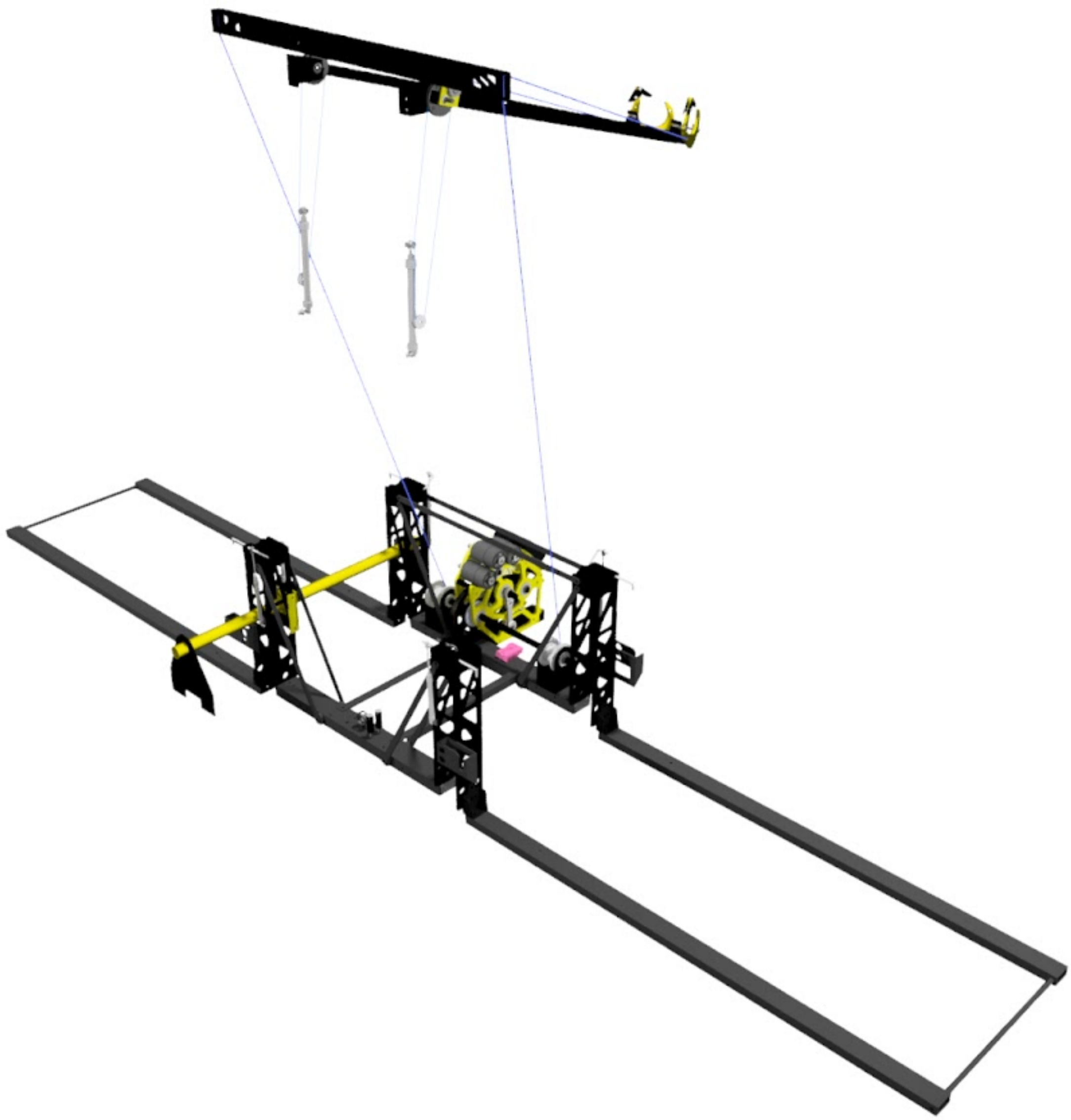
Arthur Zhang **Winter 2018**

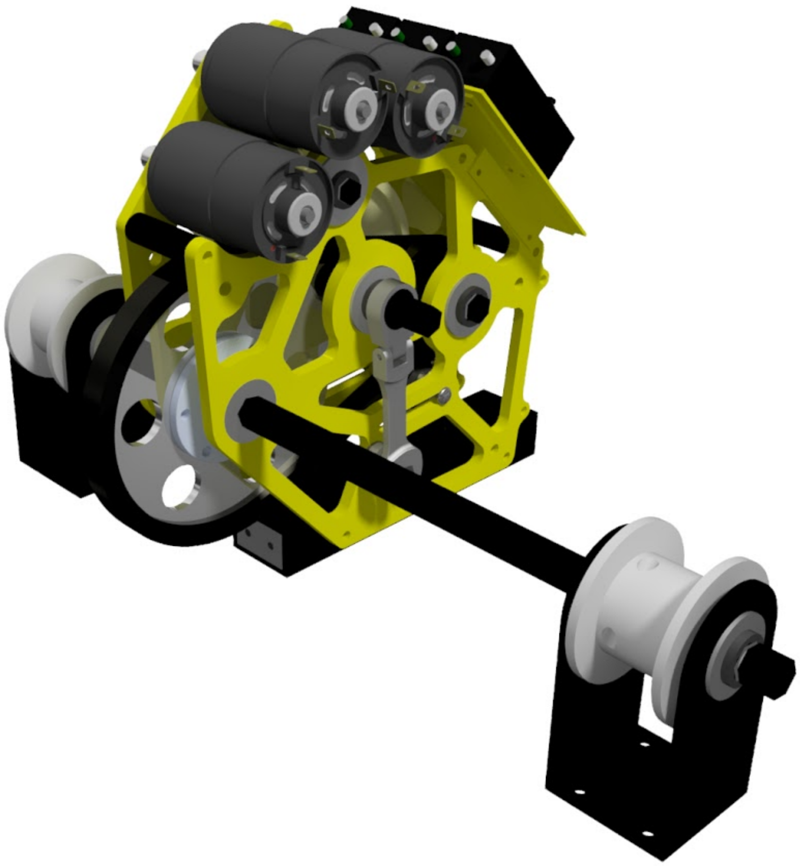
FIRST Robotics Climber System

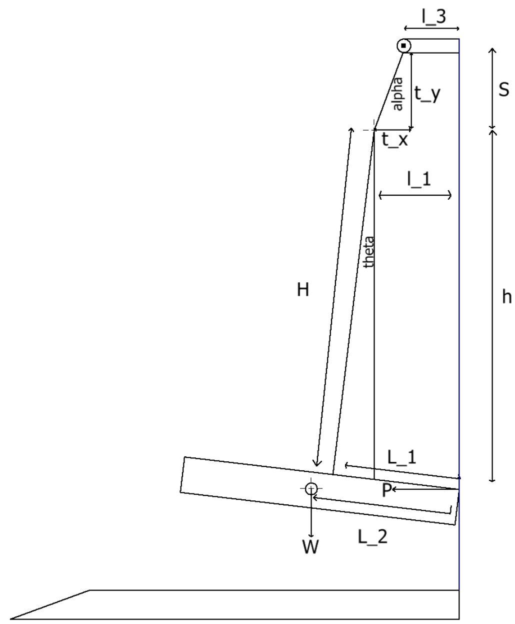


In six weeks, I led a team of five students to design, manufacture, and test a climber system from scratch using Solidworks and Autodesk Inventor for the 2018 FIRST robotics competition. I primarily designed the climbing gearbox and performed calculations for entire system while overseeing the development of the other mechanical components. By efficiently compromising with others to decide on the design and efficiently testing and redesigning each part of this system, we were able to ship a fully functional climbing system in just six weeks. This is a highly adjustable system capable of lifting two other 150 lb robots, one on either side, in three seconds or lifting our own robot in a second. It is comprised of three distinct mechanical assemblies: the gearbox, swing arm, and lifting forks.

Note: I included the original excel spreadsheets used for calculations under the Robotics Calculations Spreadsheets folder. The MotorCalculations.xlsx is for the Gearbox and LiftAnalysis.xlsx is for the Lifting Forks and tilt analysis.

