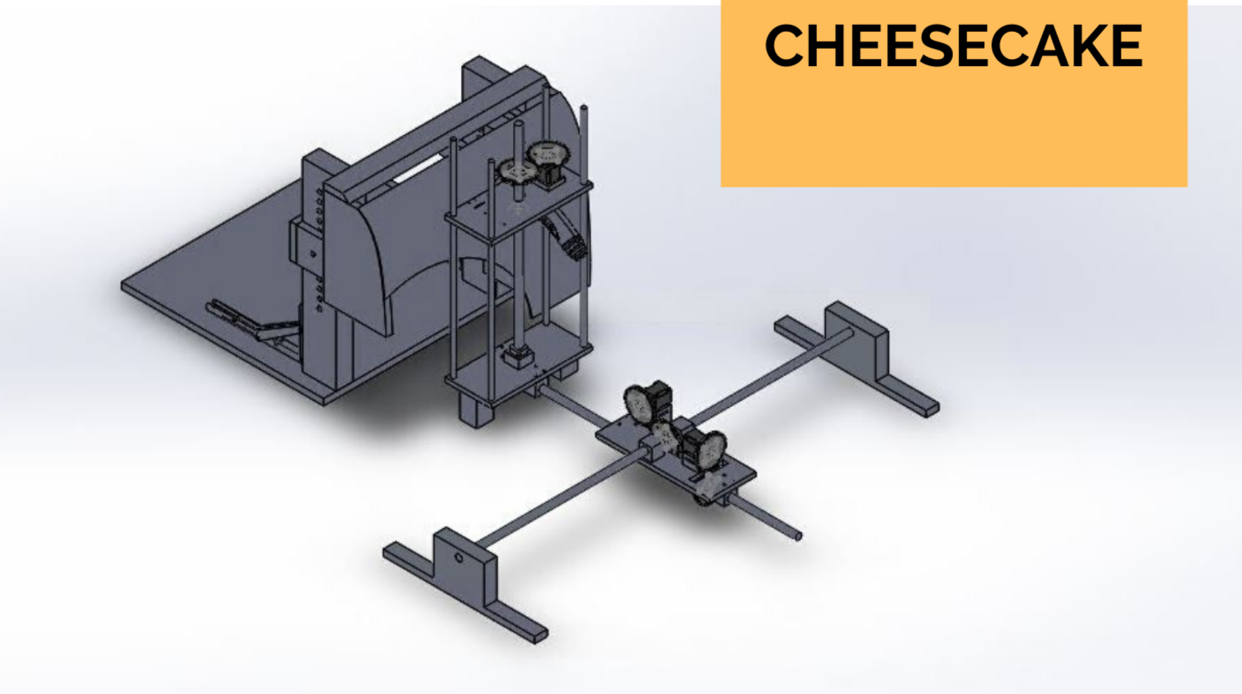
ESC204

PROJECT PROPOSAL

TEAM M19

ORANGE CHEESECAKE



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1. Problem Framing

1.1 Purpose and Problem Statement

This project proposal will outline the design and next steps for Orange Cheesecake, our design for the ESC204 final project. The challenge is to create an autonomous car charging solution to locate a charge port parked within a 0.5m x 1m area in front of the robot and then deliver and insert a charging plug into the port. The final product will incorporate mechanical, electrical and software components to create a solution that solves a real-world engineering problem.

1.2 Design Objectives

Our design objectives are as follows:

Reliability: Our design will function consistently and repeatably.

Ease of Assembly: Our robot will fulfill setup time constraints as described by the project guideline.

Safety: Any dangerous parts will be covered to avoid injury, and an emergency stop will be included.

Testing and Diagnostic: Our robot will be built incrementally, with a minimum viable product for every milestone, to allow for testing. Diagnostic displays will be included.

Usability: Our design will make human intervention as limited and easy as possible.

A pairwise comparison, performed below, indicated reliability as our most important objective.

Table 1: Pairwise Comparison between Design Objectives (1 indicates row win)

Objectives	Reliability	Ease of Assembly and Disassembly	Safety	Testing & Diagnostic	Usability	Totals
Reliability		1	1	1	1	4
Ease of Assembly/Disassembly	0		1	0	1	2
Safety	0	0		1	1	2
Testing & Diagnostic	0	1	0		1	2
Usability	0	0	0	0		1

1.3 Metrics and Measurement

We divided our problem into two categories - actuation and sensing. Our metrics are thus divided into 3 categories - those used to converge on actuation concepts, those used to converge on sensing concepts, and those that are dependent on implementation. See Appendix A for a full description.

Key metrics used in actuation convergence:

- Resolution of movement: the minimum possible actuation distance
- Isolated movement on axes: the ability to move independently on one or more axes
- Time for assembly: time required for set-up
- Actuator dependence: largest group of actuators that cannot be tested independently
- Robot size: projection on the xy-plane
- Battery requirement

Key metrics used in sensor convergence:

- Uncertainty in sensing: found online, measured in percentage error
- Resolution of sensing: calculated, minimum displacement that can be detected
- Sensor dependence: number of sensors required to complete task (in theory)

2. Design Process and Top Concepts

2.1 Actuation Concepts:

Our three initial concepts were as follows:

- Rover: a moving robot with linear actuation in the z-axis.
- Track: a Cartesian manipulator fixed to the ground.
- Arm: a chain of linkages fixed to the ground and joined by revolute joints.

The Arm concept was deemed too difficult to design in 3D due to torque and control concerns, and thus simplified to a 2D arm on a 1D prismatic joint called a Track Arm. The “Track Rover”, a rover with a 2D cartesian manipulator on it, was also considered.

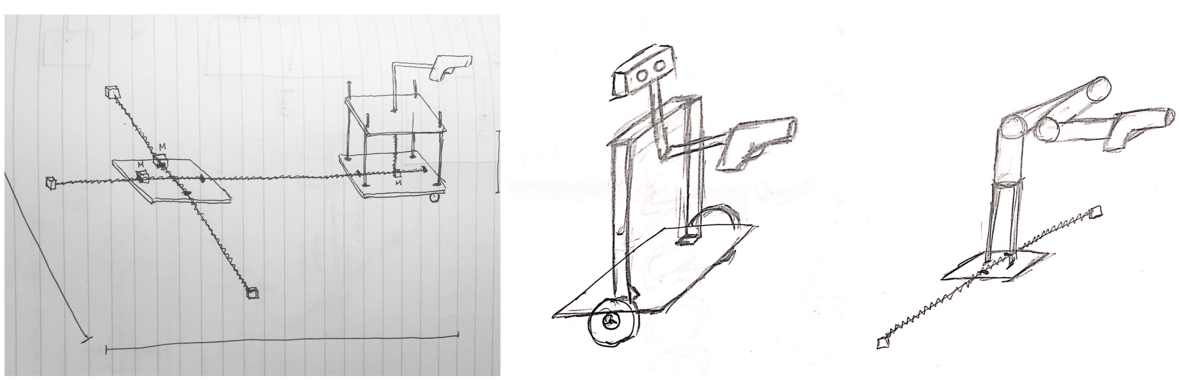

Figure 1: From Left: Track, Rover, Track Arm

Table 2: Actuation Metrics Ratings matrix

Metric	Rating			
	Track	Rover	Arm Track	Track Rover
Resolution of Movement	200 PPR for motor, 10 rev/in for screw. 1/2000 in resolution	300 increments per revolution, radius of 2 in, 4/100 in resolution	Insufficient information - requires knowledge of arm length, deflection, motor selection, etc.	Better of the two between Track and Rover
Isolated axes movement	3	1 (hard to drive straight)	1 (revolute joints cannot isolate x, y, z directions)	2 (2D Cartesian manipulator)
Assembly time	>0 seconds*	Pre-assembled	>0 seconds*	>0 seconds*
Actuator dependence	1	2	3	2
Robot Size	Biggest	Smallest	Second smallest	Second biggest
Battery	No	Yes	No	Yes

*0 seconds if robot fits in locker, longer otherwise.

