Swinging Gripper

Project 2 Final Report

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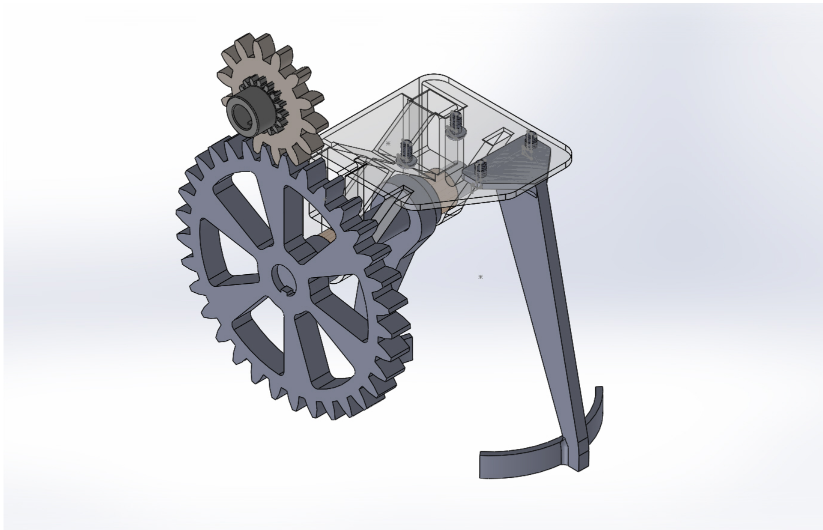
24-370 Engineering Design 1
November 16, 2018

1 Summary

a) Isometric Image



b) Description

Our gripper consists of two arms. One arm is glued to the base plate and secured via two threaded screws, and the other attaches to and rotates via a keyed shaft, held laterally in place by friction. Both arms are tapered according to their respective stress distributions. At the bottom of each arm, there is a curved gripping surface which will contact directly with the bottle. This surface is coated in a non-slip material, eliminating perpendicular swinging or any displacement of the bottle.

Torque is transmitted from the actuation shaft through a double-gear set to the shaft. With a gear ratio of 3.5, our set transfers a large amount of torque. We chose to use a gear set for torque transmission because they are easy to use and do not require additional components for movement in either rotational direction. The actuation gear uses a set screw, and the second gear uses a key to transmit torque throughout the assembly. The gear is also spoked to reduce mass.

The shaft is held in place in two planes by lubricated brass plain bearings press-fit into brackets that drop down from the base plate. We want the bearings to exert the lowest friction as possible on the shaft to not inhibit the shaft's rotation. Axially, the shaft is held in place by rubber o-rings glued to the shaft. The PLA shaft is keyed in order to increase torque transmission.

The base plate itself is a large 3-D printed plate that fits flush on the wrist and has screw holes for attachment to wrist. The base plate secures the shaft and moving arm to the wrist and keeps all components the same relative distance from each other, thus reducing attachment time.

c) Peak Force $F_{peak} = 21.41N$ *(Calculated on page 35)*

d) Grip Factor of Safety Estimate $FoS_{grip} = 1.56$ *(Calculated on page 35)*

e) Strength Factor of Safety Estimate $FoS_{strength} = 1.15$ *(Calculated on page 36)*

f) Failure Mode Prediction Our gripper will fail at the driving due to shear forces.

2 Conceptual Design Sketches

a) Notes and Sketches

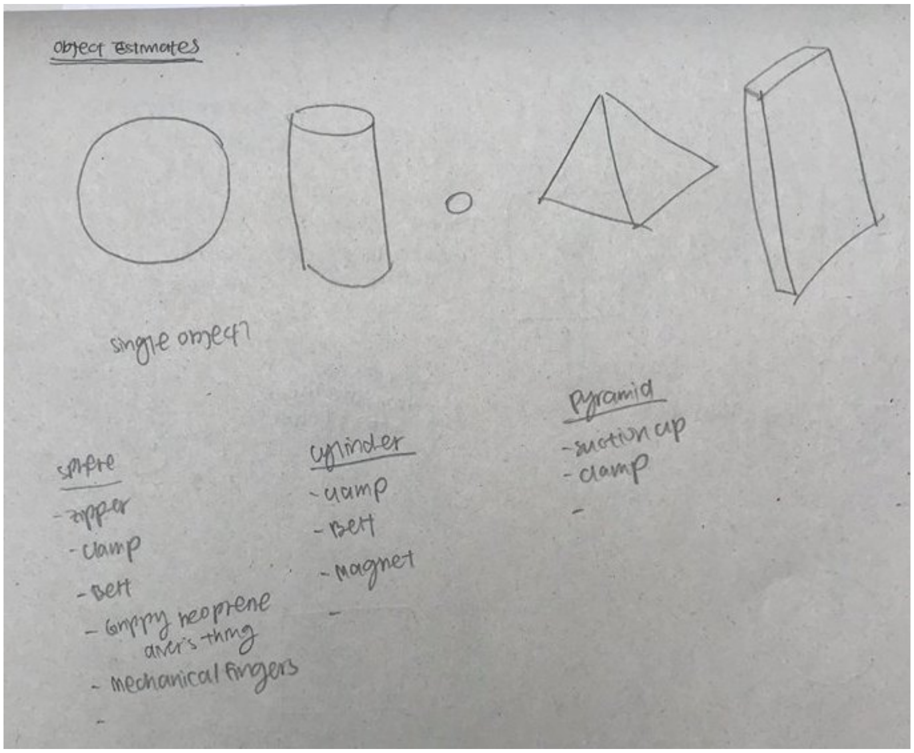


Figure 1: Initial brainstorming for different geometries before object was known.

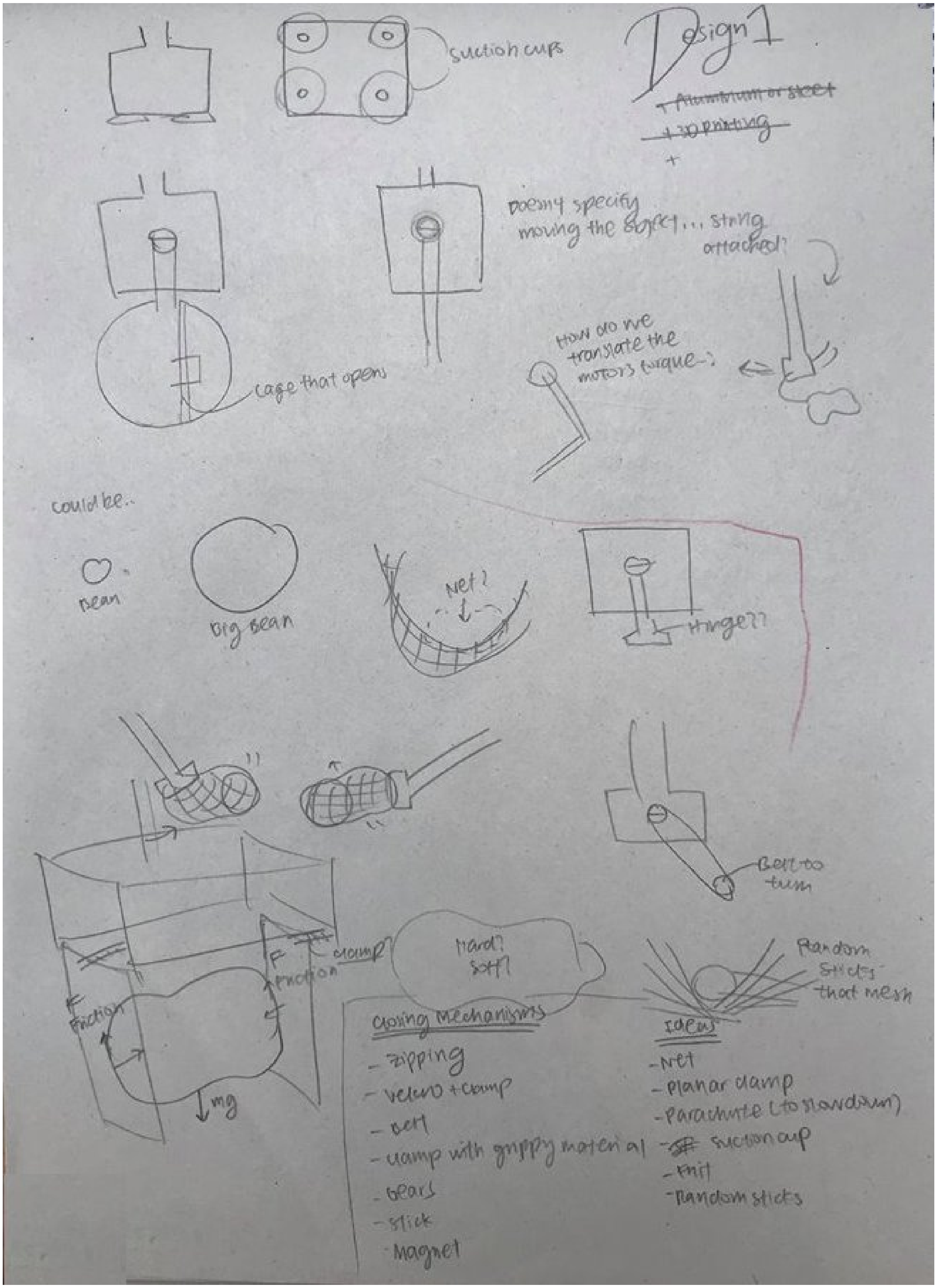


Figure 2: Early design ideas for gripper mechanisms.

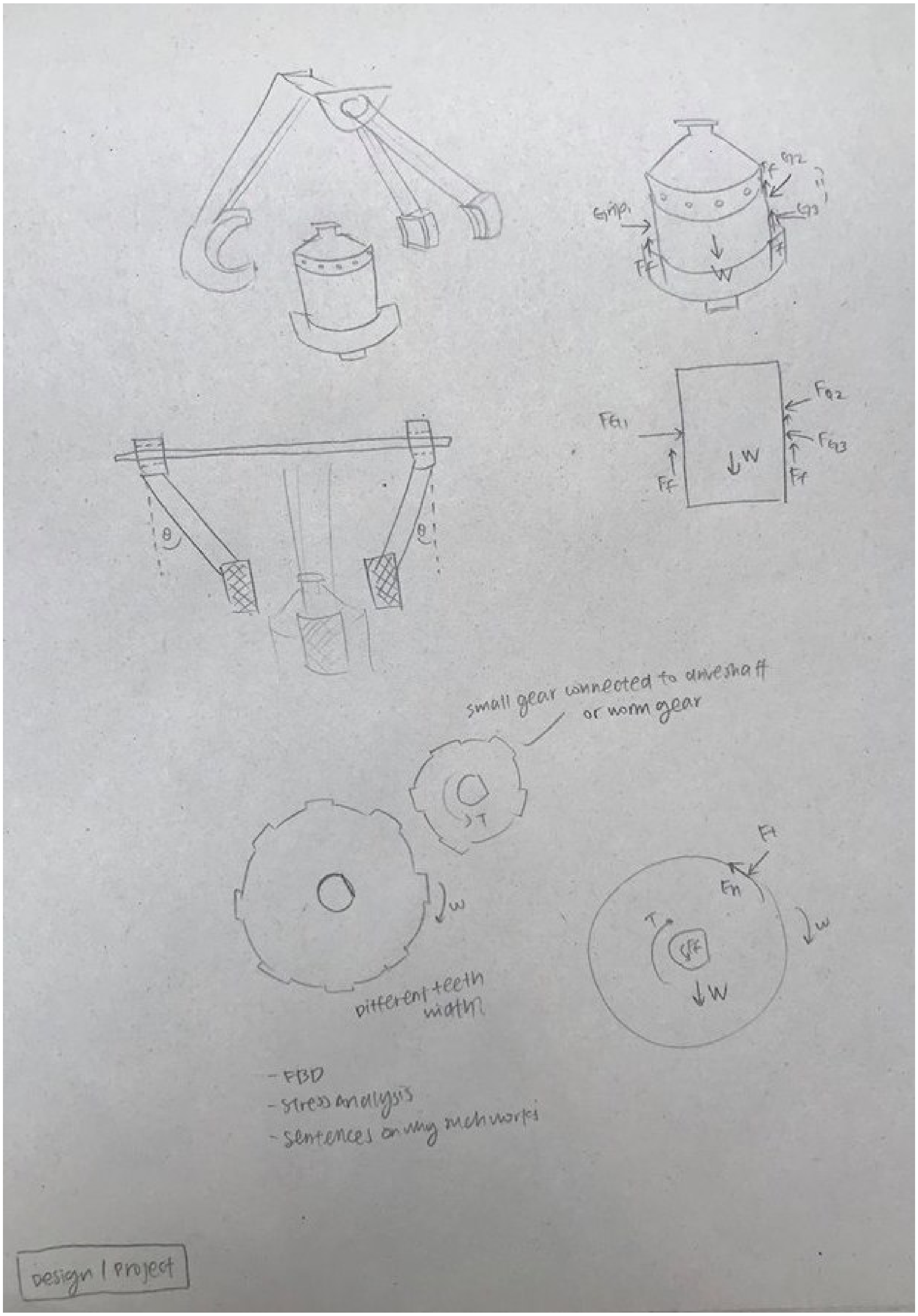


Figure 3: Early design and analysis of gripper once object geometry was known. Initial design featured three arms: two static and one moving. We determined through our analysis that only 2 arms were necessary for the final design.

