DESIGN DOCUMENT

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Project No. 101

1) Introduction

1a. Problem and Solution

Problem: The evaluation of crop success and the development of climate resistant agriculture rely heavily on studying root development of plants. Often times this process requires researchers to capture images of the roots inside clear tubes driven deep into the soil. Current commercial models designed for this task usually have some major flaws. They are either manually operated or fragile and if they are neither then they are extremely expensive, often costing upwards of $100,000. A previous project iteration successfully automated the scanning process using a motor-driven gear rack and a 360-degree mirrored camera but there were some issues with it. The design fell significantly short of being a viable, field-ready tool because the prototype was limited to a 150 DPI resolution rather than the target 300 DPI, and its current LED setup created severe light glare that obscured critical image data. Furthermore, the system architecture relied on a bulky Raspberry Pi for image processing, and exposed components such as the motor, PCB, and battery lacked the necessary weatherproofing to survive harsh, dirty, and moist agricultural environments.

Solution: Our goal for the project is to optimize and ruggedize the existing cylindrical root camera to deliver a field-ready minirhizotron device that can be relied on by farmers to give them insights about their crops. To resolve the resolution and image clarity issues we are upgrading the imaging hardware to a camera equipped with a global shutter and higher resolution, which will prevent motion artifacts during the device's descent. This will be combined with a new diffused LED lighting system to get rid of reflective glare on the conical mirror and have more of the image be usable. To improve efficiency and make the system simpler we are removing the Raspberry Pi from the system and instead the root imaging device will rely solely on a microcontroller for control logic, motor communication, image data transfer, and image processing. Lastly, we plan to extend the physical housing so that all electronics are fully enclosed and weatherproofed against dirt and moisture intrusion, making the device highly durable for continuous outdoor research.

