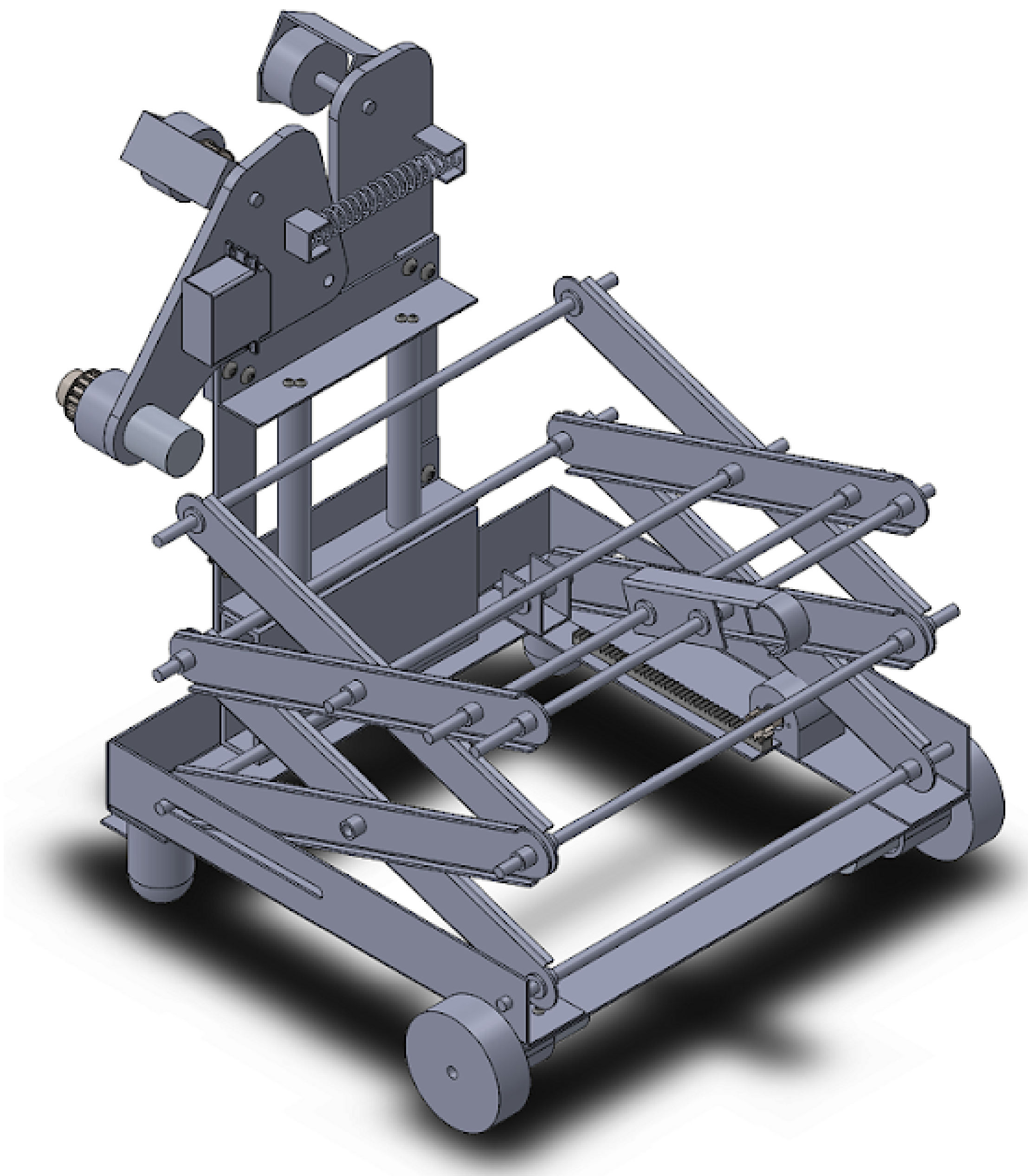
2.007 Final Design Report
Jenny XJ-9000



Jessica Horowitz

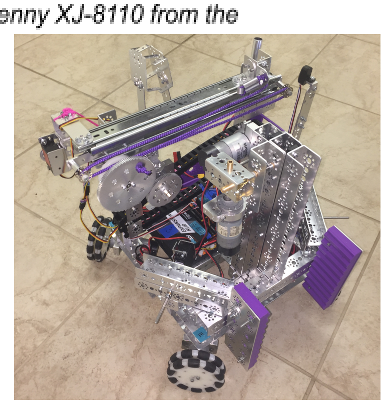
Introduction

As a FIRST robotics alumni, I was touched to hear that the theme of the competition would commemorate Woodie Flowers. This robot is dedicated to my high school FTC robotics team, 8110 (WiSE), who inspired me to pursue engineering and gave me the confidence to even apply to MIT. We named one of our robots “Jenny XJ-8110” in reference to Jenny XJ-9 from the beloved cartoon My Life as a Teenage Robot (because spending so much time in shop began to make us feel like teenage robots)! We never scored very high in competitions and we lacked resources many other teams had, but we had a lot of passion, supported each other, and learned a lot about teamwork and problem solving. In the midst of Covid-19 and things not going according to plan, I still managed to get a lot out of 2.007. Jenny XJ-9000 is a continuation of the philosophy that what matters most is how you learn and grow from a situation and the people around you. She is the “legacy” of Jenny XJ-8110.

My plan of attack underwent much change throughout the semester. After weighing the pros and cons of a ball collection method, spinning wheel and/or lifting the beaver, my first plan was to spin the wheel and lift the beaver because of the higher point-earning potential. As I continued on to design my beaver-scoring MCM, I realized that both a beaver lift and flower spinner would be too challenging, and that I should instead put my focus into perfecting one objective that I can do very well before tackling other objectives, which should be more