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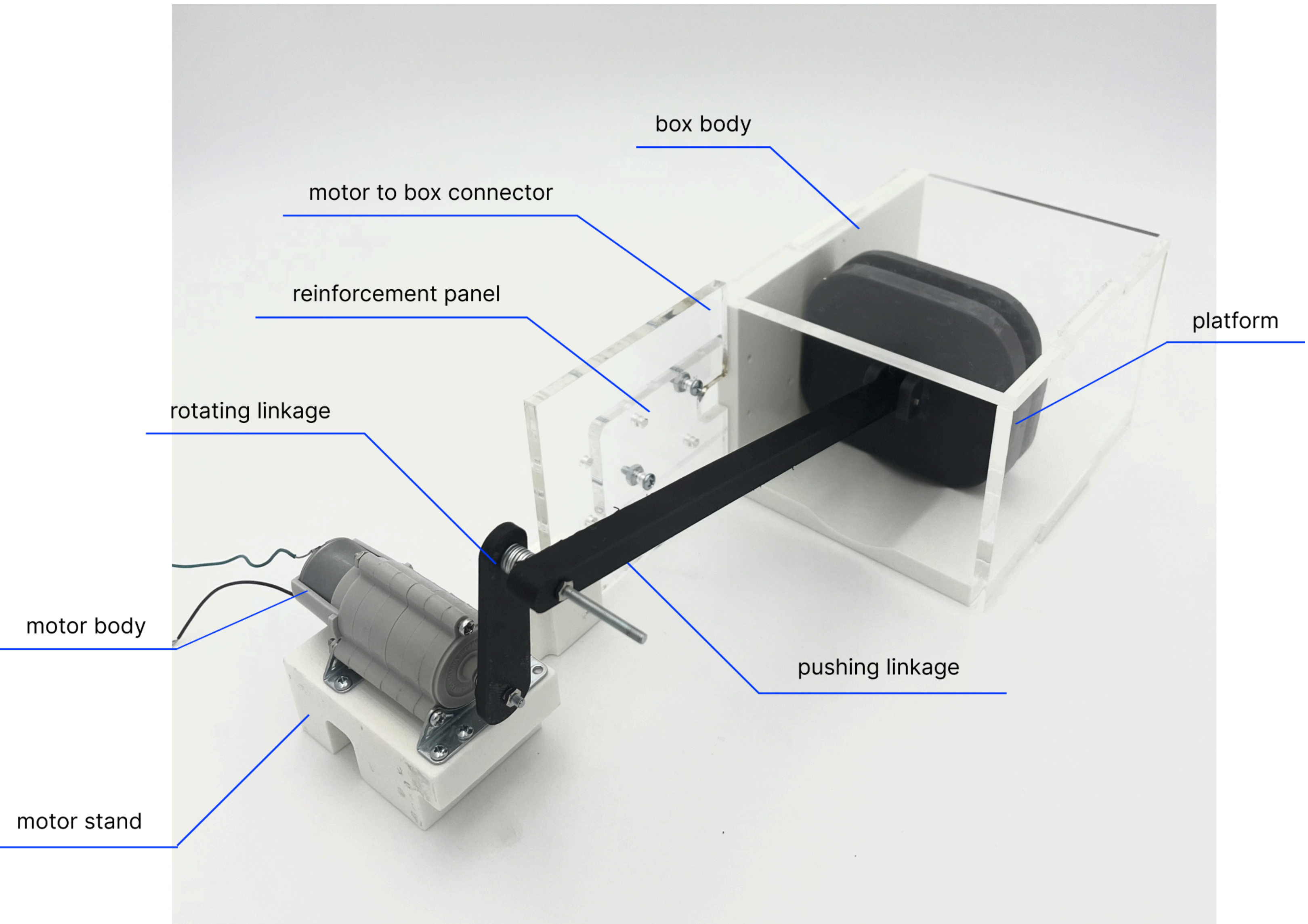
Team: The Crushers

Amy Zhou, Grace Pan, Alfonso Vigo, Sarah Chung

ME 104 Final Project



Task Definition

Task Description: Please provide a narrative description of the task your machine will complete. Remember that this should describe the *task*, and not the *design solution* that (you now guess) would complete it well.

On demo day, with its platform, the robot pushes a skateboard carrying a payload as far as possible. The skateboard slides, without rolling, as its wheels are bound together.

Task Requirements: Please list any fixed features of your task and anything that limits the solution space.

There needs to be a level clearing to ensure there are no obstructions.

Environment: List any specific objects (e.g. baseball) or substrate features (e.g. vertical I-beam) involved.

- *Level surface*
- *A skateboard to place weights on*
- *Weights*
- *The robot must be placed on a platform of 3cm to 6.5cm in order to push*

Performance: List any limits on the task time (e.g. < 100 s), distance (e.g. = 1 m), or payload (e.g. = 100 N).

- *Be able to push weight to at least a 100N payload*

Design: List any constraints on size (e.g. fits in a 20 cm box) or other features (e.g. no pre-stretch in springs).

- *Design is within a 42cm x 10cm x 25cm box, so it can encase the board's tail*

Other: List any other requirements, such as specific motions to be performed or limits on interactions.

- *The board must be placed inside the box body so it aligns perpendicular with the platform*

Outcome to be Optimized: Please provide the single, measurable outcome for which, all other things being equal, more (or less) will always be better. Examples include maximizing the mass lifted, minimizing the time to complete the task, or maximizing the distance traveled. Please make a guess as to a 'good' value.

- *The board with weights will be maximized, want to see how much weight to robot can push*

Summary Page

Task: Push a skateboard with a payload as far as possible (without rolling) under 10 seconds. Push this weighted load until the robot no longer makes pushing contact with the skateboard.

Box body

- The box body has several holes on the back panel. Screws go through the holes on the reinforcement and then the box body, securing the body to the motor stand component. There is a very slight gap between the edges of the platform and walls of the box to reduce friction with the moving platform.
- The box has a press-fit lid for easy removal and access to encase the platform.

Reinforcement panel

- A piece of acrylic connects the motor stand to the box body. This reinforcement panel secures that piece of acrylic to the box body. Screws go through several evenly spaced holes, greatly strengthening the box and preventing deformation in the axis orthogonal to robot length when the motor is running.

Motor stand/Box body connector

- This panel holds the motor stand at the distance of 162.25mm from the box body. It is strongly secured to the motor stand (forked end of motor stand slots onto panel, secured by screws) and to the box body.

Motor stand

- The motor must be secured at a certain height to evenly transfer the torque to move the platform up and down. The motor screws into the motor stand which is then connected to the box body.

Platform

- Double-layered to ensure that the platform doesn't pitch during motion

Rotating link

- This linkage allows the motor to engage with the rest of the motor, translating the rotational motion to linear motion.

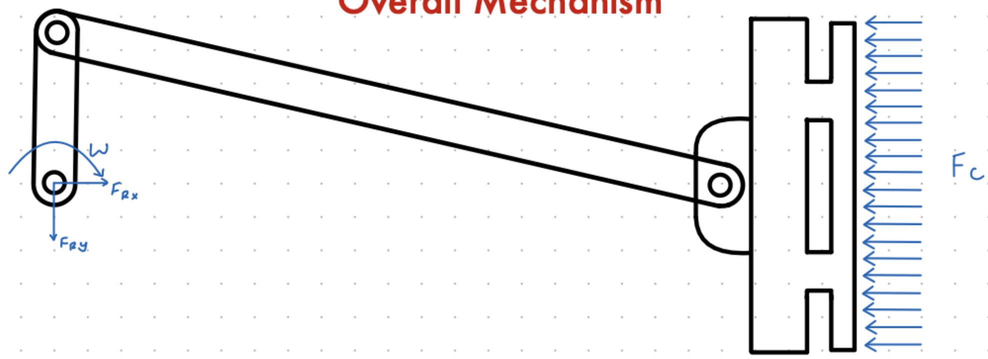
Pushing link

- Takes rotary motion from a rotating link and pushes with a linear motion with the platform connected with dowels.

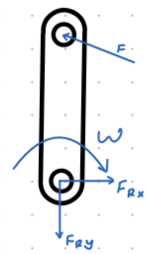
The moving mechanism, which translates rotational to linear motion from the motor, consists of the rotating and pushing link. This motion is then translated to the platform, which is encased by the box body. The box body is connected to the motor stand with the reinforcement panel. The motor stand supports the motor to ensure that the double-layered platform can smoothly deliver enough force to push the board.

