Autonomous Cylindrical Root Camera

ECE 445 Design Documentation

Fall 2025

Project #24

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Overview

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, 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 USB connection to an external computer. 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 will be tightly secured and waterproof sealed within the device casings.

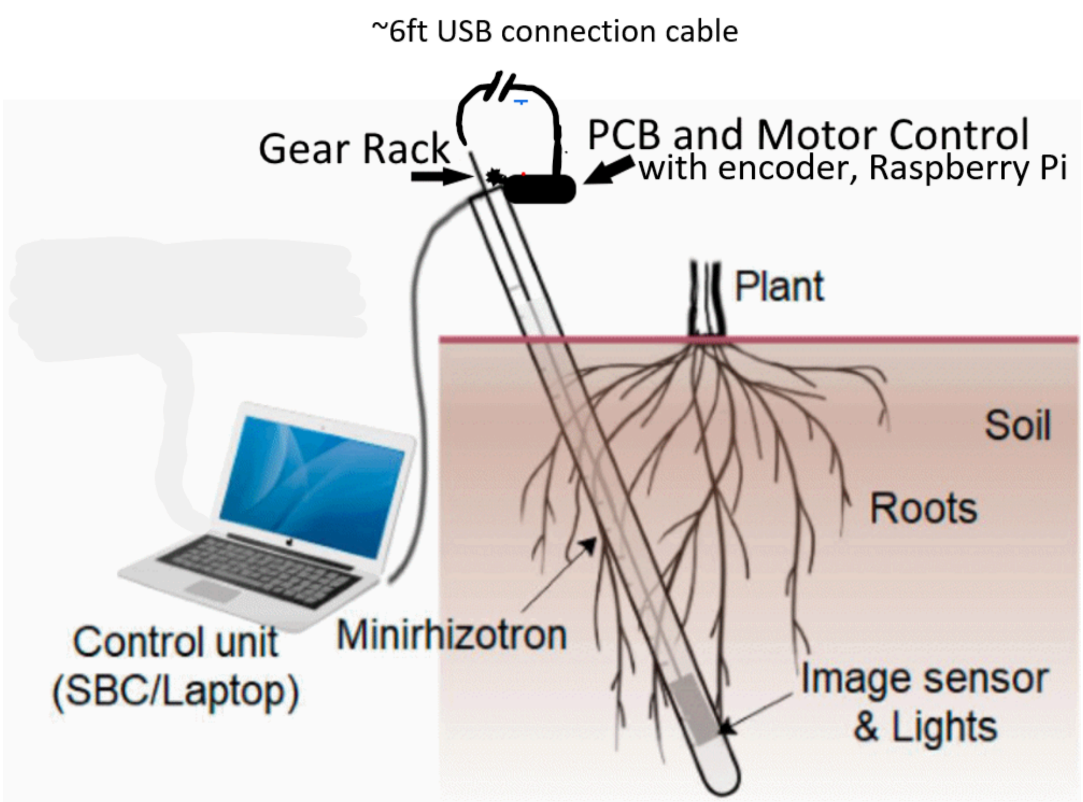

Figure 1: full scope project component visualization

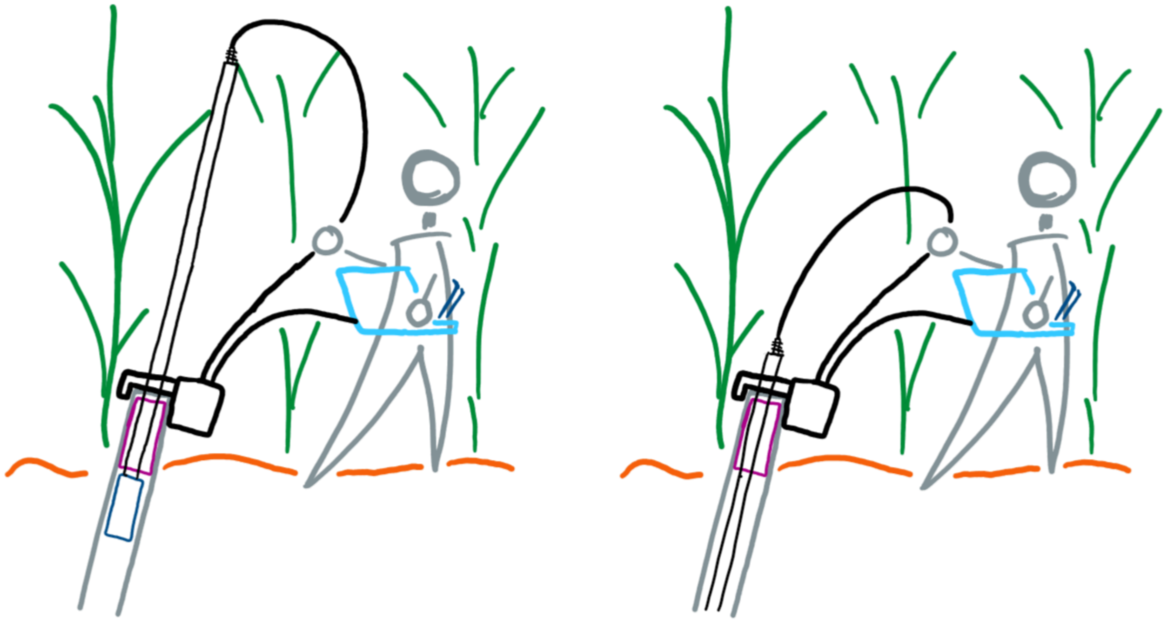

Figure 2: Single operator guiding the USB cable with one hand while controlling device from laptop with other hand. Device shown in the UP and DOWN positions. Laptop held up for the user via commercial waist harness.

