Fall 2022

MEMS411: We ROCK n’ ROVERIN'

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Washington University in St. Louis
JAMES MCKELVEY SCHOOL OF ENGINEERING

Mechanical Engineering Design Project
MEMS 411, Fall 2022

We ROCK n' ROVERIN'

The goal of this Mechanical Engineering Senior Design project is to create a remotely-controlled rover that can reliably collect dice. The customer, Chiamaka Asinugo, requires a device that meets the needs of a potential challenge that the WURocketry Team might face in future “NASA Student Launch” competitions. These needs include the rover being able to fit into a theoretical payload cylinder that is 5.36” in diameter and 8.5” long and the rover weighing less than 3.5 lbs.

To prepare for the creation of the rover, the group prepared research on previously existing devices and patents for inspiration. Additionally, the group considered how the device would be used based on safety considerations, manufacturability, and usability. Components of the rover were designed based on mathematical models to theoretically prove the feasibility and possibility of the model working.

In creating the final rover design, our group went through three main stages of concept generation: design iterations and initial mock-ups, proofs of concept, and prototypes. In the final physical tests of the design, the rover met or exceeded all prototype requirements. The design consists of a wooden frame and a 3D-printed waterwheel made out of 95A TPU. The rover itself is powered by four continuous micro-servos connected to wooden wheels attached to the servo horns. The waterwheel is powered by a servo attached to the wheel's axis via a pulley system. The waterwheel then feeds the collected ”rocks” up a ramp into the rover for collection. Additionally, the rover has a camera attachment for the user to be able to view and control the rover though. The rover is remote-controlled using a receiver and transmitter device.

This report goes into detail about the processes behind the creation of this rover.

CAINE, Ash
MA, Emily
XUE, Amy

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1 Introduction

For our project, we will be building a rock rover bot for a future WURocketry competition. The robot will be a remote-controlled vehicle that will traverse an area and collect rocks of uneven sizes, that will then be deposited in a designated area. The vehicle will have a camera attached, and will be operated remotely by a user watching the camera's video feed.

The robot will be constructed to fit certain size and weight constraints, which will be checked before the beginning of the contest. During the contest itself, the rover will have five minutes to collect as many rocks as possible and return them to a base area.

2 Problem Understanding

2.1 Existing Devices

The following devices are products that perform similar functions to our robot.

2.1.1 Existing Device #1: BeachBot

Figure 1: BeachBot (Source: Project BB)

Link: https://www.projectbb.org/

Description: The BeachBot is an autonomous AI-driven robot that traverses beaches and picks up cigarette butts, disposing of them in designated safe disposal bins. It has an automated grabber arm that extends to pick up litter and retracts to store it in a bin inside the robot. The grabber arm has two axes of movement (up/down and left/right) so it can lower itself to pick up the litter, and then raise back up into the body of the robot and move to the side to deposit the litter in the storage bin. The frame is lightweight but relatively large compared to the specifications required by the contest. The robot's AI can be trained to look for a range of materials, although it is built to pick up objects in sand instead of on solid ground. It also moves slowly, taking a little over a minute on average to scoop up a single cigarette butt.

2.1.2 Existing Device #2: NASA Perseverance Rover

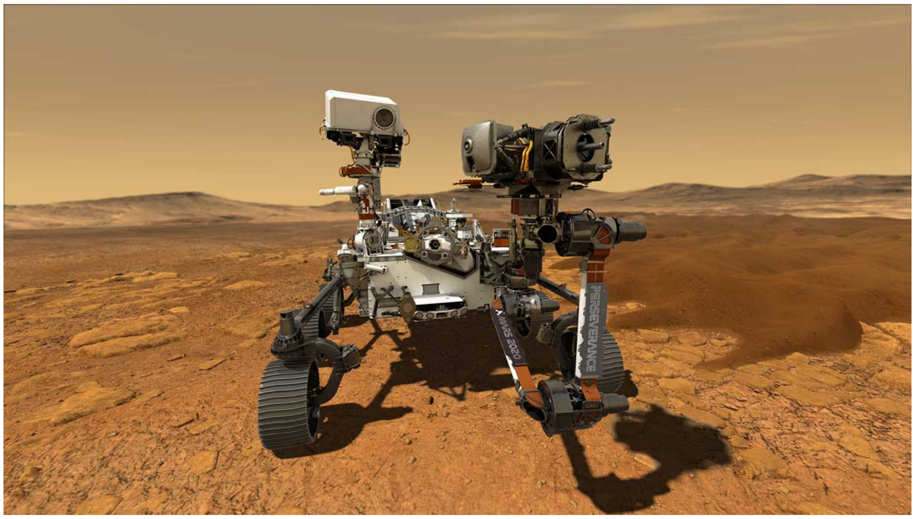


Figure 2: NASA Mars 2020 Perseverance Rover (Source: NASA Mars)

Link: https://mars.nasa.gov/mars2020/
Description: The Perseverance Rover was built to traverse the surface of Mars and take samples of the soil. It has a mounted camera to send photos back to Earth, and a retractable arm with three degrees of freedom that is used to take the samples. The arm has a small drill on the end of it to drill into the surface of Mars and collect samples, which it then stores in secure containers in the body of the rover. It is around 10 feet long, 9 feet wide, and 7 feet tall, making it much larger and heavier than specified by the rock-collecting contest.

2.1.3 Existing Device #3: RoboMaster EP Core

Figure 3: DJI RoboMaster EP Core (Source: DJI)

Link: https://www.dji.com/robomaster-ep-core
Description: The RoboMaster EP Core is a robot built for education. It can be programmed to drive autonomously and pick up objects using a grabber arm with two axes of movement. It has omni-wheels which allow it to move in any lateral direction, although it moves best on flat surfaces. It has an infrared distance sensor and mounted camera, and is also compatible with third-party sensors and hardware. It has a small space that could be used to store items that it picks up using its grabber arm, although it does not come pre-built with storage space in mind. It is also slightly too big for the contest specifications, being over a foot long and a little less than a foot wide.

2.2 Patents

2.2.1 Fast access camera mounting device (US5137238A)

This patent describes a camera mounting device that is easily mountable or removable from a vehicle and allows fast setup and removal of the camera without removing the mounting. The mount resists movement due to longitudinal, transverse, and roll forces with the assistance of a double suction cup attachment bracket and a leveling support member. As the vehicle the camera is mounted to is moving, the added support increases stability.

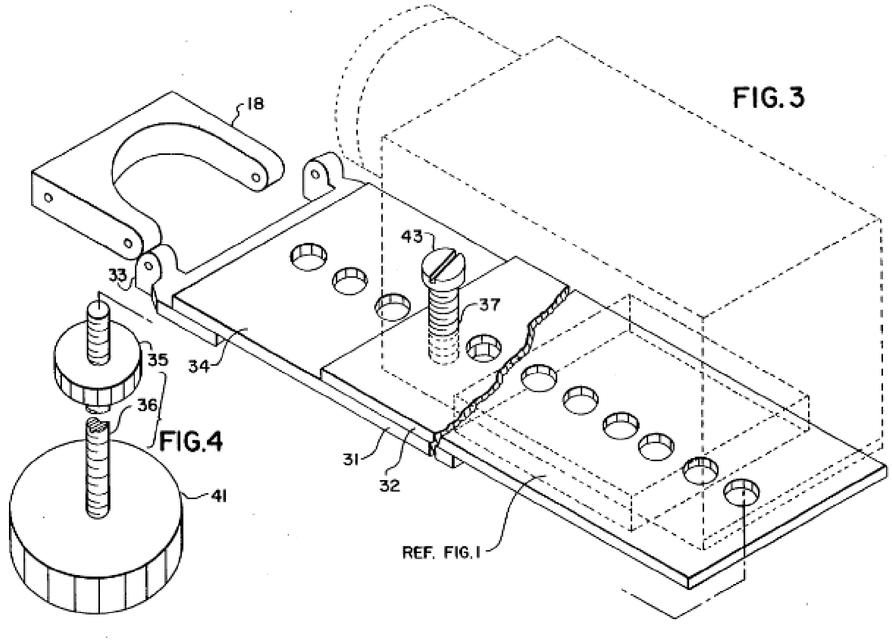


Figure 4: Patent Images for camera mounting system

2.2.2 Rock picker (US6041866A)

This patent is for the design of a rock picker that is to gather and store rocks while filtering out any dirt and debris. They key aspect of this patent is its dual-storage capacity for the rocks where it initially collects and filters rock in a basket and, once that component has reached its capacity, triggers a hydraulic cylinder to store the rocks from the basket assembly to a hopper.

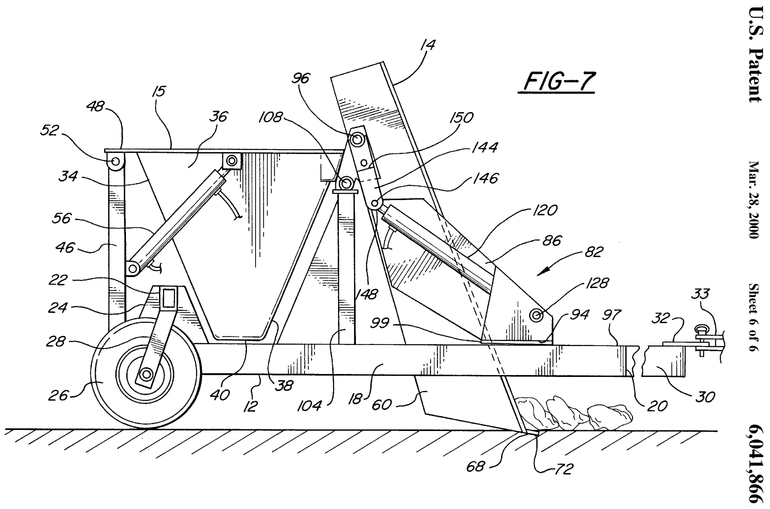


Figure 5: Patent Images for Rock Picker

2.3 Codes & Standards

2.3.1 Response Robot Sensing: Visual Acuity (ASTM E2566-17)

This standard addresses acceptable visual accuracy and field of view for cameras on robots. This is specifically for robots in urban search and rescue applications, but it's general enough to be applied to the teleoperation of many other types of robots. Some of the parameters covered are visual sharpness at near and far distances in light and dark environments. It also describes a zoom lens capability where applicable. Although the camera we will be using has no darkness requirements, the visual acuity portion of this standard will continue to be important as the rover will be operated completely remotely.

2.3.2 Dimensioning and Tolerancing (ASME Y14.5 - 2018)

This standard from the American Society of Mechanical Engineers includes standards for technical drawings, which include specifics in dimensioning, tolerances, and degrees of freedom. These will be essential when creating CAD drawings for the parts we plan on 3D printing and for when we are to present our rover and the specifics of how we designed the components.

2.4 User Needs

The user's needs were determined through a customer interview and then prioritized with an interpreted customer needs chart. We prioritized the overall size of the rover and its efficiency in being able to collect the rocks samples as the top user needs.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: McMillan G052, Washington University in St. Louis, Danforth Campus
Date: September 9th, 2022
Setting: We sat down with Dr. Potter in a lecture hall with the other teams that were also participating in the rover contest. We asked questions about certain aspects and limitations of the rover. The whole interview was conducted in the McMillan and took ∼50 min.

Interview Notes:

What is the average mass of the rocks that the rover needs to pick up?
- The average mass of the rocks, represented by various DND dice, is approximately 4 grams.

Does the rover need to be able to remove the samples at the end?
- The rover only needs to pick them up; it doesn't need to dump them out.

Can the rover interact with the rocks aside from picking them up (such as pushing the rocks around)?
- You can push them around, but the rover must be able to pick them all up at the end.

Will the rover be able to make changes once it's out of the cylinder?
- You can't manually perform any modifications to the rover when it's out of the cylinder, but if it's able to automatically make changes (or if it was pre-programmed to do something), then that's totally fine.

Does the rover need to be able to escape the cylinder it's supposed to fit in?
- No, the rover does not need to be able to escape the canister.

Do we need to worry about the rover being able to operate on various terrains or in various weather conditions?
- No, you don't need to worry about terrain/weather conditions.

2.4.2 Interpreted User Needs

These are the user needs interpreted from the customer interview and the initial project request. Each user need is given an importance rating from 1-5, indicating how crucial the need is to the project and to the user's request.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The rover is able to pick up rocks and store them once picked up	5
2	The rover performs its function without manual modification	4
3	The rover is able to deposit rocks in a designated area	2
4	The rover has a mounted camera and can be driven remotely using specific controller hardware	5
5	The rover can easily maneuver over terrain.	3
6	The rover can collect rocks efficiently in a short amount of time	5
7	The rover is compact and fits within a designated cylinder	5
8	The cost of the rover is within the designated budget	5

2.5 Design Metrics

These are the design metrics we are going to be following based on the project guidelines and the customer interview. Each metric has an associated need as well as its ideal vs actual target specification.

