Autonomous Cylindrical Root Camera

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Abstract

In this Senior Design project, a device was realized that can mount and descend five feet into minirhizotron tubes, using a novel 360-degree mirrored camera to capture a set of pictures that are edited into a full realization image of the inside surface. The functioning unit utilizes image capture, control, power, and system movement subsystems in unison to complete each run through its state machine process. This is a device that is light enough to be used by one operator, is heat and moisture resistant, and has comparable image quality to other models on the market.

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Overview

Problem

A plant's root development is one of its biggest indicators for the success of each plant. Knowing this, in order for Biological Researchers at UIUC to evaluate the crops they grow on their campus plots, they need a large base of data on how their plants are developing roots throughout the growing season. From this they can glean insights into, Which genetic strains are performing well? How are the plants performing after specific weather conditions? What is the overall root quality? From there they can implement the stronger strains into farming practice, thus increasing future yields.

The project we have developed was 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, 6 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 operators using 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 our sponsors 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 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 a microcontroller for component communication, and Raspberry Pi for image processing, and WiFi connection to a computer for image transfer. The motor, encoder, PCB, and Raspberry Pi are encased together in a cap and mount/detach from the top of each tube. From there a cable extends through the length of the rack and pinion system down to the devices mounted at the bottom end. Only the camera and LEDs need to be there to capture the desired photos. All the constituent electronics are tightly secured and waterproof sealed within the device casings.