Gearbox/Winch System





System of equations for calculating optimal eyehook position

$$F(\theta) = W\,L_2 - T_y\left(L_1 - Ht_y\right) - T_x(H + L_1\tan(\theta))$$

$$T_y = W + \mu T_x$$

$$T_x = \frac{\mathrm{W}\tan(\alpha)}{1 - \mu\tan(\alpha)}$$

$$\tan(\alpha) = l_1 - L_3$$

$$l_1 = (L_1 - H\tan(\theta)) \times \cos(\theta)$$

Robot Tilt Calculations

I simulated all possible weight distribution scenarios and determined that we could tolerate up to a 50 lb weight difference between two alliance robots before tipping. Through testing, I found that it is beneficial to route the climbing rope through an eye hook. Then, I derived a system of equations to balance the torque of the robot system during the climb. After setting up an excel spreadsheet with my system of equations, I tested all possible eye hook locations to minimize the range of angles my robot would tilt during the climbing process.

Material Strength Calculations

Unadjusted Tooth Force		
4140 Steel		
Tooth Force at 10,000 psi stress	136.72	lb
4140 Steel safe limit	20066.667	psi
Steel:	2.0067	ul
Steel Tooth Force without Y' factor	274.349	lb
Y' Tooth Factor (larger gear)	0.364	lb
Max Tooth Force with Y' factor	99.86	lb
7075 T-6 Aluminum for (20dp 24 or smaller)		
Tooth Force at 10,000 psi stress	237.50	lb
7075 T-6 Aluminum safe limit	24333.33	psi
Aluminum:	2.43	ul
Aluminum Tooth Force without Y' factor	577.92	lb
Y' Tooth Factor (smaller gear)	0.27	lb
Max Tooth Force with Y' factor	156.04	lb
7075 T-6 Aluminum for (20dp 30T or larger)		
Tooth Force at 10,000 psi stress	187.50	lb
7075 T-6 Aluminum safe limit	24333.33	psi
Aluminum:	2.43	ul
Aluminum Tooth Force without Y' factor	456.25	lb
Y' Tooth Factor (smaller gear)	0.31	lb
Max Tooth Force with Y' factor	143.26	lb

Max Torque for Hex Shafts			
7075 T-6 Aluminum Hardness, Rockwell B	87	lb/in^2	
7076 T-6 Aluminum Tensile Strength	83000	psi	
7076 T-6 Aluminum Yield Strength	73000	psi	
Safety Factor	2	ul	
Shaft Diameter	0.5	in	
Torque on shaft	413.44	lb-in	
Radius from Center to Edge	0.285	in	Measured from CAD model
Force on Hex Shaft	1450.66	lb	
Number of Edges Engaged	6	ul	
Force on Each Edge	241.78	lb	
Width of Each Edge Engaged	0.02	in	Measured from CAD model
Width of Versahub for Plate Sprocket	0.5	in	Taken from VexPro Drawings
Pressure on each edge	**24177.63**	psi	
7076 Aluminum Yield Strength with safety	**36500**	psi	
	33.76%	cushion	

