Project 3

Team 19

December 5th, 2018

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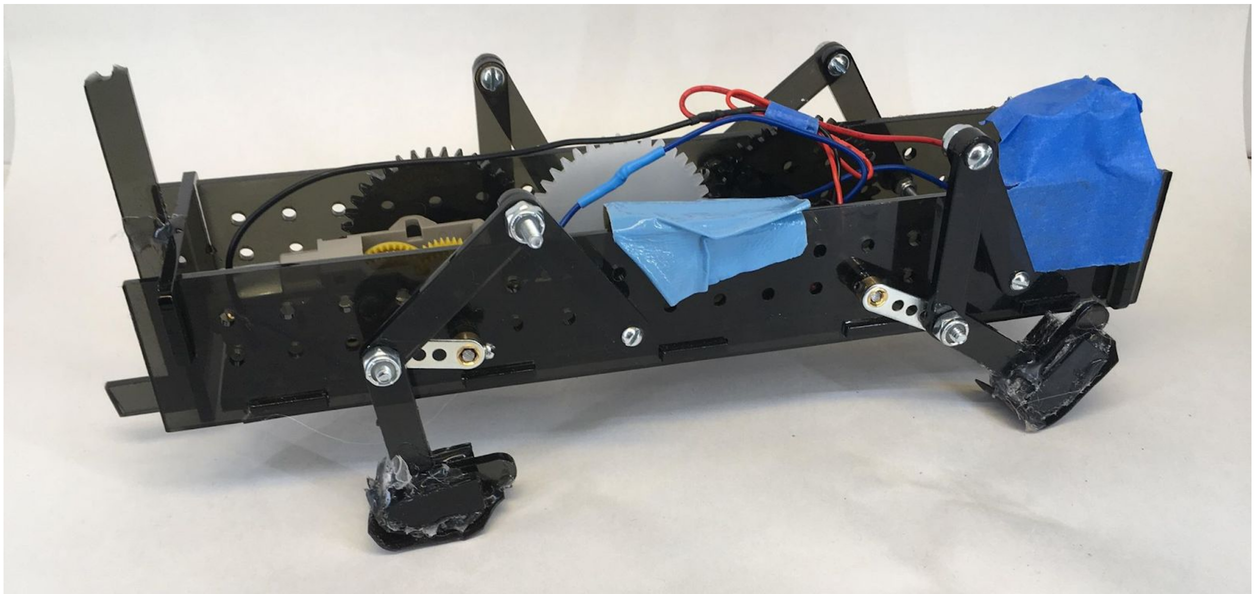
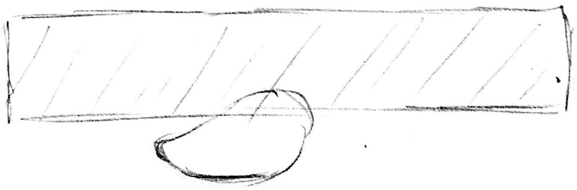
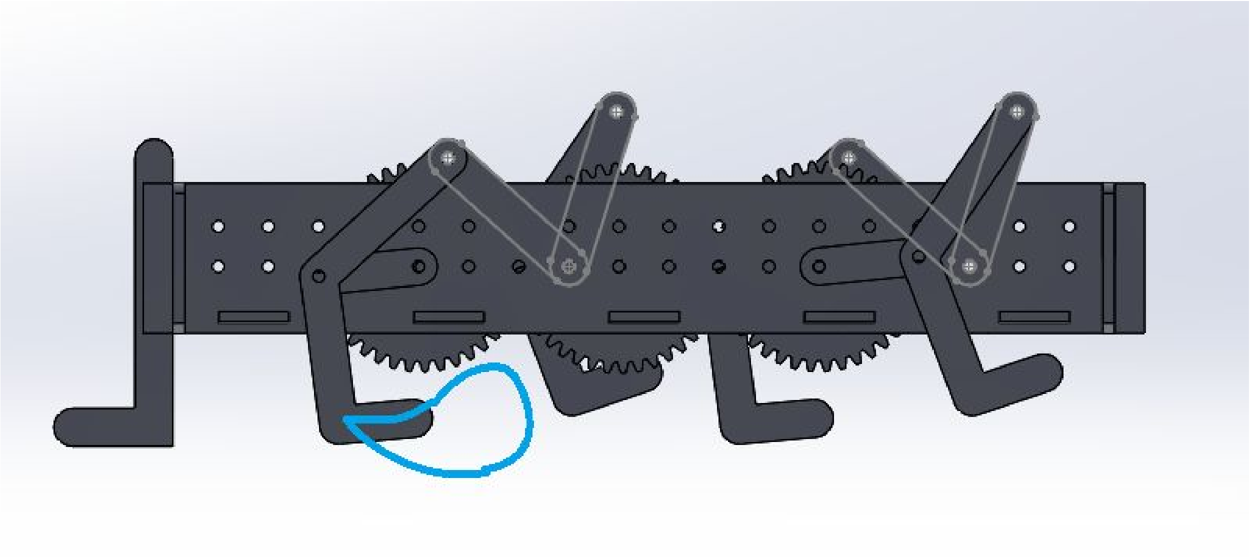


