

# Optimization of Hemispherical Imaging System for Subterranean Root Detection

Spring 2026 Team 101

By Liam Thompson, Areg Gevorgyan, Alan Ilinskiy

# Abstract

This project focuses on the continued development of a root imaging system, building on the work completed by the previous semester's group. Root imaging is important because roots play a major role in plant growth, nutrient uptake, water absorption, and overall crop health, but they are difficult to observe without disturbing the plant or soil. The goal of this project was to create a more reliable and automated device that can capture images of roots in a controlled way for research and analysis. Our design uses a battery-powered system with a camera, Raspberry Pi, custom PCB, STM32 microcontroller, motor subsystem, encoder feedback, and onboard power regulation. The system is intended to move the camera across a fixed distance while maintaining stable power, controlled motion, and image capture. The project demonstrates progress toward a portable root imaging platform that can help collect consistent visual data for studying root structure and plant development.

# Table of Contents

<b>1 Introduction</b> .....	<b>1</b>
1.1 Solution.....	2
<b>2 Design</b> .....	<b>5</b>
2.1 High Level Description.....	5
2.2 Control Subsystem.....	6
2.2.1 Raspberry Pi.....	7
2.3 Power Subsystem.....	8
2.3.1 Power Budget.....	8
2.3.2 Regulator Design.....	10
2.4 Motor Subsystem.....	11
2.5 Camera Subsystem.....	12
<b>3 Verification</b> .....	<b>12</b>
3.1 Power.....	12
3.2 Programming.....	12
3.3 Motor Control.....	13
3.4 Image Capture.....	13
3.5 Integration.....	14
3.6 Lighting.....	14
<b>4 Ethics and Safety</b> .....	<b>15</b>
4.1 Societal Impact.....	15
4.2 Engineering Standards.....	15
4.3 Code of Ethics.....	16
4.4 Electrical and Mechanical Safety Concerns.....	16
4.5 Safety Procedures and Mitigation.....	17
<b>5 Costs</b> .....	<b>18</b>
<b>6 Conclusion</b> .....	<b>20</b>
<b>References</b> .....	<b>21</b>
<b>Appendix A</b> .....	<b>22</b>

# 1 Introduction

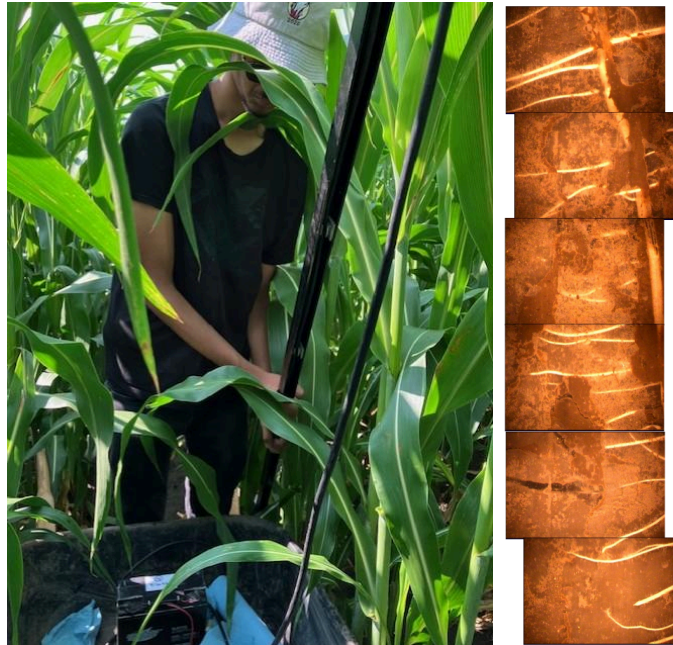


Figure 1a (left): Example of field operation of Bartz root imaging system  
Figure 1b (right): Example output image for Bartz. Note that the sub-images are monochromatic and not automatically aligned.



Figure 2a (left): Example of field operation of CI-60X Series root imaging system  
Figure 2b (right): Example output image for CI

Understanding root growth is important because roots directly affect how plants absorb water and nutrients, anchor themselves in soil, and respond to environmental stress. While the above-ground portion of a plant is easy to observe, the root system is much harder to study because it is hidden underground and can be disturbed or damaged during measurement. A root imaging system allows researchers to collect visual data of root development over time

without needing to remove the plant from its environment. This makes it useful for studying plant health, growth patterns, and how different conditions affect root structure

The typical way of imaging root systems is to plant a transparent tube in the ground, then insert a device which images the interior surface of the tube. The conventional way of doing this is to design a semi-automated device which rotates, then to combine images captured at different angles and elevations within the tube.

There are currently two main commercial solutions for root imaging, both of which implement this method. The Bartz system (Fig. 1a) was developed in the 1980s and has limited support today, in addition to providing poor image quality by modern standards (Fig. 1b). The CI-60X series provides a substantial improvement in image quality at the cost of reliability, as the system is cheaply assembled using parts re-used from a printer scanner and must travel vertically through the tube using unreliable rubber wheels that cling to the tube using friction

## 1.1 Solution

Our solution is a different type of device referred to as a minirhizotron. Rather than pointing cameras outward, the minirhizotron consists of a shuttle that translates down the tube (Figs 3, 4) containing a single camera pointing downward at a conical mirror (Fig. 5). A simple polar to rectangular transformation will recover a thin slice of the inner surface of the tube so many images captured sequentially may be stitched together to recover the entire root system. Figure 6a depicts an example raw image and figure 6b depicts the result of stitching many such processed images. This approach allows our solution to image deeper roots and remain more mechanically stable than CI's solution, while also being simpler than the Bartz system.

This project focuses on the continued development of a root imager that was originally started by a group in the previous semester. The overall goal of the device is to capture images of roots in a controlled and repeatable way by moving a camera along a fixed path while maintaining reliable power, motor control, and image capture. Our team iterated on the previous design by improving the electrical system, redesigning the PCB, selecting a new microcontroller, adding regulated power supplies, and testing the motor and encoder system used to control camera movement.

The final system consists of a battery-powered device containing a camera, Raspberry Pi, custom Printed Circuit Board (PCB), STM32 microcontroller, motor subsystem, encoder feedback, and onboard 5 V and 3.3 V power regulation (fig. 7). The device is intended to support field operation while providing consistent motion and image capture for root analysis. This semester's work focused on building a functional prototype, verifying the major subsystems, and identifying areas for future improvement, including camera integration, lighting, and image processing.

