ESC204 - Praxis III Design Proposal

Autonomous Electric Car Charging Rover

ESC204

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Team W19

Submitted February 23, 2020

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INTRODUCTION: Electric Car Autonomous Charging

Charging electric cars is a task that has become increasingly relevant as more and more electric cars are taking to the road and need to be powered to continue driving. Each Praxis III team was tasked with designing a device that autonomously inserts and removes a charger plug into a car door port in a variety of situations. The constraints of the environment are to simulate a real electric car parked in a garage having different X, Y, Z, and yaw variations [1]. This report is Team W19's proposal for a solution to the given problem; the rest of the document will outline important factors to consider throughout the design process as well as the final project solution.

STAKEHOLDERS:

It is important to consider the individuals and organizations that will be affected by the design of this device. Those affected in the process of manufacturing, assessing, verifying, and validating the design must be recognized and their values incorporated into the design process.

Primary Stakeholders

1. *Team W19 - Praxis III Team*
   This team will be the ones manufacturing, testing, and verifying our design. To make it possible to successfully complete this project within the required time frame and learn effectively from this project, their objectives must be considered and incorporated into the design.
2. *Praxis III Teaching Team*
   The teaching team has enforced certain constraints on the design (outlined in Appendix 1.1 - Project Guideline). They also wish for the design process to be a successful learning experience and that Team W19 achieves a working mechatronics design.
3. *Myhal Light Fabrication Facility*
   This facility will provide the work space and tools to complete the electrical and mechanical components of the design. They require that the design is feasible within the space they can provide.

Secondary Stakeholders

1. *Electric Car users*
   This project will offer cheaper and different alternatives to the pre-existing tesla charging robots which provides more accessible options for electric car users.
2. *Electric Car Companies*
   Should the solution be put into production, electric car companies may choose to manufacture the home charging stations to provide their customers. Electric car companies may also experience an increase in sales in their cars due to a more accessible method of charging for their customers.

REQUIREMENTS

Design for X

From the stakeholders, a list of 5 relevant DfXs was generated. They were chosen with an emphasis on the needs of the primary stakeholders.

1. ***Design for Reliability***
   The device should be able to repeat a task with reasonable accuracy so that it can be performed with a high rate of success. Reliability is defined as "the probability that a product performs its intended function without failure under specified conditions for a specified period of time"; meaning the design will have a higher probability of success at each of the milestones [A1.2].
2. ***Design for Testing and Diagnostic***

A design that can be easily tested throughout the design process is considered highly valuable; Testing each component individually while assembled within the full design allows for precise error analysis and therefore a more efficient construction of the design.

3. ***Design for Modularity***

   The design can be easily changed by using multiple modules that have the ability to be interchanged or adjusted rather than having a homogenous design. This provides the ability to adjust when verification proves that a component that was initially considered is no longer an option.

4. ***Design for Safety***

   As part of the constraints of this project [A1.1], the device must meet certain safety constraints such as having an emergency stop button, not using pneumatics etc. For the primary stakeholders, this design element ensures that the students and staff that will be working around this device will be safe and a controlled environment can be maintained in the workshops and Light Fabrication Facility.

5. ***Design for Low Cost***

   When considering a possible design, it is necessary to account for the various costs involved in the subcategories of the design: x,y, and z movements, detection of the porthole, gripping charger mechanism, and the integration of said components. For the benefit of the primary and as constrained by secondary stakeholders, cost-efficiency will be highly considered in the proposed design.

From these concepts, specific objectives were developed that incorporate our highlighted DfXs. These objectives were divided into a set of high-level objectives, which are prioritized through the design process, and low-level objectives which we will test against directly using our outlined metrics.

High Level Objectives (HL#)

HL1: The robot should be able to autonomously approach, and plug into the charging port at the known charge port location. *(Baseline Setting)*

HL2: The robot should be able to align a 3D printed charger with its corresponding alignment tab slot on the port *(Additional Setting A1)*

HL3: Robot should plug in a J1772 Charger Plug with a spring-loaded clip. *(Additional Setting A2)*

HL4: The robot should stay plugged into the charging port for at least five (≥5) seconds and then the robot should press the release mechanism on the charger to retract the plug. *(Additional Setting B)*

HL5: The robot should be able to autonomously find, approach, and plug into the charging port at a random position in X-axis between (0,1) m, Y-axis, (0,0.5) m, and Z-axis (0.37, 0.60) m. *(Additional Setting C.1, C.2, C.3)*

Note: We found yaw was the most challenging setting when determining software, electrical, and mechanical systems and organization. Therefore, we have decided to remove it from our list of objectives.

Low Level Objectives (LL#)

Objective 1: The **reliability** of the design and having the ability to perform repeated tasks [2].

LL1: The solution can perform its task without failure in its constraints over time.

Metric 1: The component's performance in its given task with over 20 trials.

Criteria: A higher number of repeatable performances is preferred.

Metric 2 (Electrical Specific): Time (min) battery powers the system until the system no longer powered (assume all components powered with max current draw → time = capacity/current draw).

Criteria: A longer run time is preferred and a rechargeable battery is highly preferred.

Constraint: Cannot last for a time shorter than milestone run time (10 min).

Metric 3 (Mechanical Specific): The amount of support the design can provide for loads. (Force or Torque Calculated/Measured vs. Torque Provided by motor or supporting Force in Nm or N)

Criteria: A greater difference between force or torque that must be supported by component and the maximum of force or torque the system can provide is preferred.

Constraint: Must support the estimated load.

Objective 2: Ease of physical **testing and diagnostic**.

LL2: The solution reduces the difficulty of physical testing of the particular functionality [3].

Metric 1: Time that is taken to edit/assemble/acquire all components required to test out the particular system.

Criteria: Less time is preferred.

Metric 2: Number of components the system relies on in order to get a proper testing protocol of the component(s) in the system with most potential for error.

Criteria: Fewer components are preferred.

Metric 3: Cost of components that will be tested and those involved in testing.

Criteria: Lower cost is preferred.

Metric 4 (Electrical specific): Steps to access points for testing voltage by multimeter

Criteria: Less steps required to access these points is preferred

Objective 3: The ease of making **changes** in the system's design [4].

LL3: Each main component in the solution is easily removable and be tested separately from the whole robot.

Metric 1: The number of modules involved in the system. Note: these modules are divided into a working sub-system.

Criteria: More sub-systems are preferred.

Metric 2: Number of specialty components for function of individual device.

Criteria: Fewer speciality components is preferred

Objective 4: Ensure **safety** of stakeholders throughout the design process [5].

LL4: When performing its given tasks, the robot can be safely shut off in case of an emergency.

Metric 1: Evaluate the risk mitigation of components that have the potential to harm stakeholders.

Constraint: Component(s) must have a mechanism to shut off.

Metric 2: Success rate of an Emergency stop.

Criteria: Rates closer to 100% are preferred.

LL5: When working with components of the robot in the building process, the primary stakeholders are not at risk of safety concerns.

Metric 1: Number of sharp edges in the mechanical design (i.e. chamfer, rounding/sanding)

Criteria: Fewer sharp edges are preferred.

Metric 2 (Electrical specific): Proper grounding and encasing of device to prevent shorting

Criteria: The more electrical safety measures put in place, the better

Metric 3 (Electrical specific): Holding torque of the alternative motor (Note: function in design of motor must be considered)

Criteria: Higher holding torque implies loads won't be dropped during performance

Objective 5: Reduce the **cost** of final design.

LL6: Reduce the cost of implemented mechanisms in the final design.

Metric 1: Estimated cost of total components cost (CAD).

Criteria: Lower cost is preferred.

Constraint: Final robot cost must not exceed three-hundred and ten (≥$330) dollars.

REFERENCE DESIGNS

When first thinking about methods of responding to the design opportunity, our team individually researched reference designs to get ideas of how individuals have developed robots with similar functionalities. In this stage, the reference designs were categorized based on the different functionalities required of our robot (Appendix 2). Examples of some reference designs are shown in Figures 1 and 2.

Figure 1: Movement in x,y, and z axis: Stationary Arm

DIVERGING & CONVERGING PROCESS

The diverging and converging process was split into different phases so that we could clearly see the progression of our designs.

Phase 0: General Brainstorming - Research and Reference Designs
Phase 1: Alternative Ideation Diverging and Converging by Ranking
Phase 2: Main 3 Alternative Component Testing/ Verifying
Phase 3: Final Design Converging via Ratings Matrix to Pugh Chart
Phase 4: Starting Each Subsection (Electrical, Software, Mechanical)

Phase 0 is outlined in the previous section with the addition of individual research. This step provided us with information about what systems have been successfully implemented in the past and inspiration for elements that could be included in our own design.

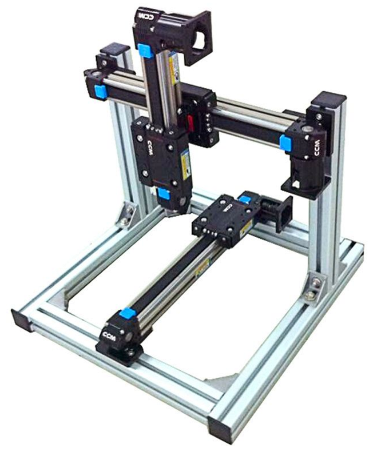
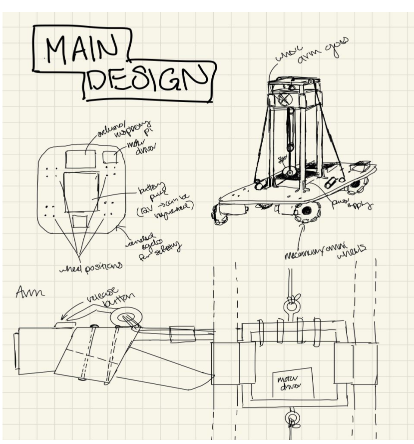
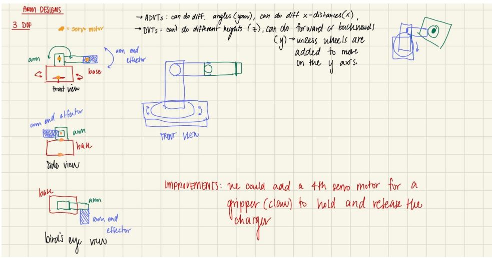
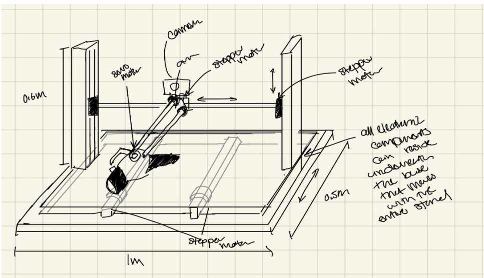


Figure 2: Moving in the x and y Printer Design

In **Phase 1.0**, we individually researched and took components from reference designs to each produce 3 different designs. A table of those generated component alternatives can be found in Appendix 2. This step provided us with a diverse range of conceptual designs to begin fine-tuning ideas into a more detailed and fully developed design. These designs are shown in Table 1.

THE THREE ALTERNATIVES - Table 1 **-** Three Alternative Designs Considered

Diagram	Mobility	Location	Manipulation of End Effector
 Note: *"Main" Design: Our team was biased towards most components in this design.*	X, Y Axis: Rover base using omni or mecanum wheels to move in the x, and y axis. Z Axis: A linear system through a pulley system or a lead screw system.	Using a camera (Pixy2 or opencv and raspberry pi). Precision through object detection and recognition.	Mechanically tightened fitted holder.

	X, Y Axis: Rover base using omni or mecanum wheels to move in the x, and y axis. Z Axis: smaller 3D arm - 3DOF made from 3D print.	Using a camera (Pixy2 or opencv and raspberry pi). Precision through object detection and recognition.	Claw end effector.
	X,Y, and Z axis: Three axis body to move in the x, y and z directions.	Using a camera (Pixy2 or opencv and raspberry pi). Precision through object detection and recognition.	Mechanically tightened fitted holder.

In **Phase 1.1** we deliberated about each of the components of the design from the alternatives that were produced in **Phase 1.0** (Appendix 2) by comparing them against our design objectives in a rating matrix.

