# Design of an Autonomous and Timed Water Delivery System in Microgravity

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## Abstract

For long-duration, manned, space exploration missions to be feasible, farming techniques in space must become reliable and fruitful. The NASA Project Veggie team currently runs experiments on the International Space Station (ISS) in order to better understand how plants react to a microgravity environment. Current watering strategies on the ISS involve manual watering of all plants by the crewmembers. This poses a problem because watering plants must be scheduled into the crewmembers' days which means less time to work, etc. The objective of Team International Space Salads (ISSa) was to create a device and prove that it could function in microgravity without electricity to autonomously water the plants in order to allow for schedule flexibility of the ISS crewmembers and to lay the foundation for watering systems for deep-space travel. The final device did not function fully as planned, however, the plant growing, surface tension experiments, and the device collectively progressed the multi-year project to a state where successive teams would have the knowledge and tools necessary to create a fully functioning device.

## 1. Introduction

NASA implemented the Vegetable Production System (Project Veggie) with a goal to produce a unit that yields salad-type crops. The crops would provide a nutritious source of fresh food for the International Space Station (ISS) crew while also supporting relaxation and recreation for the crew. Project Veggie controls the lighting, nutrient delivery, and cabin environment to promote plant growth (Veggie, 2018). Team ISSa was elected to focus on the water delivery system. Currently, the plant receives water and nutrients manually from a crew member with a syringe. Other attempts of water delivery systems using a constant flow of water forced by capillary action have been tested by Project Veggie (PONDS, 2018). Team ISSa plans to create an autonomous water and nutrient delivery system that delivers a discrete amount of water in intervals so that minimal astronaut intervention is needed throughout the lifecycle of the plant post-germination. This way, the crew can focus on their busy schedules and other experiments while also receiving a source of fresh food.

## 2. Design Objective

With the information from the past three years of MSOE senior design groups, Team ISSa has a goal to improve upon the prototype Team HERBS built in order to complete an autonomous watering system for Outredgeous Lettuce post-germination in microgravity. The project will be considered successful once a system that services plants post-germination that grows healthy, mature lettuce is made with minimal astronaut intervention, as well as hitting one key metric: the design must operate convincingly in microgravity, as we do not have the capabilities to actually

Financial support provided by Wisconsin Space Grant Consortium. Project support provided by NASA Project Veggie at NASA Kennedy Space Center. Faculty adviser is Michael Swedish of Milwaukee School of Engineering.
This is an abridged combination of two design reports; please contact the faculty adviser or authors for full reports.

test the design in true microgravity. A major goal for the duration of the project is to research plant water versus oxygen needs, as the previous senior design groups have realized that plant roots need to be put through a wet-dry cycle to produce healthy lettuce.

## 3. Target Specifications

The target specifications for this project were given by the NASA Project Veggie team. Further specifications were defined by Professor Swedish due to discoveries from previous experience.

The first specification that must be met is that the controller must provide sufficient water to the roots of the Outredgeous lettuce while also allowing enough oxygen to the roots to prevent drowning. The health of the lettuce will prove if the roots are getting the correct amount of water.

Another requirement is that the controller must be autonomous while using no electricity. This means a timing system is necessary in order to create a wet-dry cycle and have minimal astronaut intervention. NASA imposed the constraint of not utilizing any electrical power.

The final specification is that the controller volume and mass must be minimized in order to fit within the footprint of Project Veggie and be as light as possible to facilitate space travel.

## 4. Design Concepts

Two design concepts were generated through brainstorming individually and as a team. The concepts were based off Team HERBS final prototype, but adjustments were made in order to more sufficiently meet the design objectives discussed above. The first design concept revolves around the water delivery device, where the second design concept explores the timing mechanism. Both concepts will be combined for the final design.

**4.1 Design Concept #1** A design for a water delivery system was developed to deliver a set amount of water to the plant roots when a signal is received. The device needs to be able to supply water to the plant roots for the entire life cycle of the plant. The device is not allowed to use any electricity which is defined as a constraint of the project.