Free Body Diagram Analysis - Alfonso Vigo

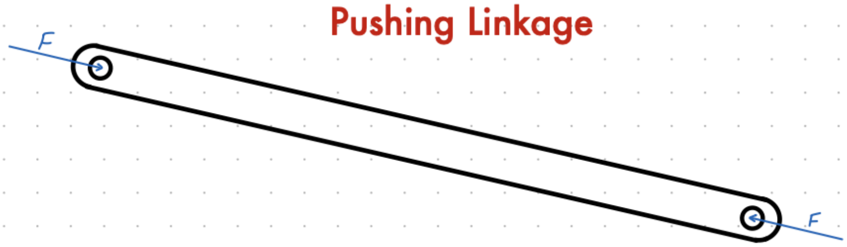
Overall Mechanism



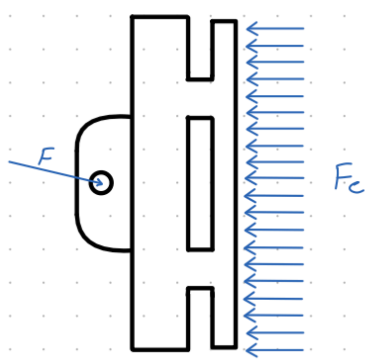
Rotating Linkage



Pushing Linkage

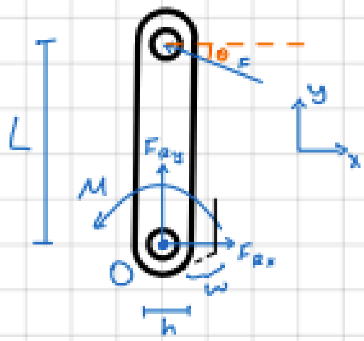


Platform



BOTEA: Stress Analysis, Failure Modes - Alfonso Vigo

Rotating Linkage



Constants: $F_c = 100N$, $\theta = 15.4°$

$$\sum F_x = -F\cos\theta + F_{Rx} = 0$$

$$\sum F_y = F\sin\theta + F_{Ry} = 0$$

$$\sum M_O = M + F\cos\theta L = 0$$

$L = 56mm$, $w = 3.87mm$

- $F_{Rx} = F\cos\theta$
- $F_{Ry} = -F\sin\theta$
- $M = -F\cos\theta L$ ((Counter-clockwise).

Modes of failure

Bending

$$\sigma = \frac{My}{I} = \frac{F\cos\theta L \cdot (h/2)}{(1/12)wh^3} = \frac{6F\cos\theta L}{wh^2} = \frac{S_y}{FOS}$$

$$\therefore h = \left(\frac{6F\cos\theta L\, FOS}{w S_y}\right)^{1/2}$$

Choosing $FOS = 2$, $S_y = 52$ MPa for carbon fiber:

$h_{min} = 17.4mm$

Axial Tension

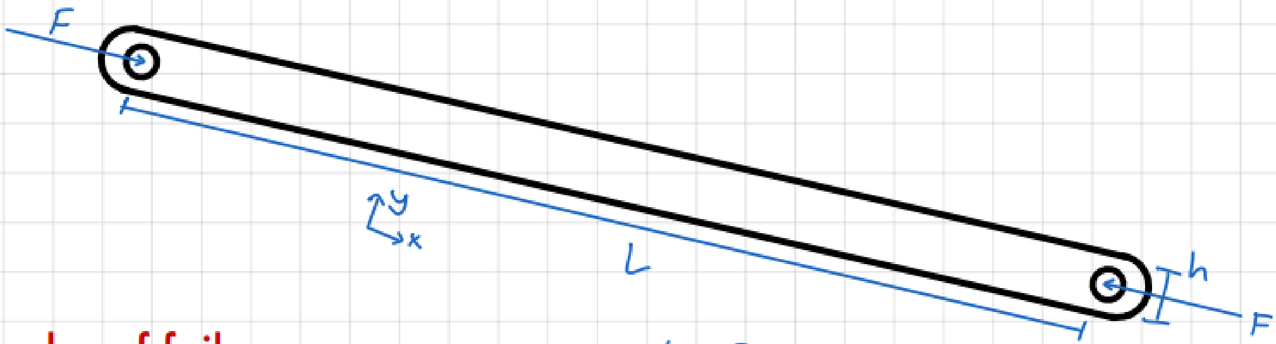
$$\sigma = \frac{F}{A} = \frac{F\sin\theta}{wh} = \frac{S_y}{FOS}$$

$$\therefore h = \frac{FOS\, F\sin\theta}{S_y w}$$

For $FOS = 2$, $S_y = 800$ MPa $\cdot$ 7.5% for carbon fiber

$\therefore h_{min} = 1.20mm$

Pushing Linkage



$L = 8in = 203.2mm$

$w = b = 0.4in = 10.2mm$

$h = 10.2mm$

Modes of failure

Axial Compression

$$\sigma = \frac{F}{A} = \frac{F}{wh} = \frac{S_y}{FOS}$$

For $FOS = 2$, $S_y = 420\,MPa \cdot 0.7\%$ for carbon fiber

$$\therefore h_{min} = \frac{F \cdot FOS}{w S_y} = 6.87\,mm$$

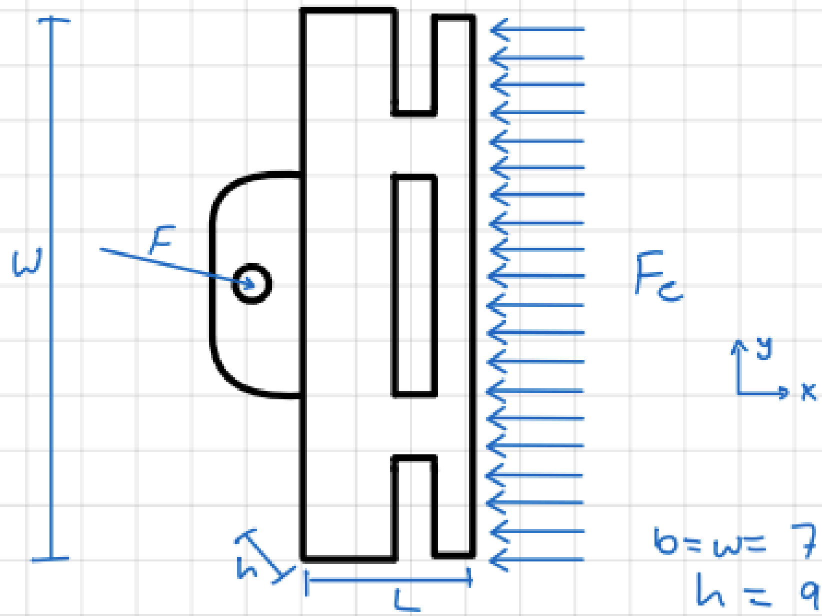
Buckling

For carbon fiber

$$F_{cr} = \frac{C\pi^2 EI}{L^2}, \quad C = 1, \quad E = 51\,GPa, \quad I = \frac{1}{12} bh^3, \quad b = 10.2mm, \quad h = 10.2mm$$

$$\therefore F_{max} = \frac{\pi^2 E b h^3}{12 L^2} = 11.0\,KN$$

Platform



$b = w = 79\ mm$
$h = 91\ mm$
$L = 1in = 25.4mm$

Modes of failure

Axial Stress

$$\sigma = \frac{F}{A} = \frac{F}{wh} = \frac{S_y}{FOS}$$

For FOS = 2, $S_y = 2.2\ GPa$ for Post-Cured Tough 2000.

$$\therefore h_{min} = \frac{F \cdot FOS}{wS_y} = 1.03 \cdot 10^{-3}\ mm$$

Buckling

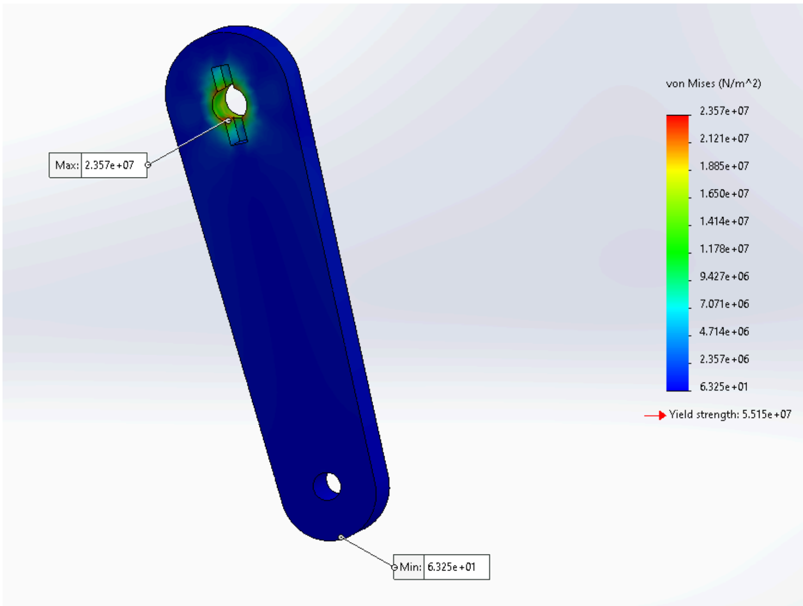
For PLA

$$F_{cr} = \frac{C\pi^2 EI}{L^2}, \quad C = 1, \quad E = 20MPa, \quad I = \frac{1}{12} bh^3$$

$$\therefore F_{max} = \frac{\pi^2 Ebh^3}{12L^2} = 1.52 \cdot 10^3\ KN$$

Computational Stress Analysis and Buckling Analysis - Amy Zhou

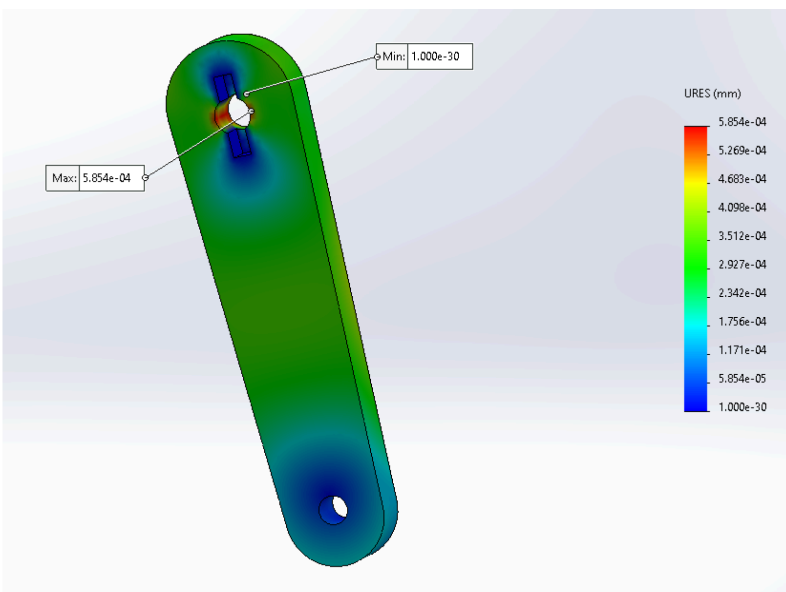
Rotating Link



Strain: After applying 100N, the stress is highest at the hole.