Reliability and testing & diagnostic capabilities are prioritized - as such, the track was chosen for its isolation of the axes of motion, and its ability to be built in steps

2.2 Sensing Concepts

Our alternatives for sensing are as follows:

- Camera: Locate the charge plug and navigate to it using computer vision and image manipulation.
- Distance Sensors (IR, Ultrasound, LIDAR): Use sensors to determine position of the charge plug relative to the port.
- Buttons: Locate the car and charge port by contacting them with strategically placed buttons.

Table 3: Sensing Metrics Ratings Matrix

Metric	Rating				
	Camera	Distance sensor			Buttons
		IR	Ultrasound	LIDAR	
Uncertainty of Sensing	1% [1]	1% [2]	3mm [2]	1% [2]	0%

Resolution of Sensing	5MP (lower than alternatives) [3]	5mm [2]	3mm [2]	10mm [2]	5mm
Sensor Dependence	1	>1	>1	>1	Min 3

A camera was ultimately chosen for its favourable characteristics, but also largely because the team wants to learn to use computer vision. Should computer vision turn out to be infeasible, the team has discussed how to accomplish the task with distance sensors and buttons in detail, and can pivot if required.

3. Proposed design solution

3.1 Mechanical design

Overview

Our design is a Cartesian manipulator consisting of three lead screws running in the x-, y-, and z-directions, allowing movement of three stages - one on each screw. The axis are defined in the picture below.

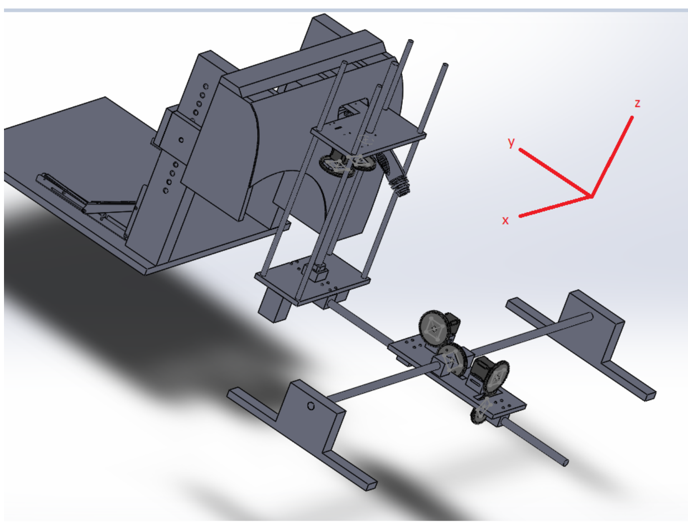

Figure 2. A CAD assembly of our design.

Why lead screws?

To produce the prismatic joints necessary for a Cartesian manipulator, linear motion is required.

Alternatives to linear motion like hydraulic or pneumatic pistons and linear actuators were disqualified due to safety and price concerns. Rack-and-pinions are more expensive than lead screws, and timing belts do not provide the structural support that lead screws do [4][5].

We selected ¾”- 10 zinc-plated threaded steel rods as our lead screws. The thickness was chosen to limit deflection (see Appendix B), and the thread count was chosen based on availability of tools such as screw taps.

Lead Screw Sizing

The lead screws in the x-, y-, and z-directions were chosen to be 5’, 3’, and 2’ respectively to ensure a range of motion large enough to cover all possible port locations with extra space for stages.

Driving Mechanism

The x-stage houses two stepper motors that control x- and y-movement. These stepper motors spin gears on the lead screw which results in linear motion of the gear. The x-stage is supported by two unthreaded platforms (machined parts that screw onto the stage and fit around the lead screw), which maintain contact with the x-gear using spacers. When the x-gears turn, the one on the x-screw will push against the spacers, moving the platform relative to the screw. The y-gears work similarly, but push the y-screw forwards instead of moving the platform. Finally, the z-stage uses the same mechanism without spacers because it stays in contact with the z-gears due to gravity. Gears will be covered for safety in the final design.

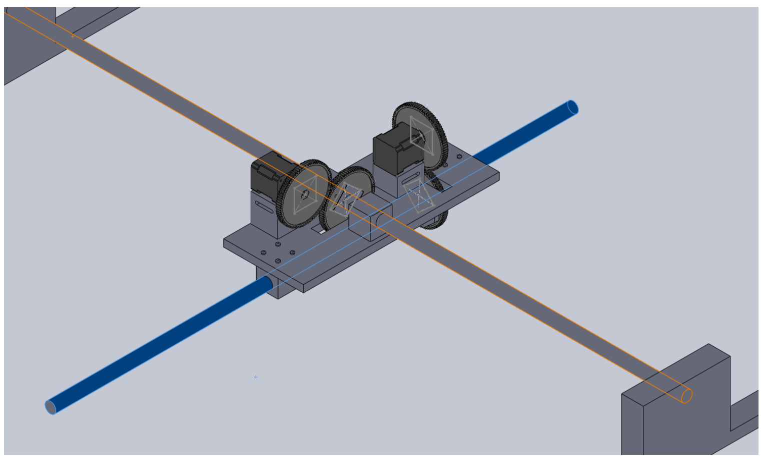

Figure 3. A view of the x- and y-drive mechanisms.

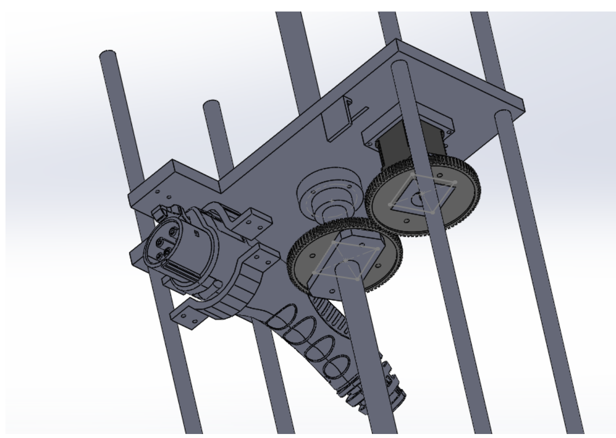

Figure 4. A view of the z-drive mechanism.

This unconventional driving mechanism was chosen to reduce the amount of rotational work needed to operate the system by eliminating the need to rotate the screws. This way, less torque is required from the motors, and thus greater speed can be achieved.

Motor Selection

We selected NEMA 17 stepper motors for their high torque and resolution. We selected 2A motors for the x- and y-directions, and 1.7A motors for the z-direction because the z-direction moves the least weight. The motors have enough torque to move our robot, as shown in Appendix B.

