System Specifications

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1.0 Introduction

Conventional agricultural methods overcompensate plant and soil needs through wasteful watering practices and excessive application of pesticides and fertilizers, leading to substantial environmental damage. This damage takes on various forms, including pollution via runoff, soil depletion, and the extinction of local pollinators.

1.1 Requirements

NILE has chosen to combat this issue with a system designed to nurture crops between the planting harvesting phases. This system will make optimal use of available resources via the precise application of water and nutrients to crops. To achieve this NILE has defined the following requirements.

a. The system shall be capable of measuring the water saturation for the soil at any point within the growing zone.
b. The system shall be capable of measuring the pH-level of the soil at any point in the growing zone.
c. The system shall be capable of measuring the temperature of the growing zone.
d. The system shall be capable of irrigating crops within the growing zone with a field application efficiency greater than 90%.
e. The system shall be capable of supplying the nutrients needed to maintain plant health within the growing zone.
f. The system shall be capable of exterminating weeds from any point in the growing zone.
g. The system shall be capable of determining the location of plant foliage, plant stems, and weeds within the growing zone.
h. The system shall be capable of being certified to an ingress protection level of IP55.
i. The system shall be capable of communicating plant health, soil health, and the detection of weeds to the end user.

2.0 Conceptual Design

After a lengthy conceptual design process in which a variety of possible implementations were considered, we settled on a cylindrical robot operating in a raised bed. The growing zone will be a doughnut shape with an outer diameter of 2 meters and an inner diameter of 0.5 meters. This configuration will allow for a realistic proof of concept while providing a path to scalability in the future.

2.1 Mechanical Concept

To support our chose growing zone we took inspiration from the ubiquitous center-pivot irrigation system for our conceptual design. Our proposal consists of a rotational joint about the center of the growing zone, a horizontal translational joint along the spinning gantry, and a vertical translational joint at the end effector. With these three joints the robot can reach any point within the growing zone in a precise, easy to implement, manner. As can be seen in the render below.

