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Group S- ARLISS Project

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FL19 MEMS 411 Mechanical Engineering Design Project

ARLISS Project

Our project was the ARLISS competition project, more specifically the second part of the project where the vehicle must survive a drop and drive to a known location over rough desert terrain. We interviewed our professor, Dr. Potter, who had previous experience with the project to understand what was required in our design.

The project started with creating concept ideas and deciding on one, which initially was an airplane to avoid designing a landing mechanism and having to drive over rough terrain. However, this design proved to have too many flaws and was scrapped. The new design was a small rover with a single motor and a one-way bearing with a parachute attached. Most of the parts in this design were 3D printed, save for the axle, parachute, battery, steel rod supports, and the one-way bearing. This design choice greatly reduced the overall weight of the design, giving us room to add extra components if necessary. Our initial prototype used PLA filament for the wheels and had the parachute in the center of the axle. This caused the parachute to not open up entirely when the rover was dropped. The battery also shifted during the drop, changing the center of gravity and making the rover fall on its wheel at an angle, causing the axle to be damaged. After these results, we redesigned the rover by focusing on the wheels, axle, the parachute, and brackets holding the battery. We designed the brackets to hold the battery at the rover's center of gravity. Since we had extra weight to spare, we changed the axle from aluminum to steel to improve the strength of the rover. A second parachute attachment was added and the parachute attachments were moved to the ends of the axle to allow the parachute to open up more. The wheels were changed from PLA material to TPE to make the wheels more flexible and able to absorb more of the impact when the rover lands on the ground. When re-testing our final prototype, the rover was able to transverse over more rough terrain. The rover was also able to survive multiple drops without any significant damage and was able to operate after being dropped.

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1 Introduction

Over 20 years ago Professor Bob Twiggs of Standford University and several of his colleagues began a program to give hands-on, practical experience to students interested in designing and launching satellites. The CanSat is this idea brought to life. Generally limited to a total mass of 350 g and the dimensions of a soda can, students can design, build, test, and launch their own satellite. Over a dozen of such student competitions exist around the world today.

The ARLISS CanSat competition has two classes; the CanSat class, with the same specifications as mentioned above, and the open class, which has a 1.0 kg payload limit, and allows a larger satellite diameter. This project will be focusing on the open class satellite. In addition to the size and weight limit imposed on us by the competition, the satellites are launched to approximately 3500 meters, and autonomously navigate to within 10 meters of a small target several kilometers away on the ground.

Due to the scope of this class, efforts will be directed towards designing and building a prototype open class vehicle that is capable of being launched to an altitude of 3500 meters, land, and drive up to 5000 meters on the ground. The vehicle will have the ability to integrate with GPS, however it is not a main focus of this project, and will be treated as an extra challenge.

2 Problem Understanding

2.1 Existing Devices

Before beginning our design we looked at products that are already in use that could be used to complete different stages of the competition. This includes looking at existing devices that can serve as inspiration for guiding our canister as it falls through the air, protecting the payload as it impacts the ground and moving our payload after it has landed on the ground.

2.1.1 Existing Device #1: Joint Direct Attack Munition - JDAM

Figure 1: Bomb equipped with the JDAM tail package being loaded into the bomb bay of a B-1 Lancer (Source: Military.com)

Link: https://www.military.com/equipment/joint-direct-attack-munition-jdam
Description: The Joint Direct Attack Munition also known as JDAM is a product that can be attached to a conventional unguided bomb to turn it into an all weather "smart" guided bomb. This technology allows the warhead to precisely hit a target that is up to 15 miles away from where it is dropped. By using a combination of GPS and inertial guidance the on board computer mechanically manipulates control surfaces on the back tail section of the bomb that guide the bomb to its final destination. Unlike a cruise missile this system does not require any propulsion system or wings to navigate it simply relies on gravity to generate enough speed to make the control surfaces effective. This technology originally developed in the United States has been used by allies around the world to precisely hit targets while minimizing collateral damage. The published accuracy of this bolt on guidance system is 13 meters, however, performance in the field has shown it to be more accurate. The true accuracy remains classified.

2.1.2 Existing Device #2: Airbag

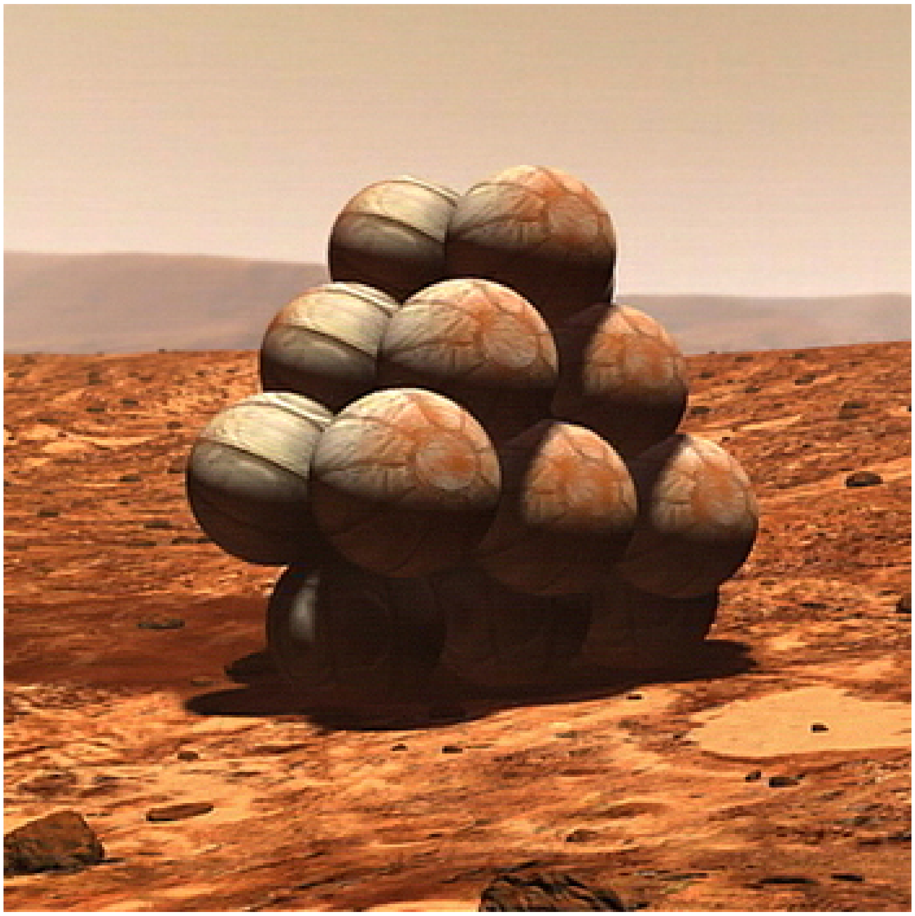


Figure 2: Artists depiction of deployed airbags surrounding the rover on the surface of Mars (Source: NASA)

Link: https://mars.nasa.gov/mer/mission/spacecraft_edl_airbags.html
Description: In January 2004 the two Mars Exploration Rovers, named Spirit and Opportunity, arrived at their destination. Before their mission could begin they needed a way to land on the unfamiliar and notably desert like surface of Mars. In order to accomplish this the twin rovers used a set of parachutes to slow it down as if flew through the atmosphere. As it got closer to the ground the parachute released and a set of airbags inflated, completely surrounding the vehicle. These airbags protected the vehicle as it bounced across the surface of Mars until it came to a rest. The airbags then deflated and allowed the vehicle to drive out of its container onto the surface of Mars. This technique assured that as the vehicle landed it would not get caught up in the parachute and could navigate out of its container with ease. This could be used in conjunction with a parachute on our design to assure our vehicle survives the drop from such a high altitude.

2.1.3 Existing Device #3: Hoverboard

Figure 3: Hoverboard (Source: Sharper Image)

Link: https://www.streetsaw.com/pages/how-does-a-hoverboard-work
Description: The Self-balancing scooter, more commonly known as a hover board skyrocketed in popularity in late 2013 and early 2014. The device allows the user to easily move around using two parallel wheels by changing their weight distribution on the board. Two independent motors control the different wheels making it easy to steer and vary the speed. By using the users weight and responding to the users movements the board is able to stay upright and functional. Due to the weight restrictions of the competition it is unlikely we could use a similar technique to keep our device upright but the same effect can be accomplished by dragging something behind the vehicle preventing the base with the control board from spinning out of control.

2.2 Patents

2.2.1 Steerable Parachute control system (US6889942B2)

Link: https://patents.google.com/patent/US6889942B2/en

This patent involves using the concept of a parachute and attaching a small computer and sensors to the end of the parachute, allowing it to be controlled with a controller or programmed to navigate the parachute autonomously. Once the item is near or over the intended target, a second parachute deploys to further slow down the descent of the item, allowing it to land softly.

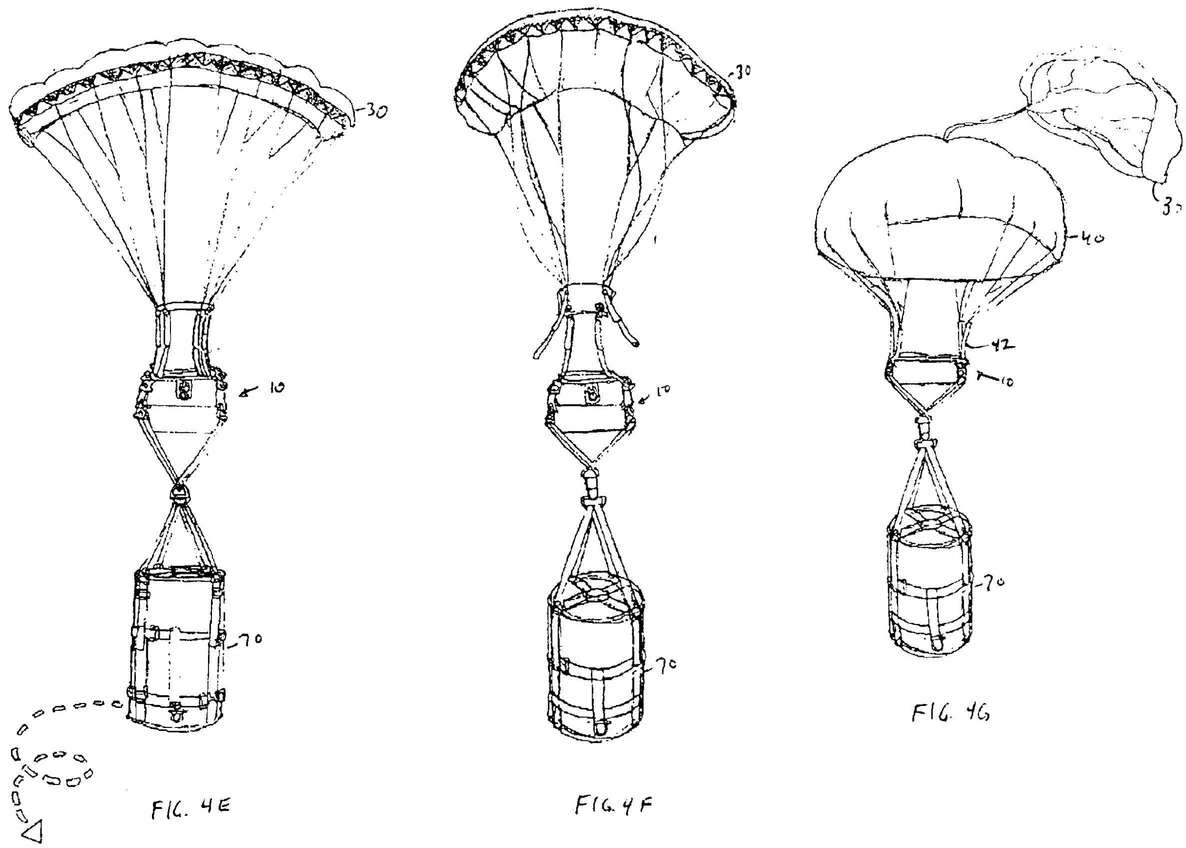


Figure 4: Patent Image for Steerable Parachute (Source: Atair Aerospace)

2.2.2 GPS Tracking System (US5379224A)

Link: https://patents.google.com/patent/US5379224A/en

This patent involves a simple GPS tracking system using global satellites to pinpoint the location of an object. The system tracks by first attaching a sensor to the desired object. Then when activated, the sensor sends a signal to the GPS satellites in the air, then the satellites send a signal to the GPS receiver, like a computer or similar device.

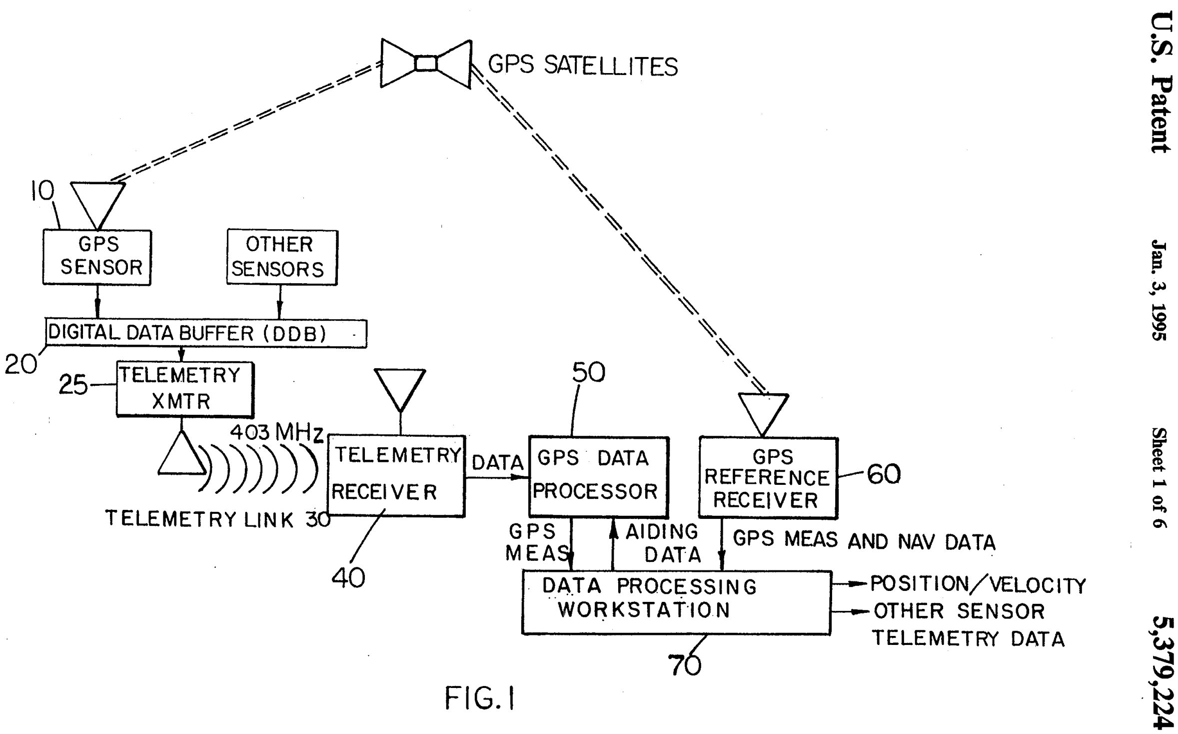


Figure 5: Patent Image for GPS Tracking System (Source: NAVSYS Corp)

2.3 Codes & Standards

2.3.1 FAA- Visual Location (AC 91-57B)

This Federal Aviation Administration standard sets the guideline that all unmanned aircraft systems (UAS) must remain the the operator's line of sight or having tracking capabilities. In order to adhere to this standard, we will have to add a GPS sensor to the vehicle so that we do not lose track of the vehicle.

2.3.2 ARLISS - Open Class Restrictions (Section 1.1)

This standard by ARLISS gives the Open class mass and dimensional restrictions for the vehicle. The mass is limited to 1050g, while the dimensions are limited to a maximum diameter of 146mm and a height of 240mm. To meet these standards, we will have to keep these dimensional and mass restrictions in mind while designing the vehicle. For example, things like the materials used can affect the total mass of the vehicle.