3 Simple Modeling of Candidate Designs

a) Sketches and Hand Analysis

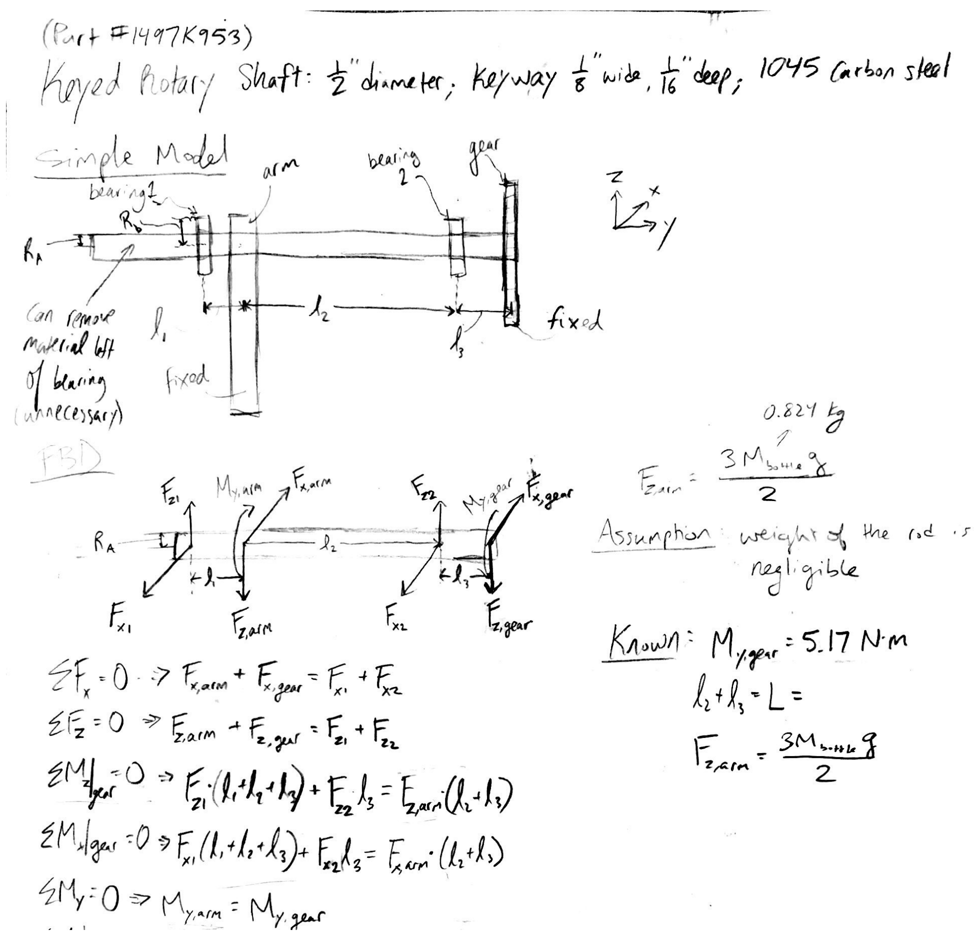


Figure 4: Analysis of forces on the shaft.

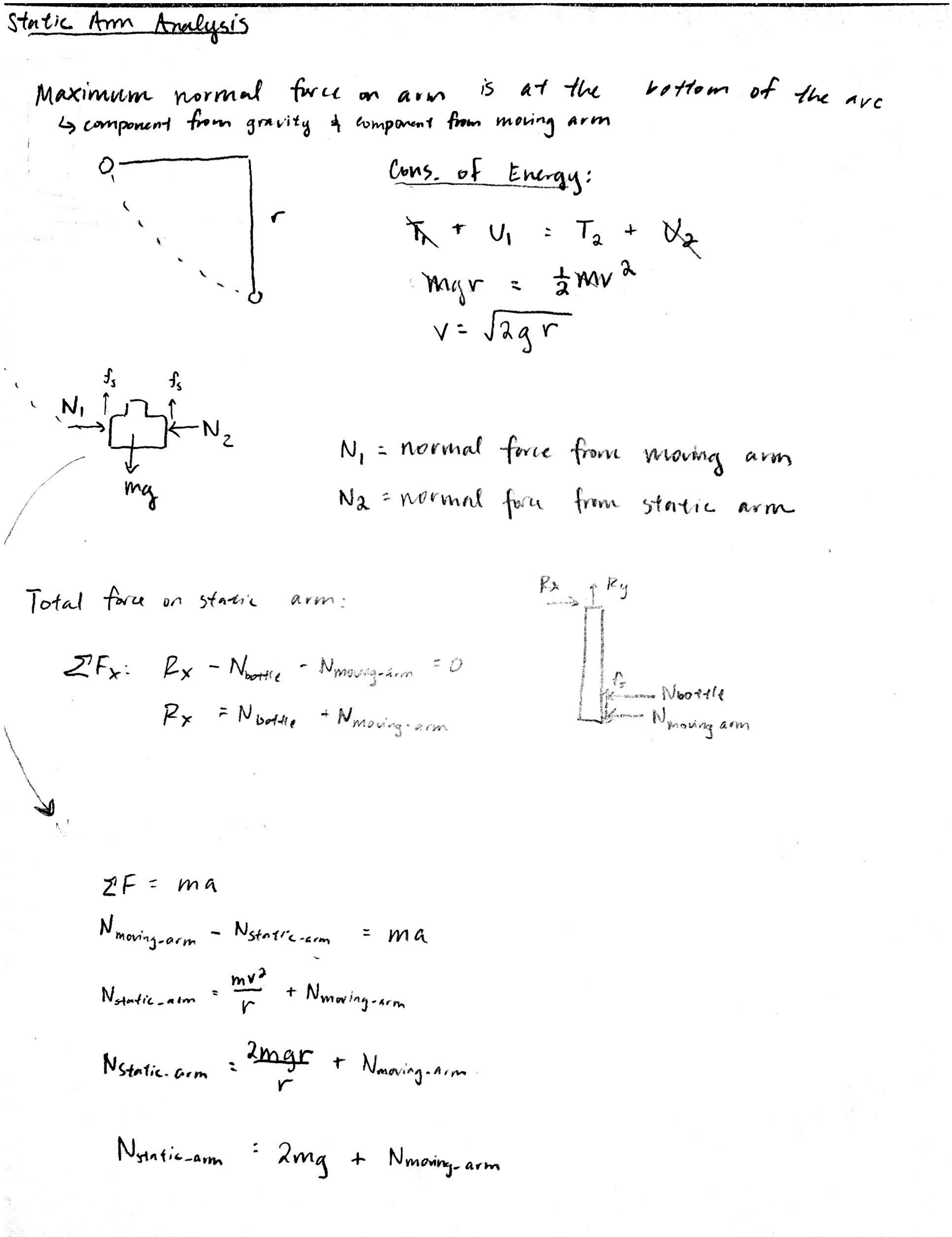


Figure 5: Analysis of forces on the static arm.

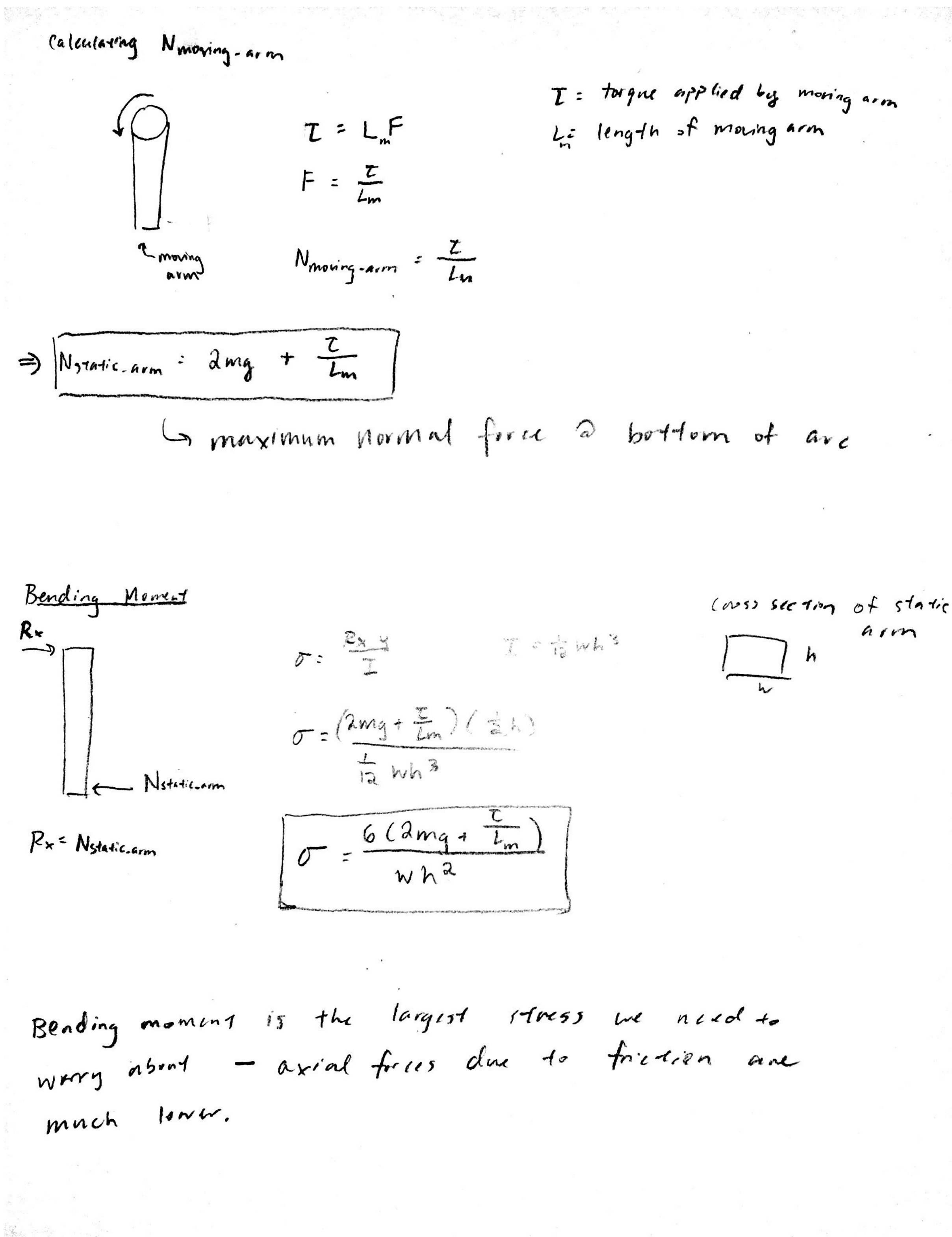
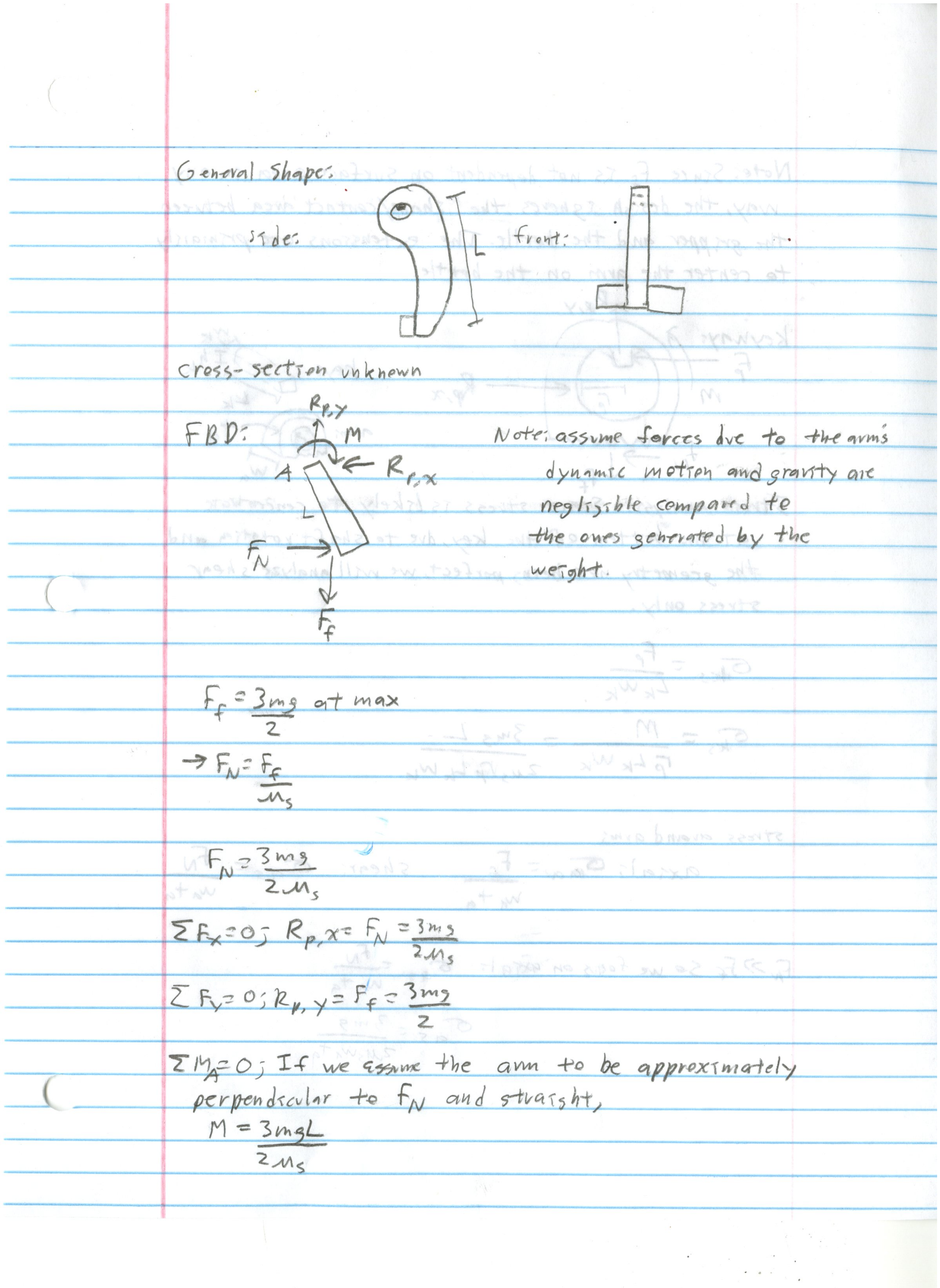


Figure 6: Analysis of forces on the static arm.



General Shape:

side: L front:

cross-section unknown

FBD: $R_{p,y}$, M, $R_{p,x}$, A, L, F_N, F_f

Note: assume forces due to the arm's dynamic motion and gravity are negligible compared to the ones generated by the weight.