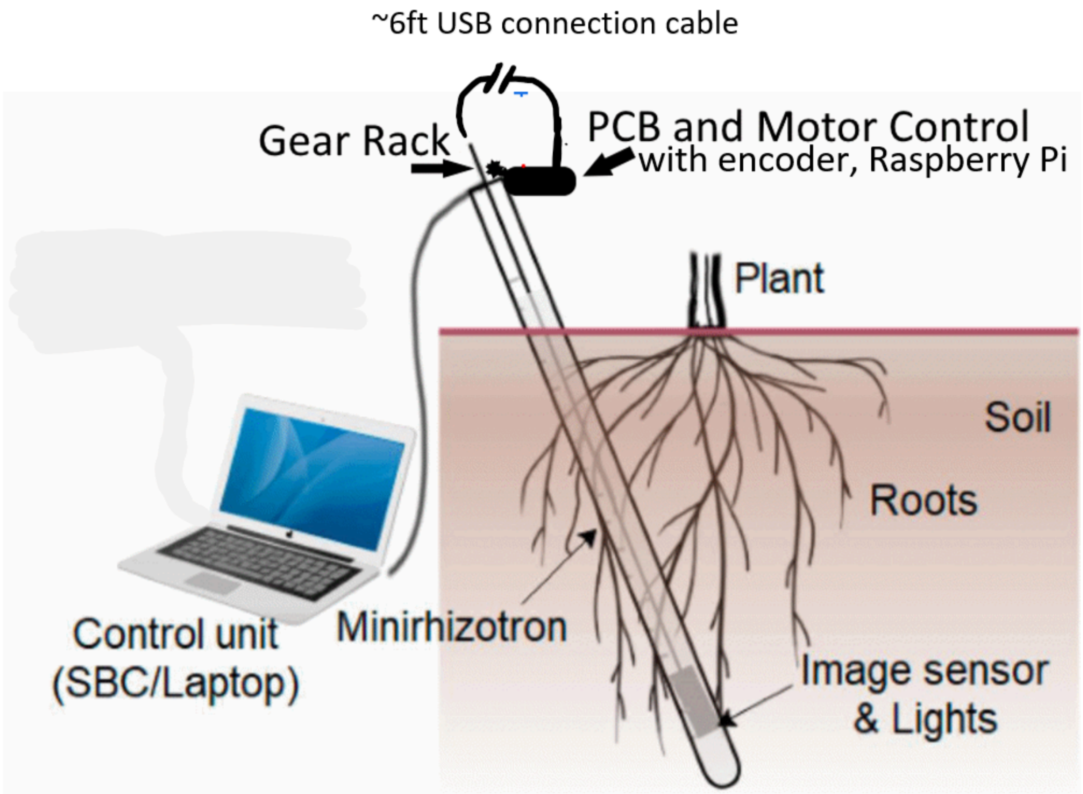

Figure 1: full scope project component visualization

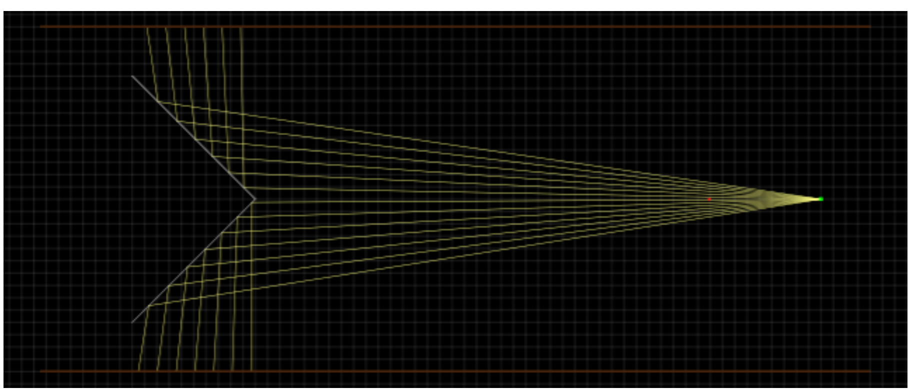

Figure 2: Ray simulation of image capture system

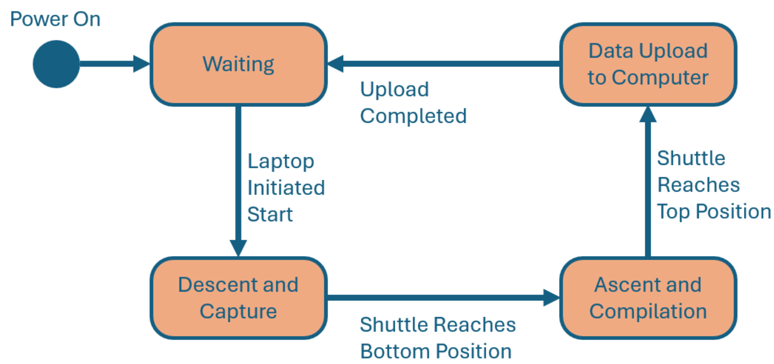

Figure 3: State Diagram

Using the device would start by establishing the connection to the Raspberry Pi from a computer and running the capture system program. For each plant, the operator would slot the camera and holding plug 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. After detecting the bottom of the tube via encoder, 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 Raspberry Pi, and it processes the data from the mirror photos and stitches them all together into the final photo. The image is then stored on the pi where it can be transferred externally onto a computer.

Highlevel Requirements

Resistant and Waterproof, able to resist high moisture content within the tubes:

Success of this goal happens after the device falls from a 3ft drop to solid surface, and all casings, mechanics, and electrical connections remain intact. The device still performs all intended tasks.

The camera subsystem can be submerged in water for multiple seconds without taking on water inside. The device still performs all intended tasks after such a test.

Reliable Movement System,

Motor and mechanical rack infrequently gets stuck or needs to be reset. Obtains clear, large, and consistent pictures of the desired root systems. Device completes the task successfully, downloading a full picture with a 70% success rate after starting the operation.

Photo Quality and Resolution:

Success of this goal happens when the camera subsystem captures 300 DPI or greater photos. 300 DPI is the bar set by the previous CID model.

Capture Speed:

Faster capture of total root images relative to market-available products, where completing each tube can happen within the 4 minute existing standard.