In **Phase 2.0**, the ratings of these modularized alternatives were produced through physical testing of prototypes or through research. The tests were divided into the three subsystems: electrical, mechanical, and software, and each had their own tests corresponding to our prioritized Low-Level Objectives. The ratings matrices of each sub-system can be found in Appendix 3.

A NOTE ON MODULARITY

We discussed as a team the best way to approach the development of our final design and found it was easiest to break down a design into subsystems. It was found that breaking the design down into components (ie. motors, methods of actuation, approaches to computer vision) was a much more effective way to test a design rather than testing the design as a whole. This prevented huge amounts of time from being sunk into developing a working prototype for three alternatives and buying many more components than needed.

This approach also allowed us to be flexible and modularize our design so that components that we were initially considering could be swapped for different ones and our design could progressively improve.

VERIFICATION, TESTING, AND PROTOTYPING

Software Design Testing Conclusions (Appendix 3 [A3.1] & Appendix 4 [A4.1])

The software testing focused on the feasibility of the design concepts and the accuracy they could provide. The main concern with software is time and feasibility as the risk of time debugging and inaccuracy could severely delay the production of the solution. The different components were tests with the possibility of combining different methods of location together to maximize accuracy and minimize cost.

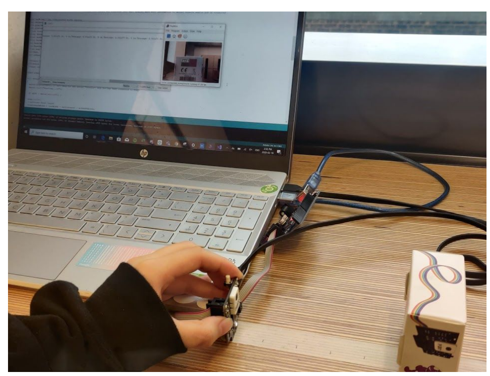


Figure 3: Testing distance detection using the Pixy2

As a result of these tests, some conclusions were reached about the feasibility and accuracy of the design concept which is described in more detail in the appendix but is summarized below:

- Base Mobility: the code from Workshop 1 can be calibrated to move in SI units and yields accurate movements. The Arduino movement code can be paired with feedback from sensors and cameras to move according to received data.
- Location: using the Pixy2 for color object detection is accurate however, additional math must be done to identify the actual location of the charging port. This may be tricky in which the RaspberryPi and OpenCV would be a good yet time-consuming backup.

Yaw: the IR sensors were not very accurate at finding the Yaw however, with more experience with Pixy2 and OpenCV, the yaw may be found using computer vision methods.

Electrical Design Testing Conclusions (Appendix 3 [A3.2] and Appendix 4 [A4.2])

The testing process consisted of using the component datasheets and descriptions for much of the testing (Appendix 5). These sheets provide much of the necessary information and prevent having to buy all the components we wanted to consider.

For testing, accuracy of the motors was determined using different rigs outlined in Figures 6,7,8.

For prototyping, circuit diagrams were drawn to determine the number of pins needed for the drive circuit, the layout of the components on the base, the location of the emergency stop, and the voltage required for the battery. Figure 7 depicts a preliminary draft that was used for the working prototype shown in Figure 7.

Figure 4: DC motor testing rig - motors were run with control to move this distance and accuracy was recorded.

This testing allowed certain conclusions to be made:

- Motors: DC motors are accurate when implemented with control code and encoders. Lead Screws are a very accurate method of actuating in the z direction but are limited by accurate and high torque motor (note the casun stepper vs. nema 17 stepper in Appendix 3[2]). Servos work best in limited motion applications and micro servos are very limited due to low torque.
- Battery: Batteries quickly get expensive as their capacity and voltage increases. To minimize cost, use the minimum voltage and rechargeable options.
- Mircocontroller: Electrically, microcontrollers have similar requirements so the software needs are more likely to determine which option is better

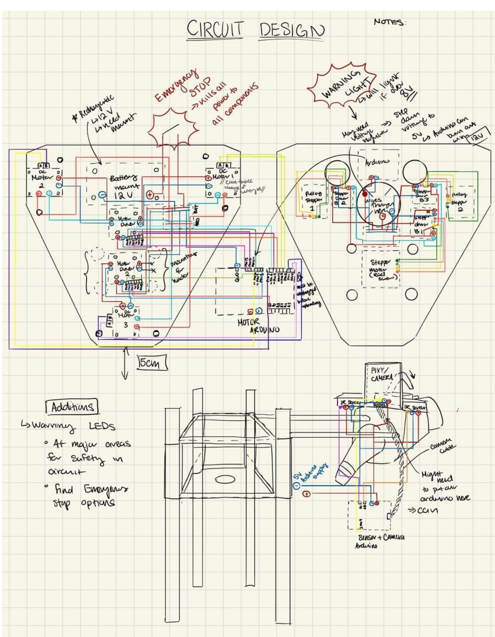


Figure 7: Preliminary Circuit Diagram

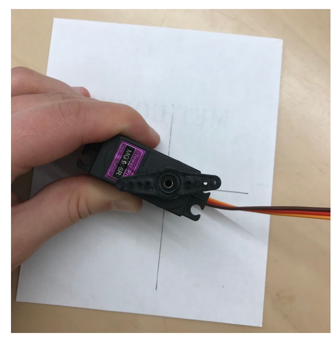


Figure 5: Servo Motor testing rig - motor was run between between 0 and 90° and accuracy recorded

Figure 6: Each stepper was run for 10 cm and accuracy was recorded.

Mechanical Design Testing Conclusions (Appendix 3 [A3.2])

While the focus of physical prototyping was testing modules (i.e. Figure 5,6) of the main alternatives, some full body systems were constructed (i.e. Figure 3) for the purpose of visualization (observe how the system could work) and get an idea of the feasibility of the design.

Figure 8: "Main" Design with a Lead Screw for z-axis movement and linear wheels for x,y movement.

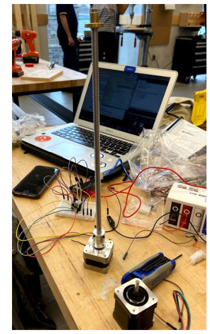


Figure 9: Lead Screw and Stepper motor movement testing.

Force calculations were produced to analyze the cantilever structure of designs in the z-axis, and to verify potential mobility restrictions of rover base designs with motors tested [Appendix A1.3]

As a result of these tests, some major decisions were concluded about certain component alternatives. The justification can be seen through the Ratings Matrix in Appendix 3, but a more detailed explanation is provided:

- The extent to which 3D printed components have flaws is large due to the precise geometry of components like an omni-wheel. Thus, large-scale manufactured wheels are a better investment, despite the added costs.
- For the sake of feasibility in terms of cost and time, not every rating was produced through a physical prototype if for example, another prioritized objective had already eliminated or largely demoted the ranking of a component, thus becoming unreasonable to waste resources testing said component. If this is the case then the rating was extracted from reference designs thus may not be in the same units as provided inquired by the original metric, however, it still provides valuable information about the theoretical performance of the component.

Figure 10: 3D printed Omni-wheel prototype.

FINAL CONVERGING

We took our ratings matrices in Appendix 3 and compiled it into this modularized Pugh chart that highlights all elements of the designs. Each of the options breaks down our previously stated three alternatives so that a better design can be produced from all of the considered elements. The result is that the design is very similar to our main design. Most elements directly align with the results from the pugh chart except for the mobility module for which the motors have been decided to be DC. This is because we are more comfortable with their function and have components to work with them already. Casun steppers will be used as a back up.

Chosen component   Backup component   *Table 2 - Final Convergence Pugh Chart*

Objective	A - Arduino RP - Raspberry Pi	**Objective 1: Cost**	**Objective 2: Testing and Diagnostic**	**Objective 3: Modularity**	**Objective 4: Reliability**	**Objective 5: Safety**
Location	**Pixy 2 Camera (A)**					
	Colour/Distance Detection	S	S	S	S	S
	2 IR sensors					

	(RP / A)					
	Yaw and distance	+	+	S	--	S
	OpenCV (RP)					
	Shape detection	S	-	-	-	S
Mobility **Note:** **Motors** here should be considered without holding torque and servo is removed because it cannot fully rotate. Also, comfort with components was considered. **Base type:** certain wheel types determine the type of base that can be used.	**Motors**					
	Casun Stepper	**S**	**S**	**S**	**S**	**N/A**
	Nema 17 Stepper	**--**	**S**	**S**	+	**N/A**
	TT motors DC	**-**	**S**	**-**	**-**	**N/A**
	3D axis	**-**	+	**-**	**S**	**S**
	Wheels					
	Linear					S
	Mecanum	S	S	S	S	S
	Omni	-	+	S	S	S
	3D printed Omni	+	+	S	--	S
	Bases					
	Triangle (omni)	S	S	S	S	S
	Square (Mecanum)	-	S	S	S	S
	H-shaped(Omni)	S	S	S	-	S
	Battery					
	NiMH (RobotShop)	S	S	S	S	S
	NiMH (Turnigy)	+	S	S	+	S
	Lithium Ion (4800 mAh)	-	-	-	+	+
	Lithium Ion (1800 mAh)	-	-	-	-	+
	Lithium Polymer	-	S	S	-	-

	Lead Acid	-	+	-	-	-
	Materials					
	Birch Plywood	S	S	S	S	S
	Acrylic	-	S	S	S	S
End Effector: **Note:** Cantilever Force of component also considered here as additional metric **[A1.3]**	**Motors**					
	Casun Stepper(200 g)	S	S	S	S	S
	Nema17 Stepper (300 g)	-	S	S	+	+
	Tower Pro Servo (55 g)	+	+	+	-	+
	Z axis methods					
	Lead screw	S	S	S	S	S
	Pulley System	-	-	-	S	S
	3 axis rail system	--	-	-	+	S
	Gripper					
	Molded Fit	S	S	S	S	S
	Claw Fit	+	-	S	-	S

FINAL DESIGN
Location:

The *Pixy 2 Camera* will be used with an *Arduino Uno*. To locate the port, coloured tape will be placed on either side of the port. The *colour detection* function of the Pixy with a *distance triangulation* method to determine the coordinates of the port in the Pixy's field of vision.

This allows for modularization of the design because the Pixy 2 is a compact component that doesn't require additional connections or devices.

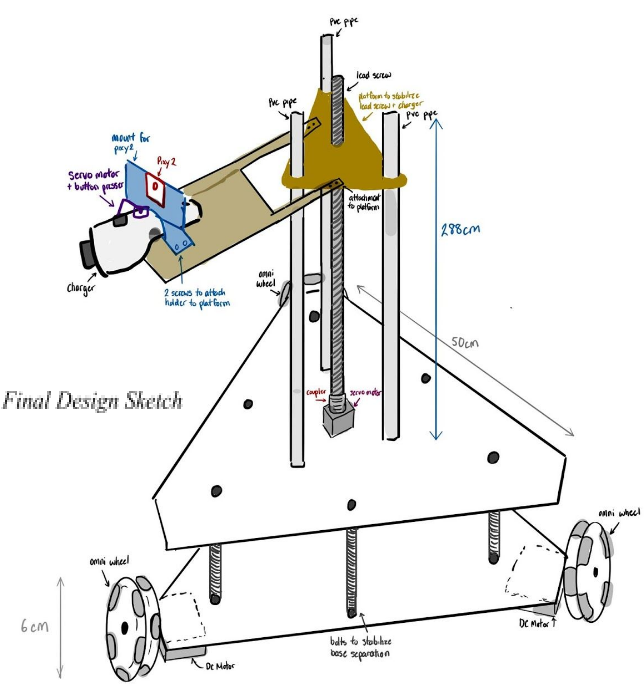


Figure 11: Final Design Sketch

Mobility:

Movement in in X-Y direction will be achieved using *3 6V TT motors DC motors* on a *rounded triangular* base of *birch plywood* with *omni wheels* mounted at each of the vertices. To power these motors, a *Turnigy 7.2 V, 3000 mAh battery pack* will be used. An additional Arduino will be used for the control of the DC motors.

The use of rounded edges and a battery pack with Tamiya connector achieves safety in the design by preventing sharp corners and implementing safety precautions for electrical devices.