1b. Visual Aid

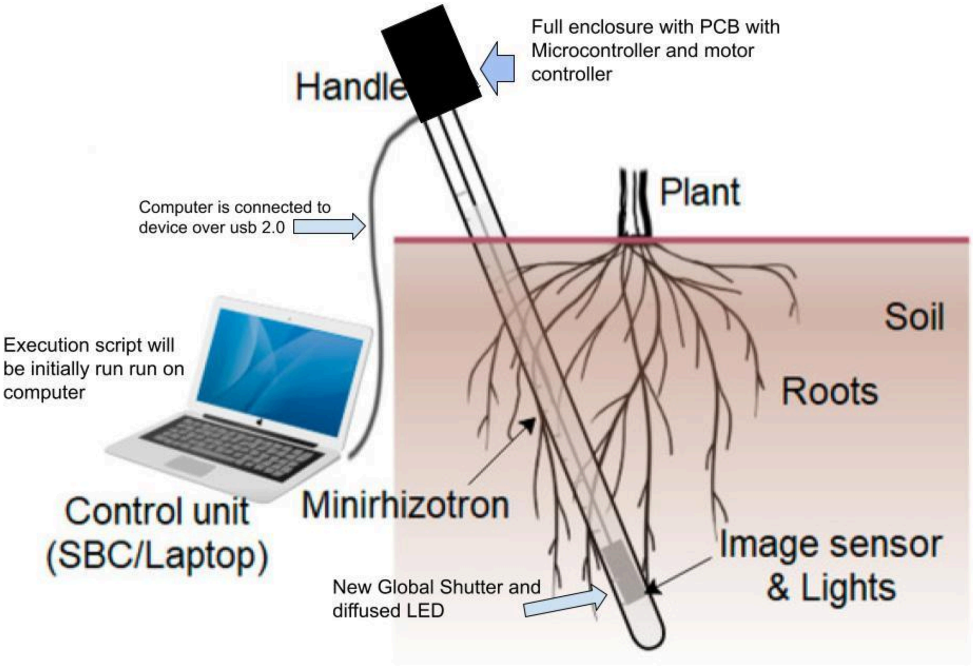


Figure 1: Visualization of Complete Design

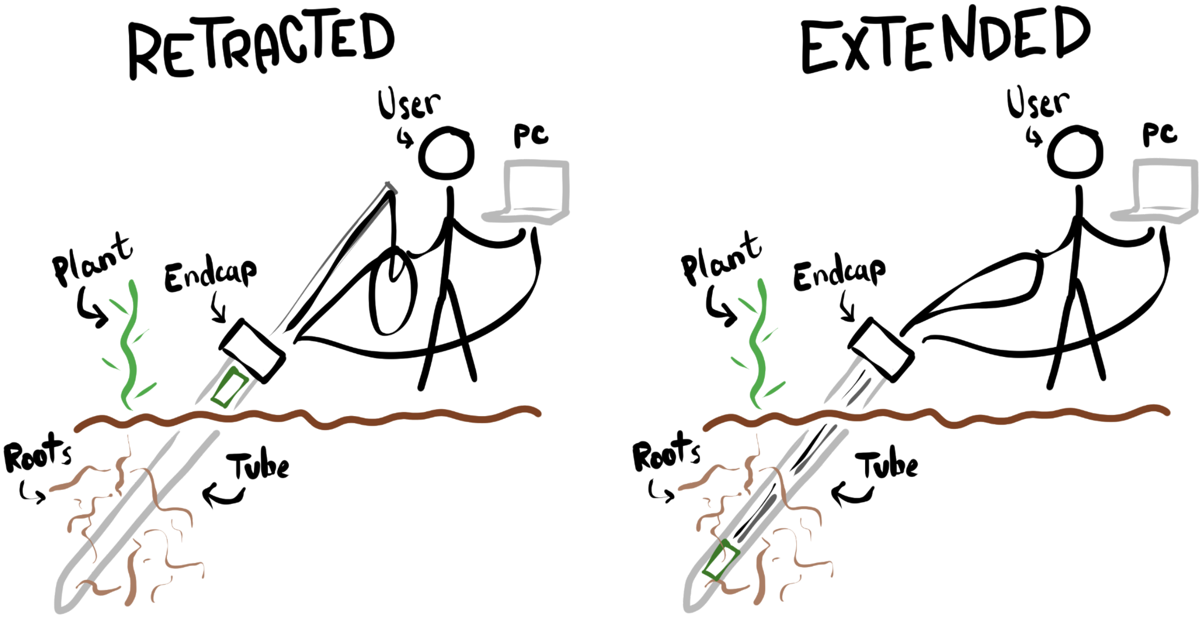


Figure 2: Sketch of Expected Operation. A single operator with a PC fixes the endcap to the imaging tube, then initiates motion using a script, causing the shuttle to translate down the tube.

1c. High Level Requirements List

- Our camera subsystem must utilize a global shutter to capture and transmit root images at a resolution of at least 300 DPI or more without unintended distortions or blurs.
- Our system must successfully execute the autonomous capture process by relying entirely on the microcontroller to descend, capture and ascend in under 4 minutes.
- Our device enclosure must be fully weatherproofed. It should be able to successfully protect all the electronics from water and dust when we are using it in the field.

2) Design

2a. Physical Design

The device is designed to take 100-200 photos of the inner surface of a cylindrical subterranean tube 5' long and 2" in diameter, and compile these images into a single photo with at least 300 dpi resolution. The system consists of two primary components:

1. A shuttle and gear rack containing the imaging subsystem, which consists of a camera and simple optical setup. The camera is positioned to image a conical mirror so that a 360 degree view of the shuttle's surroundings are visible with no rotation of the camera.
2. An "endcap" containing the rest of the subsystems; the endcap contains a motor which allows the shuttle to translate.

2b. Electrical Design

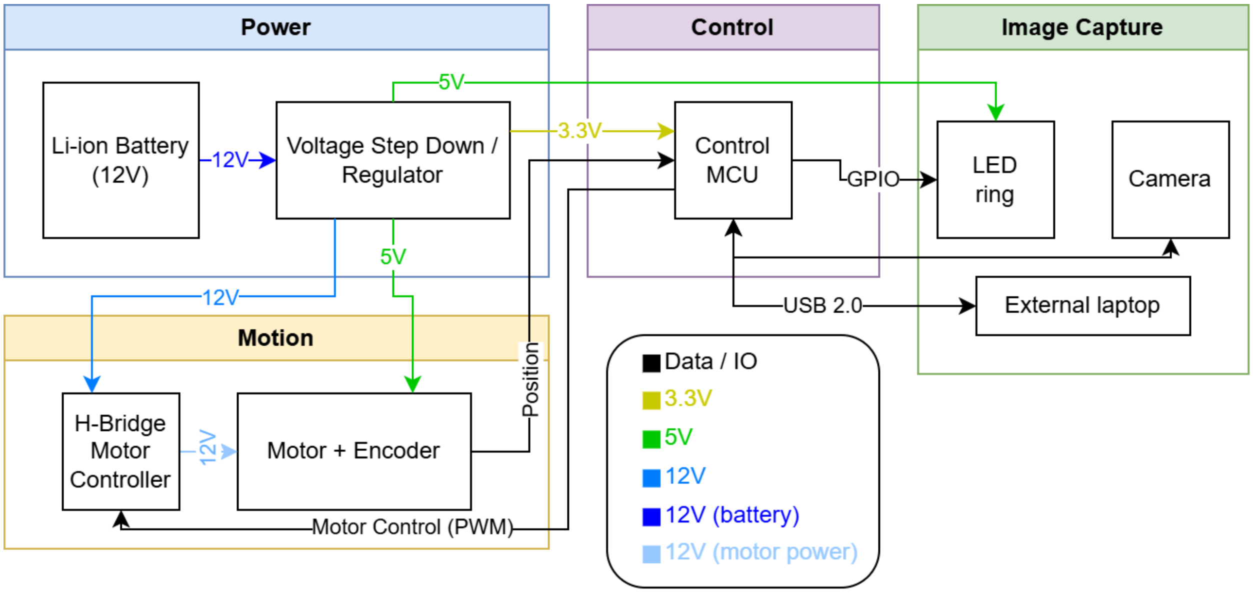


Figure 3: High-level block diagram

2bi. Image Capture Subsystem

The image capture subsystem consists of a moving shuttle containing an HD camera aimed at a conical mirror as well as an LED ring for illumination.

In order to provide the desired improvement in image quality requested by the sponsor, we will be using an HD 1080P camera for imaging. As can also be seen in fig, 4, the camera is positioned facing downwards at the conical mirror, allowing it to take a distorted 360-degree image of a thin section around the mirror, from which an undistorted image can be recovered computationally. As the shuttle travels down the tube it takes a series of photos which can be stitched together to create a complete image of the root system. The camera will be connected to our control MCU via a 12” USB cable, allowing a stream of photos to be transmitted as it descends.

The conical mirror is made of polished metal coated with silver paint for high reflectivity with a diameter of 1.5” and a 45 degree slope. The 45 degree slope was chosen so the radial position across the mirror as seen by the camera roughly matches the vertical distance along the tube. Fig 4 depicts a preliminary test done by the previous semester’s group demonstrating the functionality of this system.