Taking concepts from Team HERBS design, a design was created that still utilizes constant force springs but applies the force in a linear direction rather than torsional. The device will require energy to be put in at the start of each plant cycle but is designed to last for full plant life.

We have chosen to continue with Team HERBS design since they have already performed the engineering analysis for the main drivetrain, have a prototype printed, and have proven that their concept can work with further development. Further analysis for this mechanism can be seen in the Detailed Design section of this report.

**4.2 Design Concept #2** A design for a timer to control the watering device was developed which would initiate the watering device at specific pre-determined intervals. This idea was initially posed by Team HERBS.

This timer needs to be able to last the entirety of the life cycle of the plant post-germination, and the design can be adjusted so that watering takes place at different intervals. The design also needs to be created such that the user can initiate watering if they deem that the plant needs water. The timer must reset if a user initiates an early watering cycle.

A design based on the kitchen timer was selected due to its capability to keep accurate time. This design contains a power supply, a limiter, and a trigger wheel. The power supply will supply energy to the device via a power spring. The limiter will restrict how quickly the power spring will unwind at the desired rate via a gear train, balance wheel, and escapement gear. The trigger wheel will interact with the water delivery device to initiate the watering sequence.

The device will be designed to be rewound in order to utilize expended energy on the ISS by the crewmembers using the Advanced Resistive Exercise Device (ARED) ("The International…", 2019). The conversion from the ARED to the timing device is outside the scope of this project. Further analysis into the chosen timing mechanism can be found in the Detailed Design section of this report.

## 5. Feasibility Study

**5.1 Surface Tension** One design challenge is that design must work in microgravity. This cannot be proven, but sufficient theoretical analysis and experiments must be completed in order to prove the design is feasible. Though the design may work on Earth, water acts much differently in microgravity. The surface tension causes the water droplets to pool around the water outlet or bind around the plant root. Even considering that water acts differently in microgravity, the design is still feasible for two reasons. The current drip ring used on the ISS by the crew members to water the plants will still be utilized. Because mature plants are currently grown successfully on the ISS with crew members watering the plants with syringes through the drip ring, this autonomous design should also work. Furthermore, experiments on Earth were and are continued to be completed with a liquid that has a much higher surface tension than water in order to try to simulate what the water will do in microgravity. Cold temperatures and adding highly soluble impurities (salt or sugar) increase the surface tension of water (Hsin, 2004).

Based on studies by Okur, Chen, Wilkins, and Roke, the surface tension of liquid is more affected by magnesium chloride than other types of salts (Okur, 2017). Therefore, magnesium chloride flakes were utilized in the capillary rise experiment. A scale was used in the experiment to determine the mass and then density of the water and salt mixture. For each amount of salt added to the water, a picture was taken of the experimental setup where the 2mm diameter, open-ended glass tube was held in the mixture next to a ruler. The picture was then imported to SolidWorks, where the height difference and angle of the mixture was accurately measured. The magnesium chloride flakes were added in 5 to 10-gram increments, and this process was completed until the water became fully saturated.

The experiment was completed multiple times, verifying the results. In conclusion, the surface tension of water at room temperature can be increased to a maximum 50% by adding magnesium chloride flakes. This information was utilized during the spring quarter as the next step in proving that the autonomous design would function correctly in microgravity.

For the final experiment, two fully grown plants were transplanted to clear bins with ruler marks across a horizontal and vertical face in centimeter increments. Arcillite was placed around the roots, but the plant was placed close to a bin face so that the roots could be visible to the human eye. One lettuce plant was used as a control with distilled water injection, and the second lettuce plant was used for experimentation with the high surface tension water and magnesium chloride mixture.

