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ESC204: Project Proposal

Problem Framing

In an effort to support the transition to renewable energy and make electric cars more viable and attractive, this project aims to make the use of electric cars more convenient for its owners by allowing the car to be autonomously charged when parked while respecting the current charging method in using a plug-in charger. This way, electric cars will be more reliable as the owner of the car will never have to worry about it not being charged for its next use or having to go out of their way to specifically charge their car.

The proposed design for this opportunity is a rover style robot that can move independently in the x,y, and z-axis in addition to rotational abilities to match non-zero yaw of the port relative to the y-axis as defined in Figure 1 [1]. In addition, beyond the baseline functional objectives outlined in the project guidelines, our team has decided to focus our design on adapting to Additional settings A1, A2, and all of C (4 degrees of freedom in port).

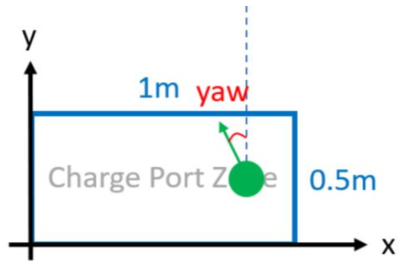


Figure 1: the charging port location [1]

Based on the values of stakeholders in this design opportunity such as us the design team, possible future users and manufacturers of this product, we have chosen to focus on the following objectives:

Global Design Objective	Sub-Objective	Justification	Design Impacts
Reliability	Minimize Failure Chances	-Want the robot to be functional and properly serve its purpose -Ensures the robot is fully functional during evaluation -Robot should be adaptable to various environments if implemented in the real world	Use of feedback loops in programming for real-time adjustment Verification of structure through FEA Use of stepper motors for different modes of operation
	Maximize Fault Tolerance	-In the event of an unexpected occurrence or failure, the robot should be able to continue its duty -Safety measure to ensure the	Redundancy in systems Use of feedback loops in programming for real-time adjustment

		robot does not completely fail if an unexpected failure occurs during the evaluation	
Simplicity	Simplicity in design and fabrication	-Should be simple enough for us to realistically fabricate given our academic schedules	Use of simple linear mechanical and control systems
	Should be designed with simple parts	-Easy to fabricate -Easy to mass produce -Simple stress testing/simulation computations	Heavy use of 3D Printing and Laser Cutting
Usability	Functionality	-Must perform the task it was designed to perform -Should meet baseline and additional functional objectives to maximize grade gain	Simple control system (linear motion in each axis)
	Portability	-Allows the device to be easily transported by any stakeholder -Allows stakeholders to easily store the robot in their garage or other storage facilities	Simple part shapes for easy storage and transportation, Minimize area required for storage
Cost	Minimize Cost	-Must minimize cost to meet cost constraints. -Minimizes future production costs	Optimizing resource use (IE fitting as many cuts on one wood stock for laser cutting)
Safety	Hazard Prevention	-There should be no exposed moved parts that could harm any users -Users/owners of the device should not be in danger when within close proximity of the robot	All hazardous components (electrical and mechanical) are securely hidden and only accessible via purposeful use of tools
Modularity, Serviceability & Reparability	Minimize Repair time	-A minimal repair time allows for fast troubleshooting as required on evaluation day or during testing -Ensures the robot can remain	Layered design so each layer can be accessed for repair, troubleshooting for testing

		functional for as long as possible	
	Dimensional Adjustability	-Easily isolate required design changes to a single subsystem	Use of non-permanent fastening methods (bolts, rubber bands...etc)
Appearance & Style	Aesthetic appeal	-Aesthetically pleasing design allows for better marketability	Easily Identifiable logo Catchy Name Minimalist outer design

The following are the corresponding metrics that we have synthesized for each global design and sub-objective:

Global Design Objective	Sub-Objective	Metric		Proposed Test
		Target	Constraint	
Reliability	Minimize Failure Chances	Repeated testing should yield 100% repeatability regardless of test fixture conditions (floor type, test rig imperfections) [2]	Must be at least functional under specified testing/evaluation environment	Is the robot fully operational on smooth floors, tiled floors, and rough floors (Yes/No)
	Maximize Fault Tolerance	All Electronic Systems should have redundancy [3]	Non-redundant Electronic systems should be functional	How many of the three fundamental characteristics of fault tolerance does the system comply with? (Replication, Redundancy, Diversity)(See Sources for definition) [3]
Simplicity	Simplicity in design and fabrication	Should have a fully operational robot with all subsystems working as intended.	Must be within the scope of 2nd year engineering students	/
	Should be designed	All parts should be designed with regularly	N/A	How many irregularly shaped

	with simple parts	shaped components [4]		components does design have? [5]
Usability	Functionality	Achieve all objectives listed on project guideline	Must achieve at least the base goal	How many objectives can be met with the design?
	Portability	Should take up less floor space than 0.48m x 0.825m [6]	N/A	How much floor space does the assembled and disassembled robot take? (in m^2)
Cost	Minimize Cost	Cost should be less than $250	Must be less than $330	Sum the cost of all parts in BOM
Safety	Hazard Prevention	Should be designed with minimum number of accessible moving parts with no moving parts exposed [7]	Must have an emergency shutoff switch	How many moving parts are exposed? Can moving/internal parts be accessed without tools? [7]
Modularity, Serviceability & Reparability	Dimensional Adjustability	Should be constructed with fully non-permanent fastening methods for easy access and repairability[8]	Must have no loose components during operation	Number of non-permanent fastening methods vs permanent ones

Alternate Designs

Apart from our final rover design, we also considered a robotic arm-based design, as well as a stationary gantry design. These designs were chosen as our top three alternatives through multiple converging and diverging stages, using tools such as Morph Charts in order to come up with ideas and then trim them down.

The Robotic Arm was considered due to it's mechanical simplicity and modularity. It would only require 4 motors in order to move all the axis, and it would be relatively cheaper to manufacture, due to the minimal requirements for parts such as pulleys, belts, and lead screws. Furthermore, as it would have a stationary base, the robotic arm would easily fulfill some requirements, such as returning to home. However, control systems from a complex robotic arm would not be within the scope of the skillset of the design team as none of us have experience with control theory.

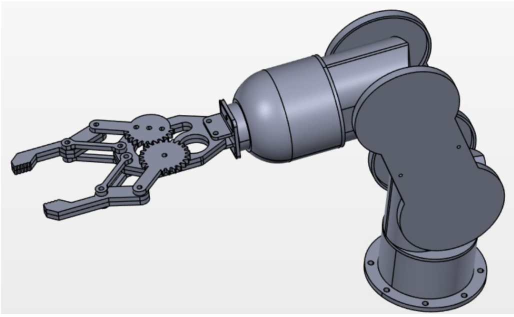


Figure 2: Reference Arm Design

The Stationary Gantry design was selected for its programming simplicity - as each axis of movement in the cartesian system would be controlled by one motor. Similarly to the Robotic Arm, it would also be stationary, which again allows us to better track exactly where the charging arm is, relative to a home position.