Stage Design

The stages are designed to hold components both above and below it. They are made of ½” birch plywood to limit deflection.

End Effector

The charging plug is held by a 3D-printed clamp under the z-stage which opens to switch plugs. The z-stage also houses a camera and a servo motor that presses the button required to unplug the charging plug. The camera was placed on the z-stage to avoid the need to perform a change of coordinates. The plug was placed under the z-stage so it would not hit the test fixture.

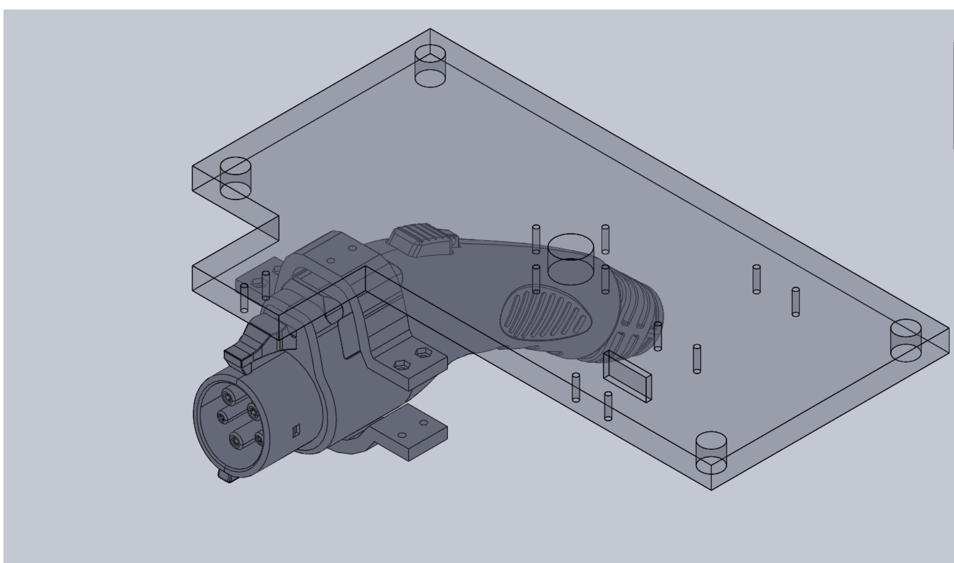

Figure 5. A view of the end effector. Servo not yet included.

Fixing the X-Screw

The x-screw is held by end supports, which will be weighed down by gravel. Tests will be performed to ensure the robot stays fixed, outlined in Appendix F.

3.2 Software Design

Microcontroller Selection

Our requirements for a microcontroller are:

- Low cost
- Take and process pictures, or send images to a computer
- Have PWM GPIO

Based on this, we selected the Raspberry Pi Zero W (RPZW) for its high processing power relative to Arduinos and low price compared to other Raspberry Pis and microcontrollers. A ratings matrix is provided below:

Table 4: Microcontrollers Ratings Matrix

Microcontroller	Price	Take images	Process images	Send images	PWM GPIO
RPZW, MicroSD Card, CSI-compatible camera	\$13 + \$20 + \$13 = \$46				
Arduino + PixyCam 2 [6]	\$5 + \$80 = \$85				
Raspberry Pi Zero [7]	\$41				
Other RP models or microcontrollers [8]	>\$60				

*Green for yes, yellow for maybe, red for no.

Price and wireless capability were heavily considered due to budgeting and the ability to offload to a laptop for computation.

Software Components

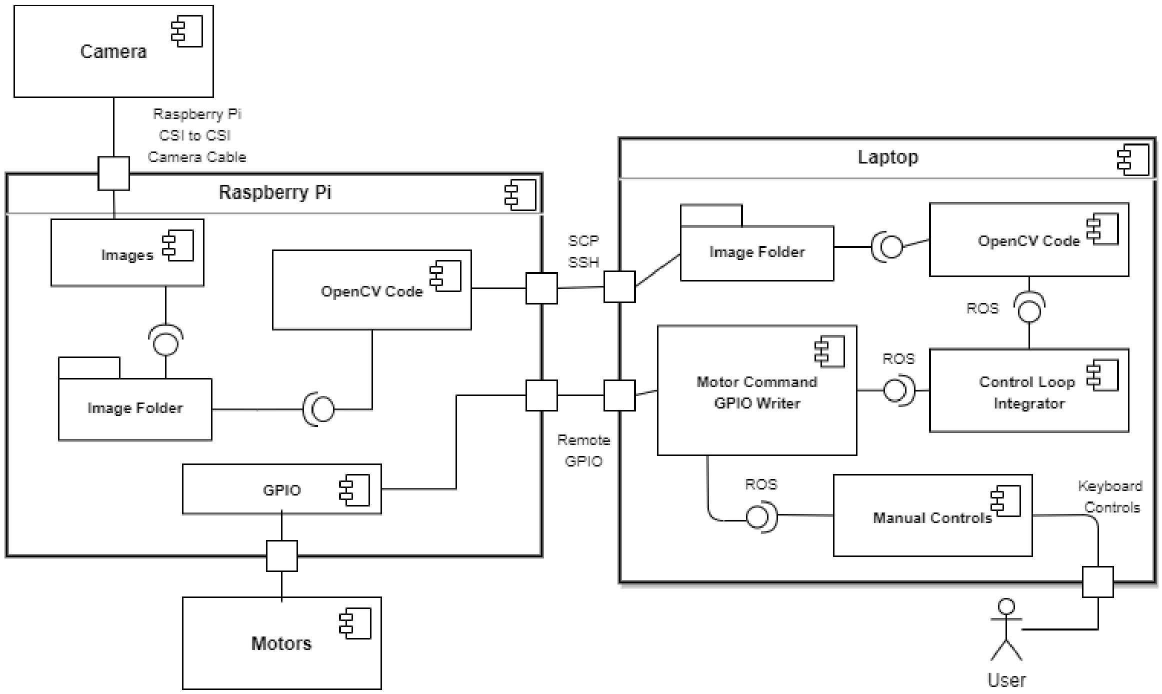

Figure 6: Software Component Diagram

The camera will take pictures and relay them to the Pi. The Pi may perform some pre-processing to reduce image size and send it using SCP to a laptop. The laptop will complete the processing with OpenCV to derive the current location of the plug with respect to the port. This data informs a Control Loop Integrator which makes decisions and publishes motor commands to the Motor Command GPIO Writer, which in turn controls the motors via remote GPIO to the Pi. The components will interface through Robot Operating System (ROS). Manual control will also be possible.

Port Detection and Image Processing

OpenCV can use a colour and greyscale filter to preprocess the image so a shape detector can be used to determine its position and size relative to the camera. More experimentation in this aspect will be performed closer to Milestone 2.