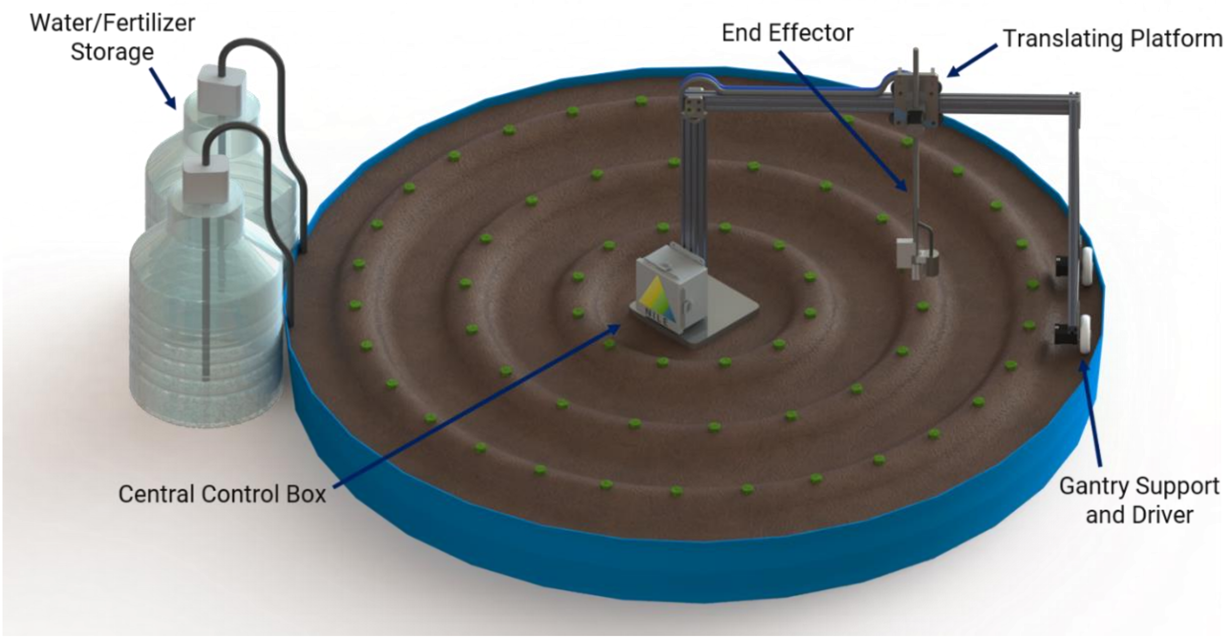

Figure 1. System Conceptual Design Render

To support its various operations, the NILE system will draw power directly from the grid along with water and liquid fertilize from two storage tanks. Rotation will be achieved via motorized wheels at the end of the rotating gantry to maximize torque. The angle of rotation will be determined by an encoder located at the central tower. The translating platform will move along the gantry via high friction wheels with position determination based up absolute distance from the center.

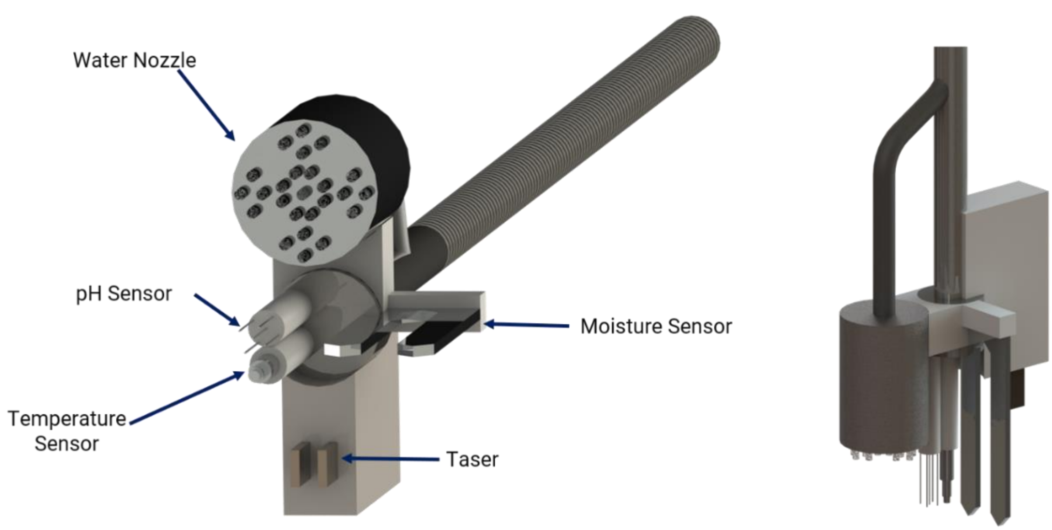

Figure 2. End Effector Conceptual Design Render

Watering, fertilizing, sensing, and weeding will be performed by an omnibus end effector that vertically translates on afore-mentioned translating platform. This omnibus will consist of a nozzle for watering and fertilizing, a taser type system for weed elimination, and various sensors. Furthermore, a stereoscopic imaging system will be mounted directly to the translating platform to provide imaging and depth information to the system.

2.2 Electrical Conceptual

Power distribution on the robot will be relatively simple. 120 Vac mains power will be fed into a power supply which will be capable of outputting a medium level (10V-20V) voltage for motors, pumps, and the HVEC (High Voltage Elimination Circuit) and a logic level (3.3V – 5V) voltage for the computers and sensors. It would need to be capable of providing around 5 A-10 A of current in to ensure the motors are properly driven and to feed the HVEC.