From the original experiment, the surface tension of the second liquid was raised from about 70 dyne/cm to 97 dyne/cm. To simulate a normal watering, each plant was injected with 50 ml of the respective liquids at a steady rate of 2 ml per second. A video and pictures of the experiment were taken in order to analyze quantitative (liquid spread and rate of liquid dispersion) and qualitative (liquid left on roots and arcillite after increments of time) results when comparing the two bins.

The experiment was completed two times to verify data. Quantitative and qualitative results were analyzed to ensure that the high surface tension liquid reacted significantly different than distilled water. From this qualitative analysis, we saw that liquid clings to the roots and arcillite, so a watering schedule with less water per day would be advised for growing in microgravity. This data can also be corroborated with the quantitative data recorded.

From the two tests, the average of the data was taken. Figure 1 displays the plot of the liquid spread horizontally across the container at the given heights. There are two important points to note. First, both liquids tend to spread more horizontally further down the container (0 cm is the top and 9 cm is the base of the container). Secondly, the high surface tension liquid is consistently spread more horizontally than the distilled water at the same height.

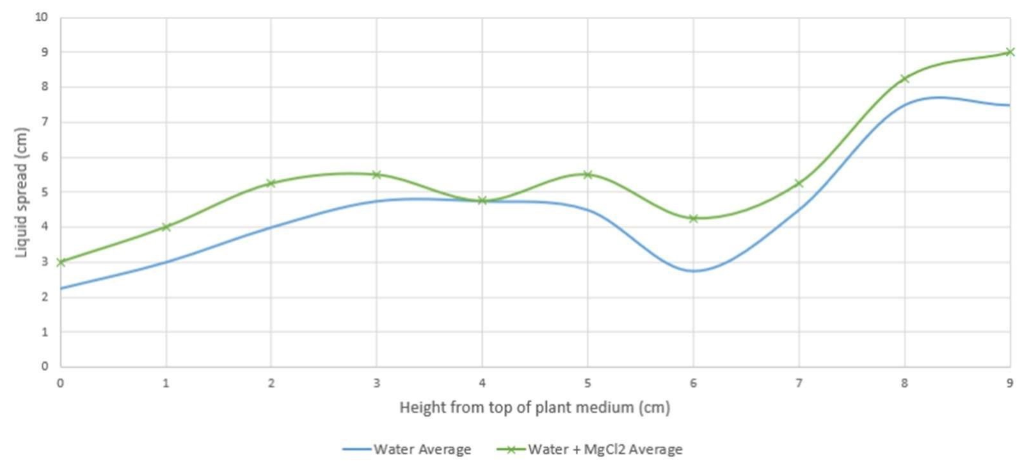


Fig. 1: Liquid spread at given heights, test averages

Data of average spread at the given heights and the time to reach different heights were also gathered and supported the conclusions obtained from Figure 1. Please see full reports for details (ISSa (a), 2019), (ISSa (b), 2019).

In conclusion, qualitative and quantitative results prove that high surface tension water reacts significantly different during the watering cycle than distilled water. Assuming this simulates watering in microgravity, it is concluded that the watering schedule aboard the ISS should be altered from the Earth schedule due to the dominance of surface tension. Less water should be prescribed per cycle to account for the water clinging to the plant roots and arcillite in order to ensure a complete wet/dry cycle for the roots. Overall, the design is feasible because it utilizes a pressure-based system rather than gravity-based, it does not utilize electricity, and an updated watering schedule should produce healthy, mature plants in microgravity.

## 6. Detailed Design

The following three sections illustrate the updates made throughout the spring quarter. The plant experts have done further research on the optimal growing environment as well as implemented a drip ring system into their growing procedure. The timing mechanism and delivery device designs were also adjusted slightly to account for unforeseen issues with material friction, the assembly of both designs to a combined device, and the trigger system from the timing mechanism to the delivery device to begin a watering cycle. For the full Detailed Design section, please see the full report (ISSa (b), 2019).