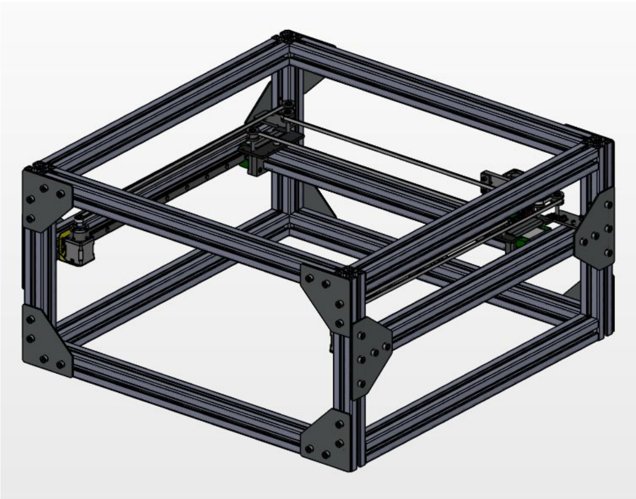


Figure 3: CAD model of the reference Gantry Design

Convergence Process

After our convergence process, we selected the Rover Design, as it best fit our criteria. However, it took us many rounds of converging and diverging in order to reach this decision.

For our first round of diverging, we simply brainstormed ideas in order to start a list of possible options (See Appendix A). However, we kept in mind what we learned last year in Praxis 2 from Professor Sheridan, and decided to do our brainstorming individually, ensuring that our ideas wouldn't be influenced by each other. Furthermore, in order to prevent anchoring, our team made an effort to prevent looking at reference designs, so that our ideas were as unique as possible.

From this round of diverging, we came up with many designs, which we needed to quickly cut down. After further familiarizing ourselves with the criteria, we used quick system 1 decisions to get rid of any designs that were simply unfeasible. For example, one of the ideas that we had was the tentacle arm that was shown in lecture - it was too complex as it pertained to continuum robotics [9] , and thus out of the scope of our design teams' skillset.

Our team noticed that there was a lot of overlap in some of our ideas, and decided to categorize our designs two categories - Movement and Autonomy. In movement, we broke it down further into subcategories featuring movement in the different axes, as well as rotation for yaw. For Autonomy, the subcategories included the different features needed, such as hole locating, distance to hole, yaw detection, among others. These subcategories allowed our team to create a morph chart (See Appendix B) from all the ideas from the first round, allowing us to mix and match different designs as we saw fit.

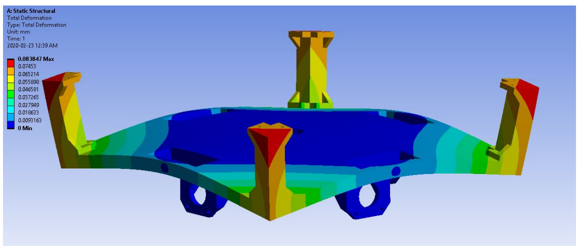
At this point, we had created our objectives and DxFs, which we used to inform our decisions while we converged using tournament-style for each subcategory. From there, we combined the top three from each subcategory to create our top three alternate designs - the rover, the gantry, and the robotic arm.

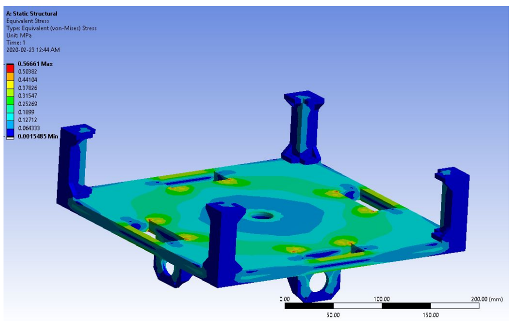
For our final round of convergence, we originally decided to prototype each design, and see which ones would be the best suited to our needs. For the robot arm, we ran simple calculations to determine the amount of holding torque needed in the worst case scenario, which resulted in a torque of 2500N-cm (See Appendix D). When looking for stepper motors with that specification of holding torque, we found that ordinary Nema17 Motors would not cut it, and the Nema42 Motors required would not fit our budget.

The gantry design was also eliminated because of the material cost and low portability. For the gantry system to work, 30 feet of 1” aluminum extrusion is needed (not including connectors). According to McMaster-Carr, 10 feet of the material cost $30.54 USD [10], which means the structure alone will consume at least half of the budget (approximately $120 CAD in total). With other components needed, we would likely exceed our budget constraint. Also, the structure is estimated to be 1.5m*0.5m*1m in size in order to reach all possible port locations, which does not comply with our usability/portability objective when compared to the other two designs,

Finally, we needed to prove that the Rover design was possible. Our two key concerns were the structural strength of the scissor lift, as well as straight-line movement with omni wheels.

We first ran key structural components, such as the base, and the scissor arms through Ansys FEA to validate its strength, letting us test our design without having to make physical prototypes. For the base, our team also checked deflection, since we were advised that omniwheels are sensitive to weight distribution. Calculating a weight of ~20N on the base, we used a factor of safety of 2.0 and tested for a case of 40N. With ½” Plywood as the main base, the deflection was negligible, while the stress was well below the yield strength of the plywood.

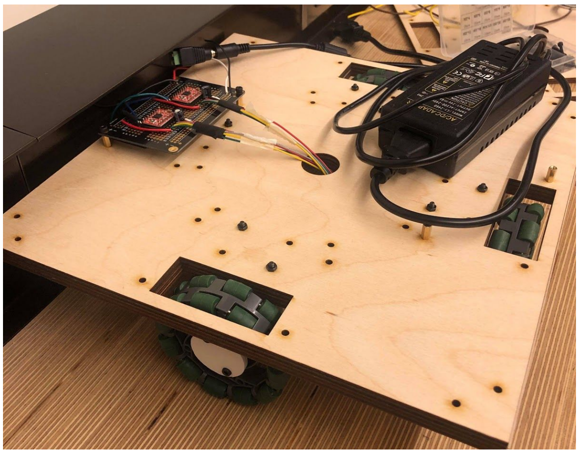




Left - Figure 4: Deflection simulation with 40N. Max deflection (shown in red) is 0.08mm.

Right - Figure 5 : Equivalent Stress with same load. Max Stress (red) is 0.5MPa.

Then, created a 1:1 prototype of the base, and tested it's mobility. Luckily for us, the robot was able to consistently move in straight lines, without any issue of straying.