2.4 User Needs

In order to fully understand the scope of the project, an interview was conducted with Dr. James Jackson Potter. This discussion gave insight into the most important design criteria, which are ranked in Table 1 below.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Urbauer 318, Washington University in St. Louis, Danforth Campus
Date: September 6^{th}, 2019
Setting: Our hour long interview conducted in the MEMS conference room was based around Dr. Potter's previous experience with a similar product. The discussion that followed focused heavily on the rules and regulations governing the ARLISS competition, as well as the level of robustness a vehicle must have to successfully complete the mission.
Interview Notes:
Would it be better for the vehicle to be controlled during it's decent, or to be controlled after it lands?

- In the past several years, two groups have attempted controlled falls, and neither succeeded. Safely landing the vehicle and controlling it's movement on the ground is the preferred option, as it is most likely to succeed.

Is there a required distance the device must travel?

- It must be able to travel 2 kilometers, however it's ideal range would be 5 kilometers.

Would a parachute be sufficient for the decent?

- A parachute would be a good method of controlling the fall of the device. You have to be careful to attach the parachute very securely, as there is a significant amount of force seen during the initial opening that could cause it to break off of the device.

What type of terrain will the device be travelling over?

- The desert can be assumed to be dry and relatively flat. If the device is capable of driving over rough grass then it should not have a hard time maneuvering in the desert.

More miscellaneous notes from the interview:

- Ensuring the parachute does not detach is important, and should be the second priority behind the device's ability to move.

- For our device we should not worry about making it fully autonomous, but is should be easy to introduce those capabilities.

- Try to include as many useful sensors as possible, however for the scope of this project it does not have to collect every single relevant piece of data.

- The temperature should be considered during flight. If the battery temperatures get too low, the device may not function properly. Heating the batteries could be an option to prevent this.

- The device will have a forceful ejection from the launch vehicle.

- While it is not a main consideration for the design of the device, it should be kept in mind that dust from the desert could potentially damage electronics or moving components like motors.
- The main points to focus on for the design are its ability to drive, turn, collect and store data, and successful execution of the landing device (i.e. it's parachute).

2.4.2 Interpreted User Needs

Based upon the information collected during the customer interview with Dr. Potter, a list of user needs has been compiled below. There are 8 items to be focused on, and each of their importance is shown on the right. The importance score of each item is rated on a scale from 1 to 5, where 5 indicates that is the need is critical, and a 1 indicates the need is relevant, however not a main contributing factor to the overall product design.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The vehicle can travel up to 5 km	4
2	The vehicle can be easily maneuvered	5
3	The deceleration device is securely fastened	5
4	The vehicle can move over rough grass	3
5	Vehicle is operational at high altitudes	3
6	Vehicle can operate from any orientation it lands in	5
7	Vehicle can travel autonomously	1
8	Substantial data is collected during the trip	4
9	Vehicle can survive launch and landing conditions	3
10	Vehicle fits inside the rocket's carrying canister and payload limit	5

The goal of the table of interpreted needs is to reduce the significant amount of information collected during the customer interview into a more useful format. It can be quickly referenced during design and testing of the product to make sure the team weighs each need with proper importance.

2.5 Design Metrics

After reviewing all of the user needs, as well as the codes and standards, a list of design metrics has been compiled, as shown in the table below. Each of the metrics listed below directly relates to one or more of the needs listed above. Because of this, the list can be used to more accurately determine how well the design is meeting the previously determined set of needs and standards.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1,10	Total weight	kg	< 1.05	< 1.05
2	1,10	Height, Diameter	mm	< 240, < 146	< 240, < 146
3	5	Max Operating altitude	ft	12000	15000
4	2,4	Max Height of Maneuverable Grass	in	2	3
5	9,3	Max Operating Acceleration	G	10	15
6	7,8	Number of Data Recording Sensors	integer	1	2
7	6	Chance of Operating from Landing Orientation	percent	90	100

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

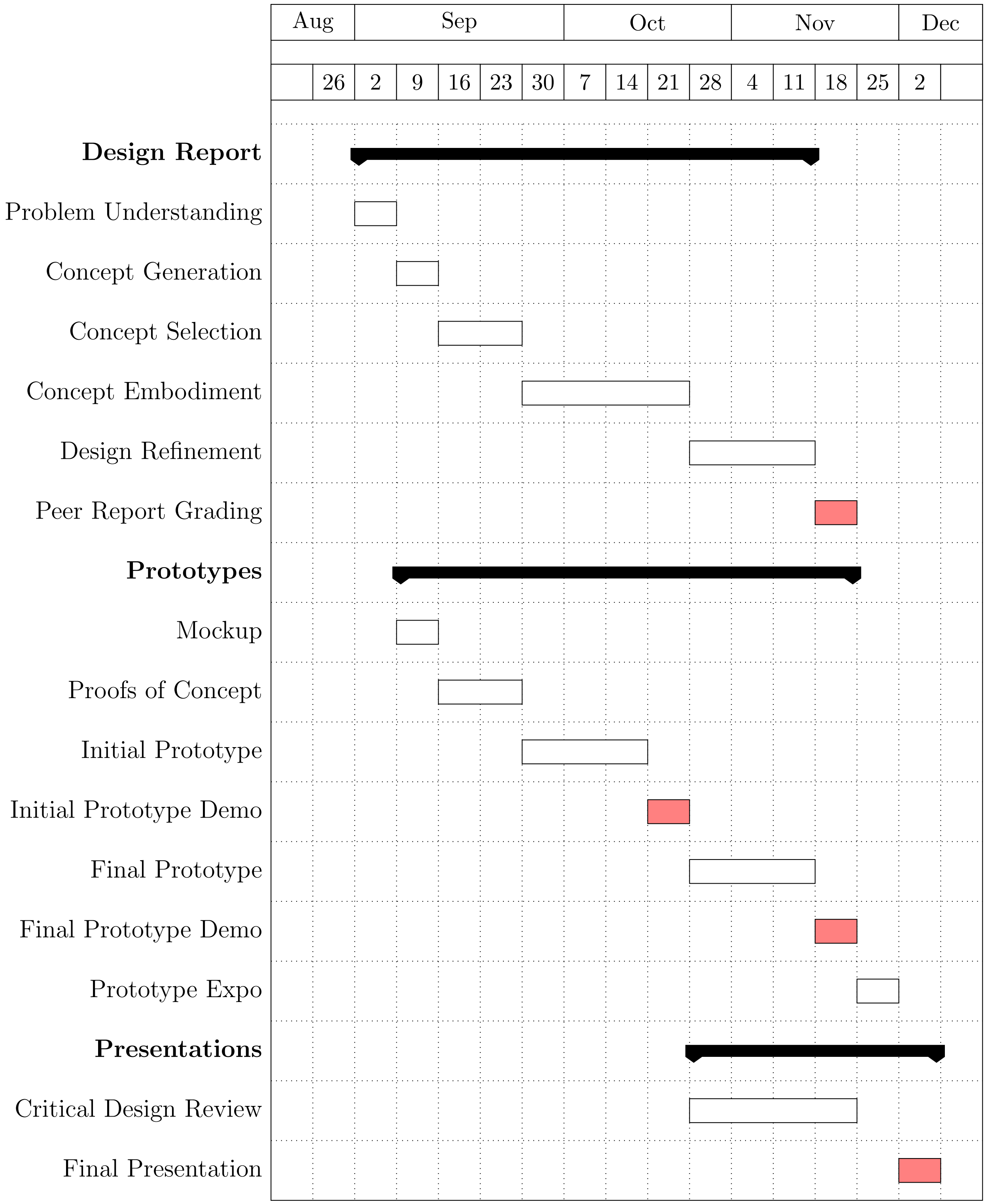


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

Below can be seen multiple pictures of the mockup prototype for this project. We chose to make the mockup prototype of the foldable glider design (as seen in section 2.4.2), because this was one of the designs with the most unknowns. Creating the mockup helped us answer many of those questions, and understand more about how the final design would look and work if we went with that design option.

From making the mockup, we realized that the design would have to be smaller than was originally envisioned. This was due to the constraints of the canister dimensions, and how the folding affected the size of the design. We also realized how fragile the design could potentially be. Because of this we know that that design would have to be made very strong to withstand the forces of being released and unfolding. Without the process of making this mockup prototype we would have never had these realizations, in the manor we did.