Coupler Curve and Four Bar Linkage Design

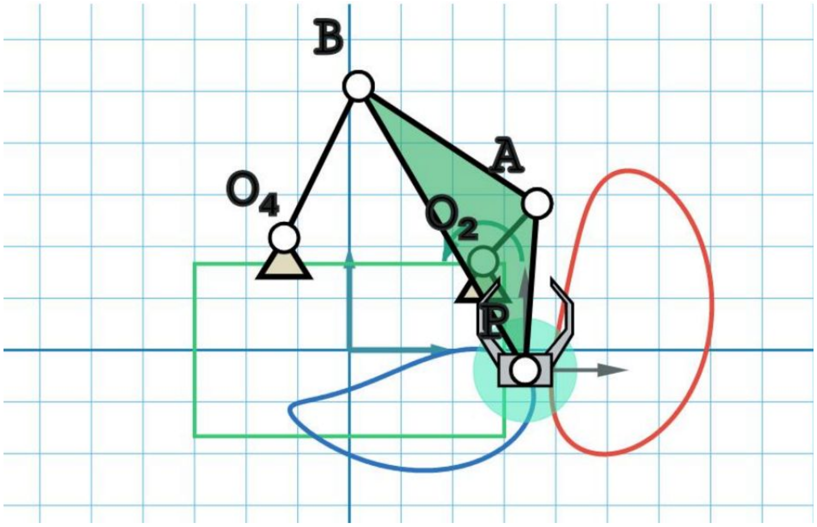
Desired coupler curve



Sketch of coupler curve



Sketch of coupler curve on CAD

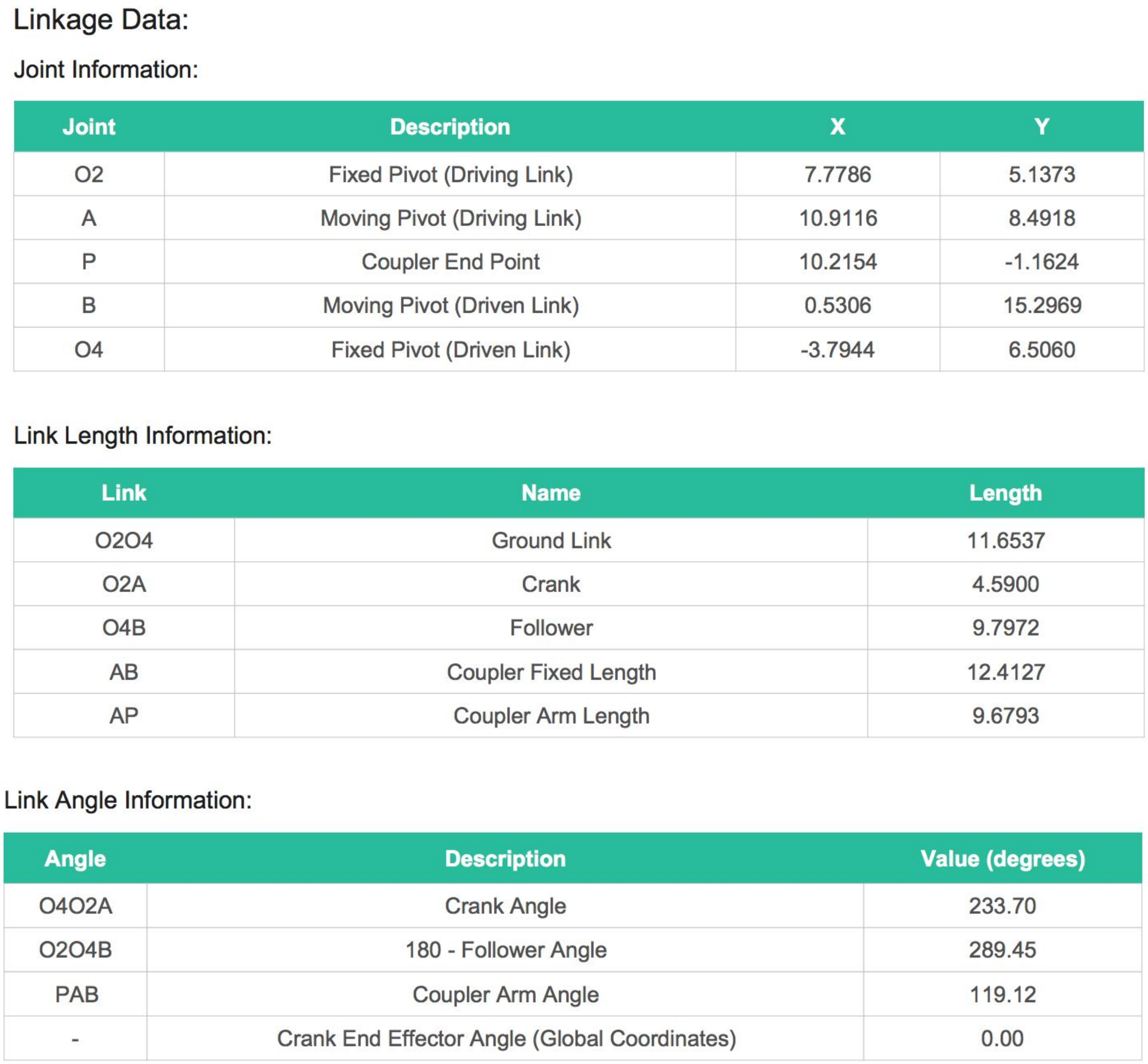


Description & Rationale for Foot Design

Our foot is rectangle shaped and curves upward at the “toe” and “heel” to allow for maximum contact with the ground while it goes through the coupler curve. We glued Dycem on to the bottom of the foot in order to to increase the coefficient of friction with the ground. This greatly aided the robot’s ability to climb over hills. At first the foot had a thinner width, but we increased the width by adding layers of acrylic in order to create more area that the robot has contact with the ground. This helped stabilize the robot greatly and prevent some pivoting.

Screenshot of MotionGen Graphic

Linkage Parameters from MotionGen



Linkage Data:

Joint Information:

Joint	Description	X	Y
O2	Fixed Pivot (Driving Link)	7.7786	5.1373
A	Moving Pivot (Driving Link)	10.9116	8.4918
P	Coupler End Point	10.2154	-1.1624
B	Moving Pivot (Driven Link)	0.5306	15.2969
O4	Fixed Pivot (Driven Link)	-3.7944	6.5060

Link Length Information:

Link	Name	Length
O2O4	Ground Link	11.6537
O2A	Crank	4.5900
O4B	Follower	9.7972
AB	Coupler Fixed Length	12.4127
AP	Coupler Arm Length	9.6793

Link Angle Information:

Angle	Description	Value (degrees)
O4O2A	Crank Angle	233.70
O2O4B	180 - Follower Angle	289.45
PAB	Coupler Arm Angle	119.12
-	Crank End Effector Angle (Global Coordinates)	0.00

Link Lengths

Link	Length
r1	1.5 in
r2	1 in
r3	1.62 in
r4	1.75 in

Other Parameters

Parameter	Value
β	125°
rp	1.5 in

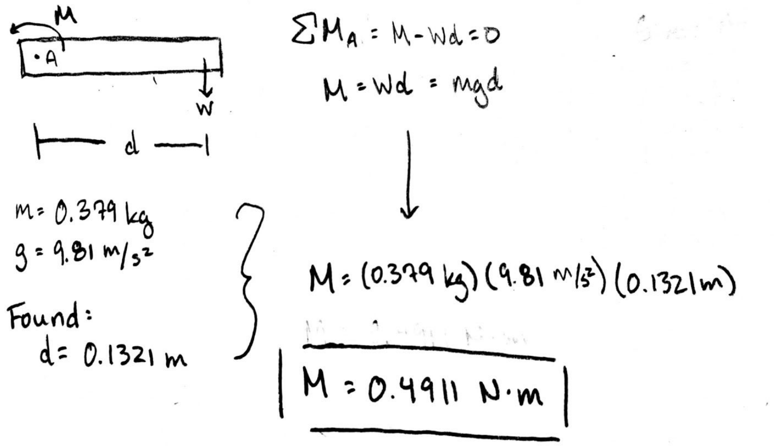
Comments on Designed vs Desired Coupler Curve

Throughout several iterations, we decided that an oval shaped coupler curve was the best way to move the robot forward while also keeping it stable. One of the major changes we made was making the link AP shorter so that the two feet did not hit each other during the robot's gait.

Motor Characterization and Gear Ratio Selection

Stall Torque & Gear Ratio at 3V

We measured an overall stall torque (of the motor shaft) of .00241 N-m at 3V with the 204 gear ratio and AA batteries. The stall torque we found for the gearbox output shaft through the motor experiment was .491 N-m.



$$T=(9.81\mathrm{m/s^2})(0.379\mathrm{kg})(0.13208\mathrm{m})=0.4911\,N\cdot m$$

$$.491\,[N\cdot m]\,/\,204\;=\;.00241\,N\cdot m$$

Measured Stall Torque vs Manufacturer Stall Torque

The stall torque that we found for our motor (0.00241 $N\cdot m$) is ⅓ lower than the manufacturer specified stall torque (0.00353 $N\cdot m$). This difference is most likely due to slight inconsistencies in the overall motor manufacturing and the amount of power distributed using the battery in tandem with possible errors while we were doing the experiment to find the stall torque.

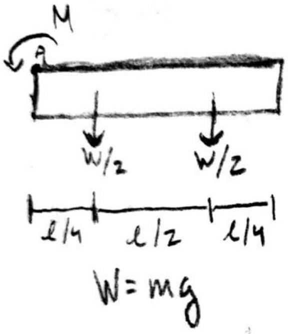
Gear Ratio for Gearbox and Outside Gearbox

We chose the 204 gear ratio for inside the gearbox, and our outside gear ratio is 1. As such, the overall gear ratio that runs our feet is 204 (the power is translated only from the inside). We chose the outside gear ratio to be 1 because the main reason we needed these gears was the translate motion. Overall, the ratio within the gearbox provided enough torque (and translated to enough force) for our robot to move at the speed that we wanted.