Design

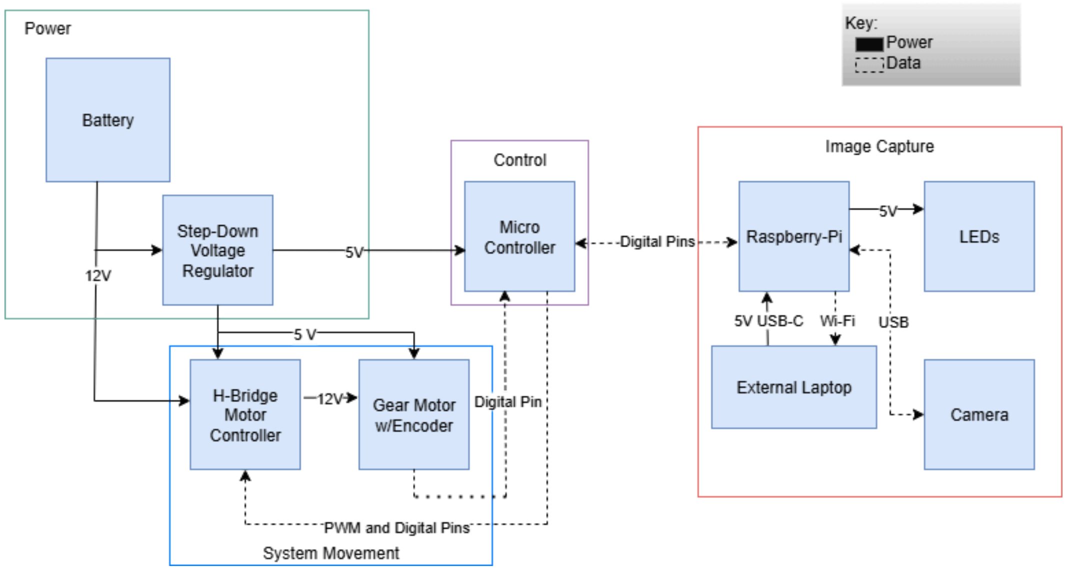

Figure 4: Block Diagram

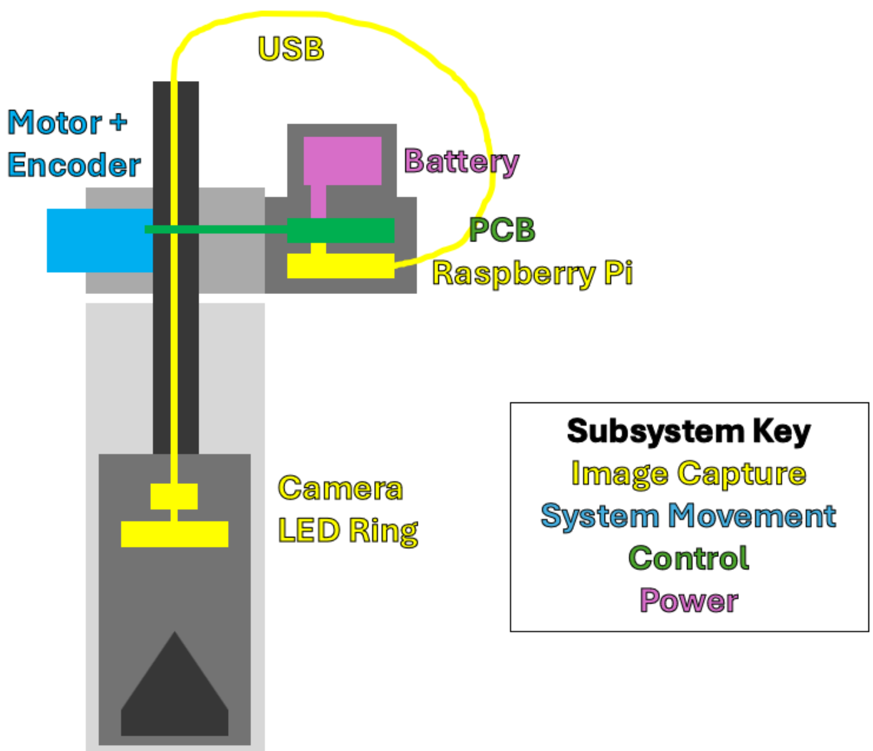

Figure 5: Orientation of Electronics Within The Prototype Color Coded by Subsystem

Subsystem 1: Image Capture System

To save costs and camera interface complexity, we used a standard camera for obtaining ring-shaped cross-sections of the tube. The camera is centered on the bottom face of the device and faces directly down. 9 centimeters in front of the lens is a conical reflective surface. The view of the camera and the mirror are close in diameter so that the camera obtains clear 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 a raspberry pi and communicates a stream of photos as it descends.

The conical reflective surface is a polished metallic cone, 1.5 inches in diameter with 45 degree angles downward to align images to the walls of the tubes. The metallic substance should is able to reliably reflect 95% of the light with little image interference; a new technique of silver painting on non-flat surfaces was completed on the mirror to further enhance reflective qualities.