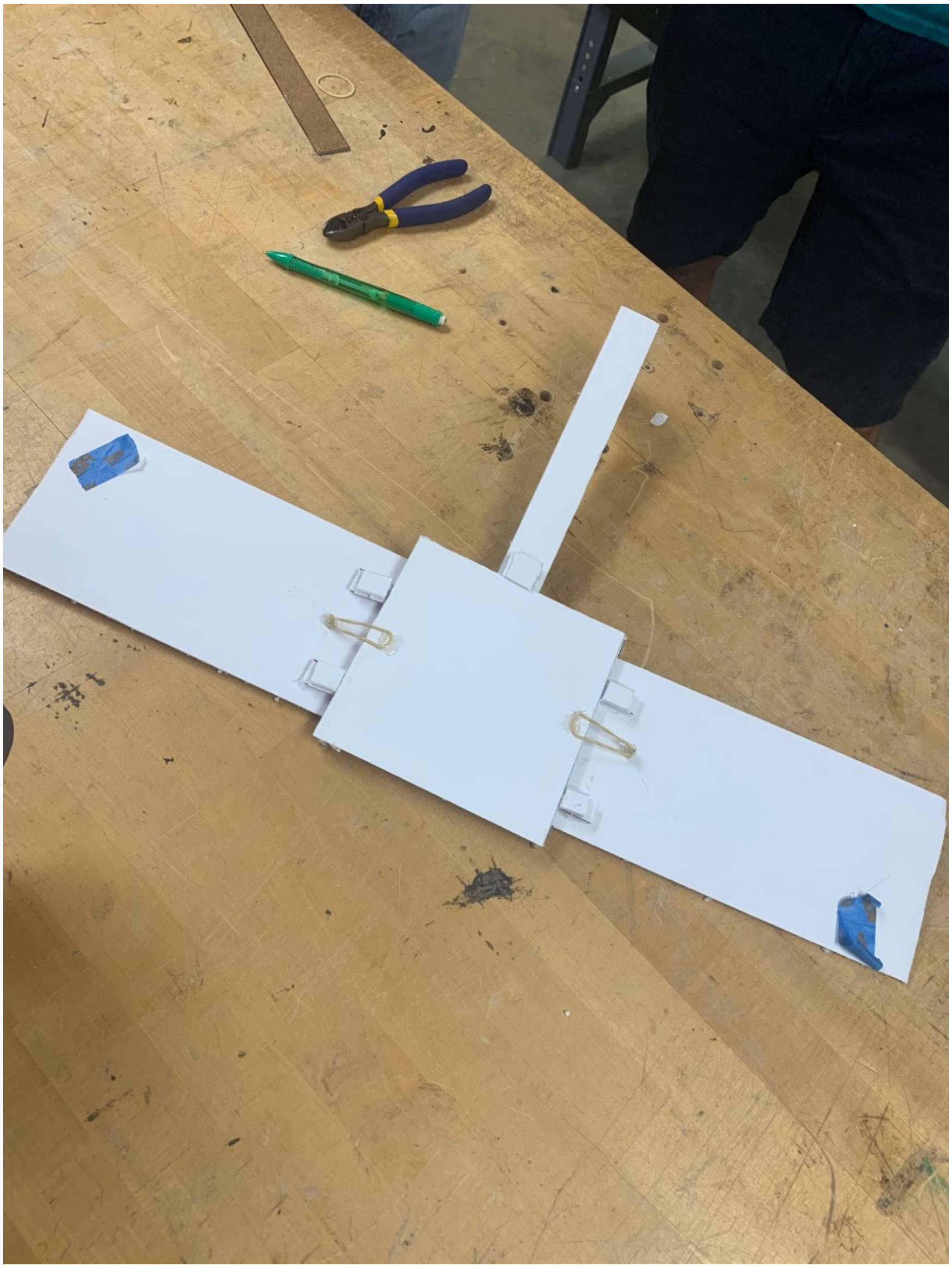


Figure 7: Bottom view of mockup prototype

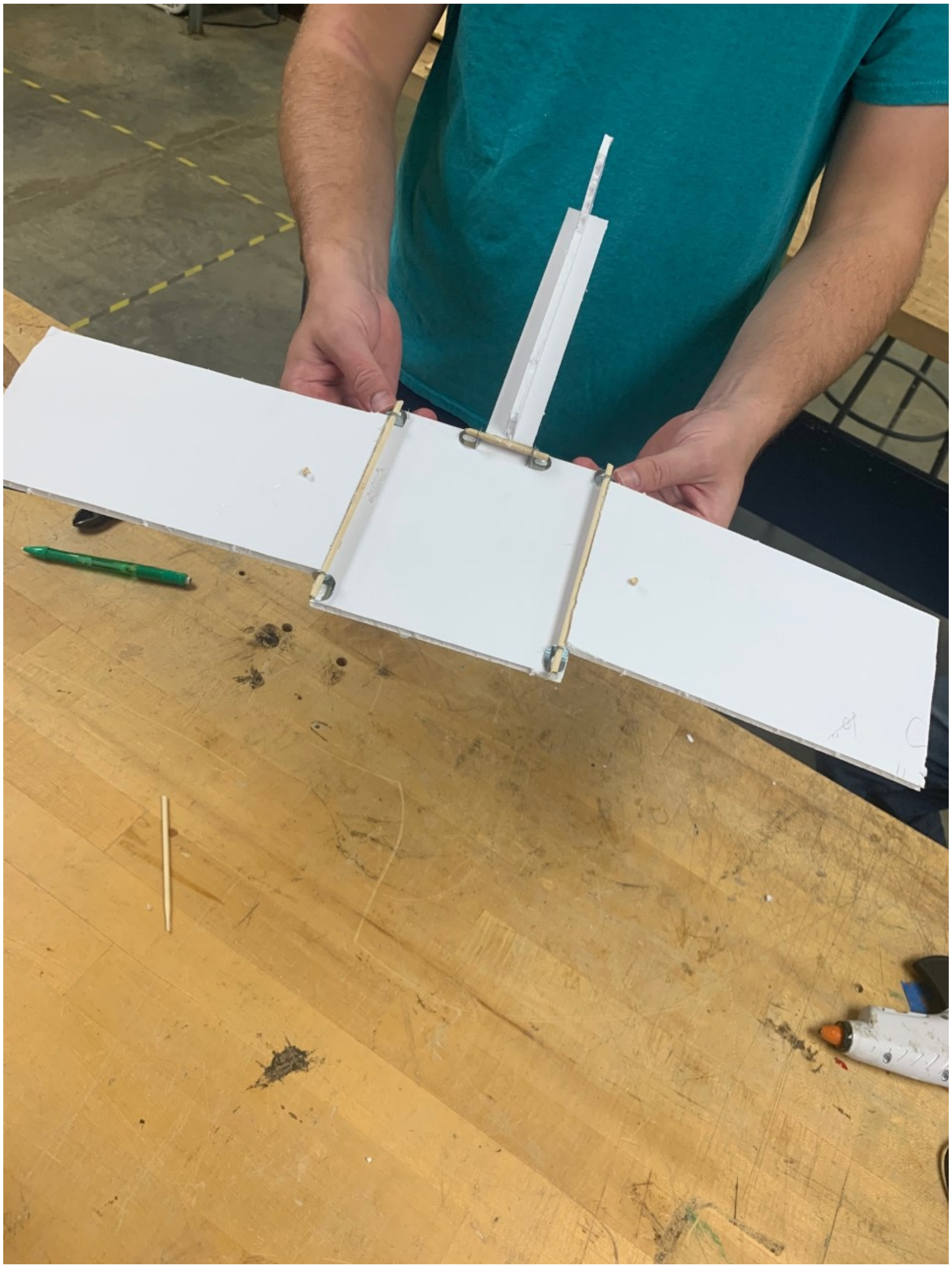


Figure 8: Top view of mockup prototype

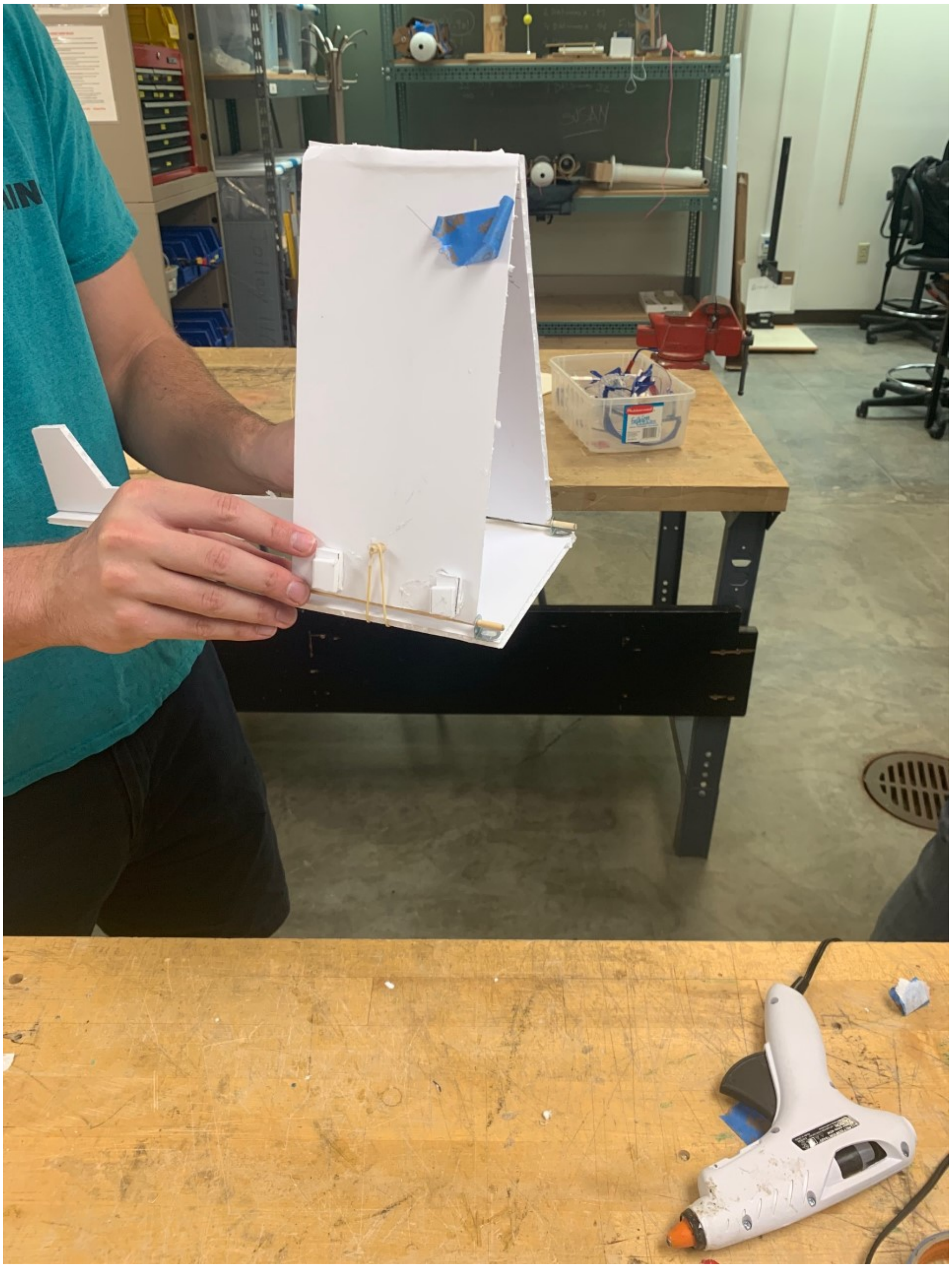


Figure 9: Side view of mockup prototype folded

3.2 Functional Decomposition

Shown below is the picture of the function tree for the ARLISS project. The first box of the tree on the left describes the primary goal of the project, which is for the vehicle to move to a set location after being landing from a high height. The boxes in the branches break down the main objective into smaller objectives that need to be met.

Figure 10: Function tree for ARLISS, hand-drawn and scanned

3.3 Morphological Chart

In the image shown below, the chart shows possible ideas or solutions to the branched boxes on function tree. Several of these ideas are present in the Alternative Design Concepts section.

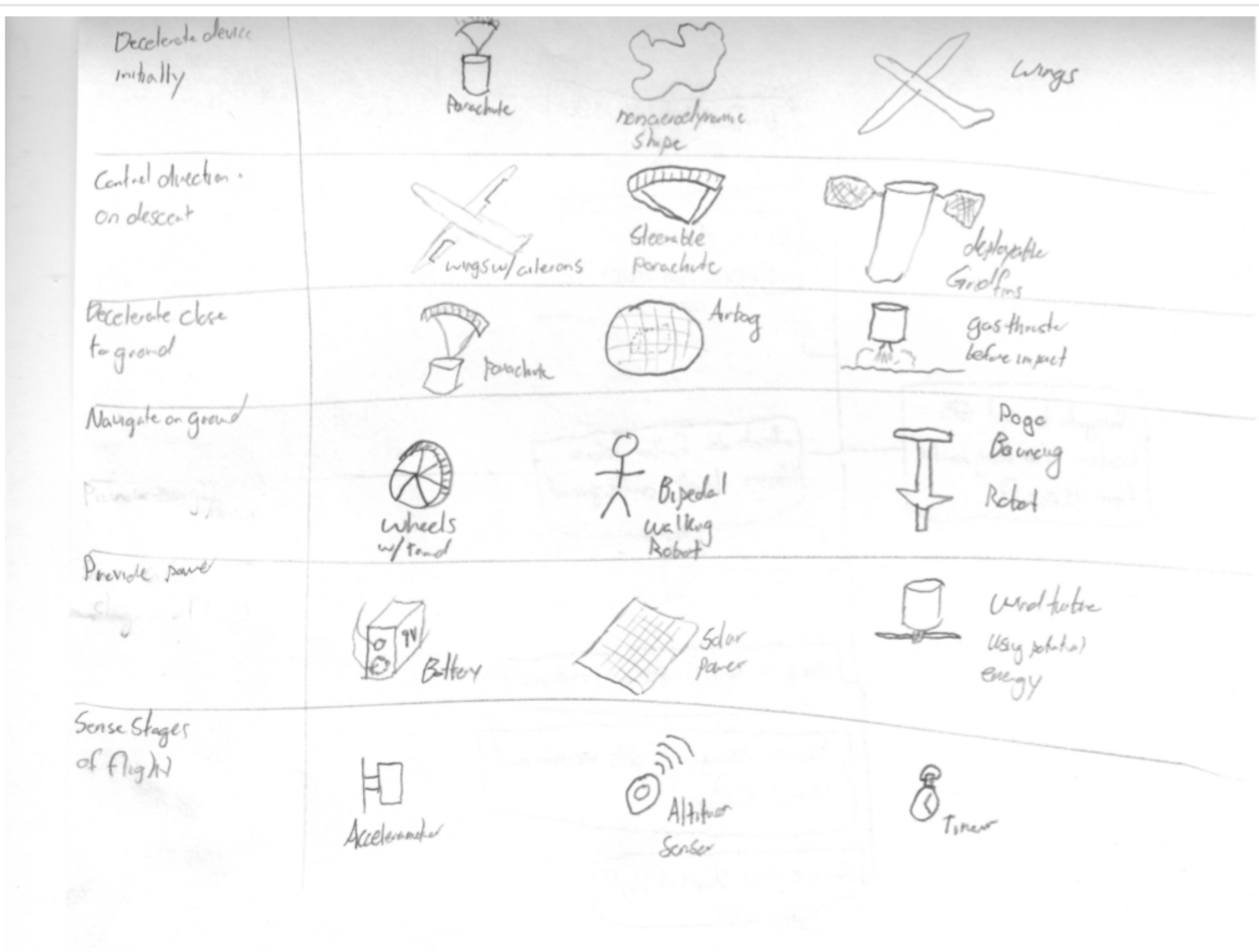


Figure 11: Morphological Chart for ARLISS, hand-drawn and scanned

3.4 Alternative Design Concepts

3.4.1 Grid Fin

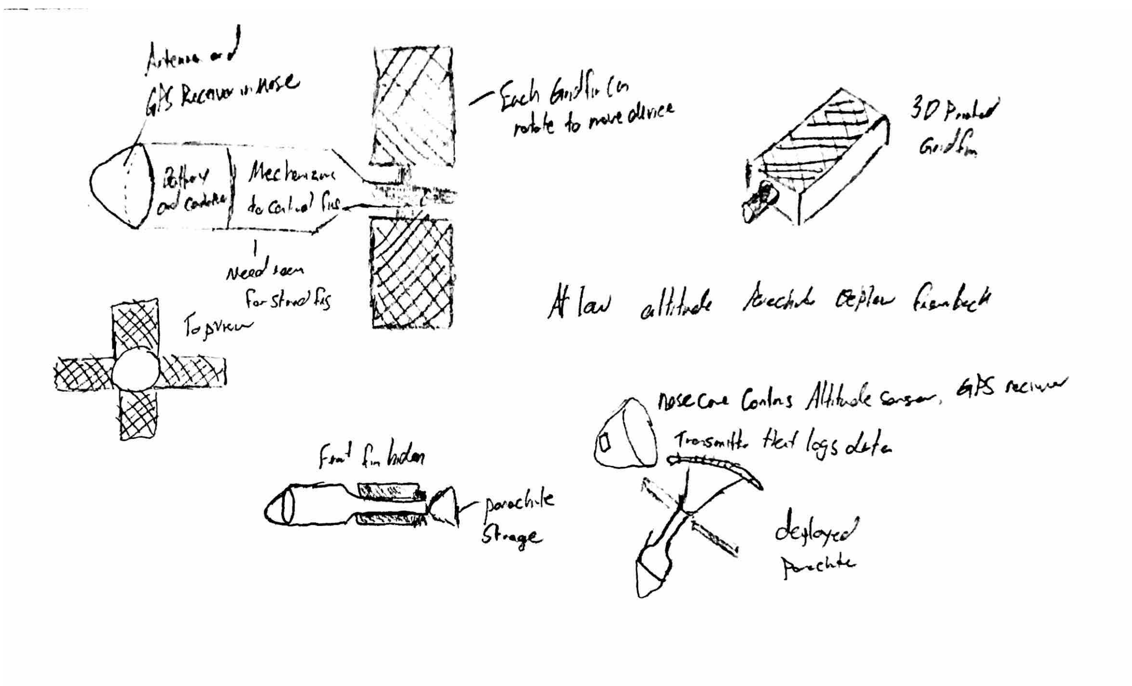


Figure 12: Preliminary sketches of Grid Fin concept

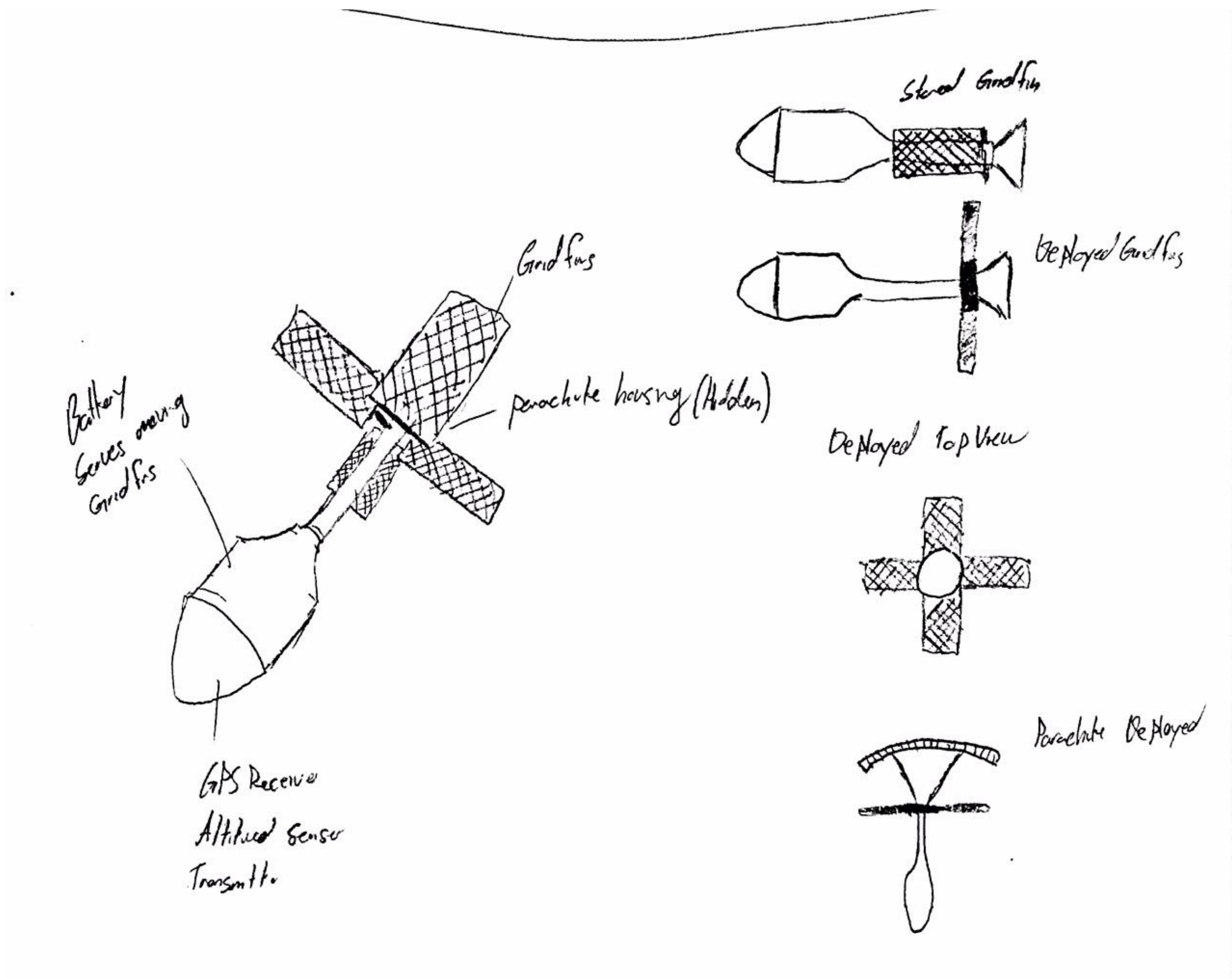


Figure 13: Final sketches of Grid Fin concept

Solutions from morph chart:

1. Grid fins decelerates the device initially
2. grid fins control direction on descent
3. Parachute slows device close to the ground
4. Battery provides power
5. Altitude sensor senses stages of flight

Description: After being ejected from the vehicle grid fins will deploy from the back of the device and be rotated to steer the vehicle towards the final GPS location. The grid fins will not only steer the vehicle but create a significant amount of drag slowing down the vehicle. When the vehicle gets closer to the ground the parachute which is stowed behind the grid fins will deploy. Once the Parachute deploys the vehicle will slow down and the grid fins will no longer be capable of steering the vehicle. For this reason the parachute must deploy at as low of a point as possible. The nose section of this device will contain the GPS receiver, altitude sensor and a transmitter for sending information back to us on the ground. The core section of the device will contain the battery used to control the fins as well as the micro controller and servos that move the fins.