Figure 7: Port with purple indicator

Control Flow

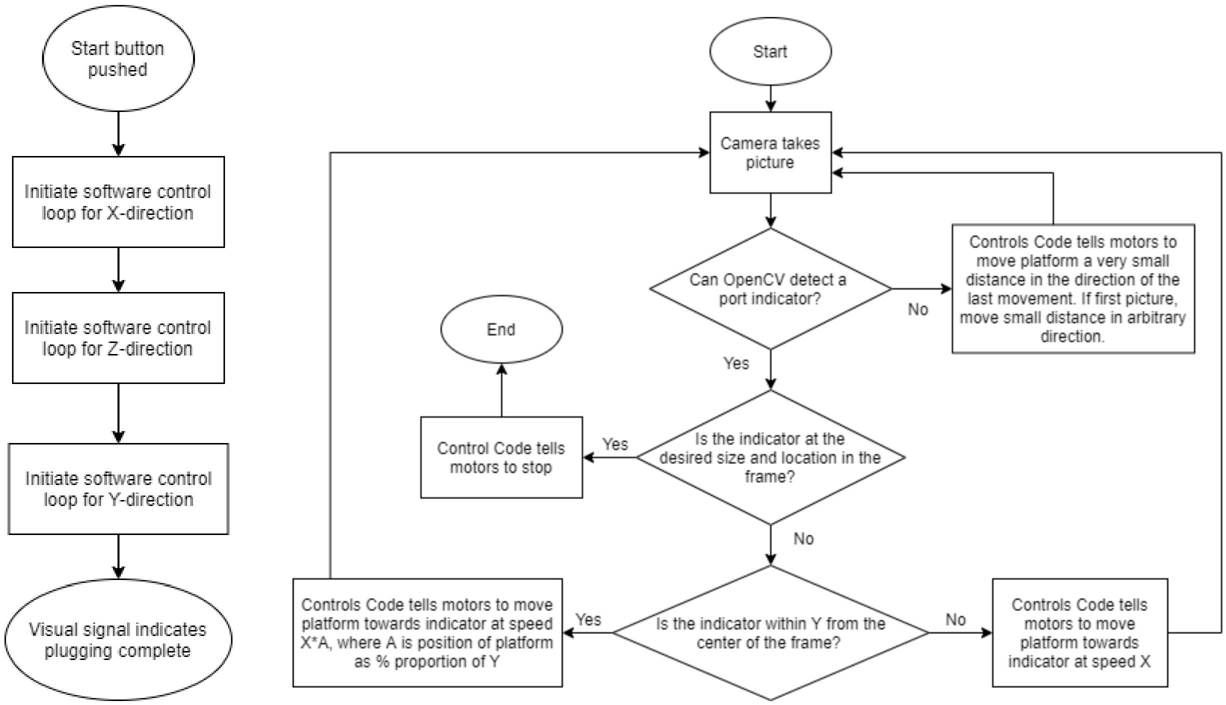

Figure 8 (From left to right): hardware control sequence. Software control loop for each axis

Movement in the x-direction will be first, as an extended y- or z-stage during movement in the x-direction causes unwanted moment. Movement in the z-direction is second, because movement in the y-direction must be performed last to insert the charge plug. Our final control code may include a PID loop or allow for minor adjustments in multiple axes once close to the port.

3.3 Electrical Design

Power Supply

We chose a 24V, 6A wall adapter because it:

- Does not need batteries
- Provides the maximum voltage for motors to maximize torque and speed
- 6A is sufficient for all devices
    - The steppers draw 5.7A. The RPZW [9] and the servo motor [10] combined run at about 5V and 0.5A, so the remaining current transformed to 5V is enough.

Circuit Diagram

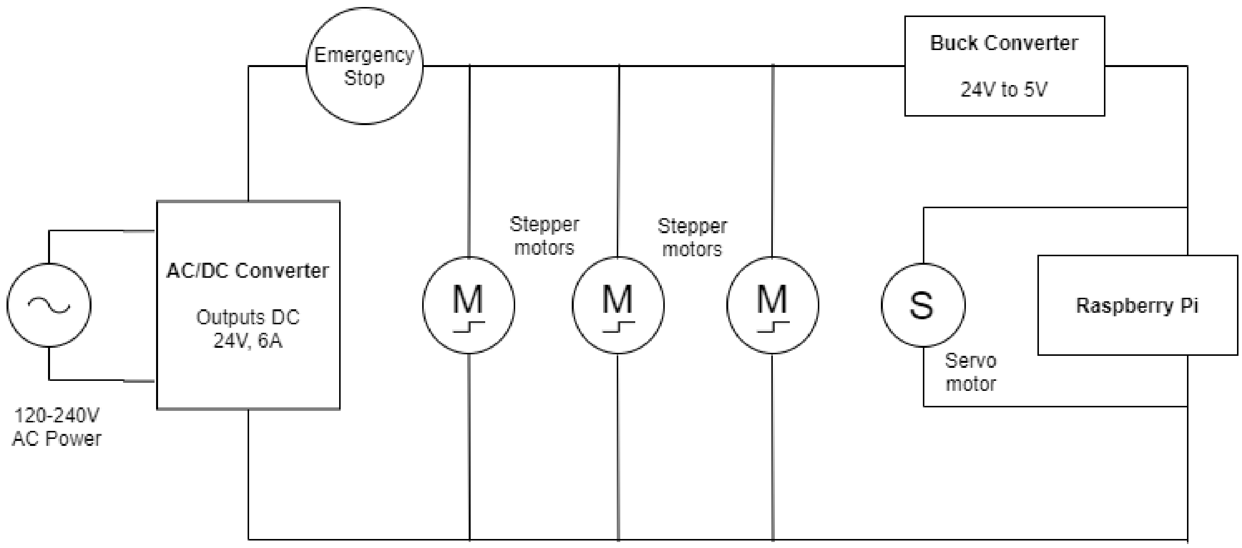

Figure 9 : A circuit diagram of the robot.

Notably, an emergency stop button is included for safety, and a buck convertor is included to reduce the voltage for the servo motor and the RPZW.

Placement of Electronics

Our power supply will plug in on the X-stage, then 12 AWG cables will carry power to the Y-stage and then to the Z-stage, powering the stepper motors along the way. Cables thicknesses were chosen based on voltages using an online resource [11]. On the Z-stage, the power cables will connect to the buck convertor, and power both the servo motor and the RPZW. The RPZW was placed on the Z-stage because the CSI to Mini CSI cable for the camera is short (only 16cm). Then, 22 AWG jumper wires will run out of the GPIOs of the RPZW and carry logic signals back to the servo, and the steppers on the Z-, Y-, and X-stages respectively. Cable management using zip ties will be important to prevent gears from interfering with wires.

3.4 Bill of Materials

Our full bill of materials is listed in Appendix D. An overview is listed below.

Structural and Mechanical Components

Lead screws: $63.31.

Custom part material: $59.07.

Material costs for 3D-printed components, wooden supports, spacers and gear coverings are currently unaccounted for because they are relatively low priced.

Electrical Components

Electrical components (without wires):$17.86.

Microcontroller, Camera, and Peripherals

The microcontroller, camera, and peripherals such as wires sum up to $51.87.

Motors and Motor Drivers

The motors and drivers sum up to $36.76. Notably, we purchased the 2A motors from an external source with a unit price of $7.92 to cut costs.

Overall

So far, $276.12 has been allocated. We expect the remaining costs to be less than $23.88, as the remaining components can be purchased at the LFF for a low price [12] .

3.5 Risk assessment

The full risk assessment is available in Appendix E. An overview is provided below.

Mechanical Risks

High moment loads on the x-screw may cause it to lock up. To test this, we will perform a "moment load screw test", outlined in Appendix F. If this test fails, we will consider adding guide rails as necessary to the x- and y-dimensions to solve the issue.