Table 2: Target Specifications

Metric Number	**Associated Needs**	**Metric**	**Units**	**Acceptable**	**Ideal**
1	7	Total weight	lbs	3.5	< 3.5
2	7	Longest rover length	in	< 8.5	< 20
3	7	Largest rover diameter	in	< 5.36	$> 4/5$
4	1	Max number of rocks storage vessel can carry	integer	> 20	> 30
5	4	Time to collect one rock	seconds	< 5	< 3
6	5	Camera visual latency	ms	< 3000	< 100
7	8	Overall cost of rover	$	< 400	< 400

2.6 Project Management

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

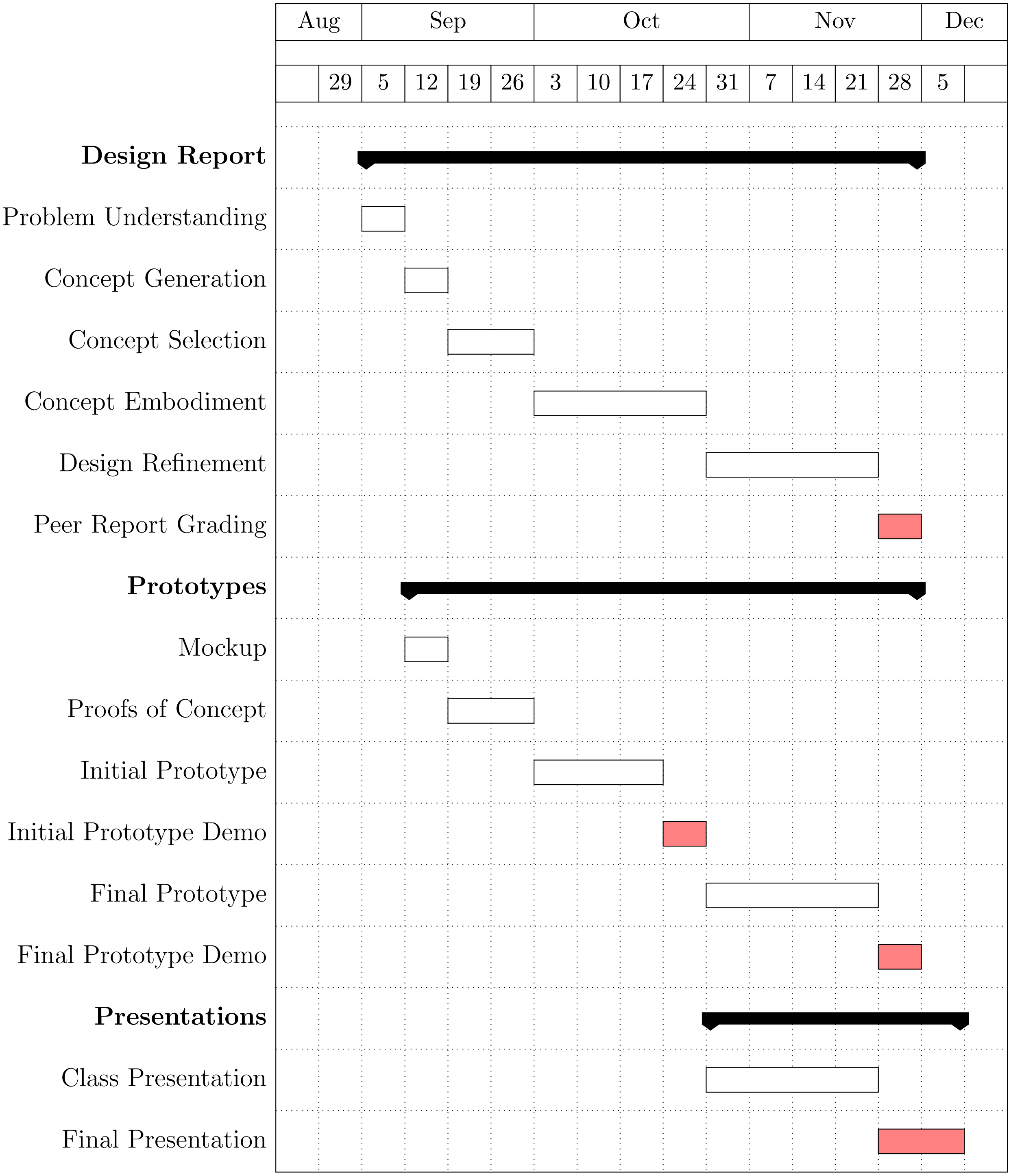


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

(a) Mockup isometric view (b) Mockup top view (c) Mockup side view

Figure 7: Images of mockup prototype.

A mockup prototype was made using materials available in the studio. Materials used included cardboard for the general frame of the rover and other components, masking tape to hold the components together, and skewers used to simulate the axels of the rover. The proof of concept was to show how our group intended the rock collecting mechanism to work. This would operate as a rover with a component spinning at the front of the vehicle that would be used to collect ”rocks.” The rover itself would be in a box-like shape in order to contain the rocks once they had been collected.

3.2 Functional Decomposition

The function tree for the rock rover is shown below in Figure 8. The five most important concepts for our rover were identified and further developed in the morphological chart.

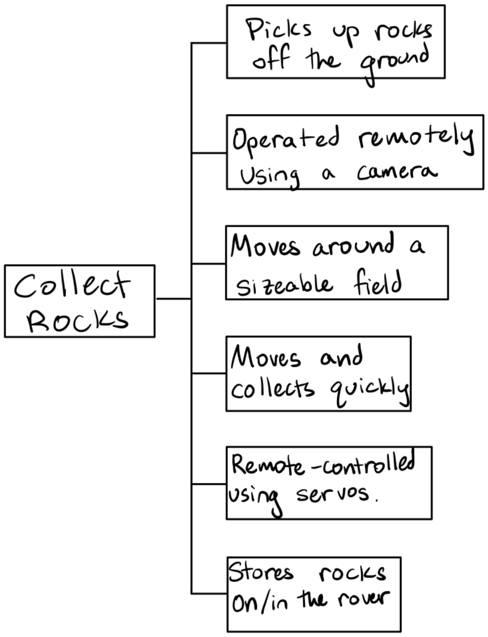


Figure 8: Function tree for Rock Rover, drawn on a tablet

3.3 Morphological Chart

Shown below in Figure 9 is the morphological chart for our rover. The different concepts generated were based on the five functions identified in our function tree.

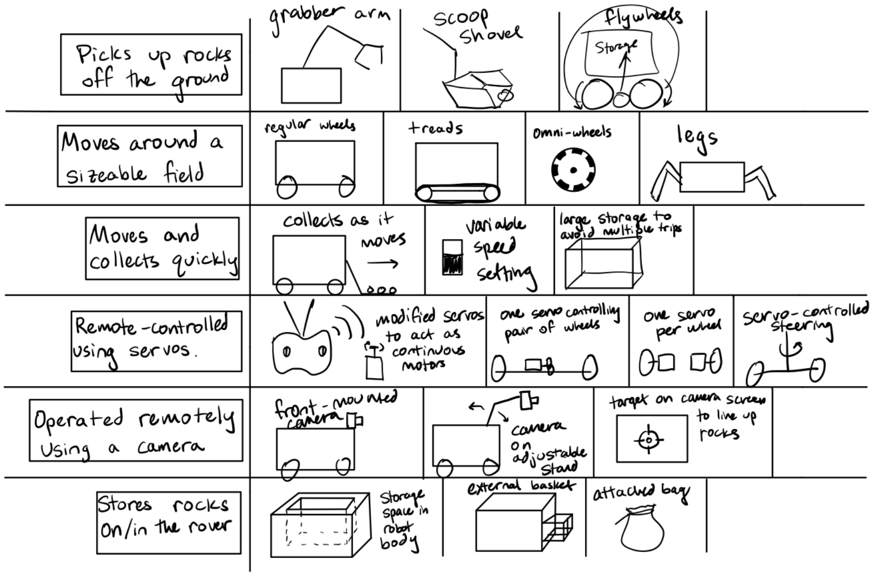


Figure 9: Morphological Chart for Rock Rover

3.4 Alternative Design Concepts

3.4.1 Concept #1: Pulley Gate

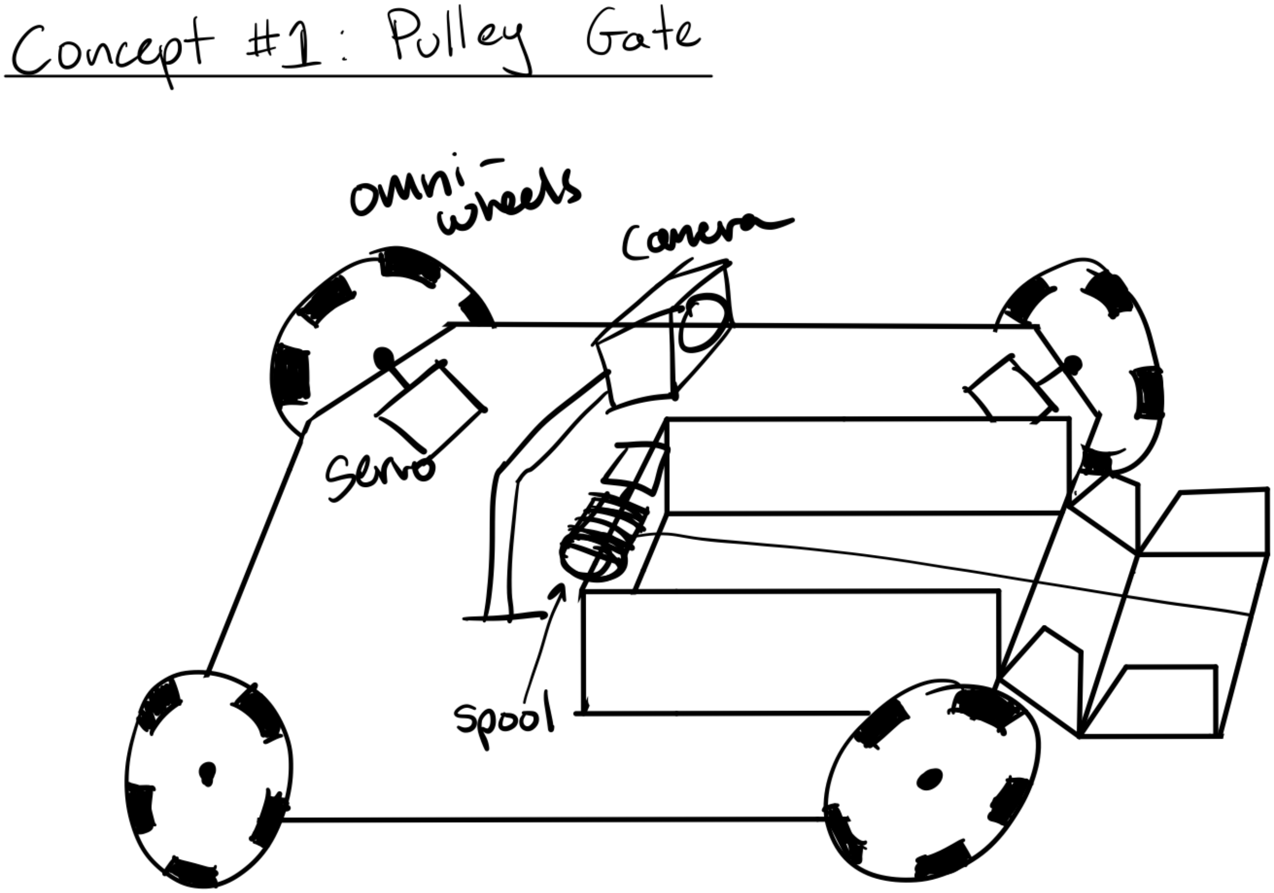


Figure 10: Sketches of Rock Rover concept

Description: Five continuous servo motors, each connected to a receiver, receive a signal from a six-channel RC controller. Four of the servos drive omni-wheels, oriented to allow the robot to move in any lateral direction. The fifth servo is connected to a spool and pulley, which can raise and lower the ramp to collect rocks and store them in a storage bin on the body of the robot.