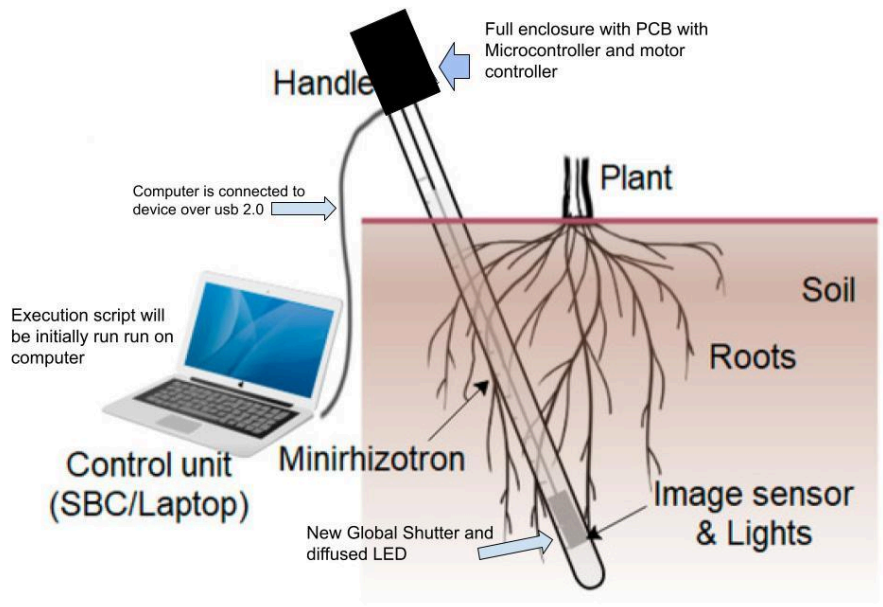


Figure 3: Generic minirhizotron schematic

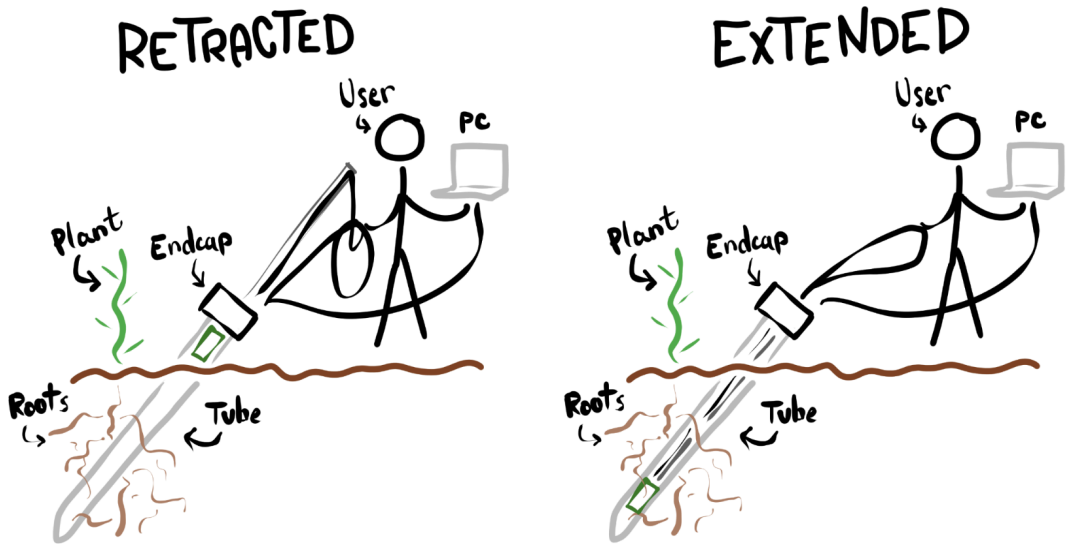


Figure 4: Cartoon depicting the expected operation

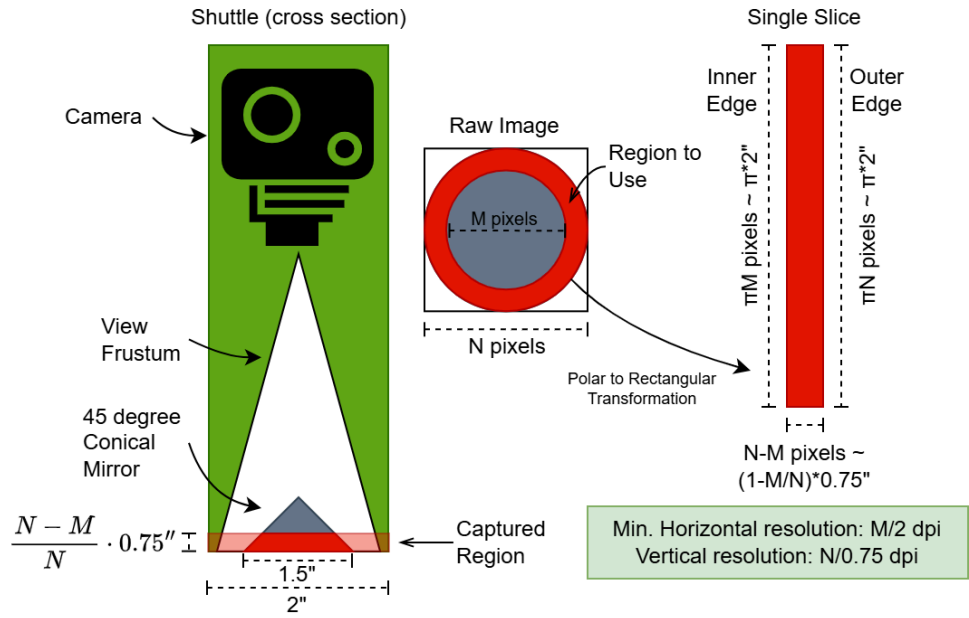


Figure 5: Schematic depiction of the minirhizotron image capture and unwrapping process, showing the expected resolution of each resulting slice.

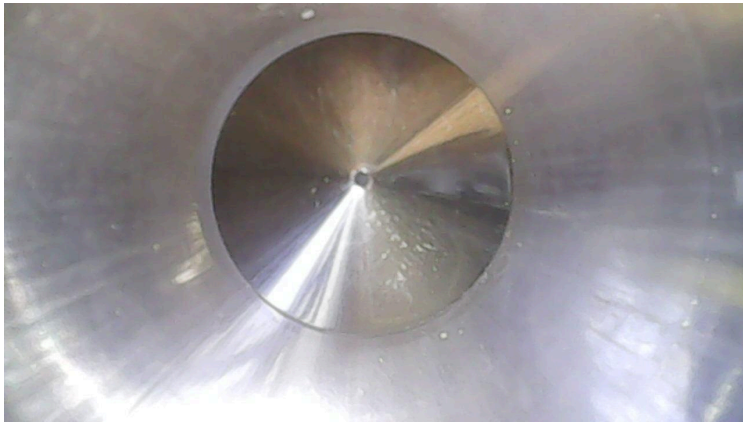


Figure 6a (left): Example raw image  
Figure 6b (right): Example output image (3" height) depicting a ruler and torn sticky note. Glare from the window visible in Fig. 6a is reproduced in the center of the image.