Estimation of Maximum Mass Without Stalling

Assumptions:

1) The robot is not tipping over (and therefore has no net moment)
2) One of the legs is directly below the motor
3) The mass of the robot is supported by one back leg and one front leg at any given time
4) Center of mass is in the middle of the robot



Maximum Mass:

$$\sum M_A = M - (W/2)\,\ell/4 - (W/2)(\ell/4 + \ell/2) = 0$$

$$0 = M - mg\ell/8 - 3mg\ell/8$$

$$M = mg\ell/2 \rightarrow m = \frac{2M}{g\ell}$$

$M = 0.491$ [N·m] {stall torque}

$g = 9.81$ [N]

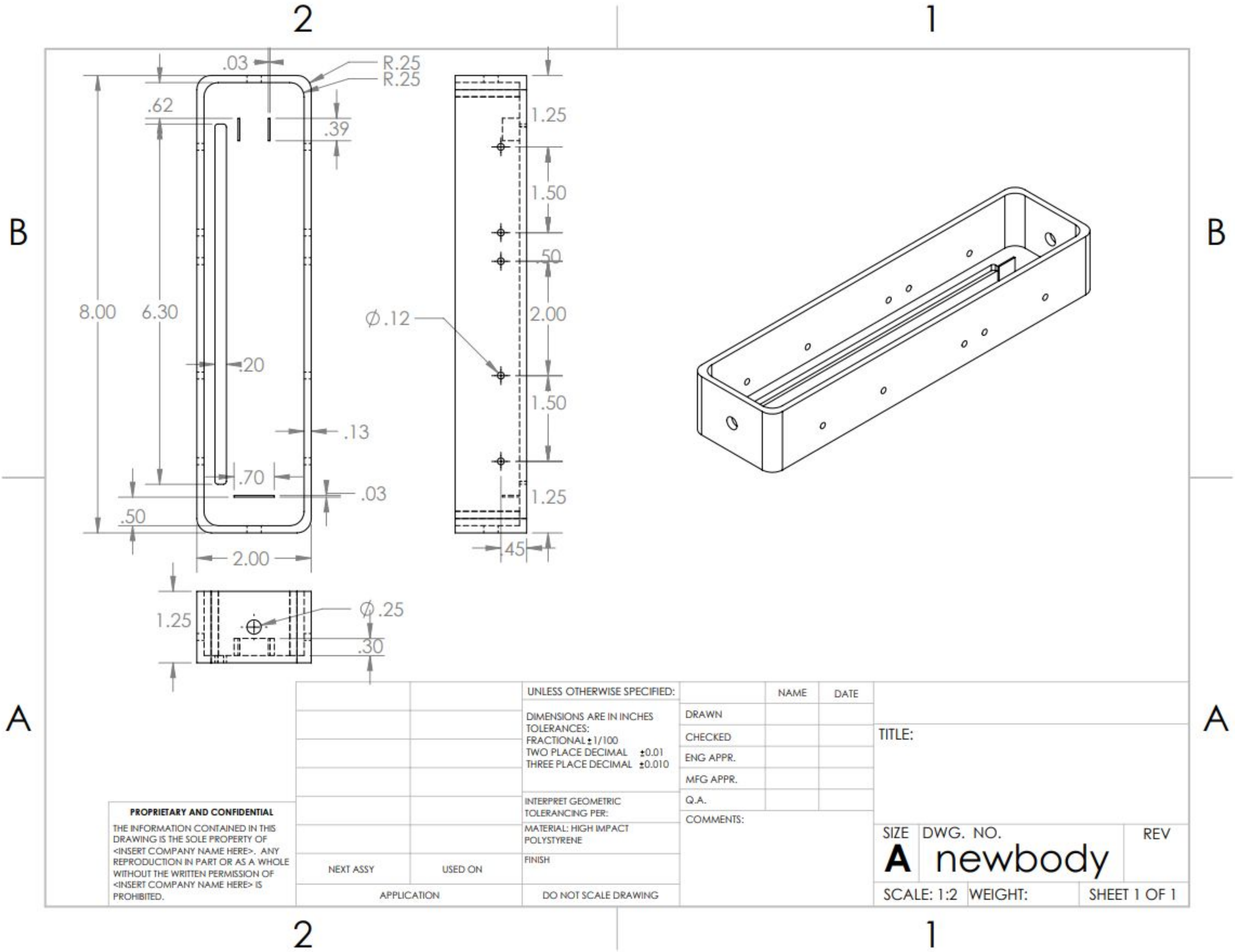
$\ell = 0.2413$ [m]

$$\boxed{m = \frac{2(.491)}{(9.81)(.2413)} = 0.415 \text{ kg}}$$

Maximum mass = 0.415 kg

Manufacturing a Better Mount Plate

Engineering Drawing



Design Process

Our improved design features a rectangular shape with rounded edges. The bottom face has a rectangular slot to house the gears. One of the main issues of the kit was the small tabs used to connect the panels together were very thin and were easily snapped off during assembly. To address this, the entire base is a single piece made of high impact polystyrene. This also prevents the panels from shifting while the robot walks. All edges and corners are filleted to decrease stress concentrations and make the toy safer for small children. The provided base plate was also unnecessarily long, making the back drag against the ground when climbing hills. Unnecessary holes were removed to make a more aesthetically pleasing design and to make assembly simpler. There are also spacers in order to hold the battery pack and gearbox in place and prevent the center of mass from shifting, keeping the robot walking in a straight line.

The most viable method for manufacturing 10,000 components given our weight and section thickness constraints is injection molding. Since there are several small and precise components with more complex shapes, we opted for injection molding as opposed to compression molding. The large initial cost for can be justified for such a high production volume. We chose high impact polystyrene due to its high strength and relatively low cost. It also has a low thermal diffusivity, dramatically decreasing the machine time and associated costs required.

Estimated Cost per Unit

Mold Base Cost

Square enclosing parts: 2 in by 2 in

$A = (4 \text{ in})(4 \text{ in}) = 16 \text{ in}^2$

$d = 8 \text{ in}$

$\text{Cost} = 1000 + 10.58A(d+6)^{0.4}$

$= 1000 + 10.58(16)(8 + 6)^{0.4}$

$= \mathbf{\$1,468.47}$

Cavity and Core Manufacturing Costs

Estimate \$30/hour labor

$A = 16 \text{ in}^2$

$SP = 53$

$\text{Cost} = 75A^{0.5} + 2700(.08 + .04(SP))^{1.27} + 300 + 120A^{1.2}$

$= 75(16)^{0.5} + 2700(.08 + .04(53))^{1.27} + 300 + 120(16)^{1.2}$

$= \mathbf{\$11,022.12}$

Cost of Materials

Material = High impact polystyrene

Volume per shot = Ad = (16 in^2)(8 in) = 128 in^3 = 0.002098 m^3

Density of High impact polystyrene = 1.59 kg/m^3

Mass per shot = (volume)(density) = (0.002098 m^3)(1.59 kg/m^3) = 0.003336 kg

Cost of polystyrene per kg = \$1.12/kg

Cost of material for one shot = (cost of polystyrene)(mass) = (\$1.12/lb)(0.003336 kg) =
= \$0.0037/shot

# of shots = 10,000

Cost = 1.03(cost of material for one shot)(# of shots)
= 1.03(\$0.0037)(10,000)
= **\$38.48**

Machine Time

h_{max} = 0.13

alpha = 0.09

Cost = $2.18(h_{max})^2$/alpha
= $2.18(0.13)^2/0.09$
= **\$0.41**

Total Cost

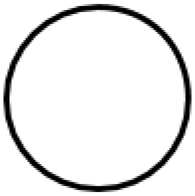
Total Cost = Mold base cost + cavity/core cost + material cost + machine time
= 1468.47 + 11022.12 + 38.48 + 0.41
= **\$12,529.07**

Unit Cost = (Total Cost)/(# of shots)
= 12,529.07/10000
= **\$1.25 / part**

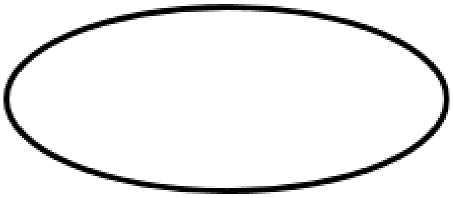
Supporting Materials

Table of Contents:

Candidate Coupler Curves



Circle

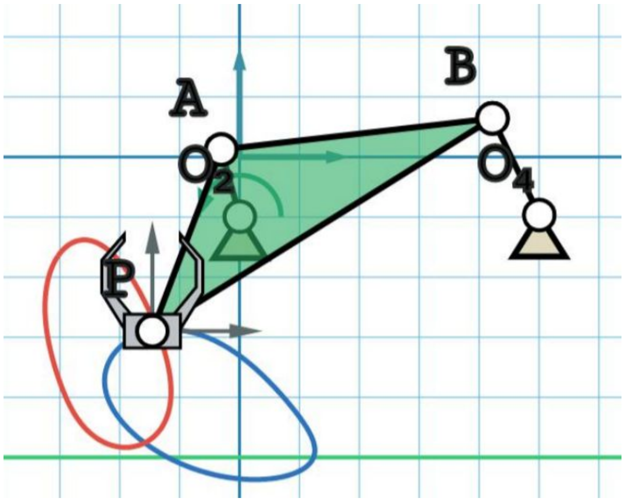


Oval

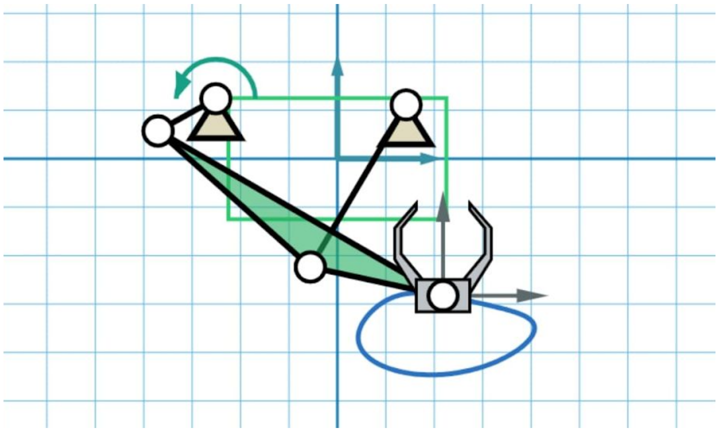
The circular coupler curve was the first curve that came to mind while designing the robot. However, by studying the gait of a cat and other animals, we determined that a circle would not have enough contact with the ground.

Next, the oval coupler curve was observed to be the coupler curve of choice that cats and other animals used the most. This was the first coupler curve we tried to design a mechanism around. However with testing, we realized a perfect oval would cause the foot not to be lifted high enough.

Alternate Four Bar Linkage Designs



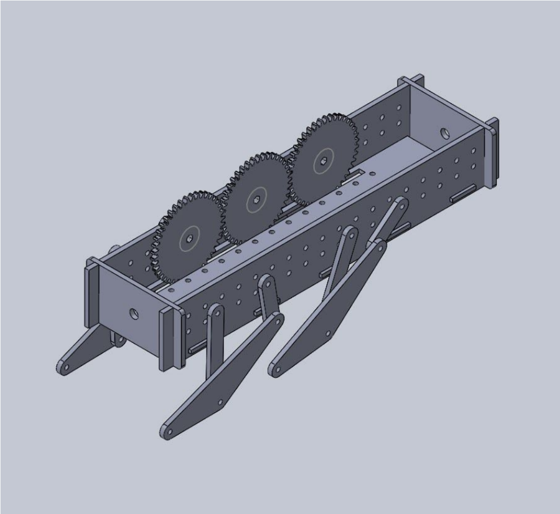
This is the first four bar linkage we designed, we attempted to mimic the gait of a cat as closely as possible. We did not attempt to build this design however because we decided there was not enough contact with the ground in this coupler curve. We then attempted to design a new curve that would have more horizontal movement in the downward position.



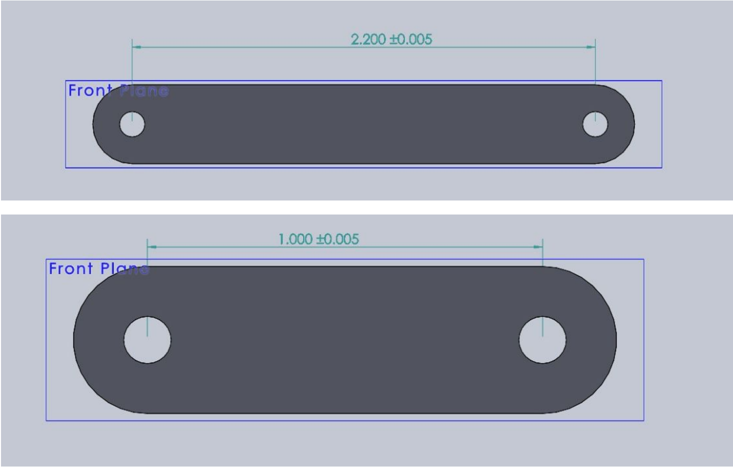
This is the second linkage that we designed. However there were several attachment problems (e.g. screws causing the linkages to become misaligned) that made us shift our design from the above to the final design.