$F_f = \frac{3mg}{2}$ at max

$\rightarrow F_N = \frac{F_f}{\mu_s}$

$F_N = \frac{3mg}{2\mu_s}$

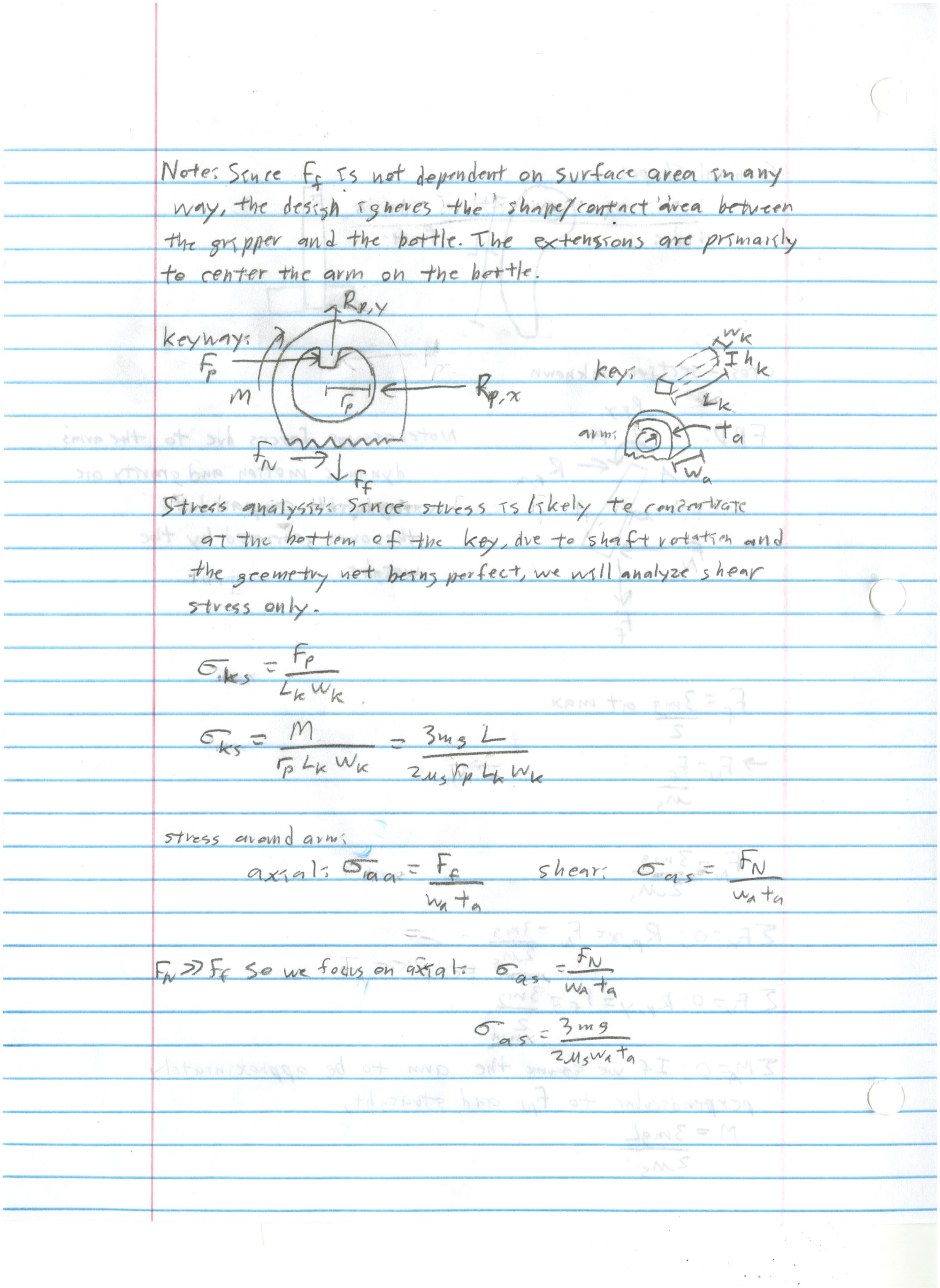
$\Sigma F_x = 0;\ R_{p,x} = F_N = \frac{3mg}{2\mu_s}$

$\Sigma F_y = 0;\ R_{p,y} = F_f = \frac{3mg}{2}$

$\Sigma M_A = 0;$ If we assume the arm to be approximately perpendicular to F_N and straight,

$M = \frac{3mgL}{2\mu_s}$

Figure 7: Analysis of forces on the moving arm.


Note: Since F_f is not dependent on surface area in any way, the design ignores the shape/contact area between the gripper and the bottle. The extensions are primarily to center the arm on the bottle.

Keyway:

Stress analysis: Since stress is likely to concentrate at the bottom of the key, due to shaft rotation and the geometry not being perfect, we will analyze shear stress only.

$$\sigma_{ks} = \frac{F_p}{L_k w_k}$$

$$\sigma_{ks} = \frac{M}{r_p L_k w_k} = \frac{3mgL}{2\mu_s r_p L_k w_k}$$

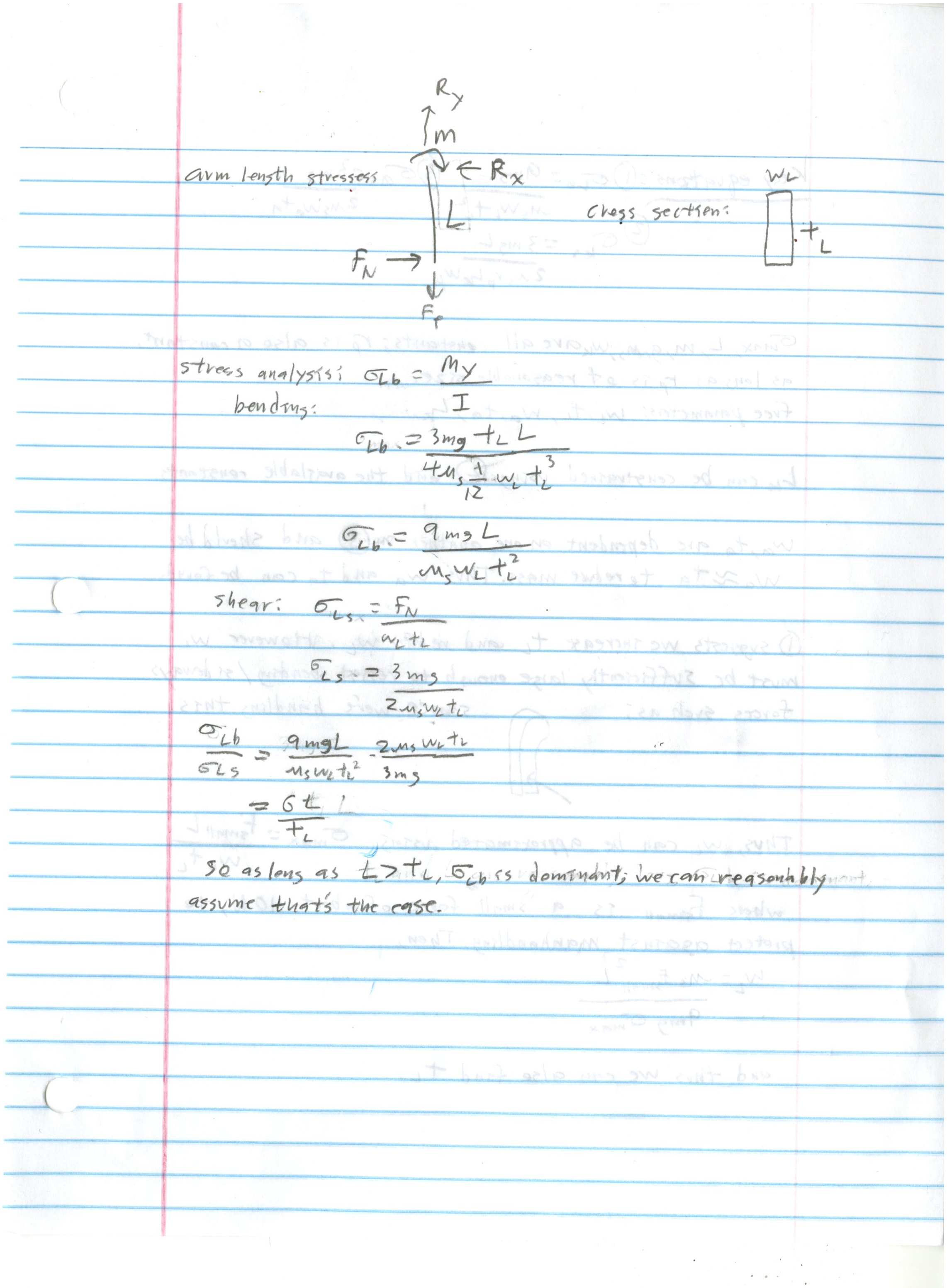
stress around arm:

axial: $\sigma_{aa} = \frac{F_f}{w_a t_a}$ shear: $\sigma_{as} = \frac{F_N}{w_a t_a}$

$F_N \gg F_f$ so we focus on axial: $\sigma_{as} = \frac{F_N}{w_a t_a}$

$$\sigma_{as} = \frac{3mg}{2\mu_s w_a t_a}$$

Figure 8: Stress analysis of the material around the hole in the moving arm.



arm length stresses

cross section:

stress analysis: bending: $\sigma_{Lb} = \frac{My}{I}$

$$\sigma_{Lb} = \frac{3mg\, t_L L}{4 n_s \frac{1}{12} w_L t_L^3}$$

$$\sigma_{Lb} = \frac{9mgL}{n_s w_L t_L^2}$$

shear: $\sigma_{Ls} = \frac{F_N}{w_L t_L}$

$$\sigma_{Ls} = \frac{3mg}{2 n_s w_L t_L}$$

$$\frac{\sigma_{Lb}}{\sigma_{Ls}} = \frac{9mgL}{n_s w_L t_L^2} \cdot \frac{2 n_s w_L t_L}{3mg} = \frac{6L}{t_L}$$

So as long as $L > t_L$, σ_{Lb} is dominant; we can reasonably assume that's the case.

Figure 9: stress analysis along the length moving arm.

Key equations: (1) $\sigma_{Lb} = \frac{9mgL}{m_s w_L t_L^2}$ (3) $\sigma_{as} = \frac{3mg}{2 m_s w_a t_a}$

(2) $\sigma_{ks} = \frac{3mgL}{2 m_s r_p L_k w_k}$

σ_{max}, L, m, g, m_s, w_k are all constants; r_p is also a constant, as long as r_p is of reasonable size.

Free parameters: w_L, t_L, w_a, t_a, L_k.

L_k can be constrained using (2) and the available constants.

w_a, t_a are dependent on one another in (3) and should be $w_a \approx t_a$ to reduce mass. Thus w_a and t_a can be found.

(1) suggests we increase t_L and reduce w_L. However w_L must be sufficiently large enough to resist bending / sideways forces such as:  since we're handling this.

Thus, w_L can be approximated using $\sigma_{max} = \frac{F_{small} L}{w_L t_L}$

where F_{small} is a "small" force of about 10 N, to protect against manhandling. Then,

$$w_L = \frac{m_s F_{small}^2 L}{9 m g \sigma_{max}}$$

and thus we can also find t_L.

Figure 10: Solving free parameters for the moving arm, based on stress analysis.

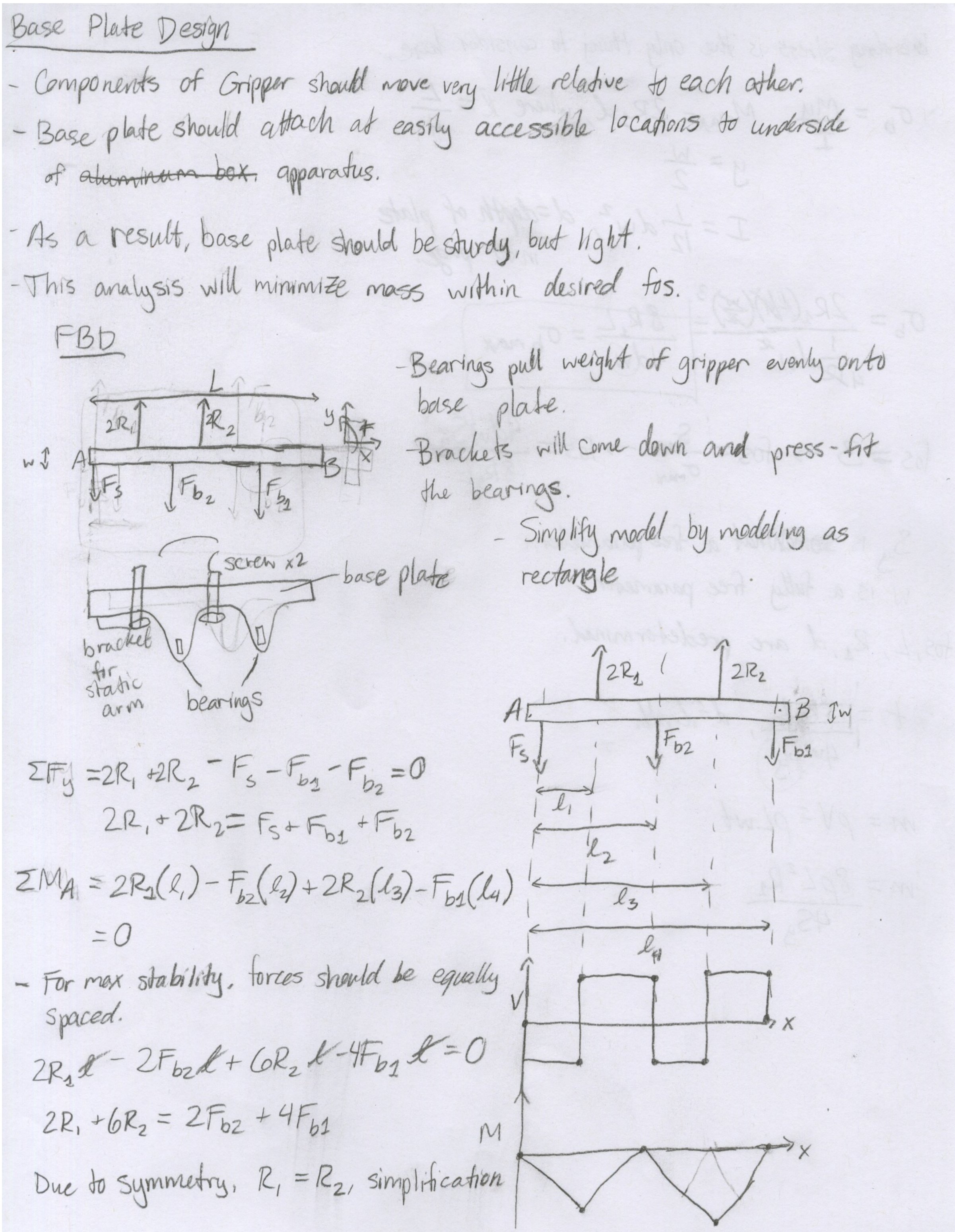


Figure 11: Analysis of forces on the base plate. F_s is the downward force from gear mesh. F_{b1} and F_{b2} are the downward forces from the bearings, loaded through support structures.