$$P = F/A$$
$$\Gamma = F \times r$$

Calculations ensuring hex shaft durability on the climber gearbox

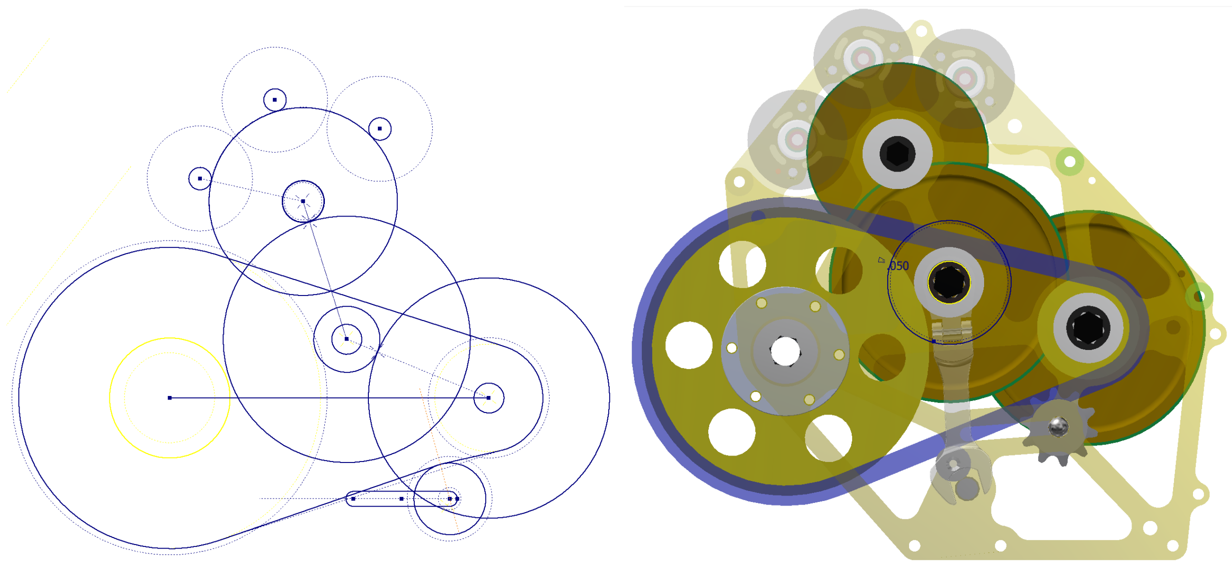
Using Y’ tooth form factor and gear dimensions, I found the max allowable force of each gear I planned on using. This depended on the both material for the gear and the size of the gear. To avoid breaking gear teeth on the output stage of the gearbox, where the force on the gear teeth was the largest, I used #35 chain on the output stage for its strength. I also wanted to make sure that I wasn’t at risk of stripping the hex shafts used, so I calculated maximum torque each shaft would experience and the maximum torque each hex shaft could tolerate.

Gearbox Calculations

Possible Free Speeds			Note: limited by the torque the second stage hex shaft can take				
Selected		18	20	22	24	1/2	
Larger gear		84	82	80	78	1/2	
3rd ratio		4.67	4.10	3.64	3.25		
Selected		14	16	18	30	3/8	
Larger gear		82	80	78	66	1/2	
2nd ratio		5.86	5.00	4.33	2.20		
Possible Reductions (ul)							
		4.67	**4.10**	**3.64**	**3.25**		
	5.86	27.33	24.01	21.30	19.04		Slow Climb
	5.00	23.33	20.50	18.18	16.25		Target Climb
	4.33	20.22	17.77	15.76	14.08		Fast Single Climb
	2.20	10.27	9.02	8.00	7.15		
Possible Climb Speeds (ft/sec)							
		0.24	0.27	0.31	0.34		
		0.28	0.32	0.36	0.40		
		0.32	0.37	0.42	0.47		
		0.64	0.73	0.82	0.92		
Target Climb Speed		0.30	ft/s				
Selecting Viable Gear Ratios							
Reduction		637.78	496.97	166.83	ul		
Rope Force w/ Gear Reduction		1079.70	841.32	282.43	lb		
Output Power		259.41	259.41	259.41	ft-lb/s		
Output Power		351.72	351.72	351.72	W		
Force after Gear Loss		877.71	683.93	229.60	lb		

Adjusting the gear ratios automatically adjusts all further calculations

I designed the gearbox to be highly adjustable, allowing me to switch the gear reduction of the gearbox from 640:1, producing 878 lbs of force, to 167:1, producing 230 lbs of force. This allows me to optimize the climb time before matches depending on the weight lifted.



I used CAD to design the gearbox as compactly as possible and check for interferences.

Motors - Combined			
Num of Motors	3	ul	
System Resistance			
Battery Resistance (old experiments d.g)			single moto
Battery at 300A	6	V	
Battery Resistance	0.02	ohm	
multiplied by number of motors	0.060	ul	this is the effective resistance per motor branch
additional resistance (wire + esc)	0.010	ohm	estimated
Total System Resistance per Branch	0.070	ohm	
Motor Resistance			
R = 12 / I_s	0.090	ohm	
Effective Total Motor Resistance	0.160	ohm	
Stall Torque and Current Reduction Factor	1.782	ul	
Stall Torque of one motor	100.54	oz-in	
Stall Torque of all motors	301.62	oz-in	
Reduced Stall Torque from System Resistance	**169.29**	oz-in	
Reduced Stall Torque from System Resistance	**1.20**	N-m	
Stall Current of one motor	134.00	A	
Stall Current of all motors	402.00	A	
Reduced Stall Current from System Resistance	**225.63**	A	
Maximum possible output power	**586.19**	W	
Quick check at 75% speed we develop 3/4 of P_mc	439.64	W	Looks promising