Manipulation of End Effector:

Movement in the Z direction will be achieved with a **lead screw and guide rails** that will be propelled by a **Nema 17 stepper motor.** The charger will be held by a **molded gripper** that is attached to a platform on the lead screw. To press the spring loaded clip release of the charger, a **Tower Pro servo** will be used.

The lead screw is both the least costly and most reliable option among the z axis actuation components. The Nema 17 also provides the accuracy that is required to move the platform carrying the charger with precise movements and deliver the end effector.

Operation:

The operation of the final design can be broken down into 7 phases:

- **Start cue is given**
- **Location Phase:** The Pixy camera in conjunction the object tracking code and distance code for IR sensors. This determines coordinates for motion.
- **Motion I Phase:** Base DC motors are powered and drive code moves according to coordinates. Note: Feedback ensures location is updated so rover doesn't go off track
- **Motion II Phase:** Once rover has reached a point where it is directly in front of port and 20 cm away, actuation in z direction beings. Stepper motor is powered and platform moves up/down guide rails.
- **Motion III Phase:** Once charger is centred with port, identified by Pixy and IR sensors, base DC motors are powered and the rover moves linearly forward towards the port.
- **Charger enters port:** Actuation moves charger into the port and spring loaded clip locks. Timer goes for 5 seconds and then Tower Pro servo rotates

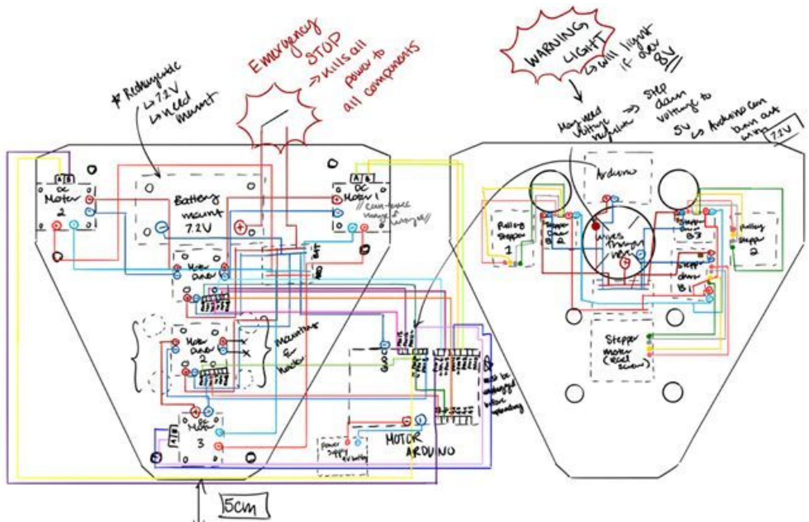


Figure 12: Final Design Circuit Diagram

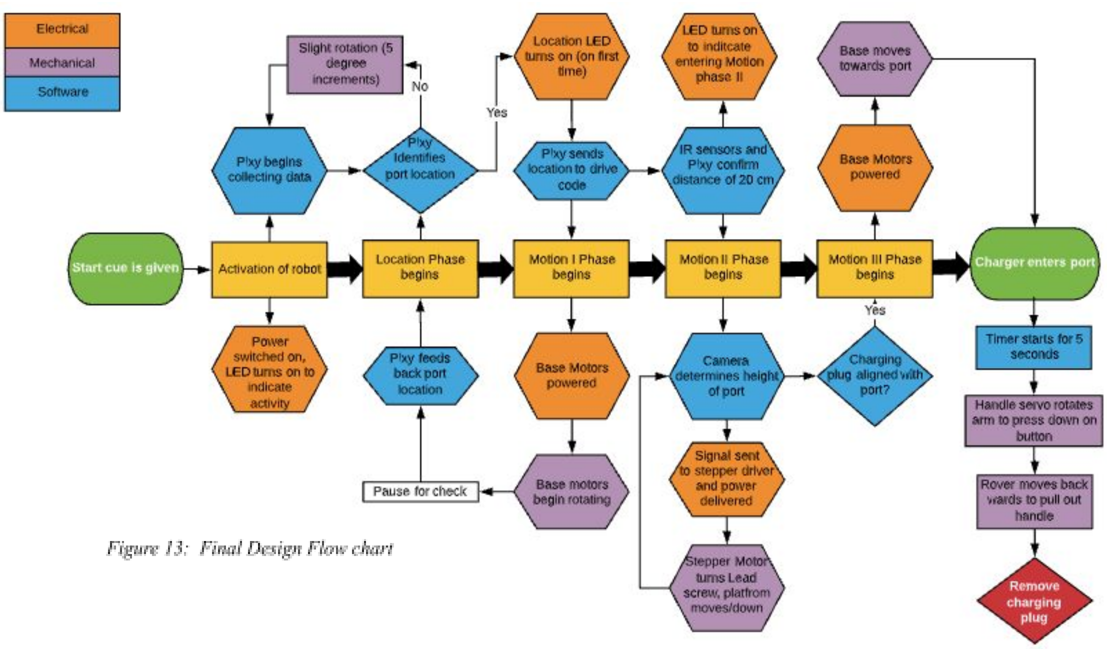


Figure 13: Final Design Flow chart

to press release button. Rover moves backwards to release.

Mechanical

More detailed explanations of why certain components were chosen are highlighted below:

Base: While all 3 geometries and wheel configurations were similar in terms of feasibility and performance, our cost-efficiency metric was prioritized and the triangular design with a three-wheel configuration was chosen as this would allow us to cut costs on the price of wheels and still perform well. Two triangular platforms will provide support for the robot's system and space for the electrical components to rest; the space between the two platforms is to not only allocate space but also to suspend the rover high enough for us to minimize the displacement of the charger in the y-axis.

Z-axis: Due to the complexity of the design, in addition to the difficult modularization of the components for testing, the pulley system design was demoted in favor of the lead screw system which provided a high load lifting torque, and performed well, while maintaining a simple design. According to our calculations (Appendix A1.3), the stepper motor should provide sufficient torque for the estimated payload but if we find that it might too unstable,

X-Y Axis: Omni-wheels/Mecanum wheels were chosen for the design as they provided a cost-benefit solution with low-error potential. 3D printed omni wheels were produced to test the maneuverability of the design and to see if a 3D printed option would be an appropriate alternative for the design. While their functionality as wheels performed adequately, the quality of performance was limited by the printing flaws. Thus, we concluded, multidirectional wheels are a good investment, we should invest in higher quality manufacturing.

End-Effector: To minimize the complexity of the design the end effector was modularized into 2 parts, one that holds the charger and one that releases the charger attachment mechanism. The micro servo motor could not provide enough torque to push the releasing button so the Tower Pro Servo Motor was chosen for this mechanism.

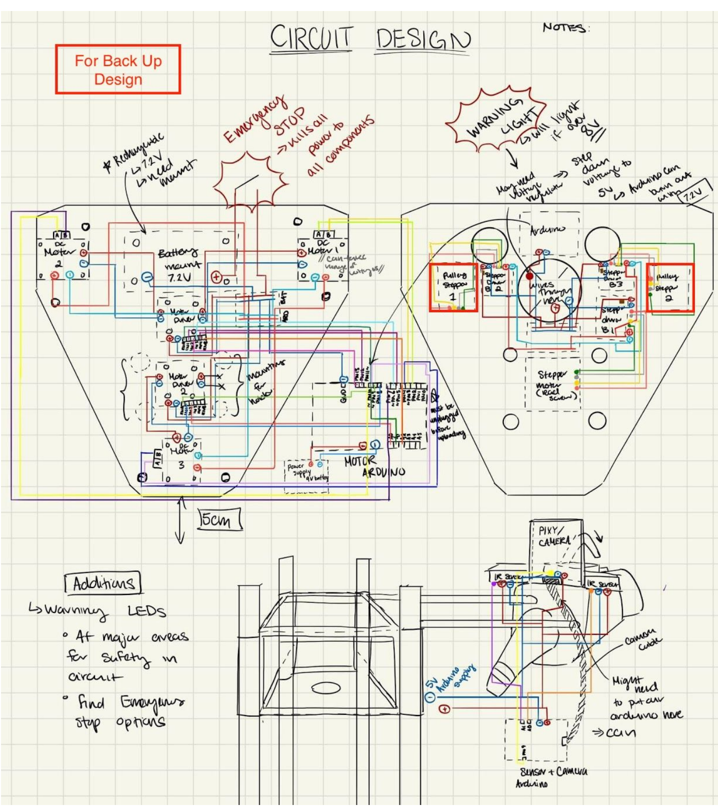


Figure 14: Preliminary Circuit Diagram

Electrical

The electrical system consists of all components being powered or are part of an electrical circuit in the design:

- 3 6V DC Motors
- 1 Nema 17 Stepper Motor
- 1 A4988 Stepper Motor Driver
- 2 L298N Motor Drivers
- 2 Arduino UNOs: These separate motor and sensor control and help modularize the system and improve testability.
- 2 Protoboards (which replace the breadboards in this diagram): These allow components to be soldered for reliability of the system
- 1 Turnigy 7.2 V NiMH Rechargeable Battery: This source improves the safety of the system by using

a detachable Tamiya connector and power harness to ensure power is constantly controlled.

- 1 9V Battery to power the sensor Arduino
- 1 HC06 Bluetooth module to communicate between Arduinos: No wired connection allows for improved modularity and reliability as wires don't become disconnected (note: if the bluetooth becomes unreliable, a wired connection will be used.

The camera and servo will be powered separately from the sensor specific Arduino using a 9V battery and battery clip to mount it.

The DC motors and Nema 17 stepper motor will be powered by the 7.2 V power supply. The arduino can safely regulate up to 12 V so there is no need to step down the voltage for the *motor specific arduino*. An *emergency stop* will be implemented directly after the main power supply using a Tamiya connection power harness. LEDs will be used throughout the system to demonstrate when different components are powered or if an issue has occurred.

Software

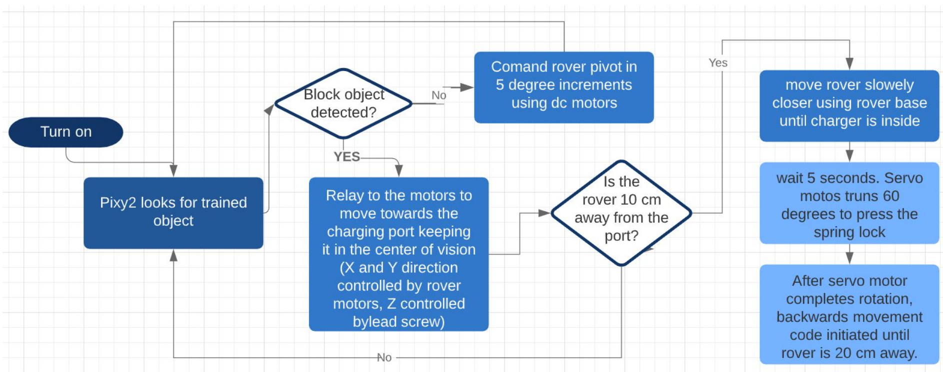


Figure 15: Software Flowchart

Step 1: Turn on the system. No movement in this step. Pixy2 will look for the trained tape objects on the four sides of the charger, constantly sending its findings to the Arduino. If detected, the Block class will appear in the feedback to the arduino.

If found, the Arduino code will attempt to center the tape in the middle of the Pixy2's view by rotating the base and move the lead screw to move the camera up or down. The Block class has properties such as height and width of the object and its X and Y position in its view. Using this information, the objects can be centered accordingly.

If a trained object is not found, the rover will turn in 5 degree increments and rise and lower it's Z direction until the target object is detected.

Step 2: Move towards the port in 5cm increments. After each 5cm increment, the rover will adjust its position according to the Pixy's feedback on the location of the port. Using a distance code that was formulated using a triangulation method, the distance from the charger will be found. And the rover must repeat Step 2 until it is 10 cm close to the port.

Step 3: Once the charger is close enough to the port, the exact location of the charging hole will be determined using the distances between the tape on all sides. Using this knowledge and the exact distance between the Pixy camera and the center of the charger, the rover will align the charger to the port.

Step 4: The rover will go directly forward and a 5 seconds timer will go off once the charger has been inserted. After the 5 second delay has passed, the Arduino will trigger the servo motor on top of the charger to turn 50 degrees so that the extrusion on the servo motor can press the spring loaded clip. The motors will then be made to move the rover directly backwards by 20 cm and the servo motor returns back to its original position.