simple and supplementary. I found the beaver challenge much more interesting to solve, and luckily, since many other students were going after the flower spinner, I would not have to worry about competing with them or getting there first. My MCM changed from a scissor lift to a component that would detach from the robot entirely and climb the column. I then decided to apply my scissor lift design, which I had begun fabricating before the pandemic, to a multiplier pull-up mechanism. In this report, I will refer to the beaver lifter as the “MCM” and the scissor lift that hooks onto the multiplier as the “Multiplier Pull-Up.”

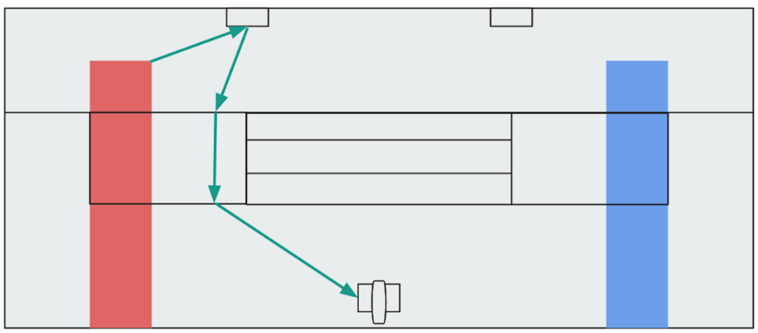
...My robotics team and I in high school wearing safety goggles and having a blast

The very chaotic Jenny XJ-8110 from the past...



Strategy

My strategy is to lift the beaver to the third level and then pull the multiplier to x2.0 during the driver control period. I expect alignment with the MCM to require precision that I am not confident in achieving autonomously. After aligning with the beaver, an ultrasonic proximity sensor on the MCM controlled by an Arduino will be triggered, allow a brief delay for final adjustments, and autonomously release the MCM from the robot, where it will autonomously scale the column. Multitasking in this way will save time, because while this is happening, I will drive the rest of the robot down the ramp, hook onto the multiplier ring, and pull up until I have reached x2.0. At this point, my strategy will be complete.



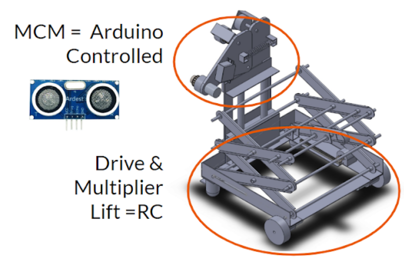


Figure 1 & 2: Planned route of robot on game board (left) and robot control diagram (right).