## 2 Design

### 2.1 High Level Description

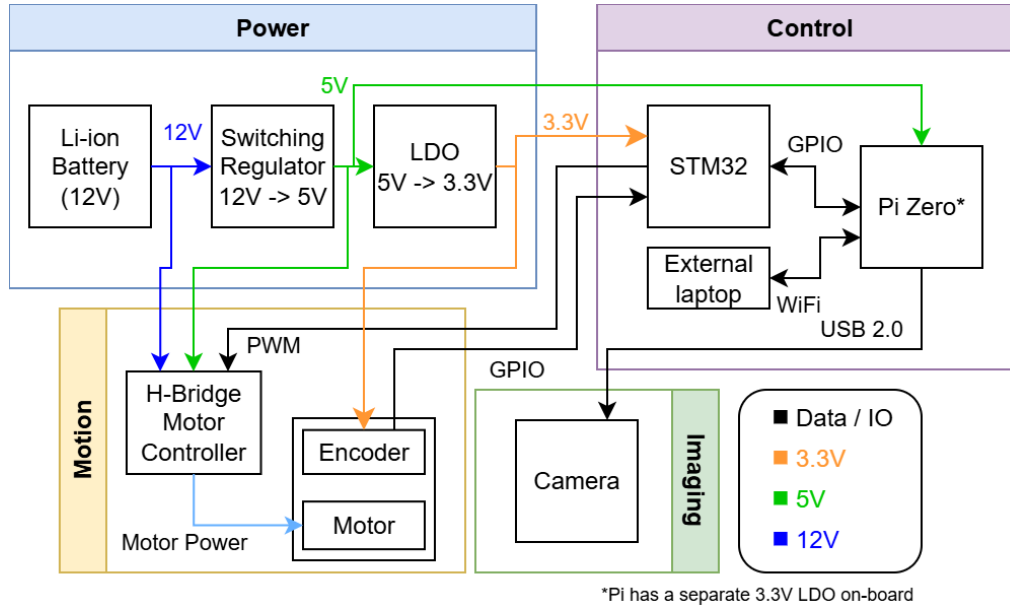


Figure 7: Block diagram of our design

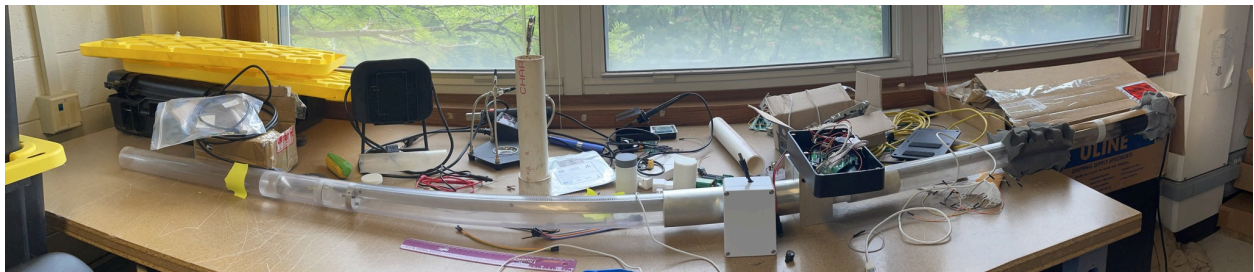


Figure 8a (top): Panoramic photo of the entire design  
Figure 8b (bottom): Photo of the electrical design enclosure

The device consists of a tube and endcap (fig. 8a). The tube inserts into the ground as depicted in fig.s 3 and 4, and rests on the endcap. A shuttle containing a camera and conical mirror is mounted on a gear rack which travels in this tube. The endcap has enclosures containing the 12 V battery, custom PCB, and Raspberry Pi, (fig. 8b). A gear motor coupled to the rack is also mounted to the endcap. The purpose of the device (the “root imager”) is to move a camera along a controlled path so that it can capture images of plant roots in a consistent and repeatable way. The root imager is designed to be portable and battery powered, allowing it to be used in the field.

At a high level, the Raspberry Pi is responsible for handling image capture and higher-level system control, while the custom PCB manages the lower-level electrical and motion-control functions. The PCB includes the STM32 microcontroller, power regulation circuitry, motor driver circuitry, encoder connections, Universal Serial Bus (USB) connections, and other supporting components. The motor subsystem moves the camera through the imaging area, and encoder feedback allows the system to track how far the camera has moved.

The device is powered by a 12 V lithium-ion battery. Since the different components require different operating voltages, the PCB steps the battery voltage down to 5 V and 3.3 V rails. The 5 V rail powers higher-current components such as the camera, Raspberry Pi, and motor driver, while the 3.3 V rail powers the microcontroller unit (MCU) and other logic-level devices. This allows the root imager to operate as a self-contained system with controlled motion, image capture, and onboard power management.

## 2.2 Control Subsystem

Our central MCU is an STM32H7S3 in the 100 pin LQFP package. This model of MCU was chosen primarily for its integrated USB 2.0 Physical Layer (PHY), eliminating the need for an external PHY [1]. The selected package was the minimum size available which included this feature but was hand-solderable.

In our design document we proposed using an STM32N6 series controller, which also includes an integrated USB 2.0 PHY in addition to being considerably more powerful and having more RAM. We elected to use an H7 series instead because N6 series MCUs are not available in hand-solderable packages, cost over twice as much, and would be considerably more complex to set up while gaining relatively little benefit in terms of the chip’s capabilities.

Due to the limited RAM on our MCU (384 KB), we added an external 8 MB RAM designed to interface over QSPI (Quad Serial Parallel Interface) [2], which would be capable of buffering one or two 3 MP images depending on the format used. The MCU supports higher width generic RAM interfaces using its Flexible Memory Controller (FMC) [1], however this would have been considerably more complex to set up and the reported read/write speeds for the selected RAM were sufficient for our expected throughput (133 Mbit/s write, 90 Mbit/s read

[2]). Ultimately the RAM was not used as image processing was moved off-board to the Raspberry Pi.

