Autonomous Cylindrical Root Camera

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Problem

The project we hope to develop is the one outlined by John Hart and Jeremy Ruther in their presentation on a new hemispherical root camera model for biological research. Currently every growing season, clear tubes about 5 feet long and 2 inches in diameter are driven in the ground at 30 degrees from vertical. Crops are then planted over the tubes (in our example sorghum), and at the end of the year photos are taken by their currently implemented scanner systems to assess the success of each plant. These photos help answer questions like 'which genetic strands are producing the most roots (and by extension being efficient with available water)?', and 'How does the plant's root growth rate respond to drought and flood conditions?'

The problem is that the current printer scanner based model needs to be lowered and rotated manually, is prone to wear and tear from use in the fields, is vulnerable to water damage from moisture in the tubes, and costs upwards of $100,000 for a small set of devices. To expedite their research they hope to have a new model developed that is up to date with current technology and addresses the issues with usability and cost-effectiveness of the current one.

Solution

Our new design is a cylindrical device that uses a 360-degree mirrored orthographic camera with telecentric lens to capture its pictures, surrounding LEDs for light, a motor to descend and lift the device gradually up and down the tube via rack and pinion, motor mounted encoder and color sensor to assess position of the rack, and a microcontroller for component communication, image processing, and bluetooth connection to an external computer. The motor, encoder, color sensor, and PCB are encased together in a cap and mount/detach from the top of each tube. From there a cable extends through the rack of the rack and pinion system down to the devices mounted at the bottom end. Only the camera and LEDs need to be here to capture the desired photos. All the constituent electronics will be tightly secured and waterproof sealed within the device casings.

