Project Number: 18418

THE SURCULUS

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ABSTRACT

The world's farmlands are depleting while the world's population is growing. An approach to solving this critical issue has been to alter "farming" to allow crop growth in urban warehouses. This technique was appropriately name vertical farming and people have invented numerous iterations of the idea. Fortunately, vertical farming has made great strides to be the minimal impact, mass producible solution to a global food shortage. However, the system has not yet been perfected and scientists worldwide are working to create the ultra-efficient system.

Team P18418 decided to attack the problem. The group was assigned the job of optimizing the Surculus, a rotational vertical farming system. Benchtop testing by way of Design of Experiments was the first step to determine the parameters to set the Surculus to. The group then designed and tested four subsystems to go into the Surculus. The subsystems included: aeroponics, trays, motor and gear system, and lighting system.

The results from benchtop and system testing demonstrated proof of concept. The fully upgraded system achieved plant growth and sustainability.

INTRODUCTION

This project was an attempt to improve and validate a vertical farming prototype, the Surculus, owned by Harbec Plastics. Harbec is a local plastics manufacturer whose goal is to adopt environmentally-friendly technology. Energy and water efficiency were the focus of this design. This was accomplished through controllable lighting and an aeroponics system. To accommodate aeroponics, the Surculus also required motor and tray updates. Testing throughout the design process was key to validate the optimization of the system.

PROCESS AND METHODOLOGY

The team had 30 weeks to plan, design, and build the improved Surculus. A client meeting was held to establish direction for the project and customer requirements. From the customer requirements, qualitative engineering requirements were formulated (Figure 1). The original budget was $500 provided by Multidisciplinary Senior Design (MSD). An increased budget of $300 was allowed from MSD and Harbec donated an additional $800. The final total budget given to the team was $1,600. This budget was used towards the test benches and subsystem upgrades (aeroponics, trays, motor, and lighting).

Customer Requirement	Engineering Requirement	Engineering Requirement Description	Units	Tolerable Value	Ideal Value
1	1	Initiation to harvest cycle	days	40-60	20-40
2	2	Time needed to plant seedlings	min	60	30
2	3	Replacement system lifetime	yrs	2	3
3	5	Adjustable buffer dimensions for plants	in	±6x4	± 9x4
4	6	Minimize energy use	W/plant	4.2	4
5	8	Minimizes water use	L/day	100	20
6	9	Module is easily assembled	hrs	5 hrs	2 hrs
7	10	Module is lightweight	kg	100	50
8	11	Temperature sensing range	F	40-120	20-180
8	12	Temperature sensing accuracy	F	within 2	within 0.5
8	13	Dimmable	NA	change intensity	relay has no effect
9	14	Daily maintenance hours	Minutes	< 180	< 60

Figure 1. Engineering requirement with their perspective customer requirement.

TEST BENCHES

Test benches were utilized to determine the parameters to set the Surculus to after building. The test benches were designed to test a 2-level factorial design experiment growing radishes, Chinese cabbage, and lettuce. Originally, the factors of the experiment included: light wattage (3W v 4.5W), water type (distilled vs tap), nutrient level (1X concentration vs 2X concentration), water flow rate (low vs high), and light exposure time (12 hours vs 16 hours). The test benches were initially built with a drip system and four different benchtops with four trays per benchtop totaling 16 cases for the experiment. This set up went through two iterations, one using milk jugs to contain the water and one using bins with milk bags. Unfortunately, the watering system did not supply the plants with enough water to survive and the test benches were switched to a wick system.

The third iteration of the test benches supported plant life, but cut the experiment's factors down. The new experiment included the factors light wattage, light exposure, nutrient level, and plant type. The experiment became a fourth resolution, full factorial design with one repeat. The responses measured were the number of days the plants were alive, number of leaves, and the maximum height to which the plant grew before dying. The plants were allowed to grow for 36 days. Data was collected daily on the plants after they were watered which consisted of each plant being sprayed twice with water.