Two USB ports were included in the PCB design, one for the 2.0 port on the MCU and another for the 1.0 port. The expectation was that the MCU could interface with a PC on the USB 1.0 port for control or image transfer, and included for future design flexibility. The USB 2.0 port was intended to power and communicate with the LEO2 camera, which turned out to be infeasible.

An SD card port configured for 4-bit MMDC communication was also included in the expectation that it would provide removable flash memory for storing either raw images or the final output image, which could then be retrieved by the user for further processing by removing the card. This feature was also not used as the FatFS library used for interfacing with the SD card was too large to fit on the MCU's internal flash memory.<sup>1</sup>

### 2.2.1 Raspberry Pi

When initially designing the root imager we wanted to control a USB 2.0 camera directly off of an on-board microcontroller. We assumed that a powerful MCU with explicit USB support and associated rich driver environment would have an appropriate webcam driver available, but this turned out not to be the case. In fact, Universal Video Class host controller drivers are not available for STM32. We determined that developing a custom driver would be too time consuming and instead moved image capture off-board to a Raspberry Pi Zero.

This choice also allowed us to take advantage of the superior processing power available on the Pi to perform local image processing, a task that likely would have overwhelmed the MCU.

---

<sup>1</sup> Specifically, a test program designed to create and write to a text file exceeded the on-chip memory by over 32 KB. A future revision would ideally include additional on-board flash memory for the MCU to avoid this issue.

## 2.3 Power Subsystem

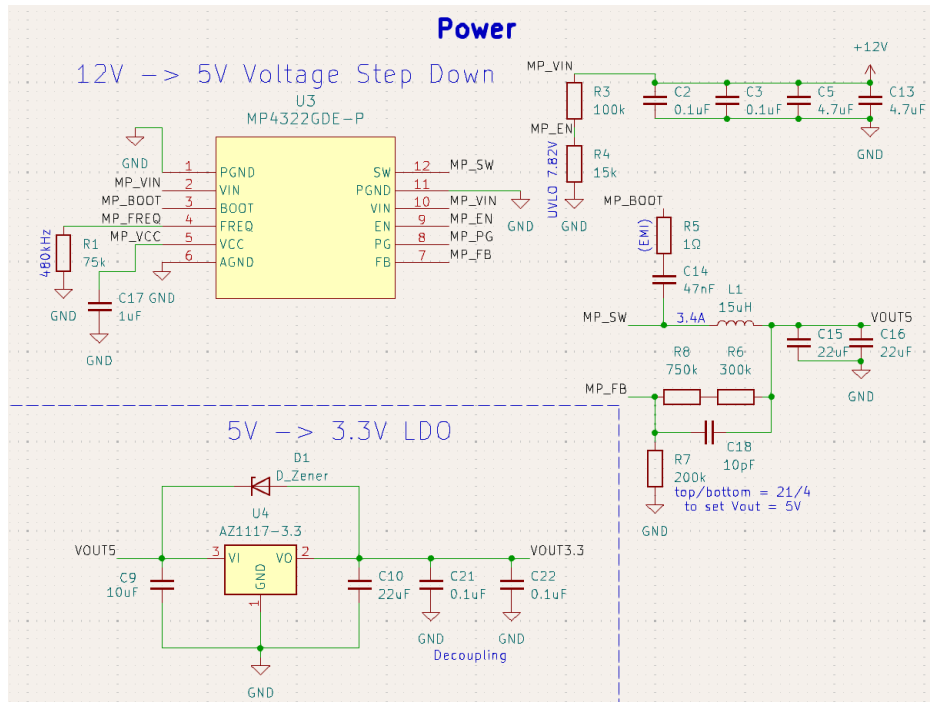


Figure 9: Power Subsystem Schematic

The board is intended to be powered from a 12 V battery supply. USB power and the H-bridge require a 5 V supply [3] while the MCU and associated peripherals require a 3.3 V supply.

A 7AH 12 V Lithium-ion battery was chosen for its high capacity theoretically allowing several hours of continuous operation in the field, as well as relative stability compared to other high energy supplies such as Lithium-polymer batteries.

Stepping down from 12 V to 5 V using an LDO would make our system considerably less efficient, whereas a switching step down regulator can achieve >90% efficient conversion [4], so we chose to use a switching regulator. The 5 V to 3.3 V conversion is a much smaller step down so we used an LDO available from the ECEB.

### 2.3.1 Power Budget

The components we initially anticipated powering from the LDO added up to about half an amp (tab. 1) meaning that a 1 A regulator would give us considerable headroom. Additionally, since our estimate for the MCU was assuming fairly unconservative operating conditions, it is likely that the design would draw considerably less power than our budget suggests.

The power consumed by the LDO was computed as follows. Using eq 1.8 from [5], taking  $I_q=40\text{mA}$  based on Fig. 4 from [6]<sup>2</sup> and assuming that  $I_{in}=I_{out}$  we found that  $P_{in}=2750\text{ mW}$ .

$$V_{in}(I_{in} + I_q) = P_{in}$$

We initially expected to power the encoder off the 5 V supply, however its current consumption is negligible so it did not factor meaningfully into the design. As seen in table 2 we required the 5 V supply to provide over 1 A. To achieve a safety factor  $\sim 2$  we decided to use an externally sourced 2 A adjustable regulator.<sup>3</sup>

Table 1: 3.3 V Power Budget

Component	Power (mW)	Current (mA)
MCU [1] <sup>4</sup>	1320	400
RAM [2]	33	10
SD Card [8]	330	100
<b>Total</b>	<b>1683</b>	<b>510</b>

Table 2: 5 V Power Budget

Component	Power (mW)	Current (mA)
LDO	2750	550
Camera [9]	3300	660
H-Bridge [3]	300	60
Encoder [10]	10	2
<b>Total</b>	<b>6360</b>	<b>1272</b>

<sup>2</sup> For the power budget we assumed our LDO would be LM3940; our final design instead used AZ1117 for the smaller footprint. AZ1117 has a much smaller maximum  $I_q$  of 6 mA [7] and should consume less power.

<sup>3</sup> A fixed output 2 A regulator could not be sourced at a reasonable price and with a simple footprint.

<sup>4</sup> Assuming operation at 105 C at 600MHz using the internal LDO with AXI SRAM, USB OTG, and SDMMC enabled [1].

## 2.3.2 Regulator Design

The 3.3 V and 5 V regulator design followed directly from the recommended layout on the datasheet (fig. 10). Some design was required to achieve the desired functionality of the switching supply.