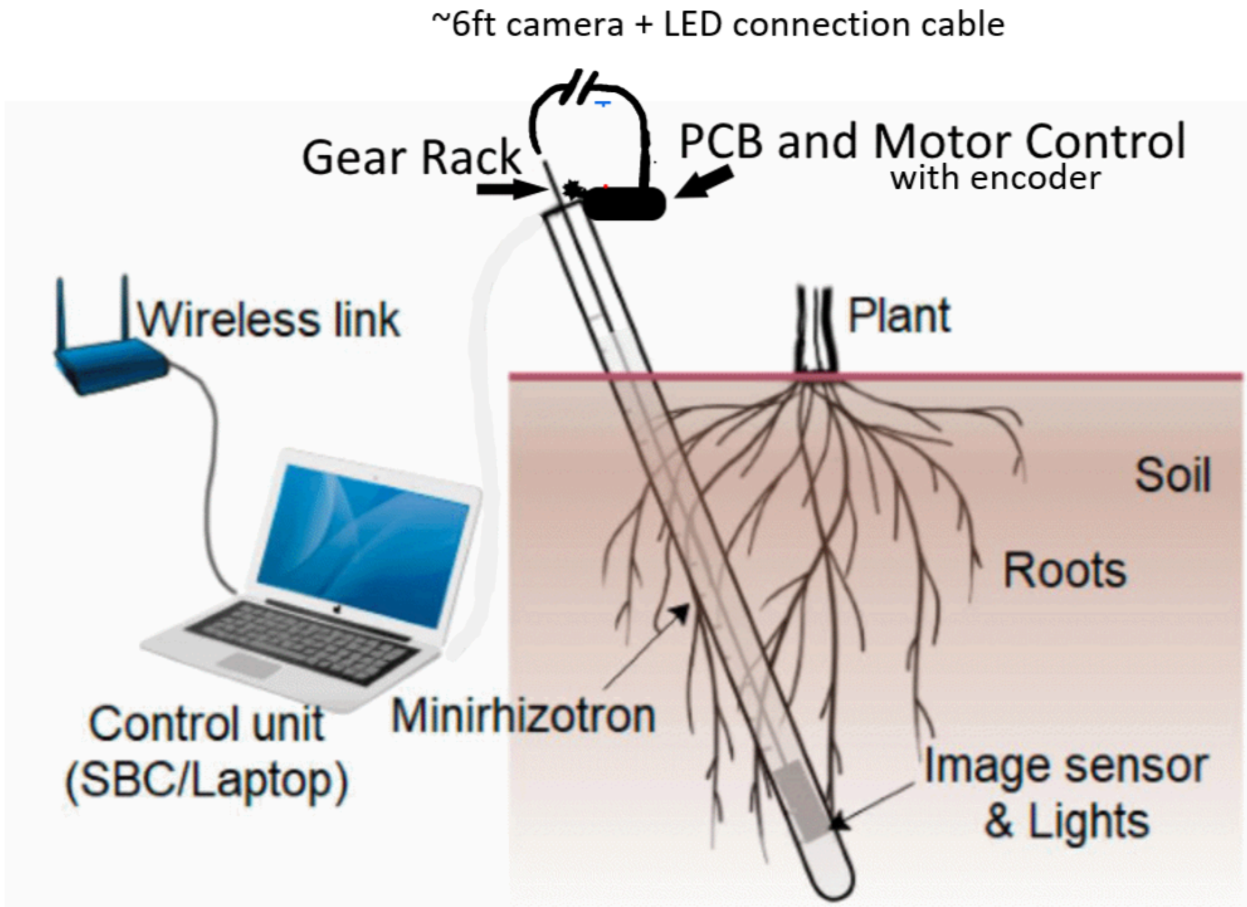

Figure 1: full scope project component visualization

Using the device would start by establishing the wireless connection between the microcontroller and a designated nearby laptop. For each plant, the operator would slot the camera into the tube and temporarily fasten the PCB/motor cap into place at the top. After the operator initializes the process from the computer, the motor descends the rack to the bottom of the tube, knowing it has reached the desired length by a color marker sticker on the rack that signifies the start position. From there it slowly ascends the rack. Through the microcontroller, the encoder provides the rate at which the camera takes the photos to enable consistent spacing between each capture. All the while, the camera is relaying its photos to the microcontroller, and it processes the data from the mirror photos and stitches them all together into the final photo. It then uploads the photo to the laptop for the user to save to the laptop's local storage.

High-level Requirements

- Drop resistant, able to be subject to repeated use.
- Waterproof, able to resist high moisture content within the tubes.
- Reliable movement system that rarely gets stuck or needs to be reset.
- Obtains clear, large, and consistent pictures of the desired root systems.
- Easy for operators to learn
- Faster capture of total root images relative to market-available products, where completing each tube can happen within the 4 minute existing standard.