COST ANALYSIS

Final Design Budget Outline

	Item	Part of Design	Price	Number of Units	Link
Mechanical Design	Triangular Birch Plywood Base Chassis 24"x18"	Everything	2.06	2	https://bit.ly/2SQ0Ima
	Omni Wheels or	X,Y axis	18	3	https://bit.ly/2vcdClj
	Mecanum Wheels (4)	X,Y axis	36.99	1	https://amzn.to/37WDPBD
	Lead Screw	Z axis	4.27	1	https://bit.ly/2HNtkWP
	Coupler	Z axis	1.43	1	https://bit.ly/2HNtkWP
	Molded Fit	Manipulation	6	1	https://bit.ly/2HNtkWP
	PVC pipe 12"	Z axis	0.97	3	https://bit.ly/2HNtkWP
Electrical Components	Pixy2 Camera	Locating Port Hole	80.05	1	https://bit.ly/32I5v1X
	TT DC Motors	X,Y axis	13.59	3	https://bit.ly/2HNtkWP
	7.2 V NiMH Rechargeable (Turnigy)	Everything	25.5	1	https://bit.ly/2HNtkWP
	Tower Pro MG996R	Release Clasp on Charger	4.8	1	https://bit.ly/2HNtkWP
	Arduino	Release Clasp on Charger	5.49	1	https://bit.ly/2HNtkWP
	Motor Stepper Driver A4988	Z axis	1.83	1	https://bit.ly/2HNtkWP
	Dual Motor Driver L298N	Z axis	2.62	2	https://bit.ly/2HNtkWP
	Stepper Nema 17, 1.7A	Z axis	13.93	1	https://bit.ly/2HNtkWP
	9V Battery	X,Y axis	1	4	https://bit.ly/2HNtkWP
	ProtoBoard	Everything	1.04	3	https://bit.ly/2HNtkWP
	LED	Everything	0.01	5	https://bit.ly/2HNtkWP
	Bluetooth HC06	Everything	5.93	1	https://bit.ly/2HNtkWP
			Total Sum	263.44	With Omniwheels
				246.43	With Mecanum wheels

Alternative Component Costs

Backup Options					
	Item	Part of Design	Price	Number of Units	Link
Mechanical Design	Square Birch Plywood Base Chassis 24"x18"	Locating Port Hole	2.06	2	https://bit.ly/2SQ0Ima
	Pulleys (Pulley System)	Z axis	2.77	2	https://amzn.to/32pmYX5
	Rope (Pulley System)	Z axis	6.52	1	Home Hardware
Electrical	Raspberry Pi Cam	Locating Port Hole	39	1	https://bit.ly/3c4t7wc
	Raspberry Pi	Locating Port Hole	80	1	https://amzn.to/2HLhaxP
	Casun Stepper	Locating Port Hole	7.53	1	https://amzn.to/38T3D2R
	NiMH Battery (RobotShop)	X,Y axis	35.8	1	https://bit.ly/32kG7cl

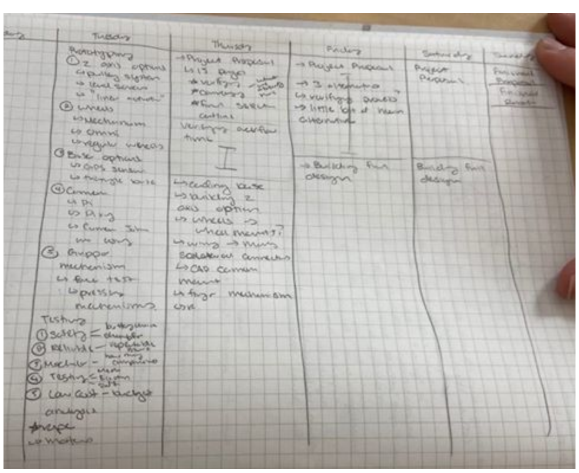


Figure 16: Main 3 Alternative Component Testing/Verifying Timeline

TIMELINE AND PROJECT MANAGEMENT

At the end of Week 6, our team planned for the testing phase of our design: Main 3 Alternative Component Testing/Verifying. This plan can be seen in Figure 16.

Essentially, testing and mechanical building was prioritized this week (Week 7), with the hope of building our final prototype on Friday-Sunday. Due to time constraints and building hiccups (i.e. parts taking too long to arrive), building the final prototype was not possible. Other than that, the timeline was followed strictly and most tests were conducted or verified through research. Our *next steps* for our project for each of subsystem are outlined below:

Mechanical

- CADing and laser cutting a less modularized chassis design which will include proper mounts, accurate screw holes and allocated space for electrical components.
- Constructing base, assembling wheels, integrating z-axis leadscrew, and building arm end-effector platform and gripper.

Electrical

- Solder protoboard together for Nema 17 stepper motor, HC06 Bluetooth module, and powerlines for all components
- Purchase and implement LEDs and resistors into protoboards as well
- Integrate motors and camera along with calibration

Software

- Integrating feedback and action loops for following an object to a certain length using the Pixy2 and the rover base
- Integrating Z direction movement to accurately locate the port using the lead screw as well as the X and Y direction movements from the rover base using the feedback from the Pixy
- Calibrating the distance between the Pixy and the tip of the charger and the discrepancy in Z height so that the rover can put the charger in the port and not the Pixy camera.
- Create backup raspberryPI and OpenCV code for circle detection in case Pixy fails.

Based on these next steps and guided by the upcoming Milestones, our timeline for the next 2 weeks is shown below Figure 18. We set discrete tasks on Trello for our team to accomplish (Figure 17), each with a

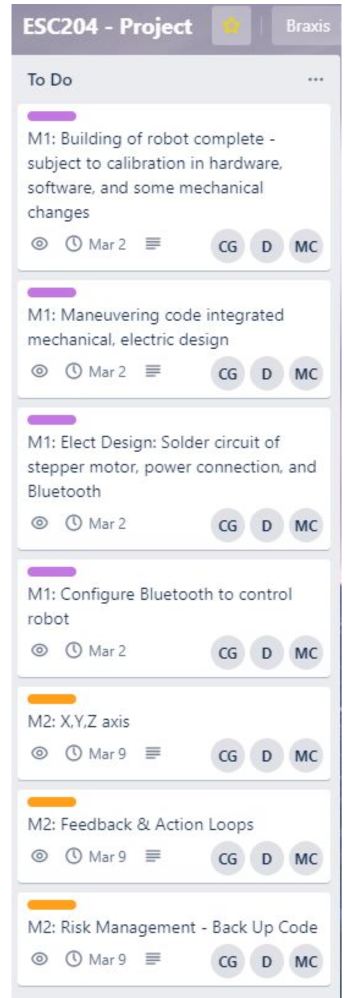
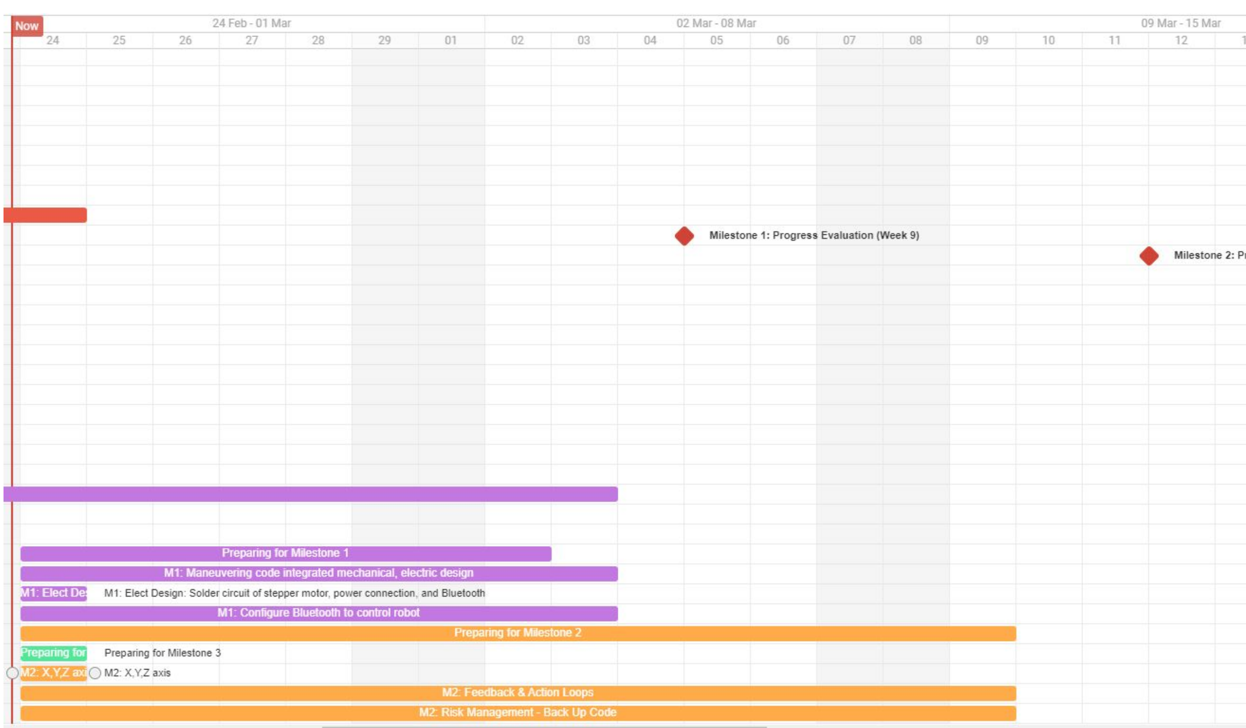


Figure 17: Tasks for the next 2 weeks on Trello.



nilestones.

deadline of 2 days before a milestone to give us a grace period in case of problem.

RISK MANAGEMENT - *Table 3 - Risk Register*

Activity	**Risk**	**Probability (1-5)**	**Impact (1-5)**	**Mitigate of Impact/Probability**
Buying Materials	Going over budget	4	4	Keep track of components as we buy them (Bill of Materials) and explore alternatives when possible **Ex.** Lead Screw replaces functionality of linear actuator and costs fraction of price
Building the final design with selected components	Investing too much time into a component and proper function is not achieved	3	5	Allocate specific amounts of time to work with a component. Develop back up plans for all of the modules in the design. (Refer to Table X highlighted blue back ups). Build reliability of other components.
Buying Materials	Materials for design are delayed in travel	2	5	Work with components are that are more readily available (ie. LFF).
Milestones	Robot does not perform on day of milestone	3	5	Do a post mortem after each milestone to discuss failures in design as soon as possible.

Appendix 1: Source Extracts

[A1.1] C. Liu. (2020). ESC204 Project Guideline. *University of Toronto*.
[A1.2] Ayyub, Bilal. (1998). Reliability-Based Design. *University of Maryland.*

The development of reliability-based design criteria for surface ship structures needs to consider the following three components: (l) loads, (2) structural strength, and (3) methods of reliability Analysis. A methodology for reliability-based design of ship structures is provided in this document. The methodology consists of the following two approaches: (l) direct reliability-based design, and (2) load and resistance factor design (LRFD) rules. According to this methodology, loads can be linearly or nonlinearly treated. Also in assessing structural strength, linear or nonlinear analysis can be used. The reliability assessment and reliability-based design can be performed at several levels of a structural system, such as at the hull-girder, grillage, panel, plate and detail levels. A rational treatment of uncertainty is suggested by considering all its types. Also, failure definitions can have significant effects on the assessed reliability, or resulting reliability-based designs. A method for defining and classifying failures at the system level is provided. The method considers the continuous nature of redundancy in ship structures. A bibliography is provided at the end of this document to facilitate future implementation of the methodology.