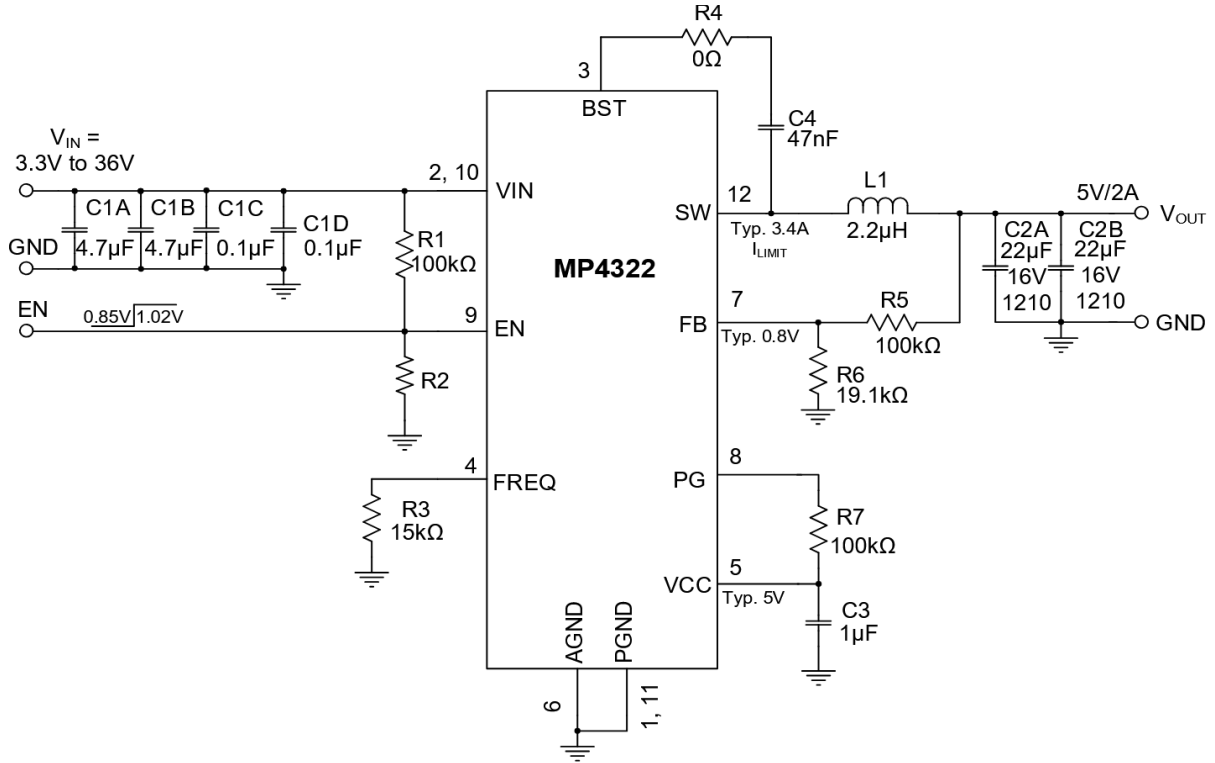


Figure 10: MP4322 Typical Application Circuit for 5 V output at 2.2 MHz (fig. 7 in [4])

The switching frequency was configured to 480kHz based on Table 2 in [4], which is considerably lower than the operating frequencies of the high-speed USB and QSPI busses associated with the MCU as well as being near the switching frequency used in 12 V to 5 V tests described in the datasheet.

For conversion from 12V to 5V the feedback resistors R5 and R6 must be in ratio 21/4 based on equation 4 from [4] (eq 1):

$$\frac{R_5}{R_6} = \frac{V_{OUT}}{0.8V} - 1 \quad (1)$$

We chose  $R_5=1050 \text{ k}\Omega$  ( $R_6+R_8$  in fig. 9) and  $R_6=200 \text{ k}\Omega$  ( $R_7$ ) based on the availability of precision resistors from the ECEB self service.<sup>5</sup>

<sup>5</sup> A 1% precision 301 k $\Omega$  resistor was ultimately used for R6 instead of 1% 300 k $\Omega$  because the 300 k $\Omega$  resistor in the eshop had leads that were too thick to fit in our chosen footprint. Eq ? predicts a resulting overshoot of 4 mV, but our tests resulted in considerably more overshoot (see table ?).

The inductor was chosen based on eq. 7 from [4] (eq. 2) and online availability.  $\Delta I_L$  is the peak-to-peak inductor ripple current, which the datasheet recommends to be 30% of the maximum load current, so  $\Delta I_L \sim 380$  mA, recommending  $L = 15.6$  uH. For 15 uH the ripple current is estimated at 405 mA.

$$L = \frac{V_{OUT}}{f \times \Delta I_L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \quad (2)$$

A 15uH inductor with saturation current 7A (>25% of 1.2 A) was selected for this purpose [s].

Layout followed the datasheet's recommendations, except that a 2 layer board was used instead of 4 layers. Via stitching was employed to minimize interference, however guard rings were not implemented.

## 2.4 Motor Subsystem

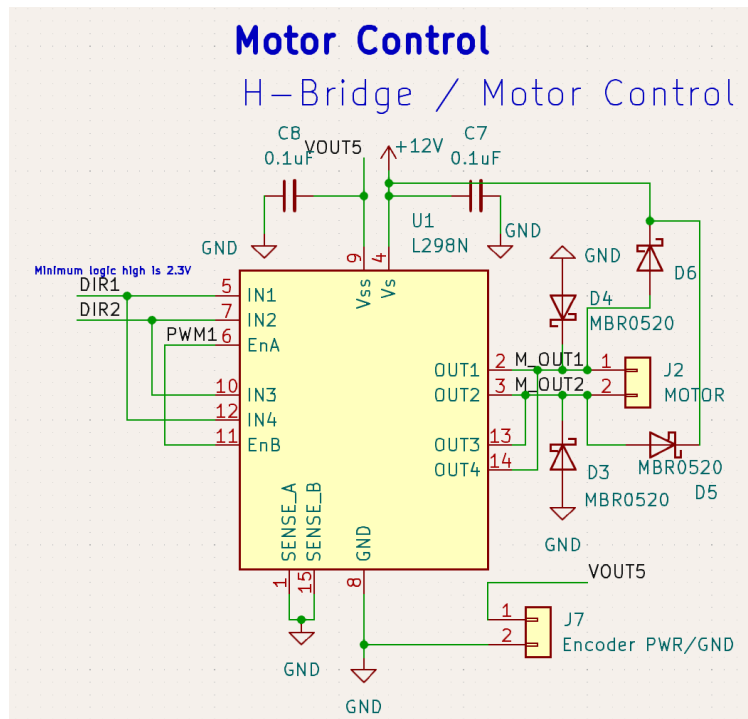


Figure 11: Motor subsystem schematic

The motor is controlled by an H-bridge motor controller which regulates the 12 V battery supply based on a Pulse-width modulated signal from the MCU. The H-bridge also allows the motor to be reversed by changing the output polarity based on the value conveyed by DIR1 and DIR2, also provided by the MCU. As seen in figure 11, the H-bridge was implemented following the datasheet guidelines [3]. Because the motor is an inductive load, Schottky diodes are placed between each output and power and GND to suppress backlash current.