Friction between the platforms and the lead screws contribute to the above. If the "platform friction test" outlined in Appendix F fails, additional wooden supports will be added to support the platforms and reduce friction.

Tipping of the y-screw is also possible, and addressed by the "tipping test" in Appendix F and can be solved by adding weight.

Electrical Risks

Accidental shorts or overloads are a risk. All reasonable precautions such as not hot-swapping, performing continuity tests before powering our robot, etc. will be taken. The risk of wire damage by pinch points is solved with proper wire management.

Software Risks

There is a risk of insufficient sensor resolution. The "sensor resolution test" will be performed as outlined in Appendix F, and additional sensors will be added to increase sensing capability if necessary.

4. Project Management

The full timeline and tasks breakdown is available in Appendix G. Project management is facilitated through Trello and communication through Slack. Screenshots are attached in Appendix H. A general outline is below:

Table 4: Summary of Project Timeline

Week	Deliverables	Tasks
5	Design Concepts and Project Plan	● Purchase rover components ● Power calculations, decide on power source ● Fabricate custom parts ● CAD gears
6		● Solder headers on the pi ● End effector design
RW		● CAD robot ● Write Project Proposal
7	Project Proposal	● Set up Pi ● Assemble three axes of the robot ● Motor control implementation ● CAD and print end effector components ● Perform T1-3 and T5. Adjust robot as necessary
8		● Assemble end effector ● Ensure T1-3, T5 passed
9	Milestone 1	● Optimize OpenCV ● Set up camera on Pi ● Link software components on different devices ● Integrate sensing with Milestone 1 product ● Testing accuracy and precision in autonomy of robot
10	Milestone 2	● Make protective cover ● Test additional settings as described in project guidelines ● Final Report
11		● Optimization of robot ● Final Report
12	Milestone 3	● Final Report
13	Final Report and Video	

References

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Appendix

Appendix A. Full List of Metrics and Criteria

Table 5: Metrics for each Objective. C and I categorize each metric as converging vs. implementation

Objective	C	I	Metric	Measurement	Criteria
Reliability			Resolution of movement	Calculate the minimum distance you can move, consistently, using the actuation method presented by the alternative.	A lower distance is better, as that indicates more precise control over movement.
			Isolated movement on axes	If the alternative can move the end effector in all of the x-, y-, or z-dimensions individually and consistently without influencing the position in the other directions, then the rating is 3. For each dimension of movement where this is not possible, subtract 1 from the score of 3.	Higher ratings are better, as it indicates a better control over the dimensions of movement relevant to the problem.
			Uncertainty of sensing	Find the uncertainty of the sensor measurement online.	Lower uncertainty is better.
			Resolution of sensing	Find the resolution of the sensor measurement online.	Higher resolution is better.
Ease of Assembly			Time for assembly	Measure the time taken to assemble and disassemble the robot.	A faster assembly is preferred, in seconds. This must occur within three and one minutes, respectively.
			Tools Required	Measured by number of unique tools needed for assembly	An assembly requiring fewer tools is preferred
			Fasteners	Measured by fraction of mechanical fasteners over total fasteners	A greater fraction is preferred. They easily attach components in the

					same orientation every time, which lends itself to faster assembly
			Sensor Dependence	Measured as the number of sensors needed to complete the entire task	Fewer sensors are preferred
Safety			Moving Parts	Measured in the fraction of covered pinch points over total pinch points.	A greater fraction is preferred.
			Emergency Stop	The design is assigned a value of 1 if an emergency stop button is present and 0 otherwise.	1 is necessary.
			Exposed Wiring	Measured in length of covered wiring over length of total wiring in centimeters	A greater fraction is preferred.
			Surge Protection	Count the number of electrical components that are not protected from voltage spikes via a voltage regulator or a fuse. A voltage regulator counts as a component (can overheat) while a fuse does not (will fail safely).	A lower number is preferred.
Testing & Diagnostic			Actuator Dependence	Split the actuators into groups that cannot be tested without having all actuators and relevant parts in the group assembled. The number of actuators in the largest such group is the rating.	Lower ratings are preferred - this favours designs with less actuators and designs that lend themselves to unit testing.
			Known Info	The GUI should display useful information. This is evaluated as a score out of 3, from each known of x, y, z position.	A greater score is preferred.
Usability			Human Interaction	Count the number of human actions required to insert the charger and return	Fewer actions are preferred.

				the robot to a position where it is able to insert the charger again.	
			Robot Size	Measured as projection on the x-y plane in square meters.	A smaller projection is preferred.
			Speed of Completion	Measure the time taken for the robot to insert the plug for 10 distinct orientations of the charge port, in seconds	A shorter average time is preferred up to a maximum of 3 mins as per project constraints.
			Battery Requirement	If the robot is not fixed to the ground (and thus requires batteries), rating is Yes. If not, rating is No.	No is preferred - eliminates need to replace batteries.

Appendix B. Bending Moment Calculations

The second moment of area was calculated using an online calculator for both ½” and ¾” rods. Then these values, along with a generic value for the Young’s modulus of steel and lengths and loads approximated from our requirements, were entered into a deflection calculator. The results are as follows.