**6.1 Plant Growing Technique** The planting and growth of Outredgeous lettuce continued throughout the spring using planting techniques developed in the winter quarter. Multiple crops were placed under purple lights and fluorescent white lights in both the Johnson Controls Lab (JCL) and the psychrometric chamber. The different light fixtures were placed on timers to simulate a day/night cycle. The lights operated at the nominal levels of intensity as set by the manufacturers. The psychrometric chamber was manually controlled to maintain a relative humidity of 40% RH but was not used for three weeks of the quarter due to laboratory experiments for other classes. No change was noticed in the psychrometric chamber crops when moved outside the chamber for a week because the humidity in the JCL was higher in spring quarter than winter quarter. All crops were planted in either static shield bags or Rubbermaid containers with 250 mL Arcillite, Nutricote fertilizer, and distilled water. Different amounts of the Nutricote fertilizer and distilled water were tested.

A total of 31 crops were completed throughout the duration of this project. Crops grown in the spring quarter were red, dense, and firm plants. Multiple plants were germinated each week to prepare for testing the water delivery device. There were four locations for growing plants: JCL white lights, JCL red/blue lights, psychrometric chamber white lights, and psychrometric chamber red/blue lights. The reason was to isolate the variables of light source and environmental conditions by having a control in each testing location.

In general, growing in the psychrometric chamber lead to plants with firmer leaves and appeared to have better coloration and moisture content in the leaves. The JCL plants tended to have drier leaves, require more water, and have a weaker/skinnier stem. The red/blue lights lead to plants with considerably redder and “rounder” leaves as the white-light plants extended farther beyond the container as the figures show above.

Static shield bags were continued to be used. The plants were able to germinate inside the bags and grow up to 4 weeks old before dying due to root rot. Drip rings were not washed when testing in the static shield bags so the unwashed material could have stunted the growth of the plants. The main issue with static shield bags is standing water. When watering too little to try to prevent overwatering, the plant becomes dehydrated. It would be good to try monitoring the static shield crops twice a day.


Fig. 2: Crop 27/A1, 4 weeks, healthy lettuce

Overall, the plants were grown remarkably well and were able to perform the same crop after crop for testing. For 250 mL Arcillite, 10-15 g Nutricote fertilizer was enough to grow optimal plants. The plants grew to an edible size and a deep red color with firm leaves. The techniques implemented should produce quality plants each time.

Figure 2 shows a mature Outredgeous lettuce plant that has grown to full size and optimal conditions. A healthy, mature lettuce was identified to have medium sized leaves, firm leaves, red coloration, and a packed head. This crop displays all those traits. A nutrition analysis would be too costly and not feasible at this time.

**6.2 Timing Mechanism** Over the course of spring quarter, the timing mechanism design was refined and then built. All pieces were either fabricated using a commercial 3D printer, created via additive manufacturing at the Rapid Prototyping Center (RPC) at MSOE, machined in the machine shop at MSOE, or ordered from McMaster-Carr.

The design of the limiter had minor adjustments from the Winter Design Report (ISSa (a), 2019). The parts were finalized and can be found in the Appendix of the Spring Design Report addendum (ISSa (b), 2019). The gear train consists of the switch gear, a 16-tooth/48-tooth compound gear, a 12-tooth/48-tooth compound gear, and a 12-tooth gear press-fitted onto the kitchen timer.

Two trigger wheels were designed to initiate the watering cycle once per two days and once per day. These rates were selected based on the watering data from the plant experts. A camshaft design was selected due to the slow rotation rate of the timer and the gradual displacement of the trigger linkage from the camshaft design.

The case was designed with four sections to allow the device to be assembled in microgravity. This is discussed in the assembly instructions of the full Spring Design Report (ISSa (b), 2019).

The power supply contained a power spring, a ratchet and pawl system used for rewinding the power spring, and a gear that connects the power supply to the gear train of the limiter. All finalized part drawings can be found in the Appendix of the full reports (ISSa (a), 2019), (ISSa (b), 2019).