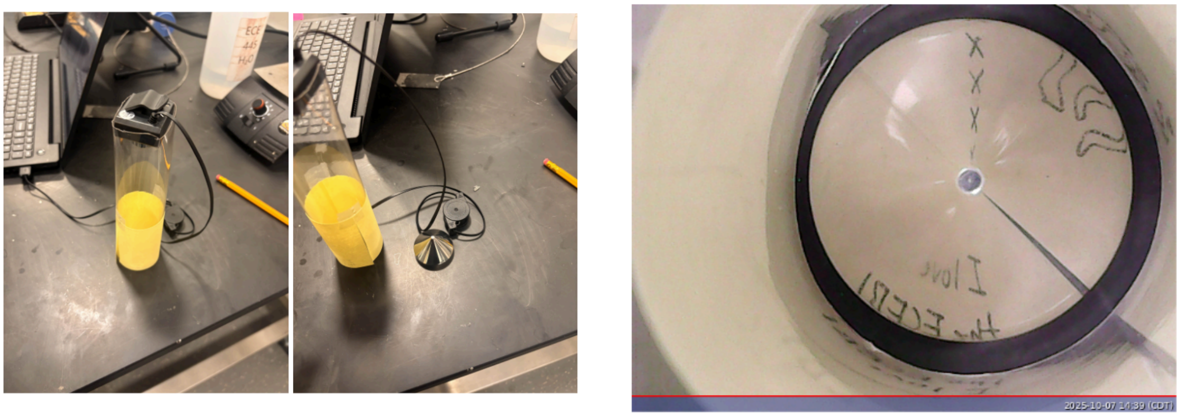


Figure 4: A,B) View of a mock tube and cone with camera from initial testing in 2025. C) View of the tube from the camera. Writing on a paper wrapped around the tube can be seen reflected on the mirror.

In order to illuminate the root system, an LED ring will be installed around the camera. However, this will introduce glare; this can be mitigated by choosing a commercial LED ring with a diffuser and using a glare mitigation cone to block direct paths from the ring to the camera, as depicted in figure 5.

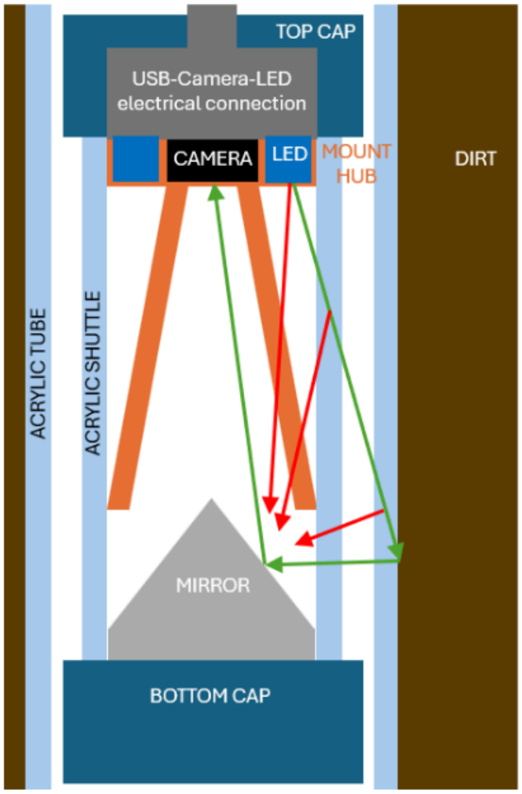
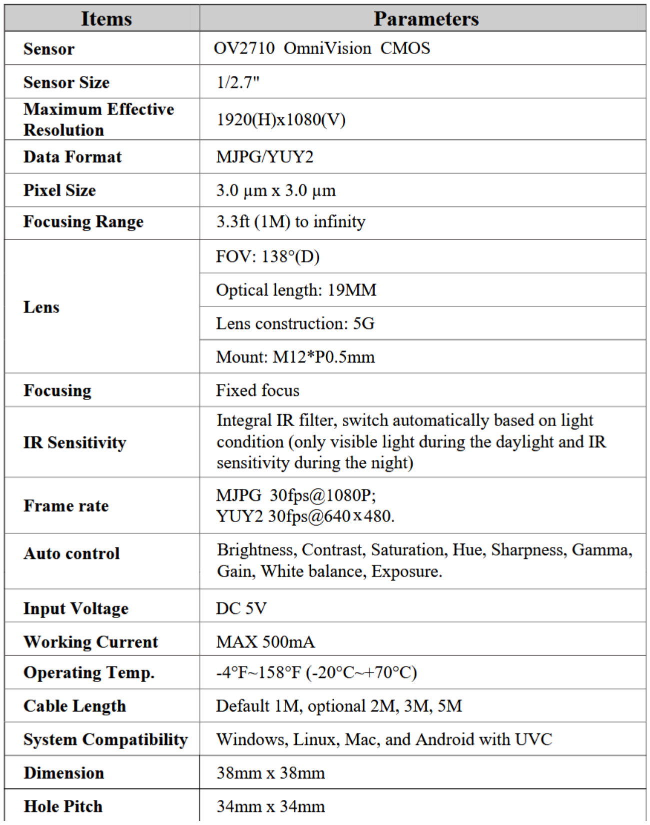