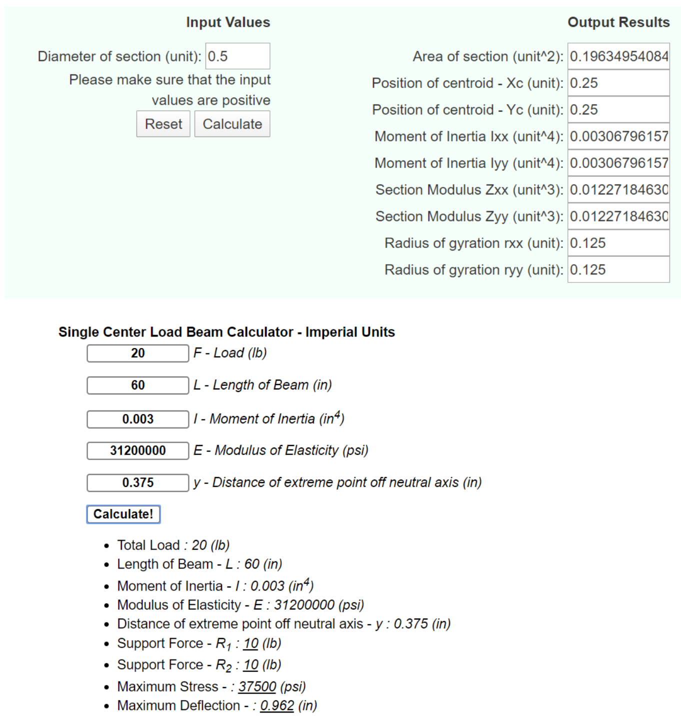

Figure 10. Bending moment calculations for a ½” thick steel rod

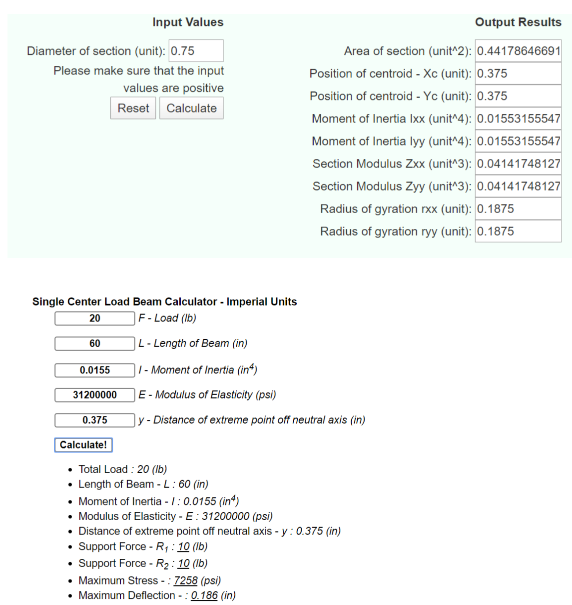

Figure 11. Bending moment calculations for a 3/4” thick steel rod

Appendix C. Lead Screw Torque and Speed Calculations

Input	
Force	20 ◉lb ○oz ○g ○N
Pitch Diameter	0.6850 ◉in ○mm
Thread density	10 Threads per ◉in ○cm
Coefficient of Friction	0.6 (See table below)
Result Units	○N*m ○N*cm ○lb*in ◉oz*in
Compute	
Result	
Torque (Raise)	72.9 (Selected Units)
Torque (Lower)	-62.4 (Selected Units)

Figure 12. Torque requirements roughly, conservatively estimated from our requirements [13].

To estimate the required torque, we conservatively estimated the load on the screw with the heaviest load (the x-screw) as 20lbs, and inputted the pitch diameter and thread density from our design. We also conservatively estimated the zinc-on-zinc static coefficient of friction as 0.6, using a website [14]. Under these conditions, the torque required to lift the entire load upwards (which is much greater than that required to simply move it side-to-side) would be 72.9 oz/in. Our 2A stepper motors operate above 80 oz/in at 2000pps, which translates to 10 rpm or 1 inch per second. At this speed, it would take about 40 seconds to traverse the entire range of the x-direction, which is fine given the 2-minute time constraint on operation. So, both our maximum speeds and our maximum torques should be more than enough for our requirements, especially considering the conservative nature of our estimate.

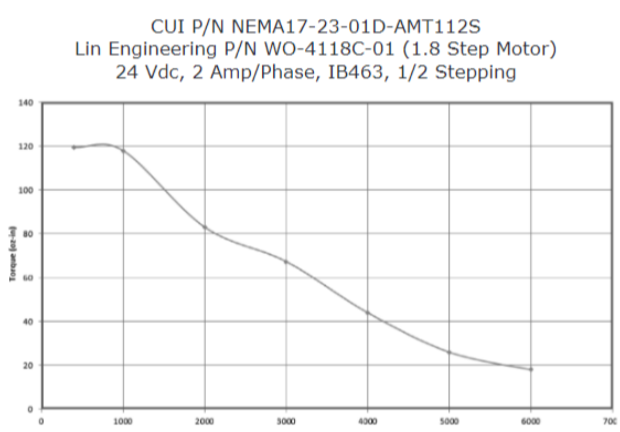

Figure 13. A torque curve for a 2A NEMA 17 [14].

Appendix D. Full Bill of Materials

Category	Item	Quantity/Area	Unit Price	Total Price	Link/notes
Structure	Lead Screws - 5'	1	$33.33	$33.33	http://bit.ly/2vVbte0
	Lead Screws - 3'	1	$16.49	$16.49	http://bit.ly/2SQE1yo
	Lead Screws - 2'	1	$13.49	$13.49	http://bit.ly/2uWaLwZ
	Support rods	4	$0.75	$3.00	http://bit.ly/2T9n6FR
	Gravel for weight (half an 18kg bag)	0.5	$7.00	$3.50	http://bit.ly/3c1ppUk
	End Supports (TBD)				
	X-Stage (1/2" birch plywood - 13.5" x 5.5")	0.515625	$1.55	$0.80	http://bit.ly/38PUdFn
	Y-Stage (1/2" birch plywood - 12" x 5.5")	0.4583333333	$1.55	$0.71	http://bit.ly/38PUdFn
	Z-Stage (1/4" birch plywood - 5.5" x 5.5")	0.2100694444	$0.96	$0.20	http://bit.ly/38PUdFn
Mechanical	Polyethylene Sliders	1	$3.79	$3.79	http://bit.ly/2SRzFGU
	Washers	4	$1.00	$4.00	http://bit.ly/3bW7iPw
	lead screw flange	1	$16.21	$16.21	http://bit.ly/2HISaHk
	lead screw platform & gear adapters	1	$42.86	$42.86	http://bit.ly/2va8Cxz
	Caster wheels	2	$2.22	$4.44	http://bit.ly/32gSkzj
	Pin	1	$1.49	$1.49	http://bit.ly/2T1DFUk
	Nuts	4	$2.29	$9.16	http://bit.ly/2vRVqgV
	Ball bearings	2	$5.26	$10.52	https://amzn.to/2Pin6T7
	Gears (Laser Cut out of 3.58" squares)	6	$0.94	$5.64	http://bit.ly/2PgYo5D
	PLA End Effector (TBD)				

Motors and Drivers	Small Servo	1	$1.50	$1.50	http://bit.ly/2SQMfGH
	NEMA 17 2A	2	$7.92	$15.84	http://bit.ly/3bZz8uh
	NEMA 17 1.7A	1	$13.93	$13.93	http://bit.ly/2HL9s6H
	Stepper Motor Driver	3	$1.83	$5.49	http://bit.ly/37Lvcd7
Microcontroller and Accessories	Camera	1	$13.00	$13.00	http://bit.ly/39VOazd
	Raspberry Pi Zero W	1	$13.00	$13.00	http://bit.ly/32iQT37
	32GB MicroSD Card	1	$20.00	$20.00	http://bit.ly/3bVK0tf
	Mini Camera Cable	1	$5.00	$5.00	http://bit.ly/2HOGToS
	Micro USB Male Plug	1	$0.87	$0.87	https://amzn.to/2SNusQx
Electrical	24V 6A Power Supply	1	$14.99	$14.99	https://amzn.to/3bYN7Al
	Female Barrel Plugs	2	$0.57	$1.14	http://bit.ly/2SSdmRD
	Breadboards	2	$0.86	$1.72	http://bit.ly/2Pjzy54
	LED	1	$0.01	$0.01	http://bit.ly/2VcUL4d
		Total		$276.91	