Design

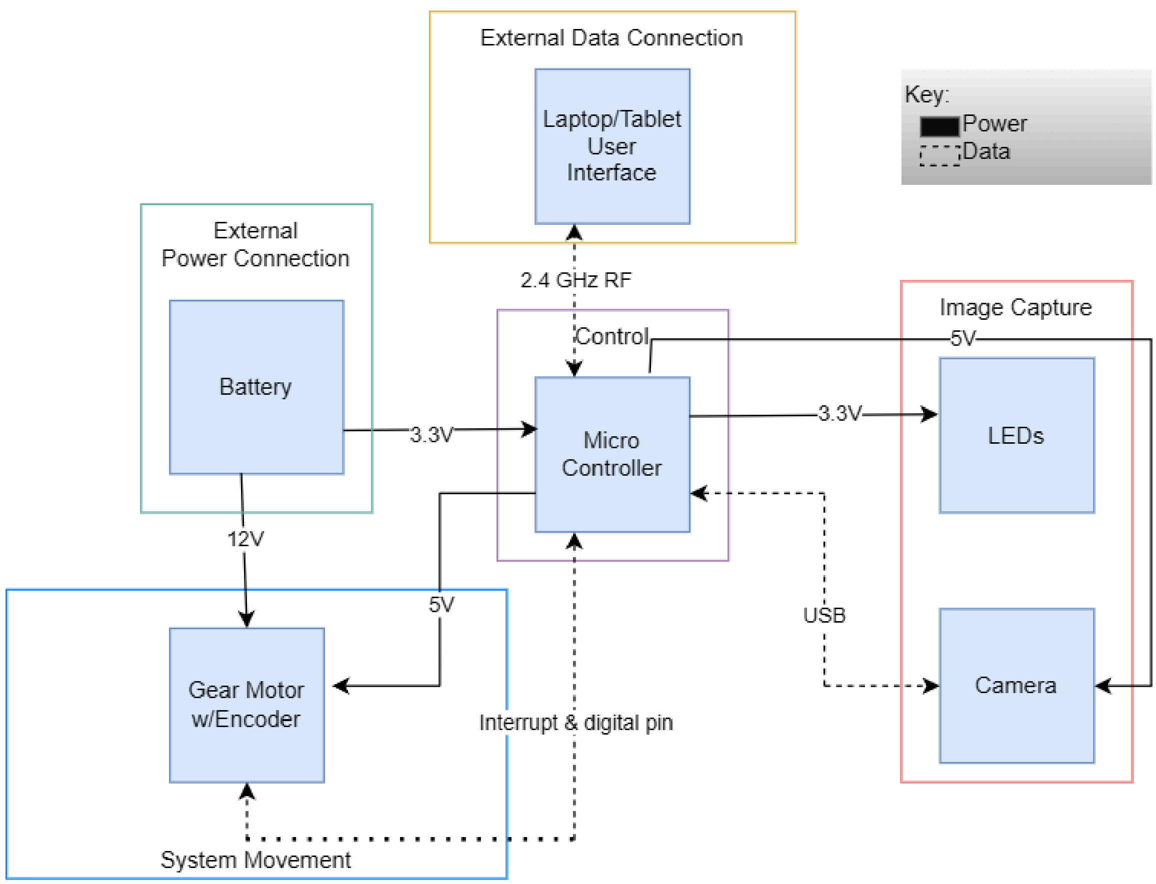

Figure 2: Block Diagram

Subsystem 1: Image Capture

To save costs and camera interface complexity, we will use a standard camera with a custom lens for obtaining ring-shaped cross-sections of the tube. The camera is centered on the bottom face of the device and faces directly down. Ahead of it, the vision of the camera is focused out into a telecentric lens. A few centimeters in front of the lens is a conical reflective surface. Both the lens and the mirror are roughly equal in diameter so that the camera obtains clear orthographic pictures of the mirror's contents. From its shape, the mirror displays a ring featuring a slice of the desired root system. The camera is connected via a cable on our rack and pinion to the main PCB and communicates a stream of photos as it descends.

A ring of small LEDs will be stationed above the camera in order to illuminate the surrounding walls of the tube; improving image quality and camera shutter speed. These will be custom assembled most likely and will need an approximate 3.3V.

Camera part number: OV5640 from OmniVision

Subsystem 2: Control

The Control system's purpose is the portion that controls the movement of the gear rack and determines the time of capture for the images. It will be stationed outside of the camera's tubing, with a near motor connection at the cap of the tube. It features a ESP32-S3-WROOM-2 microcontroller chip for image processing, data transfer, and control logic. The microcontroller is powered by a battery. We will wirelessly transfer the image data supplied to the microcontroller from the camera, externally onto a device (i.e. a tablet or a laptop). The microcontroller, given measurements from a wheel encoder that follows the movement of the gear rack, will use this information to command the lighting of the LEDs and activation of the camera.

6.2 Recommended Operating Conditions

Table 9: Recommended Operating Conditions

Symbol	Parameter	Min	Typ	Max	Unit
VDD33	Power supply voltage	3.0	3.3	3.6	V
I_{VDD}	Current delivered by external power supply	0.5	—	—	A
T_A	Operating ambient temperature	–40	—	65	°C

Figure 3: ESP32-S3-WROOM-2 datasheet voltage statistics

The main task of the microcontroller is to implement an algorithm to slice the known ring of data from each photo, reconstruct it horizontally, and stitch each slice into a final rendered picture which it saves to the local storage.

Subsystem 3: Power Connection

Power supply will be facilitated by a battery pack built into the cap device. It will supply power to the PCB and further routes the same power to all the other components of the system. The Microcontroller will send the image data, after its processing of the raw camera input, and output the image. See fig. 1 for specific voltage connections.

Subsystem 4: System Movement

There will be a gear rack aligned down the length of the tube, where a gear motor will be aligned and move the gear rack and the attached camera system. It will be controlled by the microcontroller, as well as there will be an encoder built in the motor that measures the travelling of the rack, allowing for computations and control logic that determines the camera activation. The motor will require a 12V input, with another input for the encoder of 5V. It will communicate directly with the microcontroller.

GEARMOTOR 251 RPM 12V W/ENCODER

Tolerance Analysis:

The largest part of our design that poses a risk is the movement system we currently have implemented. We are going to have a gear rack with the camera and lens mounted at the bottom, driven by a gear motor at the top. The need to include a long ~12tf cable, disconnecting important components from the pcb and adding near 6ft feet of slacked wire outside the rack could pose reliability and mechanical problems. However, feasibility seems to be plausible, as a similarly used track system was used by an older root imaging system (BARTZ). The difference between ours and the older model being the automatic driving of the shaft by a motor. These changes should be small enough to keep it feasible, and the connections of all the cables should be able to be all aligned in the main rod.

Another deviation from the BARTZ system and the CID CI-602 models is the 360 degree camera. We do not yet know with certainty that the camera system will be able capture similar quality 300dpi photos like the CID. Our first goal in our current roadmap is to demonstrate a camera prototype that meets our requirements.

Lastly, in dealing with such large high quality photos, concerns over the RAM capacity of our microcontroller arise. We are implementing a model with the highest available onboard RAM, but solutions with external RAM or a system of continuous upload to the computer during the image generation may be necessary.

Ethics:

In development, our first main ethical concern is differentiation from the existing products available. However our unique implementations of the new motor-driven rack and 360 degree camera make us confident our device is significant innovation in the field.

A safety concern for the camera operator is how a large metal rack is moving downward and upward outside the user's immediate control.This would require the user to employ a degree of caution, making sure to mount the motor cap securely to the tube and pay attention to the moving rack during its motion.