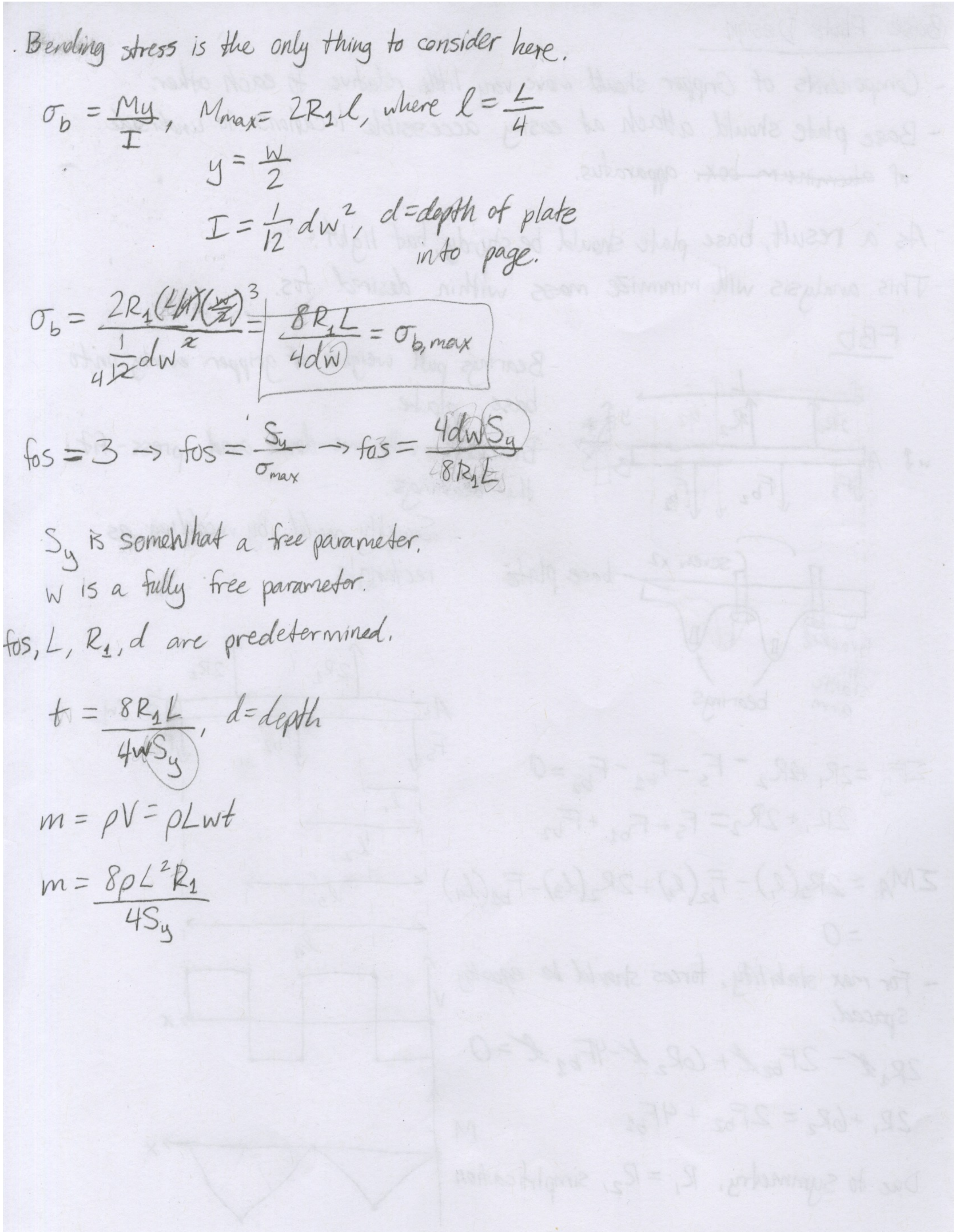


Figure 12: Analysis of forces on the base plate.

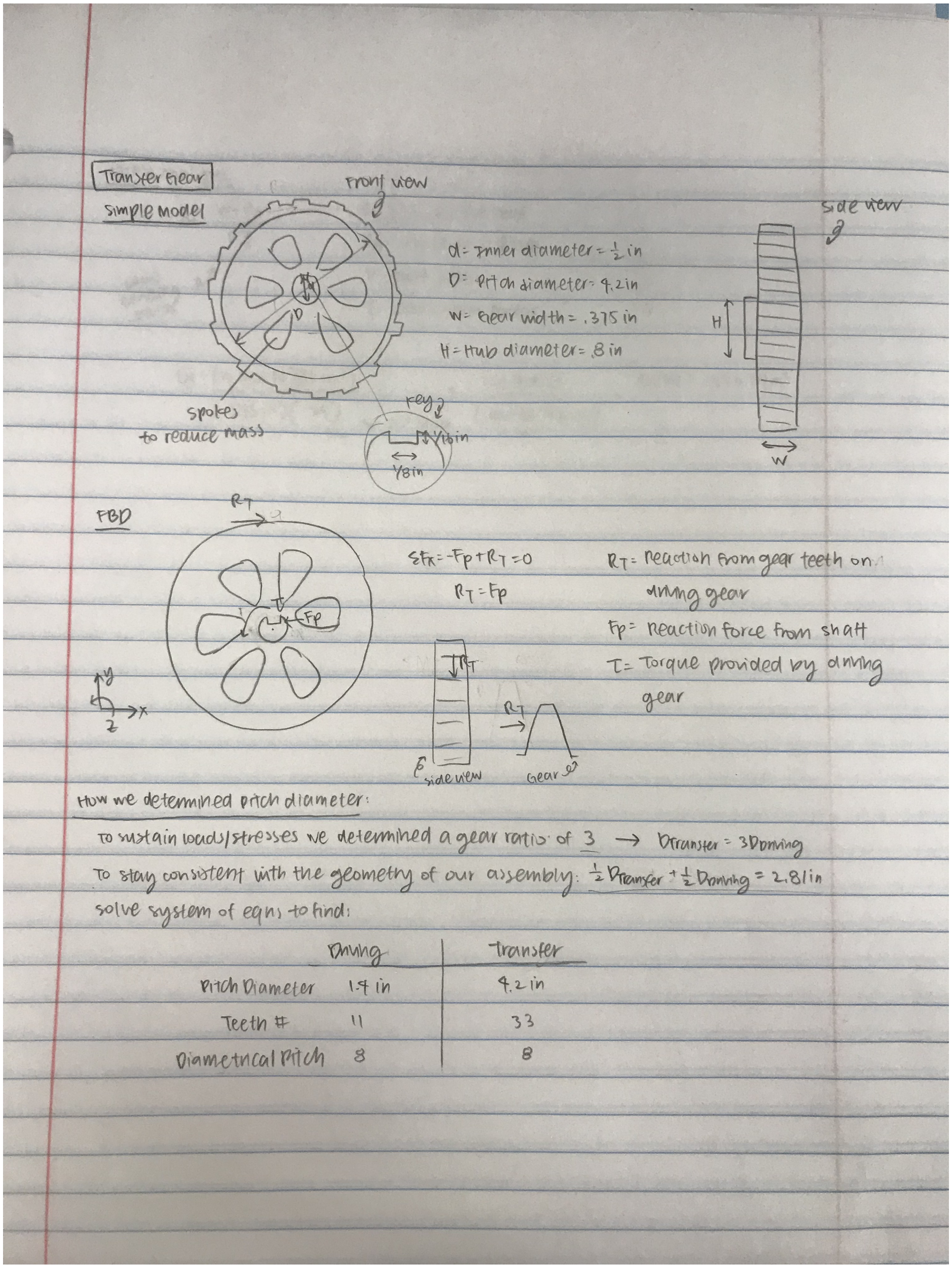


Figure 13: Analysis of forces on Transfer Gear

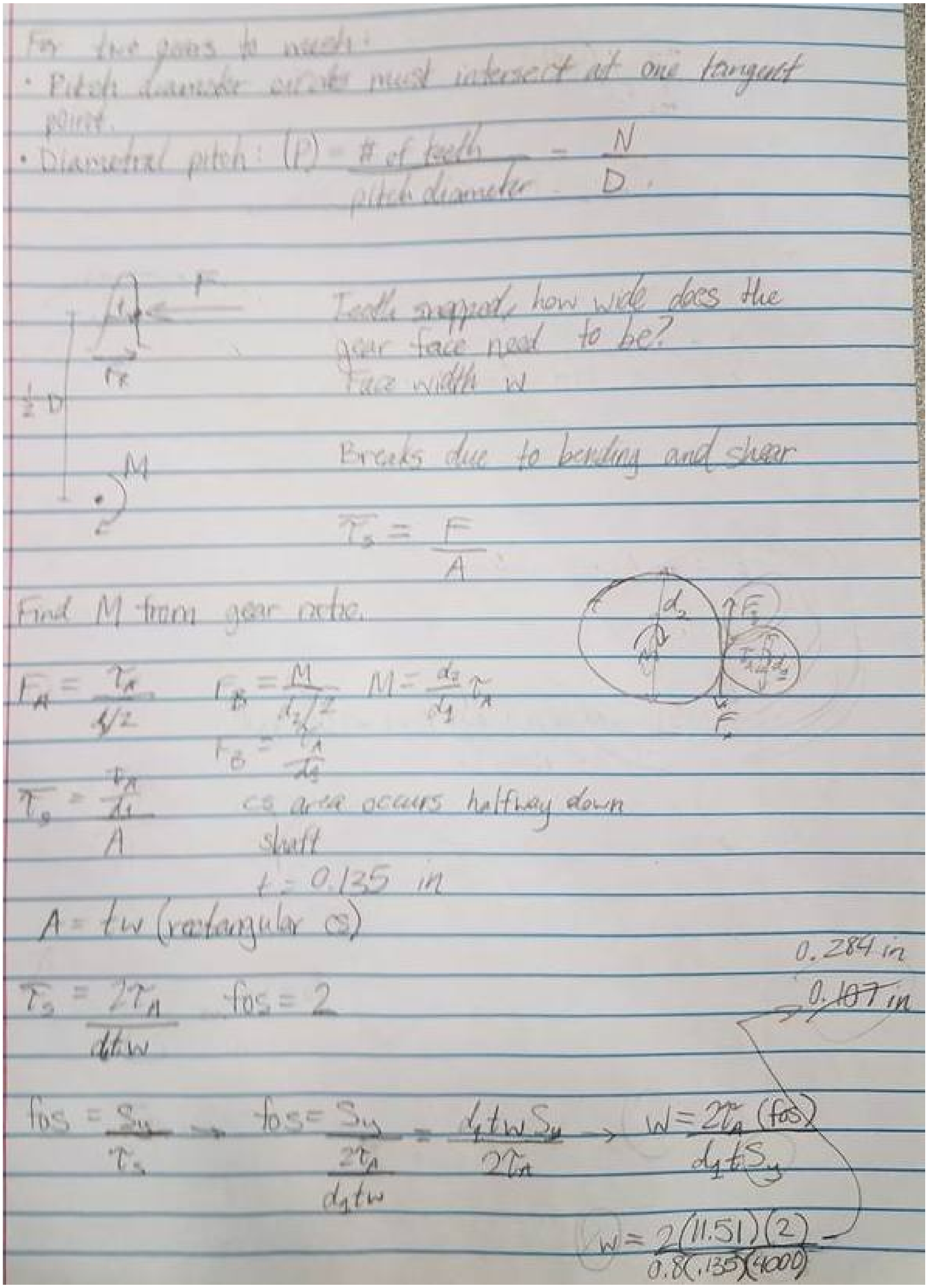
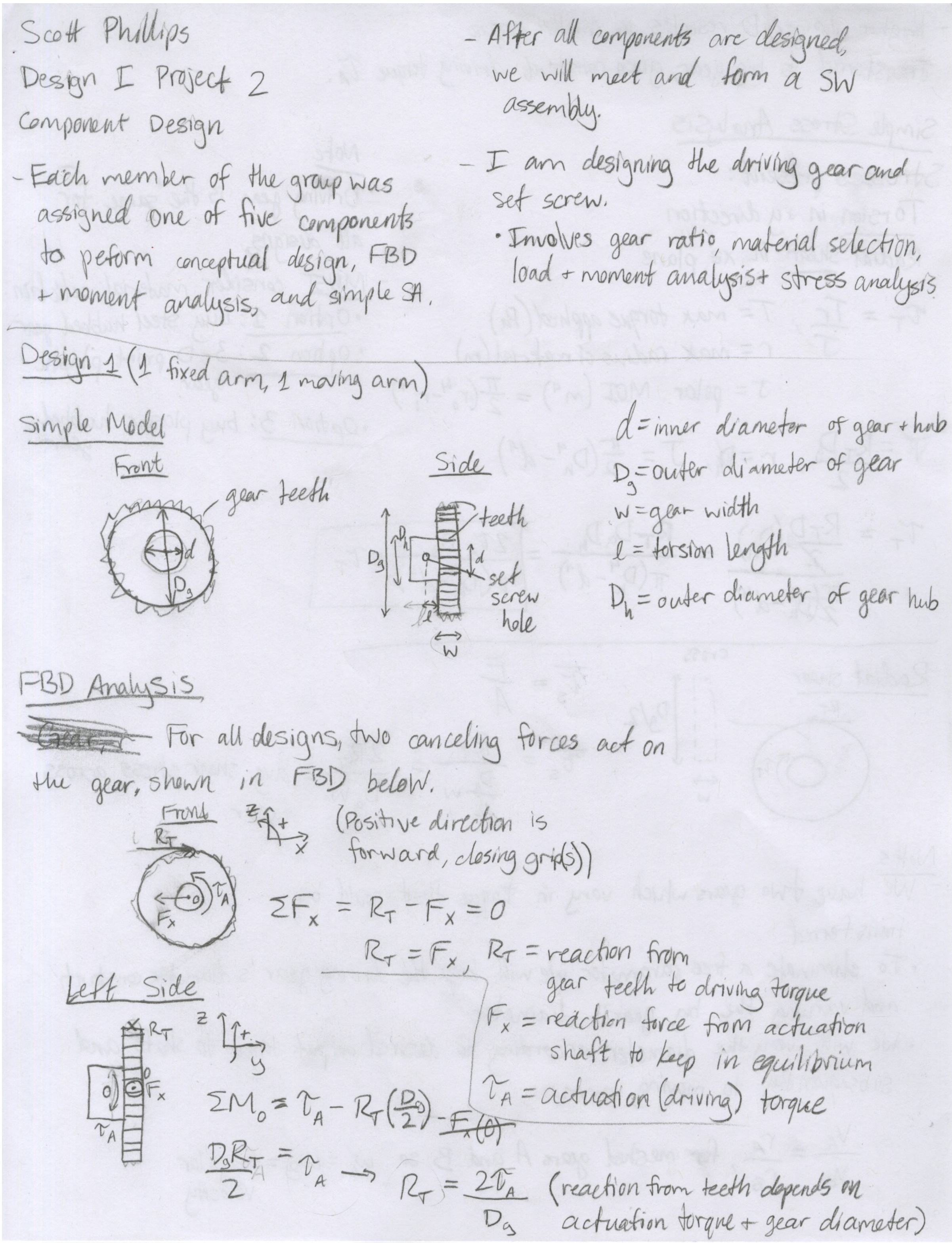