Appendix E. Full Risk Assessment

Risk	Likelihood	Severity	Mitigation/Contingency
High friction between unthreaded platform and lead screws	Medium (platforms make a loud sound when dragging across lead screw)	Medium	Lubrication, make unthreaded platform slide on an unthreaded rod instead
High friction between threaded gear adapters and lead screw	Low (we were able to easily spin the adapters on the screw with one finger)	Medium	Lubrication, increased torque on motors
Gear teeth chip and break	Medium (some chipping already observed)	Medium (fixable)	Print spare gears, perhaps with thicker teeth
Motors exert insufficient torque	Low (torque calculations completed)	High	Buy stronger motors or reduce speed
End effector moves too slowly to complete task in time	Low (speed calculated based on torque required)	High	Buy stronger motors or reduce mass of robot
Assembly of robot is impossible (ex/parts do not fit together)	Low (Full CAD of robot completed)	High	Assemble robot early to give time to adapt
Parts to build robot impossible to procure	Low (Most parts already purchased - see Bill of Materials)	High	Assemble robot early to give time to adapt
Lead screws bend significantly	Low (Loads are small, stiffness and thickness of lead screws is high)	High	Perform bending moment analysis beforehand
High moment loads	Medium (has not been	High	Test thread

cause screws to lock up	tested yet)		effectiveness under large moment loads
For some unforeseen reason, lead screw mechanism does not work	Low (many failure modes already documented)	Very High	Switch to belt drive
Y-screw tips backwards over X-screw	Low (Z-screw situated at the end of Y-screw, and is heavy)	Low (fixable with counterweights)	Test when integrating X, Y, and Z-screws - add counterweights if necessary
Vibration of robot makes sensing/precise movement impossible	Medium (has not been tested yet)	High	Move slower, only take measurements when still
Electrical components break	Medium	High	Design mounts/cases for Pi, camera, etc.
Resolution of motion too low	Low (calculated to be precise within much less than a millimetre)	High	Use physical means to limit motion
Lead screw backlash adversely affects control	Medium (backlash could affect motion by up to 1/10th of an inch - calculated from thread count)	Medium	Test the amount of backlash, and compensate in code
Robot moves relative to the ground	Low (parts are very heavy)	Low	Add mass to end supports on x-axis

Electrical Risks

Risk	Likelihood	Severity	Mitigation/Contingency

Wires damaged by gears	Medium (wires have to be loose)	Medium (can be fixed)	Ensure proper wire management
Raspberry Pi damaged	Medium (heat from soldering, electrical surge, overheating, etc.)	High	Have a back-up Raspberry Pi prepared, be careful before plugging in Pi (check voltages and polarity)
Loose connections	Medium (there are many connections)	Medium (fixable)	Keep wiring easy to access, solder permanent connections
Accidental short	Medium (many connections)	High (safety risk, damage to robot)	Wall adapter has shortage protection. Heat shrink soldered connections. Refrain from hot-swapping and be careful
Overload	Low (stepper motors, Pi, and servo combine to draw less than 6A at 24V)	High (safety risk, damage to robot)	Wall adapter has overload protection
Excess voltage supplied to circuit	Low (bought an off-the-shelf adapter)	High (safety risk, damage to robot)	Check output of wall adapter before using

Software Risks

Risk	Likelihood	Severity	Mitigation/Contingency
We can't figure out OpenCV well enough	Low (completely within our control)	High	Switch to using distance sensors and buttons (we have a plan for how to do that on Google Drive)

Resolution of camera sensing too low	Medium (have not tested yet)	High	Use more sensors to supplement camera closer to port
Camera field of view too low	Medium (have not tested yet)	High	Move camera further back, or use more sensors to supplement camera
WiFi connection issues with Pi	Medium (have not tested yet)	High	Use mobile hotspot WiFi if there is signal
Images too large to send quick enough over Wifi	Medium (not yet tested)	Low	Simplify image onboard the Pi (grayscale, reduce resolution)
OpenCV too slow	Medium (not yet tested)	Medium	Slow down polling rate

Appendix F. Test Procedures

T1. Fixed Robot Test

Test if the x-screw moves relative to the ground when the entire robot is assembled and operating at full speed in the x-, y-, and z-directions. If it moves, add more gravel to the end supports.

T2. Bending Moment Load Test

Attach the gear adapter to a dummy piece of wood with the same length as the y-screw, apply torque by pulling on the wood, and attempt to turn the screw by hand. If significant resistance is encountered or the screw locks up, the test would be considered failed.

T3. Platform Friction Test

After assembling the y-screw and its stage, actuation will be attempted with a dummy load. If friction causes the motion of the stage to become restricted, this “platform friction test” will be considered failed.

T4. Sensor Resolution Test

The camera is moved incrementally until the minimum possible difference in reading is outputted by the system. If this difference is greater than a couple millimetres when within 10cm of the charge port, the test is considered failed

T5. Tipping Test

Either fully assemble the robot, or attach the x- and y-screws to the x-stage, fix the x-screw, and add dummy weights to the y-stage. With the y-stage fully retracted, the test is failed if the y-stage caster wheel loses contact with the ground. If failed, add support to hold up the end, or counterweights on the y-stage, until the test is passed.

Appendix G: Full Project Timeline

Week	Tasks	Due Date	Done by Who	Details
5	**Design Concepts and Project Plan**	**Feb 3rd**		
	Purchase rover components	Feb 7th	Eddie/Rocco	Result: Parts from mcmaster carr, LFF parts, Pi and accessories, receipts saved in folder
	Make power calculations, decide on power source solution and make purchases	Feb 7th	Rocco	Result: decided on wall plug, purchase AC/DC power converter outputting 24V 6A, adapt to other electrical components with buck converter and voltage regulators
	Fabricate custom parts in machine shop	Feb 7th	Eddie	Result: Platforms, flanges, gear adapters
	CAD gears	Feb 7th	Grace	Result: 3x2 gears for motor and for platform movement
6				
	Solder headers on the pi	Feb 14th	Rocco	Result: completed, pins should be sufficient for controlling required motors
	End effector discussion and design	Feb 14th	Team	Result: camera above Z-stage, plug underneath. Print camera and plug mount. Stepper to press plug button
RW				
	CAD the robot	Feb 21st	Eddie	Result: cad completed, identified problems with the end effector arrangement and gear sizing with respect to the platform - will modify plan to accommodate
	Write the Project Proposal	Feb 23rd	Team	In Progress
7	**Project Proposal**	**Feb 23rd**		

	Set up Pi	Feb 28th	Rocco	In Progress: Raspbian Stretch Lite, OpenCV, and ROS done - still possibly need some image viewing software
	Assemble and test the three axes of the robot	Feb 24th	Team	Assemble all mechanical components of the robot in preparation for milestone 1 (end effector setup would be nice but not necessary) If not complete, extra work session February 25th. In parallel, perform T1, T2, T3, T5. Modify robot as required.
	Assess mechanical risks	Feb 24th	Team	With the axes of the robot assembled, perform tests of bending moment, balance and frictional risks. Use findings to adjust next steps as required.
	Control all motors with Pi (Python and ROS)	Feb 28th	Grace/Rocco	Write Python code to send motor commands to the Pi via keyboard input. Set up remote GPIO for the Pi and ensure GPIO pins are receiving the intended inputs
	Wire up the motors and Pi	Feb 28th	Team	Assemble electrical components of the robot. Integrate each motor along each axis along with the power supply and voltage regulation system to minimize risk of electrical malfunction. Care should be taken to avoid damage of any electrical components. Ensure motors move stages along each axis as intended
	CAD and print end effector components	Feb 28th	Eddie	Includes camera mount, plug mount: print in PLA. CADs currently completed
8				
	Assemble end effector	Mar 2nd	Team	Includes 3D printed plug mount, wire up stepper motor for button pressing and integrate with software controls
	Controlling the movement of the robot in various configurations of the charge port.	Mar 2nd, 6th and more as required	Team	Ensure robot meets all requirements in preparation for Milestone 1. Perform rigorous testing with all orientations of the charge port and reassess risks, specifically that of movement resolution, speed, moment torque and friction.
9	**Milestone 1 - Mobility**	**Mar 9th**		
	Optimize OpenCV	Mar 10th	Grace	In Progress: Can perform colour filtration and circle identification on a photo of the charge port - as next steps, optimize code with photos from the Pi camera, and photos of

