Ceres: A Motorized System for Plant Root Research

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1. Introduction

Objective

Imaging plant roots at ACES is a required part of research and is currently a manual process requiring 10 minutes of work by a talented individual. We seek to remove the manual work from this process to allow the researchers to direct their efforts towards analysis of the acquired data instead of taking valuable time collecting the data.

This design document covers a motorized imaging system that will take a panoramic photo of a tall plant's root system. This will be done by transporting a camera down a standard transparent observation tube into to the soil, taking pictures as it goes. These photographs will then be stitched together into a panoramic image, which is then used for scientific research in the field of agriculture. The imaging device is comprised of a base station on the ground resembling a hoist, and a suspended camera placed in the observation tube. The camera module has motors that will center itself laterally in the tube so that it always takes images facing up. A central control server serves as controller, collecting images from a fleet of imagers, and presents a GUI to the user with live progress and diagnostics data from each imager.

Background

This project is done in collaboration with the College of ACES and SoyFACE farm. The SoyFACE Farm contains a corn research facility, where an observation tube is installed by each of the over 1000 corn plants [1]. These tubes go 5 feet into the ground. Each week, researchers would collect a panoramic image of the roots of each plant to assess its health condition. The imaging process is implemented with a bulky camera mounted on a 5ft long rigid stick. The operator mounts the base of the stick on the observation tube on a fixed mounting point, and inserts the stick deep into the tube. The camera is connected to an equally bulky control box consisting of a laptop, a large car battery, and the control circuitry for the camera crammed inside a Pelican case. The camera depth can be read from a ruler on a stick, which the operator needs to input to the laptop, and invoke the `Start` command. The laptop will then verbally instruct the operator to pull the camera up centimeter-by-centimeter at a set interval (usually 1 second), taking a picture at each instruction until the camera is completely out. Any non-compliance of the verbal instruction will ruin the image and require a complete restart. The set of images are then taken to an external program to be stitched into a panoramic image. The same time-consuming and strength-demanding exercise is then carried out over each of the 1000+ corn plants each week, and the research group demands an automated solution.

High-level Requirements List

- The system must be fully autonomous, performing all functions without human intervention beyond placing the system in the observation tubes.
- The system must be scalable, allowing a minimum of 5 imaging appliances to communicate with the management platform, all operated at the same time while being managed by an operator.
- The camera assembly must fit within the observation tube, which has a diameter of 5.7 centimeters.
- The system must be as low cost as possible, with a target cost of $100 maximum for each imaging appliance.

[1] [@soyface_paper]

2. Design

Block Diagram

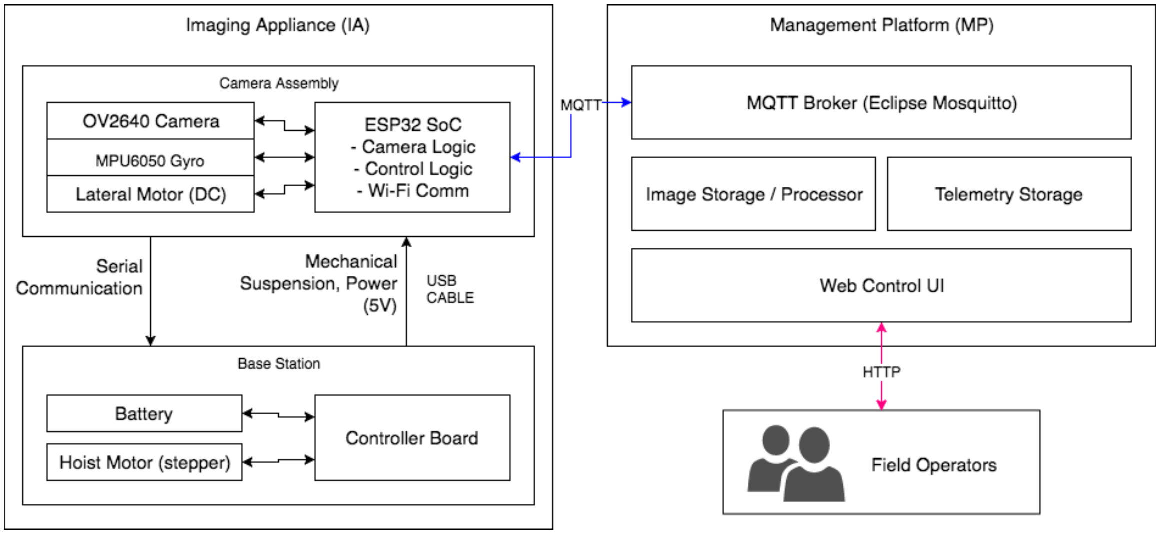


Figure 1. Block Diagram of Ceres

Physical Design

Refer to Appendix A for mechanical drawings of the devices. Both the Base Station and the Camera Assembly are 3D printed, and the overall assembly is shown as follows. The Camera Assembly appears in blue, and the Base Station appears in white.

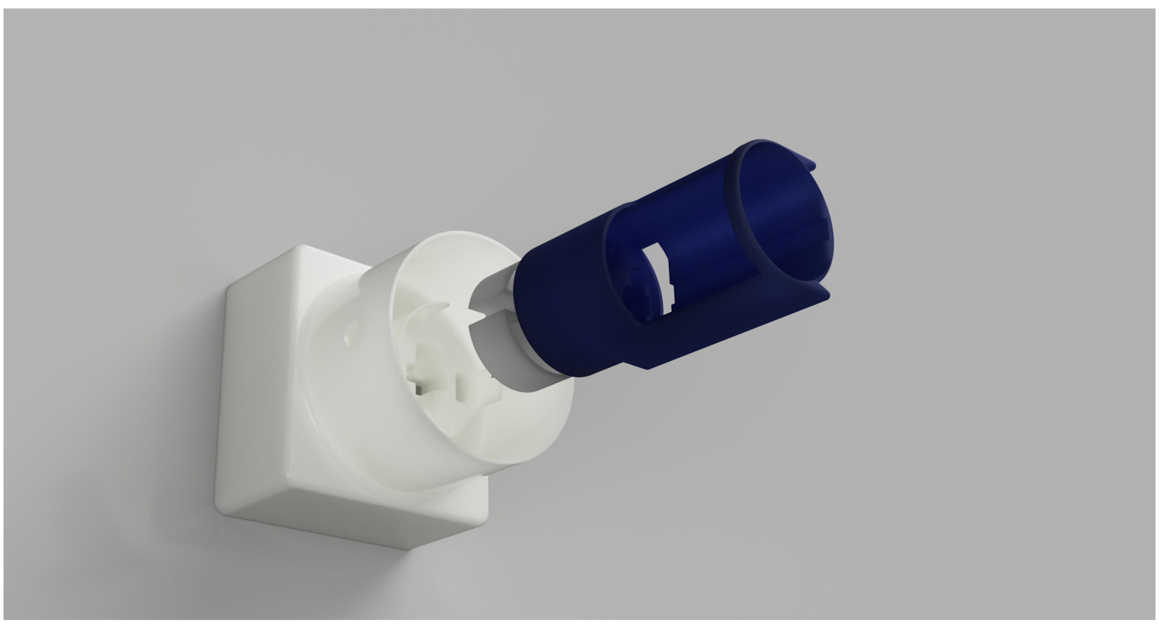


Figure 2. Physical Assembly Scheme

In a typical use case, the Base Station with the Camera Assembly sitting on top of it, is attached to the observation tube. They are held together via a spool of flat USB cable. The battery in the base station will be seated so that it is easily removed and reinserted, so that the systems can have short downtimes when they run out of power and need a new battery. During the imaging process, a motor in the Base Station lowers the camera down into the slanted tube. When the camera completes taking images the Base Station pulls it back into the homed position. The use case is illustrated in Figure 3:

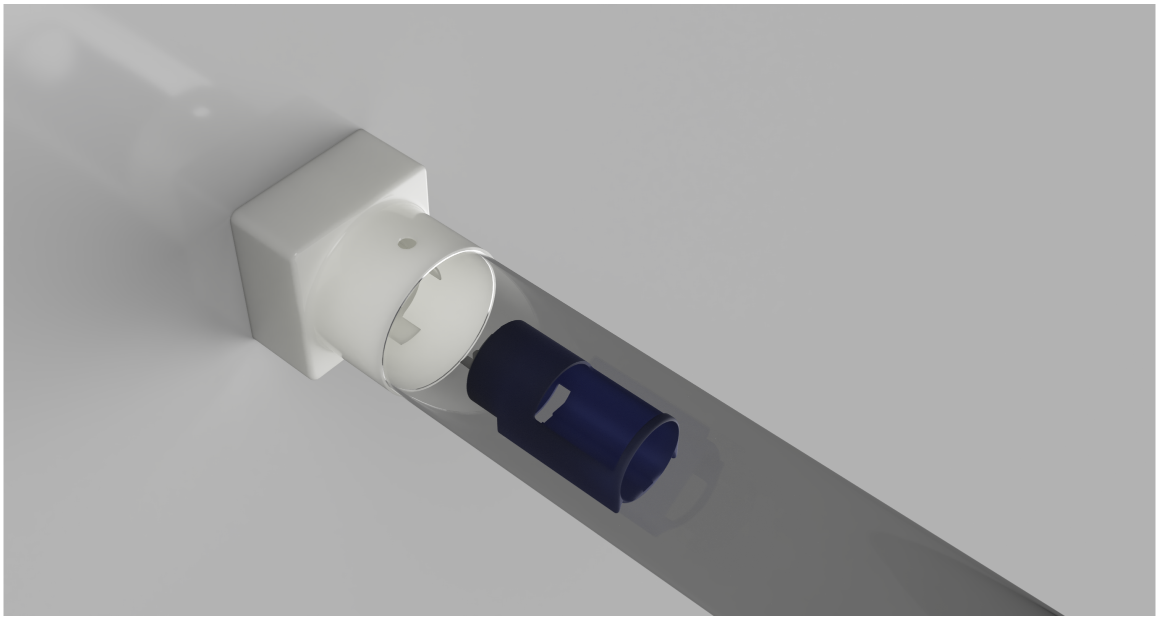


Figure 3. Use Case Illustration

Functional Overview

Ceres can be split into two components, a Management Platform (MP) and an Imaging Appliance (IA). The IA can be further split into the Camera Assembly and the Base Station. The following discussion about the components is centered around the block diagram.

The main logic of IA runs on top of an ESP32 SoC inside the camera assembly. It accepts control signal from the operator from the MP, through a MQTT connection over its built-in Wi-Fi. It also has a serial (RS-485) link to the control board in the Base Station, in order to receive battery condition data and transmit signals to control the hoist motor, which in turn manipulates the physical depth of the camera in the tube. The Camera Assembly also has a lateral motor assembly with wheels, that centers the camera view in the tube as the camera could have shifted during the up/down motion. This shift is sensed from the built-in accelerometer and corrected using PID controller. The ESP32 SoC is connected to a OV2640 camera, that captures a 2 mega-pixel image at every run. It is fixed-focus since the distance from the camera to the plant root is known. When imaging, the camera first travels up by a fixed distance (~2cm) such that the view overlaps with the previous, and takes a image. It then compresses the image into JPEG and transmits it to the MP.

All these functions will be performed autonomously after the system is placed in the observation tube. Additionally, the nature of the MP allows many Ceres systems to communicate with the Management Platform, making the system scalable enough to allow large-scale experiments to be run using the devices. The easily swappable batteries will also contribute to scaling, as the decreased time to reset the devices will add up to less overall time spent maintaining the devices in the field. Finally, because the device is constructed using 3D printing techniques and low cost electrical components, its cost is very low, especially when considering acquiring units in bulk, which would further lower the price.

Block Requirements

The base station (BS) of the IA is placed above ground, preferably mounted on top of the observation tube. It contains a battery to power the entire IA, and a stepper motor that hoists the camera assembly (CA, thereafter) into the tube. The CA sends a control signal in terms of distance to move, and the ATmega328 MCU in the ground station translates it into angular motion before commanding the stepper motor. It also has an endstop switch to indicate the home ($Z = 0$) point. The MCU is also connected to a battery charging / monitoring IC that can charge the battery and report battery level to the camera assembly, such that it can home itself and refuse imaging when the battery level drops low.

The MP runs on a physical machine of any platform (such as an x86 Linux server) and optionally also act as the Wi-Fi AP for each IA to connect to. The heart of the MP is an MQTT broker collecting telemetry and images from and emitting control signals to one or more IA'ds. Upon reception of images, it processes the image set and stores a panoramic image into its image storage. Upon reception of telemetry, it stores the telemetry in a volatile database for tracking. It exposes a Web UI to the frontend users, such that the users can view and download the images, as well as monitor and control the IA's. When used, the operator enters the name of the image (matching the current date and ID of the observation tube) and presses "Start", starting the automatic imaging sequence of the selected IA. The operator then monitors the Z depth of the camera in real time as an indicator of the imaging process. When done, the operator may download the panoramic image already stitched from the camera.

Criterion for Success

The overall effectiveness of the project can be assessed in three aspects: functionality, repeatability and effectiveness.

Functionality can be measured by having an imaging device take a panoramic picture from a real plant, and checking the following. First, a valid panorama should be returned, and each image comprising the panorama must not be yawed more than +/-15 degrees from each other to certify the lateral motion compensation. Second, the central management system should report real-time progress from the imager at all times.

Repeatability can be measured by comparing two consecutive images taken from the same plant, and there should not be significant differences in the geometry of the images and features.

Effectiveness can be measured by having the entire imager cost less than $100, without a complex manufacturing procedure that consumes more than 2 man-hours in assembly.

The success of the project can be certified if the above criteria are met.

Risk Analysis

The base station has minimal to no risk due to there being no moving parts. The management platform has minimal risk due to it being all software based, the majority of which is not complicated.