## 2.5 Camera Subsystem

We were initially instructed by our sponsors to design around Vision Datum's LEO2 camera, which is listed to achieve 1.6 MP resolution and interface over USB 3.0 [9]. However, once the camera arrived, we realized that it requires a CPU with proprietary drivers in order to run, and we did not have much time to install it into the physical design, so we decided to re-use the 0.3 MP USB 2.0 camera used last semester [11].

## 3 Verification

### 3.1 Power

As the system is intended to run off battery power, which can vary within a fairly wide margin around the nominal output voltage of the battery, we tested the on-board supplies when powered using different input voltages. Table 3 depicts the measured output of the 5 V and 3.3 V regulators for a variety of input voltages provided by a benchtop supply. No additional load was connected downstream of either supply for this test, except that the 3.3 V supply was downstream of the 5 V supply. Both supplies remained stable under both over- and under-charge conditions.

Table 3: Power Supply Output Test (no load)

<b>Board Input (V)</b>	<b>5V Supply (V)</b>	<b>3.3V Supply (V)</b>
12.5	5.036	3.310
12.0	5.032	3.310
11.5	5.034	3.310
11.0	5.046	3.310
10.5	5.046	3.310

### 3.2 Programming

After soldering the on-board MCU was connected to the SWD port on an STM32 Nucleo dev board. A simple script to blink the on-board LED was flashed from a computer. The LED was observed to blink shortly after flashing.

Flashing the MCU for the first time was noted to not require connecting the NRST pin to be connected, resulting in the flashed script persisting after power-down. Connecting the NRST pin is required to flash a new script. If the USB connection from PC to dev board is removed while the SWD is connected with NRST, then the dev board will reset the MCU, immediately erasing the current script. Disconnecting the SWD port before the USB connection was observed to allow the flashed script to persist even after power-down. This test fulfilled Requirement 4 of the R & V table (Appendix A).

### 3.3 Motor Control

Motor speed and direction control were first tested using a simple two-wire DC motor found in the lab. Before placing the L298N motor driver into the full PCB design, we breadboarded the L298N circuit separately to verify that the driver could properly control the motor. The STM32 control signals were connected to the L298N inputs, and the motor outputs were measured using an oscilloscope to confirm that the driver was receiving the correct signals and switching properly. Once the motor was able to spin both forward and backward and at slow and fast speeds under controlled input signals, we were confident that the L298N circuit was suitable to include on the final board. This satisfied Requirements 5 and 7 of the R & V table.

After verifying the motor driver separately, the actual motor and encoder were tested on the mechanical assembly. We used the encoder counts-to-inches ratio from the previous semester's code and created a test script that moved the motor a set distance by counting encoder pulses. The motor successfully moved the camera assembly 3 inches, confirming that the encoder feedback could be used to track distance. This showed that the motor subsystem could control direction, drive the assembly, and move the camera carriage by a measured distance as intended, satisfying Requirement 8 of the R & V table.

### 3.4 Image Capture

Image capture was handled by the Raspberry Pi rather than the STM32. During operation, the Raspberry Pi received signals from the STM32 after a set number of encoder cycles, causing it to capture images at consistent movement intervals. After the imaging sequence was completed, the captured images were stitched together into a final output image on the Raspberry Pi. To retrieve the result, we connected to the Raspberry Pi over SSH and used scp to transfer the stitched image from the Pi to a computer for viewing and analysis. This allowed the system to capture and export root images without needing to remove storage media from the device.

### 3.5 Integration

The major subsystems were tested together to verify that the root imager could operate as a combined prototype. The PCB was powered from the 12 V battery supply and provided

regulated 5 V and 3.3 V outputs for the system. A dedicated 5 V output pin was included on the PCB to power the Raspberry Pi, allowing the Pi to be integrated directly into the system power architecture. The STM32 controlled the motor through the H-bridge and used encoder feedback to track camera movement. Full synchronization between motion and image capture was achieved by having the STM32 signal the Raspberry Pi to take an image after a set number of encoder cycles. This allowed the device to move the camera and capture images at consistent distance intervals, demonstrating successful integration of the power, motor control, encoder, Raspberry Pi, and camera subsystems, fulfilling requirement 9 of the R & V table.

## 3.6 Lighting

While developing a new lighting system was initially part of our planned design our sponsors informally assumed additional responsibility for this aspect of the project, planning to move lighting off-board. Due to the minimal added electrical complexity of the lighting system and time constraints all our tests were performed above ground using ambient lighting rather than developing an integrated lighting solution.

# 4 Ethics and Safety

## 4.1 Societal Impact

Root imaging is important because root systems play a major role in plant health, water absorption, nutrient uptake, and crop resilience. However, roots are difficult to study because they are hidden underground and can be damaged if removed from the soil. Existing commercial root imaging systems can be expensive, difficult to maintain, and unreliable in field environments. This limits how easily researchers can collect root data, especially when working across many plants or long growing seasons.

Our project helps address this issue by continuing the development of a lower-cost and more field-ready root imager. By improving the electrical system, motor control, power regulation, and image capture process, our device makes it easier to collect consistent root images in a repeatable way. If further developed, this system could help researchers study drought resistance, flooding response, nutrient stress, and other plant traits more efficiently. This has a positive societal impact because better root research can support the development of stronger crops and more efficient agricultural systems.

The risk of misuse for this project is very low because the device is designed for a specific agricultural research purpose. The main ethical concern is data reliability. If the device captures distorted, incomplete, or poorly stitched images, researchers could draw incorrect conclusions from the data. Because of this, the system should be carefully validated before being used for serious research decisions.

## 4.2 Engineering Standards

Several engineering standards are relevant to this project. Since the device includes electronics used in field and greenhouse environments, electrical safety is important. IEC 61010-1 [12] is relevant because it covers safety requirements for electrical equipment used for measurement, control, and laboratory applications. Our system uses a 12 V lithium-ion battery, voltage regulators, a custom PCB, and motor control circuitry, so safe wiring, insulation, and protection from shorts are important.