Previous CAD

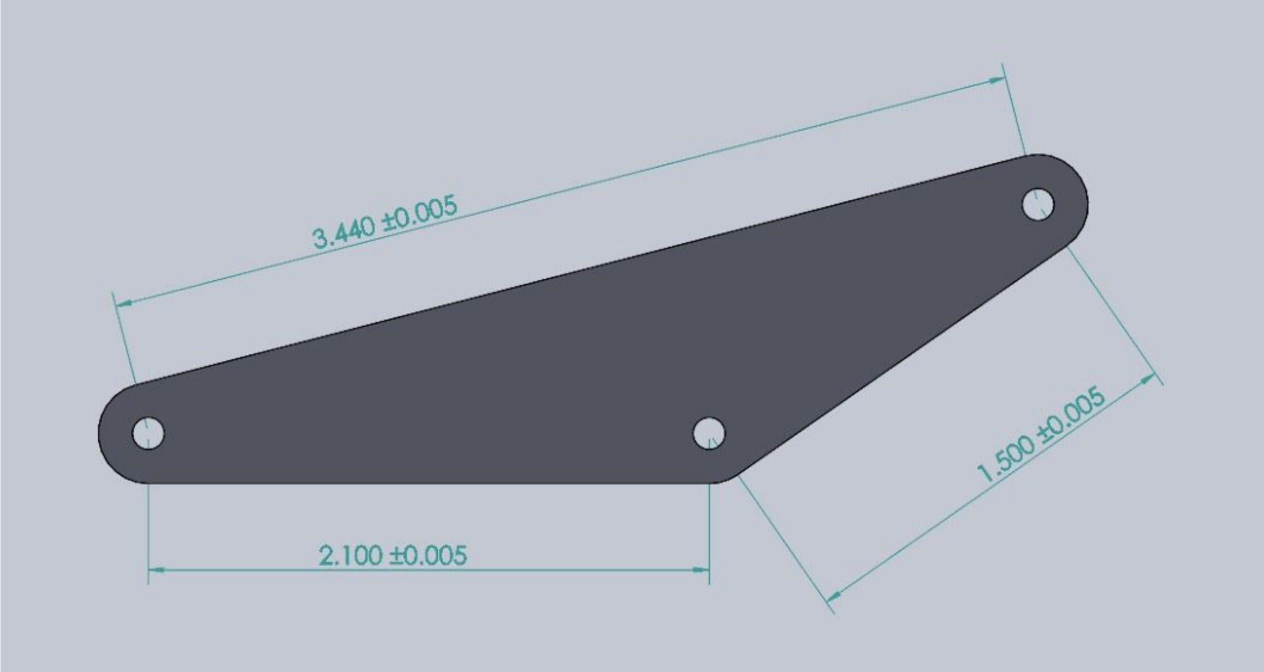
Robot



Links

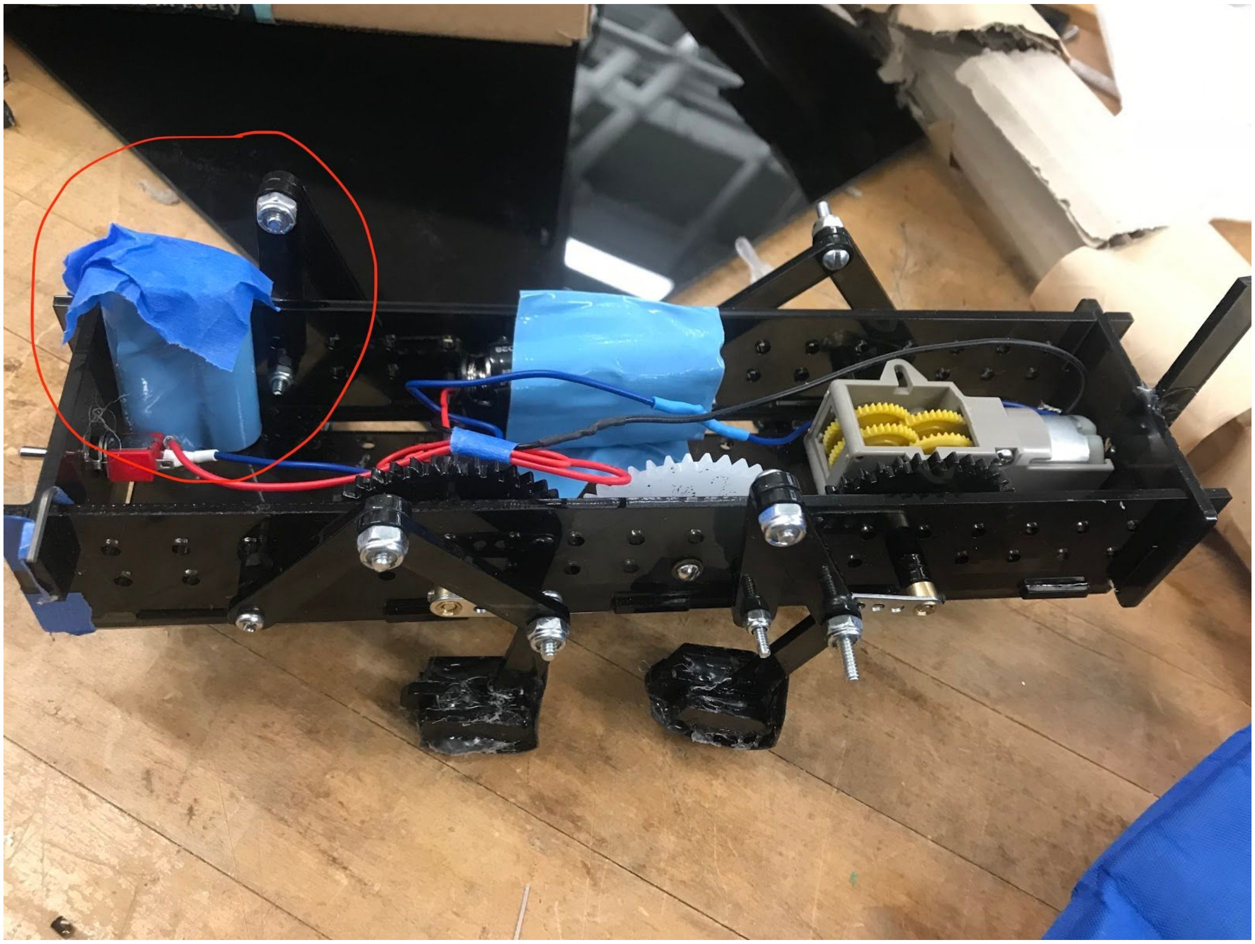


Foot



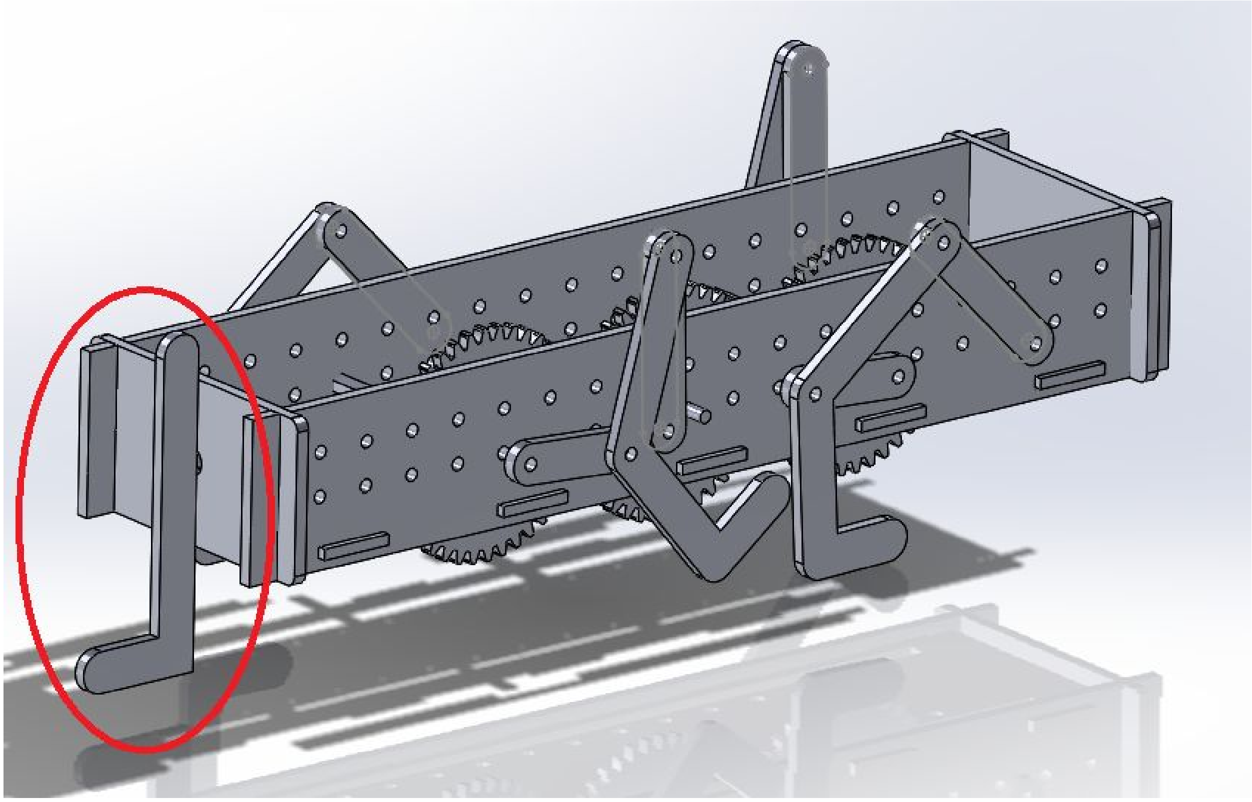
These were the original CAD designs for a robot that would mimic the second coupler curve that we had decided before we turned to our final design.

Front Weight Explanation



We added a weight at the front to offset the weight of the motor (which is located at the back of the robot). This greatly decreased the amount that the robot turned during its gait. It also created a more forward facing center of mass for the robot overall.

Tail Explanation



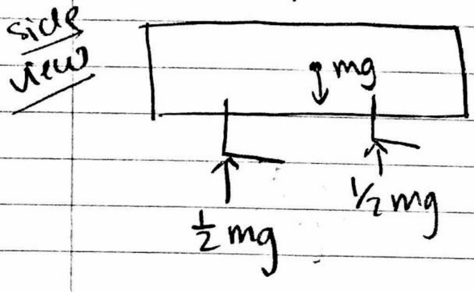
While testing the robot, we noticed that lifting the back of the robot up while it was moving would allow it to complete its gait and move forward more easily. To make this a permanent solution, we added a “tail” at the back of the robot to prevent the back from dragging on the ground. This especially helped with the final steep hill at the end of the course.

