix this problem, standard aluminum rectangular heat sinks were purchased and machined in order to properly attach the LED modules to the heat sinks. From this point, the lights had to be incorporated into the structure of the rotating drum in order to provide light to the plants. The requirements for incorporating the lights were that they had to be in the center of the drum, and neither the lights nor the wiring could affect the rotation of the drum in any way. This led the team to mounting the lights around the stationary central shaft using U brackets so the wiring would run down the middle of the shaft and out the back of the shell. The mounted lights can be seen in figure 5.3 below.

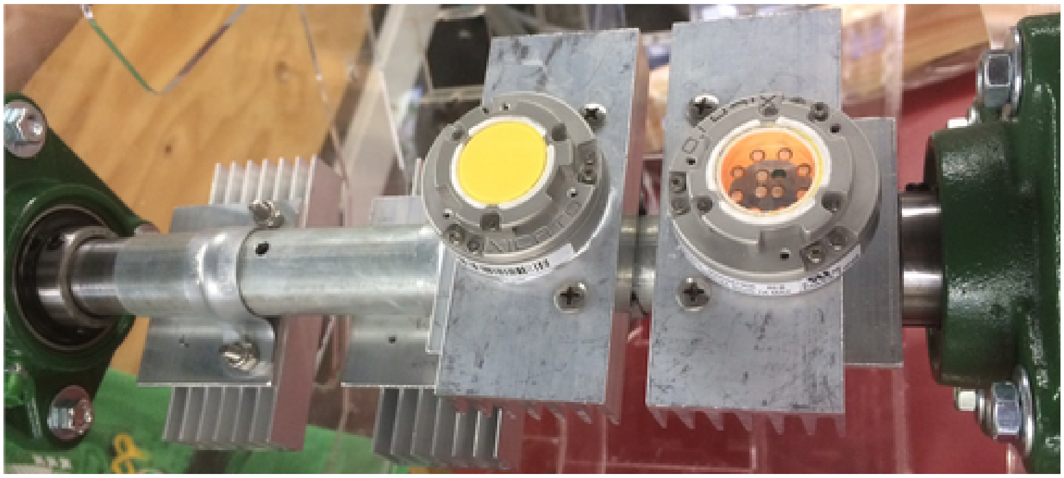


Figure 5.3: LED Assembly on Central Shaft

Once this had been done there were two major safety requirements that had to be satisfied in order to ensure the safety of anyone working with the system. The first of these requirements was the safety involved with the electrical system. In order to ensure this safety, all of the wired connections between the LEDs were made with waterproof, marine grade connectors. As a piece of added safety, the central shaft was fully waterproofed so that no water could enter the chamber with all of the connections. The other major safety concern with this system was the thermal management and stability of the modules. As was previously mentioned, the modules were required to remain below 100 degrees celcius, so it was decided that a test should be run to ensure this would be true. The test was set up with the central rod on two wood blocks without any form of forced convection. This meant that the lights should heat up more quickly than they would in the rotating chamber. The initial temperature was taken and the lights were then turned on at full power. The temperature of each module was taken incrementally and recorded. The data, which can be seen in figure 5.4 below, shows that the modules reached their steady state at about 80 $^{\circ}C$ after only an hour and a half. This promising result proved that the lights met all of their requirements in a safe manner.

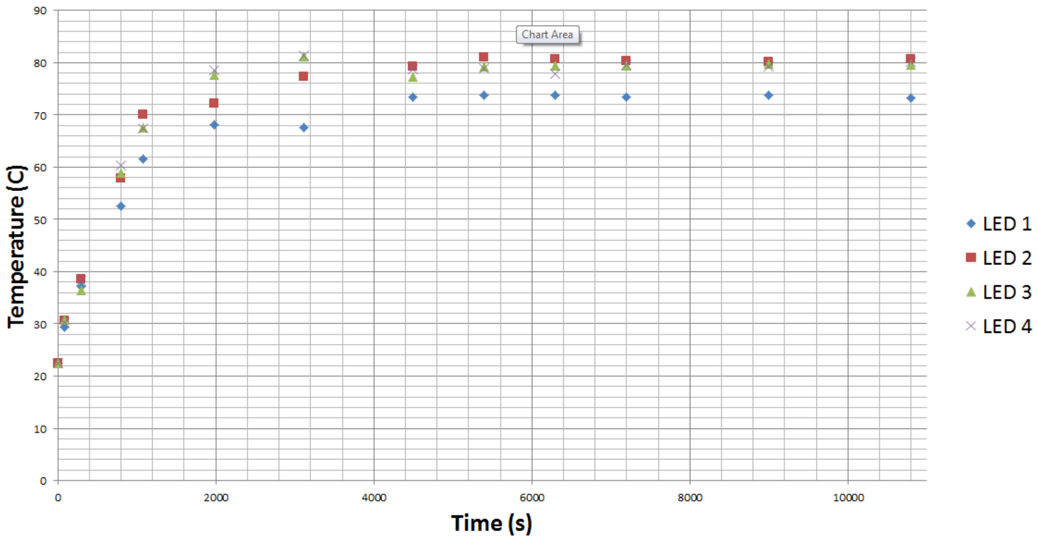


Figure 5.4: LED Assembly Temperature Test: No Forced Convection

Chapter 6

Aeroponics

6.1 Role and Requirements

The role of the Aeroponic subsystem is to house, protect, and supply water and nutrients to the cherry belle radish seeds that are to be tested. Encompassing the test beds plant modules, pump, tubing, and water-nutrient solution, the Aeroponic Subsystem works to keep our seeds in an optimal environment for growth. This subsystem needed to be capable of pumping a water-nutrient solution up to a height of 6 ft. and needed to deliver this nutrient solution to each of the 36 plant modules located along the outside of the drum. Because of the high rotation speed of the drum, the plant modules needed to secure the test plants from being damaged or dislodging, while simultaneously allowing for adequate lighting, water, and nutrients to make their way to the seed or plant roots.

In addition, the Aeroponic subsystem also involves the drainage of the excess nutrient solution from within the chamber. It is imperative that the runoff solution does not remain stagnant at the bottom of the test bed and begin to build-up and overflow from the safety shield as this could damage electrical equipment as well as the test beds surrounding facility.

6.2 Options and Trades Summary

One of the major design decisions related to the Aeroponic subsystem was whether or not to use spray nozzles to deliver the water-nutrient solution to each module. While spray nozzles are excellent at providing a wide, even distribution of solution, they arent effective at providing a concentrated stream. While spray nozzles would be the better choice in most aeroponic applications, the high rotation speeds of the test chamber make it so that a concentrated stream is of greater value than a wide mist. This also helps with the control of the water stream by focusing the water stream on one location and one location alone. The spray nozzles would make it difficult to ensure each module was receiving the same amount of water, thus adding an additional unwanted variable to the testing. In the end it was decided that leaving off the nozzles and simply using a concentrated stream from $\frac{1}{4}$ inch tubing was the superior choice for the purposes of this project.

6.3 Design Description

In order to allow for the seeds to receive adequate lighting, water, and nutrients while remaining secure and protected, the acrylic plant module shown in Figure 6.1 was designed and developed.

Each module holds 2 Gro-Blocks (essentially sponges designed to sustain plant growth) as well as a single radish seed planted $\frac{1}{2}$ of an inch into the center of the inner Gro-Block. Water and nutrients reach each seed by seeping through the grating in the module, soaking the Gro-Blocks, and thus the seed itself. The large opening in the module allows for the insertion of the Gro-Blocks as well as for the LED light to have a direct path to each seedling. A nut and bolt on either side of each module lock it in its place along the drum while allowing for each module to be easily removable. This can be seen in Figure 6.2 below.