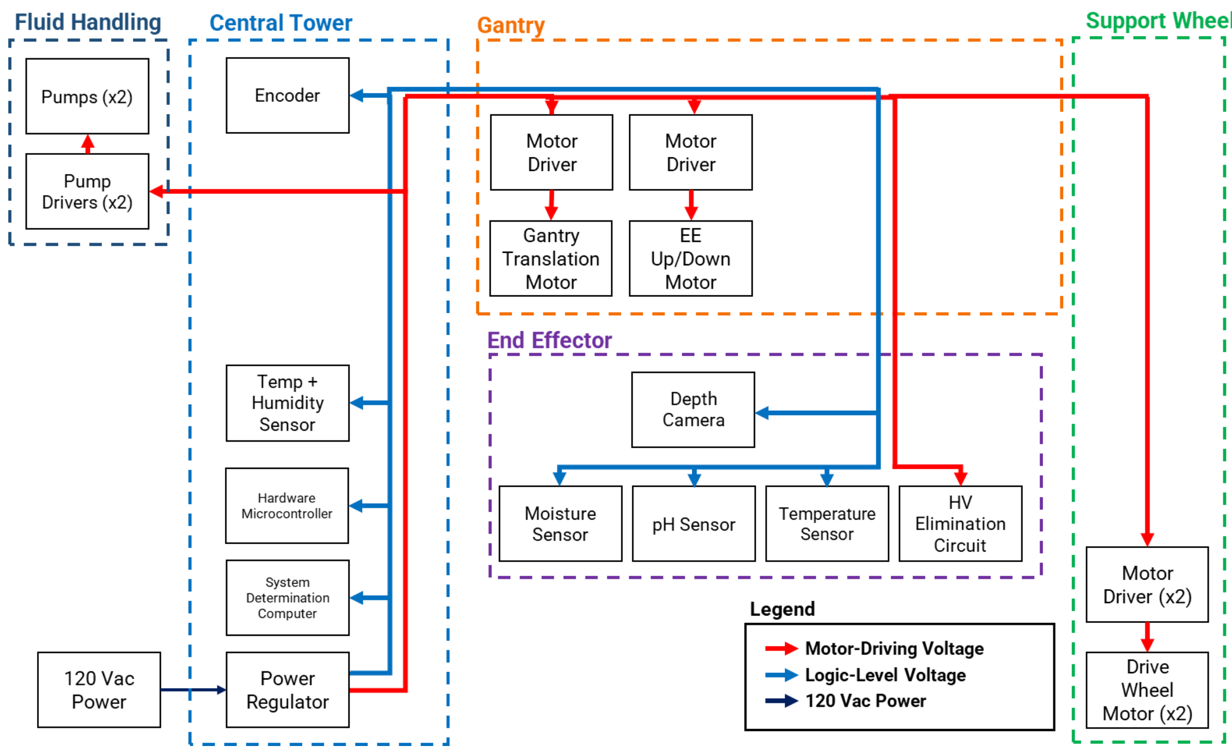

Figure 3. Electrical Block Diagram

The system will include two control units; a system determination computer (SDC) and a hardware microcontroller (HM). This system architecture allows for image and data processing to occur in parallel with low level motor control and data acquisition. The two computers will communicate via digital data line.

Acting as the brain of the system, the SDC will request data from the HM, process it, and then issue commands back to the HM to drive the motors. The SDC also uploads the processed data to an external server so it can easily be displayed to the end user via a web application. This server connection will be bidirectional so users can specify certain instructions (e.g., watering amounts, times, fertilizer thresholds, etc.) for the system to follow.