3.4.2 Foldable Plane

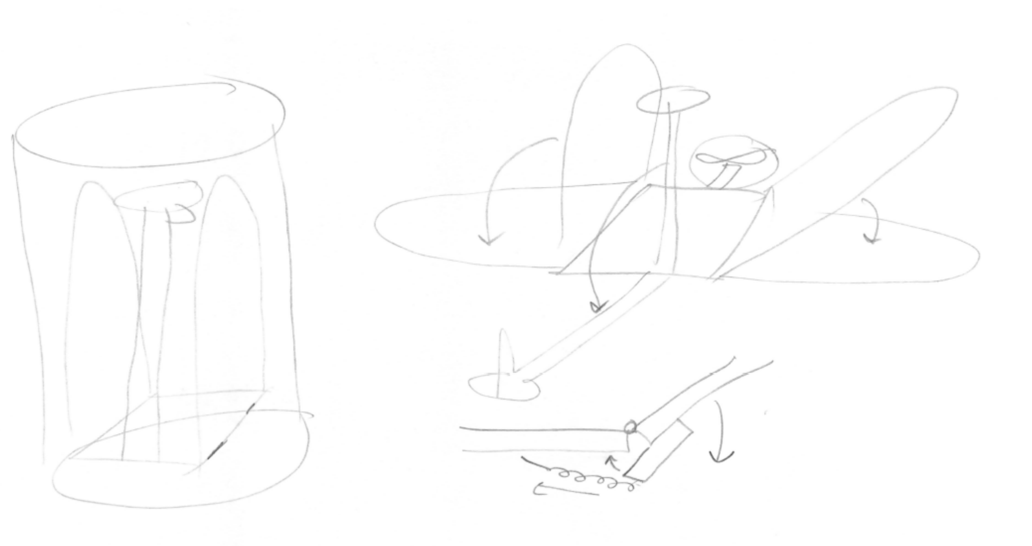


Figure 14: Preliminary sketches of Foldable Plane concept

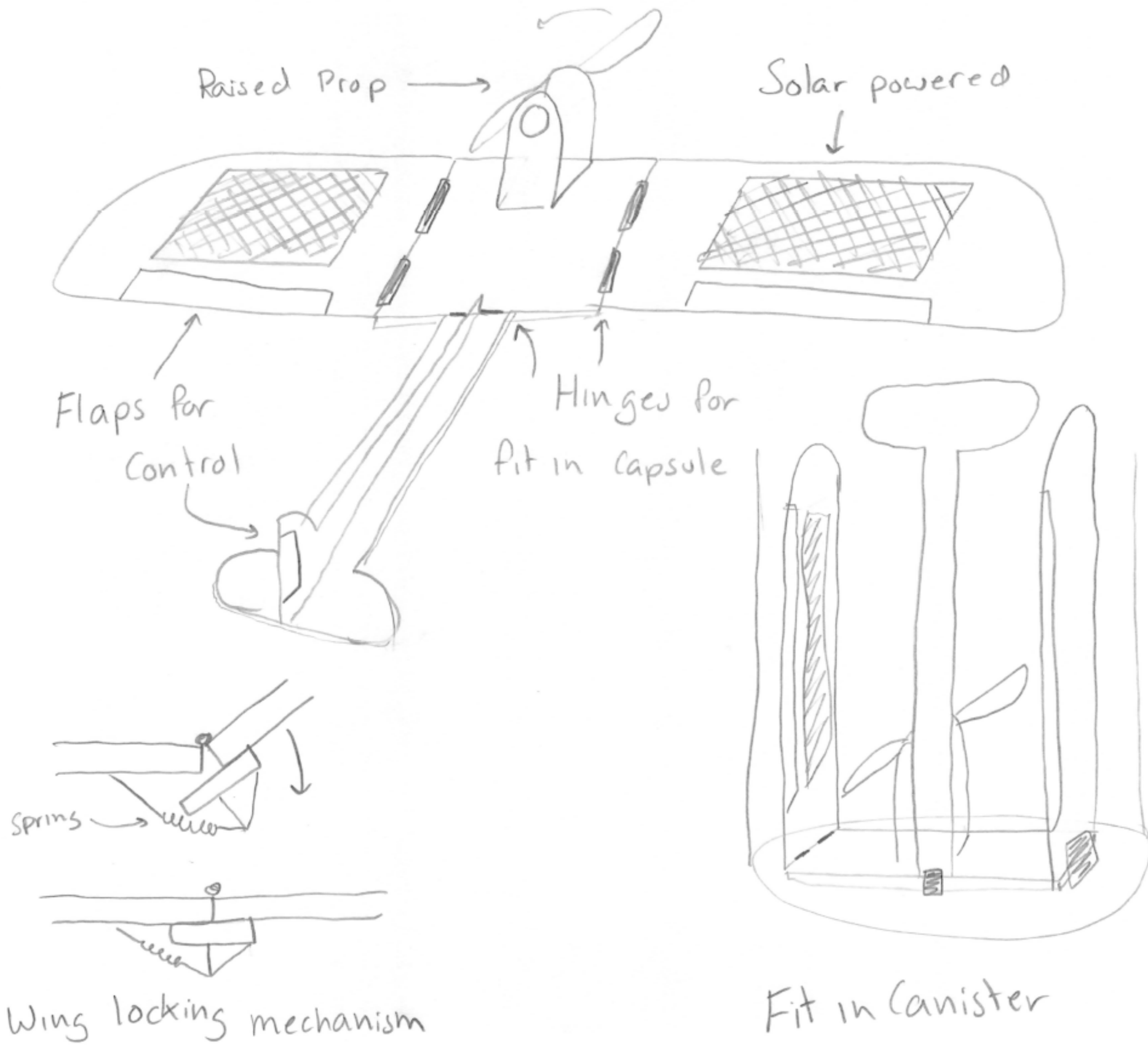


Figure 15: Final sketches of Foldable Plane Concept

Solutions from morph chart:

1. Utilizes both a parachute and fixed wings
2. Flaps to steer the plane
3. Parachute to land
4. Flying over ground removes the need for ground transportation
5. Solar to provide power
6. Altitude and GPS to gather data

Description: A remote control fixed wing aircraft, that is capable of folding up to a size that is capable of fitting inside the specified ARLISS Canister. This design would focus on decelerating and unfolding at a high enough altitude to fly to the designated ground location. Once the parachute has slowed the canister to a slow enough speed, the plane would drop out, and unfold its wings.

As this design would be solar powered, it would not need any heavy batteries, so it could be light enough to be used as a glider if the solar panels fail, or do not provide consistent power. Other sensors could also be mounted to the main plate of the plane if needed. These sensors could include the GPS module, an altitude sensor or anything else needed. The flaps that steer the plane could be set up to be controlled remotely from the ground, or even connected to the GPS module to fly autonomously.

3.4.3 Large Wheel Rover

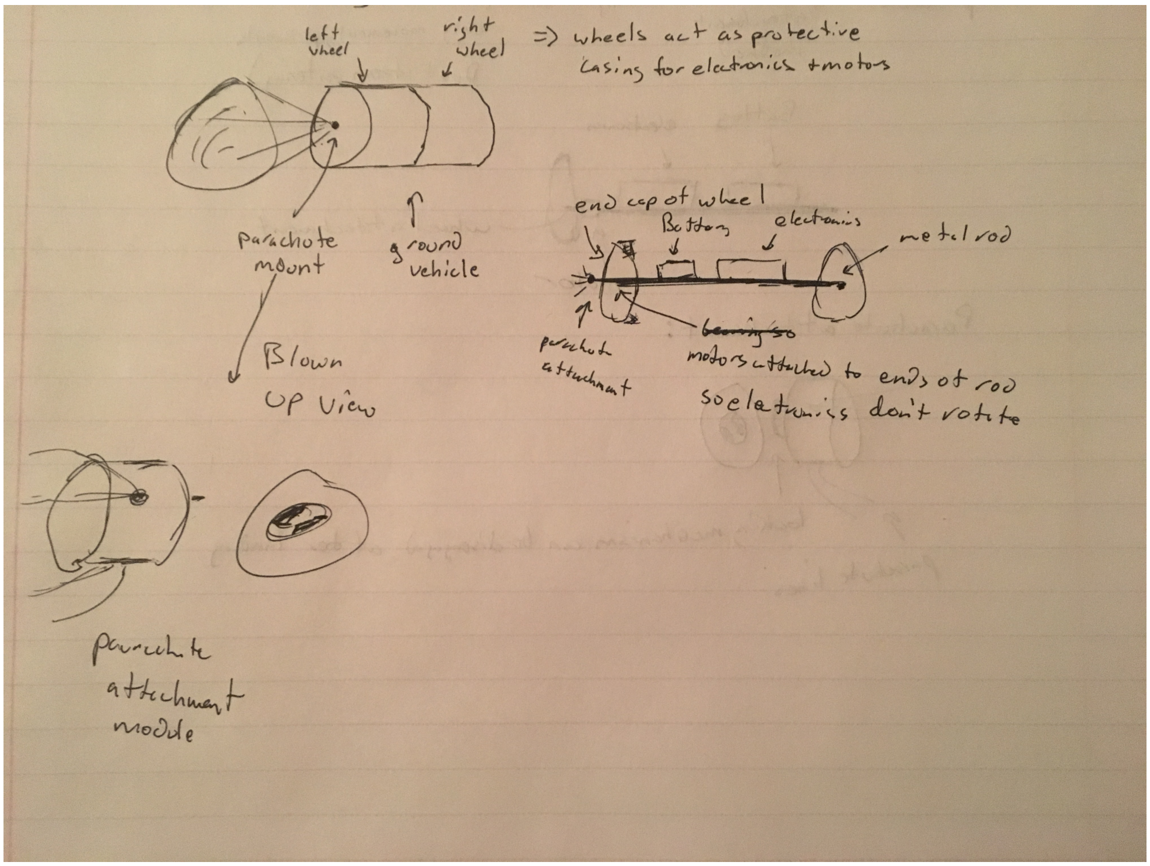


Figure 16: Preliminary sketches of Large Wheel Rover concept

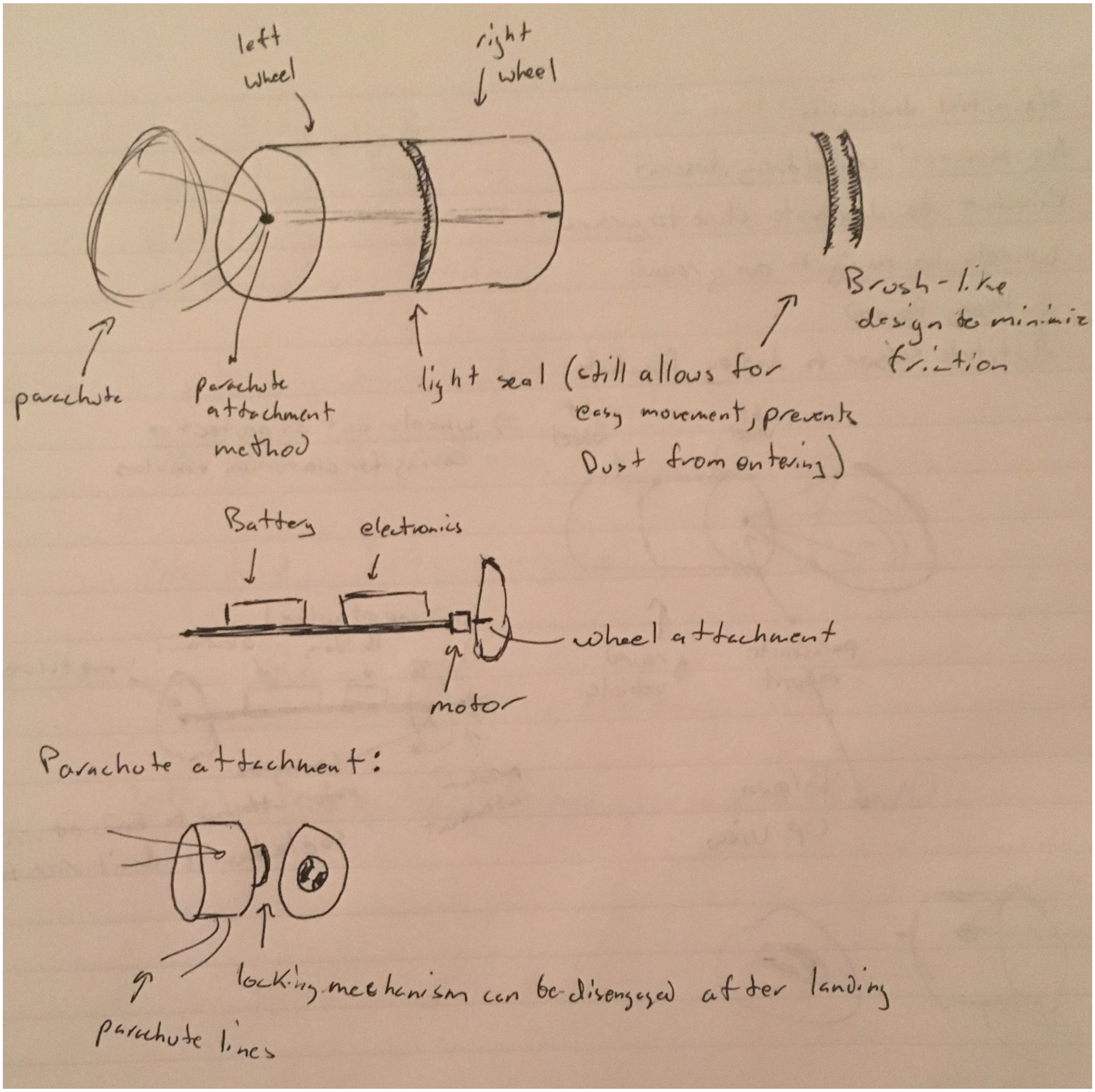


Figure 17: Final sketches of Large Wheel Rover concept

<u>Solutions from morph chart</u>:

1. No initial deceleration
2. No movement control during descent
3. Parachute to decelerate close to ground
4. Wheels to navigate on ground
5. Battery powered

6. Altitude sensor to deploy parachute

Description: There is no way to initially control the fall of the vehicle, however once it gets to the correct altitude, the parachute will deploy. Once on the ground, two wheels covering all of the electronics act as both a housing and method of transportation. Before movement, an accelerometer will detect the landing and release the parachute. Batteries inside the wheels will power the GPS and motors to move to vehicle to the final location. These solutions were chosen to minimize complexity of both the design and control of the vehicle.