Max: $2.357 \times 10^{7}\ N/m^{2}$

Min: $6.3 \times 10^{1}\ N/m^{2}$

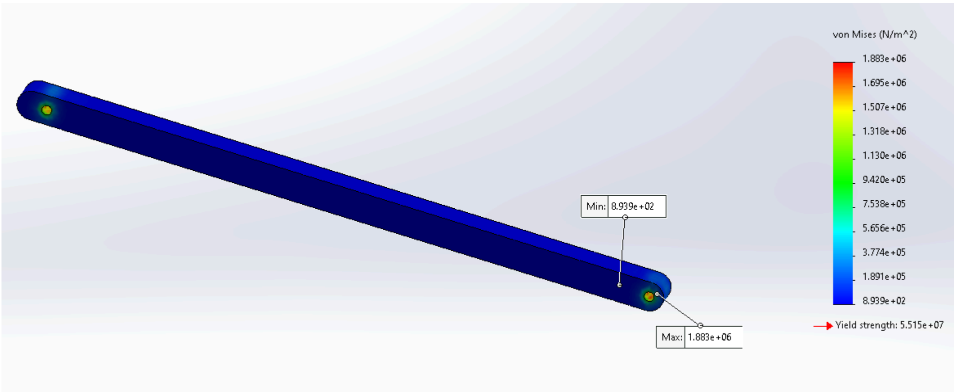


Displacement: The displacement is highest inside the hole.

Max: $5.85 \times 10^{-4}\ mm$

Min: $1.00 \times 10^{-30}\ mm$

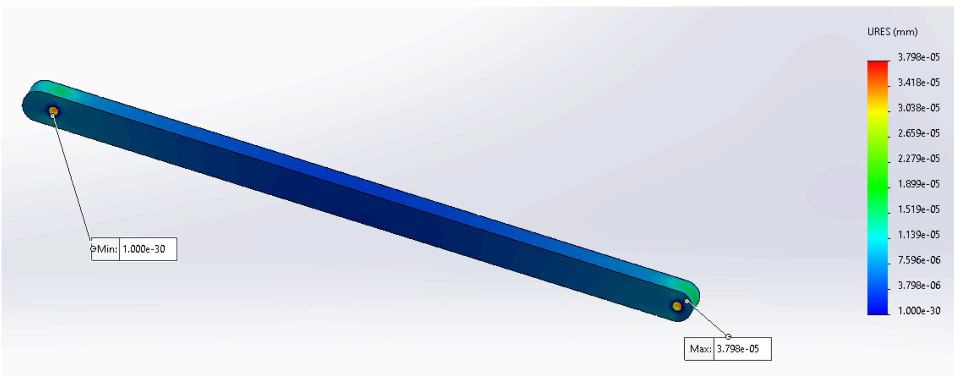
Pushing Link



Strain: With 100N applied at the holes, we see that the strain is highest at the holes.

Max: $1.89 \times 10^{6}\ N/m^{2}$

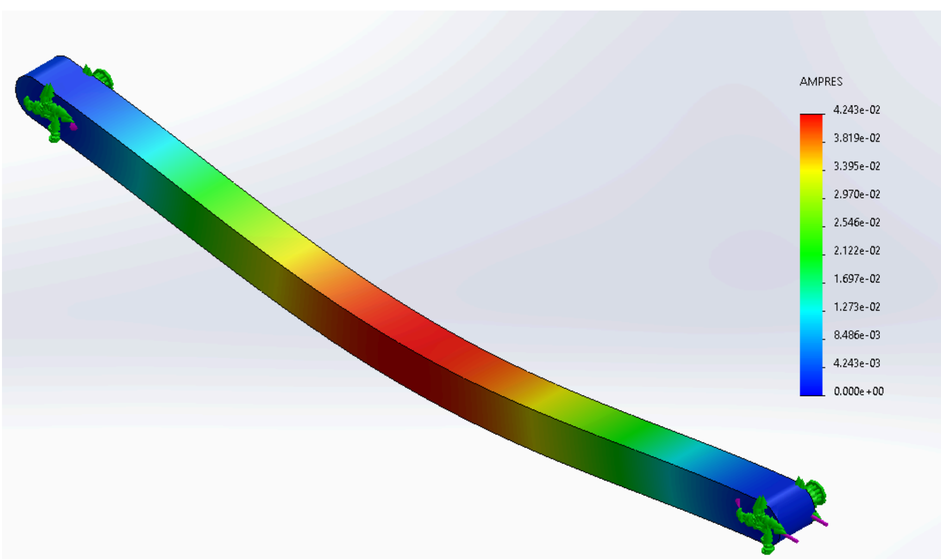
Min: $8.94 \times 10^{2}\ N/m^{2}$



Displacement: The displacement is highest in the holes because force is applied there, but the ends show some displacement as well due to compression.

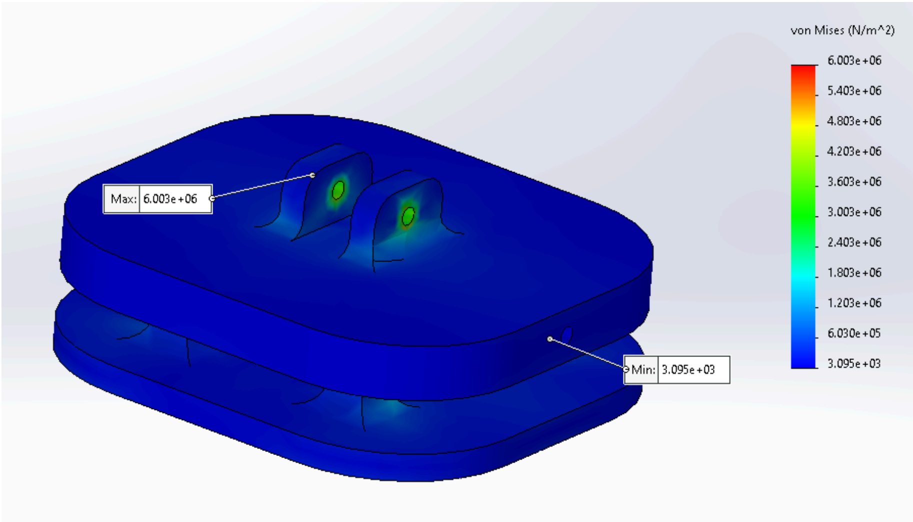
Max: $3.8 \times 10^{-5}\ N/m^{2}$

Min: $1.00 \times 10^{-30}\ N/m^{2}$



Buckling: The long pushing linkage experiences buckling. However, our F.O.S. is 2, so our situation is acceptable..

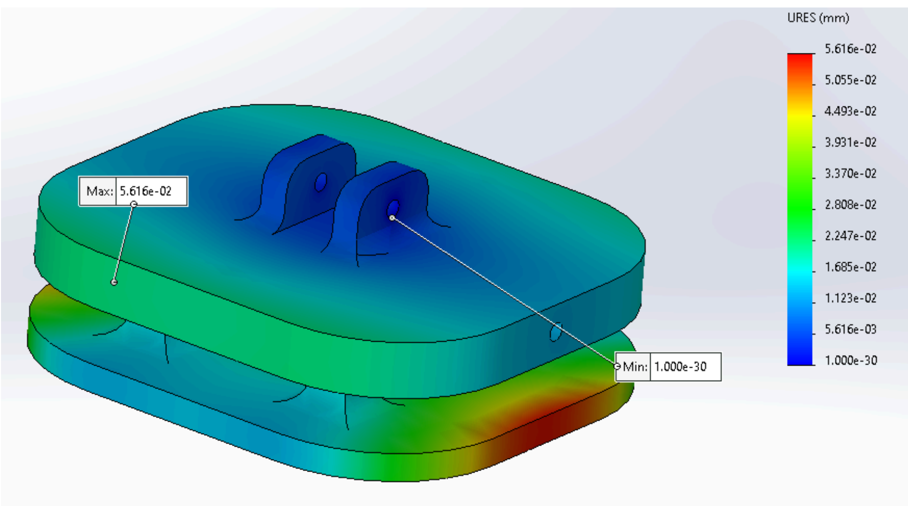
Platform



Strain: With force of 100N applied, the stress is greatest at the holes.