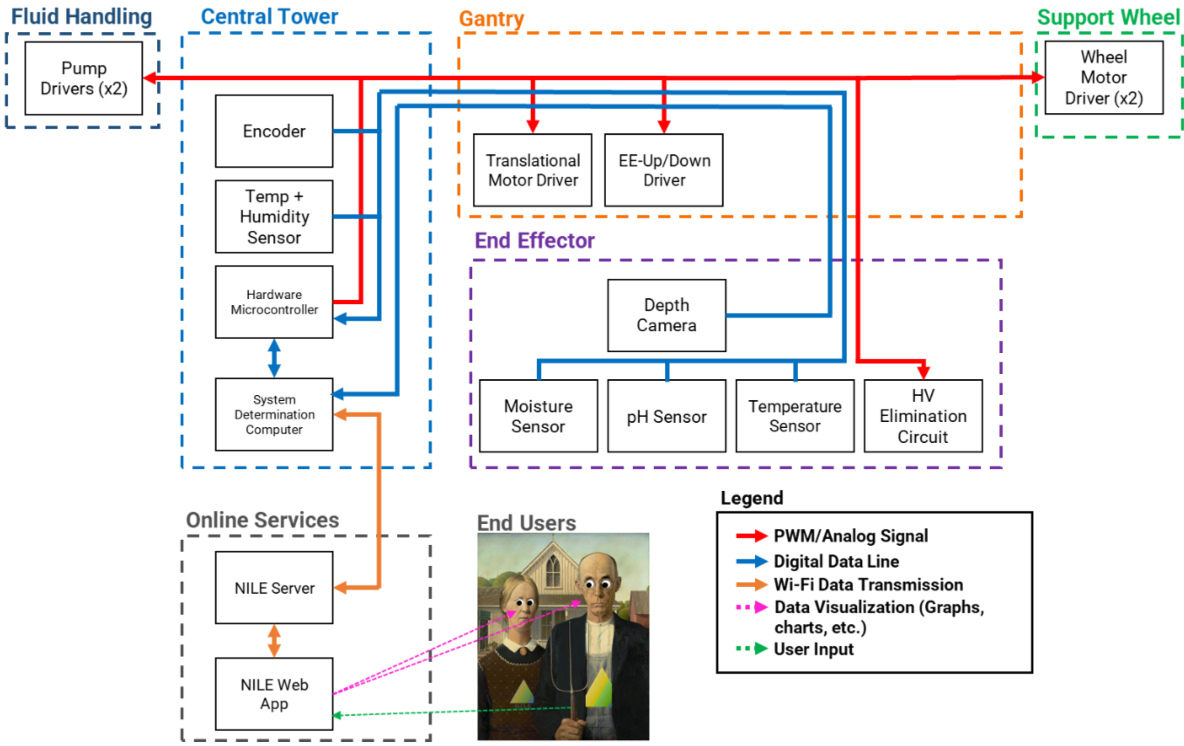

Figure 4. Data Block Diagram

2.3 Software Concept

To tend to plants within the growing zone, the system will implement a waypoint inspection algorithm. When not active, the system will remain in a computational sleep state. At regular intervals, the SDC will initiate inspection of the growing zone by positioning the end effector at predetermined waypoints for analysis. Upon reaching a waypoint, the SDC will capture an image from the stereoscopic camera and perform a combination of image processing and machine learning synthesis.

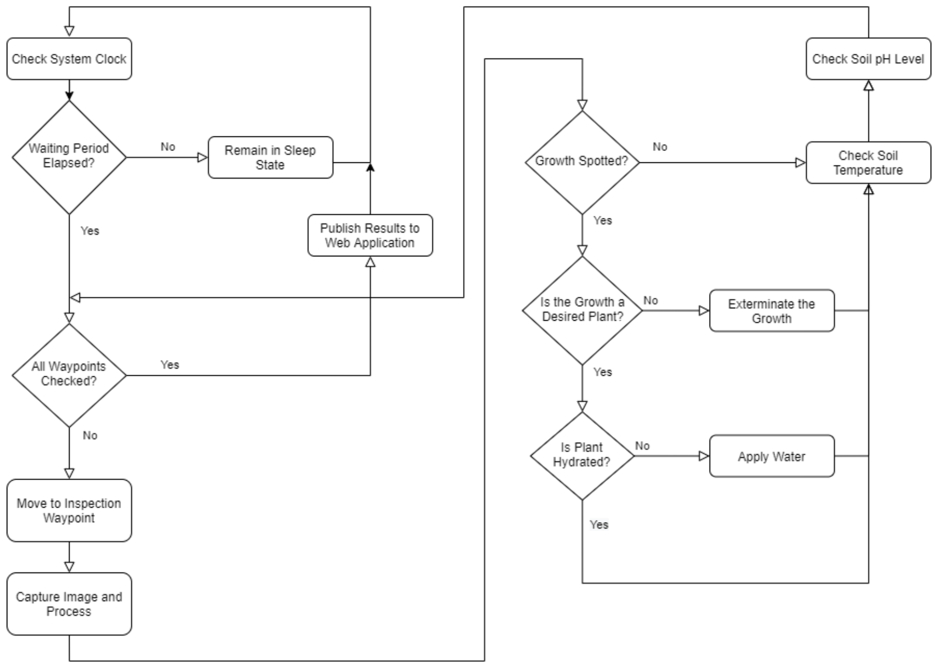

Figure 5. Plant Care Flowchart

The waypoints discussed above will be spaced such that a collage of images taken at each location will produce a complete picture of the growing zone. Then, using the capabilities of stereoscopic imaging, separation of foreground and background can be performed. Additionally, a point cloud of image depths can be applied to further to distinguish individual leaves and plant structures that overlap and occlude one another.