3.4.4 Mini-Hoverboard with Parachute

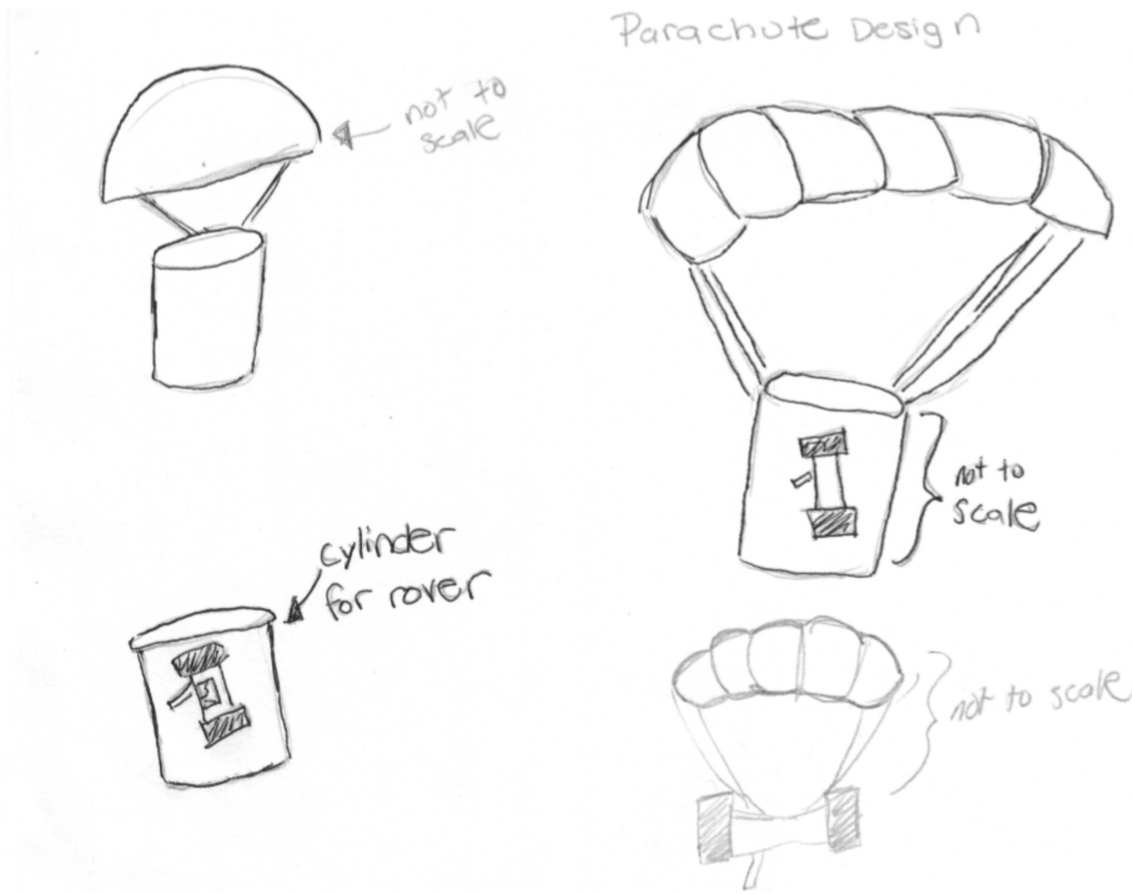


Figure 18: Preliminary sketches of Mini-Hoverboard concept

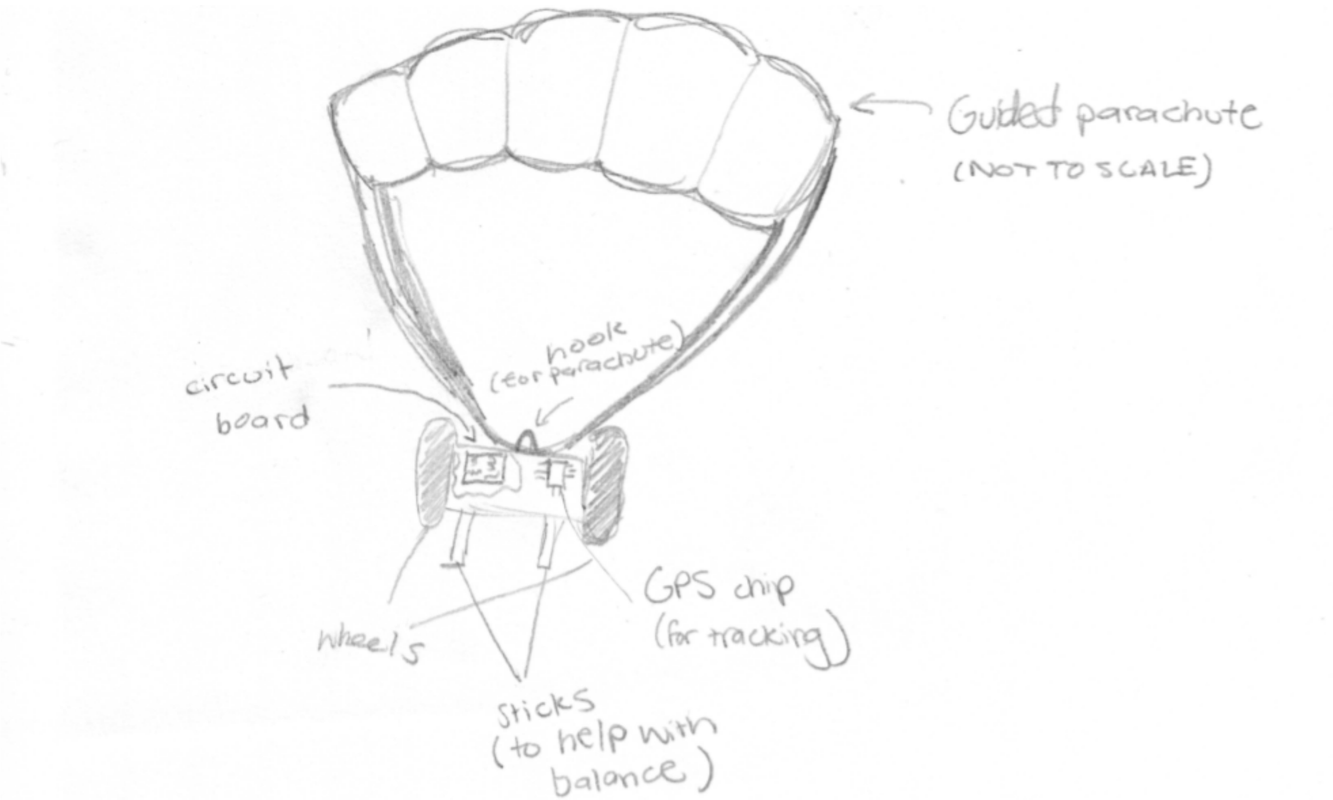


Figure 19: Final sketch of Mini-Hoverboard concept

Solutions from morph chart:

1. Steerable Parachute to safely guide vehicle
2. Parachute to decelerate descent towards ground
3. Wheels for movement on ground
4. Solar Panel to provide power
5. Altitude sensor to determine safe distance to ground
6. GPS chip to monitor location

Description: A mini-hoverboard-like design with a parachute attached to a hook on the vehicle. The parachute is steerable, allowing the vehicle to descend to more desirable location, while also slowing the descent towards the ground. On the vehicle is a board with an altitude sensor and a GPS chip that monitors the position of the vehicle. The vehicle is powered by a solar panel and has two wheels for motion along with two sticks to keep the balance of the vehicle.

4 Concept Selection

4.1 Selection Criteria

In order to determine the weights for each of the scoring criteria we used the Analytic Hierarchy Process. By directly comparing the selected criteria to each other we can accurately judge what design will best accomplish our goals.

	Cool Factor	Data collection	Manuverability	Durability	Battery Life	Cost	Row Total	Weight Value	Weight (%)
Cool Factor	1.00	1.00	0.33	0.20	0.14	1.00	3.68	0.05	4.53%
Data Collection	1.00	1.00	0.14	0.14	0.14	3.00	5.43	0.07	6.69%
Manuverability	3.00	7.00	1.00	1.00	1.00	7.00	20.00	0.25	24.64%
Durability	5.00	7.00	1.00	1.00	0.33	7.00	21.33	0.26	26.28%
Battery Life	7.00	7.00	1.00	3.00	1.00	9.00	28.00	0.34	34.50%
Cost	1.00	0.33	0.14	0.14	0.11	1.00	2.73	0.03	3.36%
						Column Total:	**81.17**	**1.00**	**100%**

Figure 20: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Using the weights that were calculated in the AHP the 4 final designs were compared. Using this Weighted Scoring Matrix we will pick our final design that will be further developed and built.

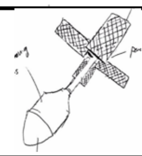
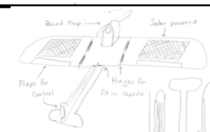
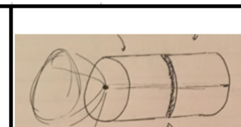
Alternative Deisgn Concepts									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Cool Factor	4.53	1	0.05	5	0.23	5	0.23	1	0.05
Data Collection	6.69	3	0.20	2	0.13	2	0.13	3	0.20
Manuverability	24.64	5	1.23	2	0.49	2	0.49	4	0.99
Durability	26.28	4	1.05	3	0.79	1	0.26	4	1.05
Battery Life	34.5	4	1.38	2	0.69	2	0.69	4	1.38
Cost	3.36	3	0.10	3	0.10	3	0.10	3	0.10
	Total score	**4.010**		**2.432**		**1.907**		**3.764**	
	Rank	**1**		**3**		**4**		**2**	

Figure 21: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

From our Analytic Hierarchy Process, battery life was deemed the most important criteria for our project design. Behind battery life, durability and maneuverability were also crucial toward our design. The criteria with the least weight was cost of materials. For this project, cost will not be an issue due to the requirements of our design.

After determining the weights of our design criteria, we rated the four designs from the Concept Generation section. The design that ranked the highest was the mini-hoverboard design. This design includes a steerable parachute for maneuverability and slowing the descent of the drop. It also has a solar panel to provide power to the design. This design was rated highly for battery life, durability, and maneuverability, which were the criterion that were weighted the most heavily. Other designs were rated equal to or higher in a few design categories, but the mini-hoverboard design rated the highest overall. Therefore this design concept was chosen since fit the design criteria of our project best.

4.4 Engineering Models/Relationships

The first model being used during the design process controls the design of the parachute, and therefore the descent of the vehicle. While many aspects of the landing vehicle can be repeatedly tested, if the parachute is not properly modeled before testing, the entire vehicle is at risk of being destroyed on landing. The following equation can therefore be implemented before testing.

$$V = \sqrt{\frac{2 * W}{C * r * A}} \tag{1}$$

In the equation above, V is the terminal velocity of the lander with the deployed parachute, W is the weight of the lander, C is the drag coefficient of the parachute, r is the density of air, and A is the total area of the parachute. For our case, C can be approximated as 1.75 and r is 1.229 kg/m^3. Both the overall weight of the lander (W) and the area of the parachute (A) are therefore the two parameters that will effect the landing velocity of the vehicle.

A second important model considered during the design process of the ARLISS lander is the battery life. In order to ensure all of the sensors are properly powered during launch and landing, and that the vehicle can travel 5000 meters after landing, the battery must be pretty large. In order to measure this, this simple equation can be employed.

$$BatterySize = CurrentDraw * time \tag{2}$$

This equation is for calculating the battery size in milliamp hours, or mAH. This metric is commonly used to classify battery size. This equation shows that if you know the current supplied to your electronic components, and approximately how long they must be powered for, you can calculate the size of the battery. Of course for this project it is possible that the vehicle has to operate for longer than expected, so some safety factor can be employed in this calculation to ensure excess battery capacity.

The third model used for the ARLISS project is a potentially useful geometrical model. The rover must be able to drive over moderately rough terrain in the desert, or for our prototype over rough grass. To easily achieve this, there must be sufficient clearance off the ground to the bottom of the electronics package. The simple equation below can be used to ensure the rover can move properly through desert terrain.

$$R_e = R_w - C \tag{3}$$

In Equation 3 above, R_e represents the maximum radius of the electronics package, and R_w represents the maximum radius of the wheels. C is the clearance off of the ground required for the electronics package. All units are inches.

5 Concept Embodiment

5.1 Initial Embodiment

The designs shown on the following three pages make up the preliminary prototype of our ARLISS vehicle. Previously, several models were introduced to assist in the design process. These provided a great guide during the design process of the prototype. The first model made choosing the parachute an easy process. Simply estimating what landing velocity we wanted and the mass of the entire rover, we were able to choose a 2 food diameter parachute.

The electronics package required many redesigns, and after testing may require even further revisions. This is thanks to the second and third models we chose for our project. The second model estimated the size of the battery required in milliamp hours. This forced us to purchase a physically larger battery than we would otherwise have opted for, and therefore reduced the ground clearance of the electronics package. As can be seen in Figure 22, the battery ended up fitting in snugly below the gear and motor assembly. This design was chosen thanks in part to the size of the battery required, and mainly due to the third model. This model made sure we considered the ground clearance. If the battery was not positioned as close to the motor as it is, there would be only a couple of millimeters of clearance off the ground. This could result in the battery being scraped on the rough desert floor during operation.

The current design was chosen also due to its ability to achieve the three performance goals of this stage. Our goals were as follows:

1. Drive the vehicle several kilometers without it failing or human intervention
2. Successfully drop the vehicle three times without it breaking
3. After landing, successfully drive away either with the parachute attached, or after it detaches itself

In order to achieve the first goal, the large battery and motor were chosen. For the second, the two foot parachute was attached to the parachute attachment ring in the center of the vehicle. Finally, for the third part, the parachute attachment ring was designed to rotate freely around the axle. This means that as the vehicle drives, the parachute can freely hang behind the rover without being caught in the wheels.

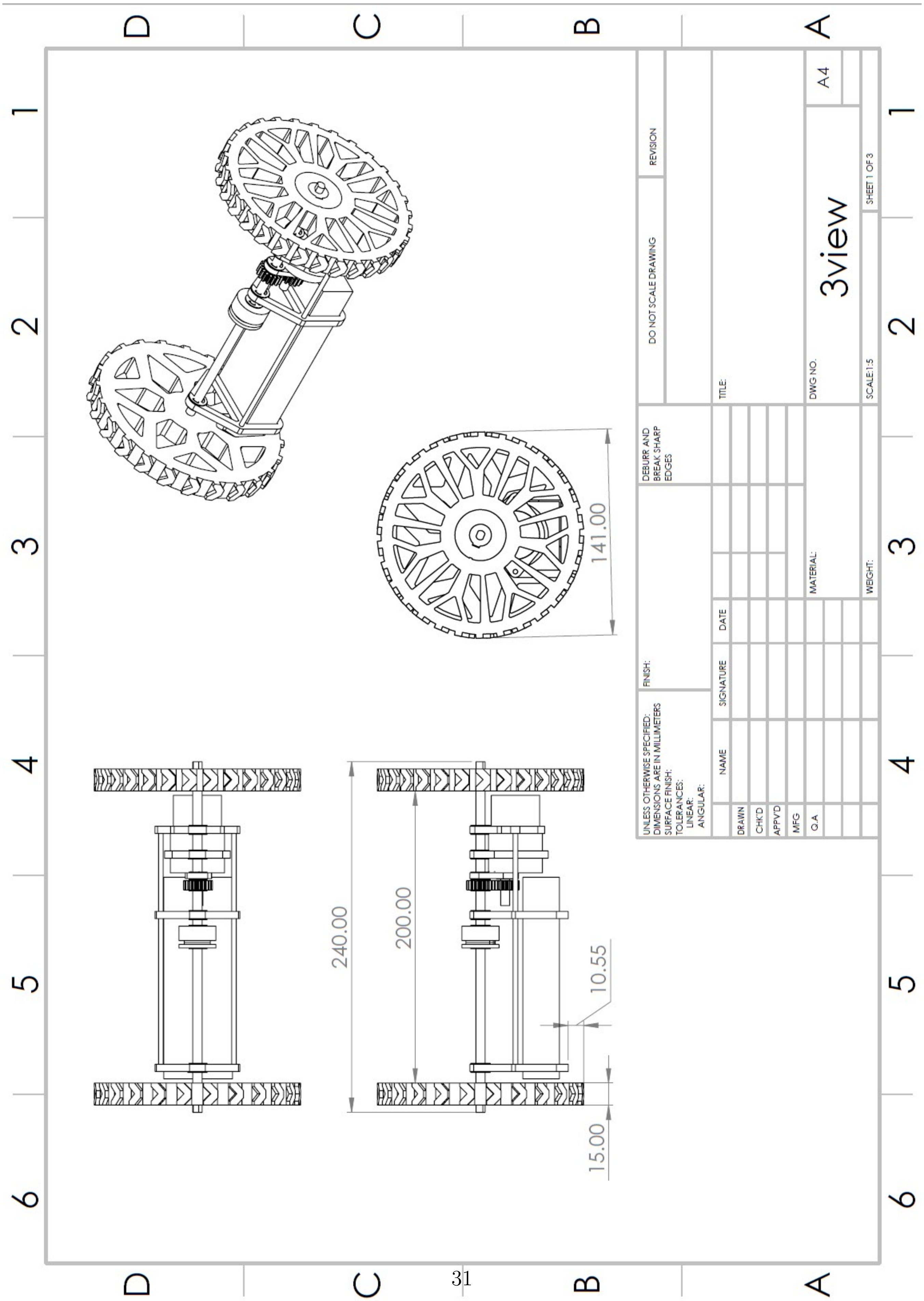
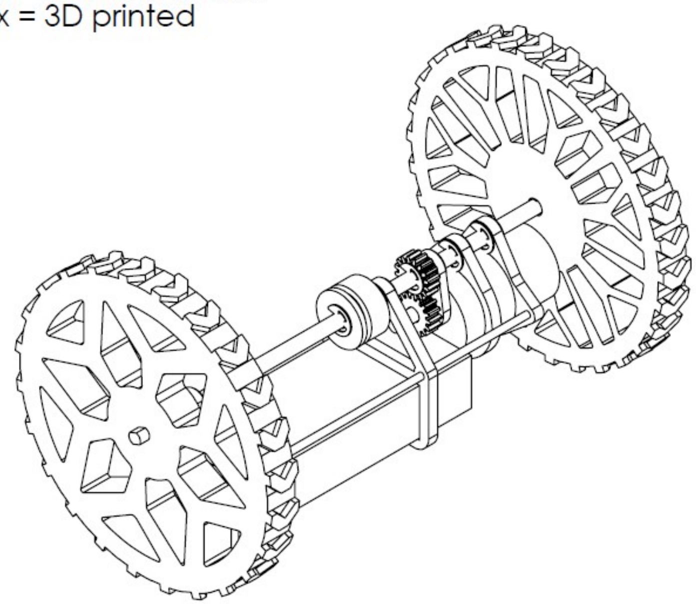


Figure 22: Assembled projected views with overall dimensions

Note: BoM does not inclue electronics,
only mechanical parts.
Part number guide:
1xx = purchased
2xx = made in house
3xx = 3D printed