Stall current and stall torque are reduced by system resistance

$$\zeta = \frac{R_m + R_{sys}}{R_m}$$

where R_{sys} is the effective branch resistance of the battery and shared wire resistance

Max Power occurs at point of half torque and half speed

$$P\_max = \frac{\Gamma_s * \omega_f}{4}$$

$$P_{max} = \frac{\Gamma_s \, 2 \, \pi \, rpm}{4 \times 60}$$

Gearbox plates, machined on our team's CNC using CAM written with HSM Express (left) System resistances for each 775pro motor, which influences motor operating efficiency (right)

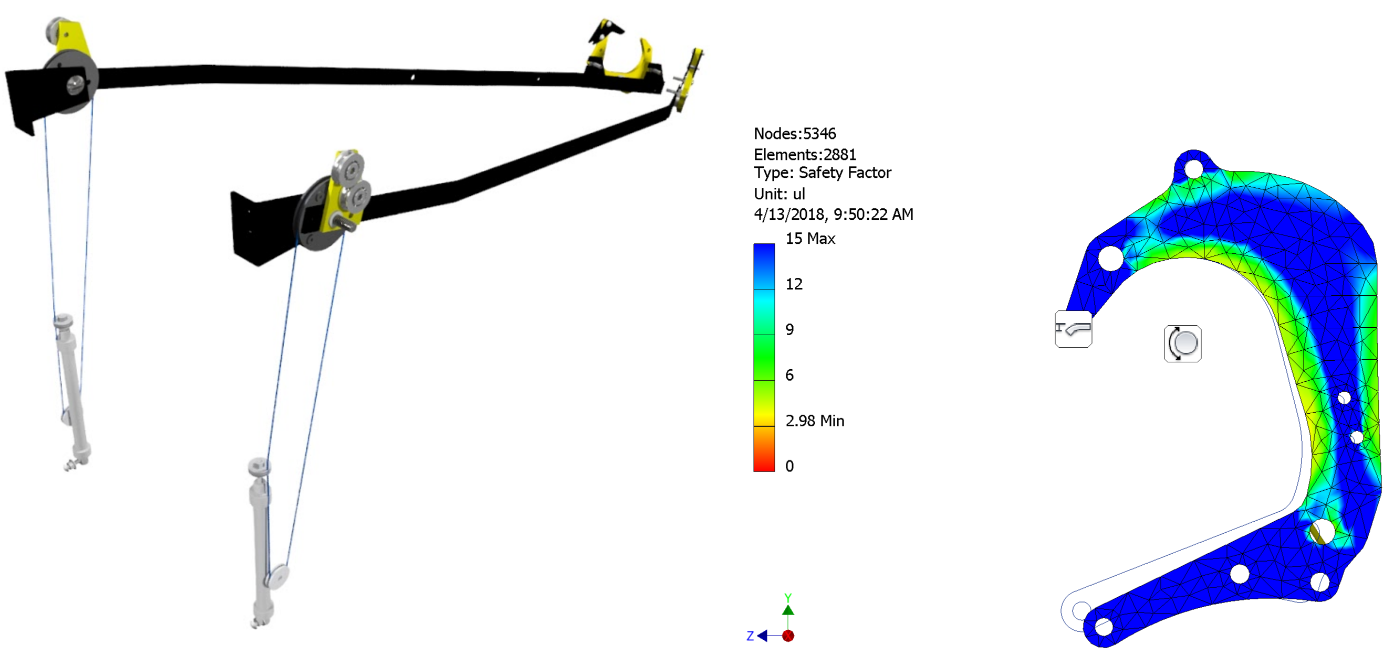
In addition, I considered the system resistance, which significantly reduces the maximum stall torque and current of the 775pro motors used. By considering these factors, I accurately determined if the maximum power output from my gearbox is enough to meet my lifting requirements.