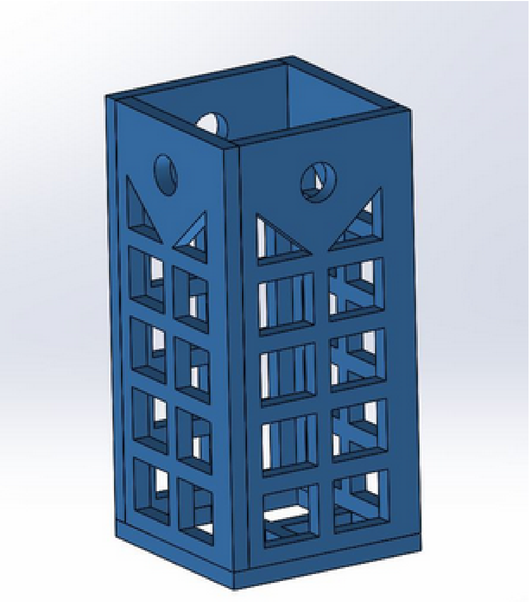


Figure 6.1: Acrylic Plant Module Design

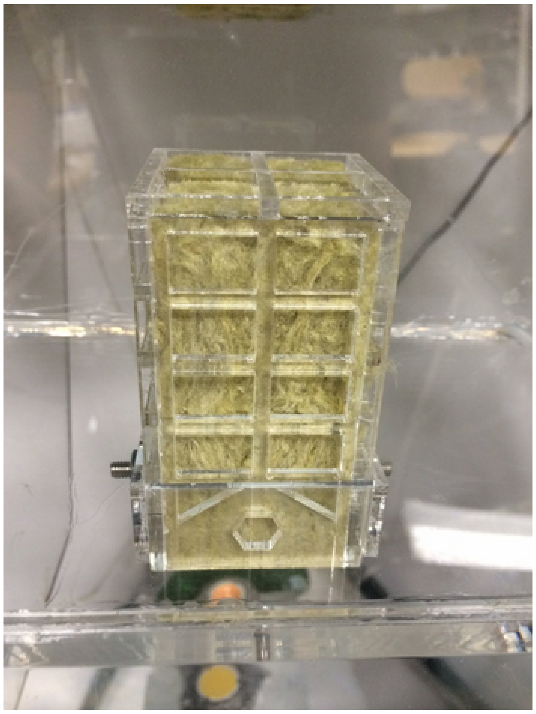


Figure 6.2: Attached Acrylic Plant Module

In order to distribute water and nutrients to each of our 36 plant modules, we designed a pump and tubing Aeroponic system. An ECO 264 submersible pump was immersed in a nutrient rich water solution within a 5 gallon holding container. The solution was then pumped through $\frac{3}{4}$ inch tubing up and over the top of the safety shield directly above the rotating drum as shown in Figure 6.3. From here, three small holes were punctured along the $\frac{1}{2}$inch tubing and a section of $\frac{1}{4}$ inch tubing was fed into each.These tubes were then passed through holes along the top of the shield with each tube hanging $\frac{1}{2}$ of an inch directly above the modules found on each of the three tiers of the drum. In this way, the spinning of the drum allows for each plant module to take its turn rotating under the solution flow and receiving its required sustenance. This setup can be seen in Figure 6.4 below. Weights were attached to the two longest sections of $\frac{1}{4}$ inch tubing to resist their natural bend and ensure that the tubes remain directly above each tier of modules.

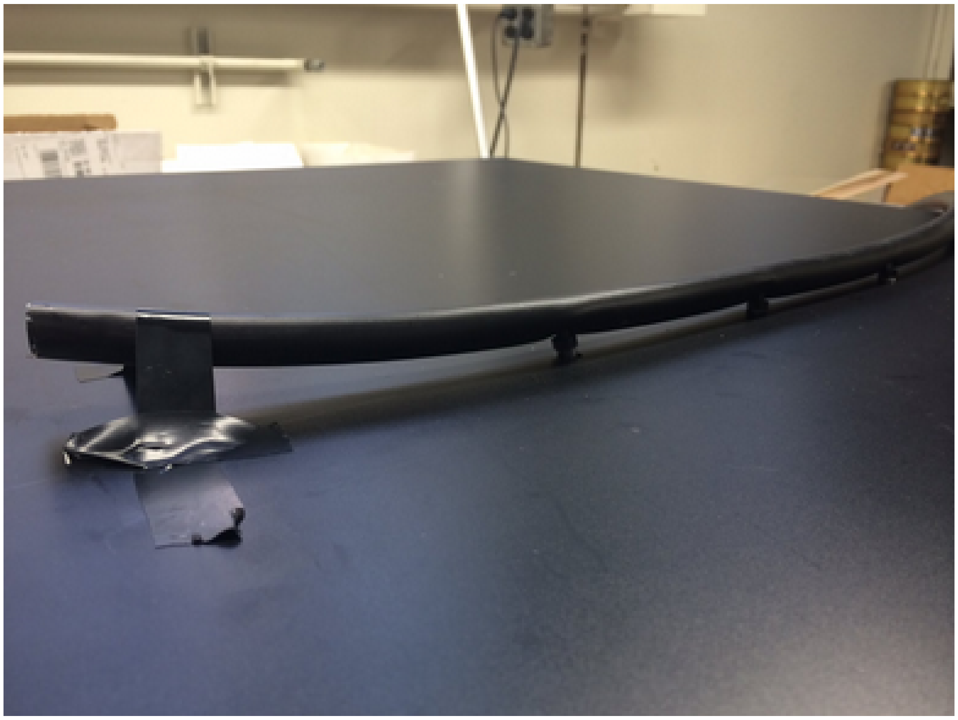


Figure 6.3: Top-Aeroponic Tubing

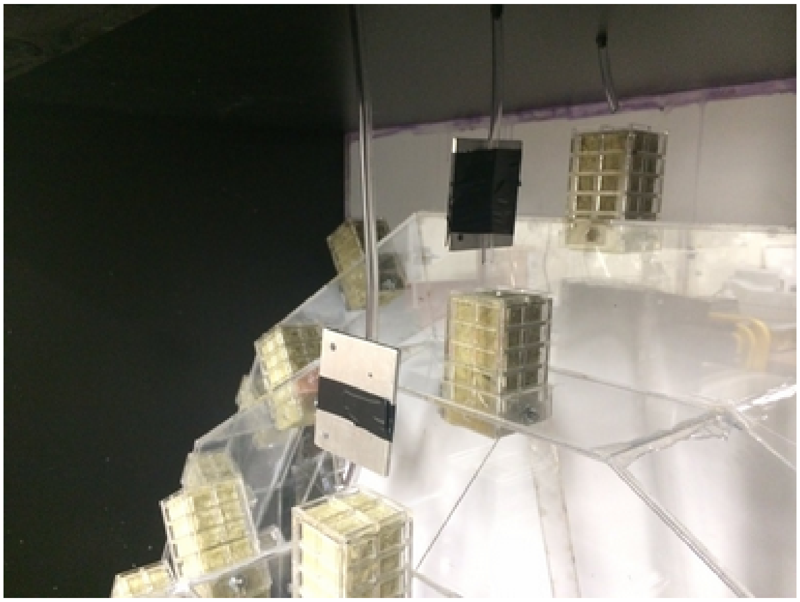


Figure 6.4: Inner Chamber Aeroponic Tubing

To drain the excess solution from the bottom of the test chamber, a small hole was drilled into the very bottom of the back side of the safety shield and a $\frac{1}{2}$ inch tube was attached with silicone caulk as can be seen in Figure 6.5. This tube siphons the extra solution to a separate 5 gallon container to be disposed of appropriately.

Figure 6.5: Drainage Tubing

Chapter 7

Systems Integration and Testing

7.1 Experimental Procedure

Experimental testing began with the planting of a single Cherry Belle Radish seed in each of the 36 plant modules with each seed located $\frac{1}{2}$ of an inch within the inner Gro-Block of each module. To develop the nutrient solution, the team mixed $\frac{1}{2}$ teaspoon of Miracle-Gro with 1 Gallon of Water. The pH of the solution was tested to ensure it was at its optimal value of 5.5. If the pH level was too high, a small amount of an acidic solution called pH Down was added until tests showed that the pH was approximately the desired value.

The modules were attached to the drum, the shield closed, and the motor turned on at its slowest speed. Once the drum reached its desired speed, the pump was activated and the nutrient rich water solution was sent to each module in turn. This slow rotation speed helped ensure that the Gro-Blocks would absorb a sufficient amount of water. After 2 minutes of watering, the pump was turned off and the motor speed increased to 90 rpm.