The image stitching itself is rather low risk, but it depends greatly on the quality of the images received from the camera assembly. This is why the most risky requirement is the lateral centering capability of the CA. This is a careful choreography between the sensor, the motor, the physical construction of the rotor, the shape of the enclosure as well as the algorithm handling the control. The hardest parts that require tweaking are the following:

- The degree of friction between the rotor (lateral wheel) and the carrying tube, which dictates the effectiveness of lateral control and the tendency to veer off center during downward motion.
- The criterion of "center" of the control algorithm. What is a threshold? How to handle the anomaly case where a single step causes the CA to veer from off the left center to off the right center?

- Tuning of the outer enclosure to make sure no self-spinning of the module occurs around the direction of advance, while the rotor can effectively control the attitude of the camera.

Hence, this requirement poses the most risk among all requirements of this project.

Requirements and Verifications

Imaging Appliance - Base Station

The base station is an equipment fixed to the observation tube. It is a passive device communicating over a serial interface with the Imaging Appliance. It supports the following single-byte commands:

- `H` for HOME, which moves the camera assembly up into a home position. It returns a byte `K` for `OK`, when fully homed.
- `S` for STEP, which moves the camera down for just a set distance and stops. It returns a byte `K` for `OK`, when motion stops. It returns a byte `E` for `ERROR` if the number of STEPs has exceeded the limit.
- `C` for COUNT, returns the number of STEPs the camera has performed since last homed.
- `P` for POWER, returns the current battery voltage as a floating point number.
- `X` for CANCEL. Stops whichever activity the base station is doing.

Requirement	Verification
BS performs HOME per spec.	1. Send `H` over serial. 2. Check that BS begins motion and stops when CA is fully homed. 3. At which point, expect `K` received over serial.
BS knows that a device is already HOME'ed.	1. Send `H` over serial. 2. Expect `K` received over serial immediately, and no motion has occured over the motor.
BS performs STEP per spec.	1.Send `S` over serial. 2. Expect BS to begin motor motion downwards. 3. Expect BS motor motion to eventually terminate and receive `K` when it happens.
BS performs STEP repeatably, with a distance error of max <=30%.	1. Place a ruler along the tube the camera travels down. 2. Send multiple consecutive `S` commands, each waiting for the motion to complete and a `K` return to be issued.
BS returns `E` for STEP when step count exceeds limit.	1. Set a hypothetical limit (10) in software. 2. Send 11 S's over serial. 3. Expect only the first 10 commands to result in motion and a `K` return. 4. Expect the 11th command to result in no motion and a `E` return.

Requirement	Verification
BS reports the correct number of STEPs when received COUNT.	1. Randomly assign an integer N <= 10. 2. Issue N S commands, each waiting for the previous motion to complete. 3. At the completion of Nth command, issue a C command. 4. Expect to receive an integer over serial, and the integer is equal to N.
BS clears COUNT when HOME is issued.	1. Perform the above verification, and issue an H command. 2. Wait for motion to complete. 3. Issue a C command. 4. Expect to receive 0 over serial.
BS reports the correct voltage for POWER.	1. Disconnect the battery, and place a voltage-dividing potentiometer that ranges from 0.0V to 3.3V. 2. Set the potentiometer to a fixed value, and read the voltage from a voltmeter. 3. Issue a P command and expect a floating-point integer to be returned on serial with a newline character. 4. Expect this number to match the voltmeter reading.
BS ignores commands when in motion, except the X command.	1. Issue multiple S commands to BS in rapid succession, before the motion resulted from the first S command had stopped. 2. Record the distance moved as D1. 3. Issue a second S command, wait for motion to end and record the distance moved as D2. 4. Expect D1 to be within 20% of D2. 6. Issue an S command again to start the motion. 6. Issue a X command right after. 7. The motion should stop immediately, and a K will be received.
After getting the X command, BS ignores all other commands until successfully homed.	1. Issue an S command. 2. While in motion, issue X. 3. Expect to receive a K and motion stops. 4. Now issue S multiple times, expect E return and no motion each time. 5. Issue H and expect BS to home the CA. 6. Once fully homed and K received, issue S commands and BS should generate motions accordingly.

Requirement	Verification
The power supply provides a stable 5V voltage rail with an accuracy of 0.3V.	1. Measure the 5V rail using a voltmeter, from the VCC and GND lines of the interconnect between the BS and the CA. 2. Expect the reading to be between 5.3V and 4.7V. 3. Repeat the measurement with lithium battery cells measured at 3.0V, 3.7V and 4.2V.

Imaging Appliance - Camera Assembly

The camera assembly consists of the main logic SoC, a lateral alignment stepper motor backed by a MPU6050 IMU and the OV2640 camera module. It performs the following tasks:

Requirement	Verification
Accept an "Image" command over MQTT, and start executing a sequence to collect images.	1. Send an "Image" command over MQTT to the SOC and observe the following sequence. 2. The verification of the sequence can be done by hooking the CA directly to a computer over serial, bypassing the motor assembly.
During image collection, periodically transmit status information over MQTT. The status information contains battery voltage level, that it is imaging (not idle) and the number of steps so far traversed.	1. After the "Image" command, observe from the MQTT broker that voltage level, the "imaging" status and number of steps are correctly reported.
Before imaging, issues a `HOME` command to the BS at the beginning of the collection sequence and waits for a `K` response for confirmation. At this point, it zeroes the roll value of the gyroscope.	1. Observe the outputs over the CA's serial port. 2. Expect an `H` from this port, and no further outputs should be expected until a `K` response is manually sent to the CA.
Before each image is taken, receive a `K` response, and then zero the gyroscopic roll.	1. Observe the outputs on the serial port. 2. Expect a `S`. 3. Expect no motion of the lateral motion until a `K` is sent manually. 4. Move the unit laterally and send `K` over serial, and it should correct itself.
After an image is taken, send the image via MQTT and then receive the next command.	1. The image should be transmitted over MQTT. 2. Receive the next instruction on the serial port.
After imaging is complete, issue a `HOME` command again to be transported back to home.	1. Observe the serial port, expect an `H` command. 2. When a `K` response is manually given, expect the status information sent over MQTT to denote that the unit is idle.

Management Platform - Web UI

The Web UI is an interface to the underlying Image Processor and Telemetry Processor, and it allows the user to perform the following actions:

- Command the IA to start capturing images.
- Command the IA to cancel imaging and return home.
- View the status of the IA, whether it is idle or imaging.
- Check and download the raw images, and the stiched panoramic images.

Since the Web UI is an inherent part of the MP, verifications of the Web UI are combined with those of the underlying components of the MP as follows.