Eyehook Loss Calculations		
Angle Between Eyehook and Rung (to horizontal)	**65.78**	deg
Rope Pull Force Required	483.56	lb
Wrap Angle	**27.47**	deg
Cof between Aluminum & Amsteel	**0.20**	ul
Ratio of Extra Force	1.10	ul
Extra Force Required	48.66	lb
Bumper Tower Friction Loss Calculations		
Cof between Polycarb and Sail Cloth	**0.23**	ul
Normal Force on Tower from Bumper	26.83	lb
Friction Loss to Tower	6.17	lb

Using the capstan equation, I found exactly how much extra force we needed.

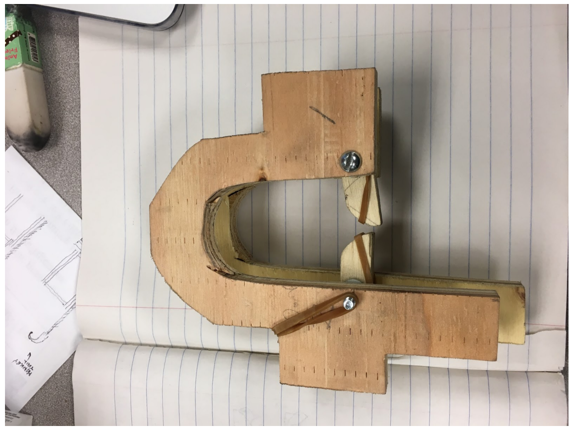
To calculate exactly how much force was needed to lift three robots, I determined the force loss to the eye hook using the capstan equation, friction loss from our bumpers against the tower, and force loss due to the angle we pulling from. Combining these factors, I determined that the maximum force our gearbox should be capable of pulling with is 550 lbs.

Swing Arm Hook Deployment System



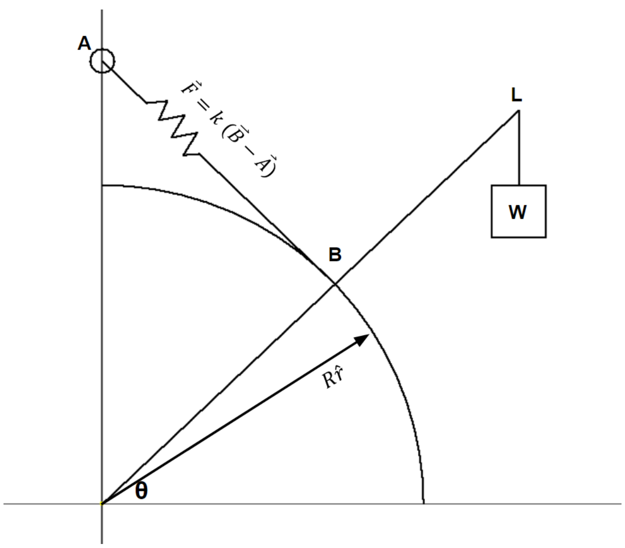
FEA stress analysis for optimizing the swing arm hook's design.

I worked with two freshmen to design a swing arm connected that deploys hooks for climbing. By overseeing my team's design work and revising it as needed, I was able to dedicate more time towards optimizing the hook design and optimizing how to raise the arm with the least amount of force. The final iteration of the design consists of a perfectly counterbalanced arm powered by a pneumatic cylinder attached to a pulley.



Wooden Hook Latch Prototype V1

Using Autodesk Inventor's stress analysis feature, I optimized the hook design to withstand 700-800 lbf of load. This is roughly three times stronger than needed. To ensure the hook never swings off, I designed a one way gate latch mechanism that allows the rung to enter the hook and act as a hardstop to keep the hook from coming off the bar. While designing this hardstop, I collaborated with other students to design several hook prototypes, like the one above.



$$\vec{A} = H\hat{y}$$
$$\vec{B} = \mathrm{R}\hat{r}$$
$$T_L = L\hat{r} \times \mathrm{W}\hat{y}$$
$$= LW\ (\hat{r}\ x\ \hat{y})$$
$$= LW \sin\theta$$
$$F_S = k\ (\vec{B}\ -\ \vec{A})$$
$$T_S = R\hat{r}\ x\ k(\vec{B}\ -\ \vec{A})$$
$$= RK\ \hat{r}\ (R\hat{r}\ \ - H\hat{y})$$
$$= -RKH\ (\hat{r} \times \hat{y})$$
$$= -RKH \sin\theta$$