The determination of plant location and health metrics within the growing zone will be accomplished via a combination of computer vision image processing and machine learning inference.

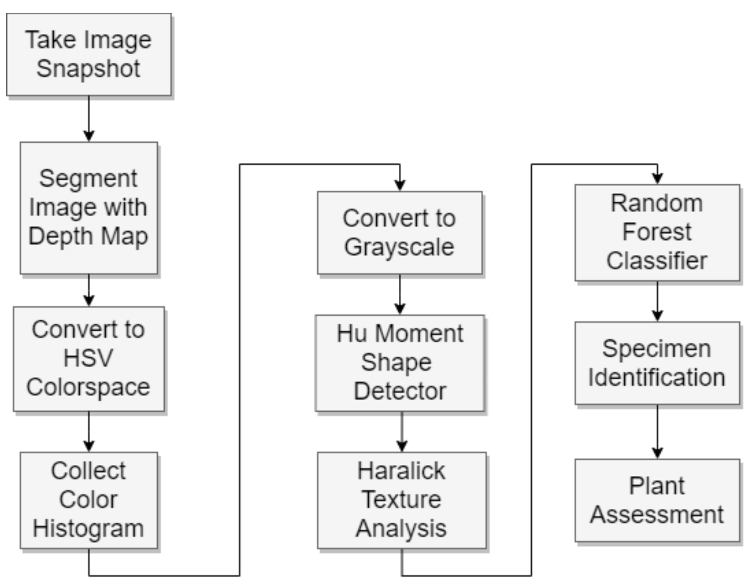

Figure 6. Plant Health Machine Learning Analysis

This algorithm, a form of supervised computer learning, will generate conclusions about the image contents in real time. Because the classifier is supervised, it will be pre-trained with a set of test images. This dataset will be a mixture of plants and weeds, healthy and unhealthy. When implemented, this classifier will be able to distinguish crops from weeds, as well as generating verdicts for healthy versus diseased leaf structures.

3.0 Plant Choice

Our conceptual design was made with the goal of supporting a wide range of plants and climates. However, due to time and climate constraints we have decided to choose a single plant to focus on for our capstone design.

Due to our capstone class schedule, we will start construction and start planting in early spring, 2022. In northern Arizona, this means wintry weather and morning frosts are common which limits our options. In addition, we have only four months to build, test, and finalize our design before graduation. All this boils down to requiring a cold-resistant and relatively fast-growing plant. Enter *Valerianella locusta*.

Figure 7. *Valerianella Locusta*

Valerianella locusta, or mâche as it is more commonly called, is a small leafy green that grows in a low rosette structure. Native to Europe, mâche has made its way around the northern hemisphere thanks to its hardness and small stature. Being able to survive temperatures as low as $-28.9°C$ and only requiring partial sunlight, it is perfect for our needs. [4]

4.0 System Requirements and Specifications

To solve the problems specified in the problem statement, the system must meet the standards and requirements outlined in the following section.

4.1 Measuring Soil Water Saturation

The system shall be capable of measuring the water saturation for the soil at any point within the growing zone. To achieve this, we define the following specifications.

1) The moisture sensor shall have a minimum resolution of ±5% field saturation.
   a) This value was chosen to ensure the system had sufficient resolution when determining how to water the soil.
2) The moisture sensor shall have an operating range of 0% – 100% field saturation.
3) The moisture sensor shall be capable of taking two independent readings within 10 cm of each plant's foliage exterior. Please refer to Appendix B: Plant Spacing Diagram for clarification.

To verify the resolution of the water saturation sensor, a series of test systems will be set up with a known amount of soil and water. The sensor will be directed to measure the saturation of the test soil and the measurement will be compared to the known ratio of water to soil.

4.2 Measuring Soil pH

The system shall be capable of measuring the pH-level of the soil at any point in the growing zone. To achieve this, we define the following specifications.

1. The pH sensor shall have a minimum resolution of ±0.5pH.
2. The pH sensor shall have an operating range including, but not limited to, 5pH to 8pH.
   a. Typical soil pH ranges are between 7pH – 7.8pH in Prescott, AZ. This range ensures coverage of that area and will give sufficient information on soil quality to the end user. [2]
3. The pH sensor shall be capable of taking two independent readings within 10 cm of each plant's foliage exterior. Please refer to Appendix B: Plant Spacing Diagram for clarification.