Environmental protection is also important because the device may be exposed to dust, moisture, and outdoor conditions. IEC 60529 [13] is relevant because it defines enclosure protection ratings against dust and water. While the prototype was not fully weatherproofed, future versions should continue improving the enclosure so that the electronics are protected during field use.

Software reliability is another consideration. IEEE 730 [14], which relates to software quality assurance, is relevant because the system depends on software to control movement, trigger image capture, and stitch images together. The software should behave consistently so that images are captured at the correct intervals and the final output can be trusted.

### 4.3 Code of Ethics

This project relates closely to the IEEE and ACM Codes of Ethics [15, 16] because it involves building a system that may eventually be used to support agricultural research. One important ethical responsibility is to prioritize public welfare. By helping researchers better understand root growth and crop resilience, the project has potential benefits for food production, water efficiency, and environmental sustainability.

Another important ethical responsibility is honesty in design and reporting. Since this project builds on the root imager created by the previous semester's group, their work should be properly credited. The existing mechanical concept, imaging approach, and overall system architecture were not created from scratch by our team. Our contribution was to iterate on that work by improving the electrical design, power system, motor control, Raspberry Pi integration, and image capture workflow.

The project also requires honest reporting of limitations. Although the prototype demonstrated the core functions of the system, some goals were not fully completed, including the use of the LEO2 camera and the development of an integrated lighting system. Reporting these limitations clearly is important so future teams understand what was completed and what still needs improvement.

### 4.4 Electrical and Mechanical Safety Concerns

The main electrical safety concern is the 12 V 7 Ah lithium-ion battery. Although 12 V is a relatively low voltage, the battery can still provide enough current to damage components, overheat wires, or create a short-circuit hazard. The custom PCB, voltage regulators, Raspberry Pi, and motor driver must all be connected carefully to avoid incorrect wiring or accidental shorts.

There are also mechanical safety concerns. The motorized assembly moves the camera through the root imaging structure, so fingers, wires, or loose parts could get caught during operation. The rack and motor system should not be touched while powered. The device also has a tall mechanical structure, so stability is important when the system is extended or operating in the field.

## 4.5 Safety Procedures and Mitigation

To reduce electrical risk, power should always be disconnected before modifying wiring, changing PCB connections, or adjusting the motor driver circuit. The battery should be inspected before use and should only be charged with a compatible charger. The PCB should also be checked for shorts before connecting the Raspberry Pi, STM32, motor, or camera. To reduce mechanical risk, operators should keep their hands away from the moving rack, motor, and camera assembly while the system is running. The scan should be started from a safe position, and the device should be allowed to complete its movement without being touched. The mechanical assembly should also be inspected before each test to make sure nothing is loose, cracked, or blocking motion.

Overall, the project has positive social value and low misuse potential, but it still requires careful attention to electrical safety, mechanical safety, software reliability, and honest reporting of system limitations.

## 5 Costs

Table 4: Total Cost of All Parts Purchased or Used

Description	Qty	Unit Cost	Total
12V 7AH Li-Ion Battery	1	\$18.26	\$18.26
12 RPM Planetary Gear Motor w/Encoder	1	\$59.99	\$59.99
1.6 MP USB Camera (LEO2) <sup>6</sup>	1	\$710.00	\$710.00
0.3 MP USB Camera	1	\$9.90	\$9.90
20' USB Male to Male Cable	1	\$15.99	\$15.99
STM32H7S3V8T6	3	\$7.63	\$22.89
IS66WVR8M8FBLL 64Mb SRAM	3	\$6.39	\$19.17
MP4322 Switching Voltage Regulator	3	\$2.13	\$6.39
AZ1117 Linear Voltage Regulator	2	\$0.27	\$0.54
LM3940	2	\$2.00	\$4.00
SD Card Connector	3	\$2.08	\$6.24
USB Micro B Receptacle	6	\$0.44	\$2.64
15uH Power Inductor	2	\$2.22	\$4.44
STM32 Nucleo Dev Board	1	\$27.00	\$27.00
Misc SMD Capacitors	30	\$0.15	\$4.50
Misc Throughhole Resistors	24	\$1.00	\$24.00
Misc Throughhole Capacitors	20	\$0.20	\$4.00
Schottky Diodes	12	\$0.77	\$9.24
Physical Design [17]			\$700
<b>Total</b>			<b>\$1,649.19</b>

<sup>6</sup> The LEO2 we acquired was on sale. The standard price is listed here.

Table 5: Estimated Labor and Fabrication Costs

<b>Description</b>	<b>Qty</b>	<b>Rate</b>	<b>Total</b>
Alan Ilinskiy	65 hr	\$45.67/hr (x2.5)	\$7,421
Areg Gevorgyan	65 hr	\$45.67/hr (x2.5)	\$7,421
Liam Thompson	65 hr	\$45.67/hr (x2.5)	\$7,421
Machine Shop	15 days	\$420/day	\$6,300
PCB Fabrication [18]	3 sets of 5	\$25/set of 5	\$75
<b>Total</b>			<b>\$28,638</b>

Table 6: Grand Total

<b>Category</b>	<b>Cost</b>
Parts	\$1,649.19
Labor and Fabrication	\$28,638.00
<b>Grand Total</b>	<b>\$30,287.19</b>

## 6 Conclusion

This project continued the development of the root imager by building on the work completed by the previous semester's group and bringing the system closer to a complete, functional prototype. The main goal of the project was to create a device capable of capturing root images in a controlled and repeatable way, while also improving the reliability of the electrical, power, motion, and imaging subsystems.

Throughout the semester, the system was redesigned around a custom PCB, STM32 microcontroller, Raspberry Pi, camera, motor subsystem, encoder feedback, and onboard power regulation. The device was designed to run from a 12 V battery and generate the required 5 V and 3.3 V rails for the different components. Testing showed that the power supplies remained stable across a range of input voltages, which is important for a portable battery-powered system. The STM32 was successfully programmed and used to control the motor through the H-bridge, while encoder feedback allowed the system to track movement and move the camera in measured intervals.

A major accomplishment of the project was integrating motion control with image capture. The Raspberry Pi was powered from the PCB using a dedicated 5 V output pin, and the STM32 signaled the Pi after a set number of encoder cycles so that images could be captured at consistent distance intervals. After the image sequence was completed, the Raspberry Pi stitched the images together into a final output image, which could then be retrieved over SSH using `scp`. This demonstrated that the system could coordinate power, motor movement, encoder tracking, camera control, and image processing as one combined prototype instead of only testing each subsystem separately.