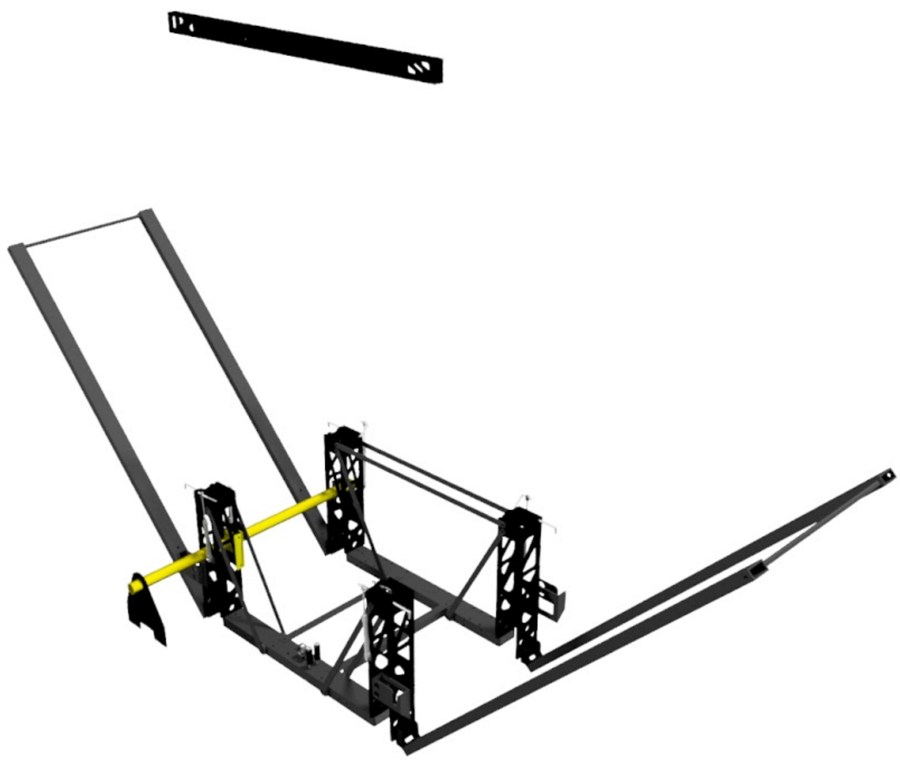
When Force of Spring equals torque of arm:

$$RKH = LW$$
$$HK = \frac{L}{R}W$$

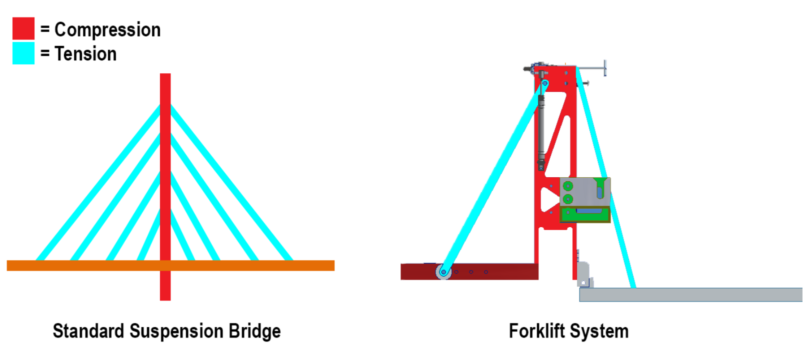
The weight is perfectly balanced at all angles from -90° to +90°,
provided HK = W ··· L/R!

To counterbalance the arm, I derived a formula for calculating the torque of the arms along specific paths and then stretched a piece of surgical tubing to act as a spring, effectively counterbalancing the arm. When done correctly the torque provided by surgical tubing equals the torque of the arm at all positions and reduces the power required to lift the arm.