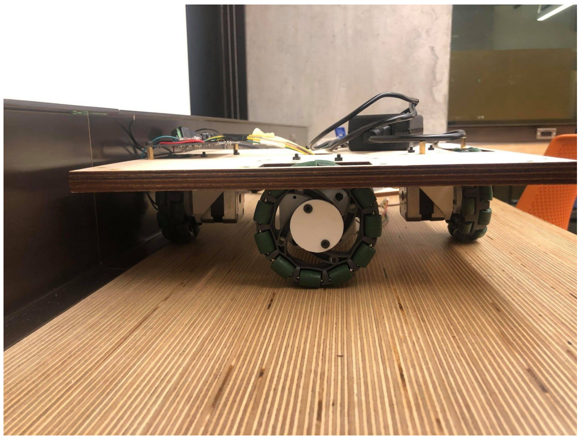
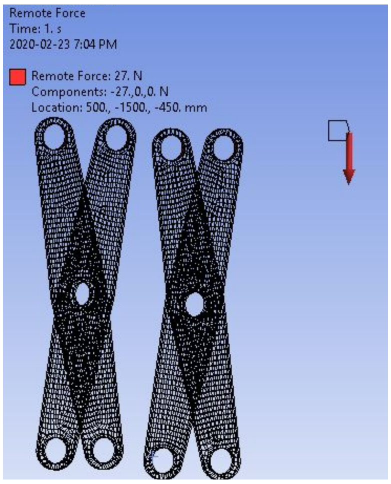
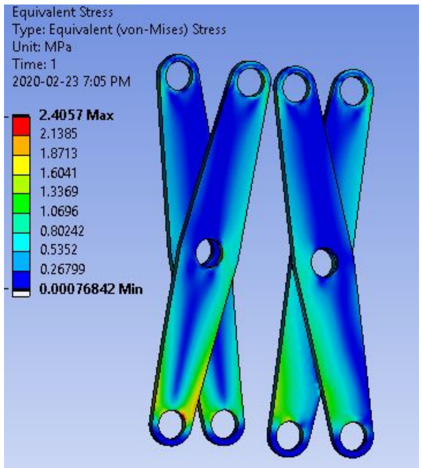


Figure 6 and 7 : Prototype Rover Movement

Similarly, the scissor arms were another component that we would be able to verify without physical prototyping. Its max load case would be when it was fully extended, as there would be an additional moment on the arm, due to its layout. With a weight of ~1.35kg on top of the scissor lift, we used a load case of 27N, which encompassed a FOS of 2.0. This load resulted in a max stress of 2.4MPa, which once again was well within the limits of the Plywood.



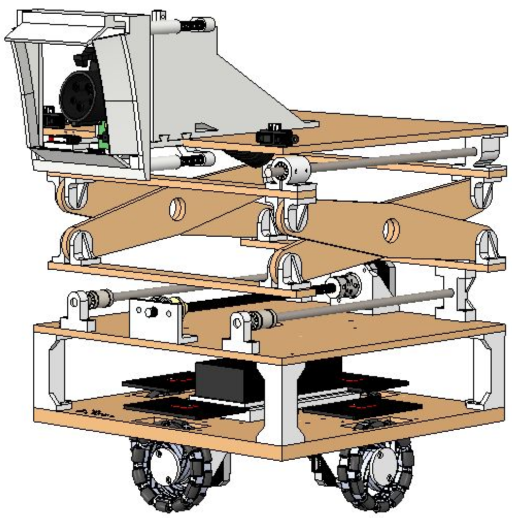


Left : Figure 8 : Load Definition, with the Red Arrow representing remote force of 27N.
Right: Figure 9: Equivalent Stress with same load.

During this time, we also prototyped the CV portion, with a calculation rate of ~30 frames a second, which was more than what we needed to get accurate data (see figure 16).

Proposed Design Solution

Mechanical and Electrical Design



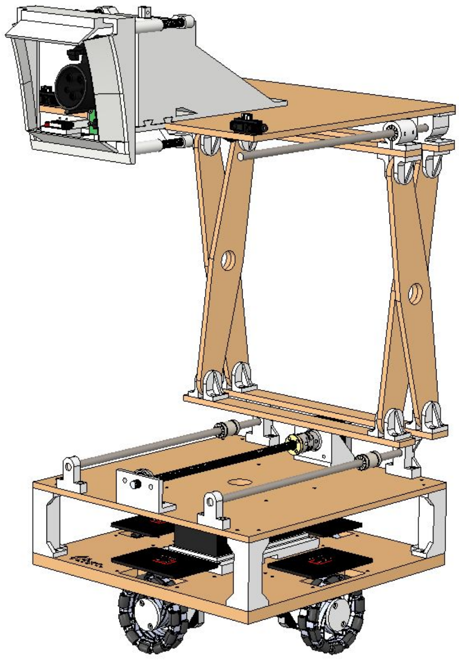
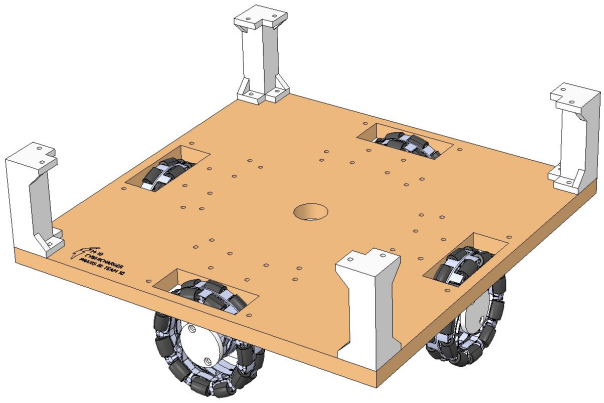
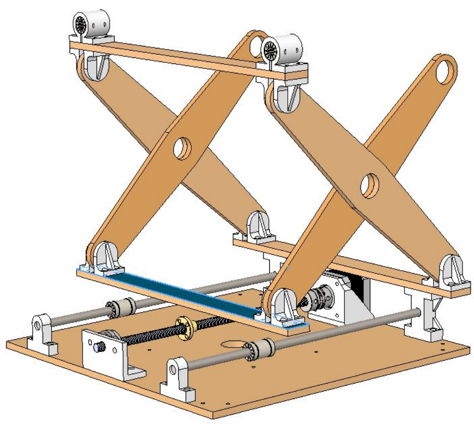


Figure 10 and 11 : Proposed Rover Design (left), with full z-extension (right). Parts shown in white are 3D printed, while parts shown in brown are laser cut.

The proposed design solution is a rover style robot with 4 omni-wheels arranged in a square formation, driven by stepper motors with two wheels driving in the x and y-axes respectively, as shown in figure 8. Movement in the z-axis is controlled by a single joint scissor lift, which is controlled by a stepper motor and lead screws, with steel rods and bearings allowing for minimal friction, seen in figure 9. This mobility system allows the robot to move in any axis independently to allow for simple control programming. In addition, the arrangement of the omni-wheels in a square formation allows for in-place rotation to address a varying yaw angle in the port.





Left - Figure 12 : Base Design, with 4 Omni Wheels, as well as mounting holes for electronics.
Right - Figure 13: Single Joint Scissor Lift

The scissor lift sits on top of a multilayered mainframe that begins at the wheel level holding the stepper motors. Then, the main electrical components such as the raspberry pi, power supply, and solder-in breadboards are secured onto the base of the mainframe. This design allows for layers to be easily removed for modularity and repairability.

Equal weight distribution is achieved by offsetting the weight of the plug and mold with the weight of the stepper motor on the scissor section, and all other parts are symmetric, allowing for the most optimal distribution for the omni wheels. Furthermore, the heaviest components such as the ½" base, power supply, and four stepper motors are as low as possible, lowering the center of gravity, further minimizing our chances of tipping.