To verify the resolution of the pH sensor chosen, the measurements taken from the soil will be compared to a known pH sample. The results will be compared to ensure measurement is within a 0.5pH accuracy of the control.

4.3 Measuring Soil Temperature

The system shall be capable of measuring the temperature of the growing zone. To achieve this, we define the following specifications.

1) The temperature sensor shall have a minimum resolution of ±1°C.
2) The temperature sensor shall have an operating range including, but not limited to, -10°C to 50°C.
   a) The soil will more than likely only vary temperature between -4°C and 17°C in Prescott, AZ [2].
3) The temperature sensor shall be capable of taking two independent readings within 10 cm of each plant's foliage exterior. Please refer to Appendix B: Plant Spacing Diagram for clarification.

To verify the resolution of the temperature sensor chosen, the measurements taken from the soil will be compared to a known valid thermometer reading taken in the same spot. The two results will be compared to see if the chosen temperature sensor is within a 0.5°C accuracy of the control thermometer.

4.4 Application Efficiency

The system shall be capable of irrigating crops within the growing zone with a field application efficiency greater than 90%. Field application efficiency is defined below.

$$\frac{\sum Water\ Delivered\ to\ the\ Growing\ Zone}{\sum Water\ Input\ to\ the\ System} \times 100\%$$

To achieve this, we define the following specifications.

1) The liquid delivery system shall be capable of supplying water to the growing zone with a minimum rate of 40 mL/s.
2) The fluid distribution system shall be capable of measuring the flow rate of liquids input to the liquid delivery system and the flow rate liquids delivered to the end effector with a resolution of ±2 mL/s.
   a) ±2 mL/s was chosen to ensure sufficient resolution to verify the field application efficiency requirement.
      i) $40\frac{\mathrm{mL}}{\mathrm{s}} \times 90\% = 4\frac{\mathrm{mL}}{\mathrm{s}}\ (max\ uncertanty)$

To verify the resolution of the flow meter, the input will be attached to a pump and the output to a beaker on a scale. The flow rate will be determined by the time taken to supply a certain volume of water to the beaker and compared against the flow rate measured by the sensor.

The flow meters will be used to verify the field application efficiency and flow rate through the fluid distribution system.

4.5 Maintain Plant Health

The system shall be capable of supplying the nutrients needed to maintain plant health within the growing zone. To achieve this, we define the following specifications.

1) The liquid delivery system shall be capable of supplying user defined liquid fertilizer to the growing zone with a minimum rate of 10 mL/s.

The flow meters will be used to verify the flow rate through the fluid distribution system.

4.6 Exterminating Weeds

The system shall be capable of exterminating weeds from any point in the growing zone. To achieve this, we define the following specifications.

1) The system shall be capable of positioning the end effector with a resolution of Δe<±0.5cm in the r, and z directions and a Δθ(deg)<0.145° on the θ axis with respect to the growing zone origin.
   a) Given the 1-meter radius of the growing zone, the encoder shall have an angular resolution of at most 0.145º. This ensures that at maximum extension, the error in arc length is at most Δe.
      i) $\Delta\theta(\deg) < \frac{\Delta e}{4\pi r} * 360 \quad \rightarrow \quad \Delta\theta(\deg) < 0.145°$
2) The weed elimination end effector shall be capable of generating at least a 15kV pulsed arc with a discharge energy of at least 135 mJ [1].
   a) This is sufficient to eliminate small weeds (4 – 6cm in height with a 1–3 mm stem diameter [1]).

To verify the precision of the end effector, the PhaseSpace motion tracking system will be used. With this system, tracking LEDs placed on the system can determine positions with under 1mm precision to comply with the specification.

To verify the discharge voltage, the maximum distance between the high voltage prongs that can produce an arc will be measured. Since air has a breakdown voltage of 30kV/cm, the voltage that the system can produce can be safely determined through that distance.

To verify the discharge energy ($E_{discharge}$), the voltage (V) derived previously used alongside the capacitance (C) of the HVEC can be used in the following equation [1].

$$E_{discharge} = \frac{1}{2}CV^2$$

Alongside this, if the HVEC can destroy weeds after the application of high voltage, its operation will be verified.