Fork System



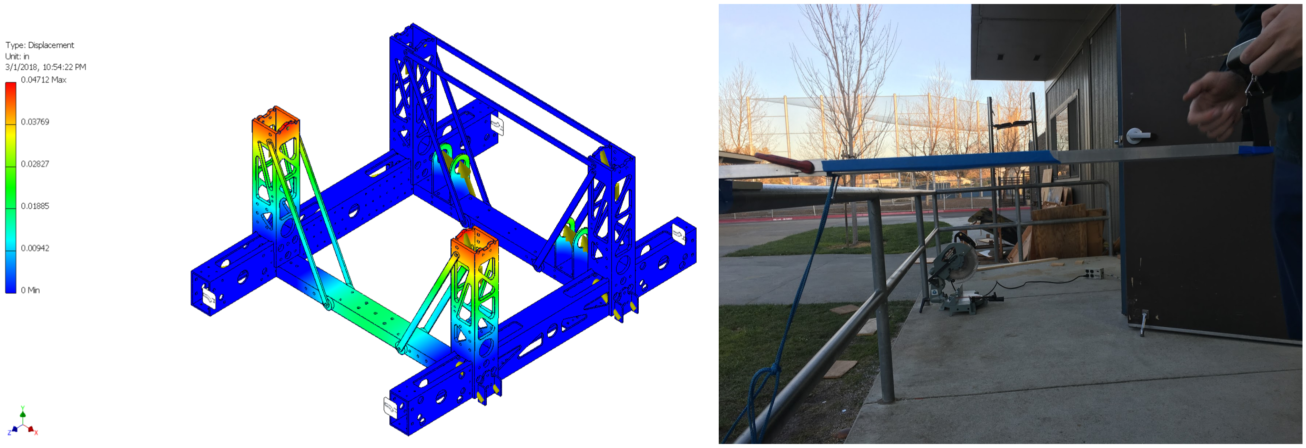
After several discussions on the optimal design to lift two other robots, my team and I settled on a system that models a suspension bridge. The forks consists of a set of forklifts on either side and a “finger” that stabilizes the robot laterally, which extends using pneumatic tubing and springs.



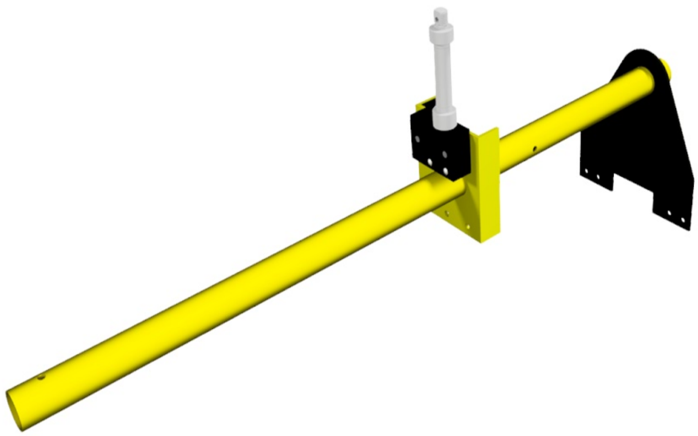
Comparison between the forks and a suspension bridge

Material Strength Calculation

The materials required to withstand the forces on this system needed to be very rigid with a high modulus of elasticity. After considering different metal options, I chose to use 6061 alloy aluminum for its superior strength and relatively low cost. Simulations demonstrated safety margin of 1.75 and in real life testing, the forks survived a load more than double the expected worst-case load.

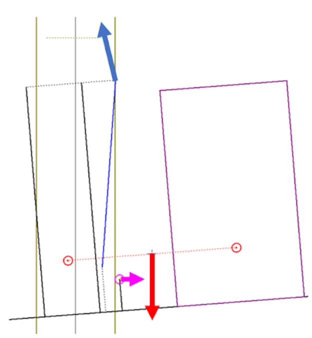


FEA stress analysis on the robot's chassis (left), real life testing to determine max bending of forks before failure (right)



The "finger" mechanism, which wedges between a protrusion on the climbing wall to resist lateral torque.

The final part of the climbing assembly is the "finger" mechanism. When our robot only lifts one other robot, it creates an imbalance of torque laterally, causing the entire system to tip. To counteract this, I designed this mechanism, which releases an aluminum pipe connected a stretched piece of surgical tubing using a simply trigger actuated by a pneumatic cylinder. The aluminum pipe acts as a hardstop to prevent other robots from slipping off our own during the climb, regardless of the weight difference.



During the design process, I constrained sketches in Inventor to simulate a side climb and make sure the robots were not tilting too far.