Overall, the project produced a working prototype that demonstrated the core functions needed for an automated root imaging system. The device was able to provide regulated power, control camera movement, track position through encoder feedback, trigger image capture at consistent intervals, stitch images together, and export the final result for analysis. Future work should focus on improving camera quality, integrating a more controlled lighting system, refining the mechanical design, improving image stitching reliability, and making the system easier to operate in field conditions. Even with the remaining improvements, this semester's work created a stronger foundation for future groups and showed that the root imager concept can be developed into a practical tool for root research and plant analysis.

# References

[1] Stm32h7s3x8 stm32h7s7x8, version 6, ST, Feb. 2026.

[2] Is66wvr8m8fall/bll is67wvr8m8fall/bll, version A1, ISSI, May 2025. [On-line]. Available: <https://www.issi.com/WW/pdf/66-67WVR8M8FALL-BLL.pdf>.

[3] Dual full-bridge driver, version 5, ST, Oct. 2023.

[4] 36v, 2a, configurable-frequency, low-iq, synchronous step-down converter with 42v load dump tolerance, version 1, MPS, Apr. 2023. [Online]. Available: [https://www.monolithicpower.com/en/documentview/productdocument/index/version/2/document\\_type/Datasheet/lang/en/sku/MP4322GDE/document\\_id/11048/](https://www.monolithicpower.com/en/documentview/productdocument/index/version/2/document_type/Datasheet/lang/en/sku/MP4322GDE/document_id/11048/).

[5] "Basics of low-dropout (ldo) regulator ics," version 4, Feb. 2025. [Online]. Available: [https://toshiba.semicon-storage.com/info/application\\_note\\_en\\_20250213\\_AKX00141.pdf?did=13766](https://toshiba.semicon-storage.com/info/application_note_en_20250213_AKX00141.pdf?did=13766).

[6] W. Fwu, "Understanding the foundations of quiescent current in linear power systems," Mar. 2021. [Online]. Available: <https://www.ti.com/lit/wp/slyy206/slyy206.pdf?ts=1773229858013>.

[7] Low dropout linear regulator, version 5 - 2, Diodes Inc., Sep. 2022. [Online]. Available: <https://www.diodes.com/assets/Datasheets/AZ1117C.pdf>.

[8] "How much current does a microsd card use?" [Online]. Available: <https://electronics.stackexchange.com/questions/33472/how-much-current-does-a-microsd-card-use/584020#584020>.

[9] Leo series area scan cameras, Vision Datum. [Online]. Available: [https://www.visiondatum.com/upload/down/Leo/VTENUSB/Datasheet\\_LEO2\\_1440S\\_250umuc\\_VT\\_EN\\_RLS.pdf](https://www.visiondatum.com/upload/down/Leo/VTENUSB/Datasheet_LEO2_1440S_250umuc_VT_EN_RLS.pdf).

[10] Ne12 magnetic encoder use parameter, Servocity.com. [Online]. Available: [https://www.servocity.com/content/downloads/ne12\\_use\\_Parameter.pdf](https://www.servocity.com/content/downloads/ne12_use_Parameter.pdf).

[11] 0.3 megapixels usb camera for raspberry pi and nvidia jetson nano, DFRobot. [Online]. Available: [https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/2719/FIT0701\\_Web.pdf](https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/2719/FIT0701_Web.pdf).

- [12] IEC. (2010). IEC 61010-1: Safety requirements for electrical equipment for measurement, control, and laboratory use – Part 1: General requirements (3rd ed.). International Electrotechnical Commission. <https://webstore.iec.ch/en/publication/4279>.
- [13] IEC. (2013). IEC 60529: Degrees of protection provided by enclosures (IP Code). International Electrotechnical Commission. <https://webstore.iec.ch/en/publication/2452>.
- [14] IEEE. (2014). IEEE Std 730-2014: IEEE Standard for Software Quality Assurance Processes. Institute of Electrical and Electronics Engineers. <https://standards.ieee.org/ieee/730/3787/>.
- [15] IEEE. (2020). IEEE Code of Ethics. Institute of Electrical and Electronics Engineers. <https://www.ieee.org/about/corporate/governance/p7-8.html>.
- [16] ACM. (2018). ACM Code of Ethics and Professional Conduct. Association for Computing Machinery. <https://www.acm.org/code-of-ethics>.
- [17] P. Z. Veldman A McGough N, “Autonomous cylindrical root camera,” 2025.
- [18] JLPCB. [Online]. Available: <https://cart.jlpcb.com/quote>.

# Appendix A

Table 7: Requirements & Verifications Table

#	Requirement	Verification	Status (Y/N)
1	300+ dpi image quality	<ul style="list-style-type: none"> <li>Stitched output image covers entire 5' vertical, 360 degree range with no visible gaps</li> <li>Output image and intermediary "slices" are at least 600 pixels wide and final image is at least 18,000 pixels tall without upsampling</li> </ul>	N
2	Glare Mitigation	<ul style="list-style-type: none"> <li>Brightness in the "slice" is perceptually uniform when imaging a blank background</li> </ul>	N
3	LED ring connection operates	<ul style="list-style-type: none"> <li>Probe supply voltage: between 4.5V and 7V</li> <li>Mechanically secure connection does not come undone when tugged</li> </ul>	N
4	Programming of the MCU over JTAG	<ul style="list-style-type: none"> <li>Successfully install blink script to blink the LED ring (doubles as verification that LED ring is functioning)</li> </ul>	Y
5	PWM output from low (~5%) to full duty cycle (100%)	<ul style="list-style-type: none"> <li>Verify max &amp; min voltages, rise times, duration &amp; stability using oscilloscope</li> </ul>	Y
6	Full-speed USB 2.0 communication with camera & PC	<ul style="list-style-type: none"> <li>Download &amp; upload test data over USB 2.0</li> <li>Use USB 2.0 connection to initiate image capture on a USB 2.0 camera</li> <li>Upload captured image from MCU to PC over USB 2.0 connection</li> </ul>	N
7	9V-12V transmitted by H-bridge and polarity can be changed by MCU	<ul style="list-style-type: none"> <li>Probe H-bridge outputs with DVM during normal operation</li> <li>Probe outputs when changing motor direction according to script on MCU</li> </ul>	Y
8	Encoder correctly tracks distance	<ul style="list-style-type: none"> <li>Probe bits of encoder output and ensure they increment as the motor spins</li> <li>Compare travelled distance to values on motor to ensure correspondence to real motion</li> </ul>	Y
9	MCU stops and starts motor according to protocol	<ul style="list-style-type: none"> <li>Program MCU to cause the motor to travel 5' down and back, ensure that the motor moves the gear rack 5' down and then reverses</li> <li>Qualitatively check mechanical stability</li> </ul>	Y