The rewinding mechanism was refined from the Winter Design Report (ISSa (a), 2019). The design had a focus of rotating the screw so that it was close to parallel to the force exerted by the spring on the pawl and adding more material around the screw to support it.

The shaft was designed to connect the power spring, the ratchet gear of the rewinding mechanism, and the connecting gear. The shaft also needed to be designed so that a wrench would be able to rewind the power spring.

The connecting gear was designed to mesh with the switch gear of the limiter. It had a keyway designed into part of its depth and a key designed into it for the rest of the depth.

The trigger linkage was selected as the starting point of the triggering mechanism design due to the precise orientation of the arm that interacts with the trigger wheel. Once the trigger linkage was designed, a part to hold the other end of the rubber band to the device was designed.

The timing mechanism was designed so that screws and nuts were in specific positions to hold the device together. Some of the nuts were difficult to align for proper assembly and gravity was used to put them into place. This is a problem when one considers the implications of this in microgravity. The solution used a rubber compound or putty to hold the nuts in place even after the screw is disengaged. For best practice, all nut slots were filled with the putty which made assembling/disassembling the device and troubleshooting much less tedious.

**6.3 Delivery Device Changes** made from the winter quarter include the following: reprinting of drivetrain components; addition of latex rubber balloon for bladder; and redesign of locking mechanism. Once the device was fully assembled at the beginning of the term, it was evident some fixes were needed in order for the device to reach a point of being functional. The first issue was to lessen the friction seen between the gear teeth while they slid in and out of contact.

All of the original drivetrain parts were printed on a personal 3D printer using PLA. Because of the way these parts are printed, the grains of the filament layers are aligned against each other so that the teeth must slide over two very rough surfaces.

The first idea was to file and sand down the teeth surfaces to create a smooth, uniform surface. Starting at 100 grit and moving all the way to 5000 grit sandpaper, each tooth was sanded, but the problem still remained. The next idea was to coat the teeth with a viscous lubricant to fill the voids in the surface and make it easier for the teeth to slide. Using lithium grease, the teeth surfaces were coated. Upon testing this solution, there was no significant difference in performance and the added grease made the device messy.

The final solution was to consult with the RPC to see if they would allow us to print some more parts in a material that had a smoother surface finish. Fortunately, the RPC was beta testing a new material for a company and needed feedback on the material's performance and characteristics.

The material as of now is called FLX-BLK-10. It is a polymer filament that is imbued with a UV curable epoxy. Initial thoughts once the parts were received were hopeful. The material feels very soft, almost supple. Upon inspection, the teeth surfaces look almost uniform and there is very little to no resistance when just sliding the teeth together other by hand. One characteristic that these new parts had was that they expanded upon curing. The original parts printed in PLA fitted on the shaft perfectly, but these new parts, printed using the same SolidWorks file, did not fit at all. After some post processing, the parts fit but not as well as originally designed.

The next part added was the natural latex rubber balloon bladder. Last year, a normal party balloon was used but it was not big enough to stretch over the whole stroke. Instead of using a standard party balloon, punch balloons were used instead because they are much bigger and fit perfectly over the seals. In order to keep the balloon from expanding outward, a small rubber band was placed around the balloon to keep the middle pinched tight.

The next change made was to the locking mechanism. The inner locking face of the original mechanism was too small to consistently engage. An attempt was made to print a usable part using PETG or PLA on the personal printer, but the part would not print right. If it did, it would just fracture right away. Without being able to print a new one in the RPC, a new solution was required. After talking to the lab technicians, reprinting the housing and using available material to replace the clip was the best and quickest option. On the personal printer, a housing was printed that contained a small slit to allow a piece of metal to be glued in the mechanism. The clip was fabricated by cutting strips of cobalt sheet metal and folding the end to imitate the original design. The piece of cobalt was then glued into the housing to create the part.