While the Cherry Belle Radishes that the team has grown outside the test chamber only required watering approximately once per day, the rotation of the drum makes the test chamber modules dry out much faster. Because of this, it was decided that the modules should be watered 3 times per day at 10:00 AM, 4:00 PM, and 10:00 PM respectively. The nutrient solution should also be replaced with pure water on every 3rd watering in order to flush the system and clear out any residue build-up within the Gro-Blocks.

The LED lights were turned on for 18 hours at a time followed by 6 hours off because it has been found that this arrangement is optimal for plant growth. This also allowed for the plants to be observed at least 3 times a day in order to determine the approximate moment sprouting occurs. The test was continued until each module had sprouted, or sufficient time had passed to indicate that sprouting was not going to occur.

7.2 Experimental Results

In order to observe the sprouts, the test bed was brought to a complete stop, and every module was numbered based on its tier in the structure, and position in the assembly. Unfortunately, one panel fell off, and two plant modules broke before testing began. This meant there were an uneven number of plant module in each tier, but there is still a significant amount of data. The 5 G tier had 12 modules, the 4 G tier had 11 modules, and the 3 G tier had 10 modules. There was also a control group of 12 modules that took place outside the test bed. Whenever the seeds were being watered, the results would be recorded. Any visible growth outside the sponge was considered that the seed had germinated and begun to sprout. It is important to note that it is not necessary to observe exactly how the plants have grown, but rather prove that the Aeroponic Test Bed for Hypergravity is a sufficient environment for plants to grow.

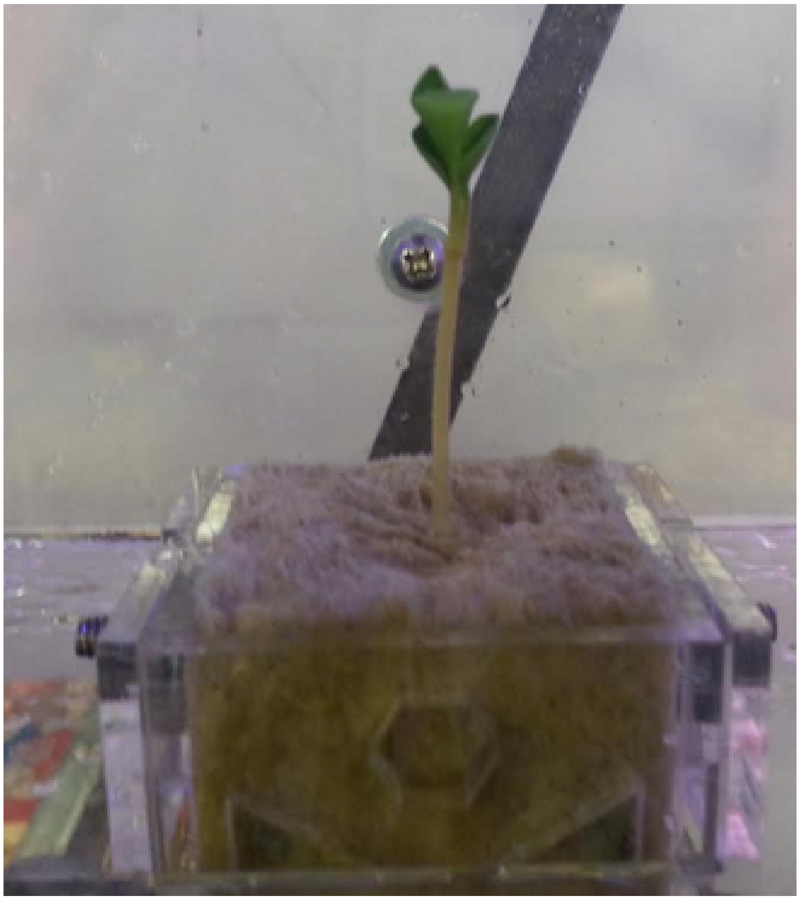


Figure 7.1: Successfully Sprouted Seedling in The Rotational Assembly

During the testing period, seeds did not sprout until hour 54 which can be seen in figure 7.2. The largest tier that induced 5 Gs on the seeds sprouted the quickest in succession. Similarly, the smallest tier which induced 3Gs on the seeds, sprouted at a similar rate, only 6 hours later. The middle tier which induced 4 Gs had the longest sprout time, but eventually the seedlings caught up with the rest of the modules. The control group of seedlings fell into the middle, and followed our tested modules. Although sprouted plants initially showed minimal activity, these sprouts continued to grow as the test continued. This shows that the plants continued to thrive in the environment created by the test bed, which further proves the test bed can continue to run the test for longer periods of time in order to provide important insights to the growth rate of cherry belle radishes in a hypergravity environment.

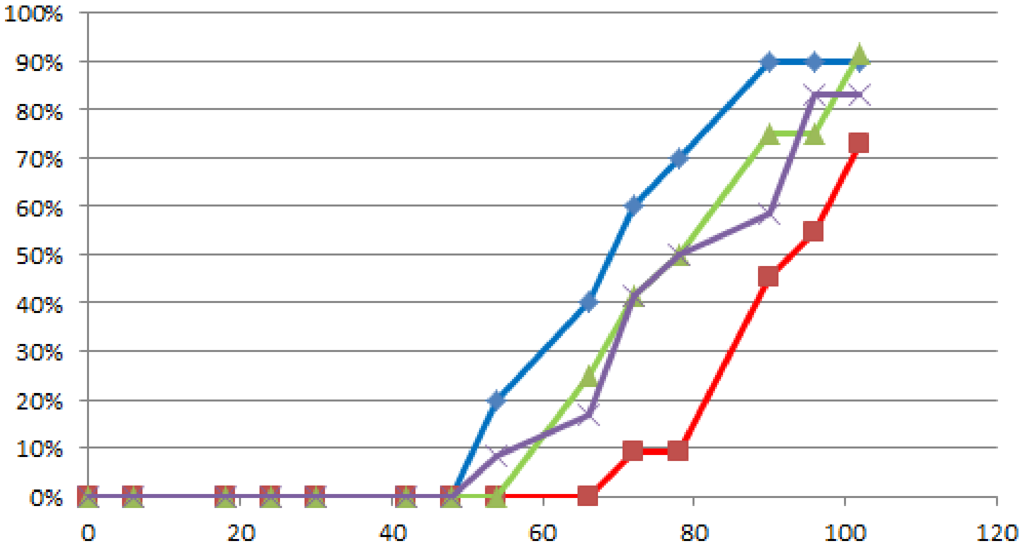


Figure 7.2: 3G, 4G, 5G, and Control sprout percentages versus hours spinning in blue, red, green, and purple respectively

Since the tested modules had similar sprout times as the control modules, this test bed shows that hyper gravity seems to have a minimal impact on the sprout times of the cherry belle radishes. The 4 G tier did sprout slightly later than the other samples though. This may be due to the lighting not effectively hitting that tier as much as the other tiers. Another potential reason could be due to the water not being absorbed within the sponges as easily as the other tiers. This is simply speculation however, since the rate at which they sprouted seemed to be the same as the other samples. This is only the first round of testing, so further testing may prove that this extended sprout time may have been an outlier. However, there are a few seeds that have failed to sprout, even in the control sample. This can be for a variety of reasons. Typically, there are some seeds that are simply bad, and are unable to grow in even ideal circumstances.

Chapter 8

Business Plan

8.1 Indroduction & Product Description

The Aeroponic Test Bed for Hypergravity is a research platform that can be used for variety of plant science research. Its main purpose is to provide a platform for testing the effects of different gravity fields on plant, but it can also be used to test the effects of lighting changes and different nutrient mixtures on plants. This device will be marketed mainly to University research departments. It has been estimated that on average 10 units will be produced per year. These units will be produced in the TecShop by an independent contractor.

The Aeroponic Test Bed for Hypergravity is an incredibly versatile structure that can be applied for both terrestrial, and extraterrestrial use. In its current state, the test bed is meant to be used as a research platform to test the effects of hypergravity on plants. Since it has been proven to show reliable data, many research facilities can use the Aeroponic Test Bed for Hypergravity for their own research ideas. This test bed can be applied to more than just radishes, but nearly any vegetable researchers are interested in. This includes, but is not limited to: lettuce, tomatoes, cabbage and bean sprouts. The amount of plant modules on the structure allow a greater data range than other similar rotating test beds. When running an experiment, more data point allows for more reliable data, and more efficiency during the testing period.