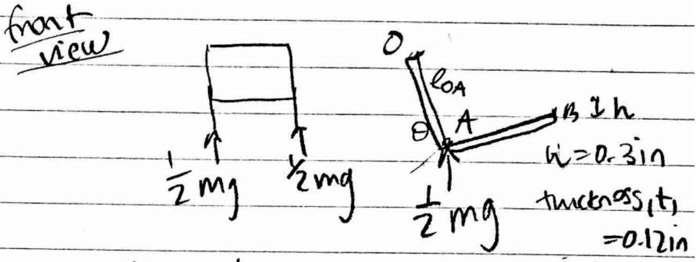
Hand Analysis

Bending moment

m = mass of robot

*assuming 2 feet in contact w/ ground at any given moment





$$\Sigma M|_O = -\tfrac{1}{2} mg\, l_{OA} \cos\theta + M_O$$

$$M_O = \tfrac{1}{2} mg\, l_{OA} \cos\theta$$

$$\sigma_B = \frac{My}{I} = \frac{\frac{1}{2} mg\, l_{OA} \cos\theta \cdot h/2}{\frac{1}{12}(t)(h^3)}$$

$$\sigma_B = \frac{3\, mg\, l_{OA} \cos\theta}{t h^2}$$

$\theta \approx 75°$

$l_{OA} \approx 1.5\text{ in} = 0.0381\text{ m}$

$m \approx .25\text{ kg}$

$t = 0.12\text{ in} = 0.00305\text{ m}$

$h = 0.37\text{in} = 0.0094\text{ in}$

$$\sigma_B = \frac{3(0.25)(9.81)\,0.0381 \cos 75}{(0.00305)(0.0094)^3}$$

$\sigma_B = 28639674\text{ Pa} \sim 4150\text{ psi}$

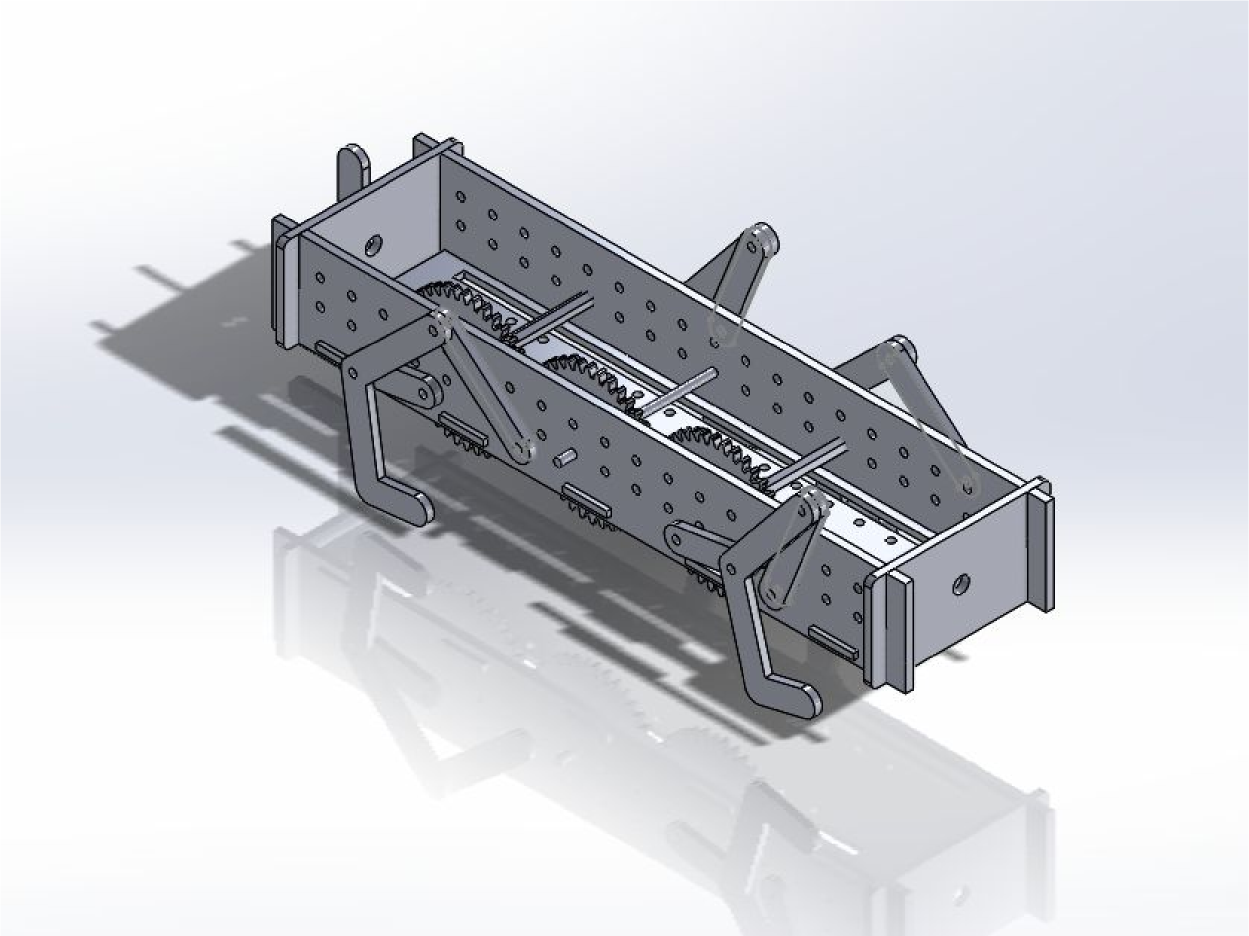
$\sigma_y = 8000\text{ psi}$

$\boxed{FOS = 1.93}$

Fatigue

Since the acrylic components are not under large stresses, there is minimal risk of fatigue. [experienced stress is ~1/2 of yield strength] The only potential for failure from fatigue is the gear stripping from the hexagonal rod, but we made sure it was a tight fit to prevent this from happening.

CAD Analysis

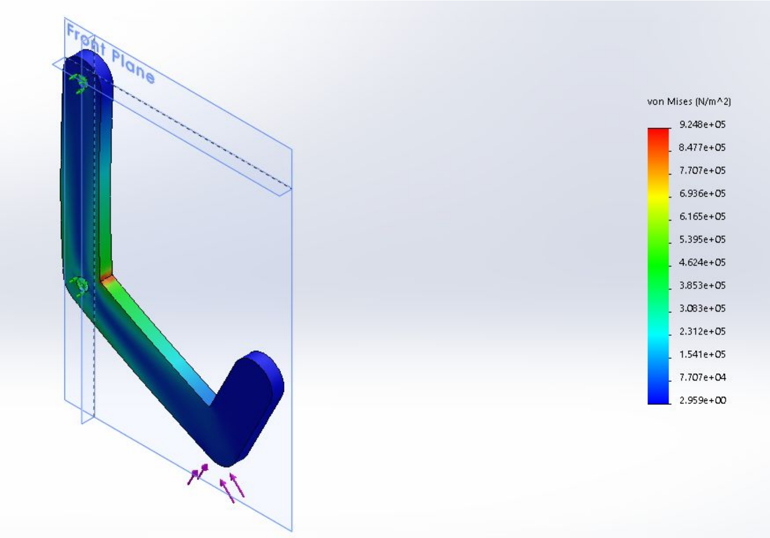


Isometric View of Walking Robot

The linkage that will receive the most stress is the longest linkage, which is the leg and foot linkage. There are points of failure for this, first when the heel touches the ground, and second when the foot touches the ground. Each leg receives at maximum half the weight of the robot since there are two legs touching the ground at any point of time.