## 7. Engineering Analysis

The force applied by the linear spring to push the water out of the bladder and into the plant must overcome the force required to push the water through the tubing as well as the ball check valve. In order to pull the water into the bladder, the force applied to the plunger must overcome the force required to compress the linear spring, the force to pull the water through the tubing, and the force to pull the water through the check valve. Additionally, frictional forces must be overcome

The force needed to pull water into the system or push water out of the system will be assumed as negligible for now as the calculation is not possible with the equations known. Last year, Team HERBS attempted to solve for major head losses using Equation 1 (the Darcy-Weisbach equation for head loss in a pipe) and minor head losses using Equation 2. Both equations were taken from White's Fluid Mechanics textbook (White, 2001).

$$h_f = f\frac{L}{d}\frac{V^2}{2g} \tag{1}$$

$$h_m = \frac{K}{V^2/2g} \tag{2}$$

The constant torque spring was chosen from stock parts listed on Vulcan Springs's website. The spring had to be long enough to fulfill the number of watering cycles required and also be strong enough to overcome the many forces opposing it. The total number of cycles the plants need to be watered was determined to be 10 from experimentation. The spring chosen has enough length to last at least 15 cycles before needing to be rewound. The force exerted by the constant torque spring must overcome the maximum force exerted by the constant force spring, $F_{\text{spring.2,max}}$, the force exerted by the compressive spring, $F_{\text{spring.3}}$, and the frictional force within the mechanism, $F_{\text{friction}}$.

$$F_{gear} = F_{spring.2,max} + F_{friction} + F_{spring.3} \tag{3}$$

$$F_{gear} = \frac{T_{spring.1}}{r_{gear}} \tag{4}$$

Initial calculations have been completed to size the springs and can be seen in the Excel spreadsheet in Appendix C of the Winter Design Report (ISSa (a), 2019). In the calculations, the friction force in the mechanism is put in as a placeholder. The frictional force will be more accurately determined through testing of the prototype. In order to determine the gear train design and select a power spring for the timer, a range of torque values needed to be calculated for the purchased kitchen timer. Equation 5 was used to determine the torque boundaries at both the maximum and minimum values from the experimental setup created to test the torques. The gravitational force, F, was used to calculate the torque required to overcome the resistive torque, $T_{res}$, that was a result of friction within the purchased timer. r is the radius of the 3D printed wheel.

$$T_{res} = Fr \tag{5}$$

The measurement was repeated multiple times to get an average value. The experiment was then repeated to determine what the maximum bounds of the range of torques were. The collected data and corresponding calculations can be found in Appendix C of the Winter Design Report (ISSa (a), 2019). Once the range of torques was determined, a gear train needed to be created in order to accurately change the rate from one rotation per hour to one rotation every two days. Equation 6 was used in order to determine the gearing ratios:

$$\omega_o = e\omega_t \tag{6}$$

where $\omega$ is the angular speed of the output gear, e is the gearing ratio, and $\omega_t$ is the angular speed of the kitchen timer. The gearing ratio can be evaluated as seen in Equation 7:

$$e = \frac{N_1 N_3 \cdots N_{n-1}}{N_2 N_4 \cdots N_n} \tag{7}$$

where $N$ is the number of teeth on gear $n$. This equation is for a compound gear train where gears 1 and 2 are meshed, gears 2 and 3 make up a compound gear, and so on. Once the gearing ratio was determined, the same gearing ratio was used to calculate the torque needed from the power spring using the torque ranges calculated above along with Equation 8.

$$\frac{1}{T_s} = e\frac{1}{T_t} \tag{8}$$

$T_s$ is the torque of the spring, and $T_t$ is the maximum and minimum torque values of the kitchen timer. Analysis was also completed regarding plant conditions. The rate of transpiration depends on many factors including the environmental conditions and the plant itself. Water potential is a measure of water's ability to do work and is the basis of the driving force for water movement from the growing media to the atmosphere through the plant (Payne, 2004). The difference between the water potential of the leaf and surrounding air represents the driving force and causes an osmotic pressure gradient within the plant to develop. The flow of water and thus the transpiration rate can be modeled using an electrical analogy as seen in Equation 9.