The Aeroponic Test Bed for Hypergravity can test more components of plant growth outside of induced Hypergravity. Its variable speed allows it to be used to test gravity forces anywhere from a simulated microgravity environment to five times the force of gravity. In addition, lights could be changed and the intensity could be altered, to see how this would affect plant growth. The mineral solution for the water is also interchangeable. For the experimental procedure, a simple store bought mixture was used for the radishes. However, many plants grown hydroponically use a specific solution of nutrients and minerals. This test bed can even act as an opportunity to test how different mineral solutions affect plant growth. The Aeroponic Test Bed for Hypergravity is an incredibly adaptable product that any research facility can apply to their interests.

The market for the areas of research that the Aeroponic Test Bed for Hypergravity enables is currently growing. Mars is the next target for space exploration, but it is incredibly difficult to reach such a lofty goal. Because transporting food in space in already difficult, NASA has increased its effort into developing systems to allow astronauts to grow their own food instead. The Aeroponic Test Bed for Hypergravity could be a crucial stepping stone in reaching this goal, by allowing researches to gather data about the effects of different gravity fields on plants.

Hypergravity research could have further consequences that could also open up new markets. The ability to find potential benefits of growing produce in hypergravity can be incredibly insightful. For example, if plants are shown to grow faster or larger, this information could be applied immediately to produce manufacturers nationwide. The ability to increase produce output could have a significant effect for local grocery stores. If local grocery stores are able to grow their own produce, this would significantly cut down on transportation costs. Transportation costs account for a significant portion of the price people pay at grocery stores. As time goes on, transportation costs will continue to rise. However, food grown locally with hydroponics have a much lower cost inflation rate than transporting the food (Lightfoot). This is also more ecologically friendly as it reduces carbon emission nationwide.

8.2 Objective

The objective of this company is to increase research into hydroponics as well as the gravity effects on plants. This will serve to facilitate bringing fresh food to all areas of peoples lives, from space exploration, to local grocery stores. More specifically, the goal of this company is to provide a low cost plant research platform for academic research. The first priority is to provide a successful product, while at the same time allowing for a financially stable company.

8.3 Potential Markets

Currently there is no competing device on the market for small scale plant research in varying gravity fields.Such devices are usually built from scratch by researchers. This lack of a product will enable this device to be successful immediately, as there exists an unfulfilled market niche.

The largest market is research facilities, both private and university run. These are facilities that are already engaging in plant research, and could benefit from the functionality of the Aeroponic Test Bed for Hypergravity. There are thousands of universities in the United States, many of them doing biological research. Because of the refined area of research that this device enables, it is likely that only a fraction the whole university market will be interested. It is estimated that on average ten units per year will be sold. Orders from this market will likely be sporadic and so flexibility in manufacturing strategy is necessary.

Another potential market are high schools, which could use this device to help students learn about plant growth. If a lesson plan was developed in conjunction with this device, this could potentially be a large market. Depending on the success of this idea, many orders could be gathered from this market sector.

8.4 Sales & Marketing

The Aeroponic Test Bed for Hypergravity will be marketed in multiple ways. One way will be to contact potential facilities directly. This will allow the business to get direct potential customer feedback as well as network to find increased business opportunities.

An online campaign will also be created. Ads through Google AdSense will be placed on hydroponic and plant science journal web sites to generate traffic to the company website. This website will be created to allow potential customers to view details about the design. Further advertisements could be pursued if the company proves successful.

8.5 Manufacturing

This product was designed to be easily assembled using only a laser cutter and basic shop equipment. Staff will manufacture the equipment at the TecShop in San Jose, which can provide all the resources necessary to manufacture the structure. This includes laser cutting the acrylic rotating assembly and cutting and drilling steel tubing for the stand and motor mount. Each system will be assembled per customer request, at that location, and shipped to the customer.

8.6 Pricing

Unit cost will be $5000. The materials cost was found to be $1600, when bulk purchases were taken into account. A manufacturing and assembly time of 15 hours adds $300. This will be done by an independent contracted technician. The manufacturing facility at TechShop costs $1400 per year. The business will be run from home, except for the manufacturing, so no cost will be accrued from requiring an office space. A part time employ will be responsible for returning emails and calls, ordering materials and sending work orders to the manufacturing contractor. This will add a salary cost of $20,000 a year.

Assuming a production of ten units per year, this gives an overhead of nearly 10,000 dollars. This is a modest, but acceptable profit for a company in its early start up phase.

As the company grows an office space can be rented. In addition manufacturing costs will grow, as a commercial license with the TecShop will be necessary. This will be tackled as the market grows.

8.7 Service & Warranties

A One year warranty will be offered to customers. Individual broken parts will be shipped to customer for customer installation. This is possible because the majority of the design is made to be easily taken apart and reassembled. A manual will be created to allow customers to service the device themselves.

8.8 Financial Plan

Because of the small scale of this enterprise, and the quick manufacturing time of this product it will be possible to operate with minimal financial backing. A small business loan will be taken out for \$40,000 to cover first years expenses. This money will be quickly recouped as orders come in. Ideally this loan will be paid off in the first year of operation. The entire structure of the design, which is the most time consuming to assemble, is made out of locally available materials that dont require ordering time. This allows this business to run with little cash reserves.

Chapter 9

Engineering Standards and Realistic Constraints

9.1 Ethical

This test bed can have a significant impact on future research regarding hypergravity and plant growth. It is most important for this test bed to provide reliable, consistent data for future research. In any professional research, it is necessary to provide conclusive and well-supported results. If this is not the case, the study can be deemed inconclusive, and all that work has been a large waste of time. It is unethical to create a product to be used by other researchers, and have the data be faulty or inconclusive. This means the test bed is going to have to critically account for a wide array of variables that could affect the plants during growth. The goal is to observe how gravity affects the plants, not moisture, temperature or lighting. This is what researchers are looking for during their tests. These data could have impactful results and potentially shape the future of space exploration.

Space exploration itself is incredibly dangerous. If astronauts are sent to space with faulty equipment, it can be catastrophic and cause their untimely death. This may be an extreme example, but it can still be applied to this test bed. Although this test bed is not being designed for space and zero gravity applications directly, this is the motivation behind the research. Being able to provide a test bed such as this can be incredibly useful, and propel future research. This test bed could provide a crucial stepping stone for great things. This means our project is going to have to be reliable enough to support further research that has come from our work.

9.2 Health and Safety

The health and safety of all product users has been big concern throughout the design process. With spinning machinery, water, and electronics, our project has several aspects that could be seen as a danger to the user. Because of this, it has been a major goal to limit the risk of potential injury or harm in any way possible. It was imperative that we kept a separation between water flowing in the test chamber and all electrical components that are at risk of shorting out. An Aeroponic system is a messy operation and it can be difficult to know for certain where the water will redirect, but it is imperative that all crucial electrical components are well out of harms way and sufficiently waterproofed.

Potential damage from the spinning of the central drum is also a real concern in this project. With high speeds, sharp corners, and near constant motion, there are countless opportunities for injuries to occur. This was minimized by ensuring that our drum remained completely enclosed within the safety shield whenever it was in motion, and by allowing for a complete stop in motion before any spinning component was to be accessed. By avoiding situations where a user would feel the need to reach in to access the central drum while it is rotating, we can eliminate any reason for damage to occur.

Because the Aeroponic Test Bed will be growing food that is supposedly for human consumption, it is also important that we maintain a clean and contaminant free growing station. Designing our chamber to maintain a water outlet so as to avoid any water puddling or stagnation will help naturally flush our system clean and minimize the risk of contaminant. While it would be difficult and dangerous to attempt to clean the chamber while in motion, in between tests we plan on thoroughly cleaning the chamber with water and disinfectants to give the system a clean slate for the following trial.

9.3 Manufacturability

Manufacturability has to do with the production of a material into a finished product. Within this subject there is a wide array of considerations including material type, human skills, monetary cost, machine availability, machine time, part design, and finding tolerances.