Figure 14: Analysis of forces between the gears (apologies for the low quality).



Scott Phillips

Design I Project 2

Component Design

- Each member of the group was assigned one of five components to peform conceptual design, FBD + moment analysis, and simple SA.
- After all components are designed, we will meet and form a SW assembly.
- I am designing the driving gear and set screw.
  - Involves gear ratio, material selection, load + moment analysis + stress analysis

Design 1 (1 fixed arm, 1 moving arm)

Simple Model

d = inner diameter of gear + hub

D_g = outer diameter of gear

w = gear width

l = torsion length

D_h = outer diameter of gear hub

FBD Analysis

~~Gear:~~ For all designs, two canceling forces act on the gear, shown in FBD below.

(Positive direction is forward, closing grip(s))

$$\Sigma F_x = R_T - F_x = 0$$

$R_T = F_x$, R_T = reaction from gear teeth to driving torque

F_x = reaction force from actuation shaft to keep in equilibrium

τ_A = actuation (driving) torque

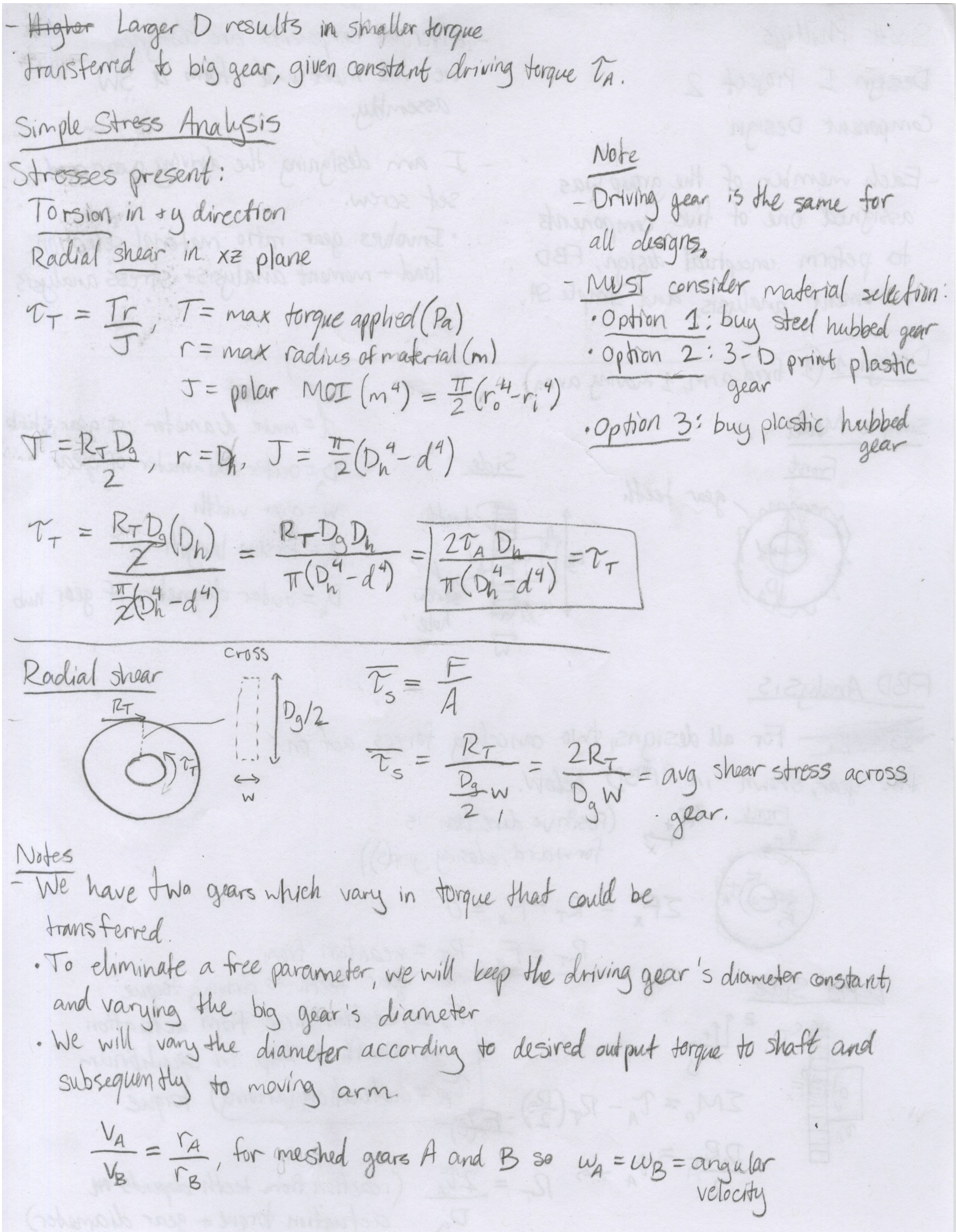
Left Side

$$\Sigma M_o = \tau_A - R_T\left(\frac{D}{2}\right) - \cancel{F_x(0)}$$

$$\frac{D_g R_T}{2} = \tau_A \rightarrow R_T = \frac{2\tau_A}{D_g}$$

(reaction from teeth depends on actuation torque + gear diameter)

Figure 15: Analysis of forces on the driving gear.



- ~~Higher~~ Larger D results in smaller torque transferred to big gear, given constant driving torque τ_A.

Simple Stress Analysis

Stresses present:

Torsion in +y direction

Radial shear in xz plane

$\tau_T = \frac{Tr}{J}$, T = max torque applied (Pa)

r = max radius of material (m)

J = polar MOI $(m^4) = \frac{\pi}{2}(r_o^4 - r_i^4)$

$T_T = \frac{R_T D_g}{2}$, $r = D_h$, $J = \frac{\pi}{2}(D_h^4 - d^4)$

$$\tau_T = \frac{\frac{R_T D_g}{2}(D_h)}{\frac{\pi}{2}(D_h^4 - d^4)} = \frac{R_T D_g D_h}{\pi(D_h^4 - d^4)} = \boxed{\frac{2\tau_A D_h}{\pi(D_h^4 - d^4)} = \tau_T}$$

Note

- Driving gear is the same for all designs.
- MUST consider material selection:
  - Option 1: buy steel hubbed gear
  - Option 2: 3-D print plastic gear
  - Option 3: buy plastic hubbed gear

Radial shear

$$\overline{\tau}_s = \frac{F}{A}$$

$$\overline{\tau}_s = \frac{R_T}{\frac{D_g}{2} w} = \frac{2R_T}{D_g W} = \text{avg shear stress across gear.}$$

Notes

- We have two gears which vary in torque that could be transferred.
  - To eliminate a free parameter, we will keep the driving gear's diameter constant, and varying the big gear's diameter
  - We will vary the diameter according to desired output torque to shaft and subsequently to moving arm.

$\frac{V_A}{V_B} = \frac{r_A}{r_B}$, for meshed gears A and B so $\omega_A = \omega_B$ = angular velocity

Figure 16: Analysis of forces on the driving gear.

4 Material Selection

1. **Fixed Arm** The fixed arm was 3D printed from PLA plastic. Its curved shape made 3D printing the most viable option for manufacturing. Additionally, the loading conditions and mass constraints of this part make plastic the optimal material.

2. **Moving Arm** The Moving Arm was 3D printed from PLA plastic in order to reduce overall weight; printing focuses mass on the surface, which is where most of the stress is located. The part was printed as 2 parts, the curved bottom and the arm, in order to increase printing accuracy, and to have the print layers line up in the optimal way.

3. **Base Plate** The base plate is primarily under bending stress as axial stress is nearly negligible. To minimize weight, 3-D printed PLA plastic was chosen as the density of the plate could be variable based on infill percentage, and could be custom-printed to fit other catalog components.

4. **Shaft** The shaft is printed using PLA, as we needed a light material with low density and a decent yield stress. Since a shaft made with 3D-printed PLA could easily be made to have a low density on the inside, this was ideal for us.

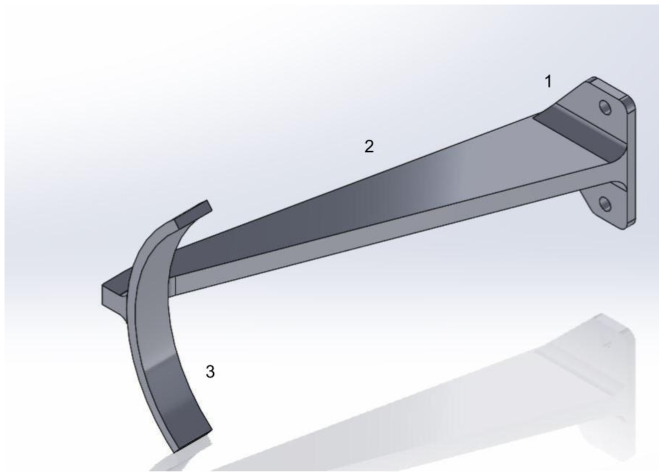
5. **Driving Gear** For proper meshing and rapid prototyping, the outer part was cut from acrylic. To transfer torque, we used a much smaller catalog set-screw hubbed gear that meshes with the inside of the acrylic gear. That gear is steel, and this material was chosen to have a very high fos and not break under any circumstances.

6. **Transfer Gear** The transfer gear was 3D printed using PLA in order to reduce mass from our original acrylic gear. Additionally, to incorporate the hub to help reduce slippage we opted for 3D-printed PLA over a heavier metal option. We chose to use PLA over ABS for its superior strength.

5 Detailed Model and Analysis of Final Design

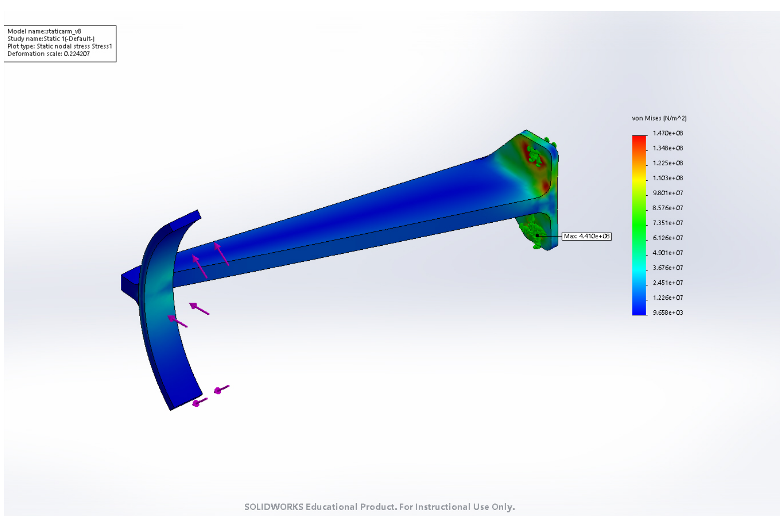
Fixed Arm

a) Isometric Screenshot



1. Filleted surface is glued to base plate and secured with hex screws through the wrist.
2. Arm with a tapered rectangular cross section to avoid bending stresses.
3. Gripping surface with 100 degree arc matching curvature of the bottle. Surface is covered in non-slip material to increase friction.