[A1.3] Maintainability of Equipment: Testability and Diagnostic. (n.a). Retrieved from https://subscriptions-techstreet-com.myaccess.library.utoronto.ca/products/484711

1. International Standard - Maintainability of Equipment - Part 5: Testability and Diagnostic Testing (IEC 60706-5)
    a. Gives opportunity to test components at every step of the design process
    b. Important for maintenance of a system
    c. Can consist of functional testing with the purpose of verifying a function can be performed
    d. Condition monitoring to track condition
    e. Replication of operational context in the testing scenario is reasonable
    f. Access using test connectors - don't have to disconnect actual connections
    g. Low cost for creating test software, conditions, hardware, mechanical situations

[A1.4] Erikstad, Stein Ove. (2019). Design for Modularity. *Norwegian University of Science and Technology.* Retrieved from https://www.researchgate.net/publication/329570713_Design_for_Modularity_Volume_1_Optimisation_of_Ship_Design_and_Operation_for_Life_Cycle

1. The division of a larger system into smaller parts or components
2. The principle of (relative) self-sufficiency of the individual parts
3. The recombination of the parts into multiple end products, according to a set of "rules" given by an overall systems architecture

[A1.5] Industrial Robots and Robot Systems - General System Safety Requirements. (n.a.) retrieved from https://subscriptions-techstreet-com.myaccess.library.utoronto.ca/products/235496

Industrial robots and robot systems - General System safety Requirements (CAN/CSA Z434-03)

a. Warnings of any potential hazards that cannot be removed must be included
b. Designed so they are not exposed to external moving components
c. Awareness signal must be generated in case of failure to perform a certain task
d. Power loss/change - these changes will not result in hazard
e. Power supply can be isolated
f. Provides controlled release of energy
g. Should be designed so axes can move without drive power
h. Avoid inadvertent operation - controls positioned as such
i. Robot can be controlled from a remote location
j. Emergency stop - override all other robot controls (as specified in constraints)
    i. Either immediate stopping of all power
    ii. Or controlled stop and then power in released
k. Etc. explained in document in full

[A1.6] S.-L. (S. Wang, "Motion Control and the Skidding of MecanumWheel Vehicles," *IJISET - International Journal of Innovative Science, Engineering & Technology*, vol. 5, no. 5, May 2018.

IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 5 Issue 5, May 2018
ISSN (Online) 2348 – 7968
www.ijiset.com

Motion Control and the Skidding of Mecanum-Wheel Vehicles

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Abstract

A Mecanum-wheel vehicle can move in any direction and re-orient on the spot. The wheel consists of many passive rollers at its rim oriented at an angle of 45° to the wheel circumference. The omni-directional vehicle was invented in 1970s but has limited commercial applications. In recent years, hobbyists and students in robotics competitions have intensified interests in Mecanum-wheel vehicles, fueled in part by reasonably priced Mecanum wheels from on-line venders In this paper, the motion control of this vehicle is introduced from the resolved force control. The tractive force at each wheel will determine the resultant tractive force that propel the vehicle to any direction. The tractive forces at the wheels can also account for the vehicle's tendency in slippage as the lateral component of the wheel tractive force will generate a tipping moment in the vehicle's roll direction. In the most prevalent movements (forward and backward travels and turning on the spot), the wheel's tipping moments will be balanced at the chassis, and there is no adverse effect. In a sideway motion, the tipping moment will bend the chassis, and the vehicle will experience slip and vibration. With the cause of the slipping identified, the chassis should be stiffened to minimize the slippage caused by the chassis bending. This insight should be helpful to hobbyist and students in robotics competition.

Keywords: *Mecanum-wheel, omni-directional vehicle, motion control, sliding.*

1. Introduction

An omni-directional vehicle can move in any direction and can re-orient to any directions at the same location. Ilon [1] first designed a Mecanum-wheel in 1975 for an omni-directional vehicle with orbiting rollers as shown in Figure 1. Each roller is keg-shaped with its axle obliquely angled about the periphery of the hub. The omni-directional motion of the vehicle is achieved as the vector summation of propelling (tractive) forces on the ground-engaging rollers can be in any direction by adjusting the wheel rotation direction and torque magnitude of the four wheels. part by reasonably priced Mecanum wheels from on-line venders [3, 4, 5].

In this paper, the geometry of Mecanum wheels and rollers are first introduced. The motion control of this vehicle will be derived from the resolved force control. The tractive force at each wheel will determine the resultant tractive force that propel the vehicle to any direction. Using the principle of virtual work, the force control can be used to formulate the motion control.

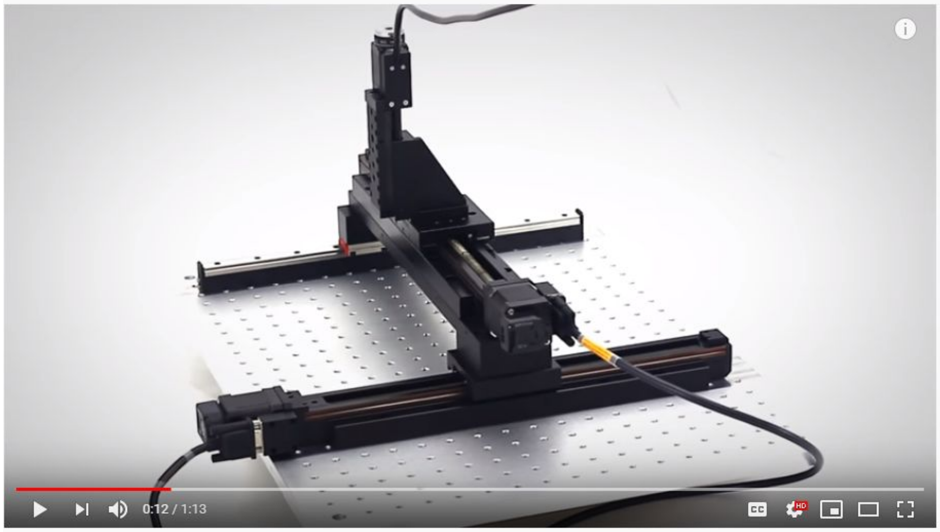
Mecanum-wheel vehicles have a tendency of slippage, and the slippage was attributed by researchers to friction between the roller and the road. However, the friction alone cannot explain why the forward/backward and turning on the spot experience no problems, while slippage in sideways directions are noticeable.

In this paper, the slippage and skidding will be explained with the lateral component of the tractive force at the wheel. The lateral component of the tractive forces will generate a net bending moment to deform the chassis. The bended chassis will cause vibration, slippage, and skidding in all directions except for those prevalent movements. With the cause of slippage identified, corrective measures can be taken.

2. Mecanum wheels

In Figure 1, a Mecanum wheel is shown with seven passive rollers at its rim oriented at an angle of 45° to the wheel circumference in three different views: (a) the front view, (b) the di-metric view, and (c) the side view. As shown in Figure 1a, the peripheral of the rollers are tangent to a cylindrical surface.

[A1.7] *XY Linear Gantry System Z-Axis Stage (3-Axis Precision Positioning)*. Youtube, 2017.

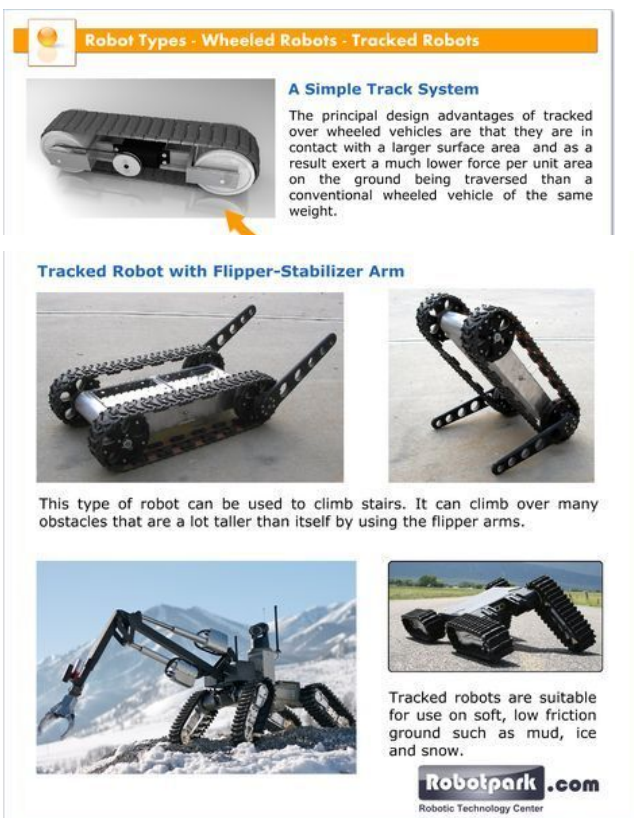


XY Linear Gantry System + Z-Axis Stage (3-Axis Precision Positioning)

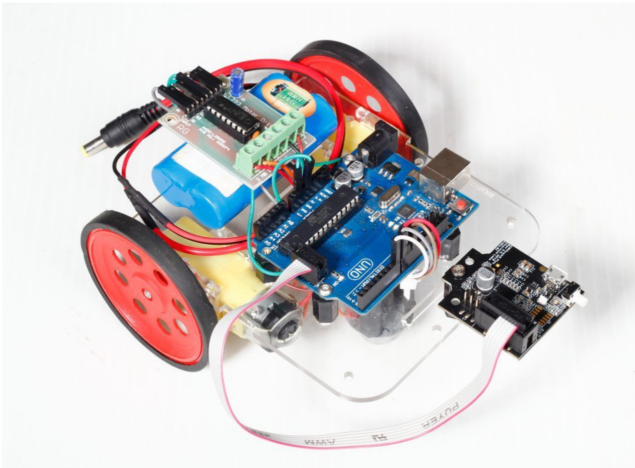
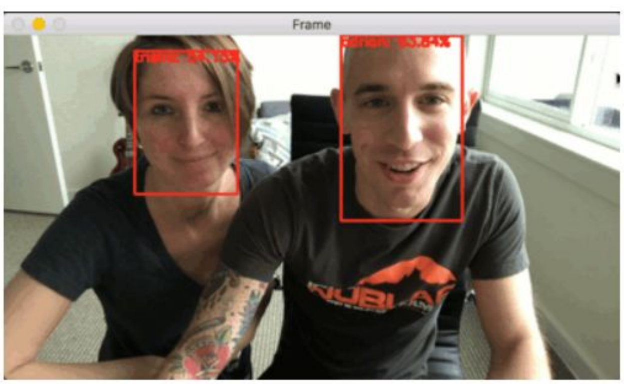
Appendix 2: Reference Design

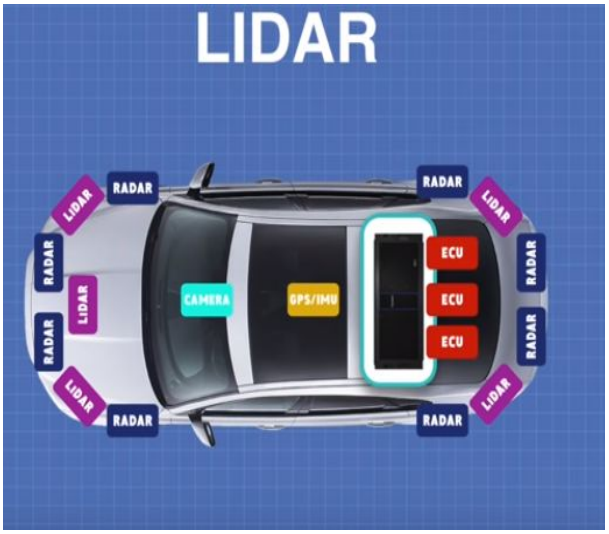
<table>
<tr><td rowspan="3"></td><td colspan="5">Functionality</td></tr>
<tr><td colspan="3">Axis</td><td rowspan="2">Locating Port Hole</td><td rowspan="2">Releasing Locking Mechanism of Charger</td></tr>
<tr><td>X</td><td>Y</td><td>Z</td></tr>
<tr><td>Reference Design</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Robotic Arms


[A2.1] DIY Arduino Robot Arm with Smartphone Control. Youtube, 2018.</td><td>✓</td><td>✓</td><td>✓</td><td></td><td></td></tr>
</table>