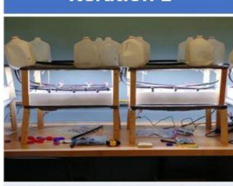
Iteration 1	Iteration 2	Iteration 3
		
Drip system using milk jugs	Drip system using milk bags+jugs	Wick system using cotton tshirts
Pros: Tested all factors of DOE **Cons**: Double milk jugs did not stay sealed and leaked on top of the lighting	**Pros**: Tested all factors of DOE, had a drainage system **Cons**: Drip system did not water plants accurately, experiment had a leakage, maintenance was too time consuming	**Pros**: Plants receive enough water, no water issues, easy maintenance **Cons**: Had to cut out two factors of the DOE
Days of Plant Growth: 0 *never started testing due to extreme leakage	Days of Plant Growth: 2 *every plant was pronounced dead by day 2	Days of Plant Growth: 6 (and still going) *does not apply to every plant, rather the majority

Figure 2. Test bench build iterations with description.

AEROPONICS

The original Surculus operated with a trough system where the trays would rotate into the reservoir full of water. This method was not effective for plants to absorb required water and nutrients. Upon research, a high pressure aeroponics watering system was selected to replace the previous system.

The aeroponics watering system uses high pressure (80-100 psi) to pump water out of misting nozzles. These nozzles create atomized water droplets about 50 microns in size. In theory, smaller droplets allow for quicker absorption of both water and nutrients which improves growth rates of plants.

Requirements for the system were simple: a water pump that can produce 100 psi continuously, misting nozzles that can spray 50 microns or smaller droplets, stability and structure that can withstand 150 psi for safety, and designing and integrating the system within budget.

Selecting the components for the aeroponics system was challenging due to budget restrictions. From the existing Surculus, the only component used in the aeroponics system is the reservoir. To increase space between the reservoir and the trays to fit the aeroponics system, all three sections of the reservoir were lowered by 7.5 inches. The Aquatec Pump 8800 was chosen for the water pump due to its ability to produce the necessary 100 psi and fit within budget constraints. Next, brass misting nozzles from arctic cove were selected that met the pressure and droplet size requirements. Schedule 40 PVC piping was selected to be the main delivery system for aeroponics due to its price and pressure withstanding performance. Lastly, various adapters including elbows and fittings were purchased to complete the system.

The designed aeroponics system has 5 nozzles for 5 plants equal distance away from each other. The entire system is removable but not all parts will be reusable. All PVC piping and fittings were primed and cemented to connect and stabilize the high-pressure system.

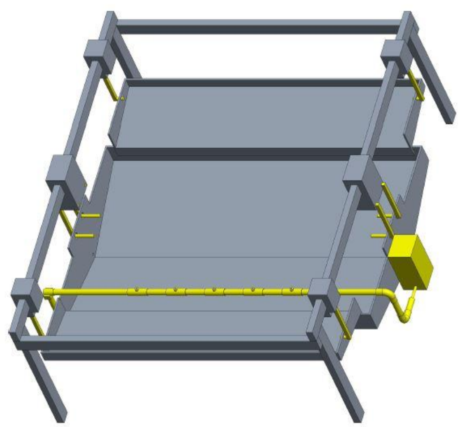


Figure 3. CAD Drawing of Aeroponics System.

TRAYS

The preexisting trays on the Surculus were made of vacuum formed plastic and included a solid bottom lined with small drainage holes. The trays were filled with strips of reticulated polyethylene foam (RPF) compressed with small blocks of foam so that the plants are held in by the pressure. To improve the trays for versatility and to accommodate the addition of aeroponics it was necessary to open up the bottoms of the trays. In the early stage of design planning several options were considered. These options included an ideal tray design that reduced material and decreased the width and height of the trays so that the tray would compress the RPF with no need for extra foam blocks. This would have required the manufacturing of new trays and due to budget restrictions, it was decided to move forward with a different option. Aside from manufacturing completely new trays there were a few options designed to modify the preexisting trays so that they would meet the needs of the aeroponics system. Since the main change needed was to allow misting from aeroponics to reach the plant roots through the bottoms of the trays, viable options were devised to open parts of the tray bottom. One was to cut holes with a diameter of 3 inches directly under where the plants would be placed for a total of five holes to accommodate the five-plant tray capacity. This would give the plant roots access to the misted nutrient water while still supporting the RPF in the trays. Another way to open the tray bottom would have been to cut out a long strip along the tray bottom that the water could spray the roots through. This option was ruled out because it would have been harder to keep the RPF supported. Due to these considerations it was decided to move forward with cutting five evenly spaced three-inch holes in the trays.