I chose this strategy because it mixes a challenging, non-competitive task that scores many points (beaver lift) with a simpler but competitive task (multiplier). With the beaver lift, I am guaranteed to score points, and I can still score some amount of points if I don't reach my goal of hitting the third level.

The drive velocity is calculated as:

$$P_{in} = P_{out}$$
$$\frac{Fd}{t} = \tau_{in}\omega_{in}$$
$$t = \frac{\mu F_{N2} d}{\tau_{in}\omega_{in}} = \frac{(1)(14.7N)}{(7\ rad/s)(0.56\ Nm)} d$$
$$v = \frac{d}{t} = 0.26\ m/s$$

At 0.26 m/s, it takes 3.4 sec to travel from the upper starting box to the beaver (approximately 3 feet). The time for the MCM to raise the beaver to the third level is calculated as follows:

$$P_{in} = P_{out}$$
$$\frac{Fd}{t} = \tau_{in}\omega_{in}$$
$$t = \frac{(25N)(1.4m)}{(0.475\ Nm)(1.76\ rad/s)} = 41.9\ sec$$

It then takes 10.9 sec to travel from the beaver (3 feet), down the ramp (30 inches), and to the multiplier (4 feet). Allow 5 seconds to lift the Multiplier Pull-Up (no load) and align with the hook. The time it takes for the Multiplier Pull-Up to retract such that it hits x2.0 follows the same equation:

$$\frac{Fd}{t} = \tau_{in}\omega_{in}$$

$$t = \frac{(36.43N)(0.27m)}{(0.46\ Nm)(4.42\ rad/s)} = 6.63\ sec$$

Objective	Estimated Points	Time (sec)	Total Time (sec)
Lift Beaver to 3rd Level	90	3.4 +7 + 41.9 = 52.3	52.3
Pull Down Multiplier to x2.0	90 x 2 = 180	10.9 + 5 + 6.63 = 22.53 (happening concurrently)	

Figure 3: Summary of competition time breakdown.

Design

There are 3 main components to the design: the beaver lifter (MCM), drive, and Multiplier Pull-Up. The MCM is controlled by an Arduino powered by a 7.4 V 850 mAH LiPo battery. It is spring loaded with a stored 1.29 J potential. Another of the same battery powers the drive train and Multiplier-Pull up on the chassis of the robot, which is controlled by an RC receiver. The total energy budget is 12.58 kJ, which is within the 30 kJ stored energy limit.

Beaver Lifter (MCM)

The beaver lifter will operate with two traction wheels that will grasp onto the aluminum extrusion track that carries that beaver lift on the game board via a spring loaded mechanism. The wheels are composed of delrin and covered with rubber for friction. The left wheel is driven by a 98:1 LDO motor via a pulley. They are mounted on two acrylic pieces on a hinge. An extension spring will be held in tension by a pin going through the acrylic. The pin is released by a Spring RC servo with a control rod attached to the servo horn. Electronics are powered by an Arduino with a 5V source.

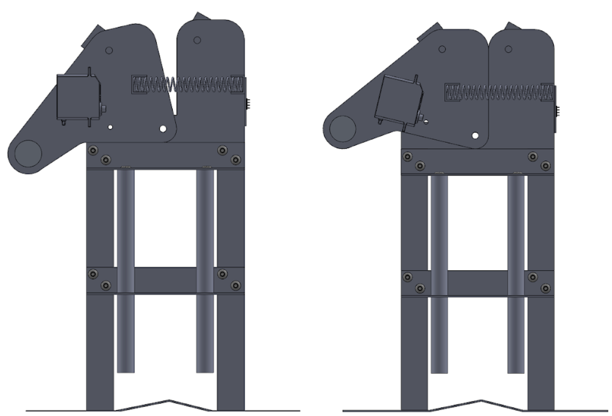
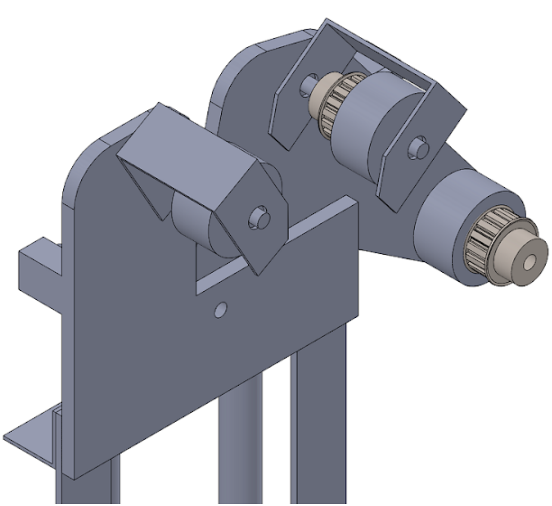


Figure 4: MCM when open and closed.