Figure 5: Schematic view of glare mitigation setup from previous semester



Items	Parameters
Sensor	OV2710 OmniVision CMOS
Sensor Size	1/2.7"
Maximum Effective Resolution	1920(H)x1080(V)
Data Format	MJPG/YUY2
Pixel Size	3.0 µm x 3.0 µm
Focusing Range	3.3ft (1M) to infinity
Lens	FOV: 138°(D)
	Optical length: 19MM
	Lens construction: 5G
	Mount: M12*P0.5mm
Focusing	Fixed focus
IR Sensitivity	Integral IR filter, switch automatically based on light condition (only visible light during the daylight and IR sensitivity during the night)
Frame rate	MJPG 30fps@1080P; YUY2 30fps@640x480.
Auto control	Brightness, Contrast, Saturation, Hue, Sharpness, Gamma, Gain, White balance, Exposure.
Input Voltage	DC 5V
Working Current	MAX 500mA
Operating Temp.	-4°F~158°F (-20°C~+70°C)
Cable Length	Default 1M, optional 2M, 3M, 5M
System Compatibility	Windows, Linux, Mac, and Android with UVC
Dimension	38mm x 38mm
Hole Pitch	34mm x 34mm

Figure 6: Arducam B0205 Specifications

The previous iteration of this project was able to capture ~150 dpi images using a standard resolution (640x480) camera over wired USB 2.0 connection; we have selected a camera with four times as many pixels, which should be capable of capturing 300 dpi images. For further information, see the tolerance analysis section (2c).

The camera will be connected to an STM32 N6 MCU via a USB 2.0 connection over a 20” cable. The cable will be chosen to withstand heat, moisture, and mechanical stress from the shuttle’s motion; additionally it will have low loss to ensure reliable data transfer. Use of USB 2.0 mitigates RF interference and allows direct, long-distance high-speed connection to either an MCU or PC while being well-supported by commercial cameras.

Raw images will be processed on the MCU if possible, but the final assembly will need to be performed by a script on the PC due to memory constraints. At minimum, the PC will receive a stream of raw output images of the mirror with timing information. Image processing will be performed using a custom script that extracts an annular region of the mirror, converts this region to rectangular coordinates, then stitches the series of “slices” into a full image.

Table 1: Imaging Subsystem Requirements & Verifications

Requirement	Verification
1. 300+ dpi image quality	● Stitched output image covers entire 5” vertical, 360 degree range with no visible gaps ● Output image and intermediary “slices” are at least 600 pixels wide and final image is at least 18,000 pixels tall without upsampling
2. Glare Mitigation	● Brightness in the “slice” is perceptually uniform when imaging a blank background
3. LED ring connection operates	● Probe supply voltage: between 4.5V and 7V ● Mechanically secure connection does not come undone when tugged

2bii. Control Subsystem

The control subsystem serves two major purposes: initiating and regulating the motor and controlling image capture. It will be positioned in a stationary “endcap” with the other subsystems, which will remain stationary. The primary component of this system is an STM32N6 MCU, chosen for its high speed USB 2.0 port and large RAM for image processing. It is powered by a 3.3V supply from the power subsystem via the voltage step-down.

The MCU receives input from a rotary encoder attached to the gear rack, allowing it to track the position of the shuttle. The shuttle’s speed can then be controlled by providing a PWM signal, and direction through GPIOs controlling the H-bridge in the motion subsystem. The MCU will then activate the LED ring and camera based on the shuttle’s position. It will also associate time and position metadata with the raw images for the stitching process. A JTAG SWJ-DP port and SWD port will be exposed for programming and debugging as well.

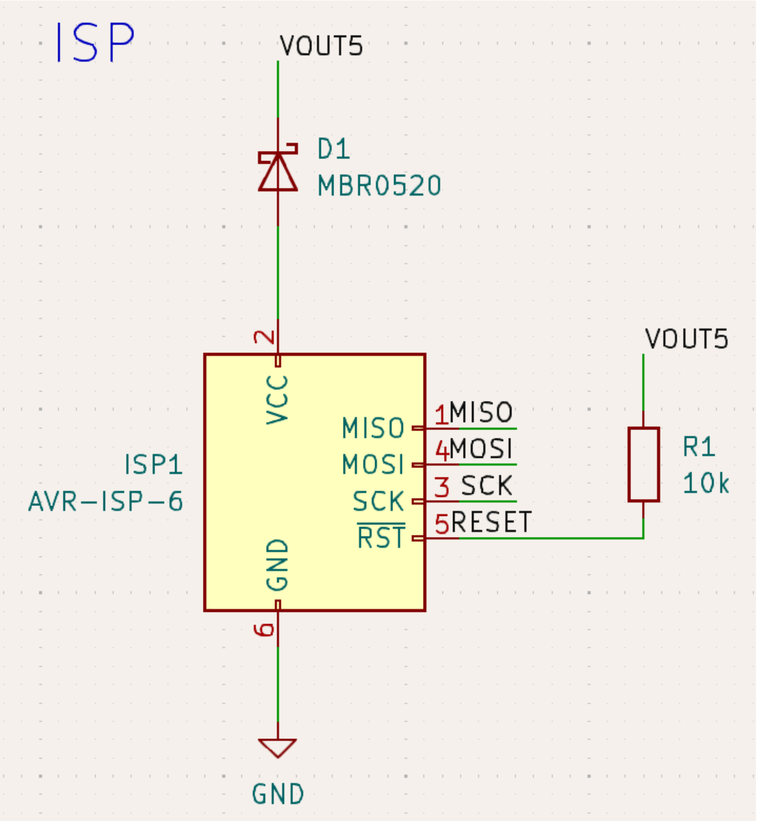


Figure 7: Control Subsystem Schematic (microcontroller omitted)

Table 2: Control Subsystem Requirements & Verifications

Requirement	Verification
1. Programming of the MCU over JTAG	- Successfully install blink script to blink the LED ring (doubles as verification that LED ring is functioning)
2. PWM output from low (~5%) to full duty cycle (100%)	- Verify max & min voltages, rise times, duration & stability using oscilloscope
3. Full-speed USB 2.0 communication with camera & PC	- Download & upload test data over USB 2.0 - Use USB 2.0 connection to initiate image capture on a USB 2.0 camera - Upload captured image from MCU to PC over USB 2.0 connection

2biii. Power Subsystem

The power subsystem needs to generate a 3.3V supply for the MCU, 5V supply for the LED ring and encoder as well as stabilize the 12V supply from a battery for smoother power delivery. The former is accomplished by an LDO, while the latter a capacitor for power banking. As the device is expected to consume a few amps during full operation, we have selected a 7AH rechargeable Li-ion battery which should power the system for several days of operation.