The plug is held by a 3d printed mold of it, which is screwed securely onto the top platform of the lift. The camera is mounted close to the plug for accuracy. A limit switch mounted beside the camera activates when the plug is inserted, giving raspberry Pi the signal that the task has been completed. There is a shroud in front of the plug. Its pyramidal shape corrects the plug if the sensors are not accurate enough, and it guides the plug to the correct location. After the plug is in the correct location, it retracts as the rover drives forward, letting the plug be inserted. To meet our modularity and ease of assembly/disassembly metric, the components are inspired by woodworking joints such as mortise and tenon joints and dovetail joints. Using these designs allow us to use the minimum amount of screws, which decreases assembly/disassembly times, decreases hardware costs, and modularises the components.

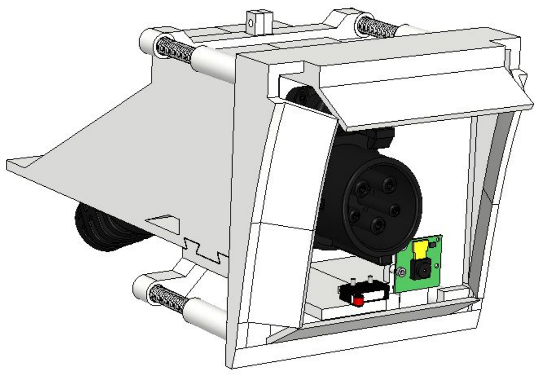


Figure 14: CAD Design of plug holder

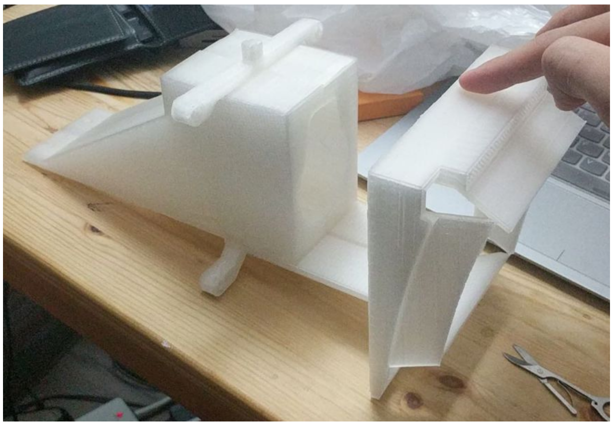


Figure 15: prototype 3D printed parts of the holder

Autonomous Systems Design

A Raspberry Pi Zero W is the main onboard controller of our robot while computer vision + IR sensors are used in the autonomous location of the charging port. The Pi controls all of the motors on the robot via its GPIO ports while providing image data via the raspberry pi camera module. The IR sensors will be used to find the yaw of the port while the computer vision will calculate how much the robot has to move in the x and z-axis knowing the marker/port length in both distance units and pixels. This allows us to obtain a conversion factor between centimeters and pixels and thus converting that value into how much our motors need to turn. Our options are detecting the whole port or a black non-reflective square taped on top of the port in the middle so that we can use the OpenCV threshold function and make everyone pixel white except for those in the black circle (cv2.THRESH_BINARY_INV). A limit switch below the charger will rely if the charger has been successfully plugged in or if readjustment is needed.

Figure 16: Preliminary detection of port and port hole using OpenCV. Red crosshair is center of image

System Strategy

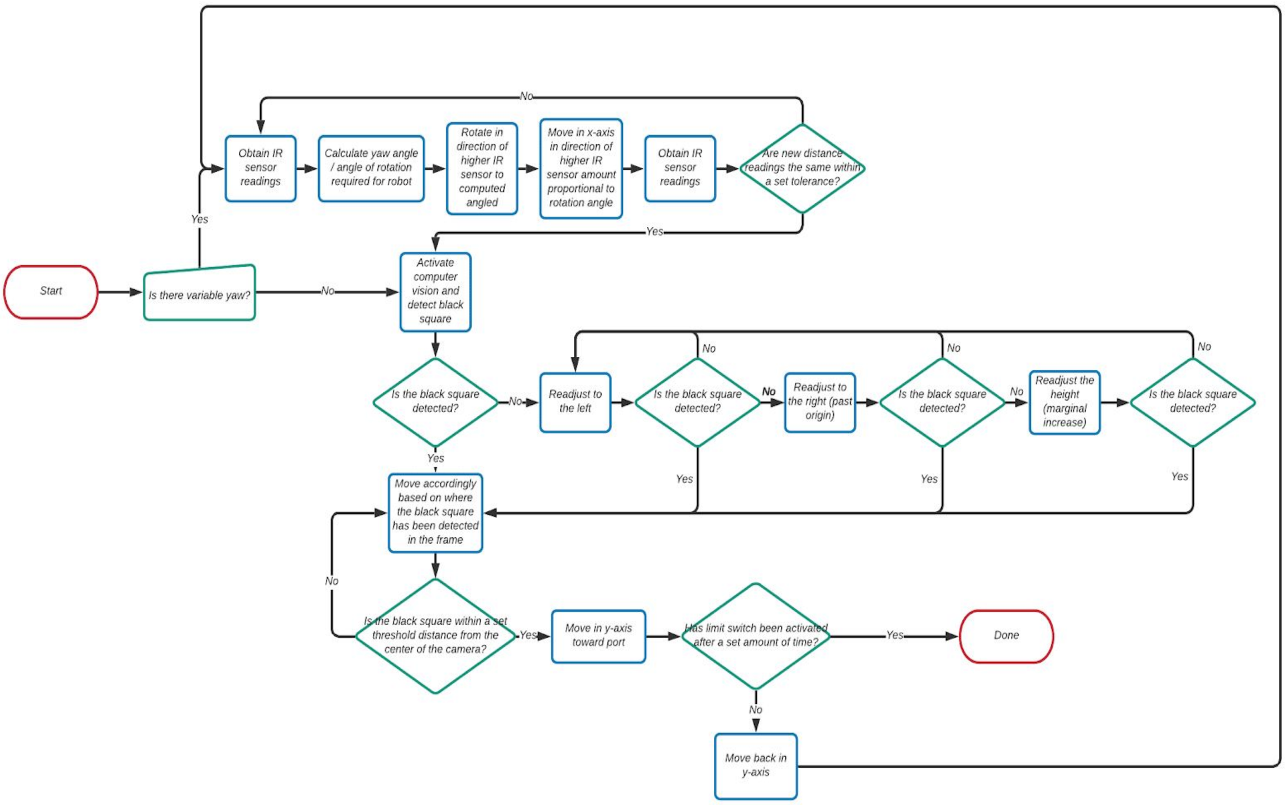


Figure 17:Flowchart for System Strategy

Risk Assessment

After conversing with some TAs during work sessions, we learned that uneven weight distribution in the body of our robot might affect whether or not the Omni wheels will traverse in a straight line, so thorough testing and symmetrical distribution of components is required to ensure that the wheels travel in as straight a line as possible whenever required.

Next, uncertainties in IR sensor measurements will also contribute to inaccuracies in the rotation of the robot in relation to the actual yaw angle. We try to account for this by using braces around the charger that ideally would guide the charger into the port regardless of inexact yaw angles.

Although preliminary testing of the computer vision software is done on a video feed, it is still uncertain how the algorithm will perform when the robot is in motion and accidentally captures extremely blurry images. Furthermore, while optimization of the computer vision algorithm can be done, as the background behind the test rig is completely random, it is uncertain if the computer vision algorithm will mistake anything in the background as a result of image noise or coincidental patterns from unexpected lighting conditions. Tests in various backgrounds and lighting conditions will have to be done to minimize the risk of failure due to an algorithmic misclassification. In addition, the speed of the robot will be adjusted to ensure usable photos are taken at every step.