4.7 Plant Location Determination

The system shall be capable of determining the location of plant foliage, plant stems, and weeds within the growing zone. To achieve this, we define the following specifications.

1) The detection algorithm shall be capable of determining the position of exterior plant and weed foliage with a resolution of +2 cm with respect to the stereoscopic camera in cartesian coordinates. [3]
2) The detection algorithm shall correctly differentiate between plants versus weeds with 99% identification accuracy.
3) The detection algorithm shall inspect the growing zone a minimum of twice per 24-hour period as the soil requires.
4) The detection algorithm shall complete all assessments prior to the start of the next inspection period.

To verify the precision of the plant detection, the PhaseSpace motion tracking system will be used. With this system, tracking LEDs placed in the growing zone can determine positions with under 1mm precision to comply with the specification.

4.8 IP55 Ingress Protection

The system shall be capable of being certified to an ingress protection level of IP55. To achieve this, we define the following specifications.

1) The system shall maintain satisfactory operation in the presence of dust after exposure to sunlight over the course of 30 day/night cycles.
2) The system shall maintain satisfactory operation when subjected to pressurized water delivered from a nozzle with a minimum diameter of 6.3mm after exposure to sunlight over the course of 30 day/night cycles.

To verify that the system maintains satisfactory operation after the specified time, the system will be directed to operate as normal for an additional 7 days. As it will be operating in an inherently dusty environment this will verify the specification. After the dust testing is complete, the system will be moved from the growing zone and subjected to pressurized water over the course of 30 minutes. If the system maintains satisfactory operation after being subjected to dust and pressurized water, then the system will be verified.

4.9 Communication

The system shall be capable of communicating plant health, soil health, and the detection of weeds to the end user. To achieve this, we define the following specifications.

1) The system shall send/receive data to and from a server through a WIFI connection, outgoing data will be displayed to the end-user via a web-application.
2) The web-application shall update the sensor readings within one minute of the system completing measurements.

The speed at which measurements are published to the end-user will be measured with a system clock that records the time between the system finishing all mechanical movements and receiving a data acknowledgement from the web-based application.

5.0 Conclusion

Overall, this conceptual design successfully meets all system requirements. It’s been a long journey from our initial problem statement to our conceptual design but with these specifications the path forward is increasingly clear. Using the requirements list, we crafted concise, testable specifications to guide the design as we move closer to a preliminary design. The specifications illustrate exactly what the system must do to satisfy individual requirements. Each specification was determined with testing in mind. Once a final product is reached, we can use the specifications to prove our design meets the goals required to solve the overall problem.

6.0 References

[1] A. Mizuno, T. Tenma and N. Yamano, "Destruction of weeds by pulsed high voltage discharges," Conference Record of the 1990 IEEE Industry Applications Society Annual Meeting, 1990, pp. 720-727 vol.1, doi: 10.1109/IAS.1990.152264.

[2] J. Schalau “The Soils and Climate of Yavapai County,” University of Arizona Cooperative Extension, [Online], Available: https://cals.arizona.edu/yavapai/anr/hort/mastergardener/mgcourseresources/soilsandclimateofyavapaico.pdf [Accessed Oct. 21, 2021]

[3] MartyG, “Achieving high accuracy with L515 or D415,” [Forum] Available: https://support.intelrealsense.com/hc/en-us/community/posts/360049091914-Achieving-high-accuracy-with-L515-or-D415 [Accessed: Oct. 18, 2021].

[4] S. Christman, “Valerianella Locusta,” Floridata, Jan. 23, 2021, [Online], Available: https://floridata.com/plant/732 [Accessed Oct. 21, 2021]