3.4.2 Concept #2: MERRY GO ROVER BAG

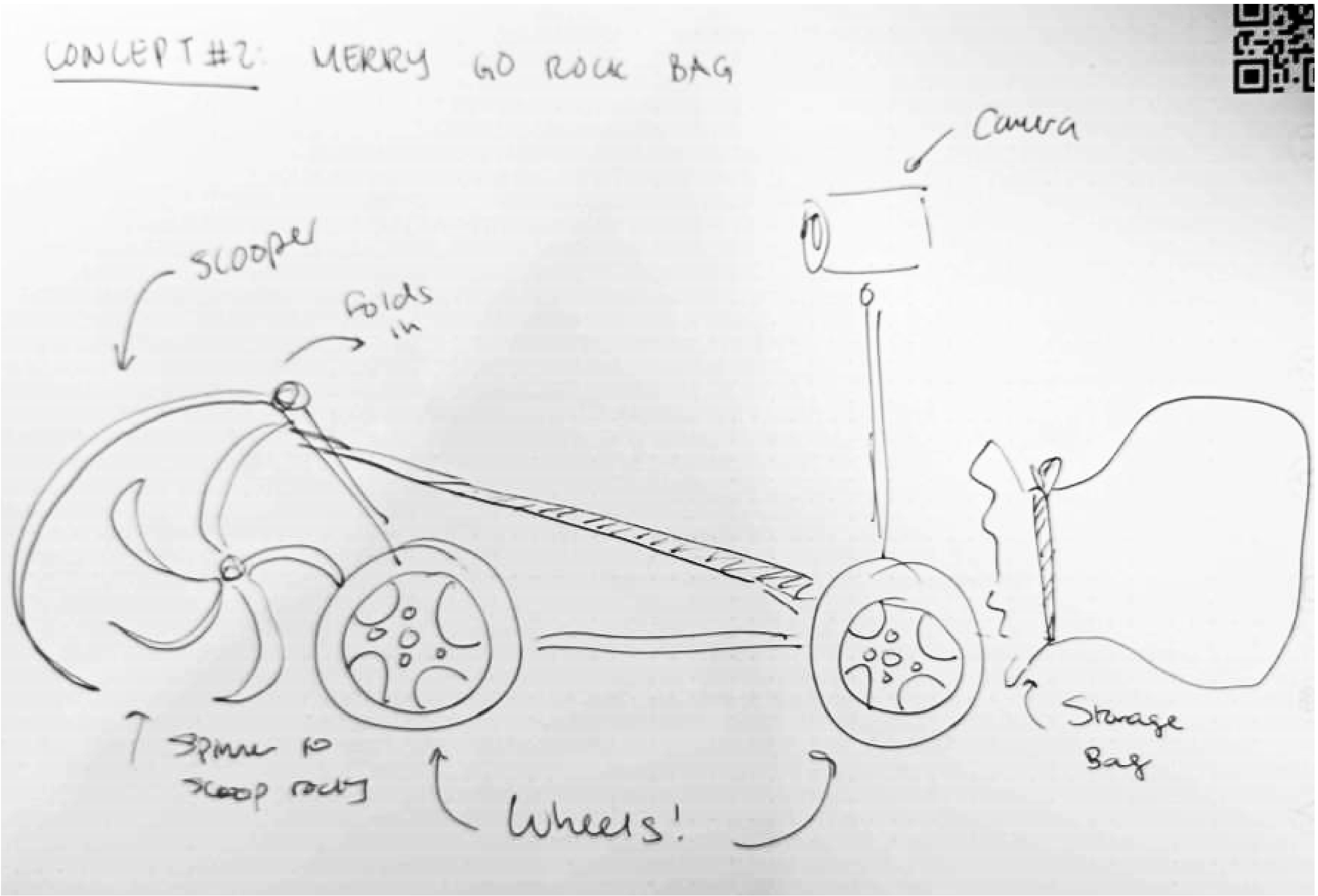


Figure 11: Sketch of Merry Go Rover Bag concept

Description: A rotational device controlled by a continuous servo is spun against the surface of a scooper to collect the rocks. The force from the rotation of the spinner will shovel the rocks over a small ramp and dumped into a storage bag. The camera is mounted towards the back of the rover to both be able to see the rocks and be out of the way of the rock collection process. All components are designed to be foldable to fit into the storage cylinder. The wheels are controlled by four separate continuous motors.

3.4.3 Concept #3: Upgraded Roomba

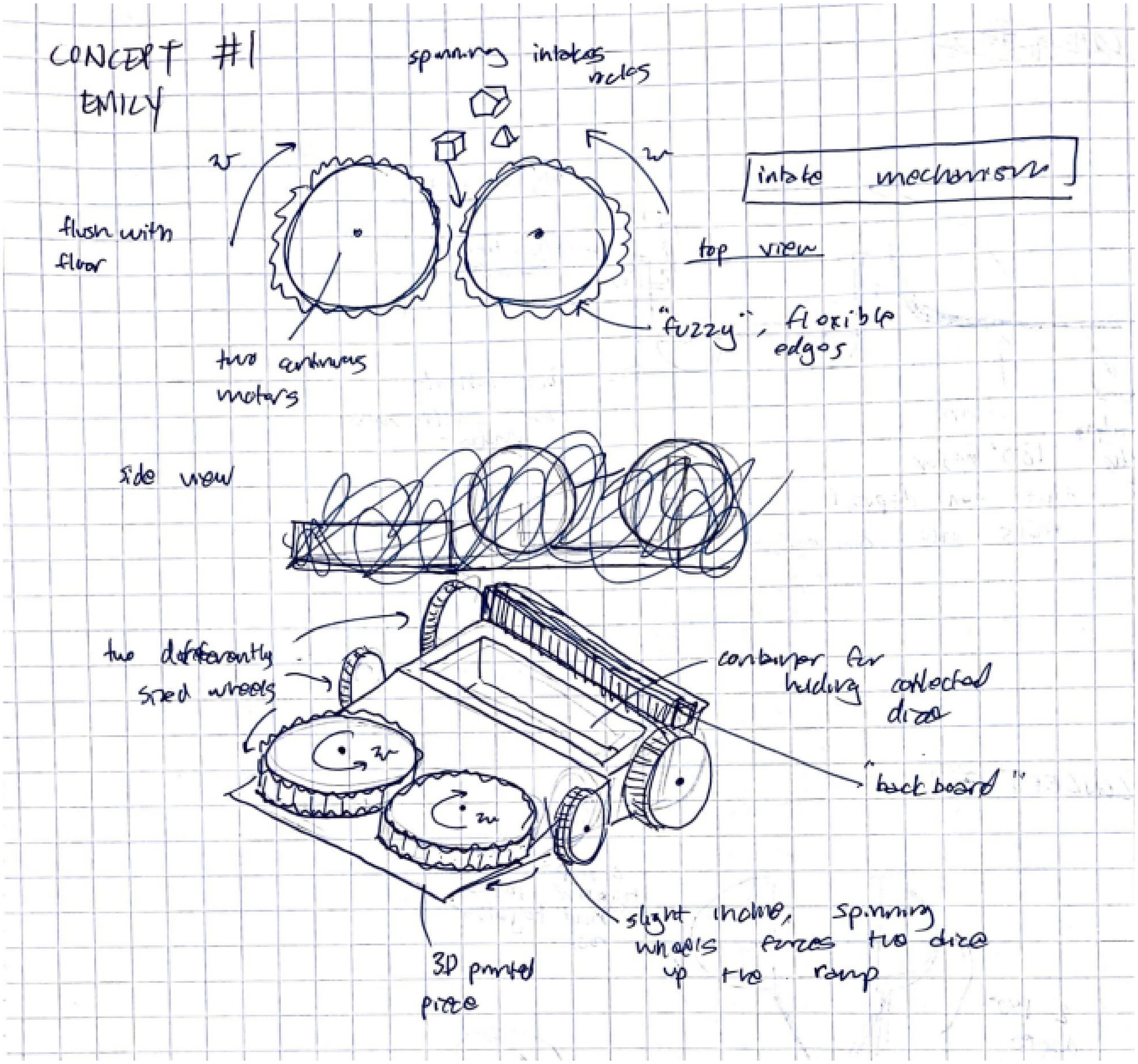


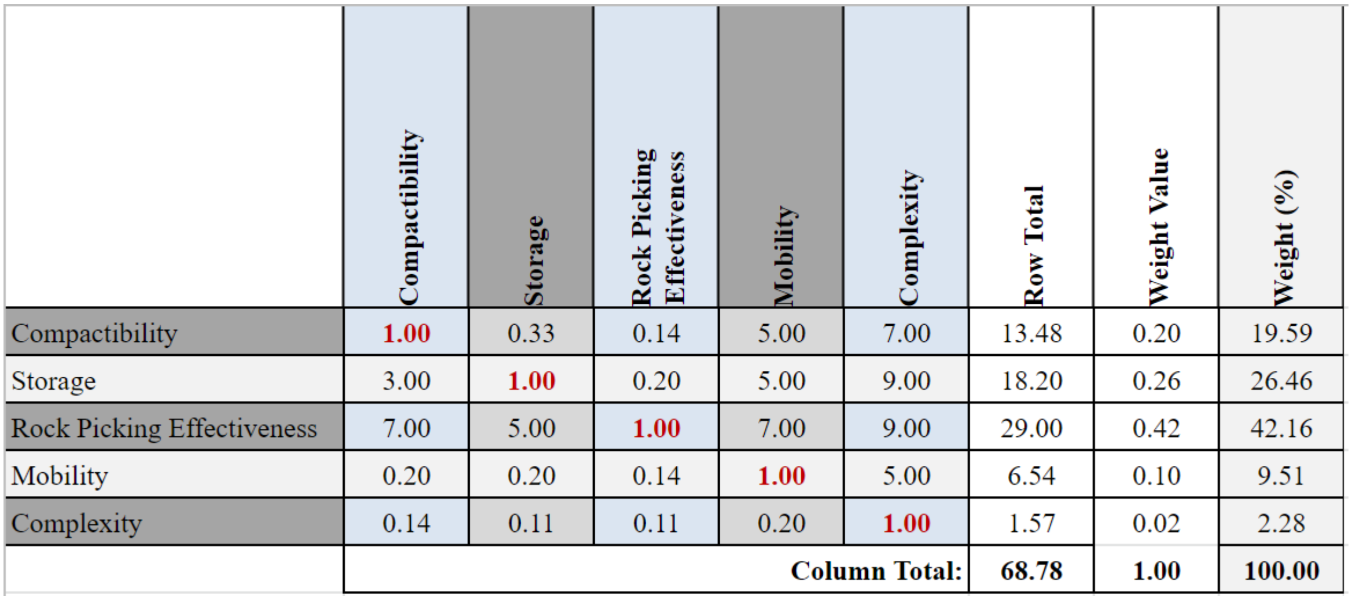
Figure 12: Sketch of Upgraded Roomba concept

<u>Description</u>: Two continuous motors spin two large wheels. As the rover drives over the rocks, the rocks are caught between the two wheels and forced up the slight ramp into the mobile storage container. There is a slight backboard to catch all rocks. The edges of the continuously spinning wheels are flexible to allow the rocks to squeeze through the gaps. This continuous motor use allows for the driver of the rover to focus on operating the rover within the test space.

4 Concept Selection

4.1 Selection Criteria

Below is an Analytic Hierarchy Process (AHP) for determining our rover design. The different factors were chosen and the weights were determined based on their relative importances to each other.



	Compactibility	**Storage**	**Rock Picking Effectiveness**	**Mobility**	**Complexity**	**Row Total**	**Weight Value**	**Weight (%)**
Compactibility	**1.00**	0.33	0.14	5.00	7.00	13.48	0.20	19.59
Storage	3.00	**1.00**	0.20	5.00	9.00	18.20	0.26	26.46
Rock Picking Effectiveness	7.00	5.00	**1.00**	7.00	9.00	29.00	0.42	42.16
Mobility	0.20	0.20	0.14	**1.00**	5.00	6.54	0.10	9.51
Complexity	0.14	0.11	0.11	0.20	**1.00**	1.57	0.02	2.28
	Column Total:					**68.78**	**1.00**	**100.00**

Figure 13: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Shown in Fig. 14 below is a Weighted Scoring Matrix (WSM) that ranks the design concepts based on the selected criteria. Each design received a score between 1 and 5 for each criterion, and those scores were weighted using the weights from the AHP.

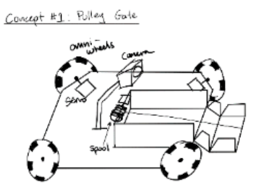
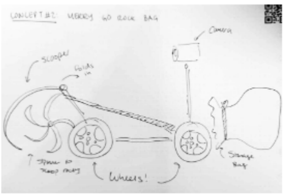
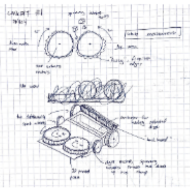
Alternative Design Concepts		**Pulley Gate**		**MERRY GO ROVER BAG**		**Upgraded Roomba**	
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Compactability	19.59	2	0.39	3	0.59	2	0.39
Storage	26.46	5	1.32	5	1.32	5	1.32
Rock Picking Effectiveness	42.16	2	0.84	4	1.69	4	1.69
Mobility	9.51	4	0.38	4	0.38	3	0.29
Complexity	2.28	5	0.11	2	0.05	1	0.02
	Total score	**3.052**		**4.023**		**3.709**	
	Rank	**3**		**1**		**2**	