Management Platform - Telemetry Processor

The telemetry processor is able to do the following:

Requirement	Verification
Track the current status of the IA. (i.e. whether it is idle or imaging + battery voltage, online or not)	1. Connect a mock IA (software simulated) to the MQTT broker. 2. Under the same protocol of a real IA, periodically send out status packets entailing the information that the IA is idle, with a battery voltage that varies from 3.3 to 0V randomly from packet to packet. 3. Check from the MP that the change in battery voltage is correctly indicated. 4. Additionally, under the same protocol of a real IA, periodically send out status packets like above. 5. Expect that the MP indicates the device is online. 6. Now disconnect the IA from the MQTT broker. 7. Wait for 30 seconds, and expect that the MP indicates that the device is offline now.
Display the current status of the IA.	1. Using the same protocol as above, present the information received from the MQTT broker on a webpage. 2. Manually inspect the status packets with what is displayed on the page to determine that the two do not conflict.
Send imaging and cancellation command to the IA.	1. Connect a mock IA to the MQTT broker. 2. Periodically send out status packet as above, to indicate to the MP that the IA is now online. 3. Expect that the Start button on the MP is now operable. 4. Click on the Start button and expect that the IA receives a command over MQTT to start imaging. 5. Now periodically send out status packets from the IA to indicate that it has started imaging. 6. Expect that MP is also indicated that the IA is in progress imaging. 7. Click on the Stop button on the MP. Now expect that the mock IA receives the Cancel command over MQTT.

Management Platform - Image Processor

The image processor is able to do the following:

Requirement	Verification
Receive images from the IA over MQTT	1. Connect a mock IA (software simulated) to the MQTT broker. 2. Send over an image of the same format taken by a real IA, under the same transfer protocol. 3. Check that the MP's log indicates successful receiving of the image. 4. Alse check that the raw image appears under the filesystem MP runs on, and that the raw image is identical to the one being sent using diff.
Stitch a batch of images into a panorama	1. Prepare a suite of images captured from a long object. 2. Connect a mock IA (software simulated) to the MQTT broker. 3. Start a periodic transmission of status packets over MQTT indicating that it's idle. 4. Click on the Start button to simulate start of imaging process. 5. Now send in each of the images in the batch in order over MQTT. 6. After sending each of them, transmit the indication that imaging is complete over MQTT. 7. Check the MP log to expect that images received are stitched, and a stitched image appears in the filesystem that the MP runs on. 8. Expect that the stitched image is a valid image file, and it contains the unique geometry of each test image in the batch. 9. Upon visual inspection, no dicernable distortion of geometry should be found in the stitched image compared to raw images.
Serve the stitched image or the raw images over HTTP as a file download	1. After completing the above verification, expect that the test run conducted shows up in the MP's Web UI. 2. Click on the corresponding buttons to start downloading the zipped raw images and stitched image. 3. Expect that the images are downloaded from the browser. 4. Using the UNIX `diff` tool, compare the downloaded images with the ones in the MP's filesystem, and expect them to be completely identical.

Tolerance Analysis

Tolerance issues are exhibited in this project in two ways: Power systems performance and mechanical dimensions.

The Power system has a wide tolerance, as the stepper motors have been tested in the primary research to work at voltages ranging from 3.7V to 6.0V. As the step-up module (outsourced) is measured to accurately produce 5.0V, with a maximum 0.1V offset, the motors can be assured in working order in terms of voltage. The AMS1117 power regulator is capable of producing 3.201-3.399V, and this falls within the operating voltage range of both our circuit, namely the ESP32, which has a range of 2.7-3.6V, and ATmega328P, with a range of 1.8-5.0V.

The tolerance in mechanical dimensions can be mostly attributed to the inaccuracy of 3D Printing. As the line width of a 3D-printed layer is 0.4mm, our design tolerance is set to maximum 3 times the line width. The make-or-break aspect, which is the fact that the CA can travel freely in the observation tube, can be largely assured by allowing this tolerance in design.

Another mechanical dimension tolerance issue will be attributed to the inaccuracy of the stepper motor. As the motors are designed for giving out accurate angular steps, the only concern is skipped steps, which are unlikely given the 5V rated voltage and a good fit of the CA in the tube. The spooling mechanism though can cause an inaccuracy in the linear steps translated by the angular steps of the motor. However, due to the way panoramas are stitched in software, the algorithm has good tolerance against offsets in images so long as there's a significant overlap between the images. Hence, the longitudinal inaccuracy arising from the spooling is not a significant source of concern.

3. Cost and Schedule

Cost analysis

Schedule

The timeline of the project is as follows:

Date	Jimmy	Nachiket	Nathaniel
2/4 - 2/15	Conceptual design of the physical construction; Prototyping the Physical Construction in CAD	Research on Image Processing; Create and test image stitching software	N/A
2/18 - 3/1	Iterate on mechanical prototype with 3D printing; Sketch and prototype PCB	Research on Networking technology and Server-side software framework; Finalize the ICD design for REST API	N/A
3/4 - 3/15	Finalize PCB wiring and create equivalent breadboard prototypes; Research into ESP32 camera stack	Implement the REST API and state-tracking algorithm on server-side software; Integrate the image-stitching algorithm onto the MQTT responder;	Modify current prototype CAD model; Revise document and review Interface Specifications
3/18 - 3/29	Unit-test imaging appliance and firmware; Create MQTT Responder Services; Create and complete ESP32 firmware for Camera Assembly	Create a simplified MQTT server for inspecting incoming packets from the Camera Assembly; Continue to develop client-side application frontend	Finalize mechanical design and base station firmware; Create whole-system Integration Testplan; Mock test base-station operation in a tube
4/1 - 4/12	Create Test Topology consisting of a Router and a Server; Work on integration and functional testing	Create mock Imaging Appliance in software and finish unit-testing server-side software; Work on integration and functional testing	Test Imaging Appliance hardware with camera assembly, using the packet inspector from Nachiket; Work on integration and functional testing
4/15 - 4/26	Field Test and Demo	Field Test and Demo	Field Test and Demo

Ethics and Safety

Safety

There is a certain level of safety that we must maintain while developing the hardware for the imaging appliance. First of all, we will be using a lithium ion battery, and lithium ion batteries can be volatile if we use it outside the batteries operating range. Our voltage regulator has to keep itself sufficiently ventilated, and operate within the acceptable temperature range according to its specification sheet, and the charging circuitry must keep the battery from overcharging or overdrawing, both in terms of acceptable current and voltage. In addition, benchmarks of the power-hungry components such as the motors, high-brightness LED lights and the ESP32 SoC will be done assuming worst-case condition, to ensure the battery selected can withstand the sum of current draw from these components.

The observation tube that the imaging appliance is designed to go in is a humid environment, which may have water accumulated at the bottom of the tube. This does not pose a risk to the imaging appliance, because it is standard procedure for the researchers to thoroughly wipe down the tube before using any sort of camera equipment. As a result, the imaging appliance just needs to be able to work in a humid environment. Still, since the imaging appliance is designed to go into a possibly wet environment, it should have some level of water resistance. These tubes are covered, so having a minimal level of water resistance should be sufficient for our purposes. This minimal level of water resistance will be achieved by the full encasing of the motors and camera board. The only parts left to be exposed should be the camera lens in the camera assembly. The battery and control PCB will be in the base station of the imaging appliance. Those can be water-proofed through encasing those components in a closed container.

While lithium batteries are a hazard when disposed of in the landfill, the EPA does not regulate the disposal of such in small quantities (40 CFR PART 273). However, the casing design should ensure that the lithium battery is easily removable from the case. Aside from disposal, the lithium battery removed from the appliance, and transported in land-only methods (IEC-61960) with a UN-3480 hazadous material marking on the package.