7.0 Appendix A: Tabulated Specifications

Req.	Spec.	Description
1	1	The moisture sensor shall have a minimum resolution of ±5% field saturation.
1	2	The moisture sensor shall have an operating range of 0% to 100% field saturation.
1	3	The moisture sensor shall be capable of taking two independent readings within 10 cm of each plant's foliage exterior.
2	1	The pH sensor shall have a minimum resolution of ±0.5pH.
2	2	The pH sensor shall have an operating range including, but not limited to, 5pH to 8pH.
2	3	The pH sensor shall be capable of taking two independent readings within 10 cm of each plant's foliage exterior.
3	1	The temperature sensor shall have a minimum resolution of ±1°C.
3	2	The temperature sensor shall have an operating range including, but not limited to, -10°C to 50°C.
3	3	The temperature sensor shall be capable of taking two independent readings within 10 cm of each plant's foliage exterior.
4	1	The liquid delivery system shall be capable of supplying water to the growing zone with a minimum rate of 40 mL/s.
4	2	The fluid distribution system shall be capable of measuring the flow rate of liquids input to the liquid delivery system and the flow rate liquids delivered to the end effector with a resolution of ±2 mL/s.
5	1	The liquid delivery system shall be capable of supplying user defined liquid fertilizer to the growing zone with a minimum rate of 10 mL/s.
6	1	The system shall be capable of positioning the end effector with a resolution of $\Delta e<\pm 0.5$cm in the r, and z directions and a $\Delta\theta(deg)<0.145°$ on the θ axis with respect to the growing zone origin.
6	2	The weed elimination end effector shall be capable of generating a 15kV pulsed arc with a discharge energy of 135 mJ.
7	1	The detection algorithm shall be capable of determining the position of exterior plant and weed foliage with a resolution of +2 cm with respect to the stereoscopic camera in cartesian coordinates.
7	2	The detection algorithm shall correctly differentiate between plants versus weeds with 99% identification accuracy.
7	3	The detection algorithm shall inspect the growing zone twice per 24-hour period.
7	4	The detection algorithm shall complete all assessments prior to the start of the next inspection period.
8	1	The system shall maintain satisfactory operation in the presence of dust after exposure to sunlight over the course of 30 day/night cycles.
8	2	The system shall maintain satisfactory operation when subjected to pressurized water delivered from a nozzle with a minimum diameter of 6.3mm after exposure to sunlight over the course of 30 day/night cycles.

9	1	The system shall send/receive data to and from a server through a WIFI connection, outgoing data will be displayed to the end-user via a web-application.
9	2	The web-application shall update the sensor readings within one minute of the system completing measurement.

7.0 Appendix B: Plant Spacing Diagram

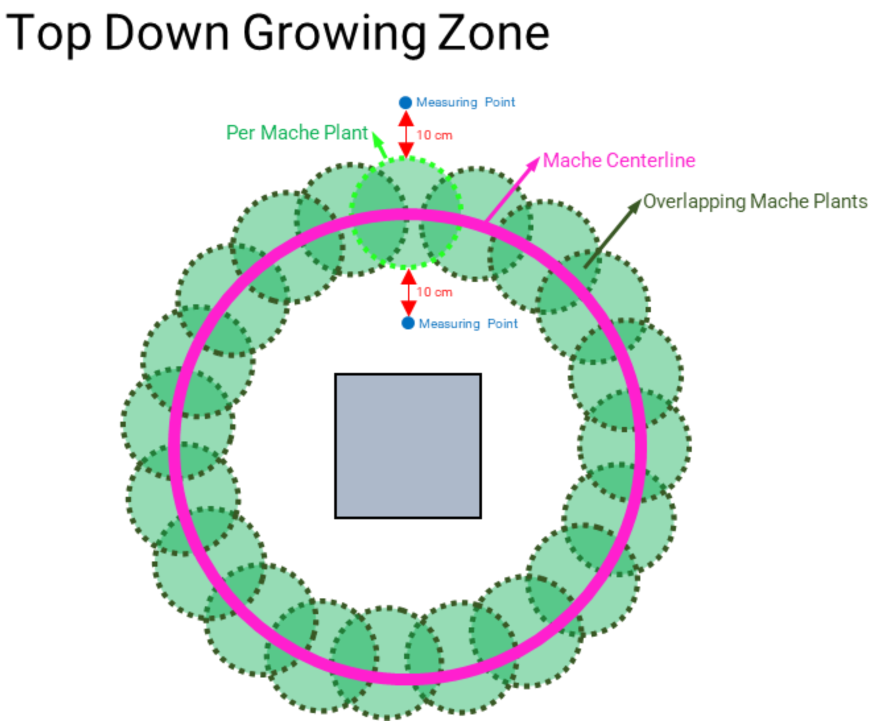

Figure 8: Plant Spacing Diagram