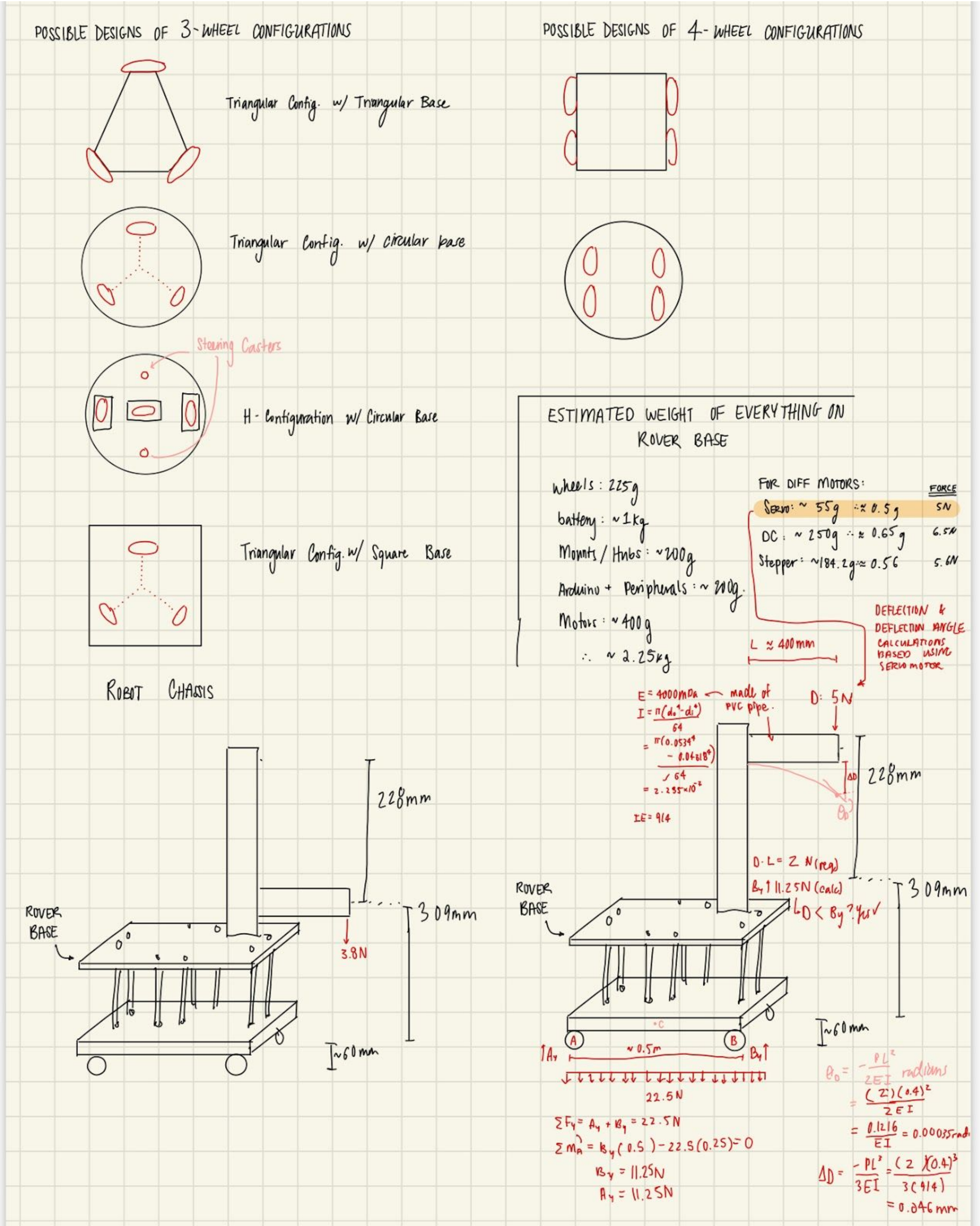
 [A2.2] S. Loveday, “Automatic Rapid Charging Robot Becomes Reality, But Not From Tesla,” *InsideEVs*, 16-Oct-2019. [Online]. Available: https://insideevs.com/news/338969/automatic-rapid-charging-robot-becomes-reality-but-not-from-tesla/. [Accessed: 24-Feb-2020].					
Tracked Wheels  [A2.3] “TRACKED Robots,” *Robotpark ACADEMY*, 2015. [Online]. Available:	✓	✓			

http://www.robotpark.com/academy/all-types-of-robots/wheeled-robots/tracked-robots/. [Accessed: 24-Feb-2020].					
3D Printing Design  [A2.4] “[Hot Item] Belt Driven Actuators 3-Axis Linear Rail for 3D Printer,” *Made-in-China*. [Online]. Available: https://ccmmade.en.made-in-china.com/product/BvJxQAuEWhYm/China-Belt-Driven-Actuators-3-Axis-Linear-Rail-for-3D-Printer.html. [Accessed: 24-Feb-2020].	✓	✓			
Line Follower using Pixy2 Camera				✓	

 [A2.5] Urvi, “Line Follower Robot using Pixy2 and Arduino,” *Robokits Resources*, 30-Nov-2018. [Online]. Available: https://resources.robokits.co.in/line-follower-robot-using-pixy2-arduino/. [Accessed: 24-Feb-2020].					
Colour and Face Recognition using OpenCV  [A2.6] A. Rosebrock, “OpenCV Face Recognition,” *PyImageSearch*, 24-Sep-2018. [Online]. Available: https://www.pyimagesearch.com/2018/09/24/opencv-face-recognition/.				✓	
Lidar				✓	

 [A2.7] *Getting Started with LIDAR*. Youtube, 2018.					

[A1.3] Force Calculations

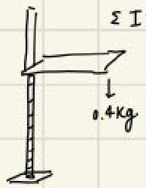


POSSIBLE DESIGNS OF 3-WHEEL CONFIGURATIONS
Triangular Config. w/ Triangular Base
Triangular Config. w/ circular base
Steering Casters
H-Configuration w/ Circular Base
Triangular Config. w/ Square Base
ROBOT CHASSIS
228mm
309mm
ROVER BASE
3.8N
~60mm
POSSIBLE DESIGNS OF 4-WHEEL CONFIGURATIONS
ESTIMATED WEIGHT OF EVERYTHING ON ROVER BASE
wheels: 225g
battery: ~1kg
Mounts / Hubs: ~200g
Arduino + Peripherals: ~200g.
Motors: ~400g
∴ ~2.25kg
FOR DIFF MOTORS:
FORCE
Servo: ~ 55g ∴≈ 0.5g 5N
DC: ~ 250g ∴≈ 0.65g 6.5N
Stepper: ~184.2g ∴≈ 0.56 5.6N
DEFLECTION & DEFLECTION ANGLE CALCULATIONS BASED USING SERVO MOTOR
L ≈ 400mm
E = 4000mPa
made of PVC pipe.
I = π(do⁴ - di⁴)/64
= π(0.0534⁴ - 0.04818⁴)/64
= 2.235×10⁻⁷
IE = 914
D: 5N
ΔD
θD
228mm
D·L = 2 N(req)
By ↑ 11.25N (calc)
D < By? yes ✓
309mm
ROVER BASE
A
B
C
Ay
~0.5m
By
22.5N
~60mm
ΣFy = Ay + By = 22.5N
ΣMA = By(0.5) − 22.5(0.25) = 0
By = 11.25N
Ay = 11.25N
θD = −PL²/2EI radians
= (2)(0.4)²/2EI
= 0.1216/EI = 0.00035rad
ΔD = −PL³/3EI = (2)(0.4)³/3(914)
= 0.046mm

TORQUE CALCULATIONS

CALCULATING LEAD SCREW EFFICIENCY & REQUIRED LIFTING TORQUE

LEAD SCREW:



$\Sigma I = mr^2$

$= (0.4kg)(0.4m)^2$

$= 0.064\ kg \cdot m^2$

$d = 17.8mm$ (of lead screw)

$\mu = 0.14$ (coeff of friction of carbon steel)

$m = 0.4kg$

thread pitch / lead distance $= 2mm$

① Velocity Ratio, VR

$VR = \frac{X_E}{X_L} = \frac{\text{displacement of effort}}{\text{displacement of load.}}$

$= \frac{\pi d \leftarrow (\text{circum.})}{(LD) \leftarrow \text{lead dist.}}$

$= 8.9\pi$

② Efficiency of lead screw, η.

$\eta = \frac{\tan\alpha}{\tan(\alpha+\beta)}$ α: angle of the slope of the thread.

$\alpha = \tan^{-1}\left(\frac{(LD)}{\pi D}\right) = 2.057°$

$\eta = \frac{\tan(2.057°)}{\tan(2.057 + 8°)}$ β: friction angle

$\beta = \tan^{-1}(\mu)$

$= 8°$

$= 0.2025 \Rightarrow 20.25\%$

③ Mechanical Advantage

$MA = VR \cdot \eta$

$= 27.96 \times 0.2025$

$= 5.662$

$MA = \frac{F_L}{F_E} \Rightarrow F_E = \frac{F_L}{MA}$ F_L ← force of load, MA ← mech. Adv.

$F_E = \frac{(0.4)(10)}{5.662} = 7.064N$

$T = F \cdot x$ ← force × distance

$= F_E \cdot R$ ← effective force × radius

$= 7.06 \times 0.0089$

$= 0.062871\ Nm$

$= 62.87mNm <$ Torque of Nema Stepper motor : 260mNm

SOURCE:

https://youtu.be/cdDYhViYO9s

WHEEL TORQUE CALCS

Torque, $\tau = F \cdot r$ [N·m]

$= (\sim 2.65kg)(10m/s^2)(0.03m)$

$= 0.675\ N \cdot m.$

$= 67.5\ N \cdot cm <$ Stall Torque $= 125 N \cdot cm$

↳ How much torque each wheel provides depends on configuration.

Appendix 2: Tools used in Design Process

[A2.1] Table 1 - Phase 1 Alternative Ideation

	Location	Mobility	Manipulation
Alternative 1	Pixy 2 Camera (Computer Vision with built in CV program)	A 2D axis Linear actuator system (3D printer reference design)	Arm (3DOF), gripper for holding plug
Alternative 2	IR sensors	Motorized base/Roomba like rover with tire wheels	Arm (smaller because in conjunction with rover), gripper
Alternative 3	Pixy 2 Camera (computer vision with built in CV program)	Stationary Base	Large Arm - needs to be able to extend from initial zone
Alternative 4	Ultrasonic sensors and IR sensors	Rover base with omni or mecanum wheels	Actuation in the z and y directions using linear actuation with mechanically tightened gripper.
Alternative 5	Computer vision using opencv on raspberry pi with camera module	A 2D axis Linear actuator system (3D printer reference design)	Arm swings out with mechanically tightened with mold
Alternative 6	Use of sensors and camera with computer vision for increased accuracy	Rover base with tire wheels	Actuation in z direction with motorized tightening grip for charging plug

[A2.2]
LOCATING

Rank					
Alternatives → **DfX(↓)**	IR sensors and Ultrasonic sensors	IR camera - raspberry pi	Pixy 2	Computer vision with raspberry pi camera (openCV)	LIDAR
Cost	• Cheaper option per sensor • IR: can be as cheap as $2 • USS: $5	• As cheap as $30 • https://www.adafruit.com/product/1567	• About $80 • https://www.robotshop.com/ca/en/charmed-labs.html	• About same as IR raspberry pi camera • Official Raspberry Pi Camera	• Expensive ○ Cheapest is ~$40 ○ Can be much more depending on accuracy wanted

				• Raspberry Pi Zero (Wireless & Bluetooth) ○ Tut ref	
Ease of Testing and Diagnostics	• Easy to set up testing for sensors with serial monitor • Already done in workshop	• More complex system than sensors	• More complex but can use arduino serial monitor pretty easily	• Would probably be the hardest to test because it has the most complex system required	• Can be difficult to calibrate according to Robotics research student
Modularity	Can work on separately	Must work with both camera and raspberry pi	One system. Must work together	Must work together	Must work together
Reliability	USS fairly accurate → if we want to be extra we may want to research how altitude and humidity affect speed of sound	Does not function well with dark surfaces or in the dark	Very reliable as it comes pre build in with the software - no error on our part	Can be difficult to work with - software can crash	Can experience blurring if moving, can result in results being skewed
Safety	Very safe option - doesn't require high power and very simple to set up (hard to burn)	Very safe for similar reasons to IR camera	Very safe - can be used with arduino or raspberry pi which is low power	Safe	Can be Unsafe but is most likely fine - power is limited to levels that don't damage human

PENETRATION (including gripping)*

Rank		

Alternatives(→) DfX (↓)	Screw-in tightened grip	Claw + Robot Arm
Cost	Probably cheap. Can 3D print and just get a screw thing	Must get mechanical and electrical components
Ease of Testing and Diagnostics	easy	Slightly difficult. Must do all code and test, modify, test, etc
Modularity	Good. can do separate of rest of project	Good. can do separate of rest of project
Reliability	Pretty robust	Wiring can be a little less reliable
Safety	safe	Non manual - can have crushing strength if not properly related

Mobility

Rank →				
Alternatives(→) DfX (↓)	Treads - tank like	Stationary base with arm	2D axis body	Rover - similar to what we have
Cost	Treads are expensive ($104) or (+wheels $250)	Extra weight from the long arm will require more weight to balance the body thus will have more costs + cost of normal arm	Expensive - requires lots of aluminum extrusion ons ($40 ea)	Cheap option - can get for a reasonable price from LFF as well
Ease of Testing and Diagnostics	Hard	hard	easier	easier
Modularity	Has more moving parts which can’t be taken apart easily thus they can get more easily damaged	Can work on arm and base motion separately and join at end??	Must work together	Must work together but less moving parts than base with arm
Reliability	Tracks need higher torque to move on from stationary	Lots of math and can be hard to properly calibrate	Pretty reliable	Accuracy is questionable

Safety	Safe	Safe	May need to be cautious of all the extra weights (if they are hanging)	Very safe - doesn't require much more than simple DC/ stepper motors

Appendix 3: Ratings Matrix for Subsystem.