The first consideration is the material choice. Because of limited funds it was necessary to build the structure out of relatively cheap materials. It was also important to be able to design and fabricate our structure ourselves. This means that it had to be able to be made of a material that can be manipulated in the Santa Clara University machine shop. Acrylic was chosen because it was easy to acquire and manufacture. It also allowed for a relatively light and strong design, which was essential for the drum to spin effectively. The transparency of the acrylic was also a beneficial trait as it allowed for easy viewing of how the inner elements of the drum are performing. Another benefit of utilizing acrylic for the structure, was that it could be easily designed in Solidworks and cut using a laser cutter. This allowed for extensive computer modelling to be used to test concepts, which could then be quickly manufactured.

For the other elements of the structure such as the support frame, central rod, and motor mount, steel was used because of its strength and workability. These elements could be easily worked upon within our machine shop, helping ease this projects manufacturability without sacrificing any strength.

9.4 Usability

The usability of a system can play a crucial role in the success of a product. The variable gravity Aeroponic system is no exception to this rule. Professionals in the field of science and technology serve as the primary customers for this product, which means the usability is critical. The main interfaces with the customer will consist of the speed control for the rotating drum, the fluid dispersion control, and the plant interface. All three of these categories will require enough ease and accuracy when operating to create a beneficial interaction between the customer and the product.

The plant interface will play a critical role in the usability of the system. The plants will need to be accessed regularly in order to gather data on the the growth and harvest rates. The plant modules will be the most effective ease of access device with regards to the plants. The chamber will also be easily opened. Together, all of these functions make the variable gravity aeroponic test bed extremely usable for the customer.

The speed controller consists of a potentiometer that is capable of adjusting the rotational velocity of the motor and is therefore capable of altering the number of gs induced on the plants. In the future this system could be improved by adding a gravitational force input device, which would allow the user to input the desired maximum induced acceleration without having to think about the calculations related to determining the necessary rotational velocity for inducing a specified g force. These calculations are not very difficult, but a researcher will not want to waste his or her time with these calculations.

The fluid dispersion control will utilize a timer function that will allow the nozzles to be spraying periodically so the user does not have to continuously return to the device. This will also increase usability because the plants will not be over watered. This will decrease the time spent on plant care by the researchers.

9.5 Sustainability

Sustainability refers to impact that a product has on the surrounding environment. For this design, sustainability relates to what materials are used, the power consumption of the test bed, the water consumption of the test bed, the waste produced, and the durability of the device. All these considerations impact the local environment through adding more trash to the local waste treatment center as well as using more power and water from the local utility.

One important consideration for sustainability is power consumption. Based on power calculations, the testbed used 66.352 kWh for a two week test. For comparison, running the testbed used about the same amount of power as 6 standard 60W incandescent light bulbs. This is a relatively small amount of power to provide the functionality of this device. During the design process an attempt was made to limit power consumption. The lighting in the test bed comes from LEDs, which are the most efficient lighting option available. They last longer and are more efficient than fluorescent or incandescent bulbs.

Another important consideration is water usage. California is currently experiencing a drought so limiting unnecessary water usage is of particular importance. The test bed uses approximately 3 gallons of water per day. This can be compared to flushing a toilet, which uses approximately 3 gallons per flush, depending on the model. Clearly, this is not very much water.

There is minimal waste in this design. The manufacturing process did produce about 10 lb of excess acrylic plastic, which was disposed of. This does add a small portion of material to the landfill that decomposes extremely slowly. The rockwool root modules were also disposed of after the testing was complete.

Chapter 10

Conclusion

10.1 Summary

In conclusion, the current lack of a sustainable food source for extended space missions has sparked a space-industry interest in finding a method for providing astronauts with a sustainable food source. Most of the research in this field has focused on the effect of microgravity on plant growth, but NASA has recently expressed interest in the effect of hypergravity which is why it was decided that a 3-tiered aeroponic test bed for hypergravity should be built. This test bed provided the plants with the proper amount of water, nutrients, lighting, and airflow necessary for promoting plant growth. The test bed has provided insights into the effect of hypergravity on sprout growth and further testing observe the effect of hypergravity on a wide variety of plant growth characteristics that NASA is interested in. The first round of testing has revealed that the sprout time of cherry belle radishes subjected to 1g is the same as when subjected to 3 gs, 4 gs, and 5 gs. While it is not extremely insightful that hypergravity had no effect on the sprout time, it is valuable to note that plants are in fact capable of growing when subjected to hypergravity forces of up to 5 gs. Thus, this initial test established that this test bed can be used to successfully grow plants for future studies on various plant growth characteristics, which is the greatest overall impact of this project.

10.2 Future Work

The Aeroponic Test Bed for Hypergravity possesses great opportunity for future exploration. This test bed can be used to test the effect of hypergravity on a wide variety of cherry belle radish growth characteristics such as sprout height, root length, bulb diameter, harvest time, and harvest mass. Additionally, the test bed could be used to test the effect of hypergravity on other plants such as peas, bean sprouts, and lettuce. A major improvement needed for this test bed is waterproofing all of the steel bars such as the A-frame and the support rod located at the central axis of the drum. Also, a controls system for regulating temperature, pressure, and CO_2 levels could be added to increase the consistency of the results and to provide more insightful data. A controls system for controlling the lighting and nutrient dispersion system would also be beneficial because it would greatly reduce the maintenance requirements of the test bed and would promote extremely consistent tests.

Bibliography

Bingham, G. E., S. B. Jones, I. G. Podolski, A. Levinskikh, V. N. Stychov, D. Or, T. Ivanova, P. Kostov, S. Sapunova, and I. Dandolov. "Microgravity Effects on Water Supply and Substrate Properties in Porous Matrix Root Support Systems." Acta Astronautica 47.11 (2001): 839-48. Elsevier Science, 2001. Web. 17 Oct. 2013.

Bula, R.J., et al. Light-emitting diodes as a radiation source for plants. HortScience 26.2 (1991): 203-205. Web."CO2 Sensor." Robot Mesh. N.p., n.d. Web. 01 Dec. 2013. http://www.robotmesh.com/co2-sensor?gclid =COSfp_G8lLsCFe01Qgoda3MAkg.

Dani Or, Gail Bingham, Scott Jones & Robert Heinse. "Modeling and Design of Optimal Growth Media from Plant-Based Gas and Liquid Fluxes.' SAE International 2005-01-2949.

Dipert, M. and Dedolph, R. The Physical Basis of Gravity Stimulus Nullification by Clinostat Rotation. Journal of Plant Physiology. 47 (1971): 756. Web. http://www.plantphysiol.org/content/47/6/756.full.pdf.

Dunbar, Brian. "Growing Plants and Vegetables in a Space Garden." NASA. 15 June 2010. Web. 18 Oct. 2013.

"Equipment-Cooling Fans." McMaster-Carr. N.p., n.d. Web. 01 Dec. 2013. ¡http://www.mcmaster.com#standard-equipment -cooling-fans/=pndyos¿.

Evonic, "Properties of PLEXIGLAs" Evonic Industries. plexiglass.net 2013 http://www.plexiglas.net/product/ plexiglas/en/about/faq/Pages/properties.aspx

Fu, Yuming, Hui Liu, Lingzhi Shao, Minjuan Wang, Yu A. Berkovich, A. N. Erokhin, and Hong Liu. "A High-performance Ground based Prototype of Horn-type Sequential Vegetable Production Facility for Life Support System in Space." Advances in Space Research 52.1 (2013): 97-104. ScienceDirect. Elsevier, 2013. Web. 17 Oct. 2013.

Gericke, W. F. Hydroponics- Crop Production in Liquid Culture Media Science, New Series, Vol. 85, No. 2198, pp. 177-178 Web. http://jstor.org/stable/1661533

Lee, Kevin. NASA Reveals Plans to Start Growing Vegetables in Space this Year. Inhabitat.com 9/12/13 http://inhabitat.com/ nasa-reveals-plans-to-start-growing-vegetables-in-space-this-year/

Lightfoot P. (2012, February 6) Paul Lightfoot: Growing Food on Top of Supermarkets. Retrieved from: http://www.tedxmanhattan.org/2012talks

Massa, Gioia D., Hyeon-Hye Kim, Raymond M. Wheeler, and Cary A. Mitchell. "Plant Productivity in Response to LED Lighting." HortScience 43.7 (2008): n.p. Web. http://hortsci. ashspubli- cations.org/content/43/7/1951.full.pdf+html .