Max: $6 \times 10^{6}\, N/m^{2}$

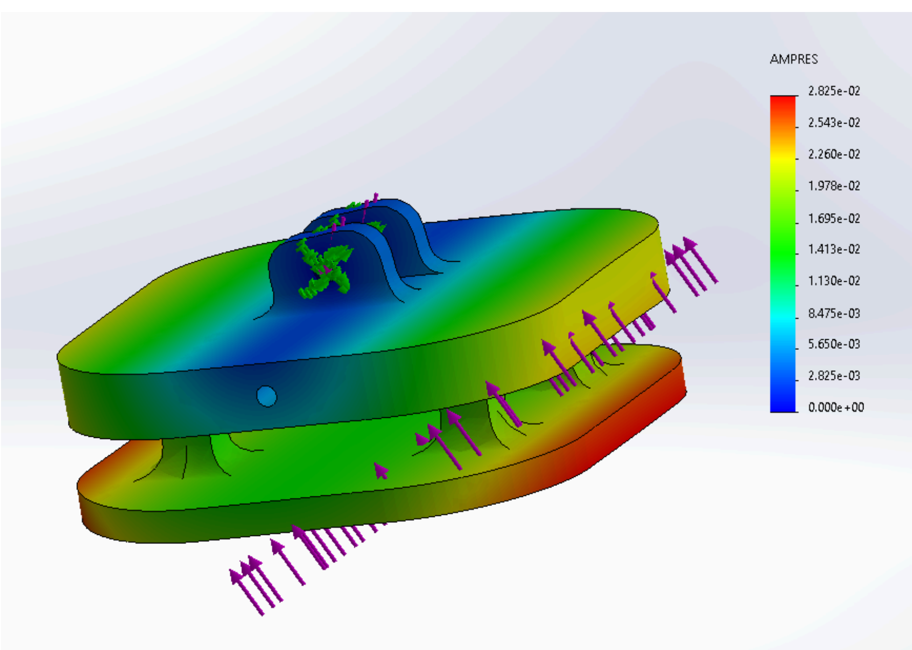
Min: $3.1 \times 10^{3}\, N/m^{2}$



Displacement: The platform experiences the most displacement at the bottom layer due to the distributed load (see FBD) that causes it to bend inwards.

Max: $5.62 \times 10^{-2}\, mm$

Min: $1.00 \times 10^{-30}\, mm$



Buckling: Platform experiences camming; the purpose of the robot box is to keep this platform in place when it is pushing.

Assembly Joint Layout - Amy Zhou + Grace Pan

Dowels

For moving joints, the robot primarily depends on connections via dowels. In order for the dowels to move appropriately, we needed one tight/rigid connection and one loose connection. We achieved this by adjusting the sizes of the holes and accounting for tolerances to make the fit tighter or looser.

Screws

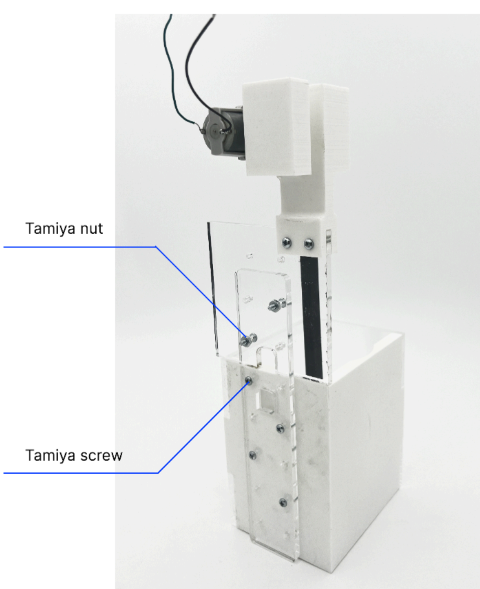
For rigid or fixed joints, our connection of choice was screws. We accomplished this by adding tolerance to the holes to be just under the outer diameter of the screw so that we could tap into the material with the screw once fabricated.

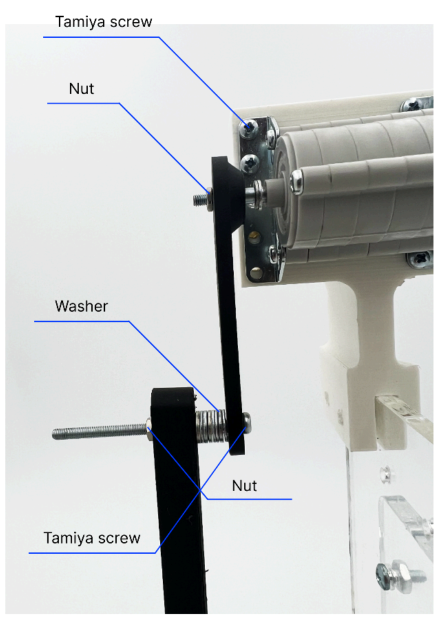
Nuts

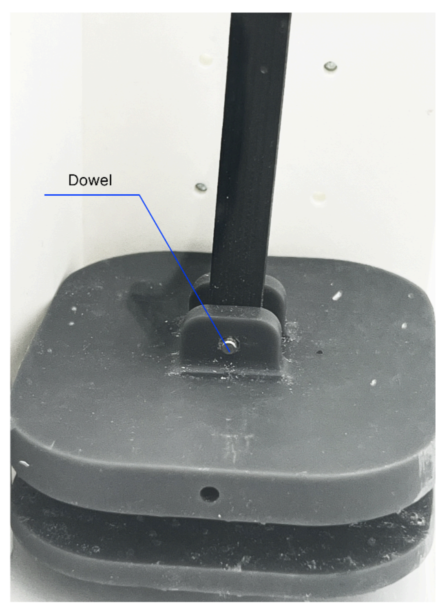
The motor and parts being held together with screws are retained by a nut, to keep all stacks close together and avoid unnecessary movement.

Washers

Washers were utilized to reduce friction between the linkages of the robot. Additionally, the added thickness from washers prevented the linkages from running into other protruding features of the robot, such as the rotating shaft or motor stand.







Mass-Efficient Component Design - Alfonso Vigo + Sarah Chung

Component: Rotating linkage

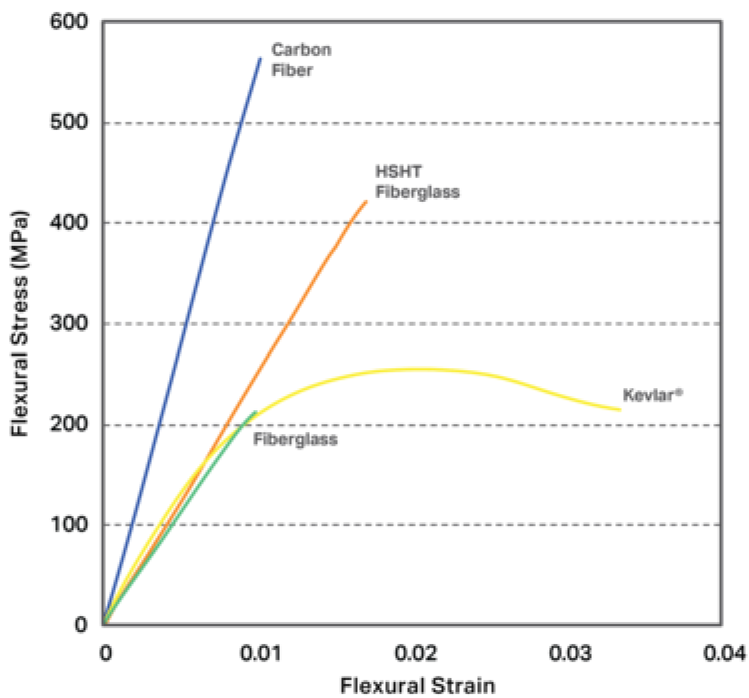
We chose the rotating linkage to be our mass-efficient component.

Originally, the thickness and the height of the linkage was symmetrical, and we planned to fabricate it from 3D-printed PLA. We assumed that this would be enough, but based on our calculations we pivoted to a different design.

We decided that a taper would be an ideal shape for the linkage because the cross-section area is minimalized (the “I” value in the engineering strain analysis equation).

We tested this intuition by conducting buckling analysis and calculating the engineering strain of the candidate design, assuming there is no friction. With our factor of safety at 2, we found that reducing the cross-section area of the end of the rotating linkage did in fact improve stress distribution. It also reduced the weight of the linkage.

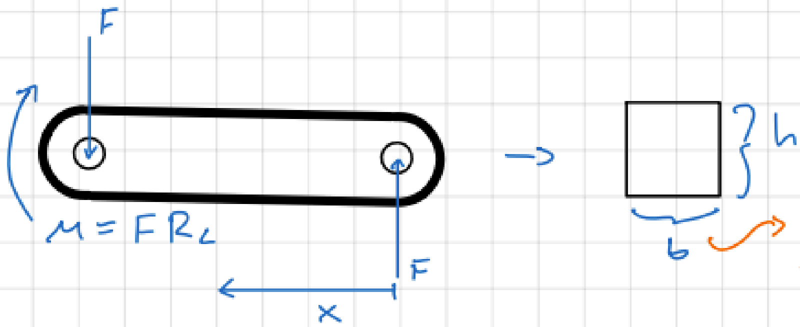
The material we chose for the rotating linkage was the Markforged carbon fiber. Below is the engineering stress-strain curve showing the strength and stiffness properties of the material.



Source: Markforged website

This material was chosen because we needed the precision of 3D printing for the dowel holes, small form factor, and the strength of carbon fiber, while still maintaining its functionality.

Design for mass efficiency



Determined from motor rod.
$\approx 5\,mm = 0.005m$

$$\sigma = \frac{My}{I}, \quad I = \frac{1}{12} b h^3, \quad y = \frac{1}{2} h$$

$$S_y = F.O.S \cdot \sigma$$

$$\therefore S_y = \frac{F \cdot R \cdot \frac{1}{2}\cancel{h}}{\frac{1}{12} b h^{\cancel{3}2}} \cdot F.O.S = \frac{6FR}{bh^2} \times 2$$

$$\therefore S_y = \frac{12FR}{bh^2} = \frac{12Fx}{bh^2} \qquad 0 \le x \le R_L = 1.95\,in \approx 0.05m\ (5\,cm)$$

$$\therefore h = \left(\frac{12Fx}{b S_y}\right)^{1/2} = \left(\frac{12 \cdot 100\ x}{0.005 \cdot 540 \cdot 10^6 \cdot 0.012}\right)^{1/2}$$

When $x = R_L$.