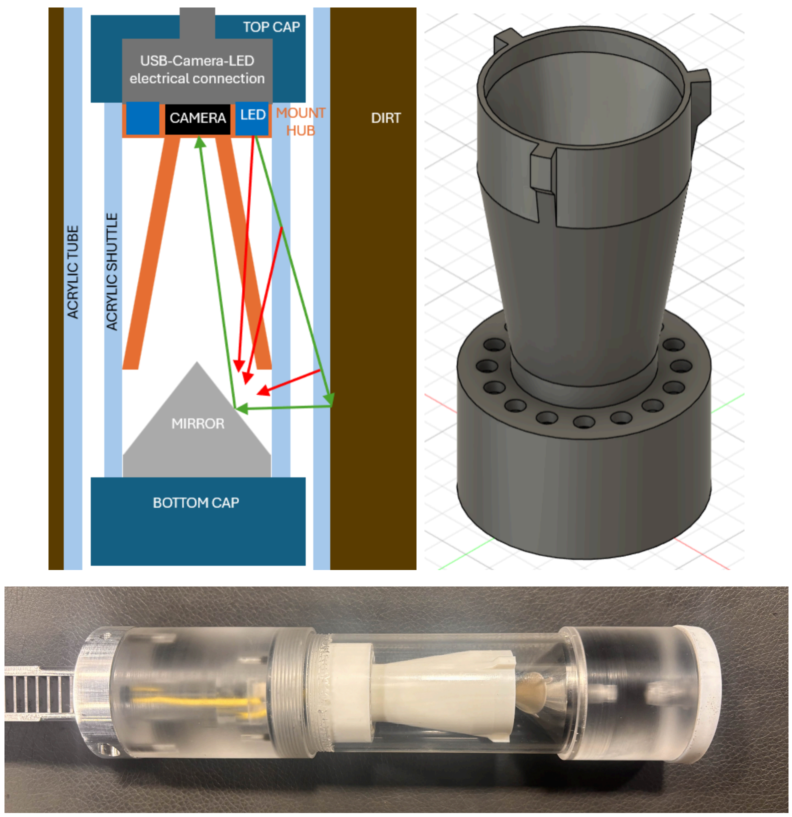

Figure 6: A) Glare mitigation cone light reflection analysis B) Autodesk Fusion light cone model C) Shuttle implementation with light cone (white)

A ring of small LEDs are stationed beneath the camera in order to illuminate the surrounding walls of the tube; improving image quality and camera shutter speed. These were custom assembled and stationed before a 3D-printed cone used for diffusing light without causing significant glare on the reflection. Effort was made to balance having some glare that reflects the minimum light required, while simultaneously limiting glare to prevent complete occlusion of the information.

The Camera is USB connected to a raspberry pi, done so as to ease the transport of the signal from 6 feet down a tube, up and out of it with slack. The camera model was chosen to have resolution large enough to create high quality output while also having resolution small enough to not overload the Raspberry Pi RAM.

The cable is 20 ft long and high quality to ensure durability. The USB connection is directly soldered onto the camera, as there was not enough space in the acrylic caps on the shuttle for a male to female connection to the camera. This would be improved in a future iteration.

The Raspberry pi we used is a Model 4 2GB, which houses enough RAM for our purposes. There is a 64GB microSD card for storage, which is plenty enough space for the amount of image data it will contain. Via an on-boot ran python script on the pi, the camera will transfer a frame of image data whenever the associated GPIO pin on board receives a HIGH from the microcontroller. From there, the script labels the image in ascending order (image1, image2, etc.) . Upon completion, the images will then be stored in a similarly labeled “album” that will correspond to each tube the camera goes down. These albums can then be transferred to a laptop through an SSH connection on the raspberry pi. The raspberry pi is powered via USB-C connection from the laptop.

The images are processed from the photos of reflection onto the final image starting on the ascent. First, the images are “unwrapped” from the circular image into a rectangular one. This is done with the OpenCV library, where we map the pixels of the desired ring of the image onto polar coordinates, and then mathematically convert those values into cartesian coordinates. Afterwards, the unwrapped image is appended to the final image, which contains the previously unwrapped images vertically in order. After all the images are finished unwrapping, the script saves the final appended image.