ITEM NO.	PART #	DESCRIPTION	QTY.
1	101	motor	1
2	102	5200 mAh battery	1
3	201	.25 in aluminum axle	1
4	301	motor bracket 2	1
5	302	motor bracket 3	1
6	303	motor bracket 1	1
7	304	Parachute attachment device	1
8	90341A107	clip for parachute attachment	2
9	305	wheel 1	1
10	306	bearing adapter	1
11	103	one way bearing	1
12	306	wheel with bearing insert	1
13	307	gears	2
14	308	battery bracket	2
15	202	.125 in steel supports	2
16	97431A300	.25 in c clips	14
17	104	parachute	1

Figure 23: Assembled isometric view with bill of materials (BOM)

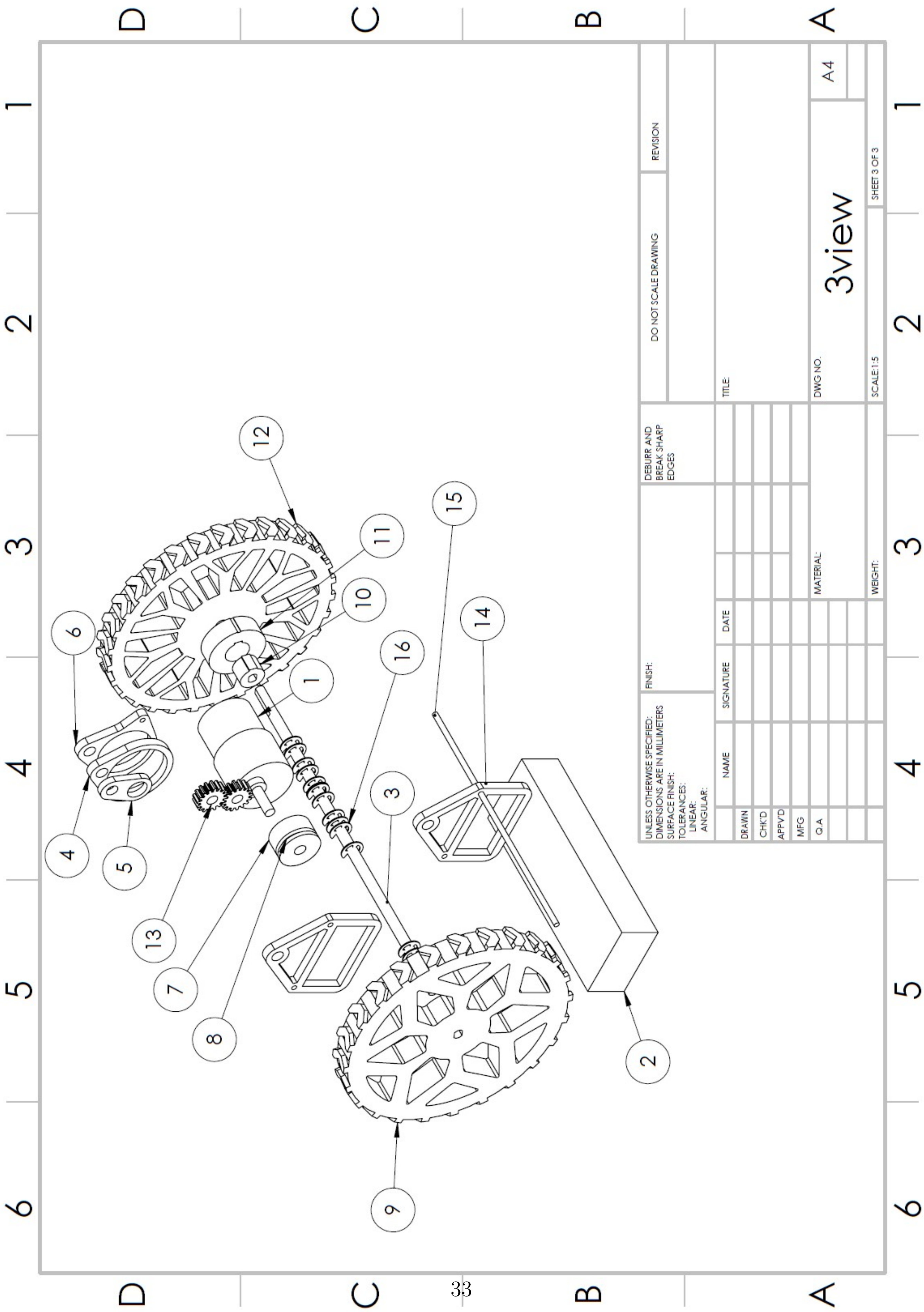


Figure 24: Exploded view with call out to BOM

5.2 Design Rationale

The main motivation and rational for this initial prototype was the decision to only use one motor. This was done in order to keep the weight, complexity, and the likely hood of failure to a minimum. The other main design rational was that without a stabilizing leg to maintain balance, the center of gravity had to be well below the axle of the rover, in order for it to drive efficiently. This was why both the battery and the motor hang below the axle, side by side. This left very little room to attach the parachute on the sides of the rover, so instead it was attached in the center of the axle. Another aspect in our design rationale was the parachute size. The size of the parachute influenced the terminal velocity of the vehicle. This relation can be seen in the following equation.

$$V = \sqrt{\frac{2 * W}{C * r * A}} \tag{4}$$

Where V is the terminal velocity of the vehicle after the parachute is deployed, W is the weight of the vehicle, C is the coefficient of the parachute, r is the density of air, and A is the area of the parachute. For r, we assumed a value of 1.229 kg/m^3, which is the typical value used for air density. For C, a value of 1.75 was used based on a typical parachute used by NASA[1]. By using an area of 2 ft^2, or 0.186 m^2 for the parachute and a weight of .800 kg, the terminal velocity is calculated to be:

$$V = \sqrt{\frac{2 * .800}{1.75 * 1.229 * 0.186}} = 3.999 m/s \tag{5}$$

This terminal velocity also assumes ideal weather conditions and that the vehicle falls straight down without any factors to disrupt the vehicle's center of gravity before hitting the ground. Another assumption made is that the vehicle lands evenly on both wheels so that the force on the vehicle upon impact is evenly distributed.

5.3 Proofs-of-Concept

Our Proof-of-Concept prototype influenced our Initial Prototype's parachute. The Proof-of-Concept was a glider, so when the prototype was to be dropped, it would glide down to the ground. Our Initial prototype design included a parachute attached to the axle. When the Initial Prototype was dropped, the parachute expanded and slowed the descent of the prototype to prevent it from slamming into the ground.

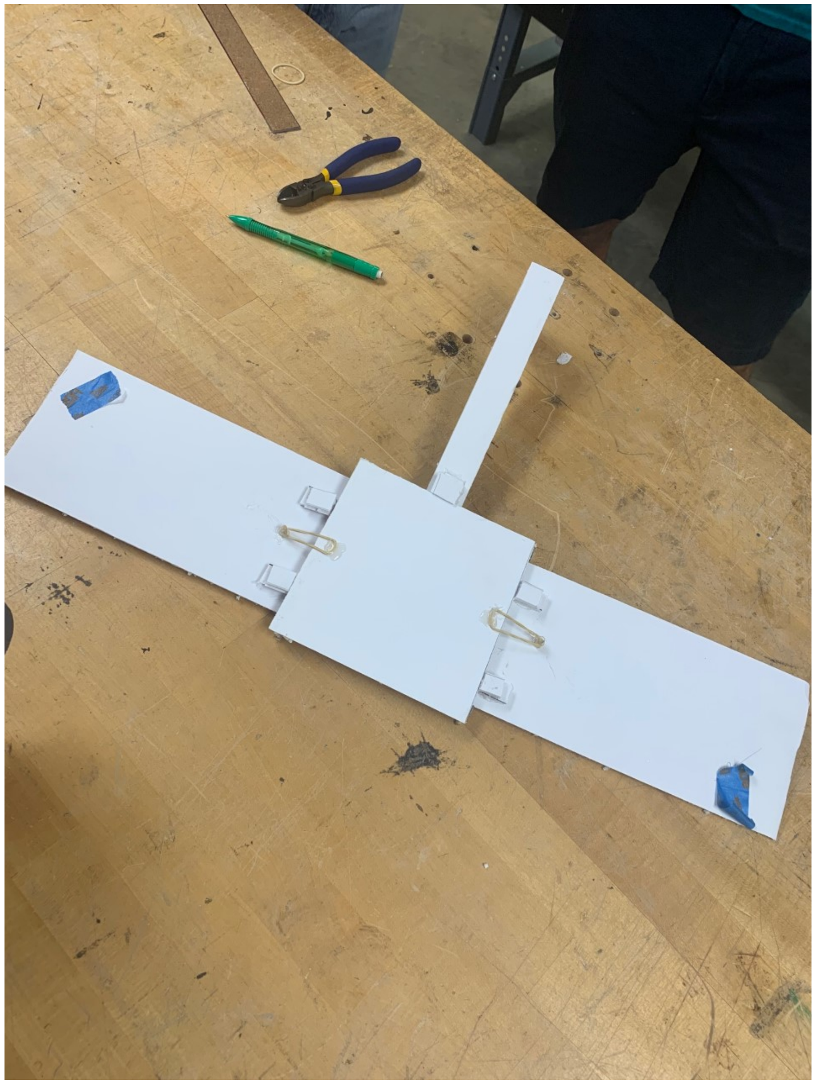


Figure 25: Bottom view of Proof of Concept

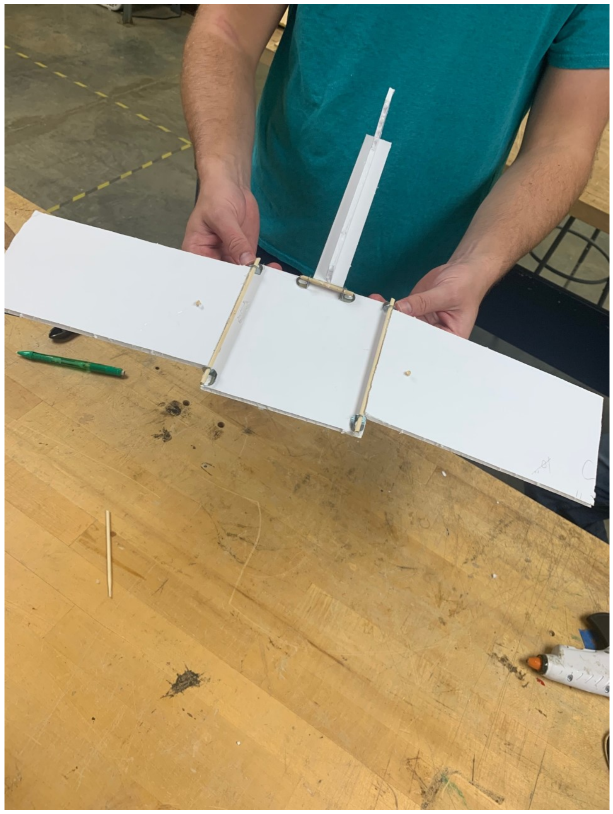


Figure 26: Top view of Proof of Concept with wings extended

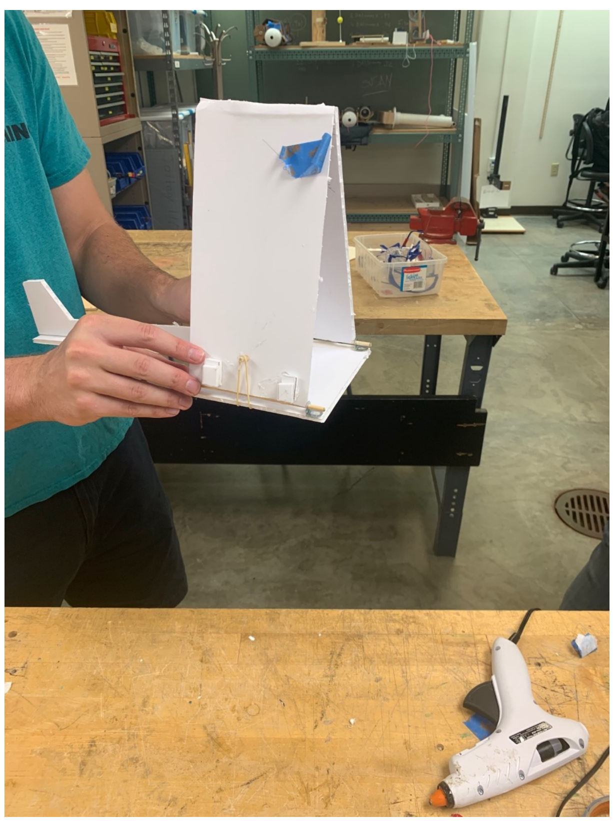


Figure 27: Proof of Concept with wings folded

Some design differences between the Initial Prototype and the selected concept from Section 4 are that the selected concept design had solar panels while the Initial Prototype only contained a large battery. This change comes from the fact that the solar panels would cost more and would not fit with the design we went with for the Initial Prototype. Solar panels would also require sunlight/strong artificial light to consistently power the rover. A large battery was used instead since it was cheaper, did not depend on light, and fit with the design of the Initial Prototype. Another difference was that the selected concept design had a plate to hold the electronics and power supply on, with the axle underneath. The Initial Prototype only had an axle with 3D printed brackets to hold the battery and motor. This difference came from the weight restriction of the entire design. The overall weight of the rover could not exceed 1.05 kg. The removal of the plate gave more freedom with what could be used in the design without exceeding the overall weight limit.

6 Working Prototypes

6.1 Overview

Our ARLISS project started with a proof of concept before moving on to and designing a initial prototype. After testing our initial prototype, we observed what needed to be changed based on the results of our testing. We redesigned our final prototype and changed what would have the most impact on our design before re-testing again.

6.2 Initial Prototype

Our initial prototype had a single motor attached to a battery to allow it to move. A one-way bearing was installed to give the prototype the ability to turn by not allowing the wheel with the one way bearing to move while the vehicle tries to move backwards. The parachute was attached to the center of the axle. When the rover was tested to see whether it would survive the drop test, the weight of the battery caused the center of gravity to change, affecting the landing of the rover. This caused the rover to land at an angle and damage the axle and one of the wheels.

6.3 Final Prototype

Learning from our testing of our initial prototype, we changed the axle to steel and added a second parachute attachment to allow the parachute to open more to keep the rover from moving side to side and land at an angle after being dropped. The battery was also secured with 3D printed brackets to keep it from altering the center of gravity of the rover. Finally the wheels were reprinted with a more flexible material to allow the wheels to absorb more of the impact rather than place all the stress on the axle. These modifications proved to work when testing our final prototype, as our rover remained intact and was able to operate after being dropped.

7 Design Refinement

7.1 FEM Stress/Deflection Analysis

As the axle not only transmits power to the wheels but also serves as our main structural component, we chose to analyze the maximum stress and deflection of our aluminum axle.

7.1.1 Setup

Any bending in the axle will not only prevent our vehicle to travel in a straight line but could prevent the axle from freely rotating within our brackets. However due to the difference in loads placed on the vehicle as it hits the ground and as it moves under its own power, 2 different loading conditions are needed. The first will assure that no plastic deformation of the rod occurs when the rover hits the ground and the second assures that the bending of the axle is not too great in any one point to cause the axle to wedge itself into one of the brackets and prevent movement. In both cases the mesh and constraints will be the same, only the magnitude of the loads caused by the hanging brackets will change.

Since the loads and constraints acted normal to each other it was decided to simplify the axle into a square beam with a diagonal dimension of 0.25 in. Meaning that the tested axle will have a smaller cross section than the actual axle and thus overestimate any stresses, not caused by singularities within the FEA solution. While this prevents the use of a bearing load, which would more accurately model the load placed on the axle by the brackets it allowed us to more realistically constrain the ends of the axle. The loads were placed at the location of each load bearing bracket on the axle. For the first test which modeled the impact with the ground, the magnitude of each load was made to be 2 lbs, creating a total load of 8 lbs. This allows for an impact of 4Gs, which is greater than the predicted impact, allowing some margin if the parachute did not fully deploy. For the case when the rover is moving on the ground this load will be changed to 0.5 lbs. creating a total load of 2 lbs, which is slightly over the weight of all the components supported by the axle. The location of the wheels were fixed in one direction with rollers preventing deflection and rotation of the wheels. This assumes that the rover lands flat on both wheels and that the wheels do not absorb any of the impact. This assumption again will overestimate our expected load as the wheels are flexible and explicitly designed to absorb a large amount of the impact energy. Despite this it is difficult to predict the elasticity of the wheels and determine how much the axle would be allowed to deflect without knowing the wheel orientation as it hits the ground. Additionally an edge on one side was fixed to fully constrain the model. This constraint should not impact our results as it does not prevent any natural movement of the part under this load pattern.