$h = 17.4mm$

Assuming the minimum height has to be around 7.62 mm, we can approximate the ideal height at any point to be:

$$h(x) = \frac{17.4 - 7.62}{0.05} \cdot x$$

Material Selection - Grace Pan

1. **Box body**
    a. **Material: Half White PLA, half ¼ in. thickness clear acrylic**
    b. **Reason**: The half of the box with more specific geometries was 3D-printed, whereas the other half was laser-cut due to time and material availability purposes. Since the box body is not subject to direct forces from the motor and target object, we knew that the material quality of strength was not a high priority for this component. In fact, PLA (printed at higher resolution) and clear acrylic are ideal choices as they are relatively smooth, minimizing friction with the platform at potential points of contact and thus allowing smooth side-to-side motion of the platform.
2. **Reinforcement panel**
    a. **Material: ¼ in. thickness clear Acrylic**
    b. **Reason**: The panel provides support and improves robustness of the robot assembly. Acrylic was chosen because we may add threaded heat-set inserts into the laser-cut holes if necessary. The thicker acrylic was chosen to increase the strength of this reinforcement piece.
3. **Motor to box connector**
    a. **Material: ¼ in. thickness clear Acrylic**
    b. **Reason**: This connecting piece allows the motor to connect to the rest of the motor, facilitating movement in the set location. It is supported by the reinforcement panel. Holes allow the fork of the motor stand to connect to this panel via threaded heat-set inserts and screws.
4. **Motor stand**
    a. **Material: White PLA**
    b. **Reason**: The stand doesn't receive as much rigorous stress as the linkages in the moving mechanism, but still needs the precision for hole dimensions to secure the motor and the reinforcement panel. 3D-printed PLA hits these benchmarks and optimizes cost.
5. **Platform**
    a. **Material: Formlabs Tough 2000 Resin**
    b. **Reason**: The platform connects to the motor via the rotating and pushing linkages and directly pushes the weighted skateboard, so it must withstand the heavy impact of the motion and mass of the skateboard. Thus, we chose Formlabs Tough 2000 Resin, which simulates mechanical properties of Acrylonitrile Butadiene Styrene (ABS) plastic which has high tensile strength and is very resistant to physical impact.

6. **Rotating link**
    a. **Material: Carbon fiber**
    b. **Reason**: The function of this component is to take motion and translate this motion to the other linkage. It is directly subject to torque from the motor and is essentially the first linkage to transfer motion. Given that this piece is also mass-efficient and is the thinnest piece of the robot, we decided to fabricate it with carbon fiber which is 5 times stronger than steel and twice as stiff, yet is lighter than steel.
7. **Pushing link**
    a. **Material: Carbon fiber**
    b. **Reason**: This linkage transfers motor torque from the rotating link to the platform. It has a relatively longer length, which makes it more vulnerable to compressive and tension forces. We addressed these factors by making the linkage thicker (0.4 in. thickness) than the rotating linkage. However, for the thickness, we still accounted for the fact that it needed to fit on the dowel with the rotating linkage and washers. To bolster the linkage for accomplishing its task, since it is affected by forces from pushing the weighted skateboard, we fabricated it out of carbon fiber.

Catalog Component Selection - Grace Pan + Sarah Chung

ITEM	QUANTITY	PART NUMBER	DESCRIPTION	MATERIAL
Tamiya screw (long)	4	N/A	⅛" diameter x 2" length	Steel
¼" dia x ⅛" length screw	2	90272A153		Steel
¼" dia x ½" length screw	8	90272A535		Steel
⅛" x 1" screw	2	90272A542		Steel
¼" dia nut	7	90473A029	7/32" height	Steel
⅛" dia nut	2	90473A258	31/32" height	Steel
Washers	7	91166A210	⅛" dia	Steel
Dowel	1	98381A475	⅛" diameter x 2" length	Steel
C-clip	1	N/A	⅛" diameter	Steel
Motor	1	N/A	Tamiya kit	Steel
Acrylic body parts	4	N/A	Laser cut parts	Clear acrylic
Carbon fiber body parts	2	N/A	Printed on Markforged	Markforged carbon fiber
Tough 2000 body parts	1	N/A	Printed on Formlabs resin	Tough 2000 resin
PLA body parts	3	N/A	Printed on Ender 3	PLA

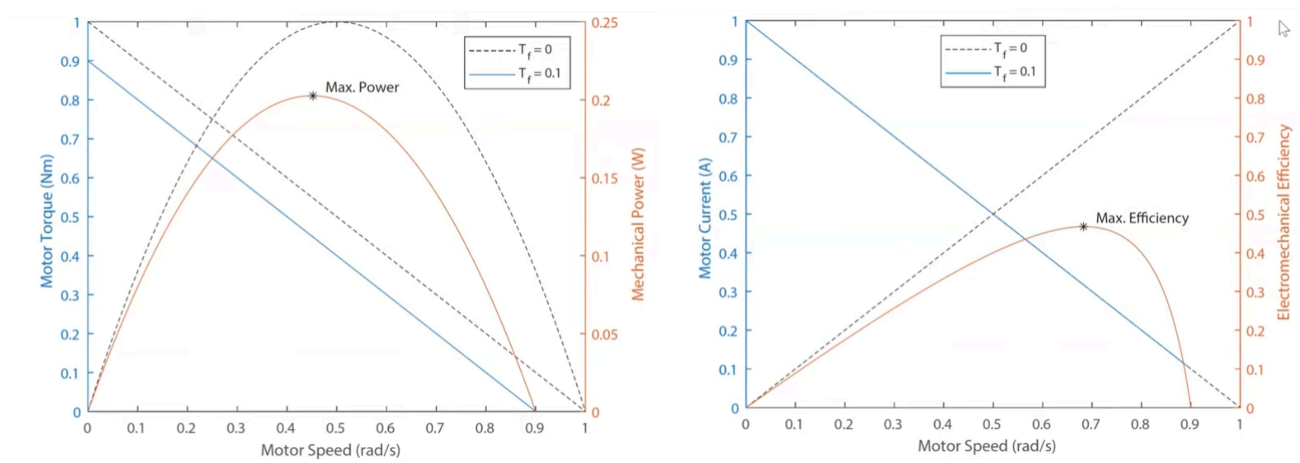
Motor Setpoint Selection - Amy Zhou

Set-Point

When we thought about setting the voltage for our motor, we decided that our task required something that was both fast and powerful for the robot to push things quickly and reach our goal of "as quickly as possible" but also sought to maximize power so that it could withstand the payload of 100N that we calculated.

Additionally, although 6 volts would apply the most power, we were concerned that the motor had the possibility of burning out and did not want to run the risk.

According to the graph on the left, the maximum power occurs at .5 rad/s. Then, referring to the graph on the right, at .5 rad/s, the motor current is at .5 Amps, which corresponds to half the voltage input. Therefore, we chose a voltage of 3V.



Source: Dr. Steve Collins

Transmission Configuration Selection - Amy Zhou

Gear Ratio

To make our robot as powerful as possible, we wanted to maximize the torque output of our robot. We tried to use 80:1 (since it was closest to our ideal gear ratio in our calculator) and 100:1 gear ratios to have a better efficiency but it did not push the skateboard as powerfully as we wanted it to. So, we used a 400:1 gear ratio instead to maximize the torque output.

$$\tau_{out} = \tau_{in} \cdot R_G \cdot \eta$$

$$\frac{\tau_{out}}{\tau_{in}} = R_G \cdot \eta$$

$$\boxed{.165} = R_G \cdot \eta$$

from gear characterization

$$R_G \cdot \eta = .165(100) = 16.5$$

R_G	$\cdot\ \eta$	= gearbox efficiency
400	$.637^4$	65.86
100	$.637^3$	25.85
80	$.637^3$	20.68
25	$.637^2$	10.14

Design for Energy Efficiency

First, you need to <u>characterize the motor!</u> There are three experiments to characterize the motor.

Experiment 1: no motor movement using naked motor using max power (3 V)

Resistance

$$R = \frac{V_a}{i} = \frac{1.25\text{ V}}{1.5\text{ A}} = 0.833\ \Omega$$

1. **First experiment** - use a naked motor, use max power of 3V, then stall the motor to stop it from moving with your finger. Divide Va by i to find the **resistance**.

Experiment 2: letting motor run using motor + gearbox using max power (3V)

motor constant

$$\text{time}/1\text{ turn} = 2.13\text{ sec} \rightarrow \frac{2\pi\text{ rad}}{2.13\text{ sec}} = 2.95\ \frac{\text{rad}}{\text{sec}}$$

$$K = \frac{V_a - iR}{\dot{\theta}} = \frac{(3V) - (.56A)(.833\Omega)}{2.95\ \frac{\text{rad}}{\text{sec}}} = .859\ \frac{V}{(\text{rad/s})}$$

gear ratio

$$\div 400 = .00215\ \frac{V}{(\text{rad/s})}$$

2. **Second experiment** - use a motor with its gearbox on, use max power of 3V, and let the motor run without stalling. Time how long it takes to turn one revolution and convert it to rad/sec. Then find K by plugging in Va, subtracting i times R (found in first experiment), and dividing all over the rad/sec value. Then divide that answer by the gear ratio (ours was 400), to find the **motor constant**.

