PROJECT PROPOSAL

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21 February 2026

Project No. 101

1) Introduction

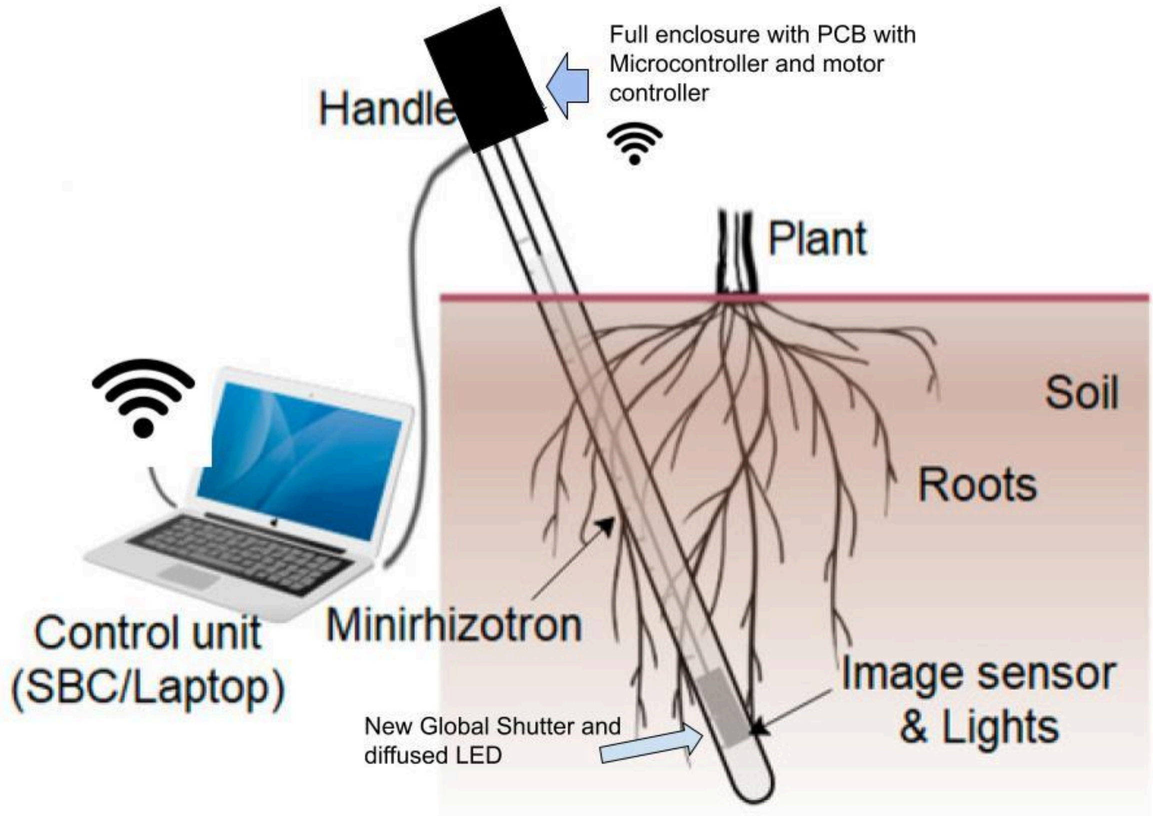
1a. Problem

Researchers evaluate crop success by studying root development, which requires taking photos inside clear tubes driven into the ground. Current market models for this process are manually operated, fragile, and can cost upwards of $100,000. While a previous prototype successfully automated the scanning process using a motor-driven rack and a 360-degree mirrored camera, it fell short of being field-ready. The prototype only achieved 150 DPI resolution instead of the required 300 DPI target, and the LED setup created unwanted light glare that obscured image data. Furthermore, the system relied on a bulky Raspberry Pi for image processing, and exposed components like the motor, PCB, and battery lacked the necessary weatherproofing for harsh agricultural environments.

1b. Solution

Our project will optimize and ruggedize the existing cylindrical root camera to make it a reliable and field-ready device. To solve the resolution and image quality issues, we are upgrading the hardware to a camera equipped with a global shutter to prevent motion blur during descent, alongside a redesigned LED lighting system to diffuse light and eliminate reflective glare. We are also completely eliminating the Raspberry Pi from the architecture making the system rely solely on a microcontroller to handle the control logic, component communication and image data transfer. Finally, we will overhaul the physical housing to ensure all electronics are fully enclosed and weatherproofed against dirt and moisture, making the device highly durable for continuous outdoor research.