The modification was carried out by first disassembling the trays from the Surculus and then removing the RPF from inside the trays and the end clips from the tray bodies. From there the location that the holes would be drilled was measured out and marked on each tray. After each tray was marked the holes were cut using a three-inch hole saw. Once all the holes were cut the end clips were reattached to the tray bodies, the RPF was placed back into the trays, and the trays were clipped back into the Surculus.

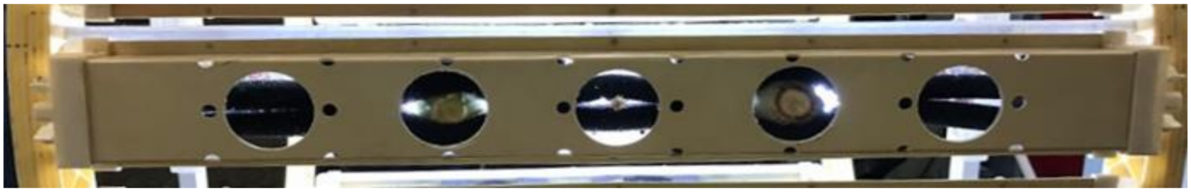


Figure 4. Tray after modifications.

MOTOR

The preexisting motor and gear configuration on the Surculus consisted of an AC motor, two gearboxes, a small gear, and a large gear. This setup rotated the system at approximately a half rotation per hour. The motor (SMK216A-GN) was running at 60 rpm and was connected to the first gearbox (2GN10XK) with a gear ratio of ten, and the first gearbox was connected to the second gearbox (2GN36SA) with a gear ratio of 36. The output shaft of the second gearbox was directly connected to an 18-tooth gear which turned an 84-toothed gear that contained a rubber strip that rotated the Surculus wheel using friction. An image that shows the setup can be seen below.

In order to accommodate aeroponics the rotation speed needed to be increased to prevent the plant roots from drying out between contact time with the misting. To increase the rotation, speed the first gearbox with a gear ratio of ten was removed. This resulted in a new rotation speed of approximately three rotations per hour.

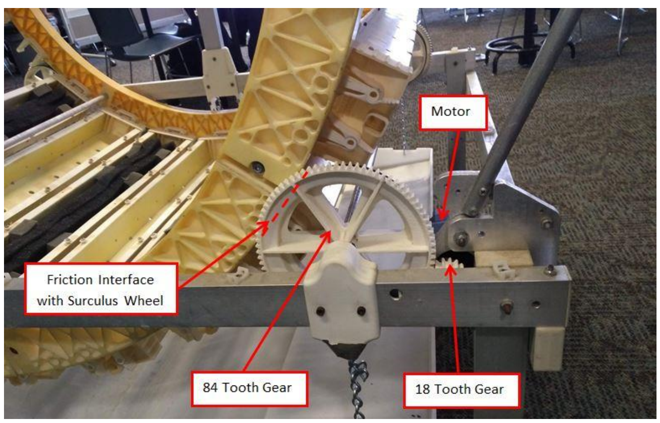


Figure 5. Motor and gear configuration for the Surculus.

LIGHTING AND DIMMING SYSTEM

The vertical farming module is designed to be used indoors. Thus, artificial lighting is needed for plants to undergo photosynthesis, the process that plants use to convert specific wavelengths to chemical energy that is used to sustain the plant. Originally, the lighting system was made up of 5050 SMD LEDs (red and blue light). The updated Surculus uses 6500K White LEDs from SuperBrightLEDs to promote photosynthesis. The LED strips used on the system were a combination of the LEDs used in test bench testing supplemented with additional purchased strips. The strips were soldered together to provide the needed 14ft strips. The strips were waterproofed using tubing and epoxy, then wrapped around the center tube 52 times to distribute the appropriate number of watts to the plants (3W/plant). The tube contains the power supplies and a power strip. A fan is positioned on one end of the tube to keep the LEDs and power supplies cool and prevent overheating.

The main challenge in the design was to allow a single controller to control a large number of LEDs with a current requirement of 50 amps. The initial design used a mechanical relay that would function as a voltage-controlled switch, where the switch would follow the pulse modulation width of the LED controller that was powered by a separate power source. The purpose was to create a buffer between the LED controller and the LEDs. The dimming system was changed based on the performance results. The final design uses parallel setups so that, if one of the setups fails the others will keep producing light and remain dimmable. The process and feedback used to come to this final design can be seen in the results section.