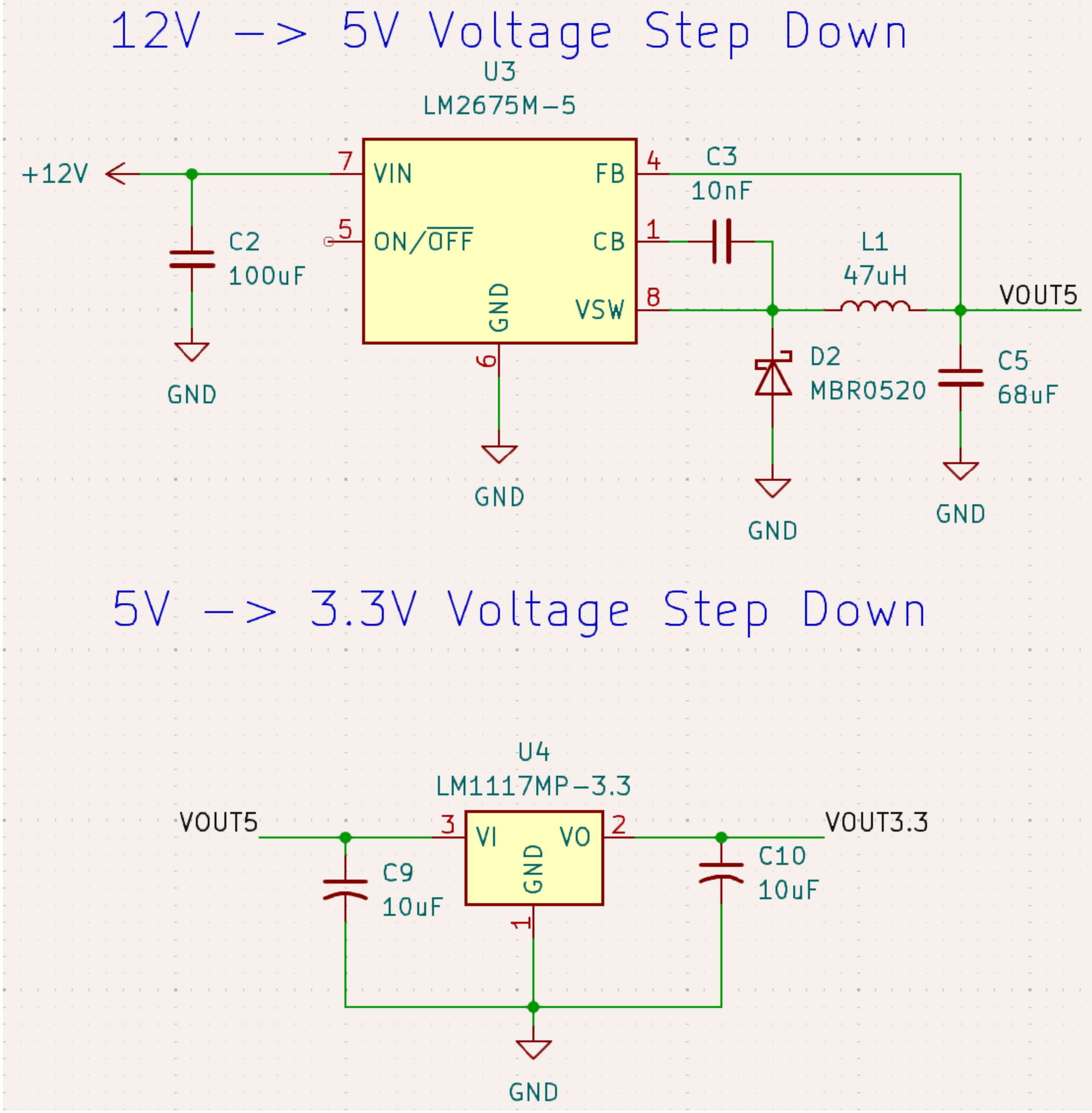


Figure 8: Power Subsystem Schematic

Table 3: Power Subsystem Requirements & Verifications

Requirement	Verification
1. Programming of the MCU over JTAG	● Successfully install blink script to blink the LED ring (doubles as verification that LED ring is functioning)
2. PWM output from low (~5%) to full duty cycle (100%)	● Verify max & min voltages, rise times, duration & stability using oscilloscope
3. Full-speed USB 2.0 communication with camera & PC	● Download & upload test data over USB 2.0 ● Use USB 2.0 connection to initiate image capture on a USB 2.0 camera ● Upload captured image from MCU to PC over USB 2.0 connection

2biv. Motion Subsystem

The motion subsystem consists of a gear motor and rotary encoder coupled to a gear rack, allowing the imaging shuttle to travel down the length of the root system for imaging. The motor will be connected to the microcontroller via an H-bridge, allowing for bidirectional movement and speed control via a PWM signal generated by the MCU. The rotary encoder built into the motor will digitally transmit the motor's position to the MCU, allowing it to regulate the motor and time image capture events. The motor will require a 12V power supply and a 5V supply for the encoder.