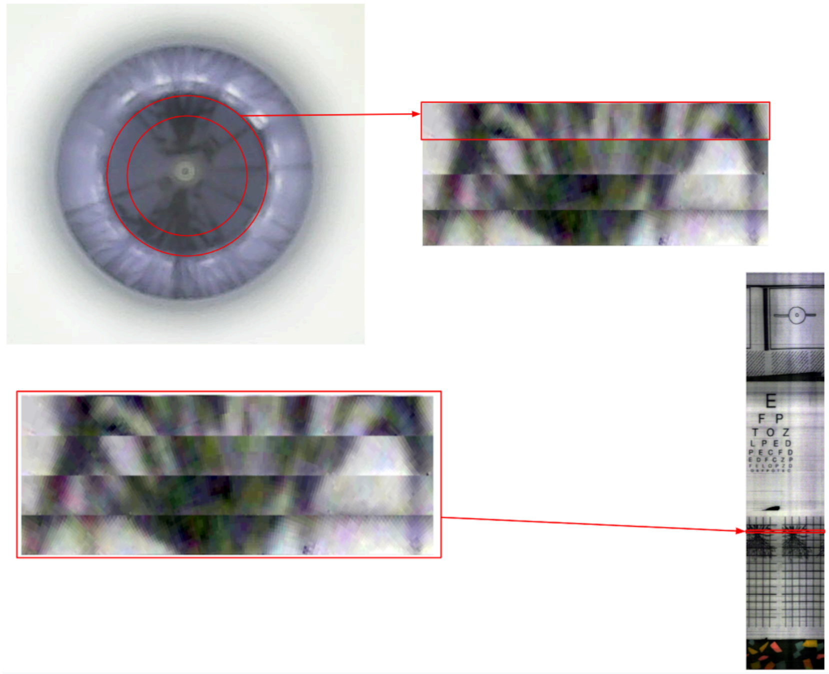

Figure 7: Visual representation of image construction

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 is stationed outside of the camera's tubing, with a near motor connection at the cap of the tube. It features a ATMega328-AU microcontroller chip for control logic. The microcontroller is powered by a 5V supply that is step-downed from the main battery. The microcontroller, given measurements from a wheel encoder that follows the movement of the gear rack, then uses this information to send a signal that commands frame acquisition to the raspberry pi. The signal sent to the pi from the microcontroller has a simple resistor voltage divider of some resistors to prevent any problems due to the raspberry pi functioning at 3.3 V and the microcontroller at 5V. Thus, the 5V signal must be lowered, however the 3.3V signal is high enough to register as a HIGH signal on the microcontroller and does not require any alteration.

The microcontroller controls the H-Bridge and then further the motor control through 3 pins: the DIR1, DIR2, and PWM1. The DIR1 and 2 pins determine direction, and the PWM pin determines the enabling and speed of the motor.

An ISP is attached to the board and it is what allows for configuration of the software on the microcontroller. As well as a capacitor and crystal circuit setup at the XTAL pins to allow for base functionality.

In determining the exact right time to take pictures we use the encoder values and some math for the distance they correlate to vertically on the rack. The encoder outputs an oscillating signal correlating to rotations of a magnet on an inner gear. Then, by using the below equation we take the encoder events per Inch, recorded by measuring rising edges of the signal, we can extrapolate the events needed per picture.

$$\frac{Events}{Inch} = \frac{Events}{Rotation} \Big/ \frac{Inches}{Rotation}$$

$$\frac{Inches}{Rotation} = Gear\ Pitch \times \pi$$

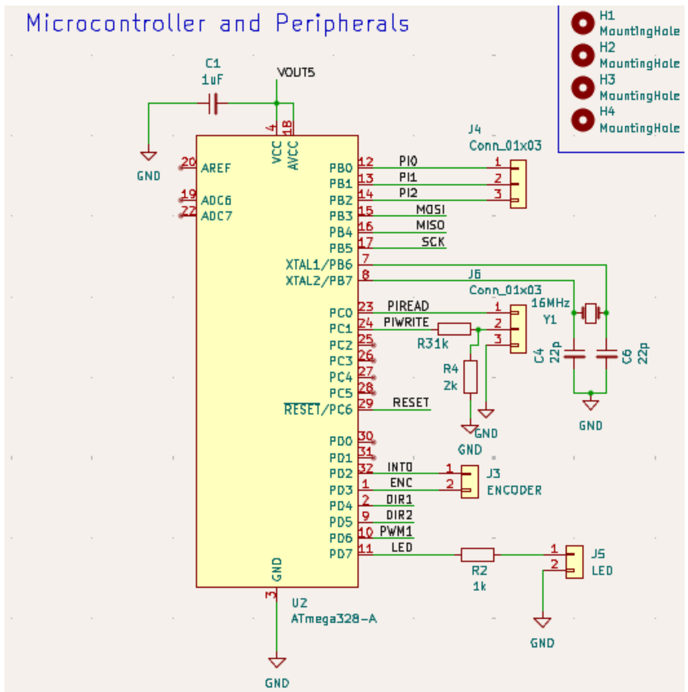

Figure 8: Microcontroller Schematic connections

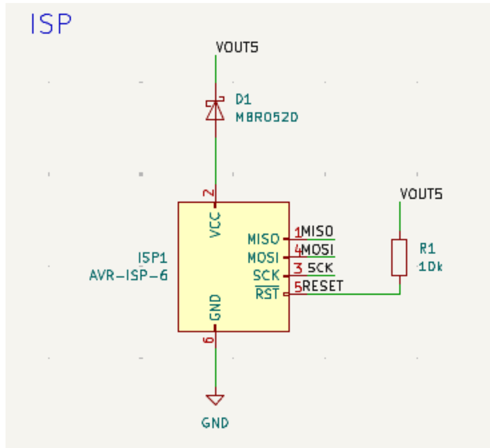

Figure 9: ISP Schematic connections

Subsystem 3: Power

The Power system is relatively simple, since the components only need 5V and 12V inputs. It supplies all the power to the components, done through an external 12V 5500mAh lithium ion battery, with a 12-5V voltage switch regulator to step-down the voltage to the lower voltage components. The setup shown in the figure below was taken from the datasheet. With this setup, this would allow for constant movement of the tube motor system for roughly 2 hours and 40 minutes, since the motor and PCB draw around 2A of current. This is not enough time for one battery since most use cases of the system would require up to 8 hours of use, and so to account for this a second battery is supplied that can charge whilst the other one is working and vice versa, allowing for constant use.