RESULTS AND DISCUSSION

TEST BENCHES

The data collected was tested at 95% confidence level with an alpha of 0.05. The data was processed with four factors: vegetable type, wattage per plant, light exposure hours, and nutrient level. There were two levels per factor for a 2-factorial design. The final experiment design was a fourth resolution, full factorial design with one set of repeats. The responses measured for the 36-day experiment were days alive, max height, and number of leaves. The Minitab analysis showed that none of the factors proved to be a statistically significant for the number of days the plants stayed alive. The only factor that showed a statistically significant impact for number of leaves was the nutrient level. Finally, the max height of the plant showed a statistically significant response to the wattage and the nutrient levels. Based on the results, 3W with 16 hours of light and a nutrient level of 1X should be used for the Surculus going forward. It is important to note that only the radishes and cabbages were examined in this data set due to the lack of lettuce growth. Only two lettuce plants survived out of 16 and the two that did survive showed little to no growth beyond the germination stage.

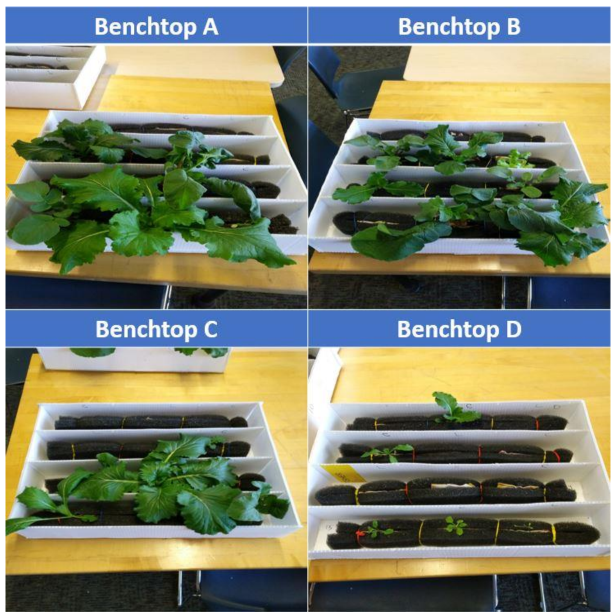


Figure 6. Image of test bench trays at the end of testing period.

AEROPONICS

The aeroponics system has five nozzles that spray at about 125 gallons per day. Most of the water drains back into the reservoir. The actual usage/loss of the system is 8.4 gallons per day ± 1 gallons. As designed, the aeroponics system is running continuously. All the PVC pipes and nozzles are primed and cemented together. The inlet and outlet tubing of the pump is ¼" which is connected to the PVC pipes with adapters. All connections and pipes can withstand up to 150 psi.

The current system is capable of supporting plant growth, there is still room for improvement. Mist from the nozzles travels outside of the footprint of the Surculus, allowing moisture to accumulate outside of the Surculus. Also, the pump is attached to the reservoir which creates additional vibration, increasing the noise level. Lastly, the filtering system has an inlet that clogs occasionally. This creates additional maintenance required to clear any debris from the filter daily.

TRAYS

After the trays were modified, each tray contains five evenly spaced holes each with a three-inch diameter. This allows the roots to be misted by the aeroponics system and still supports the RPF to hold the plants in. Since there are five holes there is room for zero to five plants in each tray as a plant can or cannot be placed over each hole depending on user needs and plant spacing needs. Since alterations were only made to the body of the tray, the end clips still clip the trays into the Surculus in the same manner.

MOTOR

The current configuration of the motor and gear system consists of an AC motor, one gearbox, a small gear, and a large gear and rotates the system at approximately three rotations per hour. The motor (SMK216A-GN) is running at 60 rpm and is connected to a gearbox (2GN36SA) with a gear ratio of thirty-six. The output shaft of the gearbox is directly connected to an 18-tooth gear which turns an 84-tooth gear that contains a rubber strip that rotates the Surculus wheel using friction.