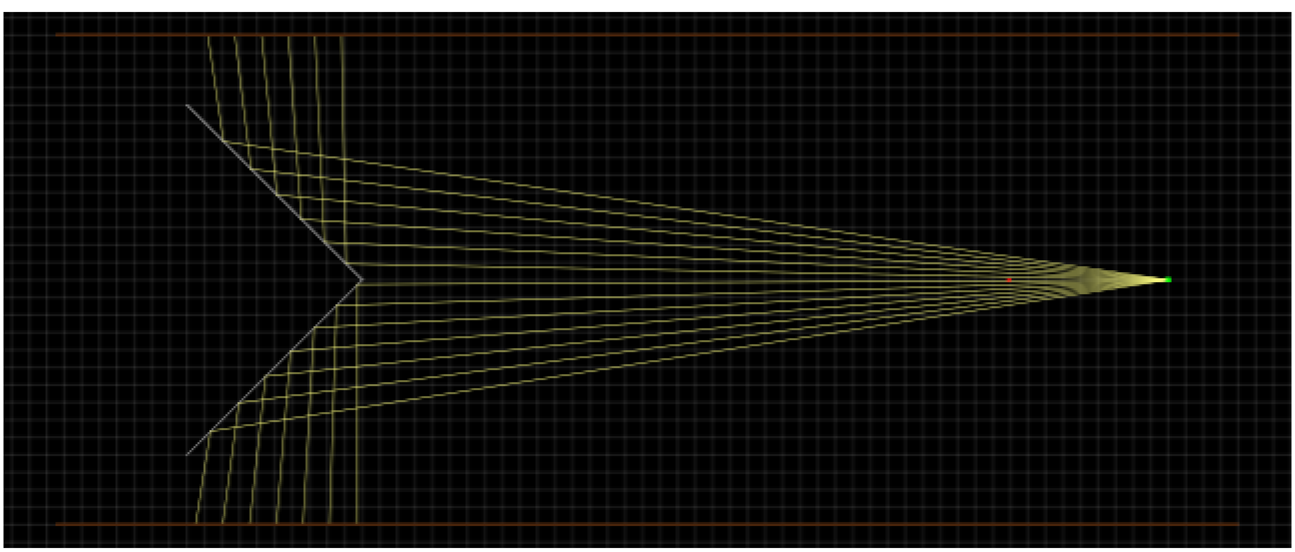

Figure 3: Ray simulation of image capture system

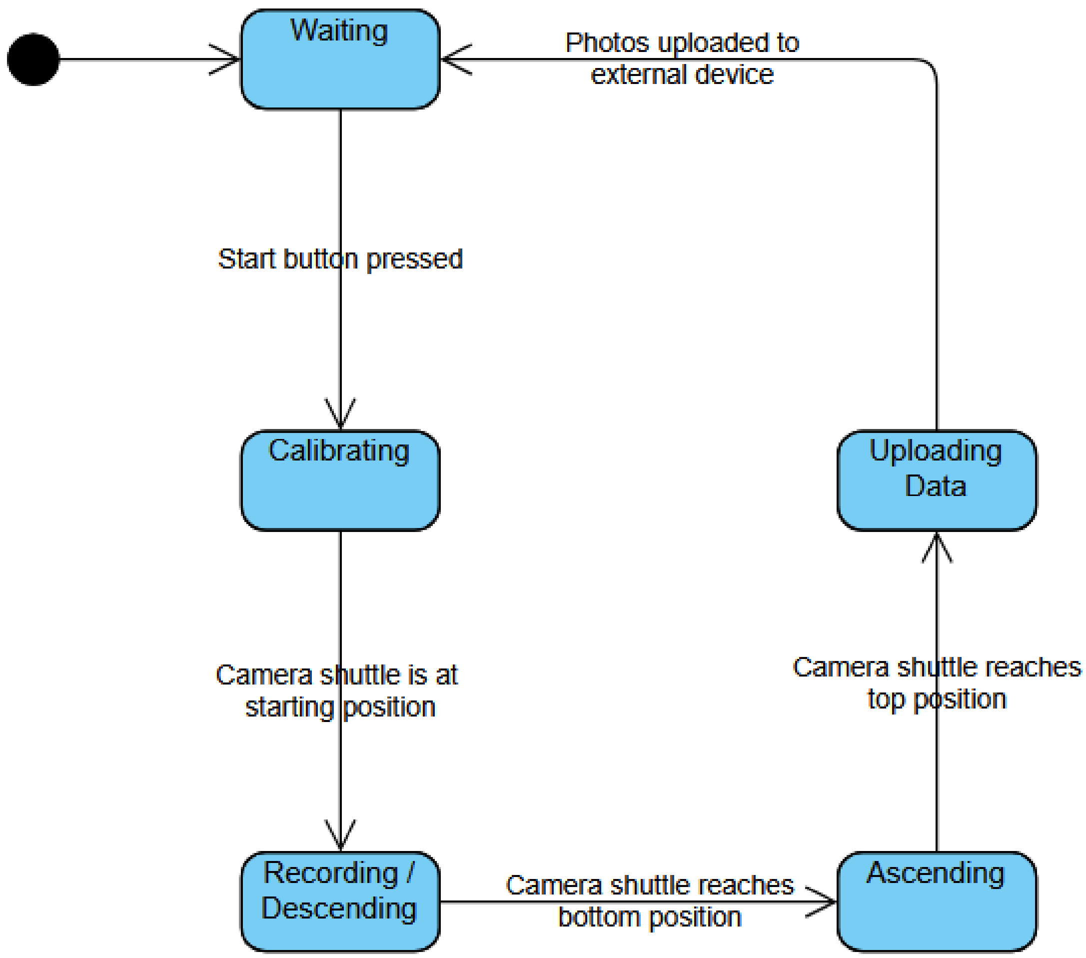

Figure 4: State Diagram

Using the device would start by establishing the usb connection onto the PCB and sending a start signal through the control unit. 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. It then uploads the photo to the laptop for the user to save to the laptop's local storage.

Highlevel Requirements

<u>Resistant and Waterproof, able to resist high moisture content within the tubes:</u>

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.

<u>Reliable Movement System,</u>

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.

<u>Photo Quality and Resolution:</u>

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.