Bill of Materials (Preliminary)

Part	Units	Unit Price	Total Price	Purchased by	Source
Electronics					
Raspberry Pi Zero W	1	$15.00	$15.00	Haoran	buyapi.com
5MP Rasberry Pi Camera	1	$17.00	$17.00	Haoran	https://www.ama
IR Distance Sensors	2	$6.57	$13.14	Anton	LFF
Limit Switches (pack of 20)	0.1	$9.99	$1.00	Kelvin	https://www.ama
Stepper Motor (Set of 5)	1	$37.65	$37.65	Haoran	https://www.ama
Stepper Motor Driver (Set of 5)	1	$16.66	$16.66	Haoran	https://www.ama
Power Supply	1	$18.99	$18.99	Kelvin	https://www.ama
Power Supply Connector (Pack of 5)	0.2	$8.99	$1.80	Kelvin	https://www.ama
Buck Converter	1	$1.27	$1.27	Kelvin	LFF
Camera Cable Extender for Raspberry Pi	1	$6.00	$6.00	Haoran	https://elmwoode
Solderable Breadboard (6pack)	1	$15.99	$15.99	Kelvin	https://www.ama
Movement					
Omni Wheels (Pack of 4)	1	$59.99	$59.99	Kelvin	https://www.vexr
Lead Screw + Nut	1	$4.27	$4.27	Anton	LFF
Lead Screw Bearing	1	$3.91	$3.91	Anton	LFF
Lead Screw Connector	1	$1.43	$1.43	Anton	LFF
Linear Rods (Set of 2*600mm)	1	$34.41	$34.41	Kelvin	https://www.ama
Linear Bearings (Set of 8)	1	$10.39	$10.39	Kelvin	https://www.ama
604zz Bearings (Set of 10)	0.8	$3.25	$2.60	Kelvin	https://www.aliex
Structural					
1/8th Ply 18"x24"	4	$2.61	$10.44	Kelvin	LFF
Misc					
JST Headers (Pack of 10)	1	$8.99	$8.99	Kelvin	https://www.ama
M3 Screws (Pack of 280 Assorted)	1	$19.89	$19.89	Kelvin	https://www.ama
PLA Plastic (1KG)	0.3	$22.90	$6.87	Kelvin	https://www.ama
Emergency Switch	1	$0.29	$0.29	Kelvin	LFF
Springs	4	$1.69	$6.76	Anton	https://www.cana
		Parts Total :	$314.74		

Figure 18 : Bill of Materials for the team, last updated on February 23, 2020

Project Management

We used Trello to manage the progress and responsibility of this project. In the Trello board, there are many lists: Legend, Things to do, Doing, Done, Meetings, Questions for teaching team, and

Risks. These lists help with identifying the status of tasks and makes the board very easy to navigate through. Inside the lists, cards are created with the name of the tasks, along with members responsible, due dates, proper categorization, and explanation.

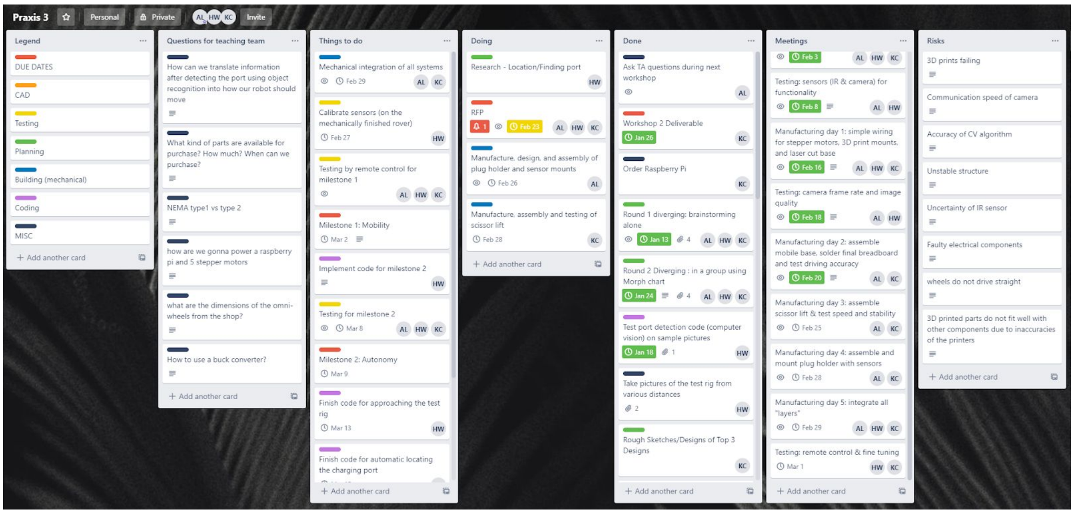
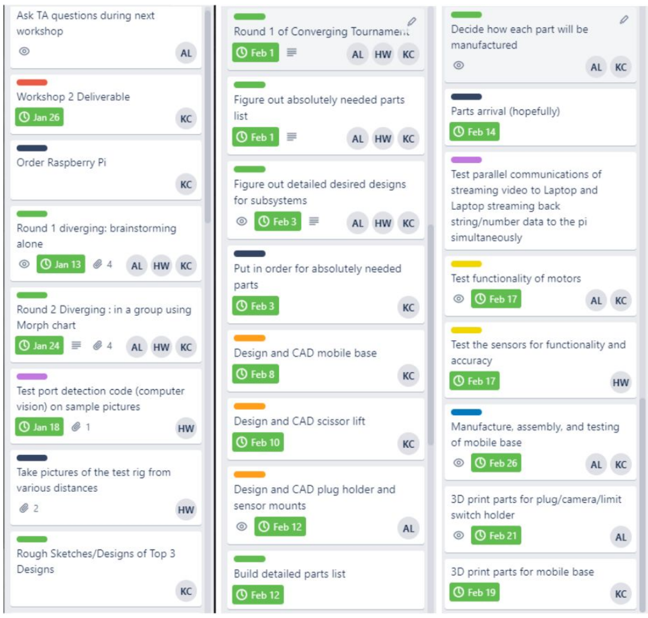


Figure 19: Overview of Trello board

The legend provides explanations of color coding, which makes navigating the board easier. For example, if someone wants to find something related to mechanical construction, they just need to look for blue markers.

Questions for the teaching team is a place to put our questions; it can be either about clarification of the project or technical details. Answers to those questions will be recorded in the description section of the card.

Things to do, doing, and done are lists that label the completion status of the tasks. The tasks within are crucial to the project because the timeline needs to be followed strictly in order to meet the milestones. Detailed explanations are provided for each task, and pictures are provided as evidence for completion.