As for the exposed moving parts, such as the lateral rotor, we need to be cautious of having loose clothing or hair getting caught in the mechanism. This is not as much of a safety hazard as the other components as this is part of safely operating the imaging appliance in general.

Ethical considerations

Our project is primarily designed for academic and research purposes. Our ethics standards must therefore comply with the standards that the project itself maintains.

According to the ACM Ethics Guidelines [2], the purpose of this project is to contribute to the society (1.1) and to be honest and trustworthy (1.3). As a device deployed in a research environment, we pledge to ensure the solution is sufficiently tested and benchmarked, and the accurate performance metrics are reported to the user. Exhaustive verifications are also required to ensure the data produced from the device exhibit the accuracy and precision as specified in this proposal.

As such, our testing procedure evident from the Block-level requirements ensure that the system is both tested under real-life scenarios and close-to-real-life mockups in verification stages, and pilot tested in the actual research facility it is deployed in. The system under test will be subject to a comparative trial. Both the image produced from this system and the legacy camera device currently in used will be audited both by researchers themselves and compared algorithmically to ensure equivalence of the devices during their transition. The algorithmic comparison will consist of running a tool like `diff` on the two images to see if there is a substantial difference. Additionally, even though file size is not a factor in how the images will look, it can be an indicator of how the two images will likely compare. If one file is substantially bigger that the other, that could be an indicator that the two images may not be similar.

[2] [1]

Appendix A: Cost Analysis

Part 1: BOM Per Set of Equipment - Camera Assembly + Base Station

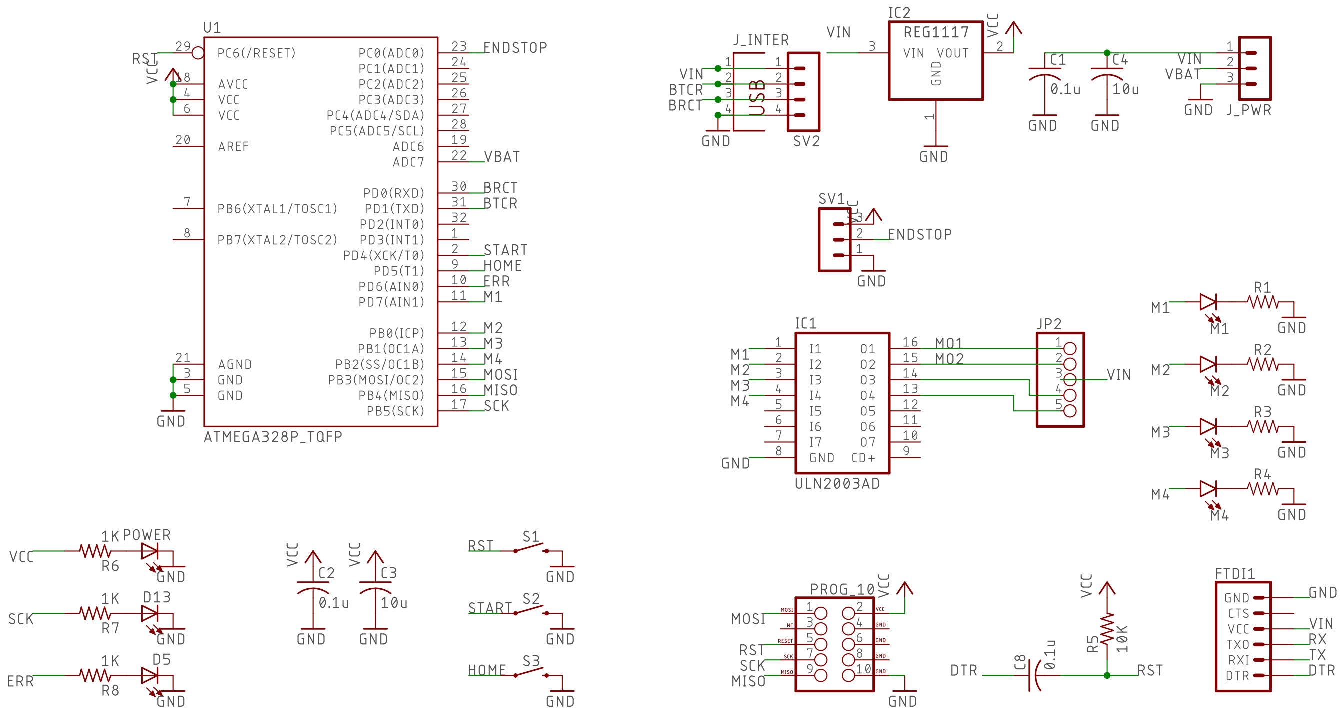
Note: Large Batch Price is the per-unit price when manufactured in batch of 500.