<u>Capture Speed:</u>

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

Design

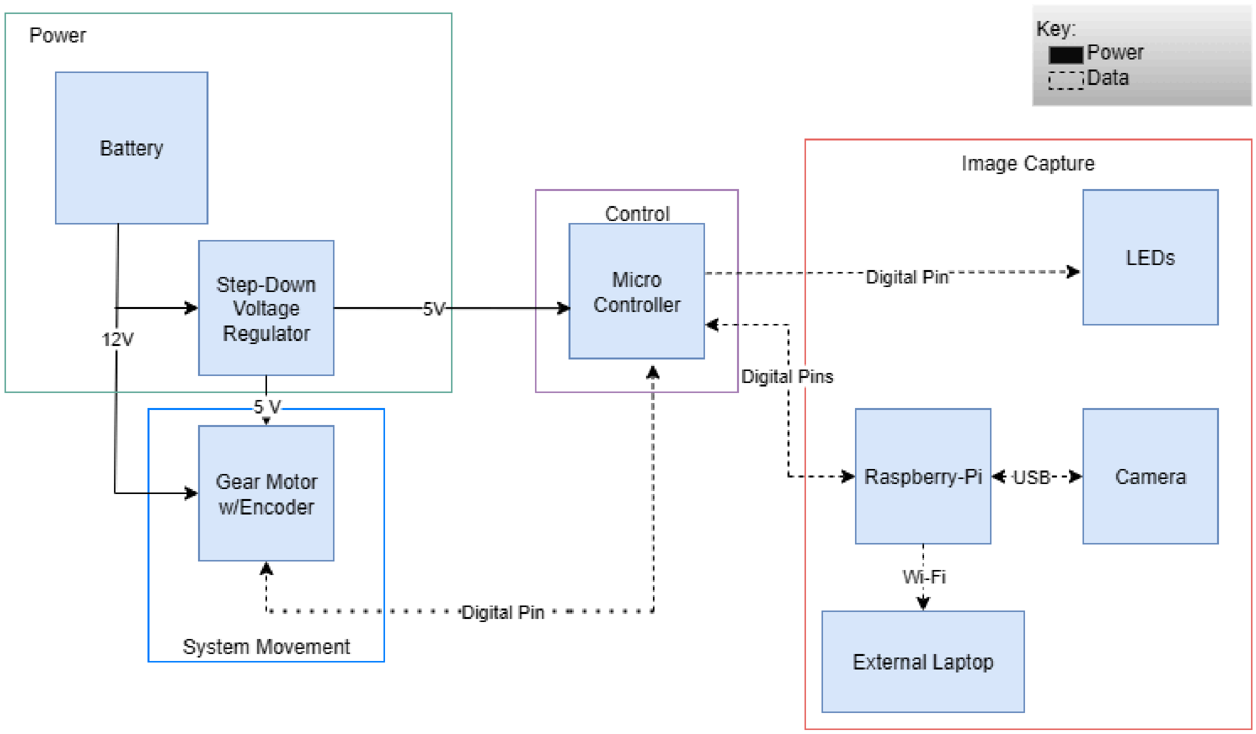

Figure 5: Block Diagram

Subsystem 1: Image Capture System

To save costs and camera interface complexity, we will use 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. 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. The view of the camera and the mirror are roughly equal 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 will be a polished metallic cone, a little under 2 inches in diameter (fit to size of tube) with 45 degree angles downward to align images to the walls of the tubes. The metallic substance should be able to reliably reflect 95% of the light with little image interference; silver painting will be done to further enhance reflective qualities.

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 and will be controlled from the microcontroller from a data pin.

The Camera will be 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 cable will be 20 ft long and high quality to ensure enough slack without loss of data. The USB connection also allows for more ease of use on the pi due to its compatibility.

The Raspberry pi we are using is 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 and a powershell command over Wi-Fi. The raspberry pi will also be powered via USB-C connection from the laptop.