LIGHTING AND DIMMING SYSTEM,

For the dimming system it was found that a mechanical relay would not meet the frequency requirements of the LED controller, so the relay was switched to a solid-state relay. The use of solid state relays increased the price of the dimming system and therefore more cost-effective alternatives were investigated. Two new options were presented which included swapping the relay out with a power MOSFET that functions as a voltage-controlled switch or splitting the LED strips and using multiple controllers, so the current load would not be an issue. The power MOSFET dimming system would work by programing an MSP430 to output a pulse width modulation signal into the gate of the MOSFET. The source of the MOSFET would be connected to the ground pin to use the MOSFET as a switch to turn the LEDs on and off. The cost of implementation was about $125. The option that required splitting the strips is made up of three components: the power supply, LED controller, and the LEDs. The LED controller is controlled with a remote that has preset settings and can increase or decrease the brightness of the LEDs. Since the LED controller can only handle a load of 5 amps, multiple setups (LED strip with power supply and controller) would have to be used to implement the lighting system. The number of setups was determined based on the number of LEDs being used to satisfy the wattage per plant requirement. Six setups will be implemented costing $66. The multiple LED strip option was chosen because it uses a parallel setup allowing for no one single point of failure that would cause all the LEDs to fail. The implementation of setting up the dimming system went as predicted.

In the implementation of the lighting system the waterproof tubing had to be cut into smaller segments to insert the LED strips. The LED strips were inserted into the tube and wrapped around the tube. There were issues with having all the LEDs on at the same time and this was easily fixed by resetting the LED controllers. This is likely due to the sensitivity of the remote being used.

PERFORMANCE OF SURCULUS

Once the upgraded Surculus was assembled, the entire system and the subsystems were tested against the engineering requirements, seen above in Figure 1. Overall, the system performed well and fell within the acceptable range for most of the requirements during testing. Unfortunately, requirements such as lifetime and time to harvest were unable to be tested due to time constraints and design unknowns. Performance of the Surculus is found below in Figure 7.

Engr. Requirement (metric)	Unit of Measure	Marginal Value	Ideal Value	Actual Value	Test Result	Direction of Improvement	Comments/Status	Test Number
Initiation to harvest cycle	days	40-60	20-40	37	Δ	↓	depends on plant, not fully tested	S1
Time needed to plant seedlings	min	60	30	30	O	↓	15sec/plant/tray = 30 mins	S2
Replacement system lifetime	yrs	2	3	?	Δ	↑	analysis subsystem lifetime was	S3
Adjustable buffer dimensions for plants	in	±6x4	± 9x4	6x4	O	↑	fixed value	S5
Minimize energy use	W/plant	4.2	4	3.4	O	↓	great result	S6
Minimizes water use	L/day	100	20	30.3	O	↓	decrease water by adding water	S8
Module is easily assembled	hrs	5 hrs	2 hrs	2.5 hrs	O	↓	2 people for transport, 1 for build	S9
Module is lightweight	kg	100	50	52.4	O	↓	does not include water	S10
Temperature sensing range	F	40-120	20-180	Sensors were dropped in MSD II. It did not fall within the scope of this MSD course. Possible future requirements if sensors were added.				
Temperature sensing accuracy	F	within 2	within 0.5					
Dimmable	NA	change intensity	relay has no effect	10%-100%	O	N/A	dimmer increases by 10% up to 100	S13
Daily maintenance hours	Minutes	< 180	< 60	20	O	↓	10 mins x2 a day for water refills	S14

TEST RESULT KEY	
X	Does not meet expectation
Δ	Caution-Undetermined if specification is met
O	Meets specification

DIRECTION OF IMPROVEMENT KEY	
X	Must be within a specified range.
↑	Improvement occurs with increasing test value.
↓	Improvement occurs with decreasing test value.

Figure 7. Engineering Requirements and their test results.

The engineering requirements were not the only measure of success for the Surculus. The system was also expected to support plant life and growth, demonstrated in Figure 8. From the test benches, it was proved that plants could successfully grow to a harvest point with similar environmental factors to the Surculus. Due to time constraints, the Surculus did not use crops originating from seedlings. Regrowth vegetables were placed in the Surculus; these vegetables included romaine, celery, and green onion. The vegetables were successfully supported by the Surculus and exhibited noticeable regrowth within the first few days (Figure 9).