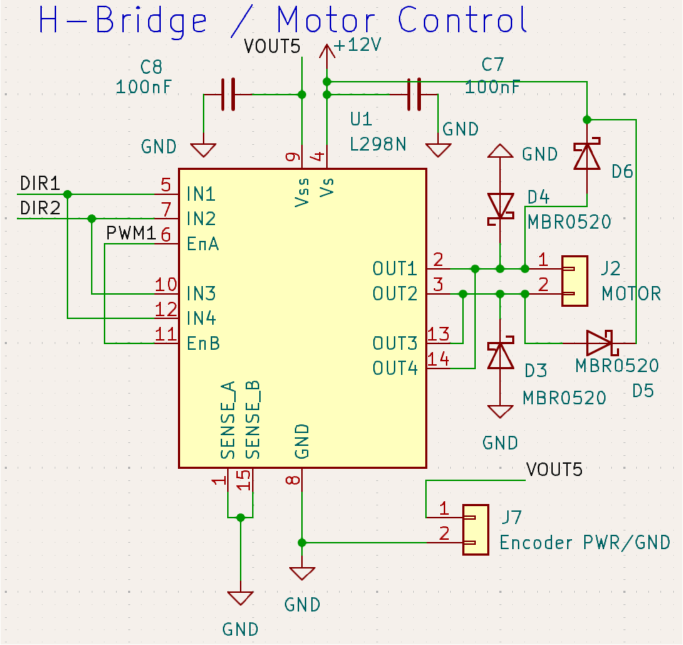


Figure 9: Motion Subsystem Schematic

Table 4: Motion Subsystem Requirements & Verifications

Requirement	Verification
1. 9V-12V transmitted by H-bridge and polarity can be changed by MCU	● Probe H-bridge outputs with DVM during normal operation ● Probe outputs when changing motor direction according to script on MCU
2. Encoder correctly tracks distance	● Probe bits of encoder output and ensure they increment as the motor spins ● Compare travelled distance to values on motor to ensure correspondence to real motion
3. MCU stops and starts motor according to protocol	● 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 ● Qualitatively check mechanical stability

2c. Tolerance Analysis

By far the most important part of the design is the imaging power. In order to make our design a meaningful upgrade, we must be able to take images at 300dpi or higher. However, due to the conical mirror requiring a nonlinear coordinate transformation, the dpi is not fixed across the scan (fig. 10)

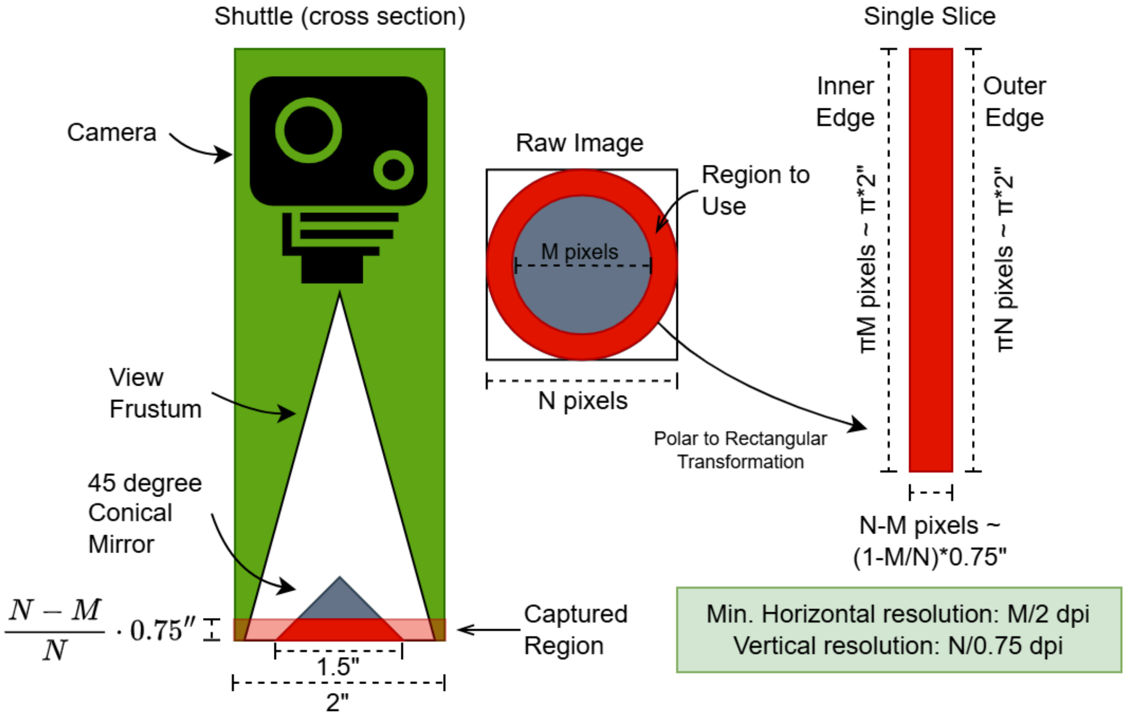


Figure 10: dpi along the edges of each "slice"

The resolution of the output will be determined by the width of the cylindrical mirror in the raw images N, and the minimum inner radius used for imaging M, both in pixels.