$$T_r = \frac{\psi_{leaf} - \psi_{air}}{\sum R} \tag{9}$$

In Equation 9, $T$ is the transpiration volume flow rate $m^3/s$, $\psi_{leaf}$ and $\psi_{air}$ are the water potential MPa of the plant leaves and surrounding air, respectively, and $\sum R$ is the sum of the hydraulic resistances experienced between the leaves and surrounding atmosphere $kg/s \cdot m^4$. The water potential of the air can be calculated using Equation 10, where R is the universal gas constant J/mol-K, T is the absolute temperature K of the air, RH is the relative humidity of the air, and $V_w$ is the partial molar volume of liquid water in the evaporating fluid $m^3/mol$.

$$\psi_{air} = \frac{R * T * \ln(RH)}{V_w} \tag{10}$$

The transpiration rates of a plant depend heavily on the environmental conditions, which influence the driving force. This also influences the plant itself, which then impacts the hydraulic resistances through the plant. In general, Equations 9 and 10 can be used to potentially predict the water requirements over the plant lifecycle on the ISS using empirical data obtained in the Johnson Controls lab or psychrometric chamber at MSOE.

## 8. Prototype Testing

Upon testing the fully assembled water delivery device, the new drivetrain parts solved the problem of the fiction between gear teeth, but now the teeth are so smooth that the force from the constant torque spring and the angle of the teeth creates a force causing the gears to disengage themselves. Also, while testing the plunger cycling, the plunger started to get stuck. Before testing with water, the plunger slid up and down with little to no resistance. Some water splashed on the device and this could have caused the PLA to expand. Another issue found was that after the constant torque spring is wound, the free end of the shaft twists.

The first time the timing mechanism was wound and tested, the device ticked for approximately five days. Each successive attempt yielded shorter times. The calculated rotation rate of the shaft was one rotation every 47 hours. This is slightly faster than designed for but more than acceptable for the watering timing. Full discussion of prototype testing can be found in the full reports (ISSa (a), 2019), (ISSa (b), 2019).

## 9. Conclusion

Team ISSa has worked diligently to create a prototype comprised of both the water delivery device and the timing mechanism. The water delivery device was updated with a new locking mechanism, and gears were implemented with a new material to reduce friction. The timing device was assembled so that the power supply and limiter could be housed together. A connection system was designed and assembled to join the timing mechanism and the water delivery device. A trigger system was implemented that allows the timing mechanism to trigger a watering cycle. Though the final device does not function perfectly, it suffices to prove that with minor adjustments (as discussed in the recommendations section of the full Spring Design Report) the device will function correctly in microgravity (ISSa (b), 2019). The device was further proved feasible with the completion of surface tension experiments. From these experiments, it was concluded that the watering schedule should be reduced to account for the surface tension in order to allow an ample wet/dry cycle for the plant roots. The plant experts were able to produce healthy, mature Outredgeous lettuce throughout the spring quarter, so an appropriate plant environment and watering schedule was determined from these successful plant experiments. Team ISSa presented the work to NASA on the 5th and 6th of May 2019 with a goal to eventually obtain approval from NASA's technology review board in order to ultimately send the device to the ISS for final testing.

**Acknowledgments**

Team ISSa would like to thank: the Wisconsin Space Grant Consortium for funding this project; the Project Veggie team and Dr. Gioia Massa for all of the guidance over the course of the project; Vulcan Springs for supplying the springs used to power the Delivery Device; Professor Michael Swedish for advising our team; Roger Hajny, Rich Phillips, and Justin Sommer for all of their help and advice; and the Rapid Prototyping Center at MSOE.

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