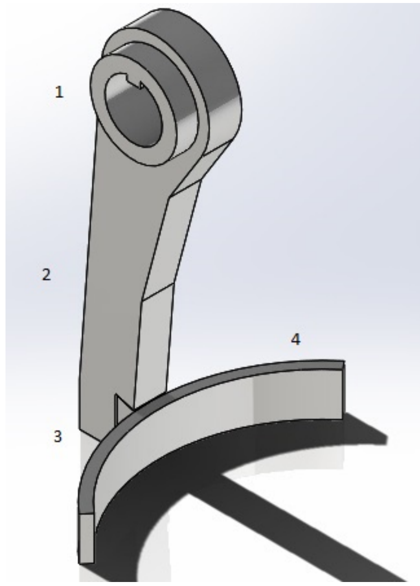
b) Stress Analysis



c) Material Properties PLA Plastic Yield Strength: 8,840 psi
d) Mass $m_{staticarm} = 13$ g

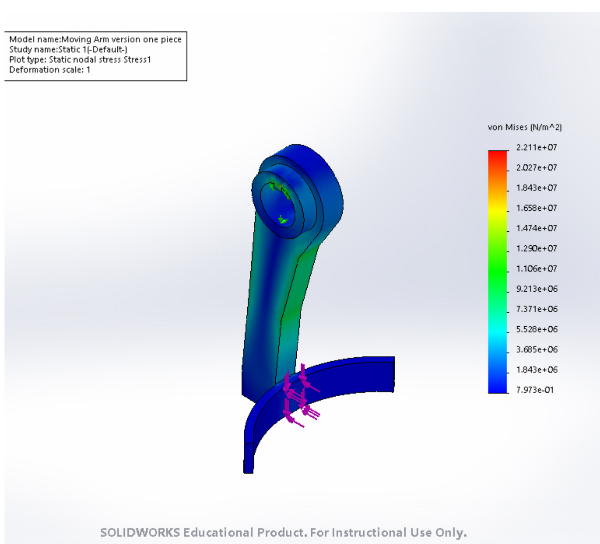
Moving Arm

a) Isometric Screenshot



1. Keyed hole fits into shaft key to transfer torque. Extended hub prevents wiggling.
2. Arm with a tapered rectangular cross section to avoid bending stresses.
3. Curved part is press-fit into the arm to allow for optimal manufacturing procedures
4. Just like the static arm, the gripping surface matches the curvature of the bottle and is covered in non-slip material to increase friction.

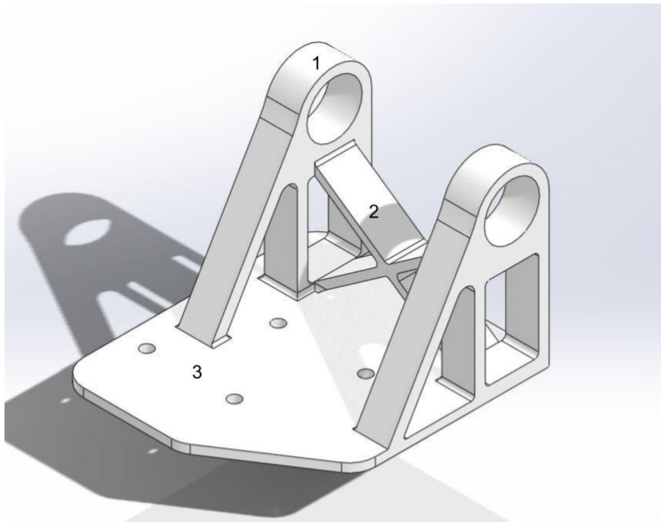
b) Stress Analysis



c) Material Properties PLA Plastic Yield Stength: 8840 psi
d) Mass $m_{staticarm} = 11g$

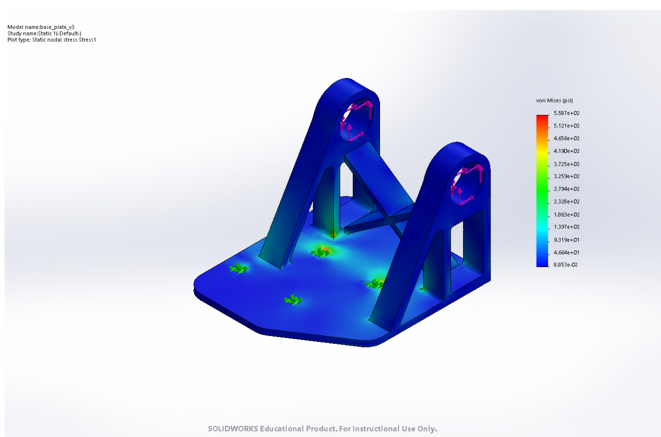
Base Plate

a) Isometric Screenshot



1. Brackets to house bearings and shaft
2. Truss structure to prevent bending in brackets due to axial forces on the shaft.
3. Holes to secure the static arm and assembly to the robot wrist.

b) Stress Analysis

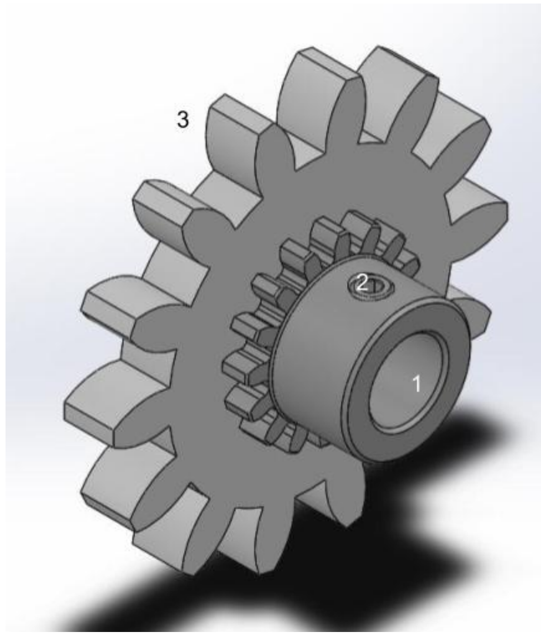


c) Material Properties PLA Plastic: Yield Strength: 8,840 psi

d) Mass $m_{baseplate} = 30.5$ g

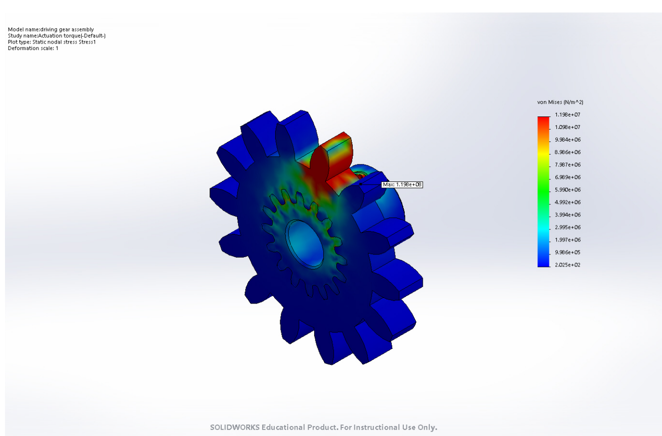
Driving Gear

a) Isometric Screenshot



1. shaft through hole
2. set screw and threaded through hole
3. Inner gear press-fits into outer gear with larger teeth

b) Stress Analysis

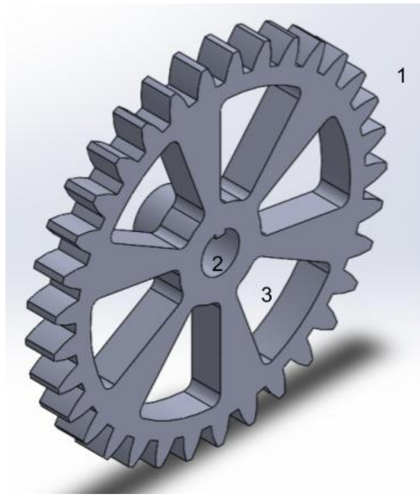


c) Material Properties PLA Plastic: Yield Strength: 8,840 psi

d) Mass $m_{drivinggear} = 12.75$g

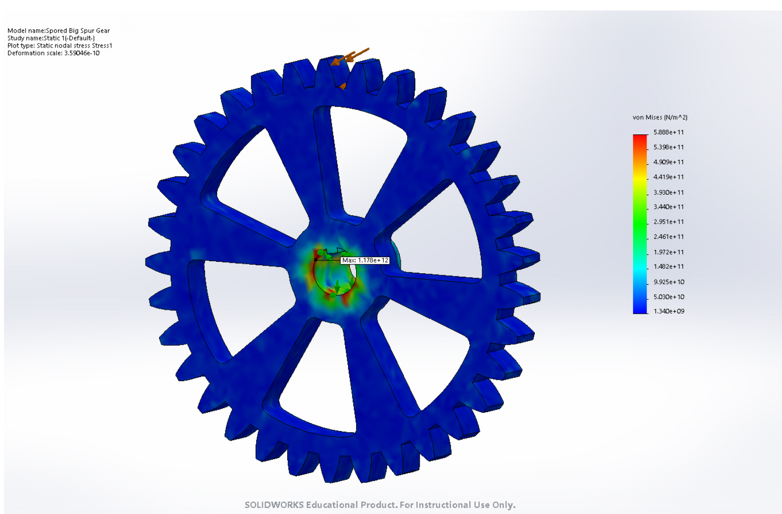
e) Transfer Gear

a) Isometric Screenshot



1. Gear teeth mesh with driving gear to transfer torque.
2. Keyed hole with hub attach to shaft.
3. Six angular spokes reduce the mass of the gear and shorten fabrication time.

b) Stress Analysis

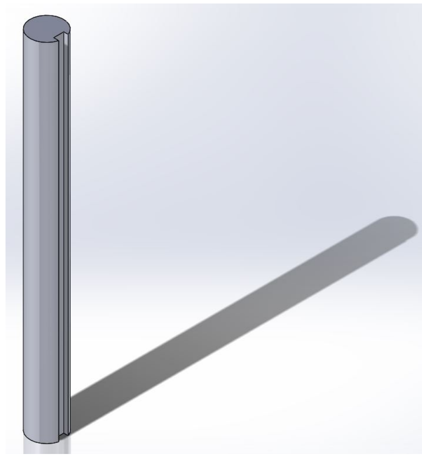


c) Material Properties PLA plastic Yield Strength: 8,400 psi

d) Mass $m_{transfergear} = 47.2$ g

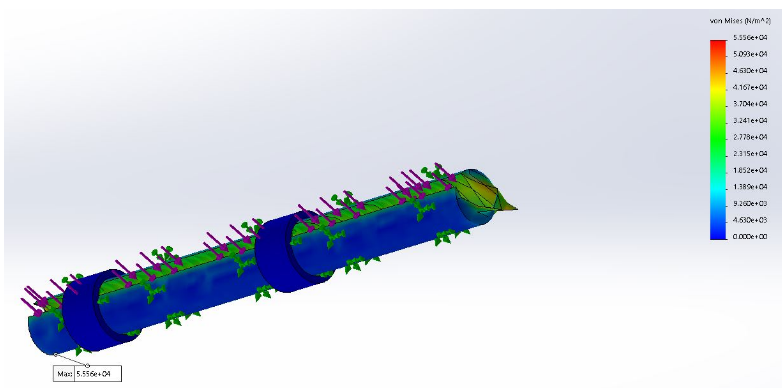
f) Shaft

a) Isometric Screenshot



Keyed shaft transfers torque to the gripper arm.

b) Stress Analysis



c) Material Properties PLA plastic, yield strength 8,400 psi

d) Mass $m_{shaft} = 12$ g

6 Catalog Component Selection

8-32 Screws, pack of 100
We used screws to secure the base plate onto the robot wrist. Screws needed to be long enough to be threaded through the static arm, base plate, and wrist with enough threads to hold the gripper in place.

Hubbed Gear with Set Screw Hole
We used a hubbed gear with a set hole screw to secure the gear onto the motor shaft. A set screw is much simpler to mount and also much lighter than a split hub clamp. The flat surface on the motor shaft greatly improves the robustness of the connection.

Rubber O-ring
We used rubber gaskets to keep the shaft from sliding axially because they are significantly lighter than a split hub clamp or shaft collar. Strength of material was not an important factor since there are no large axial forces on the shaft.

Bronze Sleeve Bearing for 1/2” Shaft, 5/8” Housing
We used plain bearings to attach the shaft to the base plate because mass and size were critical in this location while friction and slight misalignment were tolerable.

Dycem Non-Slip Material Roll
We added Dycem to ends of the gripping arms in order to increase friction on the surface in contact with the bottle. Dycem has a very high coefficient of static friction while being thin and light, so it does not contribute significantly to the mass. Additionally, Dycem is flexible and easy to cut into a custom shape.