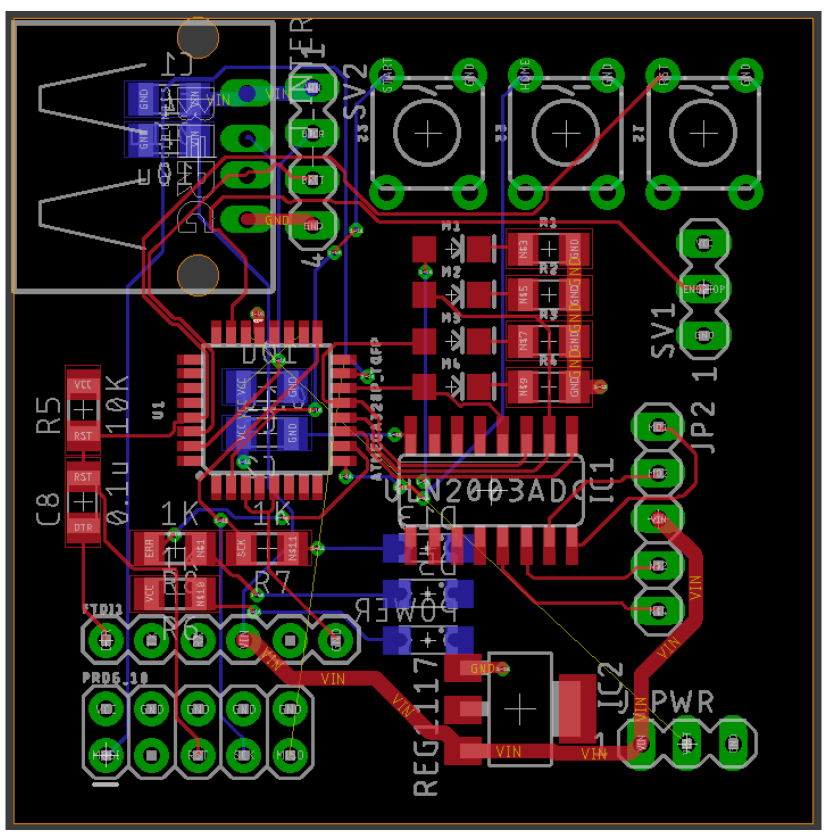
Qty	Value	Device	Package	Unit Price	Total Price	Large Batch Price	Supplier	Order Reference
3	40-pin	Header	2.54mm	$0.17	$0.51	$0.51	Amazon	
9	BLUE	LED	SMD 1206	$0.34	$3.02	$1.00	Mouser	645-599-0291-007F
3		Tactile Switches	PTH_6.0MM	$0.10	$0.30	$0.30	Amazon	
2		Tactile Switches	SMD_6.0X3.5MM	$0.30	$0.60	$0.60	Amazon	
1		USB Type A Connector	USB Type A	$1.11	$1.11	$0.30	Mouser	571-292303-1
5	0.1u	C-USC1206	SMD 1206	$0.66	$3.30	$1.00	Mouser	603-AS1206KKX7YBB104
1	10K	R-US_R1206	SMD 1206	$0.09	$0.09	$0.05	Mouser	71-CRCW120610K0JNEAC
4	10u	C-USC1206	SMD 1206	$0.71	$2.84	$0.92	Mouser	603-CC1206KFX5R7BB10
9	1K	Resistor	SMD 1206	$0.05	$0.45	$0.24	Mouser	71-CRCW12061K00JNEAC
1		ATmega328P Microcontroller	TQFP32-08	$2.04	$2.04	$1.50	Mouser	556-ATMEGA328P-AU
2		AMS1117 Regulator	SOT223	$0.44	$0.88	$0.20	Mouser	511-LDL1117S33R
1		ULN2003AD Darlington Array	SO16	$0.56	$0.56	$0.30	Mouser	595-ULN2003ADR
1		MicroUSB Connector	Micro USB Type B	$0.70	$0.70	$0.40	Mouser	798-ZX62D-B-5PA830
1		OV2640 Module		$10.49	$10.49	$10.49	Amazon	B013JMFLOA
1		MPU6050 Module		$5.79	$5.79	$1.20	Amazon	B008BOPN40
1		ESP32-WROVER-B Module		$5.00	$5.00	$5.00	Mouser	356-ESP32-WROB(16MB)
1	2000mAh	Adafruit Li-Ion Battery	Soft Package	$12.50	$12.50	$9.50	Mouser	485-2011
1		3D Printing Material Cost	PETG Filament	$5.00	$5.00	$4.30	---	
		TOTAL			$55.18	$37.81		

Part 2: Labor Cost Estimate

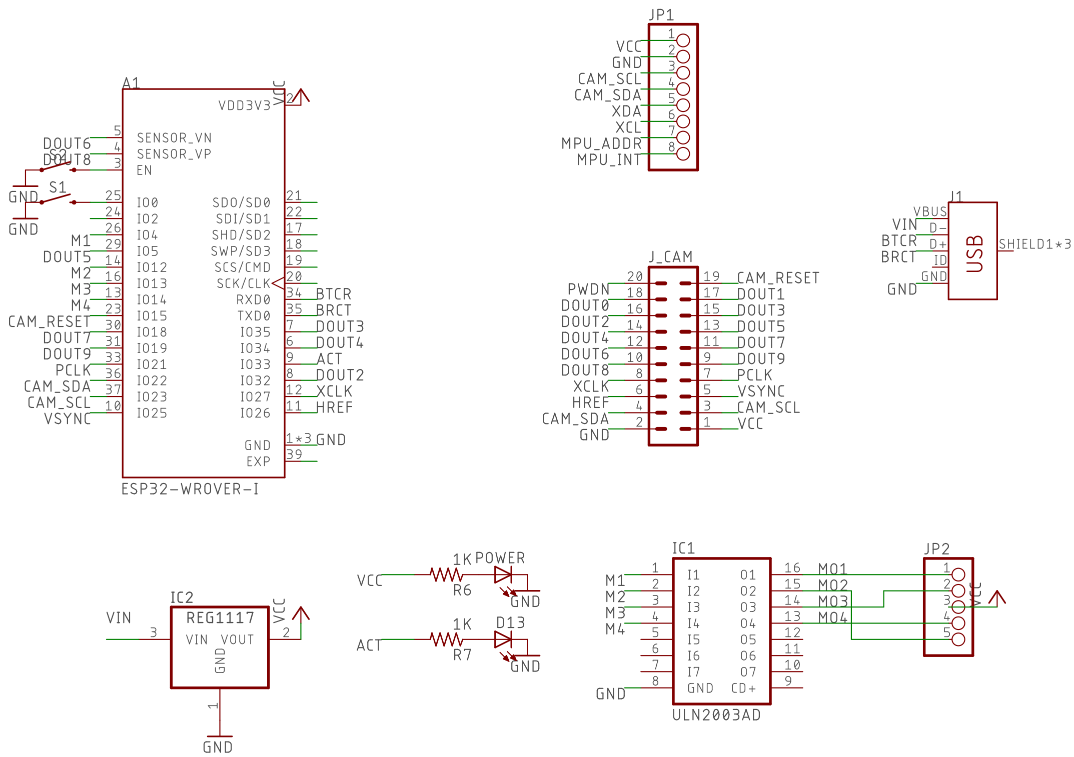
	Item	Purpose	Hours	Hourly Pay	Gross Pay	
	Development Cost	Development of the Complete System	80	25	2000	
	Testing Cost	Testing of Devices in-field	30	25	750	
	Assembly Cost	Per-device Manpower for Assembly of Device	2	15	30	

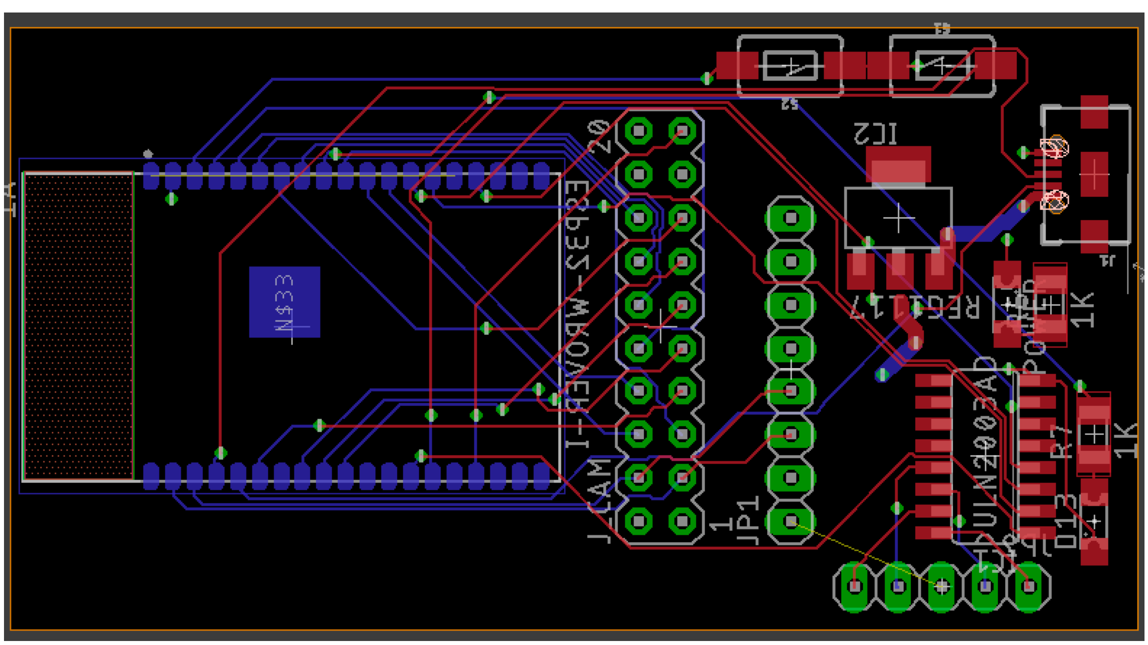
Appendix B1: Base Station Schematics and Layout