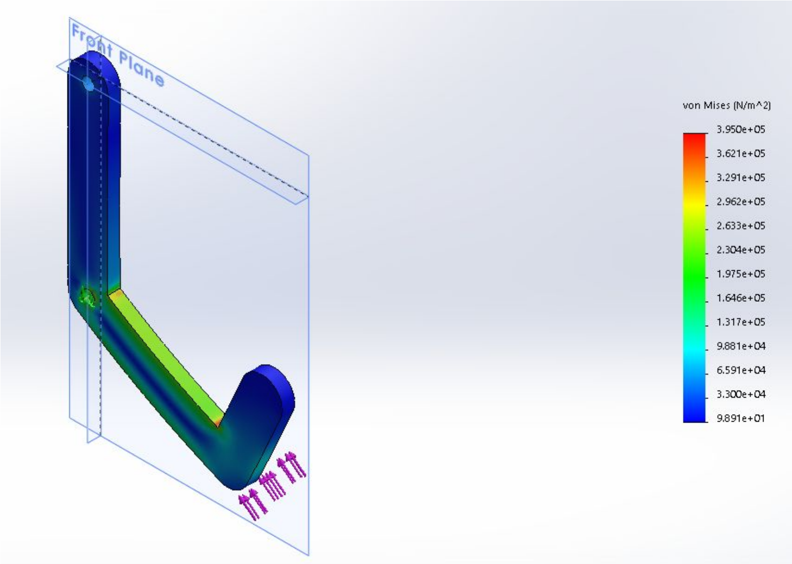
The mass of the robot is 200 g, so it exerts a total of 1.962 N down. Half of this is 0.981 N, therefore each foot will be analyzed with a force of 0.981 N.

The yield strength of acrylic is 10.4 MPa.



Stress when force is exerted on “heel”

The maximum stress is 0.9248 MPa which occurs at the bend of the “knee.” This has a FOS of 10.4/0.9248 = 11.25 which is very strong.



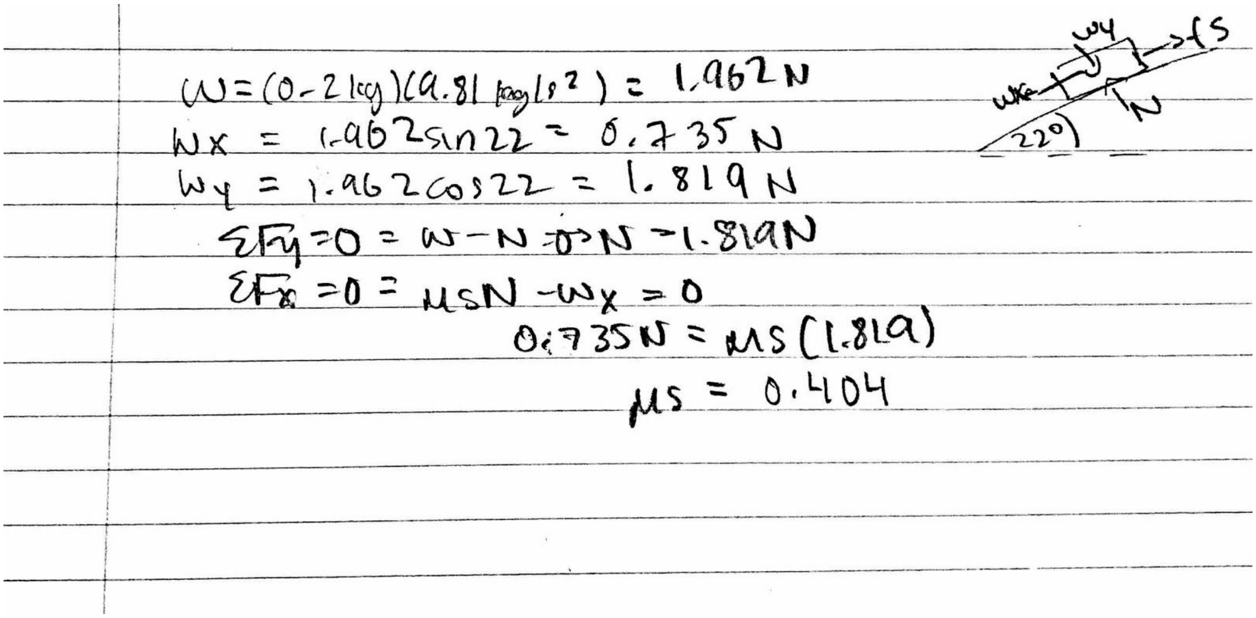
Stress when force is exerted on “foot”

The maximum stress is 0.395 MPa which occurs at the bend of the “ankle.” This has an FOS of 10.4/0.395 = 26.3 which is even stronger.

As demonstrated, the linkages are not near a point of failure even at the weakest point. The most likely point of failure is the motor stalling due to the feet getting stuck in the rocks or the weight of the robot (if we increased the weight of the robot further).

Necessary Friction

Since the highest angle on the course was 22° (measured with an angle measuring device) we calculated the necessary coefficient of friction to be 0.404.