Table 1: Image Capture Requirements & Verifications

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

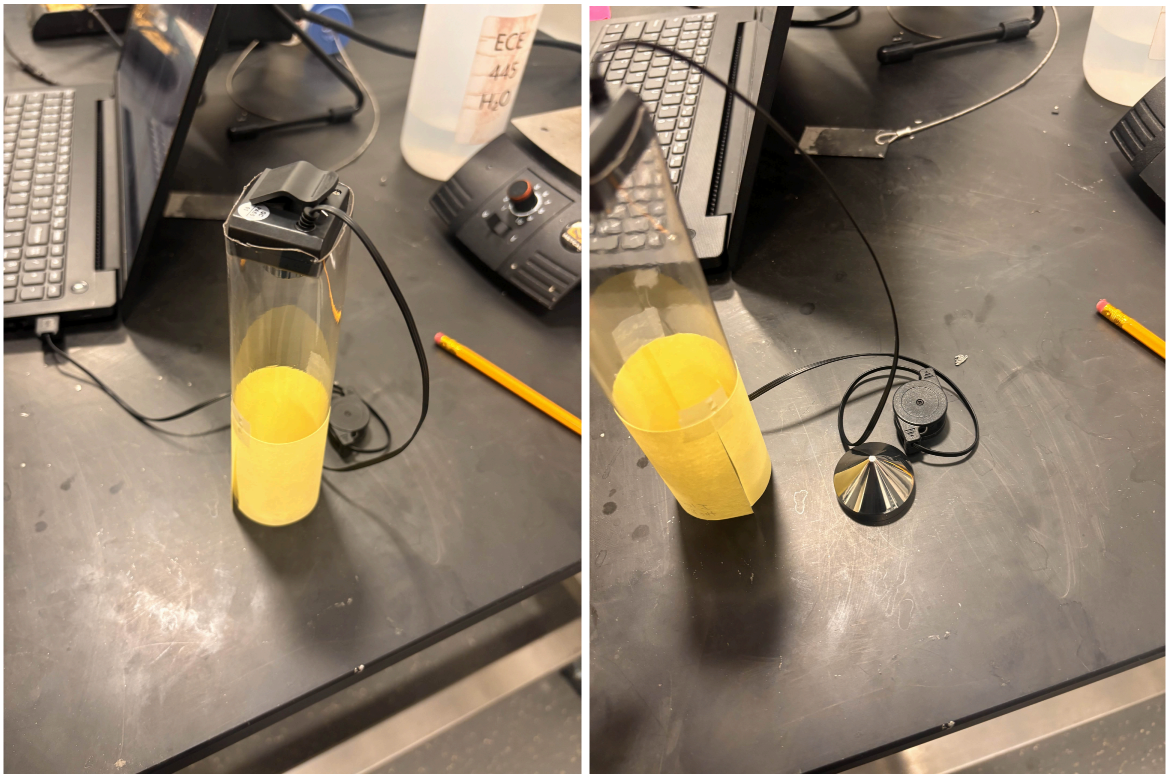

Figure 6: Camera system testing model. Using

Figure 7: Camera system testing result (640x480 pixels).

The test featured above was done 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, unlike the one we will use in the final model. Despite these limitations, we were able to clearly capture some simple hand sketches on sticky notes that simulate how the roots should look down underground.

SPECIFICATION

- Photosensitive Element: CMOS
- AGC/AEC/AWB: auto
- Infrared Filter: 650±10nm
- Supports MJPG and YUV format
- FPN: < 0.03% of VPEAK-TO-PEAK
- Connector: USB 2.0
- Pixel: 30W
- Resolution: 640*480
- Operating Voltage: 5V
- Operating Temperature: -20℃-70℃
- FCC & CE Certification
- Dimension: 30*25*21.4mm/1.18*0.98*0.84"
- Supports Windows, iOS, Android, Linux

Figure 8: Specifications of the 0.3 MegaPixels USB Camera for Raspberry Pi and NVIDIA Jetson Nano (see citations).

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 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, will use this information to command the lighting of the LEDs and activation of the camera. It controls the activation of the camera by sending a GPIO high signal to a raspberry pi, which then has the camera take a frame and transmit it, and upon finishing the pi sends a ready signal back to the microcontroller indicating it has finished the picture and can continue movement. The signal sent to the pi from the microcontroller has a 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 will command 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.