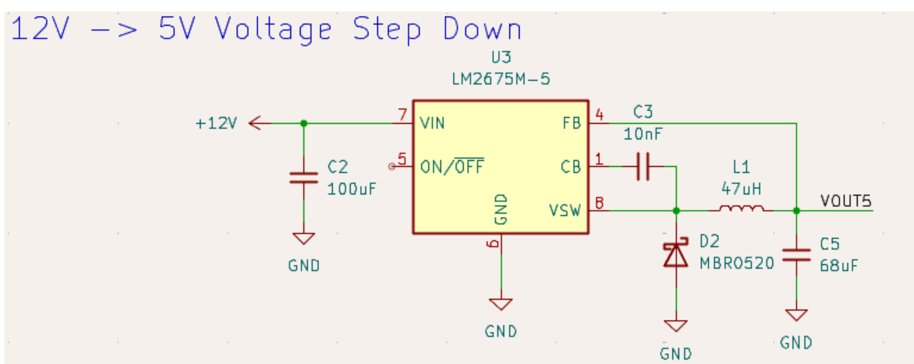

Figure 10: 12V to 5V voltage step down circuit schematic

Subsystem 4: System Movement

For our precise movement, there is a gear rack aligned down the length of the tube, where a gear motor is aligned and moves the gear rack and the attached camera system. It is 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. An H-Bridge is implemented to allow for the control and direction choice from the system. The motor will require a 12V input, with another input for the encoder of 5V.

The encoder communicates with the microcontroller through a data and interrupt pin, where it can then be measured and read digitally and computed with logic.

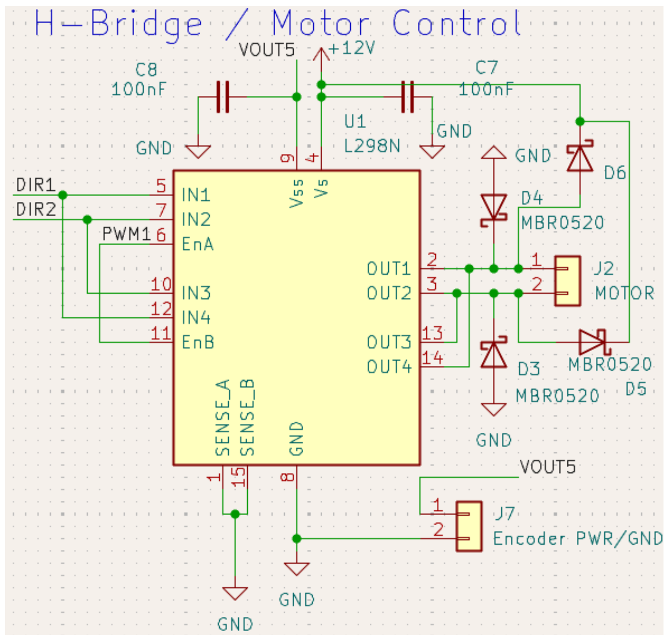

Figure 11: H-Bridge Schematic connections

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 300 DPI photos like the CID. However our initial testing, using a low resolution camera, a higher occlusion plastic housing as compared to the acrylic housing our final assembly will use, and a conical mirror with inferior polish and no glass coating, yielded 640x480 pixel photos with easily readable details in our test notes.

Cost Analysis:

Labor:

- Group Members: $30/hr * 8hr/wk * 8 wks * 3 partners = $5,760
- Machine Shop: $420/day * 15 days = $6,300

Material:

- ~$10 #D printing
- ~$10 camera (see citations)
- ~$60 motor (see citations)
- ~$700 for rack and pinion, motor mounts, cap assembly, camera housing, conical mirror
- ~$20 for PCB IC components
- ~$45 for Raspberry Pi
- ~$20 for USB A to USB A and LED power cabling
- ~$42 for Battery

Item	Manufacture	Cost
11.1V 12V 12.6V 3S2P 18650 Horizontal 7AH rechargeable lithium battery. (n.d.).	Fox Buying.	$ 18.26
12 RPM HD Premium Planetary Gear Motor w/Encoder. (n.d.)	ServoCity®	$ 59.99
ABM3-16.000MHZ-D2Y-T 16 MHZ Crystal Oscillator. (n.d.).	DigiKey	$ 0.56
Amazon.com: USB 3.0 Male to Male Cable 20 ft Type A Male to A Male Cord. (n.d.).	Amazon	$ 15.99
ATMEGA328-AU Microcontroller. (n.d.)	DigiKey	$ 2.42
C3216X5R0J686M160AB 68uF SMD capacitor. (n.d.).	DigiKey	$ 0.89
CBMF1608T470K 47uH inductor. (n.d.).	DigiKey	$ 0.16
CBR04C220F5GAC 22pF SMD capacitor. (n.d.).	DigiKey	$ 0.35
CL31A107MQHNNWE 100 uF SMD capacitor. (n.d.).	DigiKey	$ 0.40
FIT0701 USB Camera. (n.d.)	DigiKey	$ 9.90
GRM155R71C103KA01D 10 nF SMD capacitor. (n.d.).	DigiKey	$ 0.08
LM2675M-5.0/NOPB Switch Controller. (n.d.).	DigiKey	$ 5.66
LM2875 Simple Switcher. (n.d.).	Texas Instruments	$ 0.13
MBR0520-TP Schottky diode. (n.d.).	DigiKey	$ 0.23
RASPBERRY PI 4. (n.d.). TME Electronic Components.	TME Electronic Components	$ 38.00