”Mini-Blocks - 1.5 In.” Mini-Blocks - 1.5 In. 1000 Bulbs, n.d. Web. 09 June 2014. https://www.1000bulbs.com/product/93412/GROW-RWMM4040.html?utm_source=SmartFeedGoogleBase&utm_medium=Shopping&utm_term=GROW-RWMM4040&utm_content=Grodan&utm_campaign=SmartFeedGoogleBaseShopping&gclid=CN2V74SP7r4CFVJefgodLmIAqQ.

Morrow, Robert C. “LED Lighting in Horticulture.” HortScience 43.7 (2008): n.p. Web. http://hortsci.ashspublications.org/content/43/7/1947.full.pdf+html.

“Pylehome Digital Anemometer / Thermometer - Air Velocity, Air Flow, Temperature.” Sears. N.p., n.d. Web. 01 Dec. 2013. http://www.sears.com/shc/s/p _10153_12605_SPM6685993808P.

Tamulaitis, G., et al. “High-power light-emitting diode based facility for plant cultivation.” Journal of Physics D: Applied Physics 38 (2005): 3182-3187. Web. http://iopscience.iop.org/0022-3727/38/17/S20/pdf/0022-3727_38_17_S20.pdf.

T. E. Shoup, M. F. Spotts, and L. E. Hornberger, ”Design of Machine Elements,” 8th Edition, Prentice-Hall, Inc., 2004.

”Visible Light.” Mission:Science. NASA, n.d. Web. 6 Apr. 2014. http://missionscience.nasa.gov/ems/09_visiblelight.html.

Yorio, Neil C., et al. “Improving Spinach, Radish, and Lettuce Growth under Red Lightemitting Diodes (LEDs) with Blue Light Supplementation.” HortScience 36.2 (2001): n. pag. Web. http://hortsci.ashspublications.org/content /36/2/380.full.pdf+html.

Appendices

Appendix A

Design Definition

A.1 Dr. Hiremath

A.1.1 Questionnaire

Do you think that this project currently fulfills a valuable customer need? What about in the future?

One of the issues we have run into is finding an aspect of this project that needs significant improvement that is scaled in a way that we could accomplish it in 6 months. Do you have any recommendations on areas of this field that could benefit from continued design/ research?

Specifically do you think studying gravity effects is a worthwhile goal?

What about studying fluid flow?

Is it worthwhile to reiterate or tweak current research without totally changing it?

Do you know anyone who has done research in this area and might be able to provide further direction?

A.1.2 Responses

”It is a good experimental idea. Work on it and any question that come up from doing the research will provide information for further researchers to work on. That alone is something useful.”

“Look into whether all the systems necessary for plants to survive can be modeled on earth. This grabs me. It is up to you to do more research on this.”

“It is worthwhile to study both and after the study make your own recommendation. Then progress will be made just by putting out another perspective from different research.”

“It is worthwhile to replicate past studies and reason through them and maybe find some areas of improvement, that would be okay.”

“I will try and put you in contact with some people from my company who may be of help.”

A.2 Dr. Bebout Questionnaire

A.2.1 Questionnaire

Do you mind going into detail about your research and what you are looking to achieve?

Would this test bed or information from this project be beneficial to your field of work?

Are changes in gravity an important variable when studying how plants grow?

Do you think others at NASA Ames would be interested as well?

If the prototype works well enough to be sent to space, could it be applied to long-term space missions?

If this provides substantial results, could this have terrestrial applications?

Is there anything our project design could improve upon?

A.2.2 Responses

I am a research scientist at NASA Ames Research Center. My field of expertise is Microbial Ecology, and I am interested in all aspects of the ecology of microorganisms, how they survive in the sometimes harsh environments where they live, as well as how they affect our environment on Earth.My particular area of research is in microbial mats These are well developed communities of microorganisms that grow at various locations on Earth. Although they are not so common today, they are the oldest forms of life on Earth. The reason why we are interested in learning as much as we can about them, is that they teach us about early life on Earth. Since they have been alive on Earth longer than anything else, they may also have a lot to teach us about what to look for on other planets.

There is a lot that could be done while studying plants under various gravity effects. The role of microbes are incredibly important in a plants habitat. However, due to your time constraints, this is not possible. Your best interest would be studying the effects of hypergravity on plants.

Absolutely. If we are able to have a good understanding of how plants grew in hypergravity, it would change how they would be grown. It would be most helpful in designing one for out space where a gravity field has to be created.

Certainly. There are many groups at NASA Ames working on similar projects right now. One group is growing tomato plants at different gravity rates over a span of 6 months and observing their growth rate. One of the biggest problems presented to these research group is size limitations. It is incredibly difficult to qualify it for space.

A hydroponic garden such as this could work on Earth, but it must be designed completely differently than one designed for space. In space, it must be really small, but on Earth, it has to be the complete opposite and be fairly large to support a group of people. The best application of this would probably be Industrial agriculture through hydroponic gardens.

Since you guys have many limitations regarding time and money, one of the best things you could do is take hardware that is currently available and designed for the same thing, and size fit it and improve it. Regarding the variable gravity fields, the more gravity fields the better. You could never have too much data.

A.3 Dr. Djordjevic Questionnaire

A.3.1 Questionnaire

What experience do you have with the development of hydroponic plant growth systems?

What were some of the biggest problems you faced in your research?

Would the information were looking to find from this project have been beneficial to your earlier work?

Are changes in gravity an important variable when studying how plants grow?

How do you feel about the existing research on plant growth in a space-mission environment?

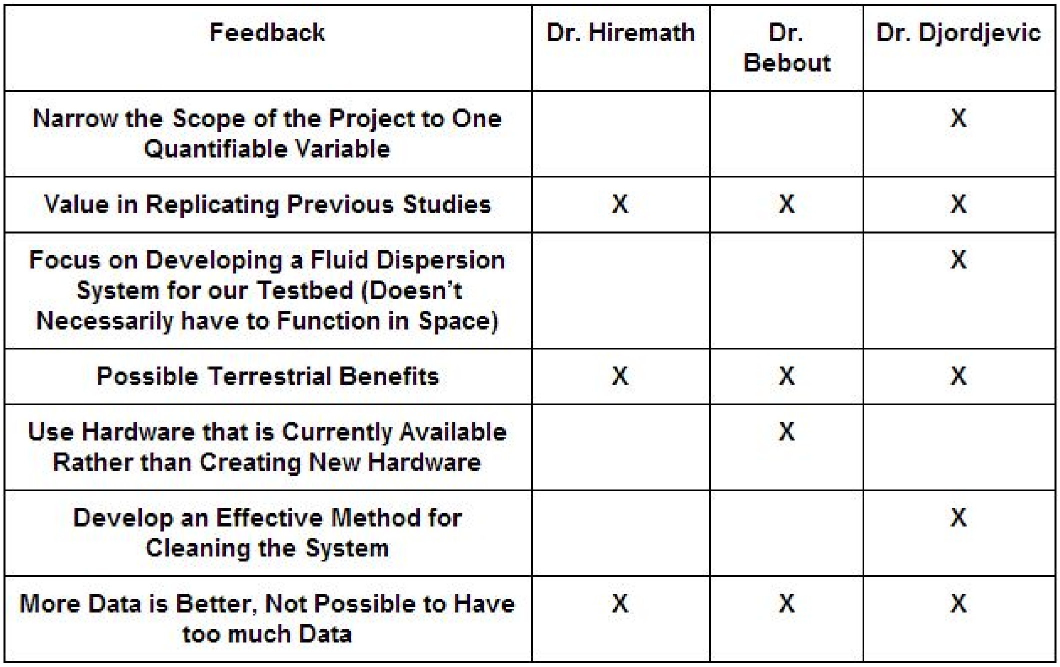
What considerations should we make in regards to fluid flow?

Is there anything our project design could improve upon?