Experiment 3: letting motor run naked motor using max power

Friction torque

$$\tau_F = k \cdot i = \left(.00215\ \frac{V}{(\text{rad/s})}\right)(.25A)$$

$$= 5.38 \times 10^{-4}\ \frac{\text{kg}\,\text{m}^2}{(\text{s}^2\,\text{rad})} \quad \text{OR} \quad \frac{J}{\text{rad}}$$

3 . **Third experiment** - use a motor naked, using max power of 3V, and let the motor run. Multiply k (found in the second experiment) by the i output to find the **friction torque.**

Next, we need to <u>find the gear efficiency</u>. This is done in one experiment with 5 calculation steps.

$$\tau_{out} = m \cdot g \cdot r$$

mass of pipe — gravity — radius of motor capstan

$$\tau_{out} = (.259\ kg)\left(9.81\ \frac{m}{s^2}\right)(14\ mm)$$

$$= .03557\ Nm$$

1. **Calculate T-out simply by multiplying the mass of the pipe (m) by the radius of the motor capstan being used by gravity.**

motor torque — motor constant — $\boxed{\text{motor current}}$ — friction torque

$$\tau_m = k \cdot i - \tau_F$$

$$\tau_m = \left(.00215\ \frac{V}{(rad/s)}\right)(.5\ A) - \left(5.38 \times 10^{-4}\left(\frac{J}{rad}\right)\right)$$

$$= 5.4 \times 10^{-4}\ \frac{J}{rad}$$

2. **Find T-m by plugging in values from the motor characterization.**

$$\tau_{in} = \tau_m \cdot R_G$$

motor torque — Gear Ratio

$$\tau_{in} = (5.4 \times 10^{-4}\ J/rad)(400)$$

$$= .216\ J/rad$$

3. **T-in is found by multiplying the motor torque found above and the selected gear ratio (ours was 400)**

$$\eta_G = \frac{\tau_{out}}{\tau_{in}}$$

efficiency

$$\frac{.03557}{.216} = .165$$

4. **Find the efficiency of the overall motor with gears by dividing T-out by T-in**

$$\sqrt[4]{\eta_G}$$

$$\sqrt[4]{.0142} = .6370$$

our gear stage is 63.7% efficient

5. Take the fourth root of the number found in step 4 (since we have 4 stages). With a **63.7% efficient gear**, our motor is within a reasonable range of efficiency.

Design for Energy Efficiency (Power Loss) - Grace Pan + Amy Zhou

There are three sources of power loss:

- The power lost in the motor (gear efficiency; calculated above)
- The friction between parts in the joint.
- The component of the force that pushes against the side of the box

1. Power lost in the motor/gear efficiency

We found above that the gear efficiency of our motor is 63.7%. The efficiency is not at 100%, meaning that not all the energy from the motor is being transferred to the pushing platform, which clearly indicates power loss from that source.

2. Friction between parts in the joint

The pathway of torque energy transfer, from the motor to the platform, involves the rotating linkage and pushing linkage. The joints related to these parts include the joint between the motor and the rotating linkage, the joint between the rotating linkage and the pushing linkage, and the joint between the pushing linkage and the platform. When rotating, despite the addition of washers and smooth dowel fitting to reduce friction between the components, the parts of the joints still experience friction which causes power loss in the system.

3. Component of the force that pushes against the sides of the box

Due to the horizontal orientation of the robot and the fact that the platform isn't rigidly held in place vertically, the platform is subject to gravity. Thus, the bottom side of the platform will always be touching and pushing against the side of the box. Additionally, the platform slightly moves side-to-side when the motor is turning due to the rotary actuation, touching the right and left sides of the chassis. Thus, the robot system experiences power loss from the component of the force that pushes against these three sides of the box.

Performance Testing - Grace Pan

Performance Goals: Successfully push a weighted object for a certain distance away from the robot such that the robot no longer has pushing contact with the object.

Experiment: Push a 5-lb skateboard carrying (increasing) weighted loads up to 20-lbs or until failure (sliding; without rolling). The time it takes to push the weighted load according to the performance goal will be recorded, if applicable.

- **Independent variable**: Weight of load
- **Dependent variables**: Time it takes to be pushed a sufficient distance; sufficiency of distance pushed
- **Constants**: Carrier (skateboard) size, shape, and weight; starting location of carrier;
- **Method**: Record video of robot for each trial. Find time elapsed from point of contact with weighted load and point of leaving contact with weighted load (accuracy down to hundredths place available from analyzing videos on phone with "edit" feature). Due to the design of our robot, if the robot does not leave contact with the weighted load and the motor stalls, the trial was not successful and the distance was not sufficient.

Notes:

- The skateboard is merely a vehicle to hold the weights at the correct height such that the robot can push the weighted load. The wheels have been taped together and thus do not roll, ensuring that what was tested is pushing and sliding.
- The skateboard is placed in a cardboard box. Two panels of acrylic are attached to the bottom of the cardboard box to reduce friction with the wooden table that the load is being pushed on.
- Weights are then placed on the skateboard/box system, and the end of the skateboard is placed into the robot chassis at a consistent distance to gauge success of pushing.
- The skateboard has a weight of 5lbs.
- Our past motors burned out very quickly, and as we were on our last motor, we were very concerned about overexerting the robot with an excess of testing.
- We held down the robot so that the opposite force exerted on the platform from pushing wouldn't push the entire robot backwards.

Videos of the experiment: [linked]

RESULTS

Experiment	Time (s)	Distance sufficient?	Notes
Trial 1: 5 lbs	4.48 s	Yes	Relatively easy
Trial 2: 5 lbs	2.13 s	Yes	Variability in testing prevalent
Trial 3: 7.5 lbs	1.43 s	Yes	Relatively easy but stuttering
Trial 4: 7.5 lbs	3.22 s	Yes	" "

Trial 5: 10 lbs	1.75 s	Yes	Choppier robot movement; beginning to express concern over motor
Trial 6: 10 lbs	2.60 s	Yes	" "
Trial 7: 12.5 lbs	5.82	Yes	Took much longer; concern about motor health
Trial 8: 15 lbs	5.31	Yes	" "
Trial 9: 15 lbs	N/A	No	Failure in several attempts; motor deteriorating?
Trial 10: 17.5 lbs	N/A	No	Attempted once to confirm motor failure
Trial 11: 20 lbs	N/A	No	Attempted to try weight for 100N exerted

ANALYSIS:

Consideration for system variability and measurement error:

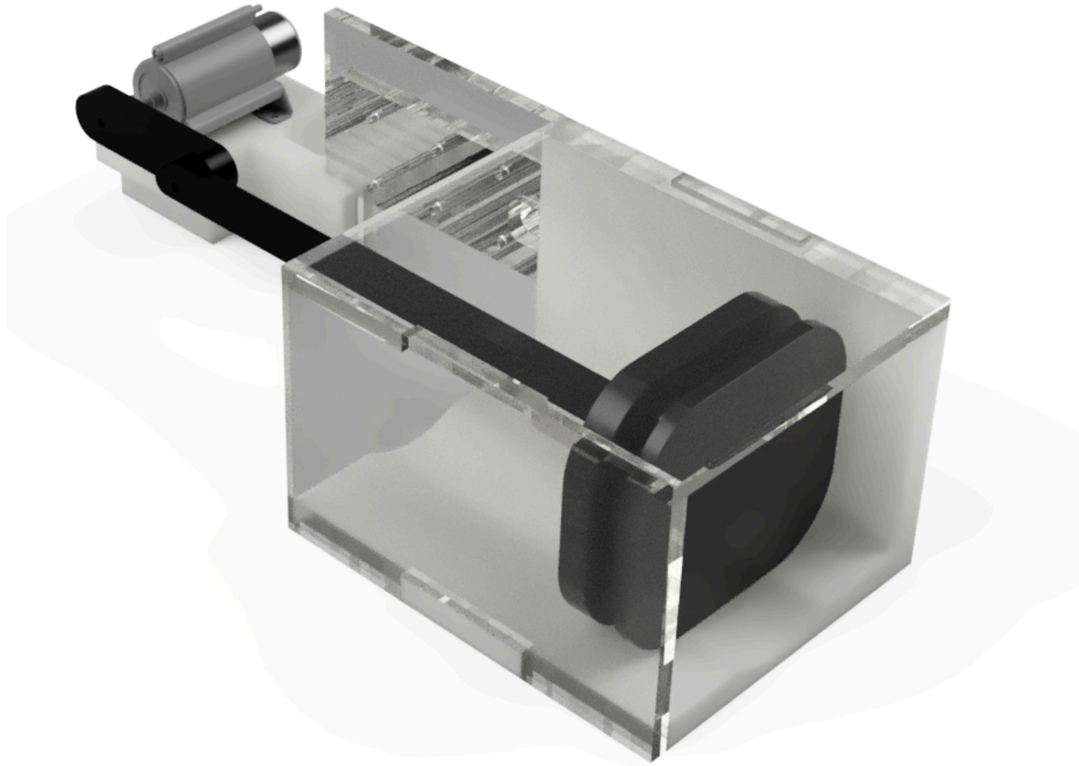
Before further analysis of our testing, it is important to elaborate on some variables that affected consistency for the system as well as some measurement errors. The robot was built to push at least a 20 lb load. However, the robot experienced significant failure on a trial attempting to push 15 lbs. Additionally, there was much stuttering that built up a lot of resistance for the robot. Since our previous motors burned out from preliminary testing and prototyping, we were especially cautious about burning out our final motor. And, we suspected that the motor was deteriorating as the tests proceeded, considering the high variabilities and the failure on the second trial of 15 lbs (seeing that it had succeeded on the prior trial).