Figure 14: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

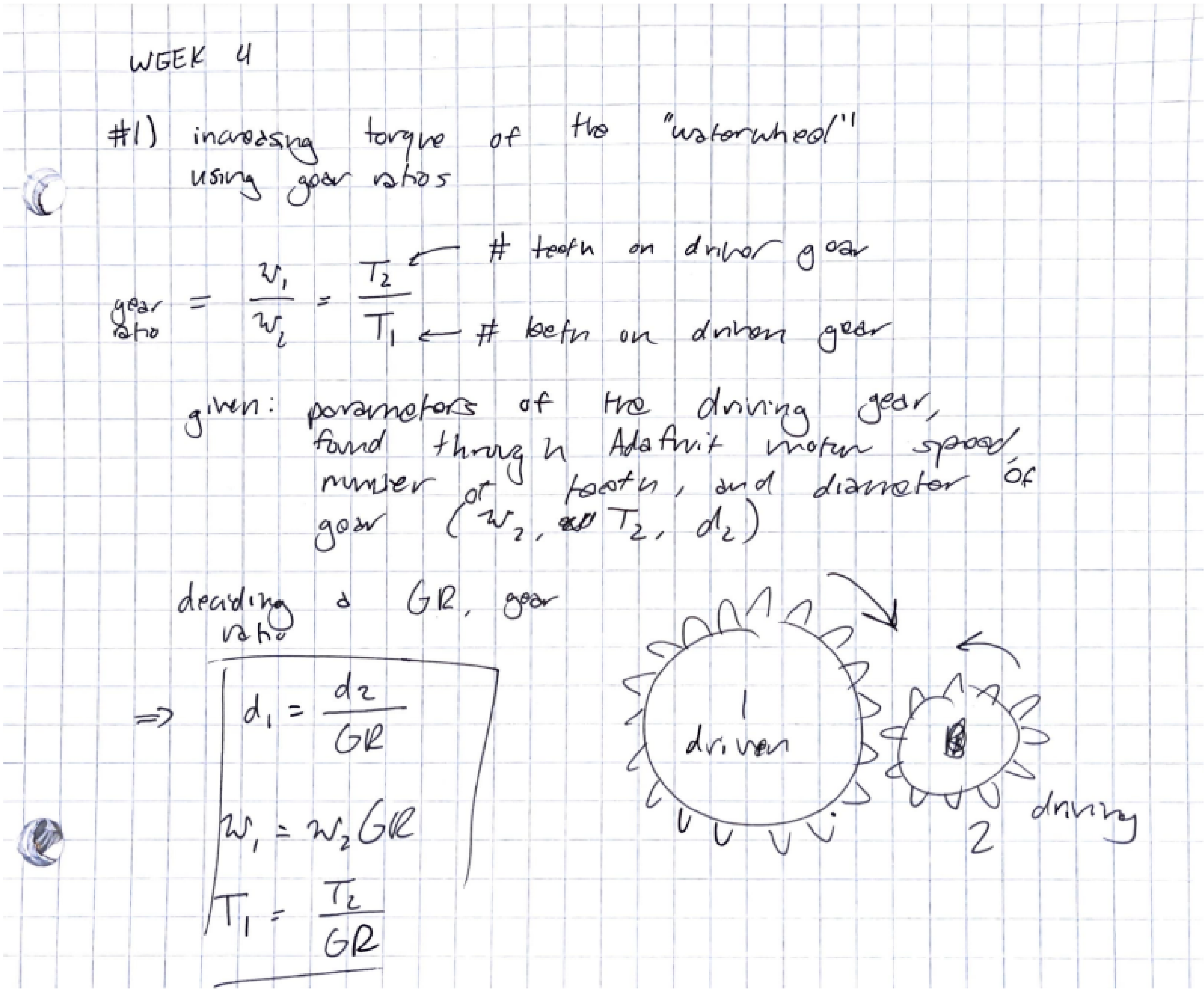
Based on the results of our AHP and WSM, concept 2 was chosen as the design we would proceed with. The criteria with the most weight was the rock picking effectiveness, which concept #2 scored a 4 in due to its ability to rotate and collect rocks of varying sizes. Additionally, concept #2 scored well in factors of storability, which it scored a 5 due to the sizing and scaling of the components, and compatibility, which it scored a 3 due to its ability to fold in the components. The overall simplicity of the design also allowed for it to score well in terms of the potential mobility of the rover, which it scored a 4 due to its simple frame. This concept scored a 2 in terms of complexity because of the amount of moving components needed in order to get the rover operable. Despite the setback due to the complexity score, concept #2 still scored the highest with a 4.023.

4.4 Engineering Models/Relationships

All the engineering models listed below describe the ”water-wheel” mechanism that forces dice up the ramp.

4.4.1 Model #1: Gear Ratios

Below in Figure 15 is a description of the requirements for calculating the number of teeth and diameter of the driven gear based on the gear ratio, diameter, and the number of teeth of the driving gear. The goal of the gear ratio is to increase the torque of the ”water wheel” mechanism rather than increasing angular speed ω. Therefore, it is important that the driven gear have more teeth and a larger diameter than the driving gear.



WEEK 4

#1) increasing torque of the "waterwheel" using gear ratios

$$\text{gear ratio} = \frac{w_1}{w_2} = \frac{T_2}{T_1} \quad \begin{aligned} &\leftarrow \text{\# teeth on driver gear} \\ &\leftarrow \text{\# teeth on driven gear} \end{aligned}$$

given: parameters of the driving gear, found through Adafruit motor speed, number of teeth, and diameter of gear (w_2, T_2, d_2)

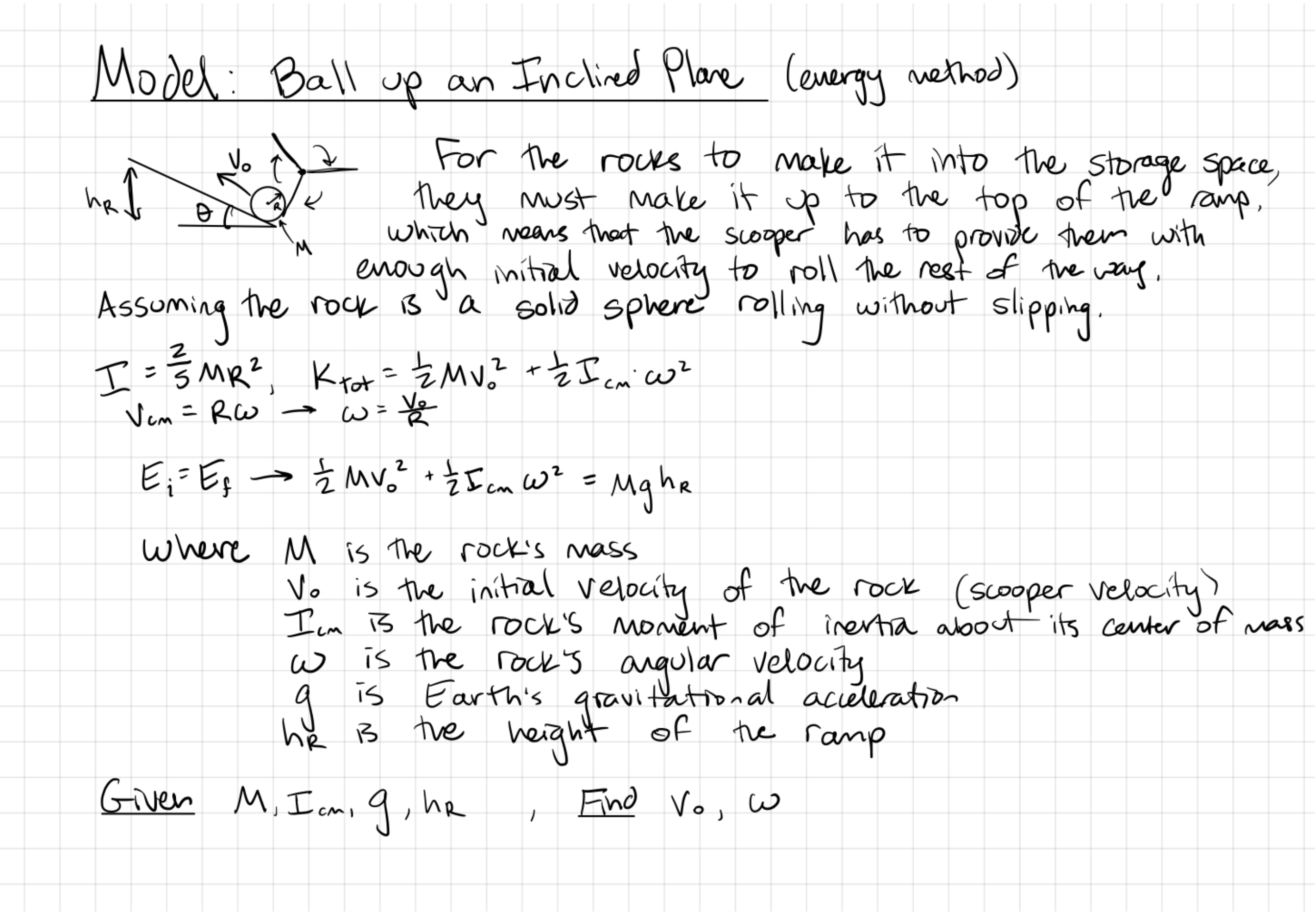
deciding a GR, gear ratio

$$\Rightarrow \boxed{\begin{aligned} d_1 &= \frac{d_2}{GR} \\ w_1 &= w_2 GR \\ T_1 &= \frac{T_2}{GR} \end{aligned}}$$

Figure 15: Engineering model to determine driven gear parameters

4.4.2 Model #2: Ball on Inclined Plane

The second engineering model taken into consideration is a ball rolling without slipping up an inclined plane, propelled by some initial velocity v_0. The ball simulates a rock being pushed up the ramp into our rover by a "water wheel" with angular velocity ω. Given the mass of the rock and the height of the ramp, we can calculate the necessary initial velocity of the rock (and angular velocity of the water wheel) to push the rock over the ramp and into the storage space.



Model: Ball up an Inclined Plane (energy method)

For the rocks to make it into the storage space, they must make it up to the top of the ramp, which means that the scooper has to provide them with enough initial velocity to roll the rest of the way. Assuming the rock is a solid sphere rolling without slipping.

$I = \frac{2}{5}MR^2$, $K_{Tot} = \frac{1}{2}MV_0^2 + \frac{1}{2}I_{cm}\omega^2$

$V_{cm} = R\omega \rightarrow \omega = \frac{V_0}{R}$

$E_i = E_f \rightarrow \frac{1}{2}MV_0^2 + \frac{1}{2}I_{cm}\omega^2 = Mgh_R$

Where M is the rock's mass
V_0 is the initial velocity of the rock (scooper velocity)
I_{cm} is the rock's moment of inertia about its center of mass
ω is the rock's angular velocity
g is Earth's gravitational acceleration
h_R is the height of the ramp

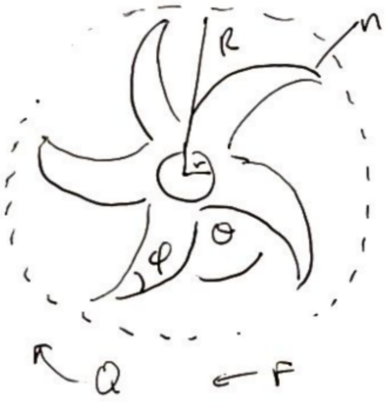
Given M, I_{cm}, g, h_R, Find V_0, ω

Figure 16: Engineering model for calculating the necessary initial speed of a ball for it to get over a ramp of set height.

4.4.3 Model #3: Wheel Rotation

Shown below in Figure 17 is the engineering model of the water wheel. This model takes into consideration the rotation of the wheel and the amount of speed required by the wheel in order to produce a force of the wheel. Given the number of spokes, the angle at which the spokes are positioned, and the radii of the wheel as a whole and the axis of rotation, we can calculate how sharp the angle of the spokes must be in addition to how many revolutions per min will produce a force.

WATER WHEEL



n = # of spokes
R = radius of wheel
θ = angle of separation between spokes
Q = Rev per min
r = radius of axis
ϕ = angle of spokes
F = force of wheel

This water wheel corresponds to the wheel in our model that will be used to pick up the rocks. The wheel will be rotating at Q rotations per minute in order to generate enough force to push the ore into the rover. The size of the wheel will be adjusted accordingly based on how much space the rover is able to fit into.

given:
n, θ, R, r

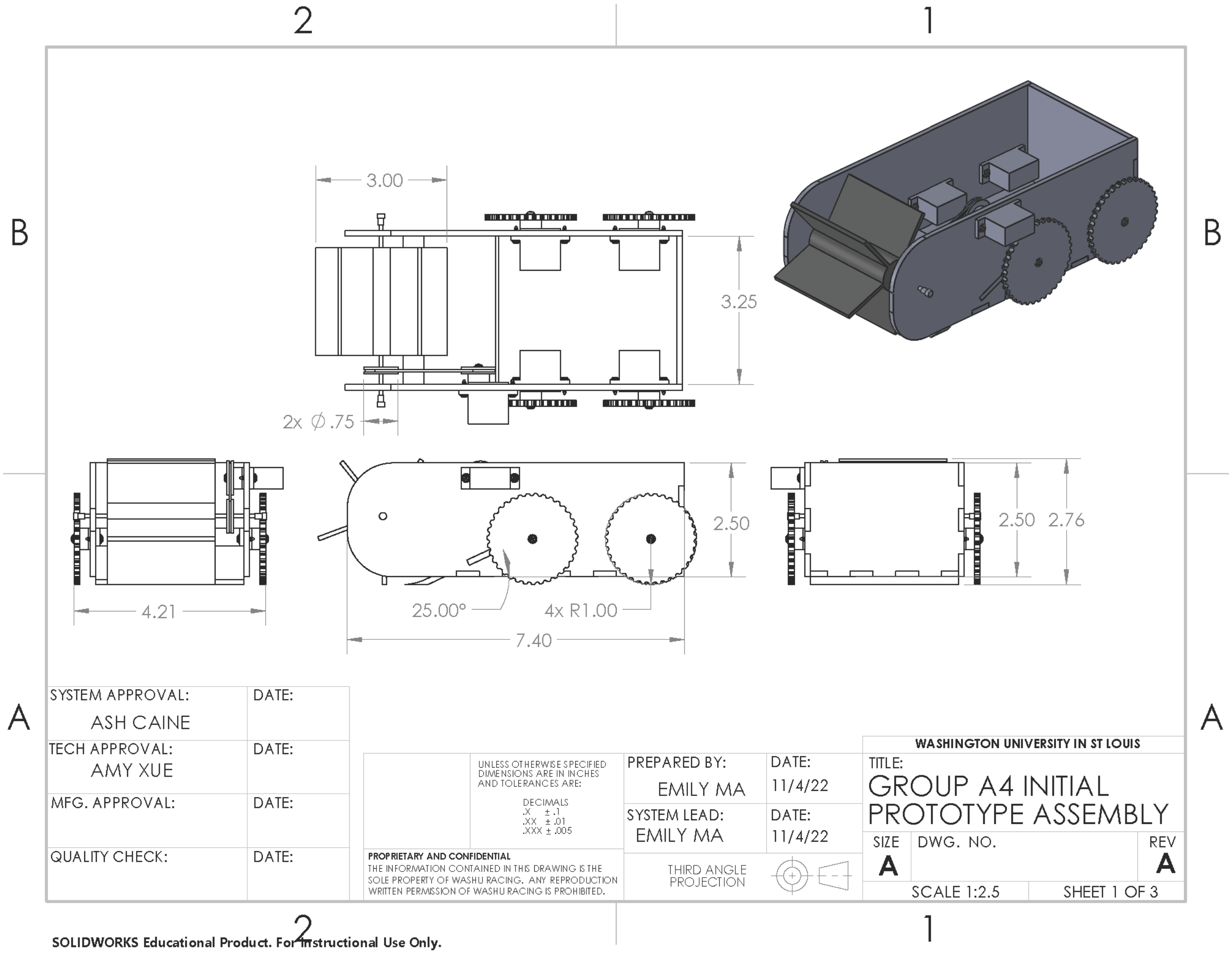
find:
Q, ϕ, F

Figure 17: Engineering model to determine the force produced by the rotation of the water wheel.