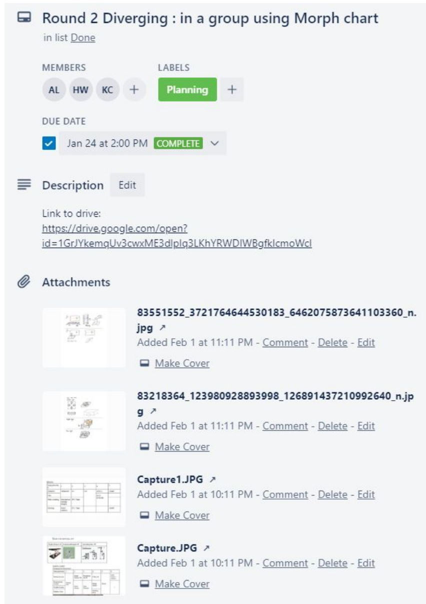
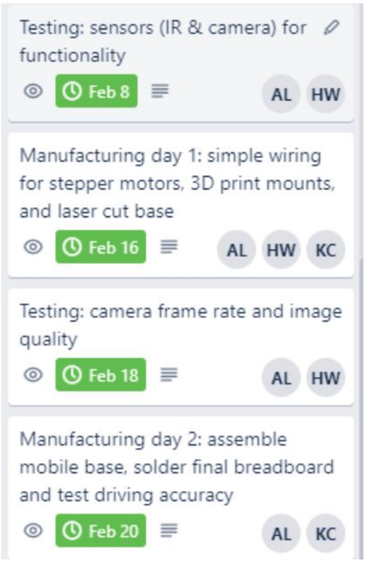


Figure 20: Examples of tasks in the done category *Figure 21: One of the tasks*

The meetings section show completed and planned meetings between members and the main cause for the meeting, along with the attendees. These meetings can be in person or online through video calls. After the meeting, the notes/minutes are recorded in the descriptions of the cards for easy access.



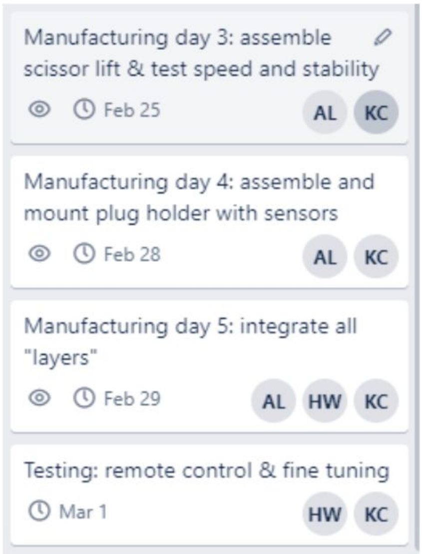


Figure 22 : Examples of past meetings *Figure 23: Examples of planned future meeting*

The risks section highlights potential risks and how to solve them on the event of the problem occuring. This section helps us to prepare for failures in our previous design processes. However, many unexpected problems can occur and this section is being updated constantly.

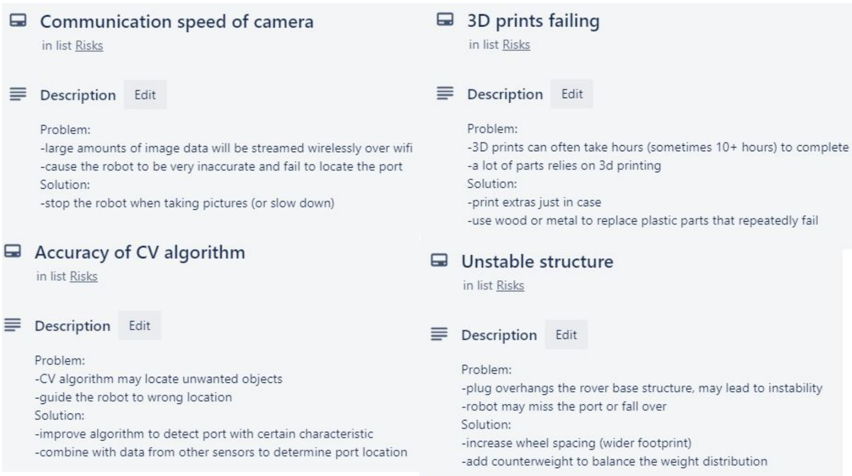


Figure 24 : Examples of risks and appropriate solutions

Using the Trello board, the team can work efficiently with easy communication and clear goals. The board allows all team members to be aware of their own tasks and lets the team be on track to complete milestones. So far, all tasks have been completed successfully and on time with little to no issues.

Project Timeline

Week 1 - Jan 6 to Jan 13:
- Receive project

Week 2 - Jan 13 to Jan 20:
- Round 1 diverging: brainstorming alone (Individual)
- Test port detection code (Computer Vision) on sample pictures (Haoran)

Week 3 - Jan 20 to Jan 27:
- Round 2 diverging: in a group setting with morph charts (Everyone)

Week 4 - Jan 27 to Feb 3:
- Round 1 converging: tournament & Pugh chart. (Everyone)
- List absolutely needed parts and purchase them (Everyone)
- Decide on three alternate designs (Everyone)

Week 5 - Feb 3 - Feb 10:
- More detailed designs of the three alternate designs (Everyone)
- Decide on a single design (rover)
- Design and CAD mobile base (Anton, Wei Hai)

Week 6 - Feb 10 to Feb 17:
- Design and CAD scissor lift (Wei Hai)
- Design and CAD plug holder and sensor mounts (Anton) **Update: camera mount relocated to front of plug instead of above**
- Build detailed parts list (Everyone)

Week 7 - Feb 17 to Feb 24:

- Decide how each component will be manufactured (Laser cutting, 3D printing) (Wei Hai, Anton) **Update: laser cutter does not cut ½” inch wood so stack 4*⅛” instead, adjust tolerance in CAD because of 3D printer accuracy**
- Test communication between Laptop and raspberry Pi (Haoran) **Update: Wireless communication is no longer used, all computations are now done locally on the pi**
- Test stepper motors (Anton, Haoran)
- Test sensors for functionality and accuracy (Haoran)
- Test camera frame rate and image quality (Haoran)
- 3D print parts for mounts (Anton, Wei Hai)
- Assemble and Prototype mobile base (Everyone)

Week 8 - Feb 24 to Mar 2:
- Manufacture scissor lift (Anton, Wei Hai)
- Manufacture plug holder and sensor mount (Anton)
- Integrate mechanical system (Everyone)
- Testing with remote control (Haoran)

Week 9 - Mar 2 to Mar 9: Milestone 1 Progress Evaluation
- Implement and test code for milestone 2 (Haoran)
- Repair any mechanical issues that occur during testing (Anton, Wei Hai)

Week 10 - Mar 9 to Mar 16: Milestone 2 Progress Evaluation
- Implement code for milestone 3 (Haoran)
- Implement audio/visual feedback when plug is inserted (Anton, Wei Hai)

Week 11 - Mar 16 to Mar 23:
- Test and improve functionality of robot (Everyone)

Week 12 - Mar 23 to Mar 30: Milestone 3 Final Evaluation
- Ensure robot can complete the milestone (Everyone)
- Work on final report & video presentation (Everyone)

Source Extracts

[1] - *ESC204: Project Guideline V1.0 Section 2.3.2 - Figure 11*

[2] - Daley, Daniel T.. (2011). *Design for Reliability - Developing Assets That Meet the Needs of Owners - 4.2 Defining DFR.* Industrial Press. Retrieved from https://app.knovel.com/hotlink/pdf/id:kt0098VX34/design-reliability-developing/defining-dfr

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- The device is not expected to function in the required manner just once so the seller can push it out the door. It functions in the same effective and efficient manner for its entire life.
- The device is not expected to function only under optimum conditions; it functions in all possible environments.