7 Bill Of Materials

Item Description	Justification/Purpose	Purchased By	Amount
Hubbed Gear with Set Screw Hole	Transfer torque	Scotty	($27.54)
Gorilla Glue, 2oz	Secure static arm to base plate	Scotty	($5.57)
Split Hub Clamp	Secure shaft (initial prototype)	Scotty	($5.37)
McMaster 8-32 screw, pack of 100	Secure base plate to wrist	Scotty	($4.87)
McMaster Carbon Steel Keyed shaft	Initial shaft used	Jeff	($21.70)
Grainger Aluminum Keyed shaft	Lighter mass shaft	Jeff	($16.95)
Bronze Sleeve Bearing	Reduce friction on shaft	Jeff	($3.16)
Oil-Resistant O-Rings	Securing shaft	Jeff	($4.42)
1/2” Thick Acryllic	Stock material for gears	Emily	($31.50)
Dycem Non-Slip Material Roll	Increase friction on gripping surface	Katherine	($20.26)
Base Plate Print	Secure components to wrist	Scotty	($9.03)
Transfer Gear Print	Transfer torque to arm	Emily	($12.50)
Static Arm Print	Hold onto bottle	Katherine	($4.20)
Moving Arm Print	Hold onto bottle	Thomas	($3.30)
Plastic Shaft Print	Lighter shaft	Thomas	($3.60)

Total Spent: \$173.97
Remaining Budget: \$176.03

Part Fabrication

Component	Fabrication Method	Team Member
Static Arm	3D Printing	Katherine
Moving Arm	3D Printing	Thomas
Base Plate	3D Printing	Scotty
Driving Gear	Laser Cutting	Emily, Scotty
Transfer Gear	3D Printing	Emily
Keyed Shaft	3D Printing	Thomas

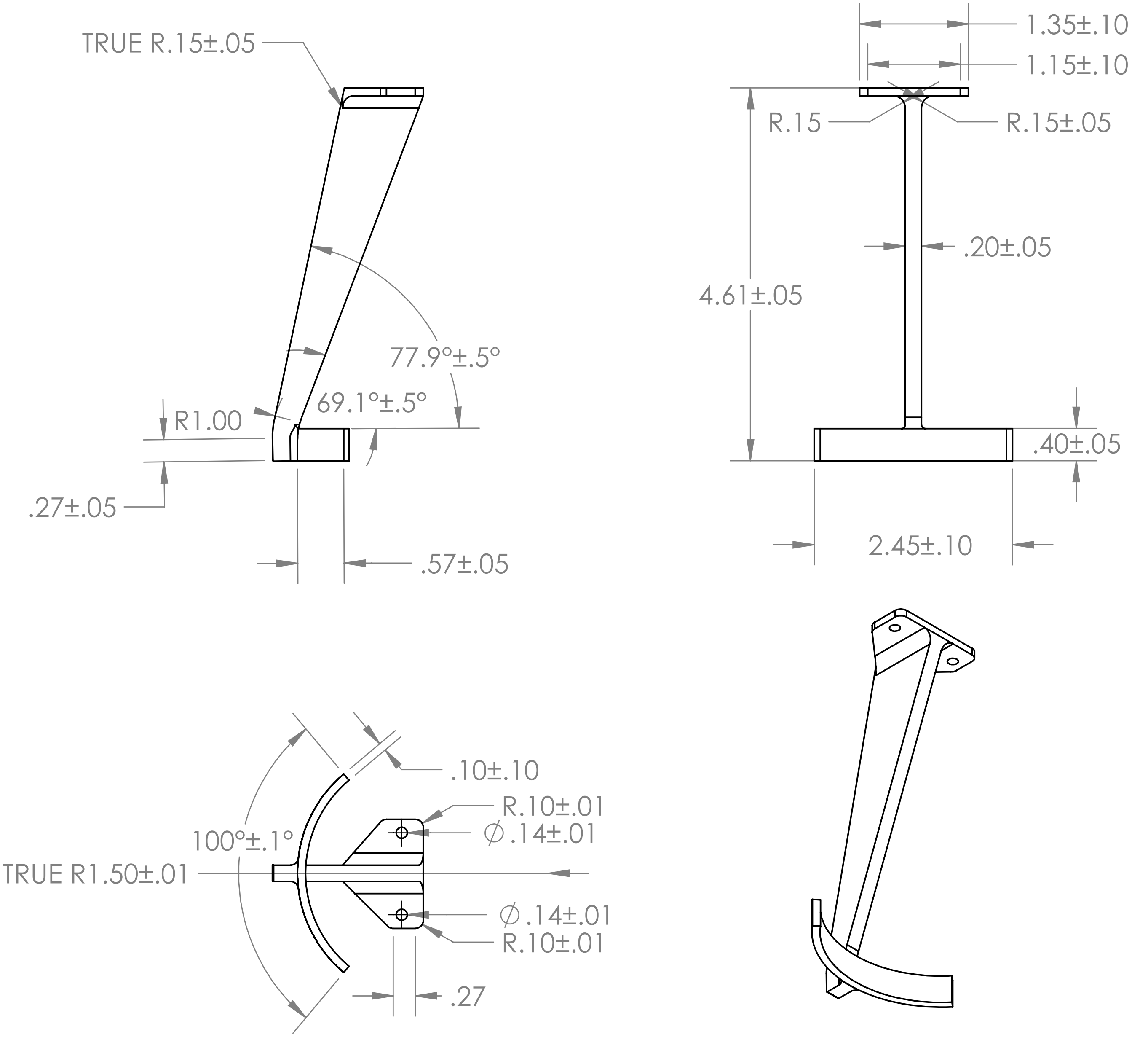
8 Engineering Drawings

See following pages for engineering drawings of:

1. **Fixed Arm**
2. **Moving Arm**
3. **Base Plate**
4. **Driving Gear**
5. **Transfer Gear**

2 1

B B



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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SIZE	DWG. NO.	REV.
A	staticarm_v8	
SCALE:1:2	WEIGHT:	SHEET 1 OF 1

2 1

2 1

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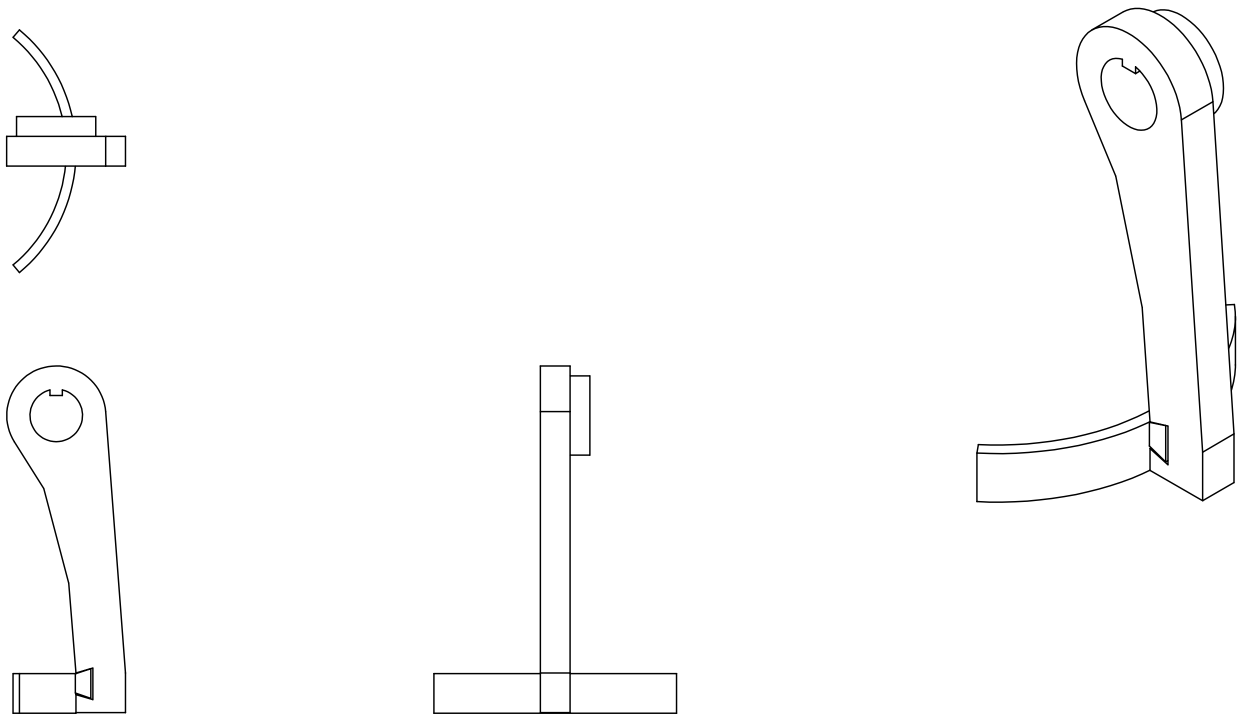

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UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE **A** DWG. NO. Moving Arm REV

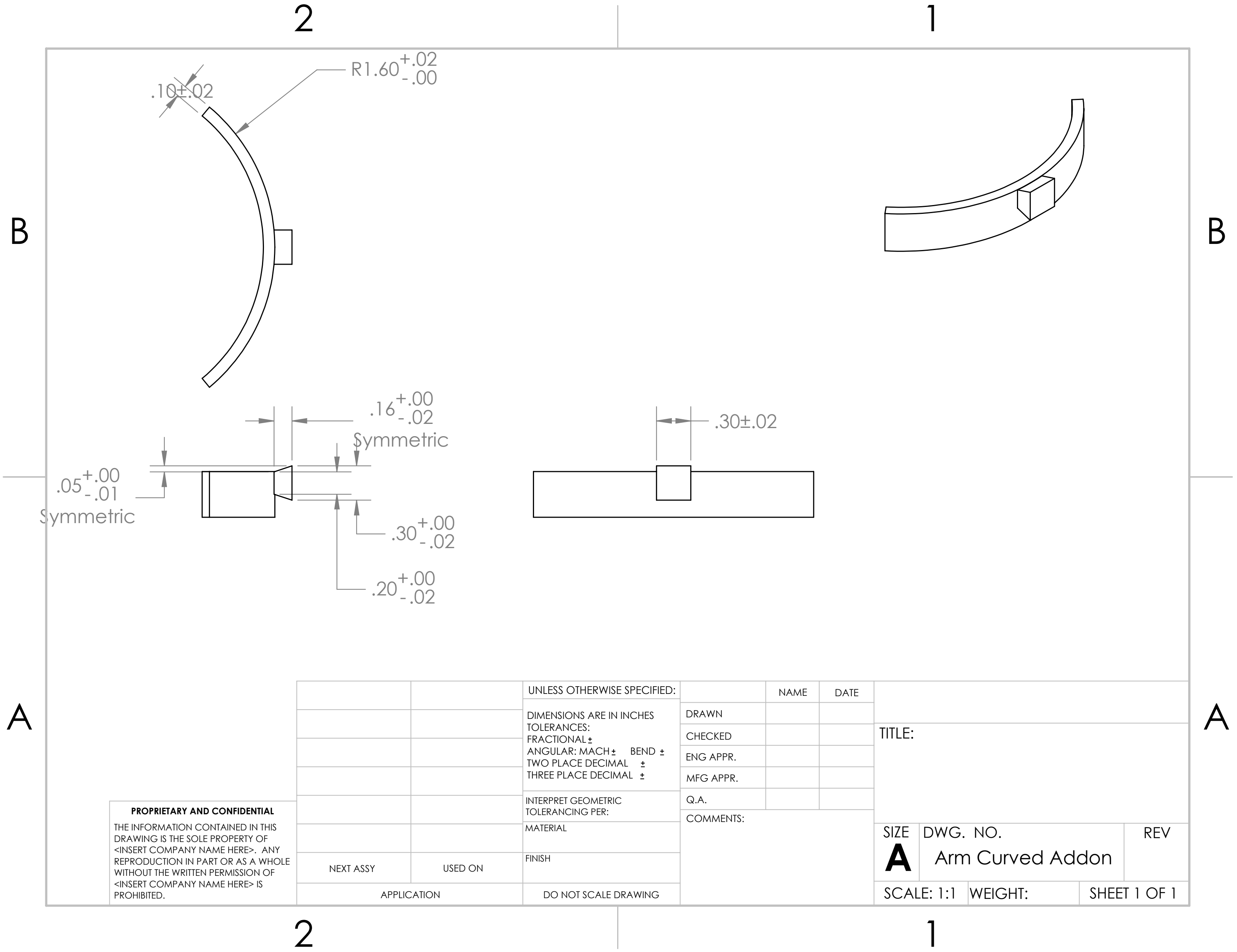
SCALE: 1:1 WEIGHT: SHEET 1 OF 1

NEXT ASSY | USED ON

APPLICATION

PROPRIETARY AND CONFIDENTIAL

2 1



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

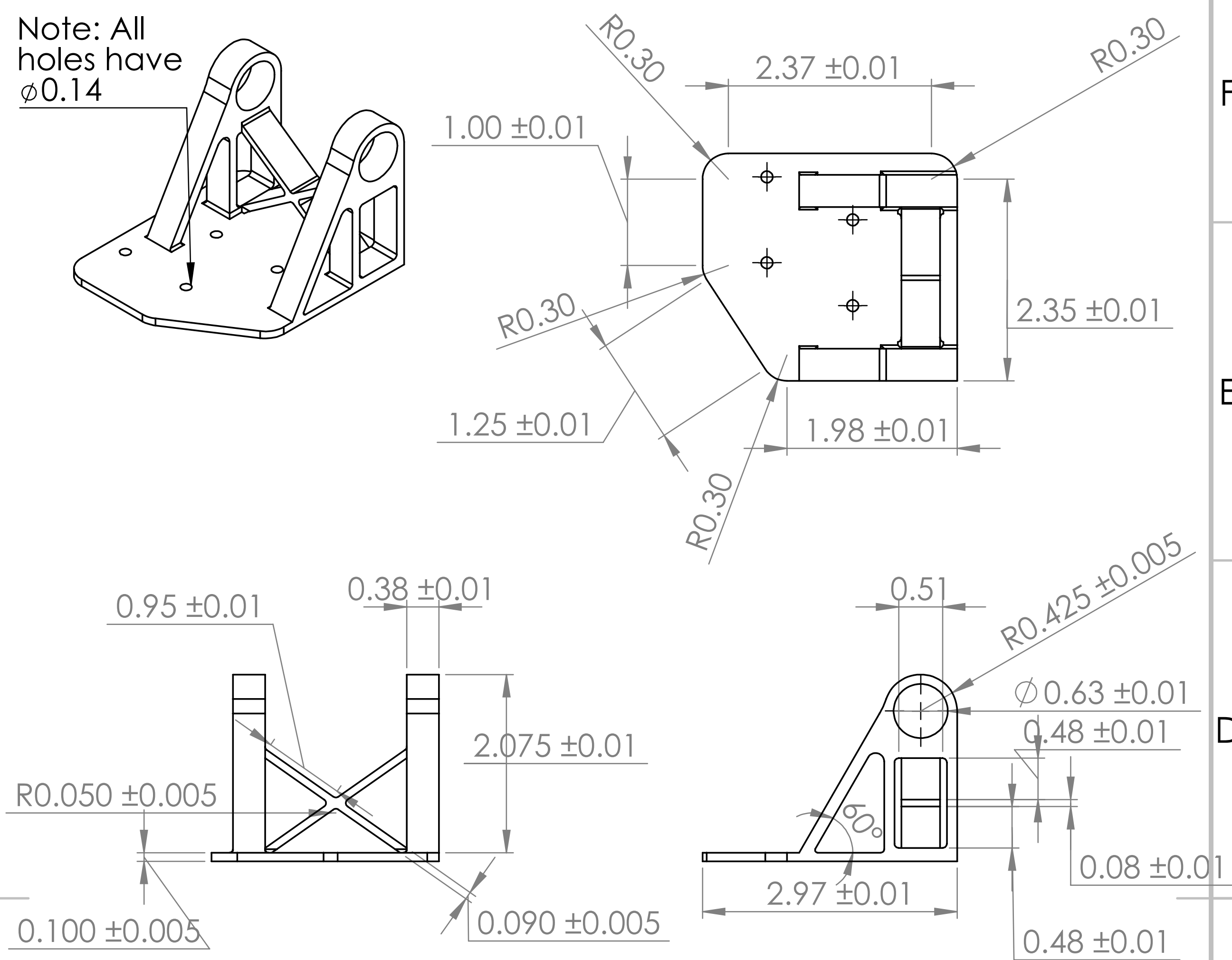
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