5 Concept Embodiment

5.1 Initial Embodiment

Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo.



SYSTEM APPROVAL: ASH CAINE
DATE:
TECH APPROVAL: AMY XUE
DATE:
MFG. APPROVAL:
DATE:
QUALITY CHECK:
DATE:

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:
DECIMALS
.X ± .1
.XX ± .01
.XXX ± .005

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DATE: 11/4/22
THIRD ANGLE PROJECTION

WASHINGTON UNIVERSITY IN ST LOUIS
TITLE: GROUP A4 INITIAL PROTOTYPE ASSEMBLY
SIZE A
DWG. NO.
REV A
SCALE 1:2.5
SHEET 1 OF 3

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Figure 18: Assembled projected views with overall dimensions

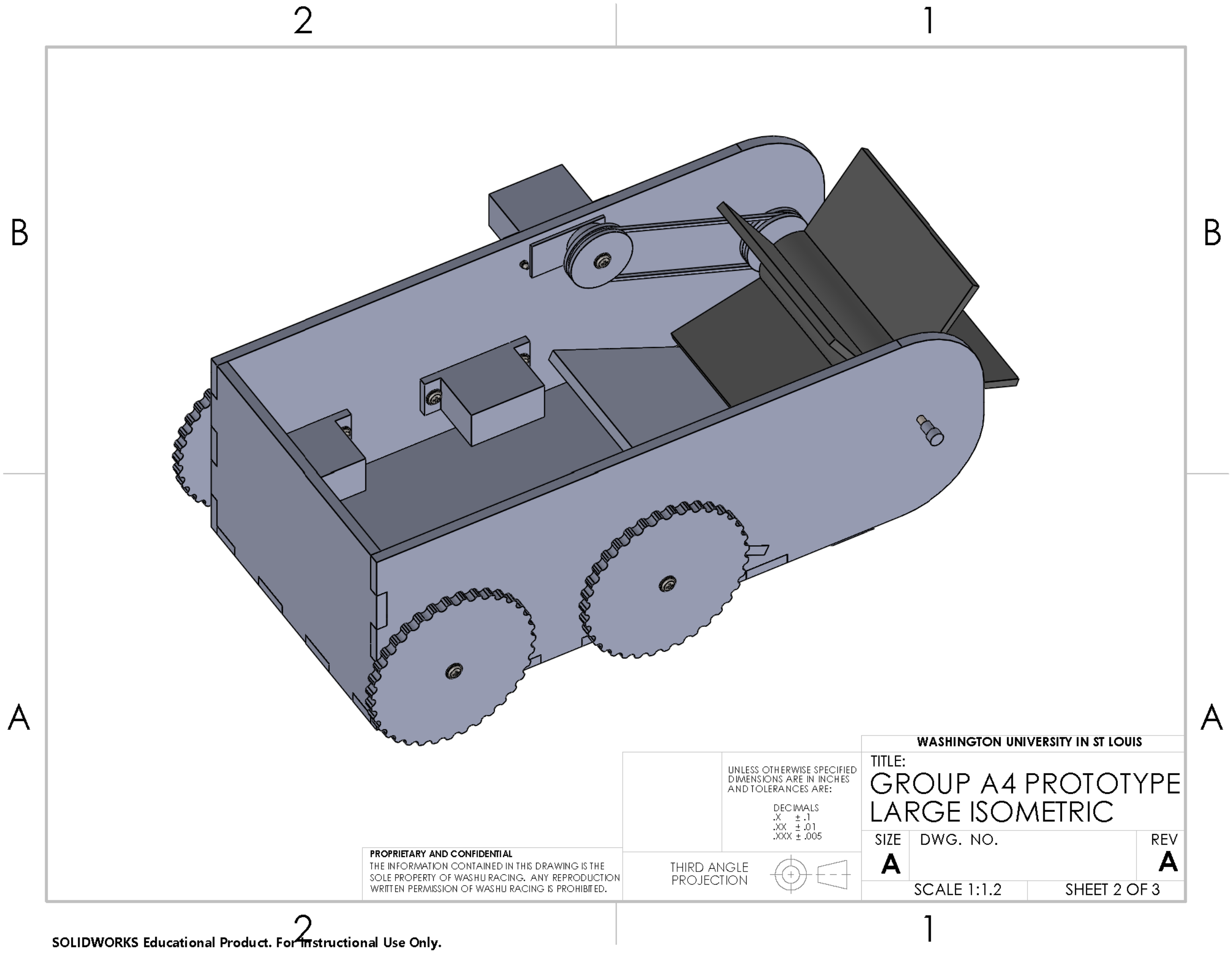
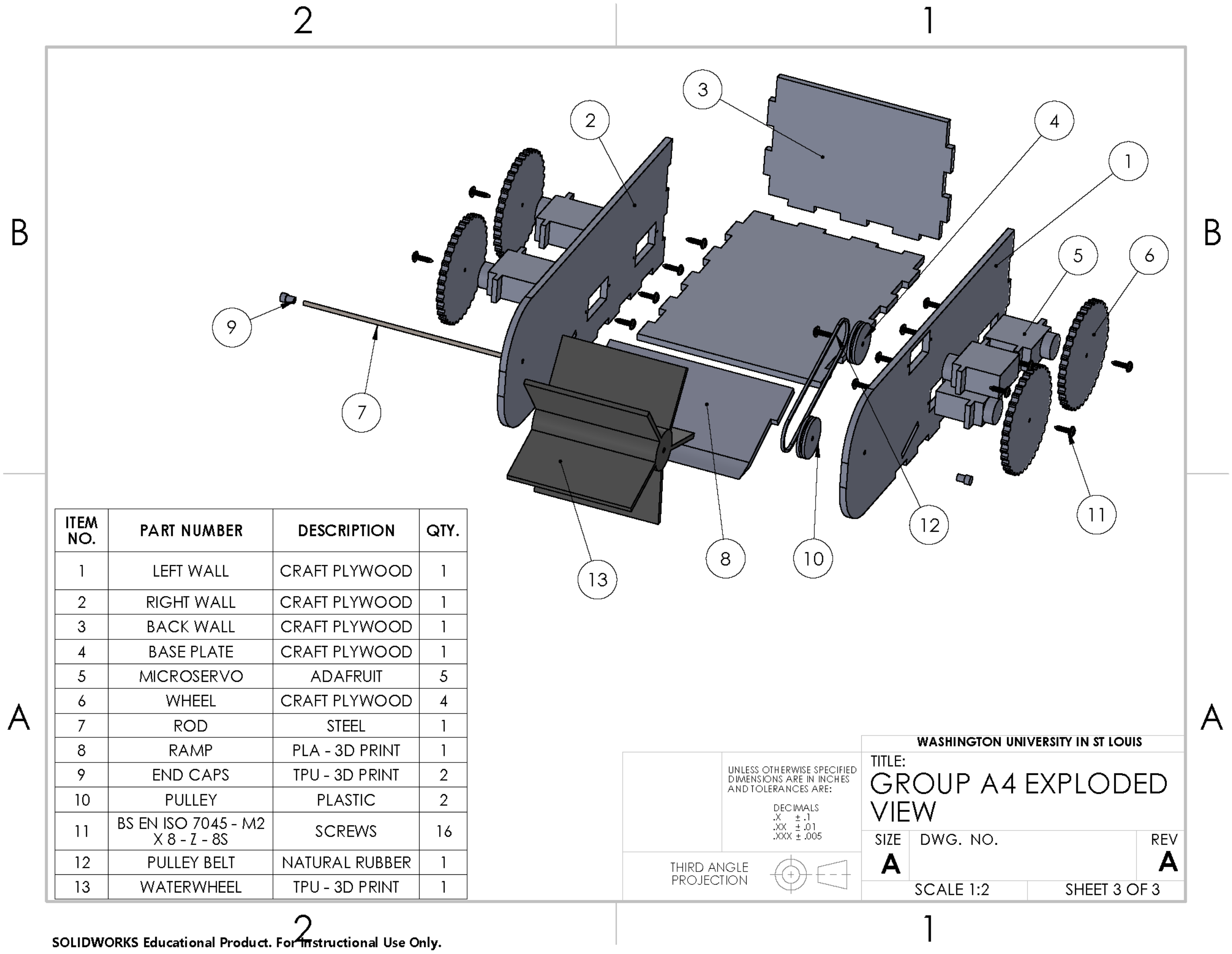


Figure 19: Assembled isometric view with bill of materials (BOM)



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	LEFT WALL	CRAFT PLYWOOD	1
2	RIGHT WALL	CRAFT PLYWOOD	1
3	BACK WALL	CRAFT PLYWOOD	1
4	BASE PLATE	CRAFT PLYWOOD	1
5	MICROSERVO	ADAFRUIT	5
6	WHEEL	CRAFT PLYWOOD	4
7	ROD	STEEL	1
8	RAMP	PLA - 3D PRINT	1
9	END CAPS	TPU - 3D PRINT	2
10	PULLEY	PLASTIC	2
11	BS EN ISO 7045 - M2 X 8 - Z - 8S	SCREWS	16
12	PULLEY BELT	NATURAL RUBBER	1
13	WATERWHEEL	TPU - 3D PRINT	1

Figure 20: Exploded view with callout to BOM

We had three prototype performance goals, which were universal to all of the rock-collecting rover groups. The first goal was that the rover would be able to hold and travel with at least 35 dice at one time, without letting the dice touch the floor. Our prototype did succeed in this goal, and was able to easily carry the necessary number of dice without any loss in mobility.

Our second performance goal was that the rover would be able to pick up at least 80% of the dice that it approaches. We unfortunately did not meet this goal in this iteration of the rover. While the waterwheel on the front was functional and did spin, the ramp was too long, so the dice were unable to get over it and into the storage area. In our final design, we will shorten the ramp to ensure that the wheel is able to push dice fully over it and into storage.

Our last performance goal was that the rover would be able to traverse a course outlined in tape in no more than five minutes while being remotely driven. We were successful in this goal, and were able to use the controller and receiver to drive the rover through the course in around two minutes.

5.2 Proofs-of-Concept

Our proofs of concept focused mostly on the control scheme of the robot, and how we were going to connect the controller to the motor servos and get the robot to actually drive. Our proof of concept showed that connecting the two servos on each side together using a Y harness splitter cable would allow us to effectively control the robot, and we went on to use that design in our prototype. We also attempted to use a gear train to drive the waterwheel in our initial proofs of concept, but found that it was much more difficult and finicky to line up, so we used a belt pulley in our prototype instead. We also used the proofs of concept to inform a host of small changes to the way the components were laid out on the robot body, in order to maximize space for dice without exceeding the maximum size that the robot could occupy.