The biggest constraint on the dpi is the minimum horizontal resolution; the vertical and maximum horizontal resolutions are always strictly larger. The vertical image size, and by extension the number of photos, the framerate, and the data rate, are all parameterized by x = M/N. Because the framerate is limited by the data rate and the data rate is limited by the MCU, it is important to pick x such that a full image is transmitted before the next one is taken.

Assuming we adjust the camera's focus for maximum efficiency, N is fixed to the smallest component of the camera's resolution; for our HD camera, this would be 1080px (to achieve 300dpi, M must be at **least** 600px, meaning HD is the minimum standard resolution we can use; 640x480 is too small). Subsampling could be used to get a lower resolution if necessary, so N=960 and N=720 are also considered:

Table 5: Framerate and Data Rate vs Image Resolution

Parameter	Value (N=1080)	Value (N=960)	Value (N=720)
x	5/9	5/8	5/6
Framerate	2.00 fps	2.37 fps	5.33 fps
Raw Image Size	3.5 MB	2.8 MB	1.6 MB
Approx. Data Transfer Rate	56 Mbits/sec	52 Mbits/sec	66 Mbits/sec

These were calculated assuming a full scan is 60” long, takes 90s, and the images have a 3:2 aspect ratio and are in YUY2 format with 16 bits per pixel.

All data rates considered are well the capabilities of the STM32 N6 series’ USB 2.0 connection, which tops out at 480 Mbit/sec. The camera’s datasheet specifies the following transmission rates (fig. 6):

MJPG 30fps@1080P;
YUY2 30fps@640 x 480

YUY2 30fps @640 x 480 corresponds to a transmission rate in the neighborhood of 148 MBits/sec, which is far higher than what we’d use, suggesting that so long as the camera’s software is flexible we should be able to transfer uncompressed images at 1080P.

Another concern is the available RAM. STM32 N6 series all have 4.2 MB of RAM, which is barely enough to hold an entire raw image at full resolution; however, most of this image may be quickly discarded, with the “necessary” portion of each raw image only being about 250 KB. (Using the MJPEG format will greatly reduce image sizes, but the images still need to be uncompressed to be processed.) Even so, it is unclear that an N6 chip without external RAM will be capable of completing the image processing in time, and this will require testing. Changing the resolution will allow more images to be stored, but decrease the time for processing; changing the motor speed is also an option if more time is needed. There is also plenty of bandwidth available to relay the raw images to a PC or more powerful system such as a Raspberry Pi over the USB connection.

3) Cost and Schedule

3ai. Labor

Table 5: Cost of Labor

Person	**Rate**	**Multiplier**	**Time**	**Total**
Alan Ilinskiy	$45.67/hr	2.5	65 hours	$7,421.88
Areg Gevorgyan	$45.67/hr	2.5	65 hours	$7,421.88
Liam Thompson	$45.67/hr	2.5	65 hours	$7,421.88
Machine Shop	$420/day	1	15 days[1]	$6,300.00
Total Labor				**$28,565.63**

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[1] Based on previous group's final report

3aii. Parts

Table 6: Cost of Parts

Description	**Manufacturer**	**Part #**	**Qty**	**Unit Cost**	**Total**
12V 7AH Lithium-Ion Battery	Fox Buying	3S2P-18650-7AH	1	$18.26	$18.26
12 RPM Planetary Gear Motor w/Encoder	ServoCity	638210	1	$59.99	$59.99
High-Resolution USB Camera (5MP)	Arducam	B0205	1	$34.99	$34.99
20" USB MF Type A Cable	Amazon		1	$12.99	$12.99
LED Ring Light	Adafruit	2855	1	$24.99	$24.99
STM32N657	STMicroelectronics	STM32N657X0H3Q	1	$20.62	$20.62
LM2596-5.0 12V→5V Switch Regulator	Texas Instruments	LM2596S-5.0/NOPB	1	$2.50	$2.50
LM1117-3.3 5V→3.3V Linear Regulator	Texas Instruments	LM1117MPX-3.3/NOPB	1	$0.60	$0.60
STM32 Nucleo Dev Board	STMicroelectronics	NUCLEO-H743ZI2	1	$27.00	$27.00
PCB Fabrication	JLCPCB		1	$25.00	$25.00
Physical Design[2]	Various			$700.00	$700.00
Other Misc. PCB Parts	Various			$10.00	$10.00
Total					**$226.94**

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[2] As we will be reusing the bulk of the mechanical design from last semester, this is the same as the cost reported in last semester's final report.

3aiii. Grand Total

Table 6: Total Cost

Category	**Cost**
Parts	$226.94
Labor	$28,565.63
Grand Total	**$28,792.57**

3b. Schedule

Table 6: Proposed Schedule

Week	Alan	Areg	Liam
Feb 23 - Mar 2	Research STM32N6 camera interface, select final camera	Research LED ring light options, finalize parts order	Review prior team's rack/pinion assembly, identify mechanical changes
Mar 2 - Mar 9	Begin researching STM code	Submit Parts Order	Begin PCB schematic with STM32H7
Mar 9 - Mar 16	Set up STM32 dev environment, test camera interface on dev board	Research image stitching algorithms for on-chip processing	Finalize PCB schematic, begin layout
Mar 16 - Mar 23	Begin on-chip image capture software	Figure out inter-STM communication (how control STM talks to imaging STM)	PCB layout complete, send for fabrication
Mar 23 - Apr 6	Image capture working on dev board, begin ring image stitching	Integrate LED ring light, verify illumination consistency, tune brightness control	PCB arrives, begin assembly and bring-up
Apr 6 - Apr 13	On-chip image processing pipeline functional	Validate power subsystem, confirm clean 5V and 3.3V rails under load	PCB bring-up complete, integrate with motor subsystem
Apr 13 - Apr 20	Test image quality vs. prior design, tune processing pipeline	Compare image output against 150+ DPI requirement, document results	Full system integration
Apr 20 - Apr 27	Prepare demo, full system test	Prepare demo, full system test	Prepare demo, full system test
Apr 27 - May 4	Conduct field/greenhouse test	Conduct field/greenhouse test	Conduct field/greenhouse test
May 4 - May 11	Final demo prep	Final demo prep	Final demo prep