A.3.2 Responses

Our feedback from Dr. Djordjevic was developed and summarized over our ongoing, in person discussions and was thus not directly recorded.

A.4 Organized Feedback



Feedback	Dr. Hiremath	Dr. Bebout	Dr. Djordjevic
Narrow the Scope of the Project to One Quantifiable Variable			X
Value in Replicating Previous Studies	X	X	X
Focus on Developing a Fluid Dispersion System for our Testbed (Doesn't Necessarily have to Function in Space)			X
Possible Terrestrial Benefits	X	X	X
Use Hardware that is Currently Available Rather than Creating New Hardware		X	
Develop an Effective Method for Cleaning the System			X
More Data is Better, Not Possible to Have too much Data	X	X	X

Figure A.1: Customer Feedback Matrix

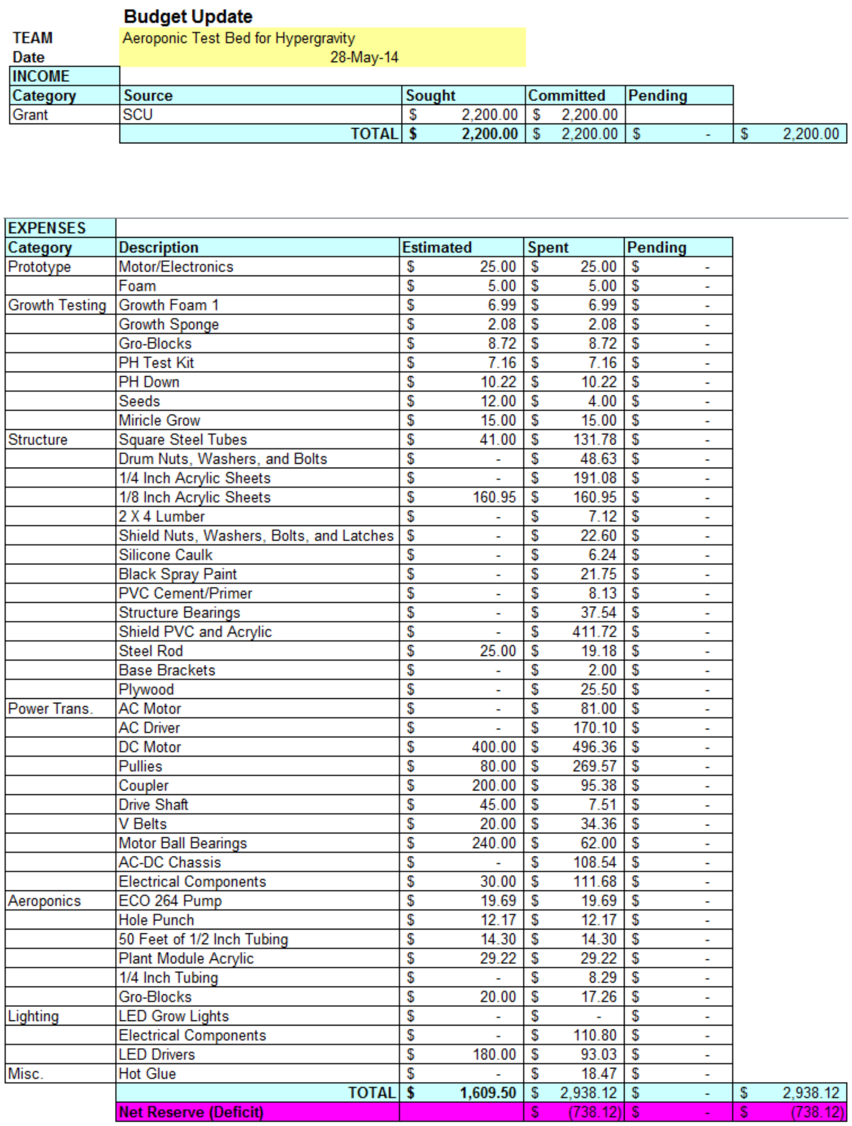
Table A.1: Targets & Benchmarks

Parameter	**Parameter Units**	**Design Criticality**	**Design Target**	**Horn-Type Producer**	**Vitacycle**	**Phytocycle**
Volume	m^3	High	1.06	.12	.75	.19
Power Demand	kW	High	.239	.308	1	.44
Pressure	kPa	Low	-.5	-.5 to -.2	—	-1.5 to -.5
Speed	rph	High	5400	12	3	4-10
Airflow	# of fans	Low	Rotational induced convection	8 fans	2 blowers at 2.5 m/s	—
Chamber Shape		Low	3 Tiered Cylinder	Truncated Cone	Spiral Cylinder	Spiral Cylinder
Diameter	cm	60, 80, & 100	75	61	75	20
Light Type	—	High	LED	LED	Fluorescent	LED
Water Tank Size	L	Low	18.93	—	20	—
Light Power	kW	High	.096	.283	.539	—
Nutrient Dispersion System	—	High	Gro-Block	Porous Tube	Capillary	BIONA-V3 fake soil
Temperature	deg C	Medium	25	23 ± 2	24	30 ± 2
Number of Plant Modules	—	Medium	36	6	10	10
Light Dist	cm	Low	25, 35, &45	5-13.5	—	4
Lights	#	Medium	2 Daylight, 2 Blue	872 red 694 white	52	438 Red 88 Blue
PlantType	—	High	Cherry Belle Radishes	lettuce	Cabbage	Celery

Appendix B

Project Management Data

B.1 Budget



Budget Update

TEAM Aeroponic Test Bed for Hypergravity

Date 28-May-14

INCOME

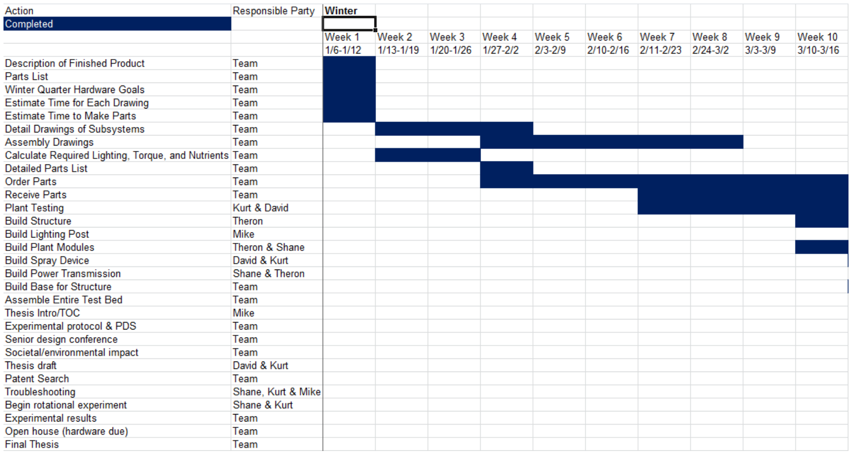
Category	Source	Sought	Committed	Pending	
Grant	SCU	$ 2,200.00	$ 2,200.00		
	TOTAL	**$ 2,200.00**	$ 2,200.00	$ -	$ 2,200.00