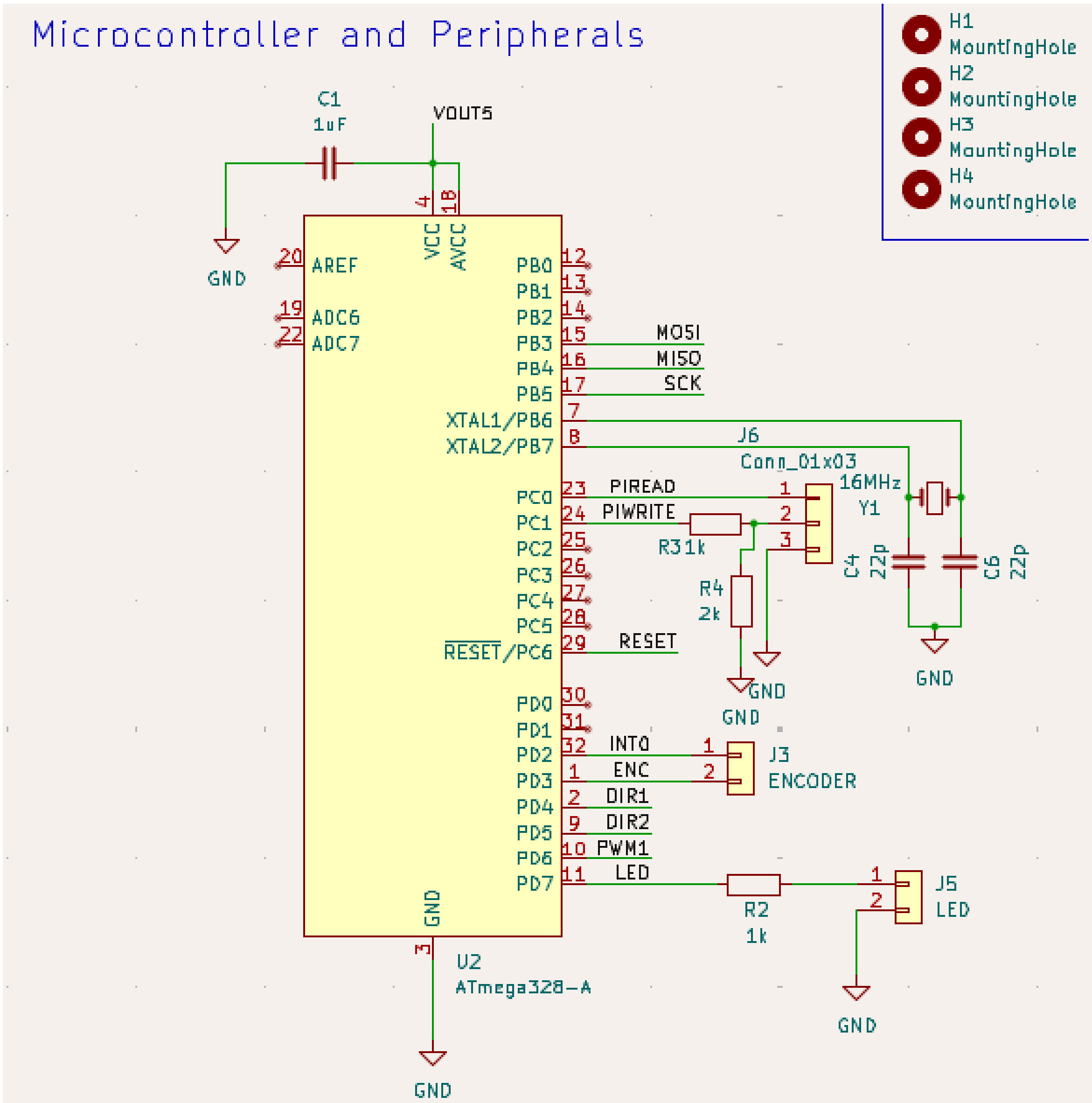

Figure 9: Microcontroller Schematic connections

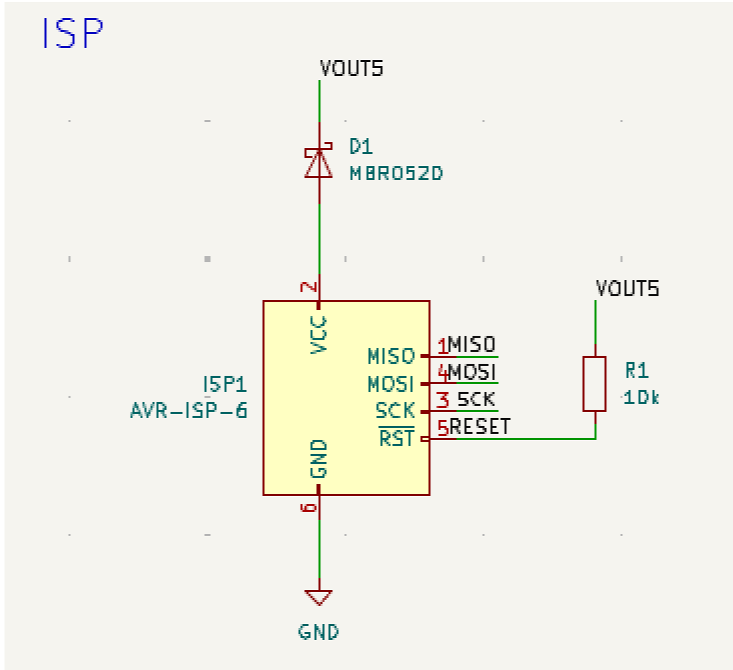

Figure 10: ISP Schematic connections

Table 2: Control System Requirements & Verifications

Requirements	Verifications
1. 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
2. Functioning PWM output from low duty cycle (5-10%) to full (100%)	• Checking frequency via oscilloscope for proper functionality
3. 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

Subsystem 3: Power

The Power system is relatively simple, since the components only need 5V and 12V inputs. It will supply all the power to the components, supplied by an external 12V 7AH 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. The battery will be connected by a peripheral connector gen. Since the motor will be moving rather slowly since it will be starting and stopping a lot, the battery can have a lowered voltage and less accommodation for the drop over time will be needed.