				lower quality with significant noise
	Set up camera and camera functions on the Pi	Mar 10th	Rocco	Connect camera to Pi, control and automate photo collection to be saved in a specific folder, ensure images can be opened and viewed
	Link together software components on different devices	Mar 11th	Rocco/Grace	Connect laptop and Pi functionalities between image collection, processing, and controls generation. Set up SSH, ensure functionality and assess risk of connection loss
	Integrate sensing with Milestone 1 product	Mar 12th	Team	Attach camera and Pi to robot, demonstrate software connections are made and behave as expected (images inform controls which translates to motion)
	Testing accuracy and precision in autonomy of robot	Mar 12th, 13th, 14th, 15th	Team	Ensure robot meets all requirements for Milestone 2. Perform testing with all orientations of the charge port to ensure that time constraints are met, sensing resolution is sufficient (T4), vibration does not have significant effects - Adjust software as required (change where image processing takes place, reduce picture quality for faster transmission etc.) with respect to metrics and risks
10	**Milestone 2 - Locating**	**Mar 16th**		
	Make a covering	Mar 18th	Team	Use foam core to construct a case for the robot to minimize any safety risks in terms of hardware or electrical malfunction
	Integrate audio/visual indication of each action	Mar 19th	Team	Wire up an LED to light up when port is located, plug delivered to port area and when plugging is complete. Adjust mechanical and software components to accommodate
	Test with various different plugs (for additional settings)	Mar 20th	Team	Make sure weight of charger is not a problem, make sure plug mount and button mechanism works for different models, make sure resolution of sensing/movement is sufficient for the alignment tab
	Implementation of retraction function (for additional settings)	Mar 22nd	Team	Should be mainly a software task - program stepper to press button again and program motors to retract the plug and then return platforms to starting position
	Work on Final Report	All week	Team	More details after assignment outline is released

11				
	Optimization, additional features	Mar 23rd, 25th, 27th	Team	Create a GUI for usability and diagnostics, improve performance of robot as informed by our metrics and risks
	Work on Final Report	All week	Team	More details after assignment outline is released
12	Milestone 3 - Project Presentation	**Mar 30th**		
	Work on Final Report	All week	Team	More details after assignment outline is released
13	Final Written Report & Video Presentation	**April 9th**		

Appendix H: Trello and Slack

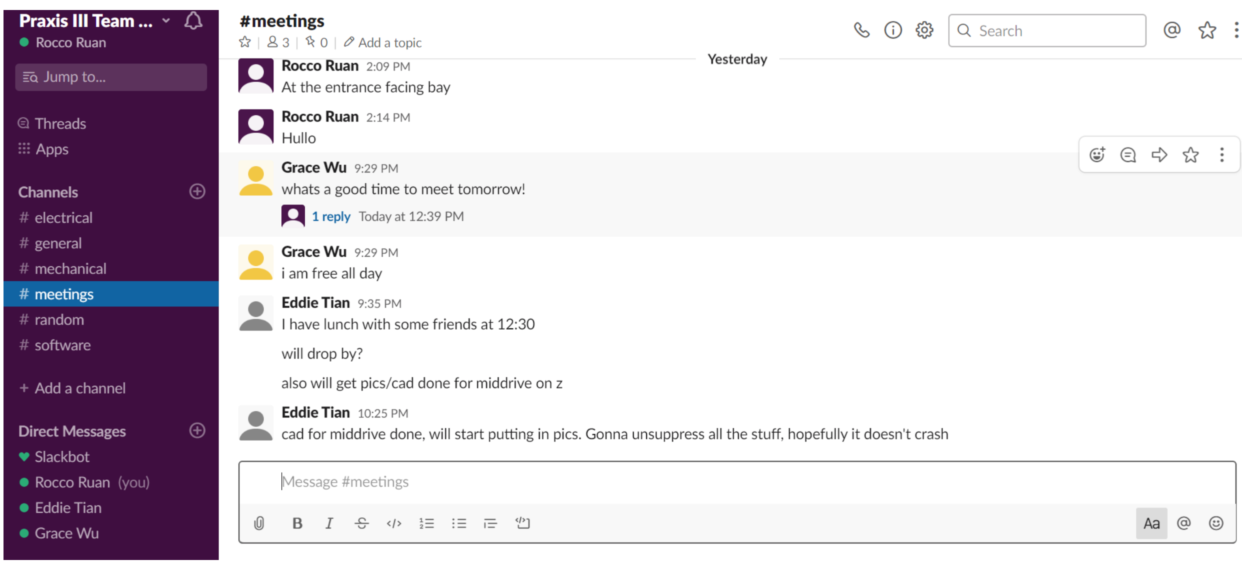

Figure 14: Slack

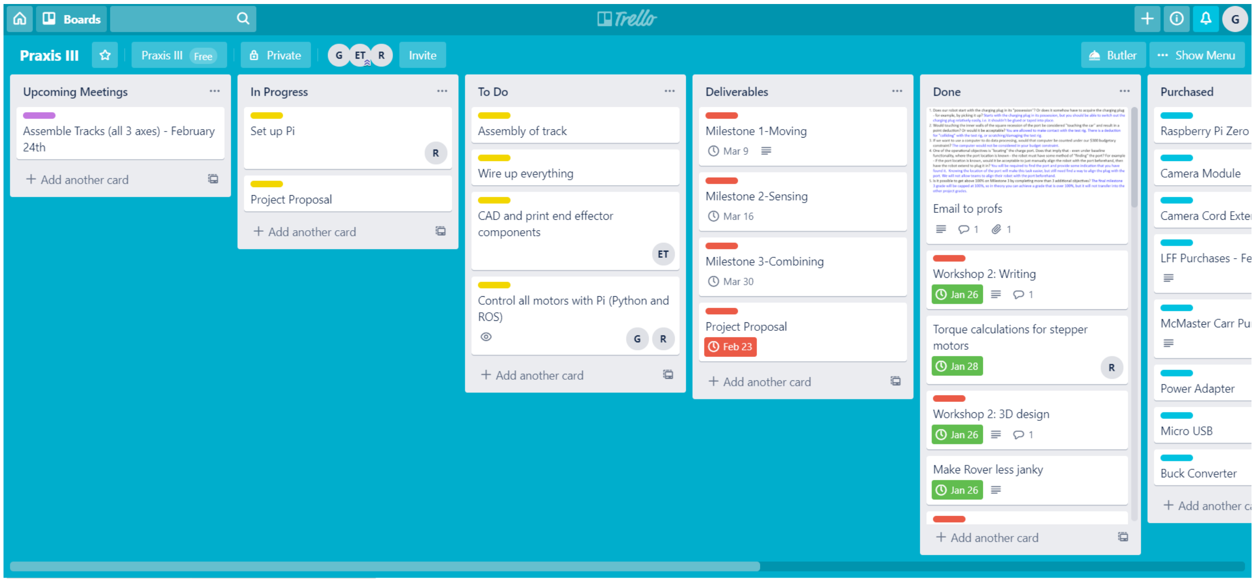

Figure 15: Trello