7.1.2 Results

Below in 28 the mesh, constraints and loads can be seen. The constraints are shown in green with the loads being shown in blue. The mesh is very fine, much finer than a test of this complexity would require but was kept as it only served to increase the accuracy of the run.

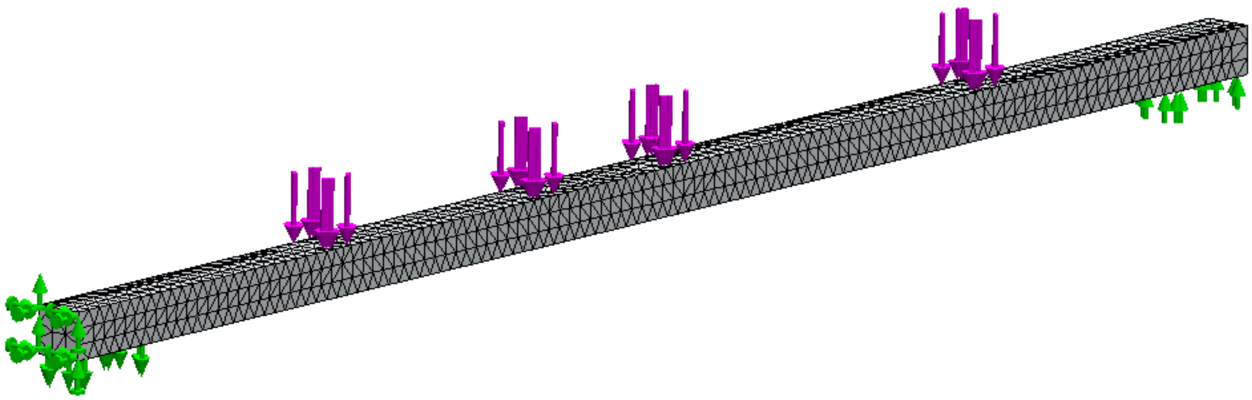


Figure 28: Unloaded Axle with Mesh and Boundary Conditions Shown

The figure below shows the stress distribution of the axle while it is experiencing the impact load of 8 lbs. The maximum stress can be identified on the axle as 2.663 ksi.

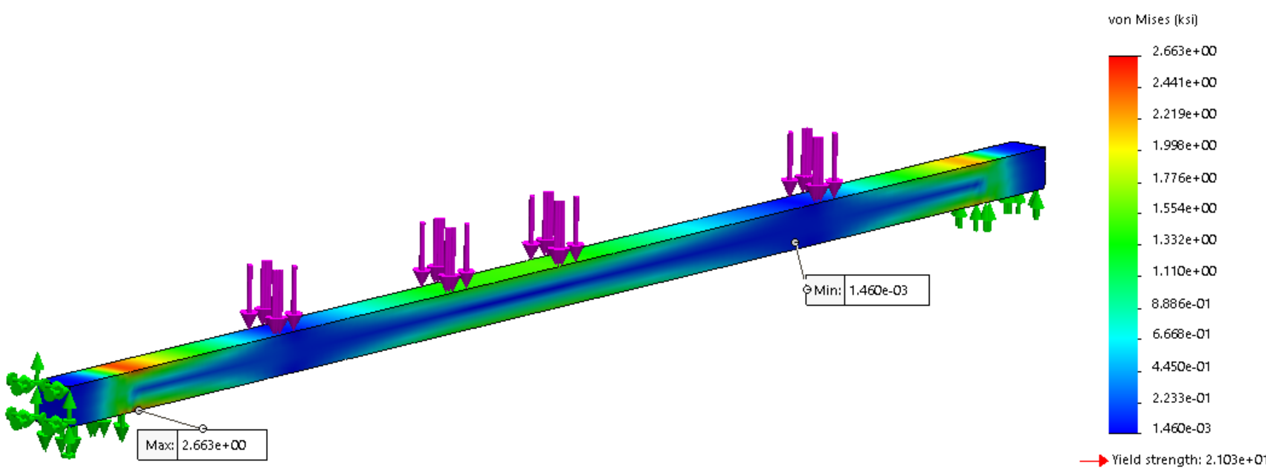


Figure 29: Von Mises Stress on Axle

The figure below shows the deflection of the rod while experiencing the impact load of 8 lbs. The deformed model is shown with a scale of 12. The maximum deformation is also identified on the figure as 0.00517 in.

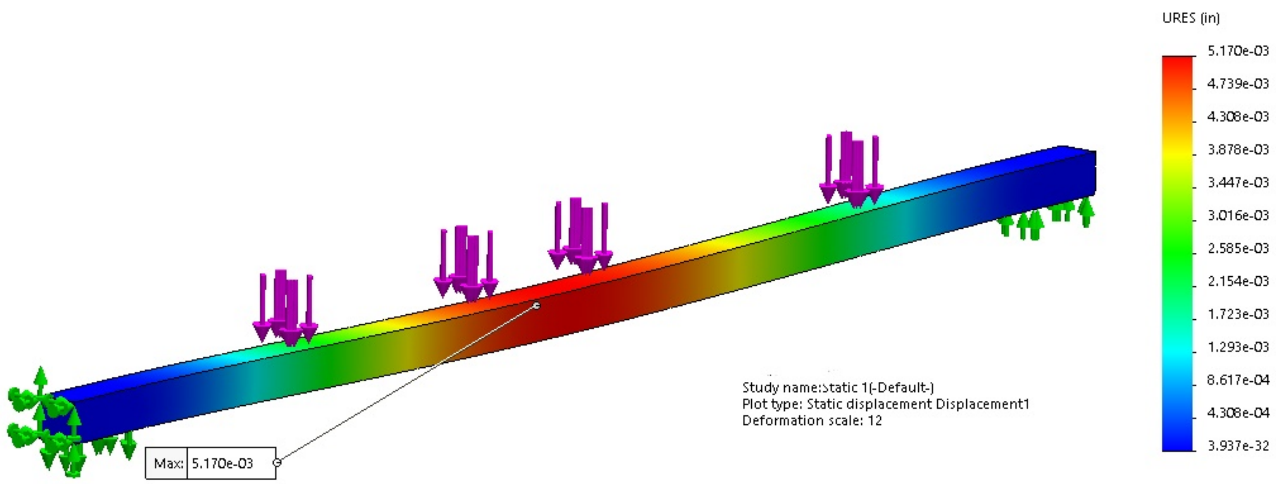


Figure 30: Axle Deflection

7.1.3 Analysis

Since the axle is a critical component and a failure of the axle would result in a complete failure of the vehicle, a high factor of safety was used. For this component the factor of safety was 2.0 on yield and 3.0 on ultimate. The axle is made out of a 6063-T5 aluminum and thus has a yield strength of 21 ksi and a ultimate strength of 27 ksi [2]. Using the maximum stress found from the FEM analysis of 2.663 ksi. This equates to a large margin of safety when calculated using the von mises failure theory.

$$M.O.S._Y = \frac{YieldStrength}{MaximumStress*FOS} - 1 = \frac{21ksi}{2.0*2.663ksi} - 1 = 2.94$$

$$M.O.S._U = \frac{UltimateStrength}{MaximumStress*FOS} - 1 = \frac{27ksi}{3.0*2.663ksi} - 1 = 3.38$$

While these margins of safety are unnecessarily high it would not make sense to use a smaller axle as any smaller size would be too difficult to machine slots for our C clips and the edges to attach to the wheels. This large margin of safety also allows for a larger than expected landing velocity or uneven landing, placing more force on one wheel than the other. Also, due to the high margins of safety, it was decided that a second run under normal driving conditions would not be necessary.

Next the deflection of the rod was found. As we did not expect the axle to yield upon impact deflection was the larger concern for our group. The free running holes in the brackets have a greater diameter than the thickness of our axle. This meant that large deflections could result in the brackets wedging itself stuck on the axle. This would prevent it from rotating and seriously hinder the movement of the vehicle. The maximum deflection occurred towards the center, in between the two closest brackets, of the axle as expected. The maximum deflection, which is identified in Fig. 30 is 0.00517". This deflection is very small and should not effect the rotation of the brackets around the axle. Approximating the location of maximum deflection to be located $\frac{1}{3}$ of the way down the axle, which would produce a more severe slope than actually expected, and assuming the battery to be rigid, a safe assumption as it is in a hard case and sufficiently supported, our holes in the brackets of 0.266" would still be able to rotate smoothly even with the rod experiencing its maximum deflection. It should also be noted that this is under the maximum loading configuration, upon landing, as long as this deformation remains elastic a larger deformation upon landing can be tolerated assuming there is a smaller deflection under normal driving conditions. However, as the deflection was sufficiently small for proper operation under the largest expected loads it was decided that a test under normal driving conditions was not necessary.

7.2 Design for Saftey

7.2.1 Risk #1: Choking hazard - small gears

Description: In order to move the vehicle, the motor is attached to the axle with two small PLA gears. One of them is glued onto the axle and cannot easily be removed, however the other is more loosely attached to the motor. During initial testing, it was found that this small gear, about the size of a marble, could be removed from the motor without much effort. This problem presents a choking hazard.

Severity: Catastrophic. Even though it is a somewhat soft material (plastic), the tiny gear teeth on it are somewhat sharp. If it were swallowed it could cause substantial damage.

Probability: Seldom. While the gear can fall off of the motor somewhat easily, the vehicle usually starts malfunctioning before it has been completely removed. This makes it slightly easier to catch the problem before it can be come a choking hazard.

Mitigating Steps: The gear can be attached to the motor shaft by a small amount of superglue or with a metal retaining ring. While the retaining ring might also pose a choking hazard, it is less likely to fall off than the current configuration (see Risk 2).

7.2.2 Risk #2: Choking hazard - retaining rings

Description: Most of the PLA brackets are attached in place by two small metal retaining rings, no larger than the size of a dime. While they are firmly attached to the aluminum axle, it is possible for them to fall off, presenting a choking hazard.

Severity: Catastrophic. Because these components are metal and have moderately sharp edges, if one were to be swallowed it would be extremely bad for the subject.

Probability: Unlikely. There is an extremely small chance one of these retaining rings fall off during setup or operation because they are designed to be secure. There has also been some moderate testing, and it has been found that while using pliers it takes a substantial amount of effort to remove a ring.

Mitigating Steps: This danger can be mitigated by applying a small amount of glue to each ring. This would make sure that the rings would not fall off even if a reasonable amount of force was applied to them.

7.2.3 Risk #3: Parachute Failure

Description: When the vehicle is dropped from a high distance, there is a chance that the parachute may not deploy and the vehicle will drop much faster than intended, posing a risk to people standing or walking in the drop zone.

Severity: Catastrophic. If the parachute does fail to deploy and completely open up, the vehicle will drop at full speed, which will greatly damage the vehicle upon impact. Furthermore, any person that is in the drop zone would be at risk of being hit by the falling vehicle, which could cause injury.

Probability: Occasional. The parachute is a little small, so there is a chance that the parachute does not open up completely due to less air being able to rush in and open the canopy. The vehicle landing safely is heavily reliant on the parachute deploying properly.

Mitigating Steps: The current design only uses one parachute attachment in the center of the axle to hold all the parachute strings. This will be changed by adding a second parachute attachment so that there will be one attachment on each side of the axle. The parachute will be more likely to open completely and keep the vehicle balanced during its descent.

7.2.4 Risk #4: Exposed gears

Description: The gears and motor are exposed while operating, which can be dangerous if fingers get caught in them.

Severity: Marginal. The gears and motor do not turn that quickly. This risk poses a greater severity to small fingers; an adult's fingers would be very unlikely to get caught in the gears and motor.

Probability: Seldom. While unlikely, small children may be able to get their fingers in between the gears and the motor while the vehicle is operating, which could cause their fingers to get caught.

Mitigating Steps: If time permits, the motor and gears can be covered with a material like PVC to prevent any fingers from getting caught in the motor or gears while moving.

7.2.5 Risk #5: End of Axle

Description: The end of the aluminum axle has been filed down to allow the wheels to fit on it. Because of this, the ends are rather sharp and can cut fingers if caution is not used.

Severity: Marginal. The end of the axle is not exposed when the wheels are attached. Additionally, the edge of the axle will only cut if one's fingers move quickly against the edge.

Probability: Seldom. The wheels are securely fastened on to the axle while the vehicle is in operation. The wheels will only come off if enough force is applied to pulling them off of the axle.

Mitigating Steps: The end of the axle is only exposed when the wheels are not attached to the axle. If the wheels are not attached, the end of the axle could be sanded or filed down further to dull the edge and prevent any cutting. However, this risk should be negligible, as the wheels are unlikely to fall off with the current design.

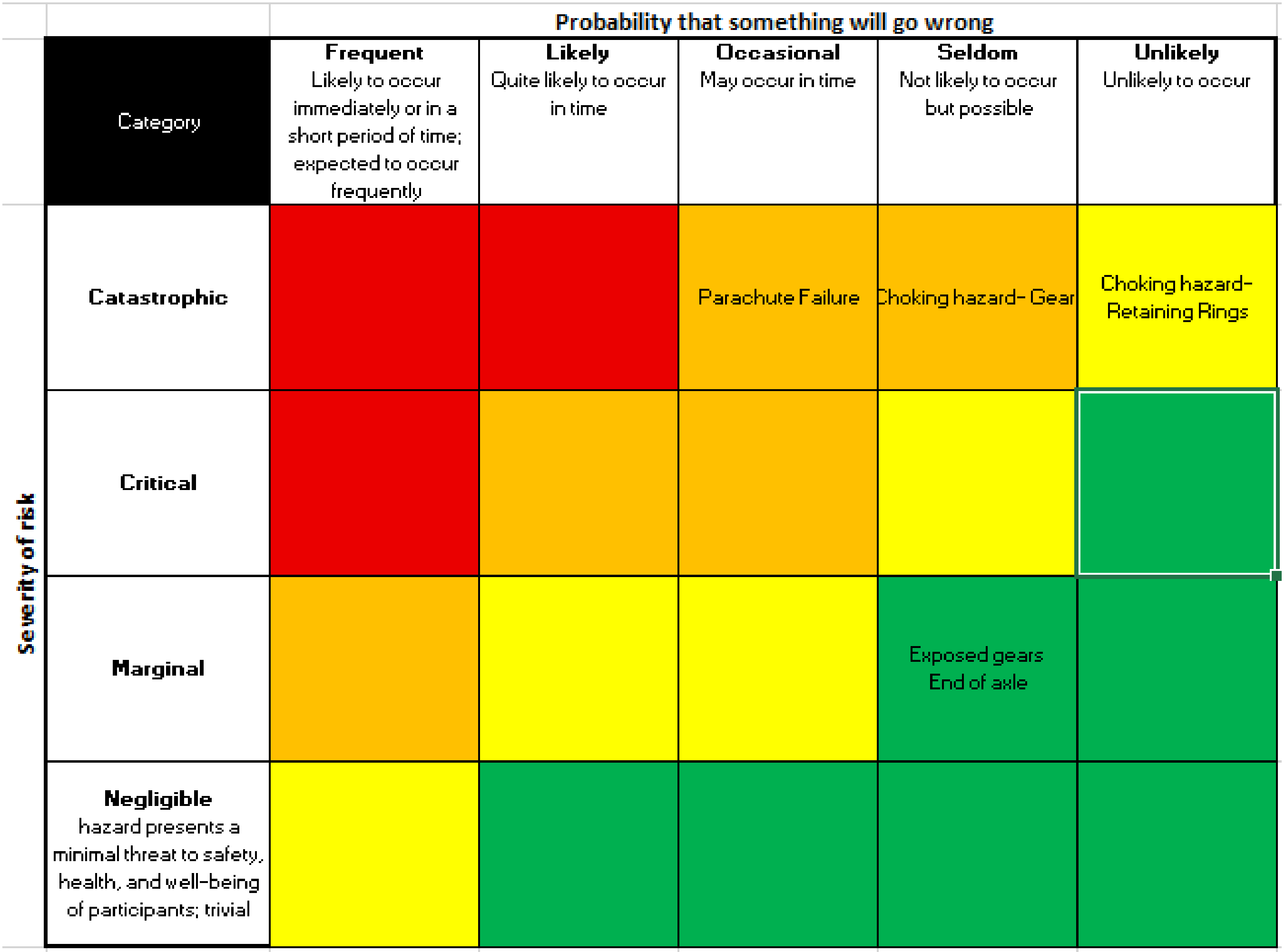


Figure 31: Heat Map of Design Risks

From the Heat Map above, the noted risks with our design are prioritized by the position and different cell shading, with the top-left red cell being the highest priority and the bottom-right green cell being the lowest priority.