5.3 Design Changes

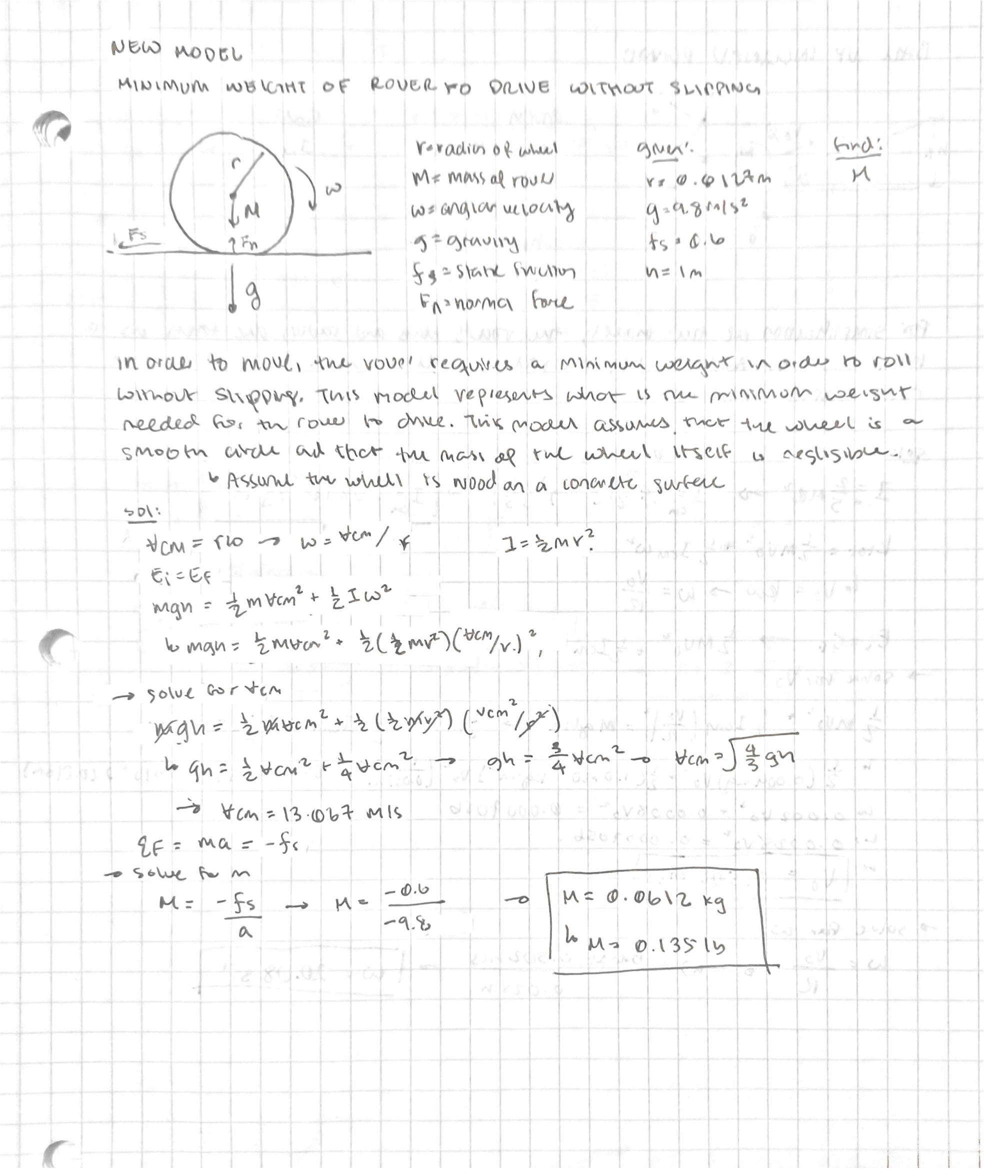
From the selected concept, our prototype had a few alterations. Firstly, the selected concept had the waterwheel rotating where the rocks would be scooped up against a surface. We changed our design from this upward scooping motion to a downwards clawing rotation. Additionally, the selected concept was a thin frame with the rocks being funneled into a bag. Our prototype differed in that it was a more sturdy box-like container that had the rocks being directly held in the rover itself. Lastly, the selected concept had the camera mounted at the back of the rover and extending upward while our prototype has the camera mounted to the side of the rover in order to have the whole mechanism fit into the required cylinder space.

6 Design Refinement

6.1 Model-Based Design Decisions

Some of the design choices that we made were validated by our previous models. However, since there had been many revisions to our design since the initial concept creation, the models have also been revised accordingly.

To start, shown below in Figure 21, is the new model. Since our rover no longer uses a gear system, this model has been revised to best determine what the minimum mass was needed in order for the rover to drive.



NEW MODEL

MINIMUM WEIGHT OF ROVER TO DRIVE WITHOUT SLIPPING

r = radius of wheel
M = mass of rover
ω = angular velocity
g = gravity
f_s = static friction
F_n = normal force

given:
$r = 0.0127\text{m}$
$g = 9.8\text{m/s}^2$
$f_s = 0.6$
$h = 1\text{m}$

find:
M

In order to move, the rover requires a minimum weight in order to roll without slipping. This model represents what is the minimum weight needed for the rover to drive. This model assumes that the wheel is a smooth circle and that the mass of the wheel itself is negligible.
↳ Assume the wheel is wood on a concrete surface

sol:

$v_{cm} = r\omega \rightarrow \omega = v_{cm}/r$ $I = \frac{1}{2}mr^2$

$E_i = E_f$

$mgh = \frac{1}{2}mv_{cm}^2 + \frac{1}{2}I\omega^2$

↳ $mgh = \frac{1}{2}mv_{cm}^2 + \frac{1}{2}(\frac{1}{2}mr^2)(v_{cm}/r)^2$

→ solve for v_{cm}

$\cancel{m}gh = \frac{1}{2}\cancel{m}v_{cm}^2 + \frac{1}{2}(\frac{1}{2}\cancel{m}\cancel{r^2})(v_{cm}^2/\cancel{r^2})$

↳ $gh = \frac{1}{2}v_{cm}^2 + \frac{1}{4}v_{cm}^2 \rightarrow gh = \frac{3}{4}v_{cm}^2 \rightarrow v_{cm} = \sqrt{\frac{4}{3}gh}$

→ $v_{cm} = 13.067\text{ m/s}$

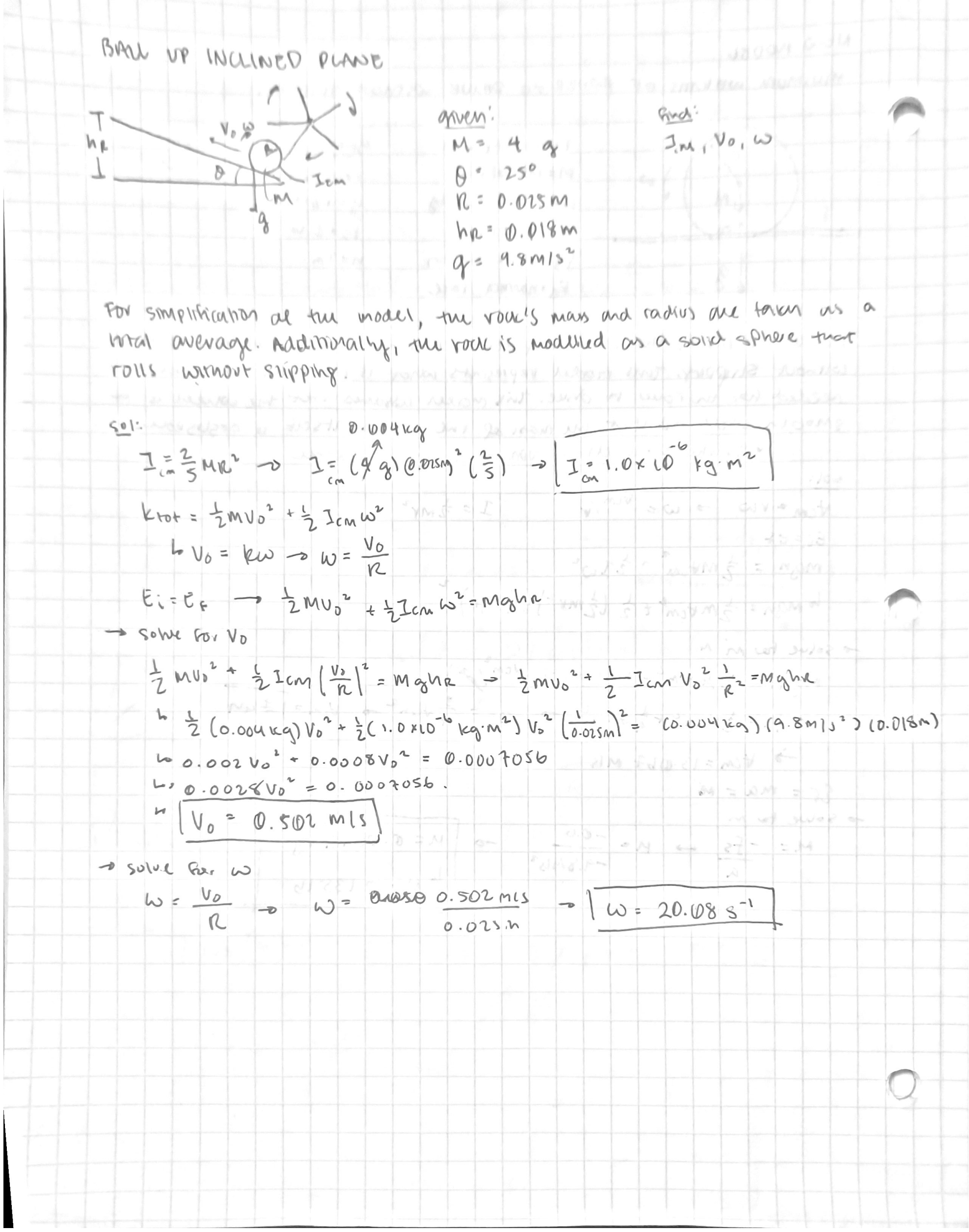
$\Sigma F = ma = -f_s$

→ solve for m

$$M = \frac{-f_s}{a} \rightarrow M = \frac{-0.6}{-9.8} \rightarrow \boxed{\begin{array}{l} M = 0.0612\text{ kg} \\ \hookrightarrow M = 0.135\text{ lb} \end{array}}$$

Figure 21: New model for the minimum required mass of the rover.

Next is the model for the "rock" up an incline, as seen in Figure 22. The numbers for the rocks, such as the mass and radius, represent the averages of the simulated rocks. Additionally, other numbers, such as the height and angle of the ramp, were taken directly from the physical model.



BALL UP INCLINED PLANE

given:
$M = 4\ g$
$\theta = 25°$
$R = 0.025\,m$
$h_R = 0.018\,m$
$g = 9.8\,m/s^2$

Find:
I_{cm}, V_0, ω

For simplification of the model, the rock's mass and radius are taken as a total average. Additionally, the rock is modelled as a solid sphere that rolls without slipping.

Sol:

$$I_{cm} = \frac{2}{5}MR^2 \rightarrow I_{cm} = (\overset{0.004kg}{\cancel{4}\,g})(0.025m)^2\left(\frac{2}{5}\right) \rightarrow \boxed{I_{cm} = 1.0 \times 10^{-6}\ kg \cdot m^2}$$

$$K_{tot} = \frac{1}{2}MV_0^2 + \frac{1}{2}I_{cm}\omega^2$$

$$\hookrightarrow V_0 = R\omega \rightarrow \omega = \frac{V_0}{R}$$

$$E_i = E_f \longrightarrow \frac{1}{2}MV_0^2 + \frac{1}{2}I_{cm}\omega^2 = Mgh_R$$

→ solve for V_0

$$\frac{1}{2}MV_0^2 + \frac{1}{2}I_{cm}\left(\frac{V_0}{R}\right)^2 = Mgh_R \rightarrow \frac{1}{2}MV_0^2 + \frac{1}{2}I_{cm}V_0^2\frac{1}{R^2} = Mgh_R$$

$$\hookrightarrow \frac{1}{2}(0.004kg)V_0^2 + \frac{1}{2}(1.0 \times 10^{-6}\ kg \cdot m^2)V_0^2\left(\frac{1}{0.025m}\right)^2 = (0.004kg)(9.8m/s^2)(0.018m)$$