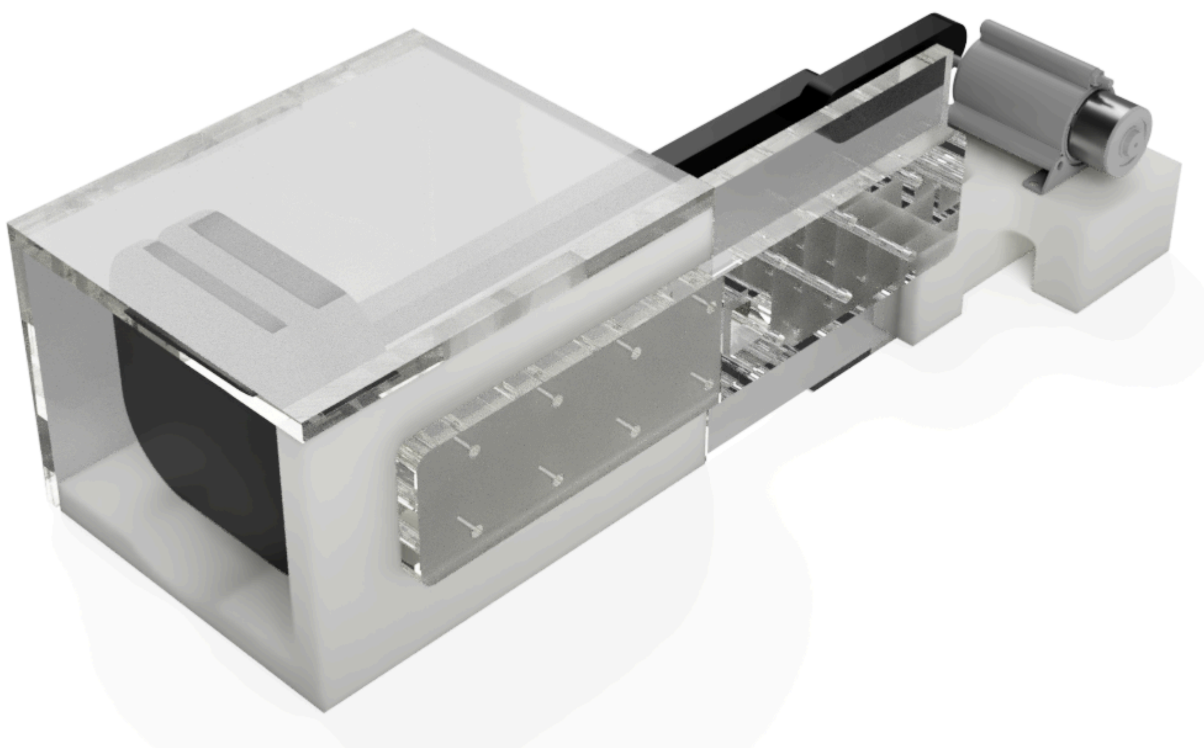
Failure analysis

Our robot was designed to push a 20 lb load. Unfortunately, this was not the case for testing. The acrylic panels, and overall bottom surface of the skateboard/carrier system, may not have been perfectly flat. Additionally, we suspect that the point of contact of the skateboard with the robot platform may not have been most optimal, causing a subpar performance during the testing.

Variation from demo day presentation

Prior to demo day, we still had to run a few additional tests. However, we were extremely concerned about our motor burning out for demo day. We modified our presentation to push a load with rolling, but throughout our journey of building this robot, we considered pushing a sliding load (with friction) in order to perform the necessary amount of work for this project.





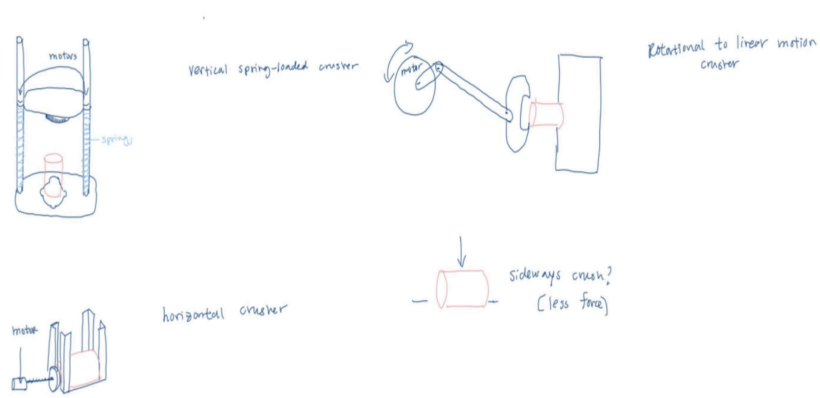
Reflection

Our journey was long and arduous, but it was a rich engineering process. Collaboration, communication, iteration, and weekly feedback from the TA's and Professor Collins, were essential to this project. We tested every design intuition and explored design options to its full potential before finalizing to ensure we had the best possible design. Despite tight deadlines, we were able to hit weekly deadlines by planning ahead and diligently attending classes.

Week 1: Set project scope

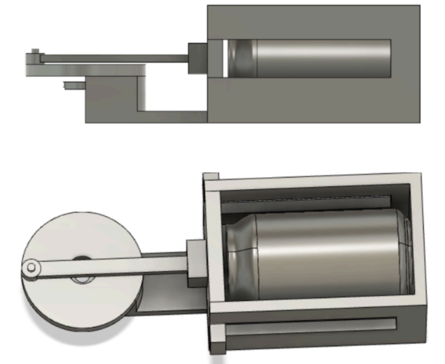
- **Ideated** a lot of different ideas, really focusing on something fun yet simple. Some included a fruit ninja robot, bartending robot.
- With input from the TA's and Steve, we decided on a **can-crushing robot**.

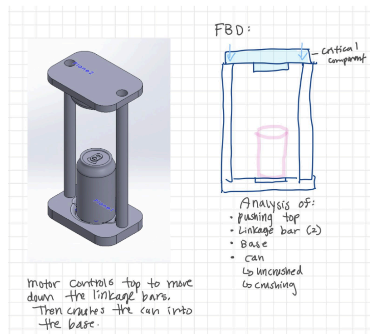
Week 2: Design concepts

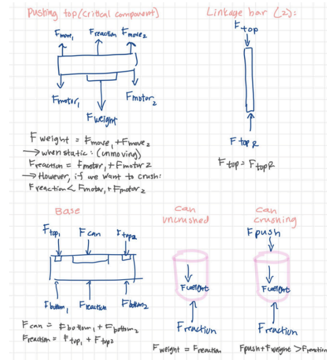


- We made some **sketches**, working on different orientations and then soundboarding them with the TA's.
- We conducted research on the **buckling of aluminum material** to ensure that the design was feasible.

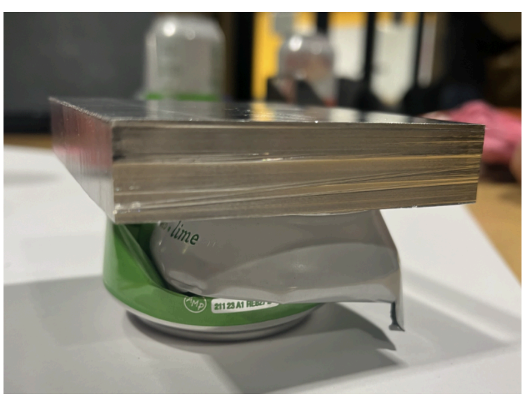
Week 3: Design the chassis



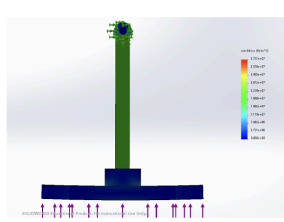


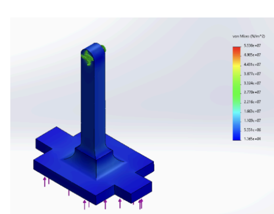


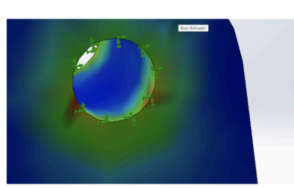
- We ended up with four designs: **vertical**, **horizontal**, **screw**, and **rotary-to-linear** crusher.
- We each conducted **FBD** and **FEA analysis** on all these designs to narrow down what design is best.
- Tested ways the can would buckle and how they would deform.
- Our goal was to find the design that had least stress while aiming for mass efficiency.

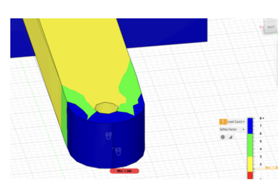


Week 4: Redesign the chassis for mass efficiency





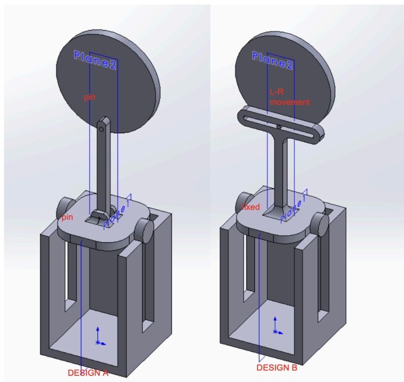


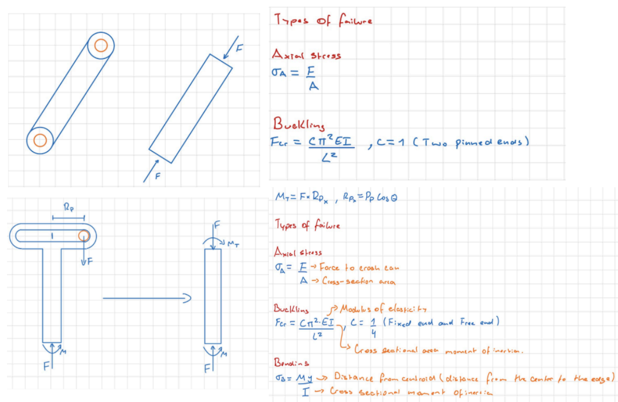


- We started thinking about **what materials** we could use, like PLA.