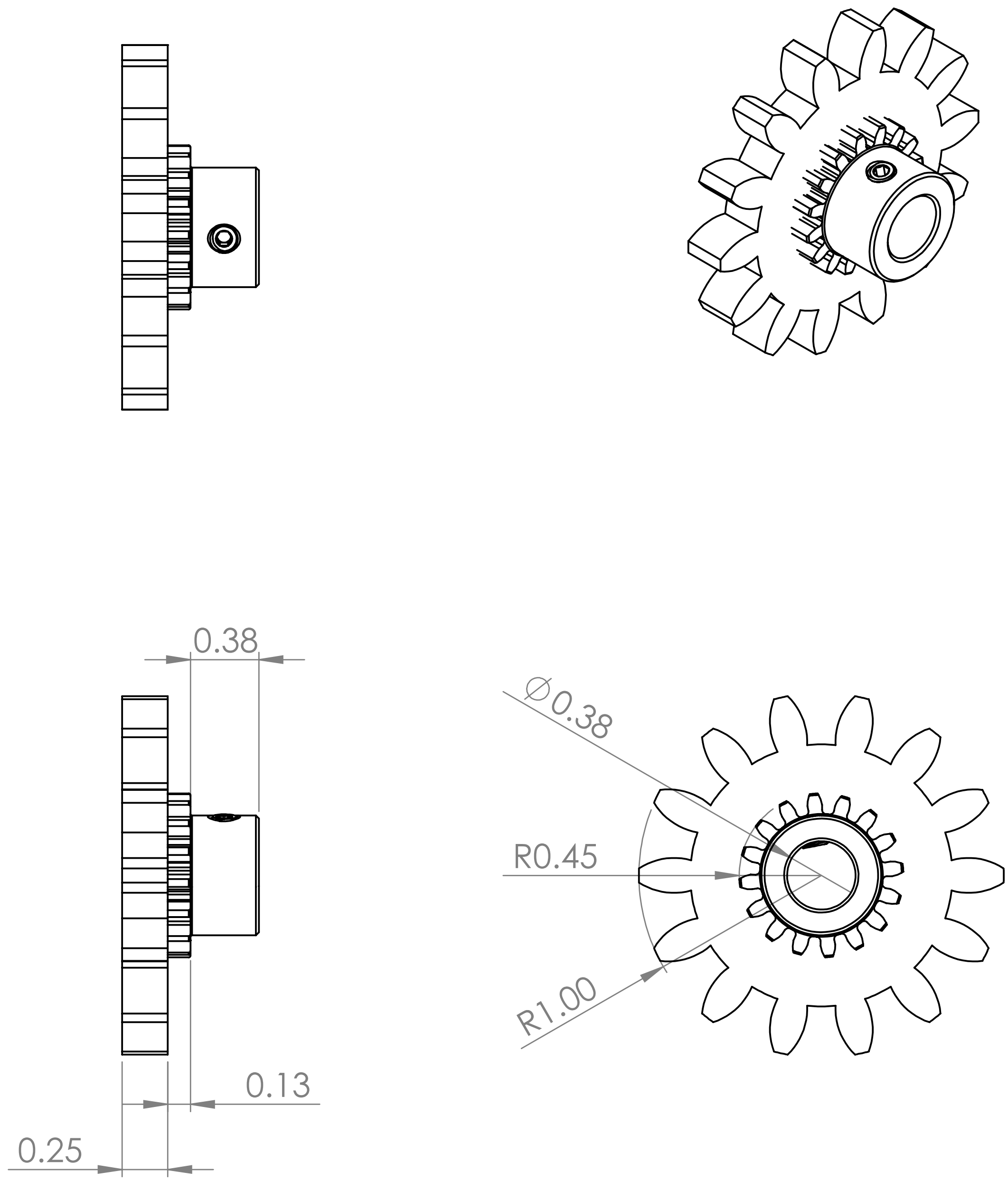
TITLE:

SIZE	DWG. NO.	REV
A	Arm Curved Addon	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. base_plate_v3	A4
				WEIGHT:	SCALE:1:2	SHEET 1 OF 1

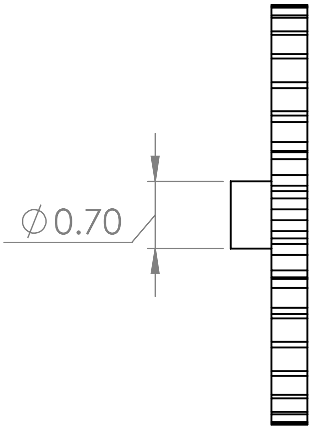


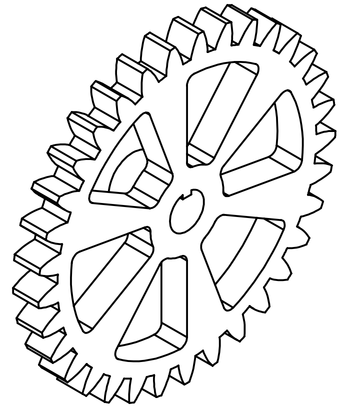
NOTE:
INSIDE GEAR
GOES THRU
OUTSIDE GEAR

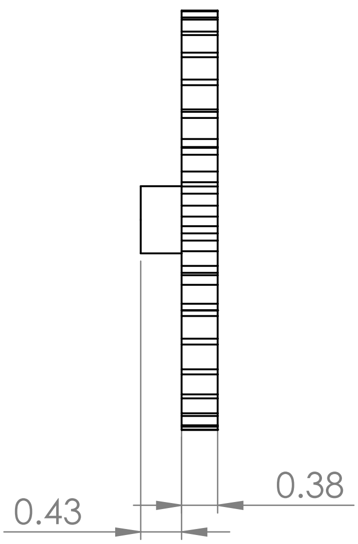
NEXT ASSY	USED ON	DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		NAME / DATE
APPLICATION		MATERIAL	DRAWN	
		FINISH	CHECKED	
		DO NOT SCALE DRAWING	ENG APPR.	
			MFG APPR.	
			Q.A.	
			COMMENTS:	

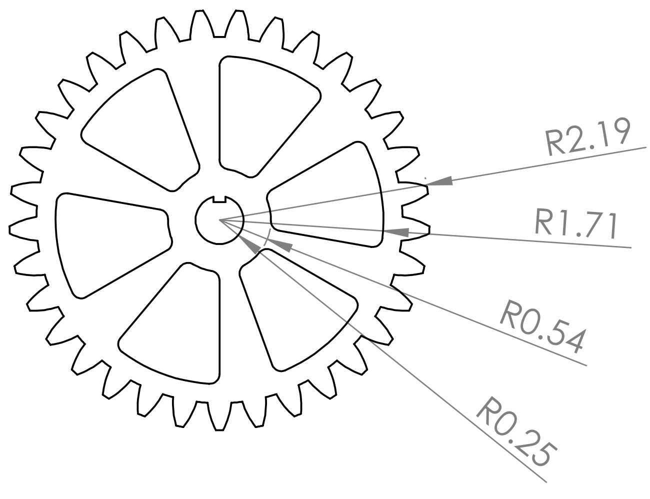
SIZE A | DWG. NO. driving gear | REV.

SCALE:1:1 | WEIGHT: | SHEET 1 OF 1









NEXT ASSY | USED ON

APPLICATION

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SIZE A | DWG. NO. Spored Big Spur Gear | REV.

SCALE:1:2 | WEIGHT: | SHEET 1 OF 1

9 Supporting Notes

a) Peak Force Calculations

Energy Balance:

$$\frac{1}{2}mv^2 = mgh$$
$$v_{max} = \sqrt{2gh} \textit{ (at the bottom of the arc)}$$

centripetal acceleration:

$$a = \frac{mv^2}{r}$$
$$a = 2mg \textit{ (since r=h)}$$

Force Balance:

$$\Sigma_y : 2m^2g = -mg + F_p$$
$$F_p = 2m^2g + mg$$
$$\boxed{F_p = 21.41N}$$

b) Factor of Safety Calculations

Grip Factor of Safety

Let D_r be the ratio of the diameters of the gears. $D_r = (D_{big}/D_{driving}) = 3$

$$FoS_{grip} = \frac{M_{transfer}}{M_{required}}$$
$$FoS_{grip} = \frac{M_{transfer}}{F_{peak}L_{arm}}$$
$$FoS_{grip} = \frac{M_{driving}D_r}{F_{peak}L_{arm}}$$
$$FoS_{grip} = \frac{(1.3Nm)(3)}{(21.405N)(.117m)}$$
$$\boxed{FoS_{grip} = 1.56}$$

Strength Factor of Safety

We calculate the max stress with Lewis Bending Stress:

$$\sigma_{bending} = \frac{W_tP_d}{FY}$$

W_t = *Tangential Load*
P_d = *Diametrical Pitch*
F = *Face Width*
Y = *Lewis Form Factor*

$$\sigma_{bending} = \frac{(21.405)(8)}{(.375)(.35)}$$

$$\sigma_{bending} = 1304$$

$$FoS_{strength} = \frac{S_y}{\sigma_{max}}$$

$$FoS_{strength} = \frac{1500}{\sigma_{bending}}$$

$$FoS_{strength} = \frac{1500}{1304}$$

$$\boxed{FoS_{strength} = 1.15}$$

c) Iterations

Prototype 1

The initial prototype used for the first round of testing failed at the gear teeth and moving arm due to shear force. The acrylic used to cut the transfer gear was too thin, causing teeth to snap when the arm was rotated past 180 degrees during nominal testing. The gripper was unable to hold onto the bottle due to the low friction between the 3D printed arms and bottle surface. Additionally, the carbon steel shaft made the gripper very heavy.

Figure 17: Initial gripper prototype used for first design review.

Prototype 2

For our second prototype, we changed several parameters in order to account for the incorrect dimensions initially given in the handout. The brackets on the base plate were lowered in order to bring the moving arm closer to the bottle and a truss support was added to resist axial forces on the brackets. Unnecessary material was removed from the base plate in order to reduce mass and create a more ergonomic design. Additionally, both the static and moving arms were lengthened and increased in thickness to account for the larger moment. A larger gripping surface and non-slip material was added to the ends of the arms in order to reduce displacement during dynamic testing. Both the transfer gear and driving gear were 3D printed using a larger factor of safety. We used an aluminum shaft instead of carbon steel in order to reduce mass. This prototype successfully passed both nominal and dynamic testing, but weighed around 220 grams due to the large transfer gear.

Figure 18: Second prototype of the gripper.

Final Design

For the final prototype, the aluminum shaft was replaced with a 3D-printed PLA shaft in order to reduce weight further. In addition, the transfer gear was now spoked instead of completely solid, in order to cut unnecessary material in the gear. This design successfully passed both nominal and dynamic testing, and weighed around 153 grams, about 70 grams lighter than prototype 2.

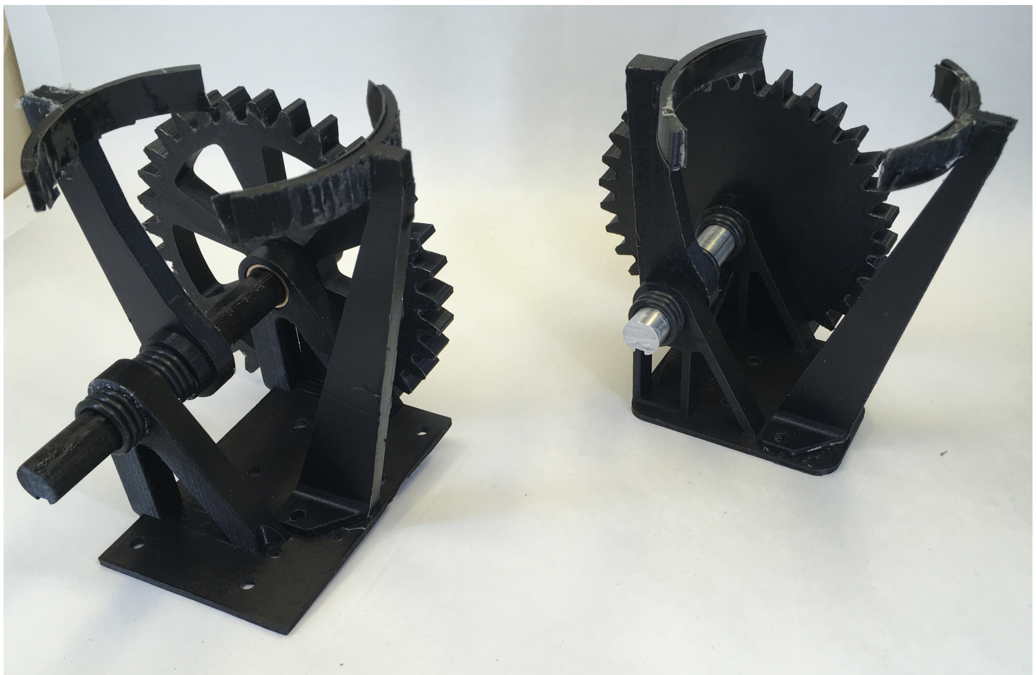


Figure 19: Final design (left) and prototype 2 (right).