1c. Visual Aid

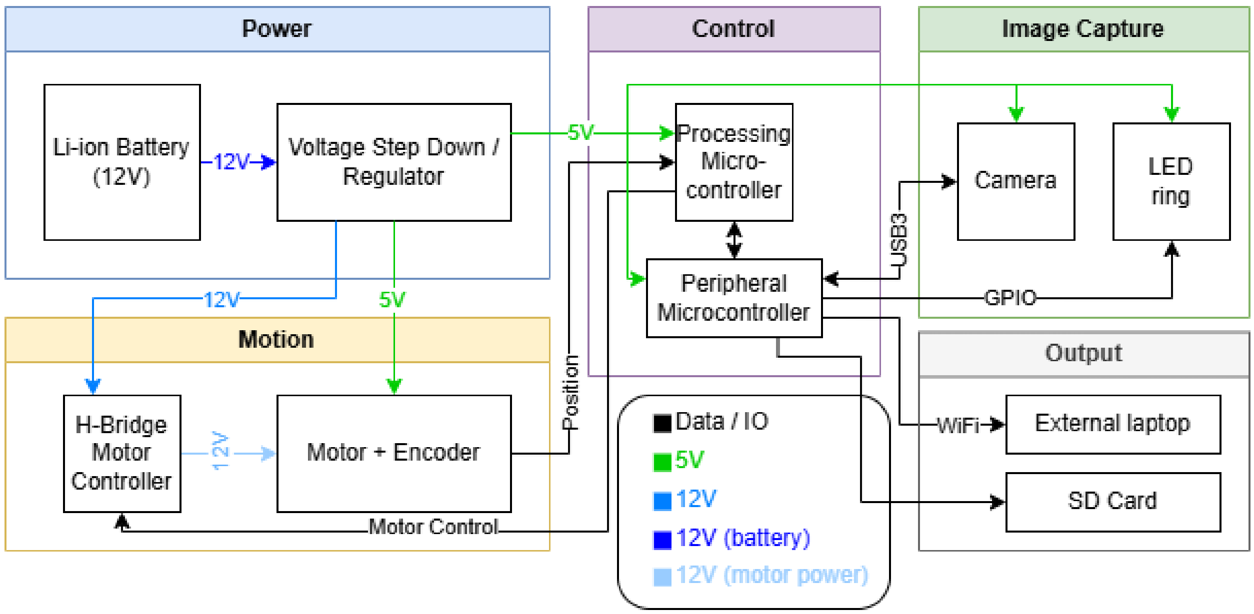


1d. High Level Requirements

- Our camera subsystem must utilize a global shutter to capture and transmit root images at a resolution of 300 DPI or greater without motion artifacts.
- Our system must successfully execute the capture process including descending, imaging, and ascending by using only a microcontroller, completing a single tube in under 4 minutes
- Our physical device enclosure must be weatherproofed, protecting the internal electronics from water and dust intrusion during standard field operation.

2) Design

2a. Block Diagram



2b. Subsystem Overview

Control Subsystem: Receives and processes raw images captured by the camera in the image capture subsystem; controls the LEDs for illumination; transmits processed images. Also controls the motion of the shuttle via the H-bridge and keeps track of its position using an encoder on the motion subsystem. Receives 5V Vcc from the power subsystem via a voltage step down. Responsibilities are split between two microcontrollers in case the image processing is too resource intensive.

Output Subsystem: Receives processed image data from the control subsystem. Processed images are downloaded to an external laptop over WiFi and/or to an SD card.

Power Subsystem: Provides a regulated supply of 12V and 5V for the motor power and digital logic level respectively.

Image Capture Subsystem: A camera and LED ring housed in the shuttle with a conical mirror which image a cylindrical section surrounding the shuttle. Image capture is initiated by the control subsystem via USB3, which also receives the raw captured images over this link. The LED ring is also controlled by the control module. Both receive 5V power from the power subsystem.

Motion Subsystem: The shuttle containing the image capture subsystem will be mounted on a motorized gear rack which is powered by this subsystem, consisting of a motor, a digital encoder to sense the position of the shuttle, limit switches as a failsafe to avoid device failure, and an H-bridge to regulate the polarity of the voltage applied to the motors. The H-bridge is controlled by the microcontroller in the control subsystem and the control subsystem receives position information from the encoder. The motor is given a stabilized 12V supply and the encoder receives 5V supply from the power subsystem.