[A3.1] Software Ratings Matrix for different software components

	Cost (Obj. 5, LL6, metric 1) [Appendix 3]	Testing + diagnostic (Obj.2 LL2, Metric 1 & 2)	Modularity (Obj.3, LL3, Metric 1)	Reliability (obj.1, LL1, Metric 1)	Safety (obj.4, LL4, Metric 2)
Mobility and stopping. Testing for accuracy in moving the rover base	DC motors: $24.24	*Criteria 2:* Medium: can use only the base of the rover to test for how accurate the robot can move a certain distance using a simple code that has been calibrated for the DC motors. *Criteria 1:* Around a day invested in the code	*Criteria 1:* Medium: use only the base to test. This prevents other members from using the base for other tests while changing this component	*Criteria 1:* Good: Can perform the same movements and distance repeatedly. Only discrepancy of <1cm each time when motor speed is not too fast.	*Criteria 1:* Safe: Included emergency stop feature
Yaw with 2 IR sensors and trigonometry	2 IR: $13.14	*Criteria 2:* Easy: only use the Arduino Uno with trigonometry added to pre-existing code from Workshop 3. *Criteria 1:*	*Criteria 1:* Easy: use only Arduino Uno and 2 IR sensors. Can be taken off the rover and tested separately	*Criteria 1:* Poor: (may be incorrectly written/ calibrated code) returns 0 degrees well but gives 45 degrees and 63 degrees if the	*Criteria 1:* Safe: Nothing that can harm humans. (must ensure the wiring is secure)

		3 hours to write the code		angle is slightly changed. Unreliable for small-angle detection but reliable for 0 degree angle detection. This may be useful in junction with other technologies	
Distance of Object (use triangle similarity or barcode or color detection)	Pixy2: $80.05	*Criteria 2:* Medium: only uses the Pixy and an object to tests (separate from the rest of the rover). Must calibrate the object for size (pixy's registered size is not in SI units) and measurements and write new code to incorporate the triangulation math. *Criteria 1:* 5 hours invested in writing and calibrating the code	*Criteria 1:* Easy: Pixy2 can be taken off the rover and tested and calibrated separately	*Criteria 1:* Good: Provides with accurate distances in inches through repeated trials and different distances up to 20 inches	*Criteria 1:* Safe: Nothing that can harm humans. (must ensure the wiring is secure)
Mobility with distance (following an object)	Pixy2: $80.05	*Criteria 2:* Hard: Must write new code to be compatible	*Criteria 1:* Hard: Must use the Pixy2 and the rover base to	*Criteria 1:* Good: Follows accurately once object is	*Criteria 1:* Safe: Must incorporate

		with the rover as well as the pixy (uses both pixy and rover base). *Criteria 1:* 1 day invested in the code and testing	test which hinders other tests and calibrations using these components	detected. Rover moves a little fast for the Pixy2 to catch up (DC motor speed can be changed to fix this)	emergency stop features
Raspberry Pi + Open CV	$40 + $54	*Criteria 2:* Hard: Must use Open CV (familiar) and raspberry Pi (unfamiliar). Troubles with using OpenCV with pi	*Criteria 1:* Easy: Easily removable from the rest of the design for testing and calibration	*Criteria 1:* Fair: Can most of the time detect circles. Not with poor lighting (may want to consider attaching a light to the end of the charger	*Criteria 1:* Safe: Nothing that can harm humans (must ensure all wiring is secure)

[A3.2] Table 2 - Mechanical Ratings Matrix for different components.

System	**Alternative**	Cost of System [Appendix 3] (Obj.5, LL6, Metric 1)	Testing + diagnostic (Obj.2, LL2, Metric 2)	Modularity (Obj.3, LL3, Metric 1)	Reliability (Obj.1, LL1, Metric 1 & 3)	Safety (Obj.4, LL5, Metric 1)
X, Y axis	3D printed omni wheels w/ DC motor.	CR1: ~$12 (3 wheels) ~$15 (4 wheels)	CR1: 2 days of assembling + 4 days of printing. = 6 days	CR1: wheels are 1 system CR2: requires motors, wheels, and platform = 3	CR1: Rollers fall off the wheels 1/10 times. CR3**: 67.5 $[N \cdot cm]$ < 375*** $[N \cdot cm]$ CO3: Meets constraint.	CR1: No sharp edges.
	Omni Wheels w/ DC motor	CR1: ~$55	CR1: 1 day of shipping. =1 day	CR1: wheels are 1 system CR2: requires	CR1: Wheels spin as they are designed to. CR3**: 67.5	CR1: No sharp edges.

				motors, wheels, and platform = 3	$[N \cdot cm] < 500$ or 375 $[N \cdot cm]$ CO3: Meets constraint.	
	Mecanum Wheels w/ DC motor	CR1: ~$40	CR1: 7+ days of shipping = +7 days	CR1: wheels are 1 system CR2: requires motors, wheels, and platform = 3	CR1: Wheels tend to slip in the lateral component [A1.6] CR3**: 67.5 $[N \cdot cm] < 500$ $[N \cdot cm]$ CO3: Meets constraint.	CR1: No sharp edges.
	Linear Wheels w/ DC motor	CR1: ~14	CR1: 0 days	CR1: wheels are 1 system CR2: requires motors, wheels, and platform = 3	CR1: wheels spin as design to in y direction, cannot spin in x direction thus rover must make multiple maneuvers to realign itself and face the initial position maneuver. CR3**: 67.5 $[N \cdot cm] < 500$ $[N \cdot cm]$ CO3: Meets constraint.	CR1: No sharp edges.
	3-axis rail system w/ Stepper Motor	CR1: ~$120	CR1: 2 days of shipping = 2 days	CR1: each axis is 1 system → can split 3 axis system into 3 subsystems. CR2: requires motors, aluminum extrusions, bearings,	CR1: No slipping, precise but slow movements [A1.7] CR3**: 67.5 $[N \cdot cm] < 2250$ $[N \cdot cm]$ CO3: Meets constraint.	CR1: No sharp edges.
Z axis	Pulley system w/ Stepper Motor	CR1: ~$67	CR1: 1 day of shipping + 0.5 days of	CR1: Pulley system is 1 module → cannot split	CR1: Not very stable, performs 100% of the time CR3**: 67.5	CR1: No sharp edges.

			assembling and testing = 1.5 days	into further modules. CR2: requires motors, pulleys, rope, rods, a weight or the charger, a platform.	$[N \cdot cm] < 2250$ $[N \cdot cm]$ CO3: Meets constraint.	
	Lead Screw w/ Stepper Motor	CR1: ~$18	CR1: 1 day of shipping + 0.4 days of assembling + testing = 1.4 days	CR1: Lead Screw System can be broken down into (1) the lead screw and (2) mechanism to support the cantilever charger. CR2: requires lead screw, motor and a weight	CR1: Stability must be supplemented with guide rails, very precise with correct motors CR3**: 62.9 $[mN \cdot m] < 260$ $[mN \cdot m]$ CO3: Meets constraint.	CR1: No sharp edges.
	3-axis rail system w/ Stepper Motors	CR1: ~$120	CR1: 2 days of shipping = 2 days	CR1: each axis is 1 system → cannot split into further modules. CR2: requires motors, aluminum extrusions, bearings.	CR1: No slipping, precise but slow movements [B] CR3**: 67.5 $[N \cdot cm] < 2250$ $[N \cdot cm]$ CO3: Meets constraint.	CR1: No sharp edges.
Gripping Mechanism	3D printed CAD gripper + small arm	CR1: Estimate of ~$6	CR1: 2 days printing* + 0.5 of CADing	CR1: Can be broken down to 2 modules (1) the	CR1: Has the potential of slipping.	CR1: No sharp edges.

	to release clip in w/ Servo Motor		= 2.5 days	method that holds the gripper and (2) an arm to release clip. CR2: requires the 3d print, a small arm, servo motor	CO3: Physical testing: Can push the button thus meets constraint.	
	3D printed claw + small arm to release clip in w/ Micro Servo Motor	CR1: Estimate of ~$4	CR1: 2 days printing + ~1 day CADing = 3 days	CR1: Can be broken down to 2 modules (1) the method that holds the gripper and (2) an arm to release clip. CR2: requires the 3d print, a small arm, servo motor	CR1: Performs 100% of the time. CO3: Physical testing: Cannot push the button thus does not meet constraint.	CR1: No sharp edges.
Material	Birch Plywood	CR1: ~$2	CR1: 3 days laser cutting* + 0.5 assembling = 3 days	N/A	CR1: For light loads, performs 100% of the time. CO3: Physical testing: Can support estimated weight thus does meet constraint.	CR1: Can have sharp edges, would need to be sanded, or laser cut with fillets.
	Acrylic	CR1: ~12	CR1: 3 days laser cutting* + 0.5 assembling = 3 days	N/A	CR1: Performs 100% of the time. CO3: Physical testing: Can support estimated weight thus does meet constraint.	CR1: Can have sharp edges, would need to be sanded, or laser cut with fillets.

Wheel Configurations	Triangular	CR1: Min ~$32 Max ~$74	CR1: 0.15 day of testing	N/A	CR1: Performs 100% of the time.	N/A
	Square	CR1: Min ~$35 Max ~$97	CR1: 0.15 day of testing	N/A	CR1: Performs 100% of the time.	N/A
	H-shaped	CR1: Min ~$35 Max ~$78	CR1: 0.15 day of testing	N/A	CR1: Should perform well, but is weak in x-axis, as 1 wheel is used.	N/A

Notes:
***Includes waiting time in queue of LFF submissions.**
****Calculations of these ratings can be found in Appendix 1.3**
*****Amount of torque for the entire system, not just 1 motor.**

Table 3 - Electrical components Rating Matrix (Reference **Appendix 6** for Datasheets)

Component	**Options**	Cost (Obj.5, LL6, Metric 1) Note: delivery time considered	Testing + Diagnostic (Obj.2, LL2, Metric 2, (Microcontrolller , Motor), Metric 4 (Battery)	Modularity (Obj.3, LL3, Metric 2)	Reliability (Obj.1, LL1, Metric 1 (Motors, Mircocontroller), Metric 2 (Battery - draw assumed to be 2700 mA(Appendix 3)) *(Chart X)	Safety (Obj.4, LL5, Metric 1 (microcontroller), Metric 2(Battery), Metric 3(Motors)
Battery	7.2 V NiMH Rechargeable (Robotshop)	26.60 (short - Canadian)	1	0 (have Tamiya harness from workshop)	35 min Rechargeable	3 - packaging, tamiya, wiring
	7.2 V NiMH Rechargeable	25.50 (LFF)	1	‘’ ‘’	67 min Rechargeable	‘’ ‘’