$$\hookrightarrow 0.002V_0^2 + 0.0008V_0^2 = 0.0007056$$

$$\hookrightarrow 0.0028V_0^2 = 0.0007056.$$

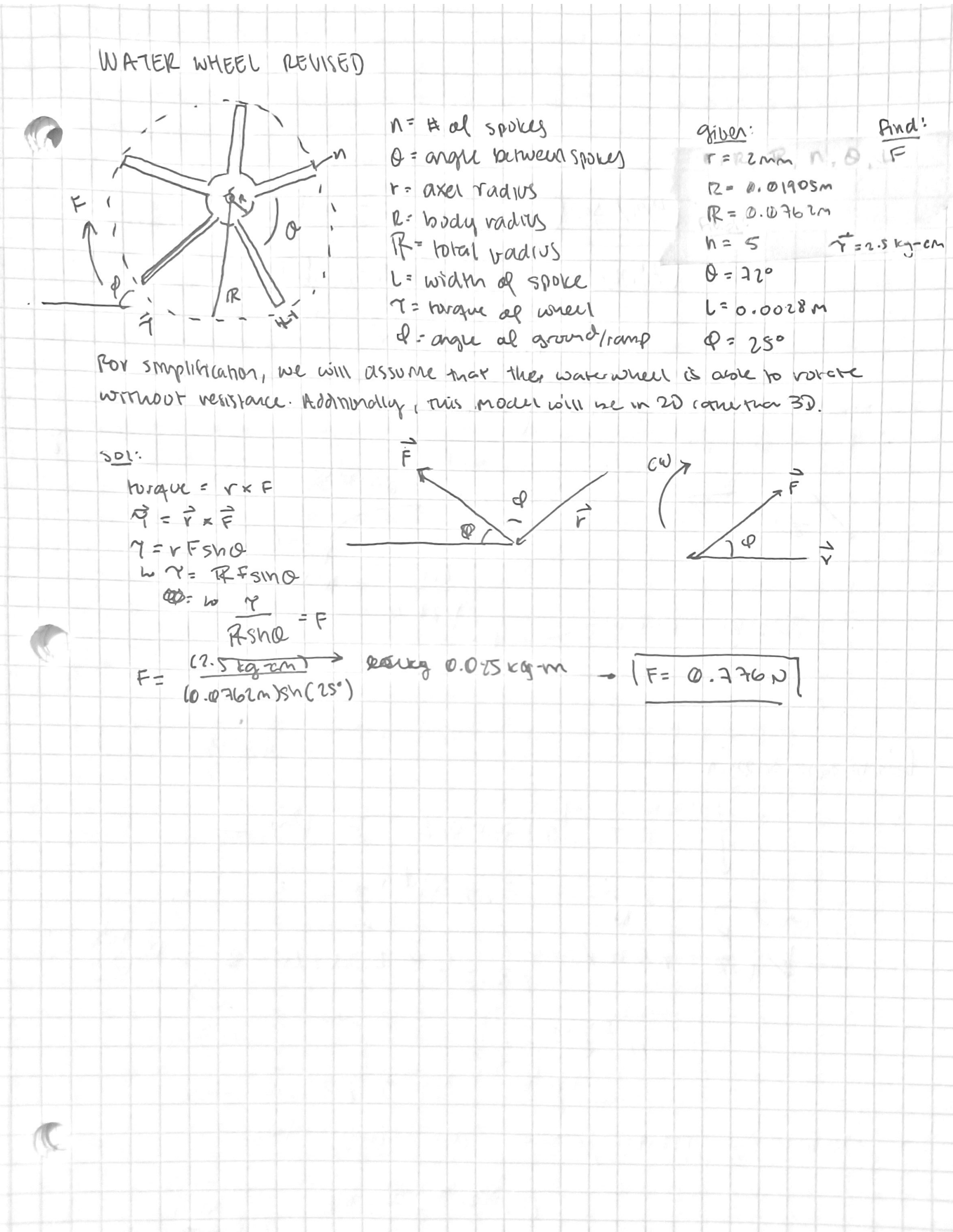
$$\hookrightarrow \boxed{V_0 = 0.502\ m/s}$$

→ solve for ω

$$\omega = \frac{V_0}{R} \rightarrow \omega = \frac{0.502\,m/s}{0.025\,m} \rightarrow \boxed{\omega = 20.08\ s^{-1}}$$

Figure 22: Model of ball up inclined plane.

Finally, the original water wheel had changed from a curved design to a straight, spoke design. As such, this model, shown in Figure 23 now takes that new geometry into account in order to determine how much force would be produced by the water wheel.



WATER WHEEL REVISED

n = # of spokes
θ = angle between spokes
r = axel radius
R = body radius
$\mathbb{R}$ = total radius
L = width of spoke
τ = torque of wheel
ϕ = angle of ground/ramp

given:
r = 2mm
R = 0.01905m
$\mathbb{R}$ = 0.0762m
n = 5
$\vec{\tau}$ = 2.5 kg-cm
θ = 72°
L = 0.0028 m
ϕ = 25°

Find:
F

For simplification, we will assume that the waterwheel is able to rotate without resistance. Additionally, this model will be in 2D rather than 3D.

sol:

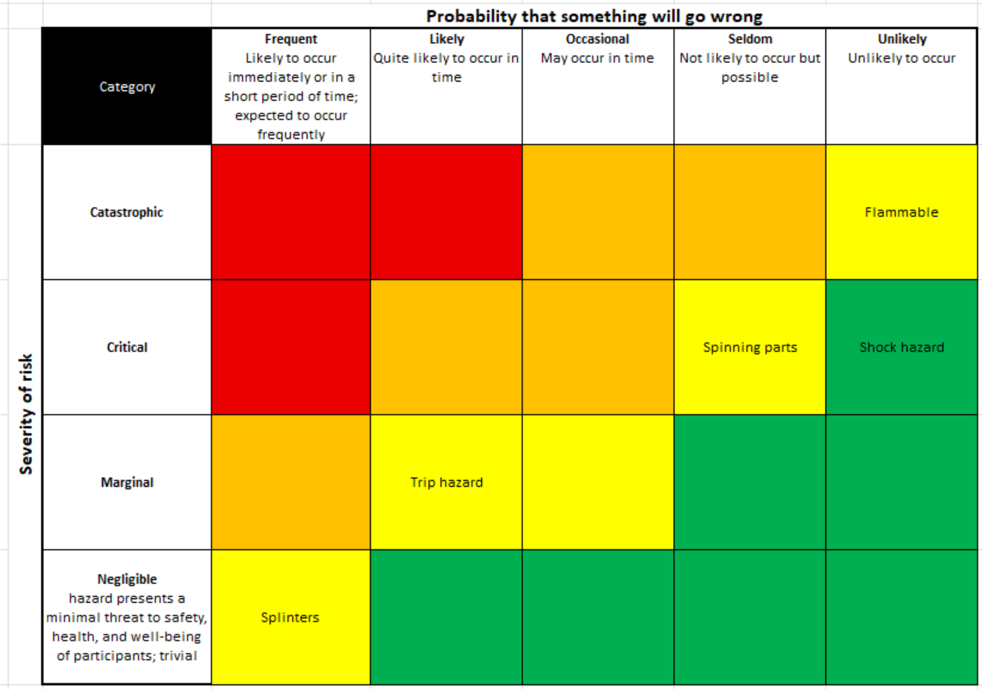
torque = r × F
$\vec{\tau} = \vec{r} \times \vec{F}$
$\tau = rF\sin\theta$
w/ $\tau = \mathbb{R}F\sin\theta$
$\rightarrow$ w/ $\dfrac{\tau}{\mathbb{R}\sin\theta} = F$

$$F = \frac{(\cancel{2.5\,kg\text{-}cm}) \longrightarrow 0.025\,kg\text{-}m}{(0.0762m)\sin(25°)} \rightarrow \boxed{F = 0.776N}$$

Figure 23: Revised model of water wheel.

6.2 Design for Safety

A few factors were taken into account when evaluating the potential risks that could occur when creating our design. Shown below in Figure 24 is the heat map of the five risks we took into account.



Probability that something will go wrong

Severity of risk

Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Catastrophic	🟥	🟥	🟧	🟧	🟨 Flammable
Critical	🟥	🟧	🟧	🟨 Spinning parts	🟩 Shock hazard
Marginal	🟧	🟨 Trip hazard	🟨	🟩	🟩
Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial	🟨 Splinters	🟩	🟩	🟩	🟩

Figure 24: Heat map of risk assessment.

6.2.1 Risk #1: Splinters

Description: Since our rover is made out of wood, there is a nonzero chance that a user could get splinters from handling the device. This risk's severity could increase if the device's frame were to be broken. Additionally, dryer environments can lead to the development of more splinters.

Severity: This risk is considered **negligible** because splinters do not cause much harm to either the user or the device and are easily dealt with.

Probability: This risk would occur **frequently** because our device is made of wood, and the user is regularly in contact with wooden parts.

Mitigating Steps: In order to mitigate this risk, we have sanded down the rover and minimized hand-cut parts.

6.2.2 Risk #2: Trip Hazard

Description: Our rover operates on the ground level, so it can be easily overlooked and stumbled upon when walking. On terrains that are slippery, a user is more likely to loose balance and trip over the rover.

Severity: This risk is considered **marginal** because tripping over the device would cause more harm to the device than the user.

Probability: This risk is **likely** to occur because our device is often traversing the floor and is relatively small, so an unassuming participant could trip over the device.

Mitigating Steps: In order to mitigate this risk, we are brightly decorating the rover to be better spotting against the plain floor and keeping it in designated operating areas.

6.2.3 Risk #3: Spinning Parts

Description: Our rover has a lot of spinning parts, including the four wheels and the waterwheel used to pick up dice. Losing control/connection to the device could cause the rover to uncontrollably spin and cause a risk of injury from the moving parts.

Severity: This risk is considered **critical** because the moving parts could cause harm to the user and any objects near the parts.

Probability: This risk is **seldom** to occur because our device has very noticeable moving parts that aren't easy to get caught on.

Mitigating Steps: In order to mitigate this risk, our parts are spinning at a speed that can easily be stopped if needed.

6.2.4 Risk #4: Shock Hazard

Description: There are many metal screws used for the servos of the device and many electrical parts connecting the components. Dry environments could lead to potential shock when touching metal components.

Severity: This risk is considered **critical** because a shock could cause the electronic components to fail, which would make some parts of the system inoperable and would hurt the user.

Probability: This risk is **unlikely** to occur because our device does not have any exposed wiring that could shock the user.

Mitigating Steps: In order to mitigate the risk of shock, the electrical components are inspected to ensure that there is no damage with the wire casing.

6.2.5 Risk #5: Flammable

Description: We have many electronics for our device. Humid environments or water damage could cause the electrical components to short, resulting in a fire. Additionally, the frame of the rover is made of wood, which is easily flammable.

Severity: This risk is considered **catastrophic** because if any part were to catch on fire, the entire device would fail and the user would be at risk of being burned.

Probability: This risk is **unlikely** to occur because the components that are likely to cause a flame are unlikely to fail.

Mitigating Steps: In order to mitigate this risk, our device is equipped with electronics that are encased, so there are no exposed electronic components.

6.2.6 Risk Prioritization

Four of our five risks, splinters, trip hazard, spinning parts, and flammability, fall into the third tier of classification, which is based on the severity and probability of the risk occurring. Since these four risks are about the same in terms of their classification, the risks will be prioritized based on their frequency. Splinters are prioritized because they have the highest frequency of occurring, despite the severity being nearly negligible. Next is the rover being a trip hazard. This risk is likely to occur and cause more damage than splinters but not enough to prioritize it higher than splinters. Following trip hazards is the risk of spinning parts. While this risk is not likely to occur, the possibility of it happening is still there and measures should be taken into account to prevent such accident involving said risk from occurring. Finally is the risk of flammable parts. This risk is very unlikely to occur, but, if it were to occur, it would have severe consequences. The final risk bring prioritized is the shock hazard because it is equally as likely to occur as flammability but would be slightly less detrimental.

6.3 Design for Manufacturing

Taking into account both the physical prototype and the CAD embodiment, there are quite a few components that the rover has. However, for manufacturing purposes, there are parts that can be combined and simplified into a single component.

Total number of parts, excluding threaded fasteners: 29
Total number of threaded fasteners: 16
Theoretically Necessary Components (TNC): 12

The first TNC is the waterwheel. This component needed to be counted as a separate component because it is being printed in TPU, which is a different material from the rest of the rover. The next TNC would be the axis the waterwheel is being rotated on. Since this part is moving relative to other parts and currently made of a different material from the rest of the rover, it can be considered a TNC. Next would be the base of the rover itself. In order to simplify the rover, the three frame pieces and the ramp has been combined into one part. This part would them be altered to be printed in TPU instead of the wood that it currently is. Finally, another TNC would be the battery pack. Since this component is essential to the rover and unable to be combined with another component, it can be counted as an individual TNC.

There are a few changes that we can make in order to minimize the number of components used in the design of the rover. To start, the three frame pieces of the rover and the ramp can be combined together to form a single part. This can be achieved by 3D printed the component rather than laser cutting each part with wood. While it would make assembly of the rover as a whole a bit more difficult, it would theoretically be possible to simplify the frame into a single piece. Additionally, each wheel and the servo horn it is connected to can be combined into one part. This simplifies 8 components into 6 by swapping out our current wheel design for more of a tread-like design, as shown below in Figure 25. Additionally, this change would also simplify the wiring as there would no longer be a need for the y connectors currently being used to connect servos.

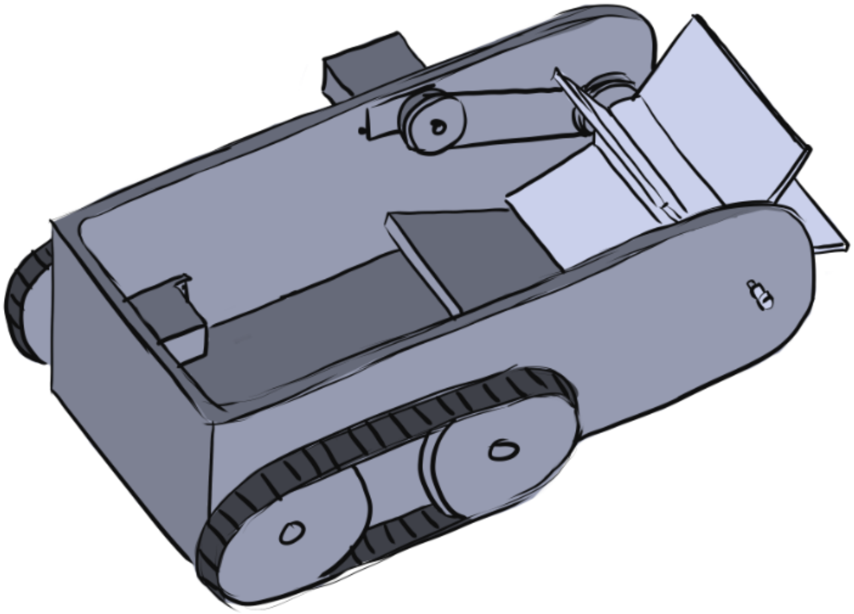


Figure 25: Drawing of rover with TNCs.