[3] - Kaboli, Shahriyar Oraee, Hashem. (2016). Reliability in Power Electronics and Electrical Machines - Industrial Applications and Performance Models - 11.2 Redundancy. IGI Global. Retrieved from https://app.knovel.com/hotlink/pdf/id:kt010YSCO2/reliability-in-power/redundancy

REDUNDANCY

Redundancy is the provision of functional capabilities that would be unnecessary in a fault-free environment (Hao, Covic, & Boys, 2014). This can consist of backup components which automatically "kick in" should one component fail. The idea of incorporating redundancy in order to improve the reliability of a system was pioneered by John von Neumann in the 1950s.

Providing fault-tolerant design for every component is normally not an option. Associated redundancy brings a number of penalties: increase in weight, size, power consumption, cost, as well as time to design, verify, and test. Therefore, a number of choices have to be examined to determine which components should be fault tolerant:

Spare components address the first fundamental characteristic of fault tolerance in three ways:

- **Replication:** Providing multiple identical instances of the same system or subsystem, directing tasks or requests to all of them in parallel, and choosing the correct result on the basis of a quorum;
- **Redundancy:** Providing multiple identical instances of the same system and switching to one of the remaining instances in case of a failure (failover);
- **Diversity:** Providing multiple *different* implementations of the same specification, and using them like replicated systems to cope with errors in a specific implementation.

[4] - Kutz, Myer. (2019). *Handbook of Farm, Dairy and Food Machinery Engineering (3rd Edition) - 16.8.1.2 Container Geometry.* Elsevier. Retrieved from https://app.knovel.com/hotlink/pdf/id:kt012286HE/handbook-farm-dairy-food/container-geometry

16.8.1.1 Design Simplicity

The shape should be as regular as possible: oval or round. Narrowing or restricting the body of a cylinder can make the contents explode or blast out of it. A "lobster shape" is an attractive way of marketing a microwavable version of a crustacean; however, irregular shapes with broad and narrow areas create serious temperature nonuniformity issues.

[5] Alison, “What are regular and Irregular shapes,” *Home Education Resources - Primary & Secondary - National Curriculum*. [Online]. Available: https://www.edplace.com/blog/edplace-explains/what-are-regular-and-irregular-shapes. [Accessed: 23-Feb-2020].

What are regular and irregular shapes?

The definition of a **regular shape** is that all the sides are equal and all the inside angles are equal. An **irregular shape** doesn’t have equal sides or equal angles.

[7] - *IEEE Std 13482-2014, IEEE Standard Robots and robotic devices - Safety requirements for personal care robots*

5.13 Hazards due to contact with moving components

5.13.1 General

Personal care robots shall be designed so that the risk of hazards caused by exposure to components such as motor shafts, gears, drive belts, wheels, tracks or linkages is acceptable.

Personal care robots shall be designed in compliance with ISO 13857 in order to prevent hazard zones being reached by parts of the body.

5.13.2 Inherently safe design

The following measures shall be applied where appropriate:

a) the personal care robot shall be designed with the minimum number of accessible moving parts;

b) the personal care robot shall be designed with moving parts in which components such as motor shafts, gears, drive belts, wheels, tracks or linkages are not exposed.

5.13.3 Safeguards and complementary protective measures

Hazards due to moving parts shall be prevented either by fixed guards or by movable guards, depending on the foreseeable frequency of access, in accordance with ISO 14120.

Appropriate method(s) shall be chosen from the following.

a) Where fixed guards are used, the following measures shall apply:

   1) fixed guards shall be installed so that they can be opened or removed only with tools;

[8] - Kosky, Philip Balmer, Robert Keat, William Wise, George. (2010). *Exploring Engineering - An Introduction to Engineering and Design (2nd Edition) - 20.5 Design for Adjustability.* Elsevier. Retrieved from
https://app.knovel.com/hotlink/pdf/id:kt00TY3631/exploring-engineering/design-adjustability

20.5 DESIGN FOR ADJUSTABILITY

In engineering courses there is usually only enough time and resources to manufacture one design, and that design almost never performs as planned on the first try. Optimizing performance by building several designs is not an option. The only remaining course of action is to design adjustability into the initial implementation.

There are a number of ways to design for adjustability. One way is to design the system with modularity. This can serve to isolate required design changes to a single subsystem. In a mechanical system, dimensional adjustability can be attained by using nonpermanent fastening methods such as screw joints instead of a permanent method like epoxy.

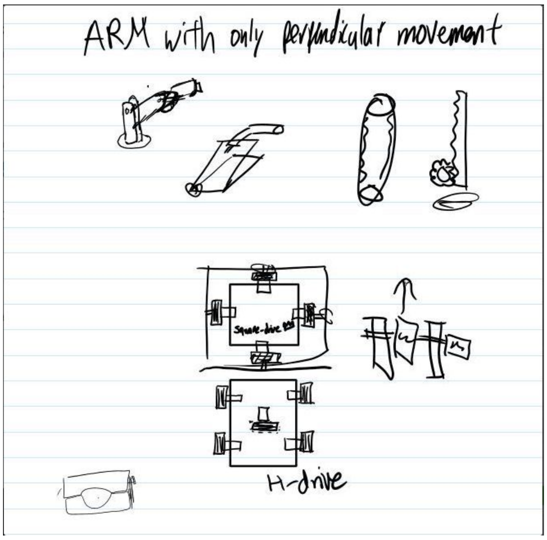
[9] - Walker I.D., Green K.E. (2009) Continuum Robots. In: Meyers R. (eds) Encyclopedia of Complexity and Systems Science. Springer, New York, NY

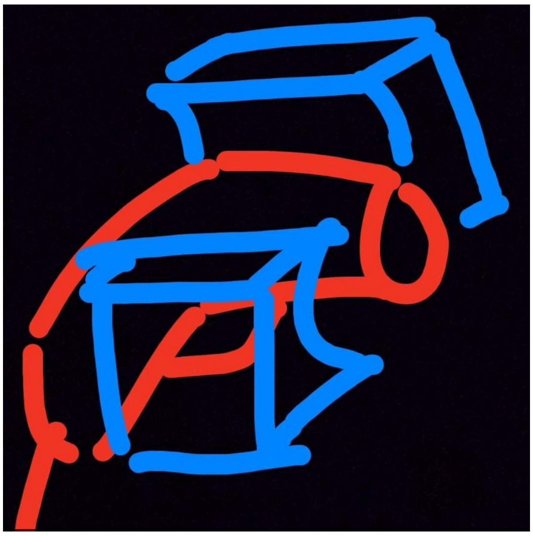
[10] - *McMaster-Carr. [Online]. Available: https://www.mcmaster.com/aluminum-extrusions. [Accessed: 24-Feb-2020].*