$$W = (0.2\,\text{kg})(9.81\,\text{m}/\text{s}^2) = 1.962\,\text{N}$$

$$W_x = 1.962 \sin 22 = 0.735\,\text{N}$$

$$W_y = 1.962 \cos 22 = 1.819\,\text{N}$$

$$\Sigma F_y = 0 = W - N \Rightarrow N = 1.819\,\text{N}$$

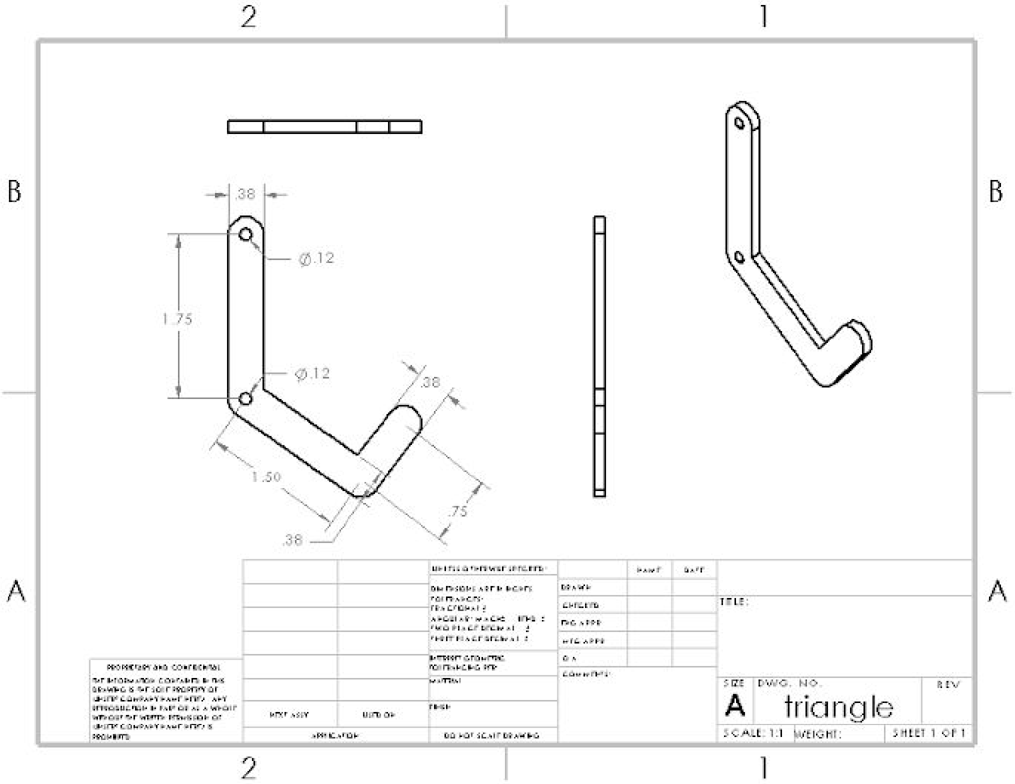
$$\Sigma F_x = 0 = \mu_s N - W_x = 0$$

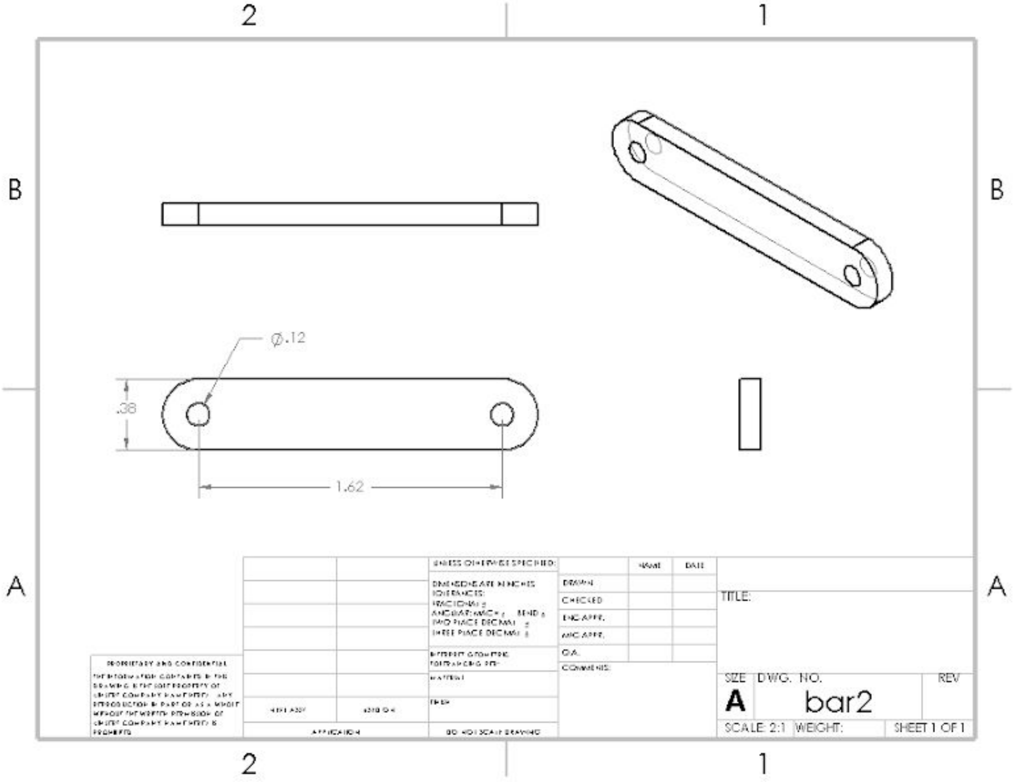
$$0.735\,\text{N} = \mu_s (1.819)$$

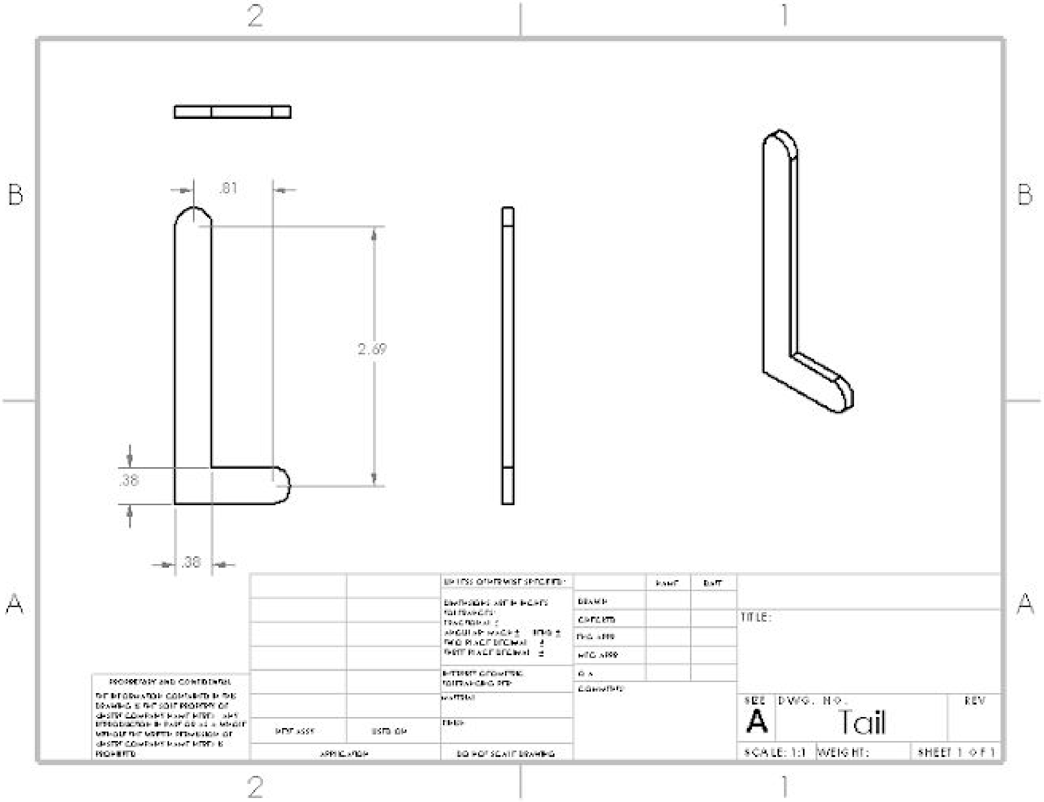
$$\mu_s = 0.404$$

To achieve the required friction, we used dycem, which has a coefficient of friction close to 1, so it is more than enough to help our robot tackle the final hill. We glued dycem to the bottom of each foot.

Engineering Drawings of Custom Parts



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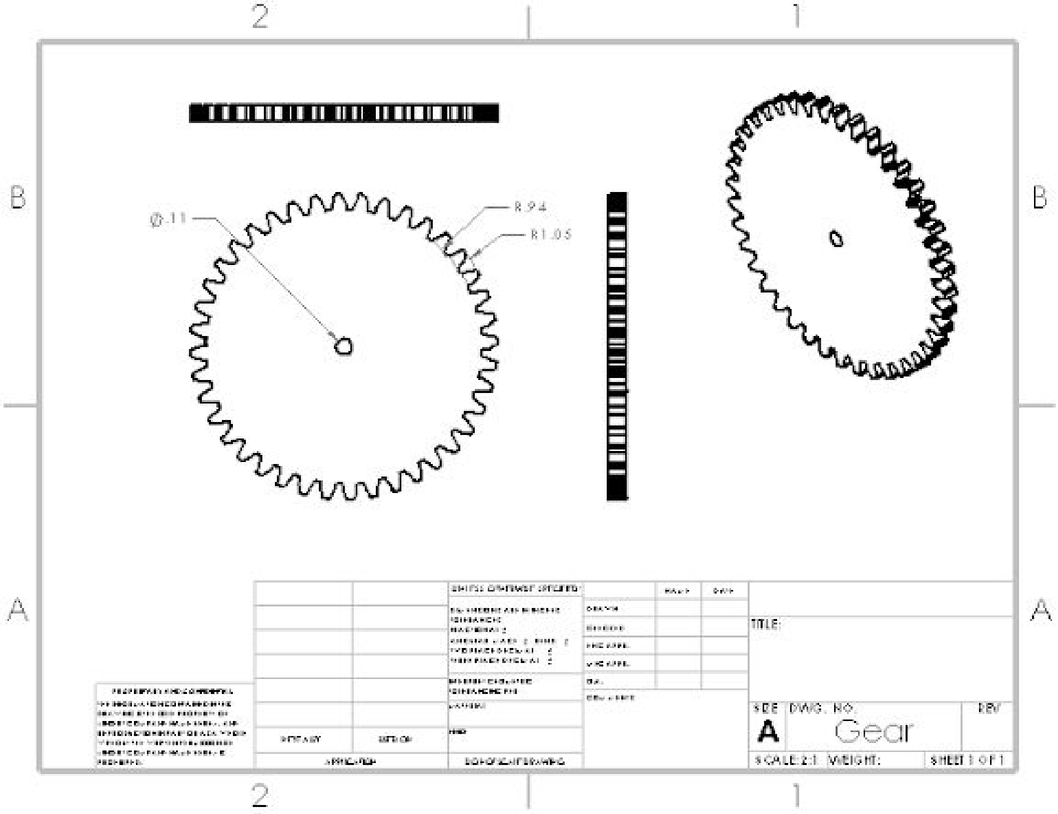
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Animal Gait Coupler Curve

For our design we wanted to mimic the walking gait of a cat, as shown above. This gait is an oval that is slightly turned upward at the front of the motion.