Total:

Rough cost estimate **$12,967**

Ethics and Safety:

Originality (IEEE code of ethics tenet #4):

In development, our first main ethical concern is differentiation of our project 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. Our research sponsors have noted the shuttle subsystem could be worth pursuing a design patent for.

Operator Safety (IEEE code of ethics tenet #1):

A safety concern for the camera operator is how a large metal rack is moving downward and upward autonomously. The center of mass of the rack shifting upward and becoming top-heavy is one of our biggest concerns, which is why we are designing a 1ft long plug into the top of the cap that reinforces the connection to the tube.

The rack's movement, while slow, would still 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 rack during its motion. A final product would have warning stickers (likely on the motor casing) reminding the operator to avoid the moving rack.

Conclusion:

Revisiting Highlevel Requirements

Resistant and Waterproof, able to resist high moisture content within the tubes:

We were able to create a device with firm metal construction, with a shuttle specialized to resist moisture with tight bolt connections and a long disassembly thread with gasket. We were not able to run rigorous stress tests on the heat and moisture resistances, but those are planned to be done in spring 2026.

Reliable Movement System,

The motor rack and pinion system is both smooth and operates with significant torque to spare. In testing and demonstration, the system only failed to develop an output photo when the connected laptop dropped its connection from its own end. Again we were not able to push the model to breaking point, but those tests are also planned to be done in spring 2026.

Photo Quality and Resolution:

The system was able to create modest ~150 DPI images. The research team was confident photos meeting the requirements could be developed with further image processing and potential camera upgrade.

Capture Speed:

Our full capture process was timed at five minutes and ten seconds. This is about one minute short of the goal, however an adjustment of the rack and pinion gear ratio could greatly improve the maximum speed.

Unlike the other manually operated models, our model enables one operator to start the process of multiple devices simultaneously. In this way, an operator alternating between just 2 models could double their productivity, effectively neutralizing the run time issue.

Continuing Support from Research Team

The consensus from our sponsoring team was that our project at this time has been largely successful and is worth continuing in the future. In the following months, we will be looking into potential grant funding, a deep dive into stress testing, increased production of more models, sale on the market for profit, and a design patent on the image capture subsystem.

Continuation

In the coming months of development, we hope to address these outstanding issues that ought to exist for a field ready model. The researcher hope to have such a model by next June.

- Camera to USB Male/Female connection that allows for easy replacement in case of broken cable
- Independent LED power cable
- Automatic calibration before runtime loop
- Higher camera quality with new camera model
- More advanced image post processing
- Weatherproofing the motor, PCB, and battery
- Creating a user friendly interface software
- Expanding the software with user customizable settings
- Reconsideration of PCB and Raspberry Pi, as the Raspberry Pi could potentially be removed in favor of the laptop performing its functions. (Note this was not implemented initially as a limitation of the senior design class)

Citation:

11.1V 12V 12.6V 3S2P 18650 Horizontal 7AH rechargeable lithium battery. (n.d.). Fox Buying. https://www.foxbuying.com/11-1v-12v-12-6v-6-cell-7ah-18650-horizontal-rechargeable-lithium-battery-pack-for-outdoor-street-light-monitoring-power-supply.html

12 RPM HD Premium Planetary Gear Motor w/Encoder. (n.d.). ServoCity®. https://www.servocity.com/12-rpm-hd-premium-planetary-gear-motor-w-encoder/

ABM3-16.000MHZ-D2Y-T 16 MHZ Crystal Oscillator. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/abracon-llc/ABM3-16-000MHZ-D2Y-T/2344578

Amazon.com: USB 3.0 Male to Male Cable 20 ft Type A Male to A Male Cord. (n.d.). Amazon. https://www.amazon.com/dp/B0D7STZKN9

ATMEGA328-AU Microcontroller. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/microchip-technology/ATMEGA328-AU/2271029

C3216X5R0J686M160AB 68uF SMD capacitor. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/tdk-corporation/C3216X5R0J686M160AB/3951907