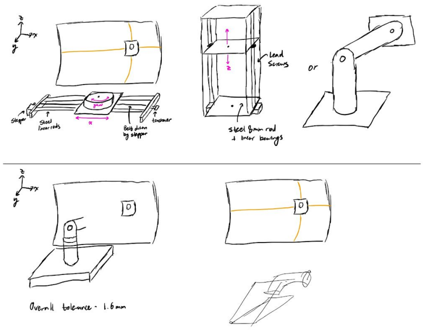
Single Four Slot Rails

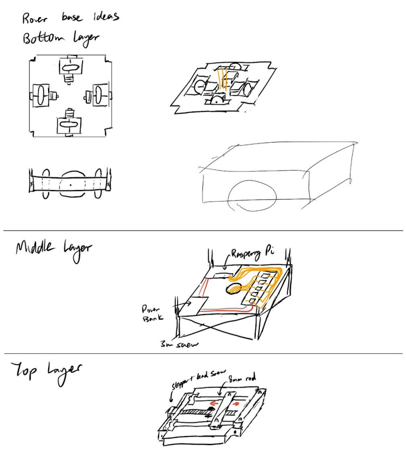
Rail Ht.	Rail Wd.	Rail Construction	T-Slot Wd.		1 ft.	2 ft.	3 ft.	4 ft.	5 ft.	6 ft.	8 ft.	10 ft.
Silver Anodized Aluminum												
1"	1"	Solid	0.256"	47065T101	$5.84	$7.79	$10.57	$12.31	$16.28	$17.68	$23.57	$30.54

Appendix A: Brainstorming Evidence









Distance Sensors

	IR	LIDAR	Ultrasonic	VSCEL
Pros	- Range: 20cm-150cm(may be less depending on model) - Refresh interval 80ms - Inexpensive - Moderate update rate, faster than Ultrasonic, slower than LIDAR)	- Excellent Max range - Very fast Update Rate	- Low current draw - Easy interface options - Does well when facing objects dead-on[2]	-Range: 4cm-4m *Advertised, reviews vary Super small minimum range - Inexpensive - Wide input voltage range - Very fine resolution +/- 1mm
Cons	- Narrow beam, might miss surface - Affected by Colour - High minimum range (>20cm)(model dependent) - Might need voltage to distance conversion graph/range	- High current draw - Expensive - Some are class 1 laser hazard	- Low resolution - Slow refresh rate - Will be inaccurate with any angles relative to surface [2](yaw)	- Very low max range - I2C Interface only/ Troubles interfacing/communicating

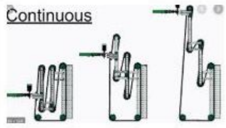
For such very short ranges (<6m), it is usually more practical and cost-effective to use simple infrared (IR) reflection instead of more complex/costly LIDAR systems. [3]

Example of VSCEL: https://www.sparkfun.com/products/14722

Source:
https://www.sparkfun.com/distance_sensor_comparison_guide

[2] http://web.csulb.edu/~wmartinz/rssc/content/pros-and-cons-range-sensors.html
[3] https://www.robotshop.com/community/blog/show/lidar-light-amp-laser-based-distance-sensors

IDEAS FOR VERTICAL LIFT:

Single Scissor Lift	4-bar/parallelogram lift	Cascade/pulley Lift
		Continuous 

Appendix B: Morph Charts for diverging

MORPH CHART

Diverging tool Movement :

<table>
<tr><td>Subsystem/Idea</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td></tr>
<tr><td>Vertical (Z-axis)</td><td rowspan="4">Robotic Arm</td><td>Single Scissor Lift</td><td>Parallelogram lift</td><td>Pulley Lift</td><td rowspan="4">Drone</td><td>Lead Screw + Grantry</td></tr>
<tr><td>Perpendicular (Y-axis)</td><td rowspan="3">Omni-wheels</td><td rowspan="3">Tank Threads</td><td rowspan="2">Belted Gantry</td><td rowspan="3">/</td></tr>
<tr><td>Parallel (X-axis)</td></tr>
<tr><td>Rotation (Yaw)</td><td>Rotating Base</td></tr>
</table>

Sensors

<table>
<tr><td>Subsystem/Idea</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Distance</td><td rowspan="2">Ultrasonic</td><td rowspan="2">IR</td><td rowspan="3">CV</td><td>VCSEL</td><td>LIDAR</td></tr>
<tr><td>Yaw</td><td rowspan="2">Limit switches</td><td></td></tr>
<tr><td>Hole-Locating</td><td>Mechanical (wedge shape)</td><td>IR + Tape</td><td></td></tr>
<tr><td>Homing</td><td>Motor rotation</td><td>IR + Tape</td><td></td><td></td><td>LIDAR</td></tr>
</table>

Appendix C: Pugh Charts for converging

Overarching Objectives :

1. Reliablity
2. Simplicity
3. Usability
4. Cost
5. Safety
6. Modularity, Serviceability & Reparability
7. Appearance & Style

Movement Subsystems :

Z Direction :

	Robotic Arm	Single Scissor Lift	Parallelogram lift	Pulley Lift	Drone	Lead Screw + Grantry
Robotic Arm	/	Single Scissor Lift	Robotic Arm	Robotic Arm	Robotic Arm	Robotic Arm
Single Scissor Lift	Single Scissor Lift	/	Single Scissor Lift	Single Scissor Lift	Single Scissor Lift	Single Scissor Lift
Parallelogram lift	Robotic Arm	Single Scissor Lift	/		Parallelogram lift	Parallelogram lift
Pulley Lift	Robotic Arm	Single Scissor Lift	Parallelogram lift	/	Pulley Lift	Lead Screw + Grantry
Drone	Robotic Arm	Single Scissor Lift	Parallelogram lift	Pulley Lift	/	Lead Screw + Grantry
Lead Screw + Grantry	Robotic Arm	Single Scissor Lift	Lead Screw + Grantry	Lead Screw + Grantry	Lead Screw + Grantry	/

Top 3 Choices: Robotic Arm, Single Scissor Lift, Lead Screw & Gantry

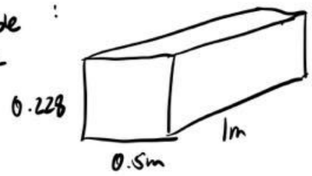
X & Y Direction :

		Robotic Arm	Rover		Belted Gantry	Drone
			Omni Wheels	Tank Treads		
Robotic Arm		/	O	Robotic Arm	Gantry	Robotic Arm
Rover	O	Omni Wheels	/	O	O	O
	T	Robotic Arm	O	/	Gantry	T
Gantry		Gantry	O	Gantry	/	Gantry
Drone		Robotic Arm	O	TT	Gantry	/

Top 3 Choices: Omni-Wheeled Rover, Belted Gantry, Robotic Arm

Appendix D : Calculations

Moveable volume :



∴ Longest Arm = 0.5m

Force = Weight × g

Weight worst case: Motors × 3 + Plug + Structural

Assume motors = 0.3kg each = 1 kg total

Assume Plug + Holder = 0.5kg

Assumge Structreal = 1kg

∴ Total weight = 2.5kg

∴ Force = 25 N

FOS of 2 ∴ Force = 50N

$\tau = F \cdot d =$ 50N · 50cm = 2500 Ncm.