2c. Subsystem Requirements

The control subsystem requires a high-performance microcontroller (eg STM32H7 series) ideally capable of image processing, as well as a peripheral microcontroller capable of USB3 communication with the image capture system and communication with an SD card or WiFi connection to an external laptop. Both need to avoid failure due to overheating in 90+ degree conditions using a heat sink.

Image processing at minimum consists of an algorithm to extract a ring-shaped portion of the raw image data and convert this to rectangular coordinates. If there is still available overhead, this can be extended to rendering the complete image by combining slices from all the raw images.

Digital communications between microcontrollers and between the peripheral controller and output subsystem must also be sufficiently fast to transmit and receive images without loss.

The output subsystem needs to be capable of reliably receiving and storing processed images from the control subsystem without loss.

The power subsystem requires a rechargeable Li-ion battery capable of ideally several hours of continuous operation, which is also capable of withstanding high temperatures without failure. The voltage regulator should be capable of providing steady 12V and 5V supplies during varying power demand to provide constant illumination and avoid brownouts.

The image capture subsystem should have a camera capable of collecting raw color images at 300dpi with minimal noise, and have a global shutter to minimize distortion caused by the shuttle's motion. The LED ring should be positioned in a way to minimize glare on the outer portion of the conical mirror so that as much of the raw image is usable as feasible while also providing sufficient illumination to use the camera's full dynamic range.

Prospective camera part number: LEO2 1440S-250UC/UM

The motion subsystem should be able to operate steadily when supplied with 12V power without overheating when combined with a heat sink. Motion should be uniform enough that captured raw images are not distorted by motion. It should also start and stop quickly when instructed by the control system or when reaching its limits to avoid damaging the shuttle or the motor.

2d. Tolerance Analysis

Based on reports from the previous semester's group's attempt at this project, the movement system poses the highest safety and reliability concern. As the device needs to be capable of imaging nearly 12ft down a narrow underground tube, it features a 12ft gear rack and USB cable. By placing everything except the imaging subsystem in a stationary "cap", potential issues with transporting and powering electronics across this distance is minimized. Electronic communications between the cap and shuttle were reportedly challenging; this could be tackled by implementing a more sophisticated power regulation system and using actual USB connections instead of ad-hoc solder joints for I/O. Although the existing steel gear rack was operational, we will attempt to manufacture a more flexible gear rack due to concerns about long-term reliability.

Another significant issue is the quality of the raw images provided by the imaging subsystem. Glare was a significant issue last semester, however we are confident we can cut down this problem substantially by substituting their ad-hoc LED ring with a commercial or custom solution featuring a diffuser for more uniform illumination as well as more time spent iterating to find the solution which minimizes glare.

As for the camera itself, their system was limited primarily by their choice of a cheap, low-quality camera for testing, while we plan to use a significantly more expensive device capable of 1.6 MP / 1080p resolution, which, if focused on the 2" diameter conical mirror, should achieve >300dpi so long as the outer half of the mirror is free of glare.

3) Ethics, Safety, and Societal Impact

Our main ethical responsibility is producing reliable imaging data. If the system outputs misleading images, it could derail years of crop breeding research. Per IEEE Code of Ethics Principle 1, we have an obligation to the public welfare since this research supports climate-resistant food development (IEEE, 2024). ACM Principle 2.4 calls for honest evaluation of systems so we'll be transparent with the agriculture team about what our system can and can't do, and clearly document its limitations (ACM, 2018). We also properly credit the prior team's prototype work. For safety, the main risks during development are standard lab hazards which are soldering, 3D printing, and working with electronics. We follow ECE 445 lab safety protocols. In the field, moisture and dirt exposure are the primary concerns, so we're designing a sealed enclosure to protect both the electronics and the user. Misuse risk is minimal as this is a niche agricultural tool. The biggest realistic failure is bad image data going unnoticed, which we mitigate through validation with Prof. Leakey's research group. On the societal side, root phenotyping is a major bottleneck in developing drought-resistant crops. A more portable and durable system reduces labor hours, minimizes wasted data, and accelerates research that ultimately helps address global food and water challenges.