CBMF1608T470K 47uH inductor. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/taiyo-yuden/CBMF1608T470K/1007996

CBR04C220F5GAC 22pF SMD capacitor. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/kemet/CBR04C220F5GAC/3479641

CL31A107MQHNNWE 100 uF SMD capacitor. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/samsung-electro-mechanics/CL31A107MQHNNWE/10479833

FIT0701 USB Camera. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/dfrobot/FIT0701/13166487

GRM155R71C103KA01D 10 nF SMD capacitor. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/murata-electronics/GRM155R71C103KA01D/587215

LM2675M-5.0/NOPB Switch Controller. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/texas-instruments/LM2675M-5-0-NOPB/271162

LM2875 Simple Switcher. (n.d.). Texas Instruments. https://www.ti.com/lit/ds/symlink/lm2675.pdf

MBR0520-TP Schottky diode. (n.d.). DigiKey. https://www.digikey.com/en/products/detail/mcc-micro-commercial-components/MBR0520-TP/717250

RASPBERRY PI 4. (n.d.). TME Electronic Components. https://www.tme.com/us/en-us/details/sc0193-9/raspberry-pi-minicomputers/raspberry-pi/raspberry-pi-4-model-b-2gb-ram/

Parts Mentioned: “FIT0701 DFRobot | Development Boards, kits, programmers | DigiKey,” DigiKey, https://www.digikey.com/en/products/detail/dfrobot/FIT0701/13166487

Raspberry pi 4 model B specifications – raspberry pi, https://www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications/

“Board index,” Raspberry Pi Forums - Index page, https://forums.raspberrypi.com/viewtopic.php?t=359482

“Using USB webcams,” The Raspberry Pi Guide, https://raspberrypi-guide.github.io/electronics/using-usb-webcams

JoseBarreiros and Instructables, “Trigger a webcam with a button and Raspberry Pi,” Instructables, https://www.instructables.com/Trigger-a-Webcam-with-a-button-and-Raspberry-Pi

Papado 10311 gold badge11 silver badge44 bronze badges et al., “Fast cartesian to polar to cartesian in python,” Stack Overflow, https://stackoverflow.com/questions/9924135/fast-cartesian-to-polar-to-cartesian-in-python

“IEEE code of ethics | IEEE,” IEEE, https://www.ieee.org/about/corporate/governance/p7-8

Appendix A Requirement and Verification Table

Requirements	Verifications	Verification Status (Y/N)
1. 150+ dpi (dots per inch) image quality	• Proper alignment of camera in shuttle • Post-image review of pixel width per	Y

	image via image software on laptop	
2. Voltage within 3.3V-5V for LED connection	• Probe output pin on PCB with voltmeter to ensure data pin is outputting voltage high enough • Secure cable connection and check as cable goes downward in rack	Y
3. USB camera to Pi connection remains stable to transmit data	• Ensure proper connections in USB ports • Secure cable connection and check as cable goes downward in rack	Y
4. Proper 5V to 3.3V step down on PIWRITE signal	• Proper soldering of resistors • Probing at output connector before GPIO connection to ensure proper stepdown with voltmeter	Y
5. Functioning PWM output from low duty cycle (5-10%) to full (100%)	• Checking frequency via oscilloscope for proper functionality	Y
6. 5V Data pin control signals maintain range within 3-5.5V	• Probing pins of contact with voltmeter • Checking for correct soldering of pins and hole-through connectors	Y
7. Battery must supply 12V to the motor and switch regulator	• Ensuring good PCB connection on board from battery • Testing battery health (ensuring high enough voltage) by probing through holes with voltmeter • Confirm voltage is within 9.5 - 12 V via probing with voltmeter	Y
8. Switch regulator must supply a steady 5V	• Ensure proper soldering of IC component	Y

output to encoder and microcontroller dropped down from 12V	● Probing output of switch regulator subsystem with voltmeter ● Confirm voltage is within 4.5-5.5V	
9. Battery must be able to last multiple tubes in outdoor environment	● Secure connection onto PCB even through movement, confirm steady wire connections by probing of voltmeter ● Modularity; easily removable and attachable wires in case of battery replacement ● Allow for easy recharging of batteries; making sure charging ports are accessible.	Y
10. 9.5 V-12V line through H-bridge is transmitted during PWM signal	● Probe output and input pins of H-Bridge with voltmeter ● Probe connector through hole pins to motor connection with voltmeter ● Confirm 9.5V-12V	Y
11. Encoder is properly functioning for correct distance it tracks	● Test distances with real time comparisons	Y
12. Motor moves gear rack without error	● Ensure proper alignment of cap and attachment visually ● Ensure gear motor to gear rack connection is secure	Y