EXPENSES

Category	Description	Estimated	Spent	Pending	
Prototype	Motor/Electronics	$ 25.00	$ 25.00	$ -	
	Foam	$ 5.00	$ 5.00	$ -	
Growth Testing	Growth Foam 1	$ 6.99	$ 6.99	$ -	
	Growth Sponge	$ 2.08	$ 2.08	$ -	
	Gro-Blocks	$ 8.72	$ 8.72	$ -	
	PH Test Kit	$ 7.16	$ 7.16	$ -	
	PH Down	$ 10.22	$ 10.22	$ -	
	Seeds	$ 12.00	$ 4.00	$ -	
	Miricle Grow	$ 15.00	$ 15.00	$ -	
Structure	Square Steel Tubes	$ 41.00	$ 131.78	$ -	
	Drum Nuts, Washers, and Bolts	$ -	$ 48.63	$ -	
	1/4 Inch Acrylic Sheets	$ -	$ 191.08	$ -	
	1/8 Inch Acrylic Sheets	$ 160.95	$ 160.95	$ -	
	2 X 4 Lumber	$ -	$ 7.12	$ -	
	Shield Nuts, Washers, Bolts, and Latches	$ -	$ 22.60	$ -	
	Silicone Caulk	$ -	$ 6.24	$ -	
	Black Spray Paint	$ -	$ 21.75	$ -	
	PVC Cement/Primer	$ -	$ 8.13	$ -	
	Structure Bearings	$ -	$ 37.54	$ -	
	Shield PVC and Acrylic	$ -	$ 411.72	$ -	
	Steel Rod	$ 25.00	$ 19.18	$ -	
	Base Brackets	$ -	$ 2.00	$ -	
	Plywood	$ -	$ 25.50	$ -	
Power Trans.	AC Motor	$ -	$ 81.00	$ -	
	AC Driver	$ -	$ 170.10	$ -	
	DC Motor	$ 400.00	$ 496.36	$ -	
	Pullies	$ 80.00	$ 269.57	$ -	
	Coupler	$ 200.00	$ 95.38	$ -	
	Drive Shaft	$ 45.00	$ 7.51	$ -	
	V Belts	$ 20.00	$ 34.36	$ -	
	Motor Ball Bearings	$ 240.00	$ 62.00	$ -	
	AC-DC Chassis	$ -	$ 108.54	$ -	
	Electrical Components	$ 30.00	$ 111.68	$ -	
Aeroponics	ECO 264 Pump	$ 19.69	$ 19.69	$ -	
	Hole Punch	$ 12.17	$ 12.17	$ -	
	50 Feet of 1/2 Inch Tubing	$ 14.30	$ 14.30	$ -	
	Plant Module Acrylic	$ 29.22	$ 29.22	$ -	
	1/4 Inch Tubing	$ -	$ 8.29	$ -	
	Gro-Blocks	$ 20.00	$ 17.26	$ -	
Lighting	LED Grow Lights	$ -	$ -	$ -	
	Electrical Components	$ -	$ 110.80	$ -	
	LED Drivers	$ 180.00	$ 93.03	$ -	
Misc.	Hot Glue	$ -	$ 18.47	$ -	
	TOTAL	**$ 1,609.50**	$ 2,938.12	$ -	$ 2,938.12
	Net Reserve (Deficit)		$ (738.12)	$ -	$ (738.12)

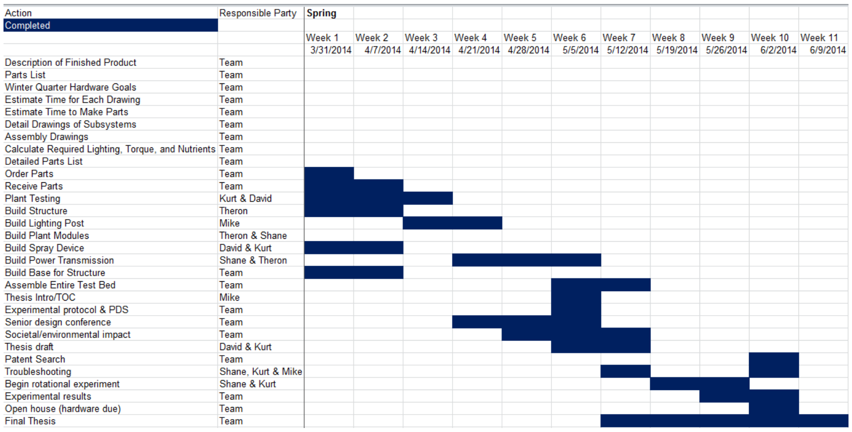
Figure B.1: Project Budget

B.2 Gantt Chart



Action	Responsible Party	Winter									
Completed											
		Week 1 1/6-1/12	Week 2 1/13-1/19	Week 3 1/20-1/26	Week 4 1/27-2/2	Week 5 2/3-2/9	Week 6 2/10-2/16	Week 7 2/11-2/23	Week 8 2/24-3/2	Week 9 3/3-3/9	Week 10 3/10-3/16
Description of Finished Product	Team	■									
Parts List	Team	■									
Winter Quarter Hardware Goals	Team	■									
Estimate Time for Each Drawing	Team	■									
Estimate Time to Make Parts	Team	■									
Detail Drawings of Subsystems	Team		■	■	■						
Assembly Drawings	Team				■	■	■	■	■		
Calculate Required Lighting, Torque, and Nutrients	Team		■	■							
Detailed Parts List	Team				■						
Order Parts	Team				■	■	■	■	■	■	■
Receive Parts	Team							■	■	■	■
Plant Testing	Kurt & David							■	■	■	■
Build Structure	Theron										■
Build Lighting Post	Mike										
Build Plant Modules	Theron & Shane										■
Build Spray Device	David & Kurt										
Build Power Transmission	Shane & Theron										
Build Base for Structure	Team										
Assemble Entire Test Bed	Team										
Thesis Intro/TOC	Mike										
Experimental protocol & PDS	Team										
Senior design conference	Team										
Societal/environmental impact	Team										
Thesis draft	David & Kurt										
Patent Search	Team										
Troubleshooting	Shane, Kurt & Mike										
Begin rotational experiment	Shane & Kurt										
Experimental results	Team										
Open house (hardware due)	Team										
Final Thesis	Team										

Figure B.2: Winter Quarter Gantt Chart



Action	Responsible Party	Spring										
Completed												
		Week 1 3/31/2014	Week 2 4/7/2014	Week 3 4/14/2014	Week 4 4/21/2014	Week 5 4/28/2014	Week 6 5/5/2014	Week 7 5/12/2014	Week 8 5/19/2014	Week 9 5/26/2014	Week 10 6/2/2014	Week 11 6/9/2014
Description of Finished Product	Team											
Parts List	Team											
Winter Quarter Hardware Goals	Team											
Estimate Time for Each Drawing	Team											
Estimate Time to Make Parts	Team											
Detail Drawings of Subsystems	Team											
Assembly Drawings	Team											
Calculate Required Lighting, Torque, and Nutrients	Team											
Detailed Parts List	Team											
Order Parts	Team	■										
Receive Parts	Team	■	■									
Plant Testing	Kurt & David	■	■	■								
Build Structure	Theron	■	■									
Build Lighting Post	Mike			■	■							
Build Plant Modules	Theron & Shane											
Build Spray Device	David & Kurt	■	■									
Build Power Transmission	Shane & Theron				■	■	■					
Build Base for Structure	Team	■	■									
Assemble Entire Test Bed	Team						■	■				
Thesis Intro/TOC	Mike						■					
Experimental protocol & PDS	Team						■					
Senior design conference	Team				■	■	■					
Societal/environmental impact	Team					■	■	■				
Thesis draft	David & Kurt						■	■				
Patent Search	Team										■	
Troubleshooting	Shane, Kurt & Mike							■			■	
Begin rotational experiment	Shane & Kurt								■	■		
Experimental results	Team									■	■	
Open house (hardware due)	Team										■	
Final Thesis	Team							■	■	■	■	■

Figure B.3: Spring Quarter Gantt Chart

B.3 Purchased Hardware Specification Sheets

B.3.1 Power Transmission

1. DC Motor: http://www.mcmaster.com/#59825k49/=sc6jrr
2. DC Motor Chassis: http://www.kbelectronics.com/kbsearch/descriptions/popup_kbic_120.htm

3. DC Motor Shaft: http://www.mcmaster.com/#1346k17/=sc76rk
4. DC Motor Shaft Coupler: http://www.mcmaster.com/#61005k533/=sc6m5o
5. Large Pulley: http://www.mcmaster.com/#6204k53/=sc6ln4
6. Small Pulley: http://www.mcmaster.com/#6204k13/=sc6lh8
7. V-Belt: http://www.mcmaster.com/#6186k148/=sc76i7

B.3.2 Lighting

1. LED Driver: http://trpssl.com/driver_spec_sheets/PLED-96W.pdf
2. LED Modules: http://www.xicato.com/sites/default/files/documents/XSM%20Artist%20Datasheet.pdf

B.3.3 Aeroponics

1. Pump: http://media.hydroponics.net/item-documents/ecoplus/Ecoplus_submersiblePumps_Instructions.pdf

Appendix C

Detailed Drawings