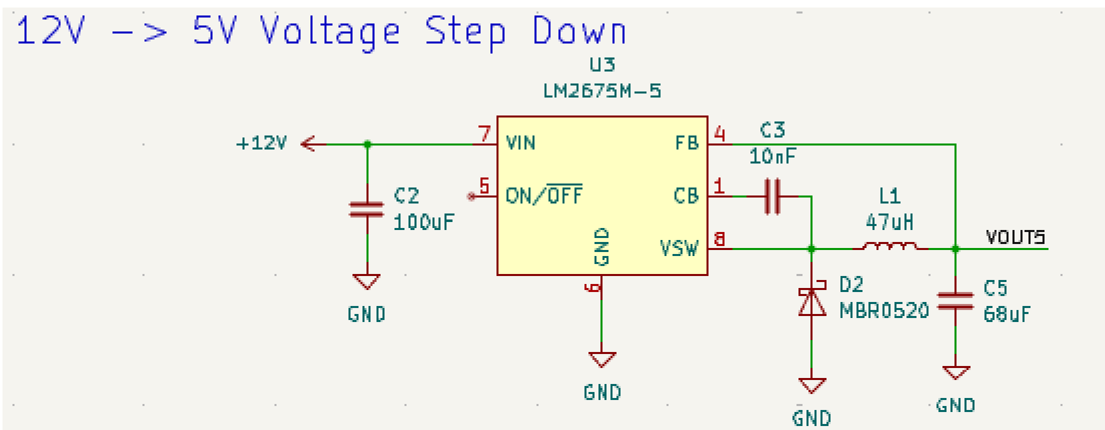

Figure 11: 12V to 5V voltage step down circuit schematic

Table 3: Power System Requirements & Verifications

Requirements	**Verifications**
1. 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
2. Switch regulator must supply a steady 5V output to encoder and microcontroller dropped down from 12V	● Ensure proper soldering of IC component ● Probing output of switch regulator subsystem with voltmeter ● Confirm voltage is within 4.5-5.5V
3. 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.

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. An H-Bridge will be 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 will communicate with the microcontroller through a data and interrupt pin, where it can then be measured and read digitally and computed with logic.

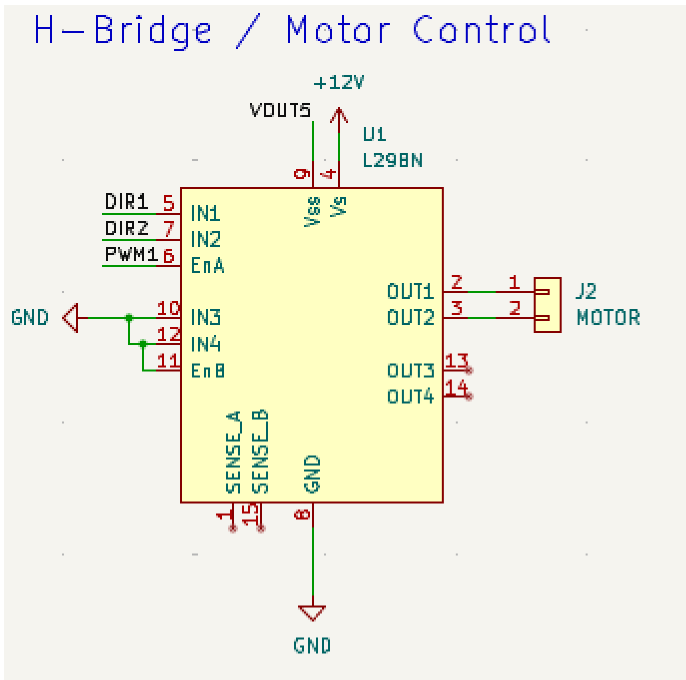

Figure 12: H-Bridge Schematic connections

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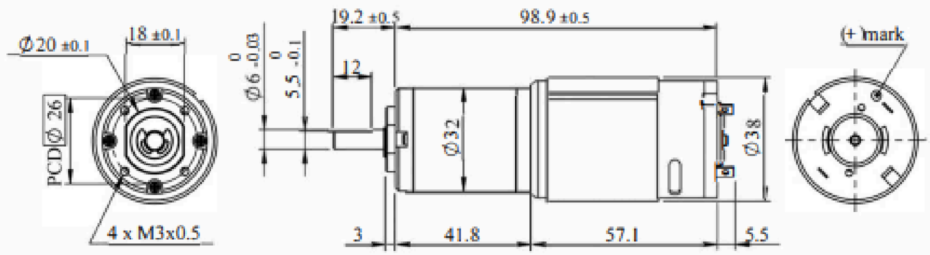
DIRECTION OF ROTATION