4) Discussion of Social Impact, Engineering Standards, Ethics, and Safety Considerations

4a. Societal Impact

Root phenotyping is a major bottleneck in developing higher-performing crops. Every growing season, researchers need to capture detailed images of root systems inside buried tubes to understand how different plant genetics respond to drought, flooding, and nutrient stress. The current scanner based systems cost upwards of $100,000 per device, are prone to wear and water damage, and require tedious manual operation which means data collection is slow, expensive, and error-prone. That limits how fast agricultural research can move, which has downstream effects on developing drought resistant and water efficient crops that could matter a lot as climate variability increases.

Our project optimizes the system prototyped last semester to make it more reliable, higher resolution, and more field-ready. A more accurate and portable system means researchers can collect better data faster, at lower cost per device. That translates directly into faster phenotyping cycles, more robust research output, and ultimately better crop varieties getting to farmers sooner. The economic benefit is real: reducing device cost from ~$100K to a few thousand dollars makes this technology accessible to research groups that couldn't afford the existing commercial options. Environmentally, accelerating the development of water-efficient crops is directly relevant to addressing agricultural water usage, which accounts for roughly 70% of global freshwater consumption.

Misuse potential is essentially nonexistent as this is purpose built niche agricultural research equipment. The main failure risk is producing subtly flawed image data that a researcher doesn't catch, which is why validation with Prof. Leakey's team is built into our testing process.

4b. Engineering Standards

The following standards apply to this project:

Electrical Safety:

- IEC 61010-1 — Safety requirements for electrical equipment for measurement, control, and laboratory use. Our system uses electronics in field and greenhouse environments where moisture exposure is a real concern.

Enclosure and Environmental Protection:

- IEC 60529 — Relevant to the waterproof enclosure requirements. The prior design called for waterproof sealing; we are carrying this forward and ensuring the design will be as waterproof as possible.

Software:

- IEEE 730 — Software Quality Assurance, relevant to ensuring the image capture and control scripts behave reliably and reproducibly across field sessions.

4c. Code of Ethics

Both the IEEE and ACM Codes of Ethics center on the responsibility engineers have toward the public and toward honest, careful practice. Several principles are directly relevant here.

Public Welfare (IEEE Tenet 1 / ACM 1.2): Our system supports agricultural research with real downstream implications for food security and water efficiency. We take this obligation seriously by making sure our improvements are measurable and validated against what the research group actually needs, not just what looks good on paper.

Originality and Proper Credit (ACM Code of Ethics 1.5): Our project is an explicit optimization of a prior ECE 445 team's prototype. We properly credit that team's design: the rack and pinion movement system, the conical mirror optics concept, and the overall architecture are their work. Our contributions are in improving image resolution, durability, portability, and field reliability. We don't represent any of the prior design as our own original work.

4d. Electrical and Mechanical Safety Concerns

Electrical:

- The system runs off a 12V 7AH lithium-ion battery with a step-down regulator to 5V. While this is relatively low voltage, a 7AH cell can deliver significant current under fault conditions, and improper connections or shorts on the PCB during development are a real hazard.

Mechanical:

- The rack and pinion system moves down a 6-foot tube. The prior team identified top heaviness as a concern when the rack is fully extended upward, which is why the 1ft cap plug reinforcement was designed in. We're carrying that design choice forward.
- The gear rack and motor assembly moves slowly but will pinch or catch fingers if someone reaches in during operation. This is the primary mechanical hazard during testing.

4e. Safety Procedures and Mitigation

Lab Safety:

- All soldering is done with ventilation and eye protection in ECE 445 designated lab spaces, following course safety guidelines.
- Power is always disconnected before modifying wiring or swapping components on the PCB.

Battery Handling:

- The 12V lithium-ion battery is inspected before each use for swelling or damage.
- The battery is only charged with a compatible charger and never left unattended during charging

Mechanical Safety:

- No hands near the rack during powered operation. The operator initializes the scan from the laptop and steps back.
- The conical mirror assembly at the bottom of the rack is inspected before each use — any cracking or delamination gets flagged before running a scan.

5) Citations

- IEEE. (2020). *IEEE Code of Ethics*. Institute of Electrical and Electronics Engineers. https://www.ieee.org/about/corporate/governance/p7-8.html
- ACM. (2018). *ACM Code of Ethics and Professional Conduct.* Association for Computing Machinery. https://www.acm.org/code-of-ethics
- 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://www.iec.ch/publication/3608
- IEC. (2013). *IEC 60529: Degrees of protection provided by enclosures (IP Code). International Electrotechnical Commission*. https://www.iec.ch/publication/2420
- 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/
- YUY2 yuv pixel format. Fourcc.org. Published 2023. https://fourcc.org/pixel-format/yuv-yuy2/
- Veldman A, McGough N, Perkins Z. (2025). *Autonomous Cylindrical Root Camera*.
- *Arducam Datasheet*. Accessed February 28, 2026. https://www.uctronics.com/download/Amazon/B0205_OV2710_Day&Night_UVC_Camera_Datasheet.pdf