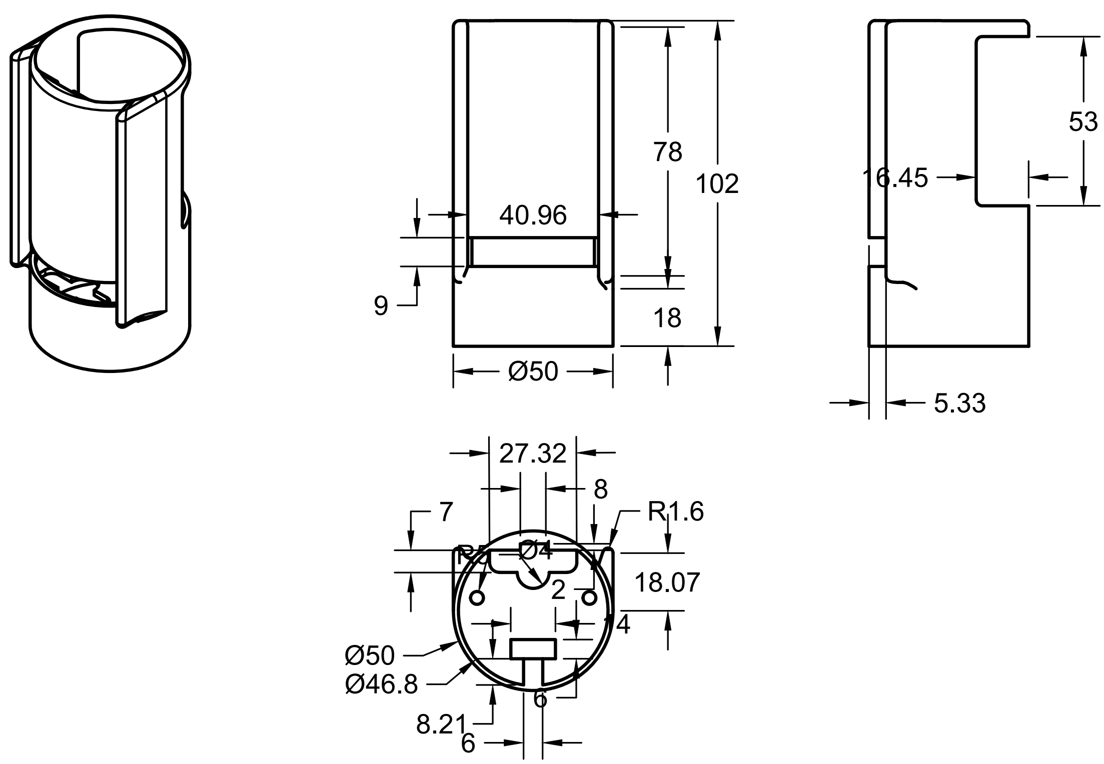


Appendix B2: Camera Assembly Schematics and Layout

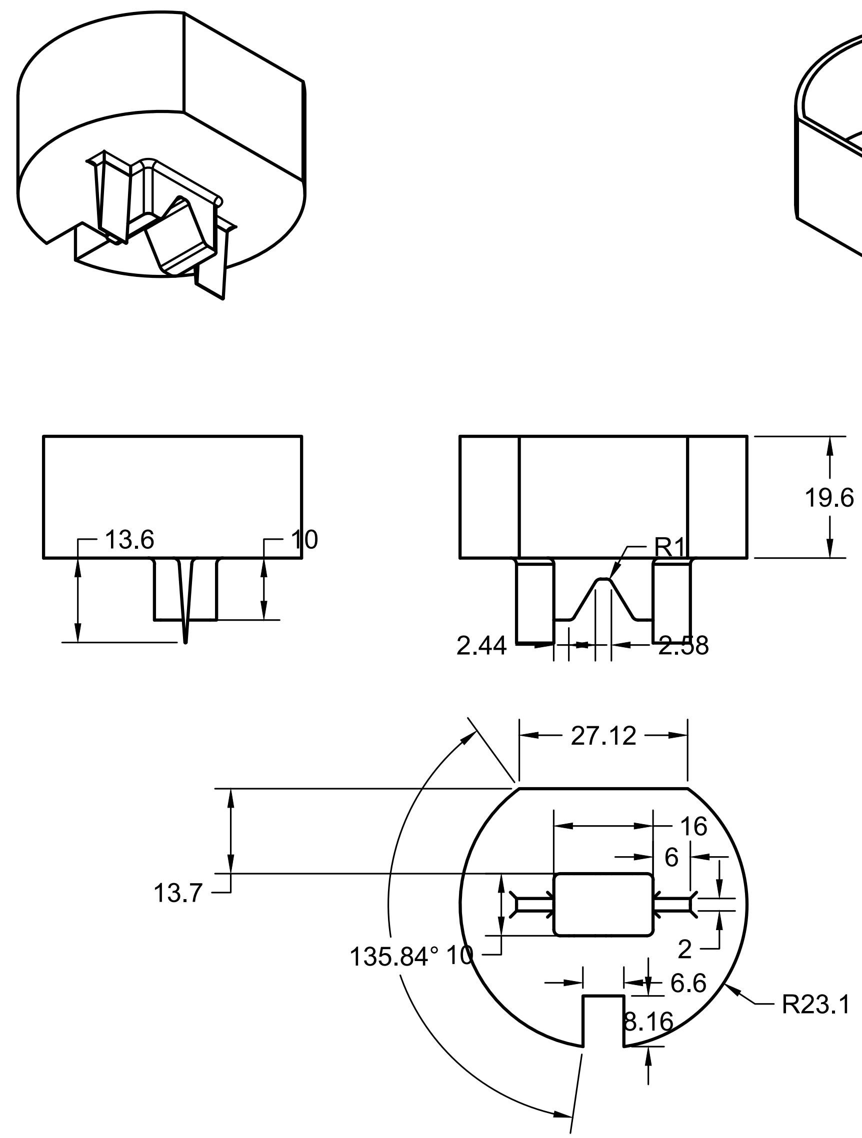




Appendix C1: Camera Assembly CAD diagram

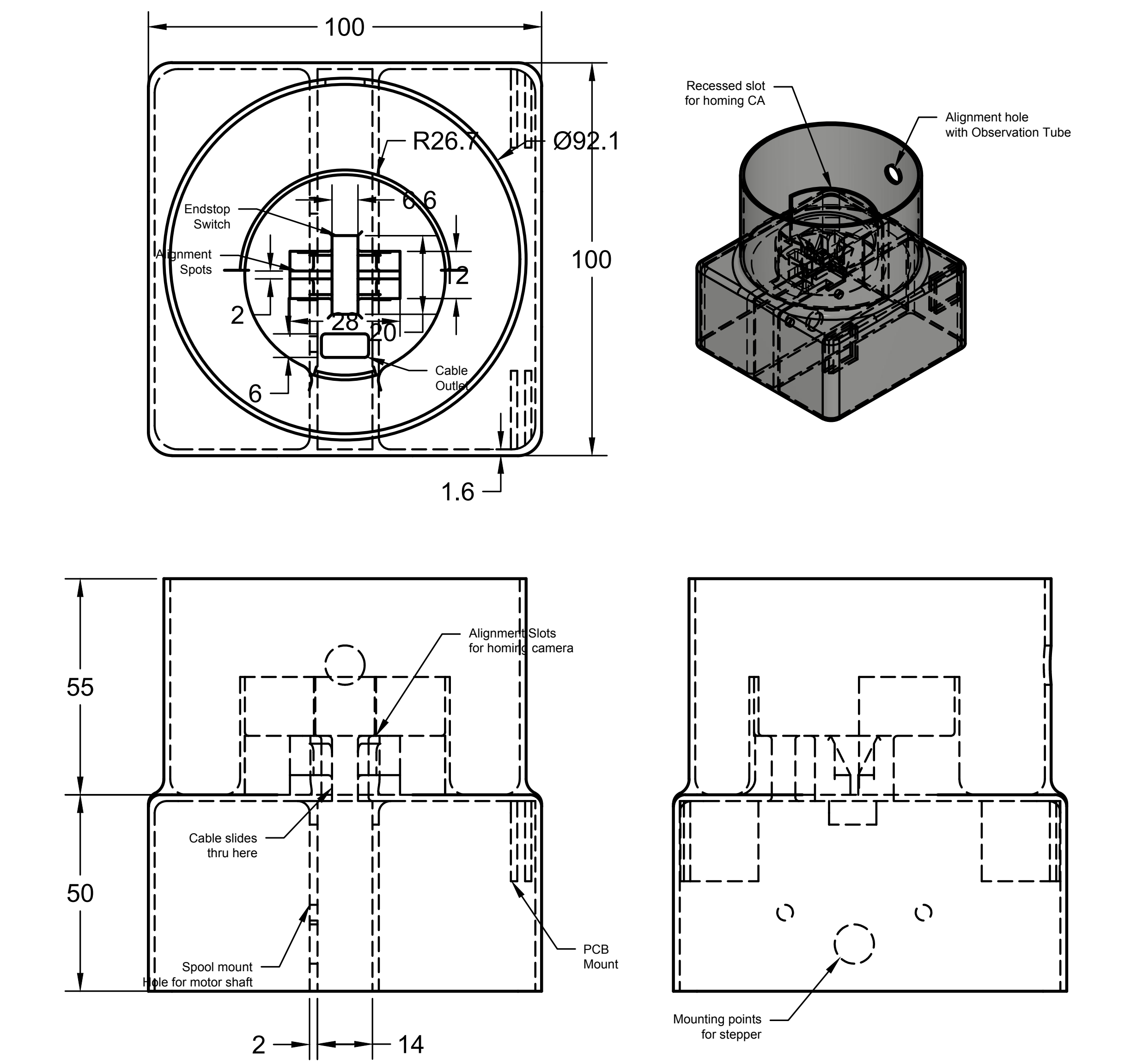


	PROJECT ECE 445			
	TITLE Camera Assembly Camera Base Section			
APPROVED Nachiket Joshi	SIZE A	CODE	DWG NO	REV
CHECKED				
DRAWN Jimmy He 2019/2/17	SCALE 1:2	WEIGHT	SHEET 1/2	



	PROJECT ECE 445				
	TITLE Camera Assembly Interface Plate				