Based on the Heat Map, the risk of the parachute failing is the highest priority for our design, as it should be. The parachute is heavily relied on for when the vehicle is dropped. If the parachute does not deploy as intended, the vehicle will be damaged upon landing and may not operate. The next two risks listed in order are the gear and retaining ring choking hazards. Both of these items are small and a gear is more likely to come off before a retaining ring, so the order that these risks are prioritized in are correct. The last two risks are the exposed gears and the end of the axle. These risks are in the same cell on the Heat Map. However, the exposed gears are more likely to pose a greater risk than the end of the axle being too sharp. This is because the axle ends are covered by the wheels and are very unlikely to come off. The ends of the axle can also be sanded down further to make the ends more dull to prevent cutting.

7.3 Design for Manufacturing

In this section, several manufacturing processes are discussed in order to consider some difficulties that may arise from mass production of the ARLISS rover. First, in figure 32, a before and after image is shown of the parachute attachment mechanism using Solidworks draft analysis.

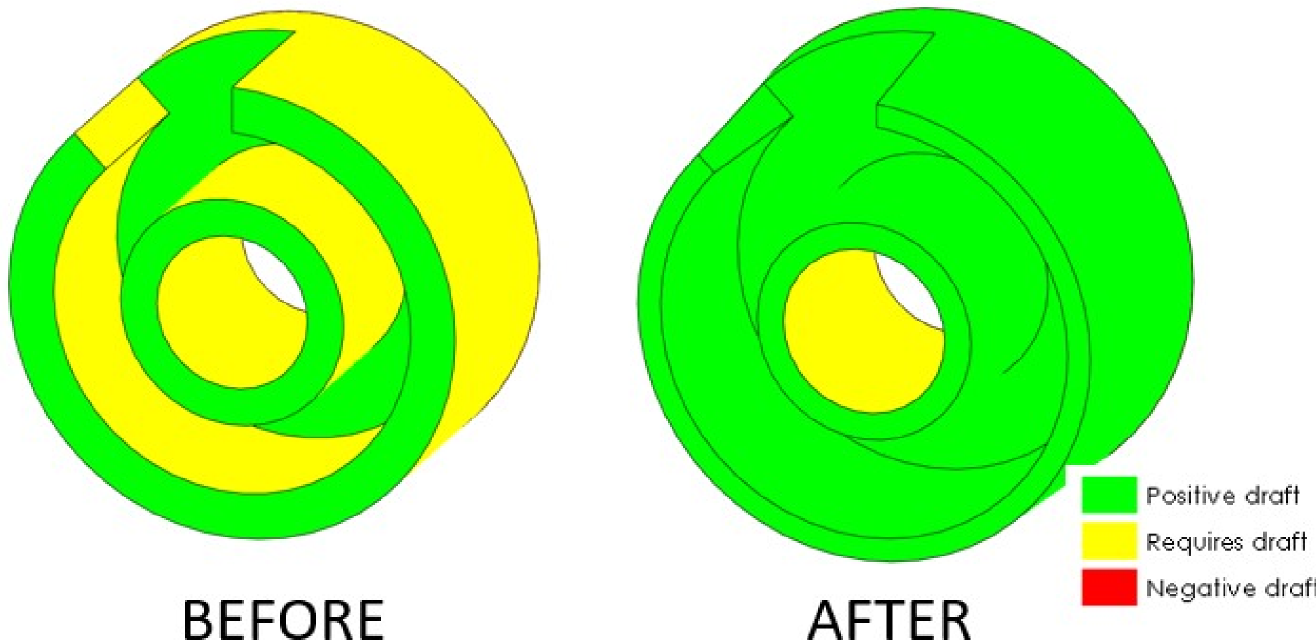


Figure 32: Before and after images of the parachute attachment mechanism using Solidworks draft analysis

The part on the right (labeled "after") is the result of a 3 degree draft being put on all sides except for the center hole. The drafts help with injection molding, however they create slanted sides on parts. Because the center hole has to fit over the aluminum axle of the vehicle, the hole must be in complete contact with the axle. This is why a draft was not applied in that area.

Below are two more images showing tests for design for manufacturing. Figure 33 and 34 show the problems our right battery bracket might have during injection molding and milling. A major redesign may be in order if either of those processes were to be used to mass produce the rover.

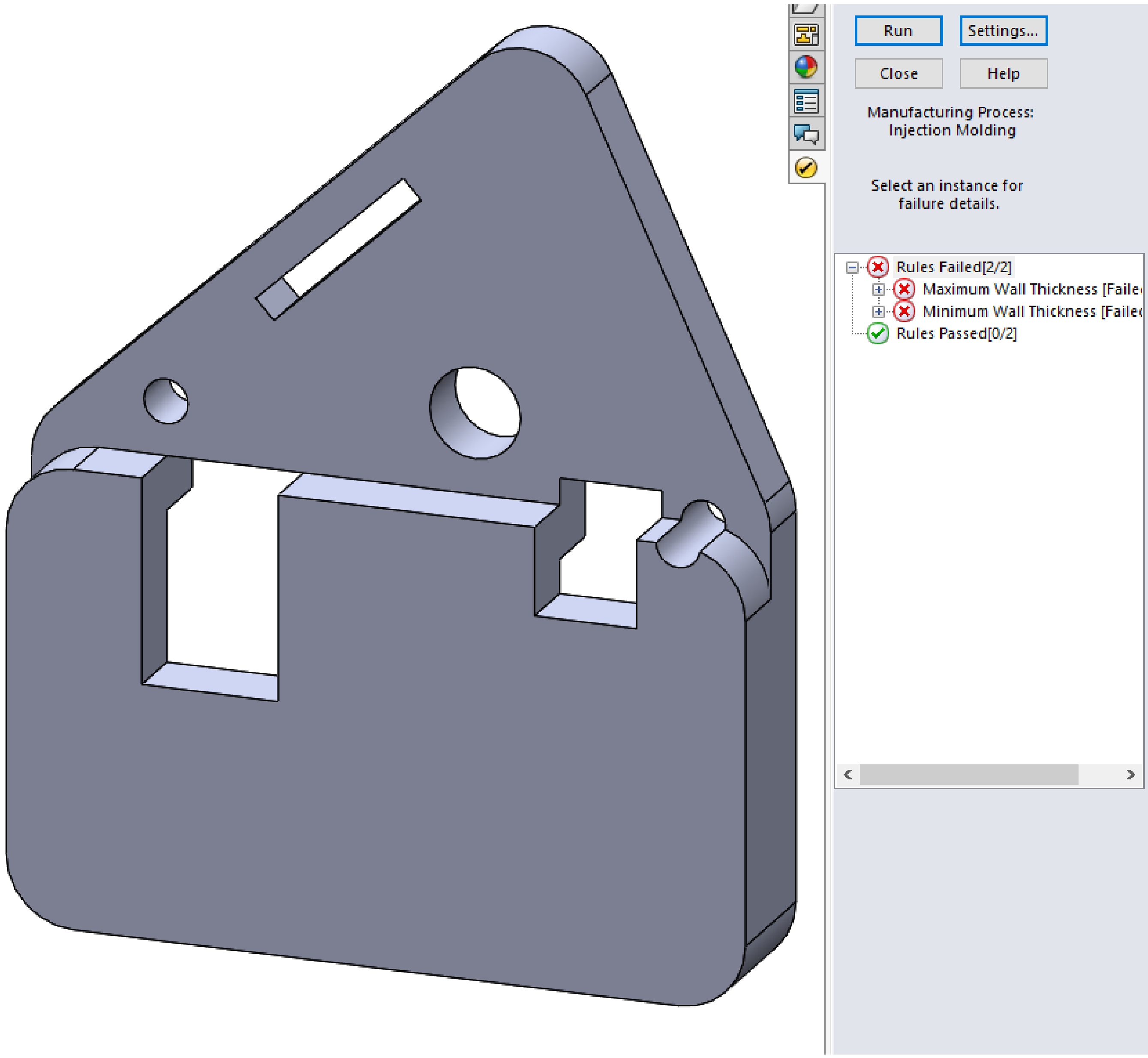


Figure 33: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

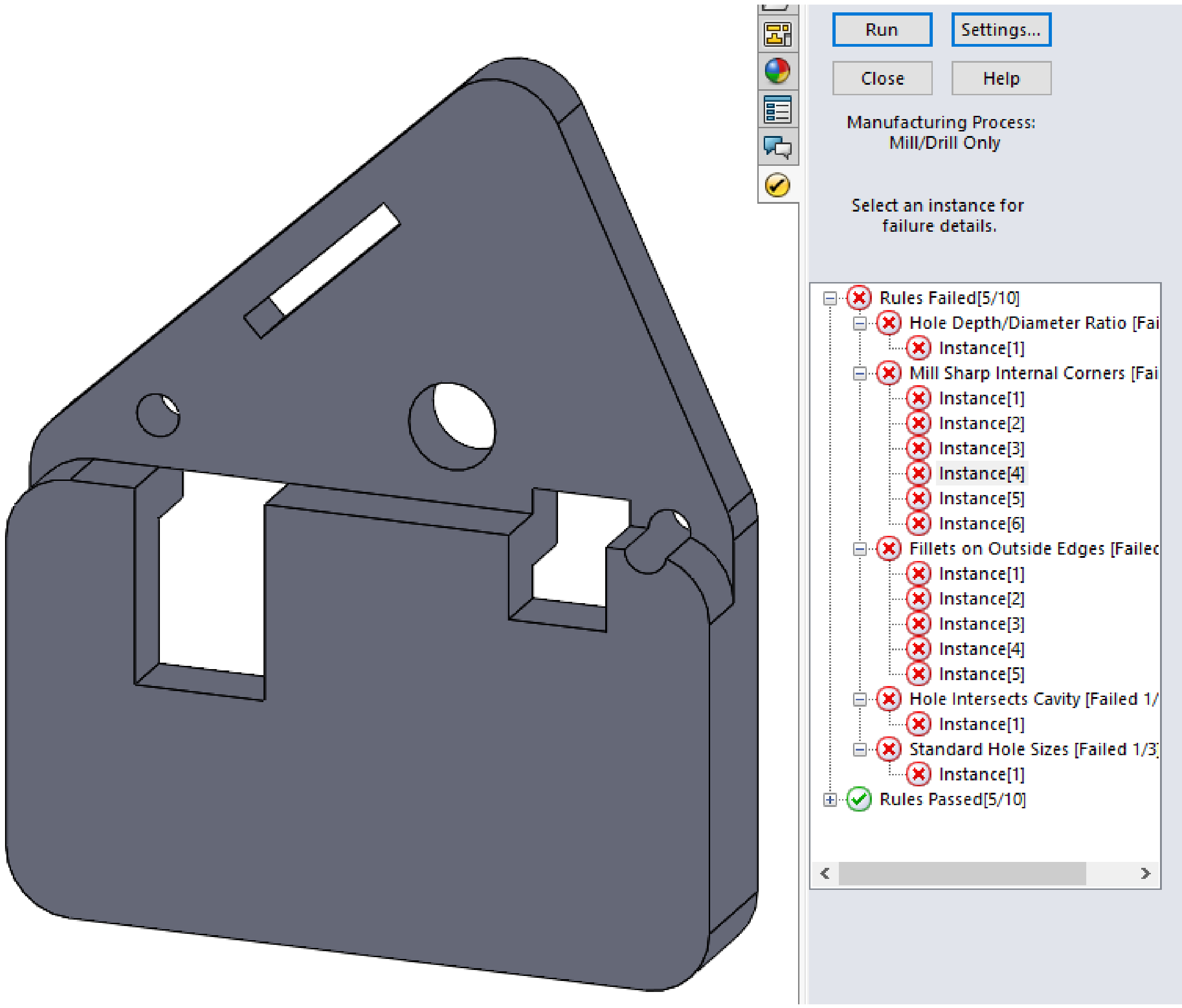


Figure 34: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

The main issue with injection molding the current design is that many of the walls have a thickness of 5 mm. In order to properly cool injection molded parts quickly, it is recommended that the maximum wall thickness does not exceed 2mm in any location. Shelling the component so that all walls are 2 mm thick would be an easy way of meeting that standard.

There were a substantial number of issues found if we were to attempt to make this bracket on a mill. Many of the issues found involve removing the fillets on the outside of the part, and adding a small fillet on the inside. These problems are easily remedied in the model before manufacturing.

7.4 Design for Usability

Vision Impairment: A visual impairment could potentially be detrimental to the use of the ARLISS rover, depending on the type. Color blindness, for example, might cause a small inconvenience in wiring the electronics. Complete blindness would make setting up the rover for operation almost impossible. This is because the layout of the electronics requires careful placement in a tight space. If you are unable to see exactly where each wire belongs it is easy to mix them.

Hearing Impairment: A hearing impairment would not hinder the use of the AIRLISS project.

This is because nothing on the device makes any noise, and not being able to hear it fall would make little difference. The only thing required in the setup of the rover is mechanical setup: putting the project together by hand.

Physical Impairment: One of the most difficult engineering problems encountered during this project was the size constraint. The size constraint also means that it can be difficult to set up the rover for operation, even for someone without any physical impairments. The biggest problem something like arthritis could cause is preparing the electronics. All of the electronics are very small, and ensuring the wires are properly connected before operation can be a difficult task.

Control Impairment: Control impairment could cause some serious problems during the setup of rover. One important problem that could arise from fatigue or distraction is the setup of the parachute. If the parachute is attached incorrectly the rover could be completely destroyed during landing. It is possible that the electronics could be set up incorrectly as well due to this, however anybody could have this problem regardless of an impairment.

8 Discussion

8.1 Project Development and Evolution

Does the final project result align with its initial project description?

- Yes, our final project aligns with the the initial project's description, specifically the second part of the project which involved the rover surviving the drop and being able to drive over rough terrain.

Was the project more or less difficult than expected?

- The project was more difficult than expected, mainly because of the project restrictions, which restricted the dimensions and the weight.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

- Should have spent more time designing the gears and the brackets, as they had to be reprinted several times in order to get correct. The part that required less time was the designing the axle and parachute attachments.

Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

- The wheels were difficult to create with TPE, so only two wheels were printed due to time constraints and the difficulty of the print.

In hindsight, was there another design concept that might have been more successful than the chosen concept?

- Using two motors and bigger wheels with bigger treads would make the rover have an easier time moving and not slip on the ground.

8.2 Design Resources

How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

– Our parachute was important in the design concept, as it was designed to slow the descent of the rover so that the impact would be lessened.

Was your group missing any critical information when it generated and evaluated concepts?

– None

Were there additional engineering analyses that could have helped guide your design?

– Strength tests of the wheels

If you were able to redo the course, what would you have done differently the second time around?

– Design the rover to have bigger wheels and a second motor to power the rover, provided it remains within the weight requirements.

Given more time and money, what upgrades could be made to the working prototype?

– Buy a better motor and battery.

8.3 Team Organization

Were team members' skills complementary? Are there additional skills that would have benefited this project?

– Yes, but having another team member with an electronics background would have been helpful.

Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

– Yes, designing prototypes for other classes that involve using a design process consisting of designing, creating prototypes, and testing.

Bibliography

[1] Tom Benson. *Velocity During Recovery*. URL: https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/rktvrecv.html.

[2] URL: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6063T5.

A Parts List

- Motor
- 5200 mAh battery
- .25 in. steel axle
- motor bracket 1
- motor bracket 2
- motor bracket 3
- Parachute attachment devices
- clips for parachute attachment (2)
- wheel
- wheel with bearing insert
- bearing adapter
- one way bearing
- gears (2)
- battery bracket (2)
- .125 in. steel supports
- .25 in. C clips
- 2 ft. diameter parachute