6.4 Design for Usability

There are various impairments that might make it difficult for a user to operate our device. When creating and designing our prototype, there were a few impairments that we considered.

6.4.1 Vision Impairment

For those with vision impairment, there might be some difficulty in use, mostly due to how small the device itself is. Some difficulty might occur with the user checking to see if the device is working properly, which can be fixed by making a larger water wheel component. Additionally, the rover is operated with the use of a very small camera. The minimal resolution of the camera could be difficult with those with some visual impairments to navigate. Otherwise, impairments, such as color blindness, will not affect the usability of our device.

6.4.2 Hearing Impairment

A user's hearing impairment should have minimal effects on the usability of our device. Our device does not rely on any sort of auditory factor, such as any cues to load the rocks or any sort of audio cues when the device is operating, in order to use the device. There are some aspects, such as ensuring the transmitter is paired with the controller, that have auditory cues, but they also have a visual light cue to help indicate a pairing. Similarly, there could be sounds of the waterwheel stalling a bit or other maintenance audio cues, but they also have a corresponding visual cue with them.

6.4.3 Physical Impairment

Physical impairment might slightly affect the usability of our device due how interconnected all our components are. Due to the size constraints of the rover, there might be some difficulty in navigating the components because of how small and interconnected everything is. Additionally, there might be some difficulties operating the rover using the controller because of the precision needed to maneuver the course. Otherwise, the use of the rover itself should not be affected by physical impairments.

6.4.4 Control Impairment

Control impairments might have some effect on the usability of our device. Some disorientation might make our device a bit confusing to navigate, especially since our device does not exactly have a distinct top or bottom to it. We could improve this by creating a more distinct visual language of our device. Additionally, impairments, such as excessive fatigue and intoxication, could prevent the user from operating the rover to maneuver small areas.

7 Final Prototype

7.1 Overview

After six iterations of the prototype, the group finalized the design of the rover. It consists of a laser-cut 3 mm craft plywood frame and wheels, a 3D-printed 95A TPU waterwheel and PLA ramp, and five continuous microservos to power the four wheels and the waterwheel. The light and thin plywood ensured the rover did not surpass the 3.5 lb weight limit, and 3D printed parts gave the design significant customizability. Additionally, the rover is driven by connecting each of the side wheels to the same transmitter channel via Y-splitter wires. The rover's battery pack is secured to the outside of the back panel of the rover while the transmitter is connected to the inside of the back panel of the rover. The camera is secured to the right side of the rover with a 3D-printed PLA bracket. The camera's battery pack is also secured to the side panel of the rover.

7.2 Documentation

An image of our final design can be seen below in Figure 26:

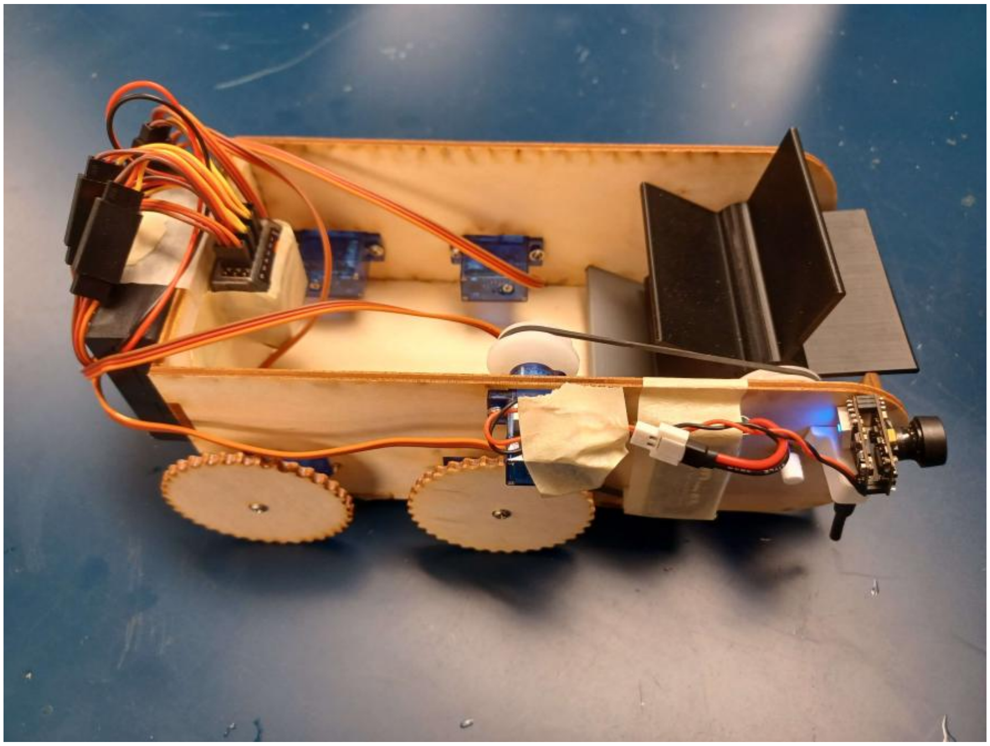


Figure 26: Final prototype.

Additionally, an exploded view of the CAD of the rover can be seen below in Figure 27 to better showcase all of the components.

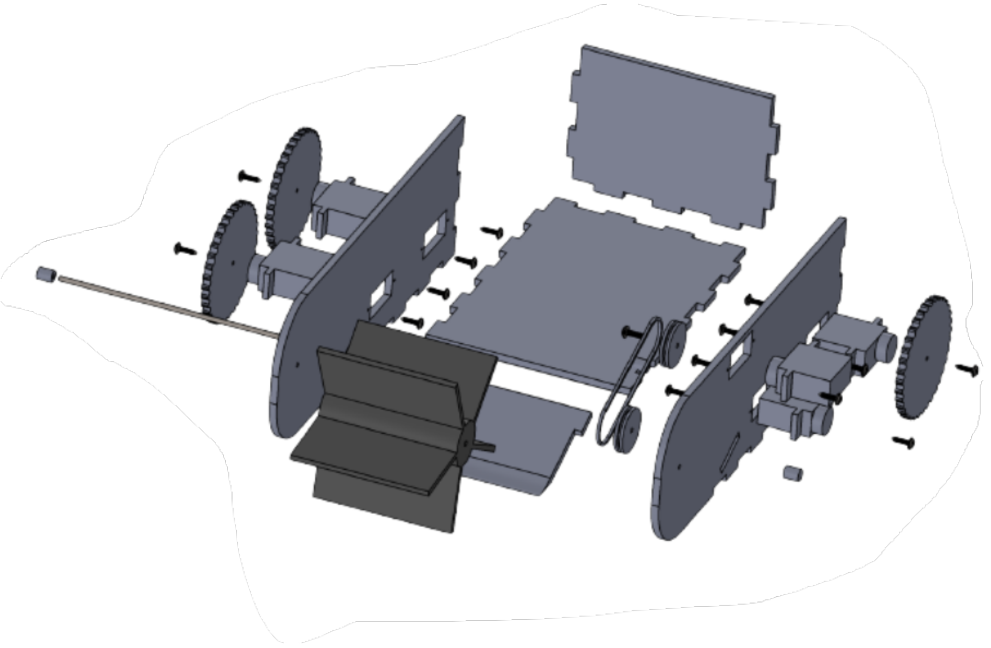
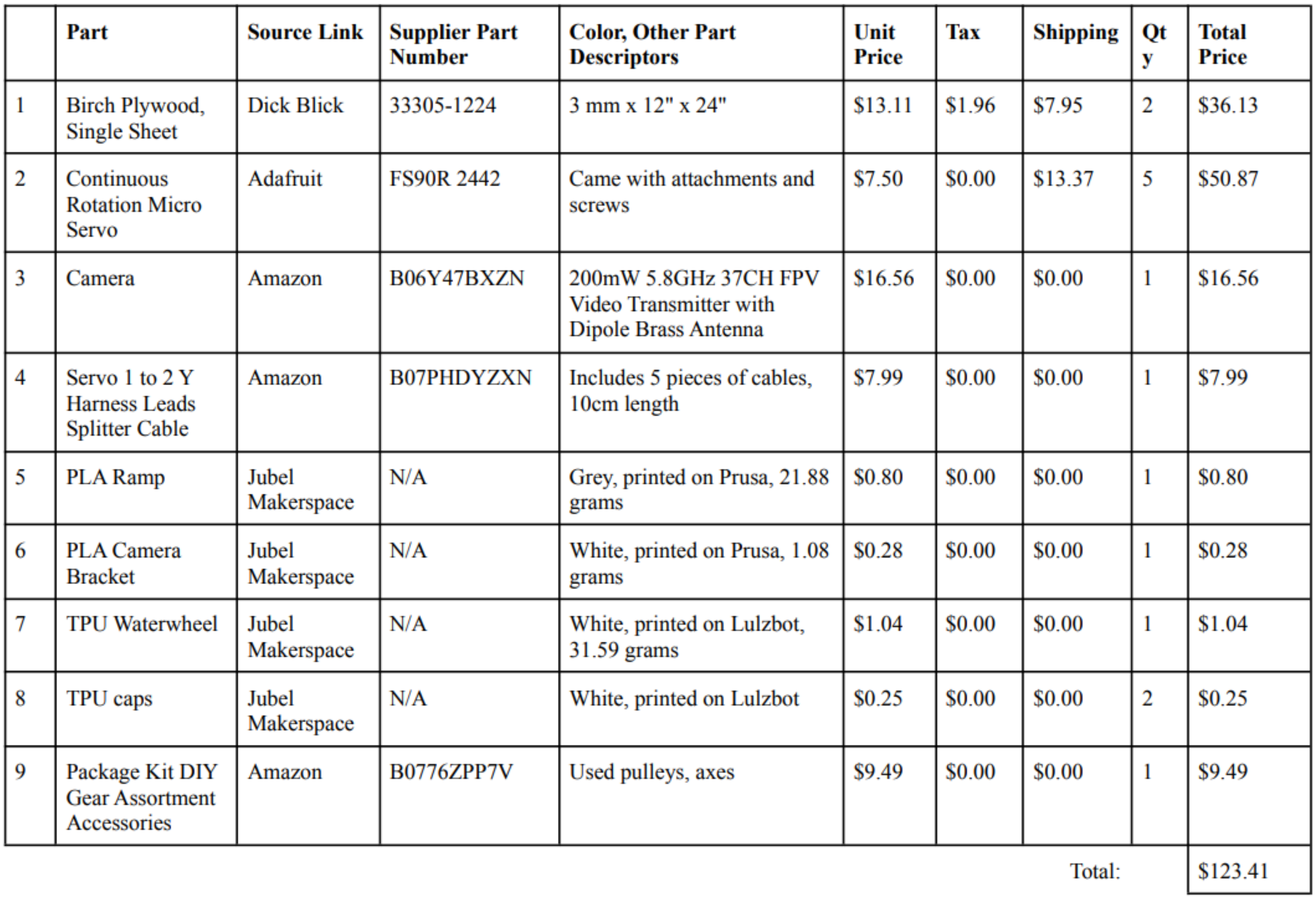


Figure 27: Exploded CAD of the rover design.

The design was able to achieve all the performance goals our group had initially set out to achieve. The rover was tested on the agility course, and the driver was able to successfully navigate the rover through the course without touching the green lines and while looking only through the camera in less than three minutes. Next, the sizing of the rover allowed it to comfortably fit the 35 required rocks and was successfully able to store more within its frame. Finally, when tested, the rover was able to collect and store the rocks on various terrain.

A Parts List



	Part	Source Link	Supplier Part Number	Color, Other Part Descriptors	Unit Price	Tax	Shipping	Qty	Total Price
1	Birch Plywood, Single Sheet	Dick Blick	33305-1224	3 mm x 12" x 24"	$13.11	$1.96	$7.95	2	$36.13
2	Continuous Rotation Micro Servo	Adafruit	FS90R 2442	Came with attachments and screws	$7.50	$0.00	$13.37	5	$50.87
3	Camera	Amazon	B06Y47BXZN	200mW 5.8GHz 37CH FPV Video Transmitter with Dipole Brass Antenna	$16.56	$0.00	$0.00	1	$16.56
4	Servo 1 to 2 Y Harness Leads Splitter Cable	Amazon	B07PHDYZXN	Includes 5 pieces of cables, 10cm length	$7.99	$0.00	$0.00	1	$7.99
5	PLA Ramp	Jubel Makerspace	N/A	Grey, printed on Prusa, 21.88 grams	$0.80	$0.00	$0.00	1	$0.80
6	PLA Camera Bracket	Jubel Makerspace	N/A	White, printed on Prusa, 1.08 grams	$0.28	$0.00	$0.00	1	$0.28
7	TPU Waterwheel	Jubel Makerspace	N/A	White, printed on Lulzbot, 31.59 grams	$1.04	$0.00	$0.00	1	$1.04
8	TPU caps	Jubel Makerspace	N/A	White, printed on Lulzbot	$0.25	$0.00	$0.00	2	$0.25
9	Package Kit DIY Gear Assortment Accessories	Amazon	B0776ZPP7V	Used pulleys, axes	$9.49	$0.00	$0.00	1	$9.49
							Total:		$123.41