Figure 8. Fully assembled, working Surculus with crops.

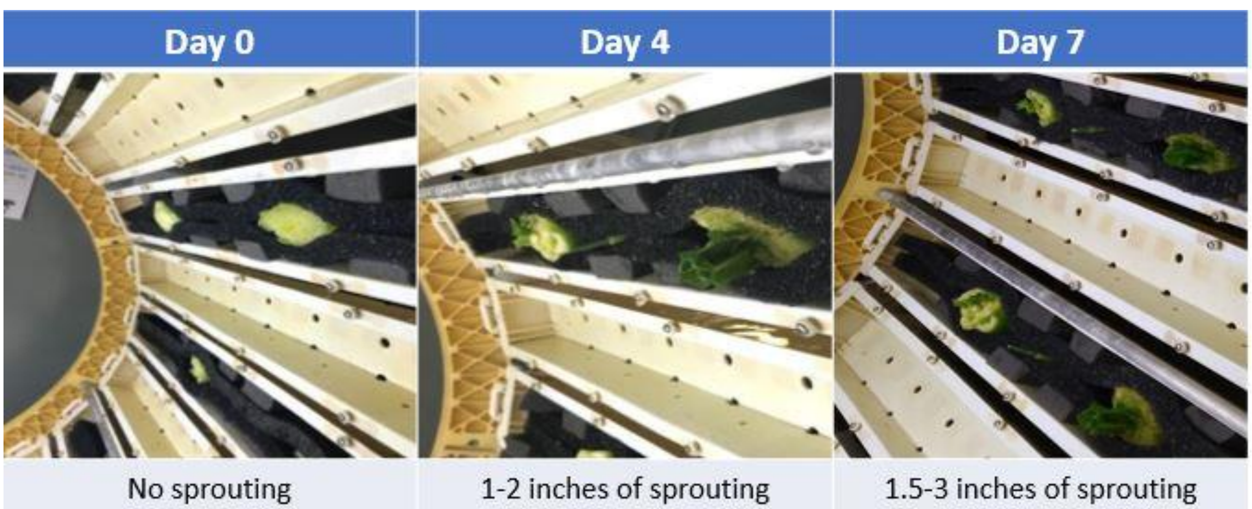


Figure 9. Surculus crop growth.

CONCLUSIONS AND RECOMMENDATIONS

The Surculus, although great in theory, had originally been failing in execution. The team's goal was to improve the design of the Surculus and ultimately grow edible plants. Data collection was a large part of this project to satisfy Harbec's quest for knowledge. The project got off to a slow start in MSD 1 and seemed to lack a concrete direction. It was unknown if the Surculus was going to be transported to RIT. Ultimately, it was decided to design and build test benches to collect data. The data collected from the experiment included days alive, number of leaves, and maximum leaf height. The testing was a success as some plants grew and the parameters for the Surculus were set (16 hours of light, 3W/plant, recommended nutrient levels).

Fortunately, the team was able to arrange for transport of the Surculus to RIT. Efficiency was maximized by working to modify the Surculus during the testing of the test benches. The four subsystems designed and implemented into the Surculus were deemed a success. Plant growth was evident from system testing. It was concluded that the Surculus was able to support plant life and growth in an eco-friendly, efficient manner which was the overall goal of this project. The only main failures during MSD II consisted of poor timing with fabrication/order arrivals and inability to meet up with the customer.

RECOMMENDATIONS

Recommendations for future work on this project include a superior motor and gear design. A variable speed motor would allow us to have more control of the system, giving us another test factor and yielding better results. An updated electrical box would give the system a sharper look and ensure that the electrical components were housed safely. Gathering more data on how the light amount and exposure time affect the plants would help determine the importance of the lights and help find the sweet spot for plant growth. Finally, it would be beneficial to implement a sensor system to measure changes within the environment and adjust depending on how the environment varies.

If this project were to be repeated it would be recommended to find a good project direction early. That way, time is not wasted on figuring out where to go/what to accomplish but working towards that goal. Avoid spending time worrying about things that have already happened and more importantly focus on what can be controlled in the future. Lastly, get together with the customer weeks in advance when scheduling design reviews. Customers are usually successful professionals, making their time scarce and very valuable.

ACKNOWLEDGMENTS

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