SPECIFICATIONS

DC Planetary Gear Brush Motor



(unit:mm)

A. Operating Conditions:

1	Operating Voltage Range	6~12	VDC	4	Operating Temperature	-10~+60	°C
2	Rated Voltage	12	VDC	5	Storage Temperature	-30~+85	°C
3	Rated Load	21	kgf-cm	6	Test Position	Horizontal	~

B. Electrical Characteristics:

1	Max. No-load Current	0.54	A	6	Max. Stall Current	20	A
2	No-load Speed	12±2	rpm	7	Insulation Resist.(500V)	20	MΩ
3	Rated-load Current	0.8	A	8	Dielectric Strength	250	VAC
4	Rated-load Speed	11.3±1	rpm	9	Motor Brush Type	Graphite	~
5	Min. Stall Torque	584	kgf-cm	10	Output Power at Max.Eff.	9	W

C. Mechanical Characteristics:

1	Gear Type	Planetary	~	7	Max. Shaft Radial Load	3.5	kgf
2	Gear Ratio	1/721	~	8	Max. Shaft Runout	0.05	mm
3	Gear Material	Metal	~	9	Max. Shaft End Play	0.30	mm
4	Rated Tolerance Torque	22	kgf-cm	10	Bearing Type	Dual Ball	~
5	Moment. Tolerance Torque	44	kgf-cm	11	Net Weight	380±20	grams
6	Max. Shaft Axial Load	2.5	kgf				

Figure 13: Motor specs

Table 4: System Movement Requirements & Verifications

Requirements	Verifications
1. 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
2. Encoder is properly functioning for correct distance it tracks	● Test distances with real time comparisons
3. Motor moves gear rack without error	● Ensure proper alignment of cap and attachment visually ● Ensure gear motor to gear rack connection is secure

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 and Schedule:

Cost:

<u>Salary:</u>

- $30/hr * 8hr/wk * 8 wks * 3 partners = $5,760
- ~$500 in machine shop commission hours (tbd)

<u>Material:</u>

- ~$10 camera (see citations)
- ~$60 motor (see citations)

- ~$200 for rack and pinion, motor mounts, cap assembly, camera housing, conical mirror (tbd)
- ~$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

<u>Total:</u>

Rough cost estimate $6,650

Schedule:

Week of 10/13:

Aidan	Finalize PCB
Nate	Begin work with Gregg on Motor/Rack and Pinion assembly Test acquired motor performances
Zach	Begin work with Gregg on Motor/Rack and Pinion assembly Test acquired motor performances

Week of 10/20 and 10/27:

Aidan	Finalize PCB Begin work with Gregg to build power subsystem
Nate	Complete work with Gregg on Motor/Rack and Pinion assembly Begin work with Gregg to build Camera subsystem
Zach	Complete work with Gregg on Motor/Rack and Pinion assembly Complete code to turn circular image data into rectangular image

Week of 11/3:

Aidan	Test operation of Rack and Pinion, fix errors and malfunctions Fully connect and power all subsystems to raspberry pi and PCB Complete work with Gregg to build power subsystem
Nate	Test operation of Rack and Pinion, fix errors and malfunctions Fully connect and power all subsystems to raspberry pi and PCB Complete work with Gregg to build Camera subsystem
Zach	Complete code to correct rectangular image data for distortion

Week of 11/10:

Aidan	Test operation of power subsystem, fix errors and malfunctions Fully assemble all device subsystems and ensure functionality in unison
Nate	Test operation of camera subsystem, fix errors and malfunctions Fully assemble all device subsystems and ensure functionality in unison
Zach	Complete code to stitch together rectangular images into tube-length image

Week of 11/17 (MOCK DEMO):

All members	Prepare for mock demo Design Presentation Conduct tests on full code implementation Conduct tests detailed by high level requirements Conduct tests on device's performance in the field

Week of 11/24 (FALL BREAK):

All members	Continue any code edits Continue edits and rehearsal of the Presentation

Week of 12/1 (FINAL DEMO):

All members	Prepare for final demo and presentation Conduct tests on full code implementation Conduct tests detailed by high level requirements Conduct tests on device's performance in the field

Week of 12/8 (FINAL PRESENTATION):

All members	Prepare for presentation

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.

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.

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/