- But the main focus was to experiment for the critical component: the platform
- Through failure analyses, we learned that **fillets are awesome for structural design**. It distributes the stress load over a wider area.

Week 5: Select materials + components, order parts



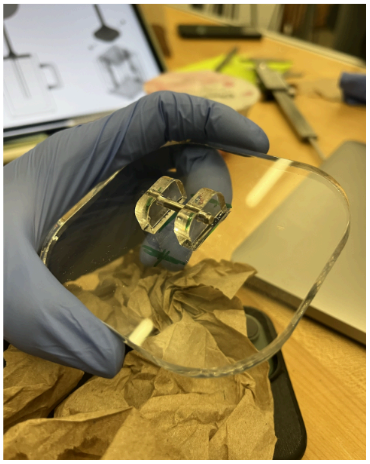
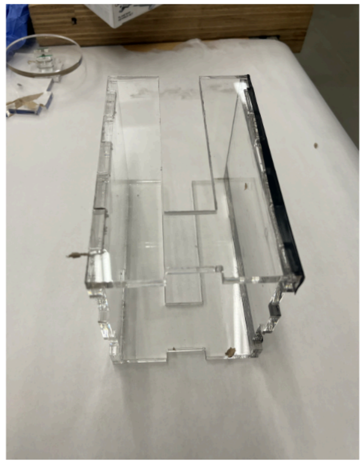
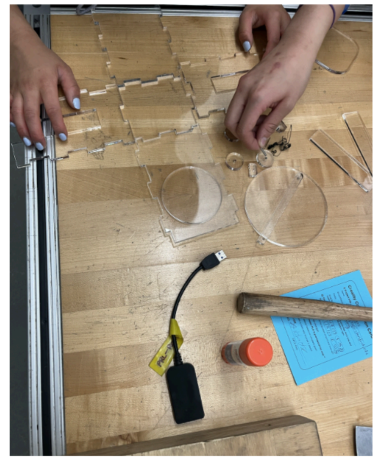


- At this point we started finalizing the critical component. Ensuring we were efficient in translating the rotary motion from the motor to linear motion, we CAD'd 2 designs: a **rotary circle** and a **yoke**.
- We experimented with acrylic, aluminum metal, and PLA. To reduce friction, we added wheels to the platform.
- We tested our assumptions with FBD and FEA.
- To ensure the **CAD model was more user friendly**, we added other components: rubber feet, handles for easy grabbing.
- We started prototyping with laser cut acrylic and makeshift wheels we created out of rubber.

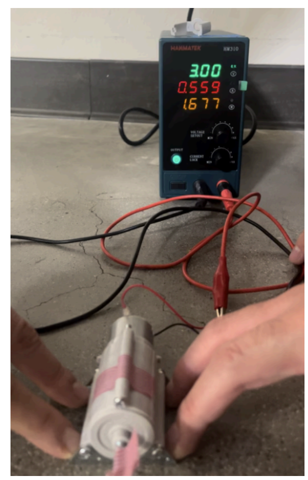
Week 6: Select motor operating point

- Deciding we want the strongest material we could possibly design, we settled on **carbon fiber for the moving mechanism**.
- We played around with **generative design** as possible options for mass efficiency.

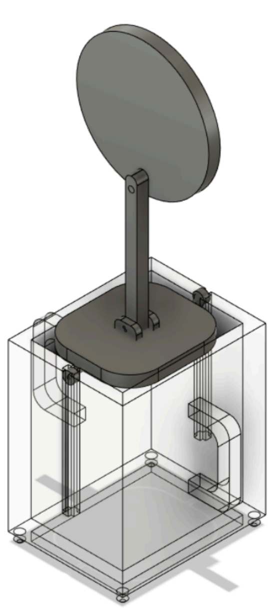
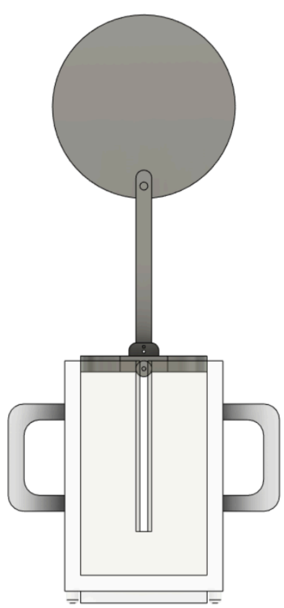
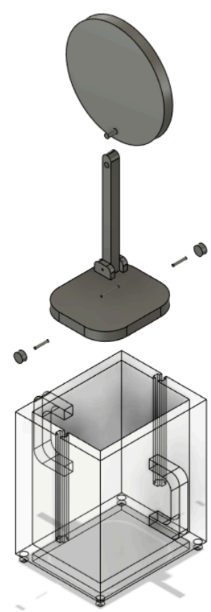
- Conducted assembly of **“looks-like” prototype** to determine what components we needed for the final design and test feasibility of design without motor.

Week 7: Select gearbox configuration

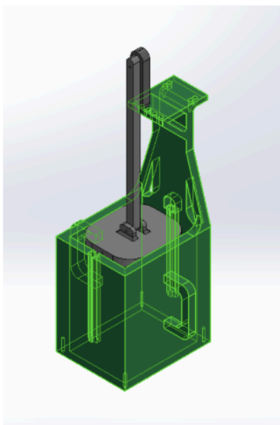
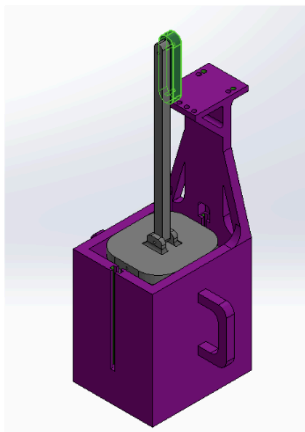
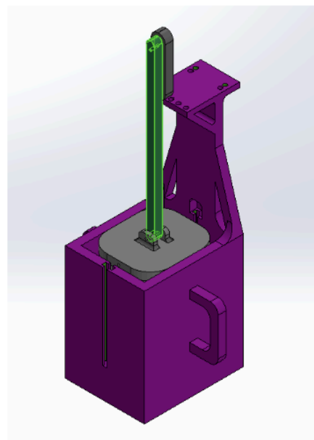
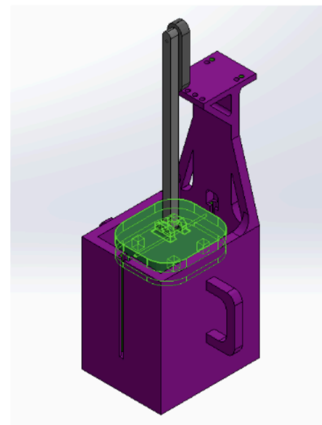


- From the results of the prototyping, we updated the CAD model through rounds of iterations and feedback from the team–particularly concerns of **camming**, **bending**, and **stresses** in our design.
- Assembled motors of different gear ratios: 80:1, 100:1, 400:1
- With those three different motors, we conducted a series of tests to **characterize key properties of the gearbox** and optimize our gear efficiency for the task.
- Iterated until we received our desired gear ratio to maximize our torque output from the motor.

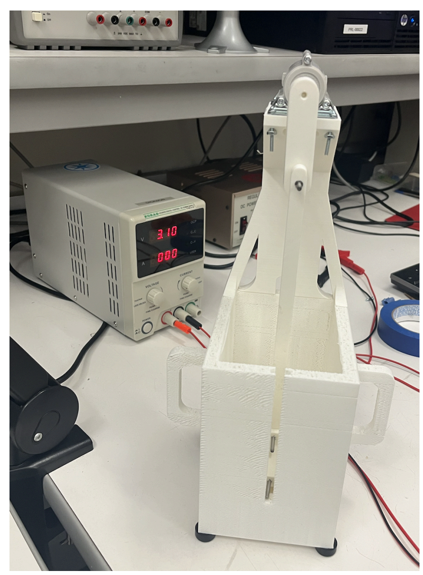




Week 8: Design the drivetrain

- Incorporated **trusses**, designed motor stand, and reinforced platform design for our **second prototype**–now 3D-printed.
- Our main areas of concern were bending in the critical components, so we went back to the drawing board and **drew new FBD's** for the improved components.
- With assembly of the working PLA prototype, we were able to finalize the assembly joint layout and determine dimensions. However, we realized that our model was incapable of crushing an aluminum can and **brainstormed ways to pivot**.

Week 9: Fabricate, test, reanalyze, learn, redesign, iterate



- Through CAD, we completely **changed orientation of the model** and **task definition** of our robot, recycling joint assembly and components from the previous model.
- Based on testing and feedback from TA's, we determined **3 sources of power loss** from the motor based on the prototype.
- With those takeaways, we made major improvements to the CAD's joint assembly layout and overall design: **reducing friction** in the joints and between parts, **improving gear efficiency**.
- Printed many many 3D parts with those improvements.

Week 10: Functional prototype

- Lots and lots of fabrication
- Lots and lots of assembly
- Working late nights together as a team, improving things on our project
- Running tests with our robot!!!

Thanks for reading! For more detailed information about our process, find our slides here.

Sincerely,

The Crushers