APPROVED Nachiket Joshi	SIZE	CODE	DWG NO		REV
CHECKED	A				
DRAWN Jimmy He 2019/2/17	SCALE 1:2		WEIGHT	SHEET 2/2	

Appendix C2: Base Station CAD diagram

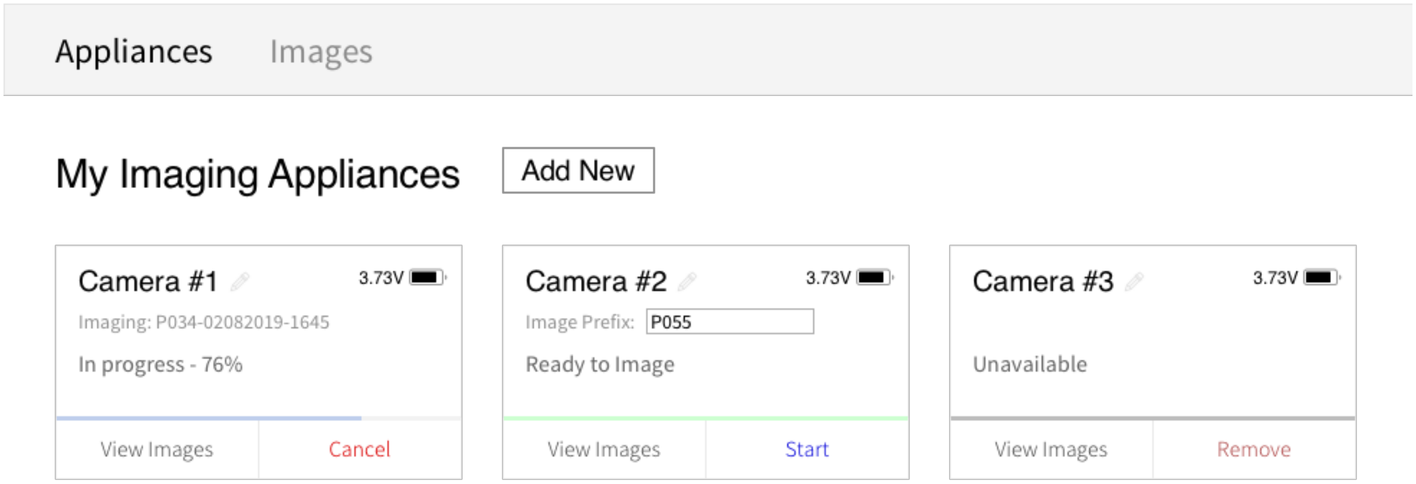


PROJECT
ECE 445

TITLE
Base Station Drawing

APPROVED Nachiket Joshi	SIZE A	CODE	DWG NO	REV 1
CHECKED				
DRAWN Jimmy He 2019/2/13	SCALE 1:1.5	WEIGHT	SHEET 1/1	

Appendix D: Web UI Mock Drawing



References

[1] The code affirms an obligation of computing professionals to use their skills for the benefit of society.