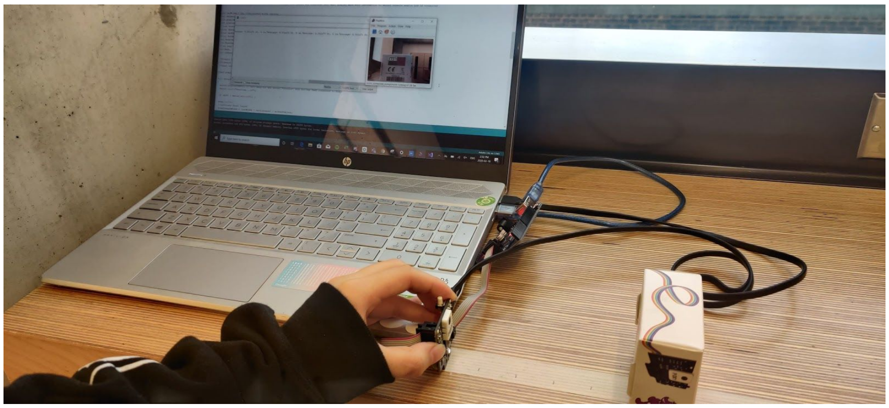
	(Turnigy)					
	12 V Rechargeable Lithium Ion (4800 mAh)	11.99 (17-61 days delivery)	2	>1 Barrel connections - would need specialty connections	107 min Rechargeable	4 - packaging, barrel, wiring, on off switch
	12 V Rechargeable Lithium Ion (1800 mAh)	18.25 (14-85 days delivery)	2	>1 Barrel connections - would need specialty connections	40 min Rechargeable	‘’ ‘’
	12 V Rechargeable Lithium Polymer	25.13 (15-20 days delivery)	1	0 (have Tamiya harness from workshop)	44 min Rechargeable	3 - packaging, tamiya, wiring, BUT lithium ion danger, no storage in myhal
	12 V Lead Acid	15.11 + 20 shipping (unknown shipping time)	0	>=2 need alligator clips or soldered option	27 min Non rechargeable	1 - packaging (very heavy, requires additional soldering)
Motors	Casun Stepper Motor	7.53	13 Requires: 12 wires, 1 stepper drive board (A4988)	Requires: speciality stepper drive board	Encoding method present - use step count (1.8 º per step) 2 mm avg. inaccuracy*	260 mN.m
	Nema 17 Stepper Motor	12.17	13 Requires: Motor driver(easiest	Requires: specialty stepper motor	Encoding method present - use step count	590 mN.m

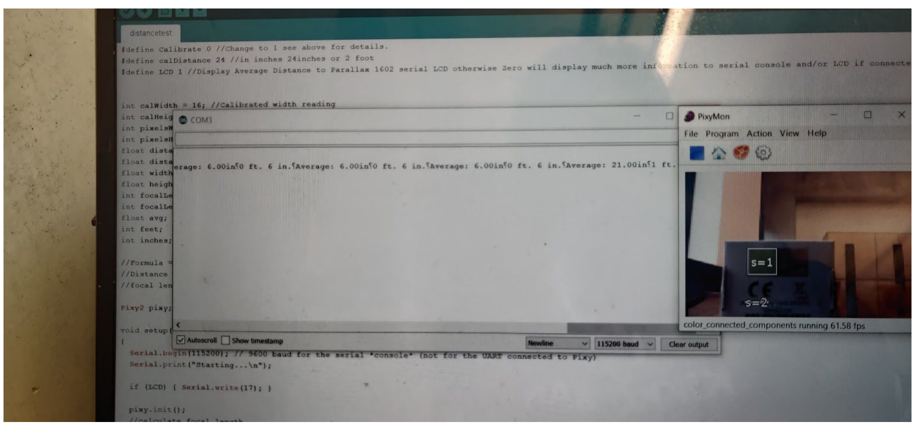
			way to control), 11 wires, code control	driver	(1.8 º per step) 0.5 mm avg. inaccuracy*	
	Micro Servo (9g)	1.50	3 Requires: 3 wires	Requires: nothing	Encoding method present - use angle input 5º avg inaccuracy	176.5 mN.m
	TT motor - DC 6V motor	13.59	17 max Requires: 16/12 wires, 1 stepper drive board (A4988)	Requires: specialty driver board	Encoding method present - use hall effect sensor on wheel in conjunction with control code Highly variable accuracy dependent on control code 2 cm accuracy*	None
	Tower Pro MG996R (servo)	4.8	3 Requires: 3 wires	Requires: nothing	Encoding method present - use angle input 5º accuracy *	921.825 mN.m
Microcontroller	Raspberry Pi 3B +	46.75	3 - mouse, keyboard, charger, SD card	Requires: mouse, keyboard, LCD screen(optional), SD card	100 % accuracy but have had problems with downloading OpenCV - unreliable elements	Good grounding, emergency shut off present (battery pack), can over heat
	Arduino Uno	5.49	1 - USB cable	Requires: USB cable	100% accuracy	Good grounding, no emergency shutoff (need to

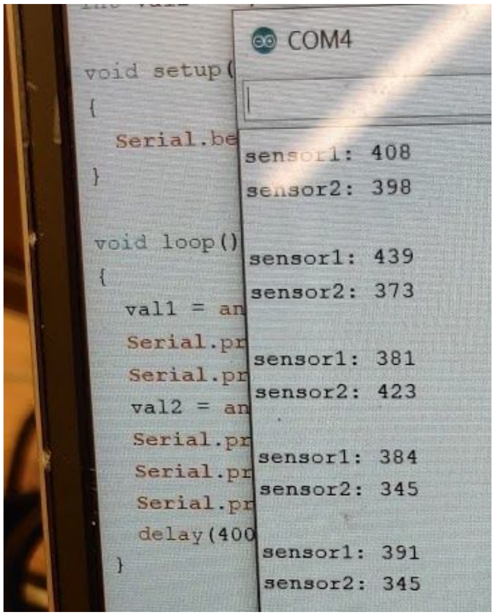
						unplug/kill power)
	Arduino Mega	14.18	1 - USB cable	Requires USB cable	100% accuracy	‘’ ‘’

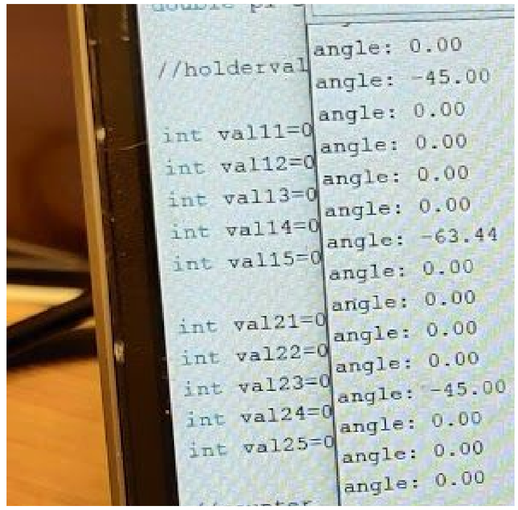
Appendix 4 - Additional Testing Images from Testing

[A4.1] Software



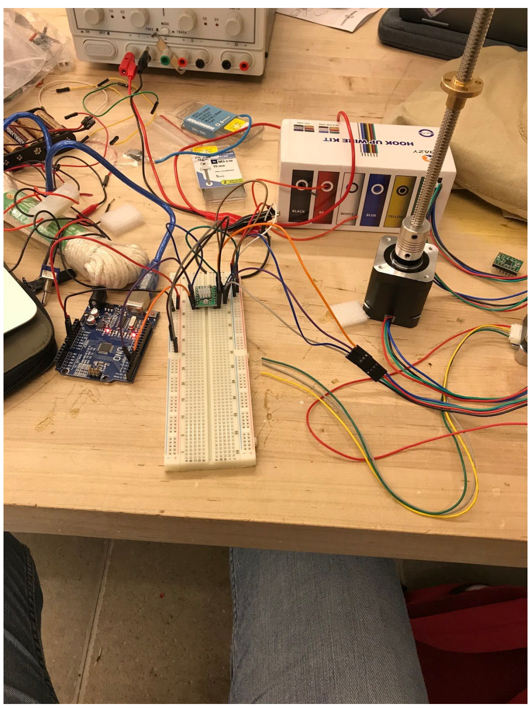






[A4.2] Electrical

Testing stepper motors



3D printed Charger Gripper

Set up for testing DC motor

Appendix 5: Cost of Items Referenced

Item	Part of Design	Price	Link
Triangular Birch Plywood Base Chassis 24"x18"	Everything	2.06	https://bit.ly/2SQ0Ima
Omni Wheels or	X,Y axis	18	https://bit.ly/2vcdClj
Mecanum Wheels (4)	X,Y axis	36.99	https://amzn.to/37WDPBD
Lead Screw	Z axis	4.27	https://bit.ly/2HNtkWP
Coupler	Z axis	1.43	https://bit.ly/2HNtkWP
Molded Fit	Manipulation	6	https://bit.ly/2HNtkWP
PVC pipe 12"	Z axis	0.97	https://bit.ly/2HNtkWP
Pixy2 Camera	Locating Port Hole	80.05	https://bit.ly/32I5v1X
TT DC Motors	X,Y axis	13.59	https://bit.ly/2HNtkWP
7.2 V NiMH Rechargeable (Turnigy)	Everything	25.5	https://bit.ly/2HNtkWP
Tower Pro MG996R	Release Clasp on Charger	4.8	https://bit.ly/2HNtkWP
Arduino	Release Clasp on Charger	5.49	https://bit.ly/2HNtkWP
Motor Stepper Driver A4988	Z axis	1.83	https://bit.ly/2HNtkWP
Dual Motor Driver L298N	Z axis	2.62	https://bit.ly/2HNtkWP
Stepper Nema 17, 1.7A	Z axis	13.93	https://bit.ly/2HNtkWP
9V Battery	X,Y axis	1	https://bit.ly/2HNtkWP
ProtoBoard	Everything	1.04	https://bit.ly/2HNtkWP
LED	Everything	0.01	https://bit.ly/2HNtkWP
Bluetooth HC06	Everything	5.93	https://bit.ly/2HNtkWP
Rope	Z axis	**6.52**	Home Hardware
7.2 V NiMH Rechargeable	Locating Port Hole	26.6	https://bit.ly/2HNtkWP
12 V Rechargeable Lithium Ion (4800 mAh)	Everything	11.99	https://bit.ly/37P5B33
12 V Rechargeable Lithium Ion	Everything	18.25	https://bit.ly/2T3QmxW
12 V Rechargeable Lithium Polymer	Release Clasp on Charger	25.13	https://bit.ly/37PVCL2
12 V Lead Acid	Release Clasp on Charger	15.11	https://bit.ly/32me8tg
Casun Stepper Motor	Z axis	7.53	https://amzn.to/2SV10bA
Micro Servo (9g)	Z axis	1.5	https://bit.ly/2HNtkWP
Raspberry Pi 3B	Z axis	80	https://amzn.to/2HLhaxP
Arduino Mega	X,Y axis	14.18	https://bit.ly/2HNtkWP
IR Sensor	Everything	13.14	https://bit.ly/2HNtkWP
Linear actuator for 3-axis rail system	X,Y axis	20	https://amzn.to/2HQZzUZ
Acrylic	Everything	12	https://bit.ly/2SQ0Ima

Appendix 6: Datasheets

[1] Raspberry Pi, “Raspberry Pi 3 Model B+” 3 Model B + Datasheet [No date]
[2] Tower Pro, “ Servo Motor SG90”, Tower Pro Micro Servo 9g SG90 Datasheet [No Date]
[3] OYO Stepper, “Stepper Motor”, 17HS19-2004S1 Datasheet [No Date]
[4] Tower Pro, “High Torque Metal Gear Dual Ball Bearing Servo” MG996R Datasheet [No Date]
[5] Handson Technology, “L298N Dual H-Bridge Motor Driver”, L298N Datasheet [No Date]
[6] Casun, “Casun Stepper Motor”, Model 42SHD0001, [No Date]
[7] Pololu,“Pololu 8-35V 2A Bipolar Stepper Motor Driver A4988” A4988 Stepper Motor Driver Carrier [No Date]
[8]Arduino, “Arduino Uno” Arduino Uno R3 Datasheet [No Date]
[9]TT Motors, “GM25-370CA-EN Gear Motor” GM25 Datasheet [No Date]