The body of the MCM is composed of sheet metal. Two ¾” inch delrin rods engage with holes in a box extrusion piece that is mounted to the chassis, which disengage smoothly for deployment. The bottom ledge is bent into a contour to support the bottom of the beaver.

I selected the 98:1 LDO motor for the 1.5” diameter traction wheel to raise 25N 56” (third level) by finding the required torque $\tau_{in} = rF_T = 0.475\ Nm$. Comparing the stall torques for available LDO motors at 5V, I found the 98:1 LDO motor operates at maximum $\tau_{max\ power} = \frac{\tau_{stall}}{2} = 0.354\ Nm$ which is the closest to the 0.475 Nm required torque. I checked that the MCM would be able to raise the beaver in ample time:

$$P_{in} = P_{out}$$
$$\frac{F_T d}{t} = \tau_{in}\omega_{in}$$
$$t = \frac{(25N)(1.4m)}{(0.475\ Nm)(1.76\ rad/s)} = 41.9\ sec$$

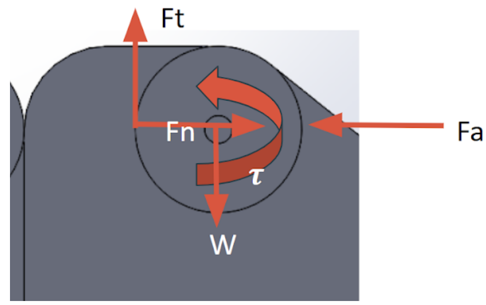


Figure 5: Free body diagram of traction wheel.

In order to select a suitable spring, I found that the required gripping force is $F_{grip} \geq \frac{F_T}{\mu}$ =25N. Choosing a spring of 1000 N/m that is stretched 2” from equilibrium length yields a spring force of $F_s = kx = (1000\ N/m)(0.05\ m) = 50\ N$. Summing the torques based on the free body diagram in Figure 6 we get:

$$F_{spring}r = F_{grip}L + 0.033$$
$$r = \frac{(25N)(3.75")+0.033}{50N} = 1.89"$$

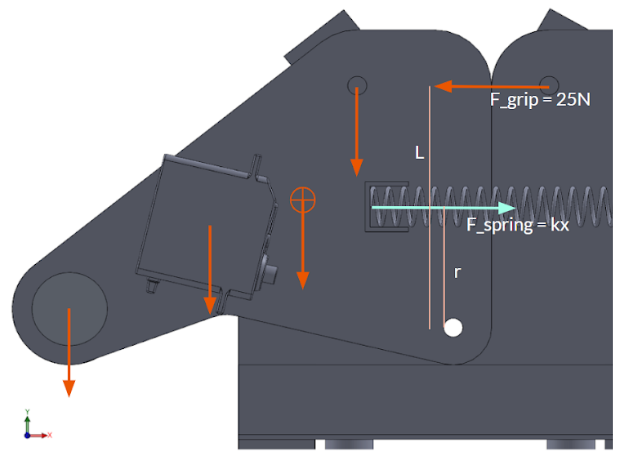


Figure 6: Forces and moment arms considered to calculate spring placement.

Therefore, a moment arm of at least 1.89” between the spring and the pivot point will allow the MCM to maintain enough traction with the beam on the gameboard.

Another concern was such a large horizontal force causing the bearings of the traction wheels to bend. In response, U-bracket supports were added. The deflection of the bearing was approximated as simply supported and calculated:

$$L_1 = 1.67" = 0.042m$$
$$M_{max} = \frac{-TL_1}{4} = 0.26Nm$$
$$\Delta = \frac{TL^3}{48EI} = 1.66 * 10^{-9}\ m$$

This amount of deflection is insignificant.

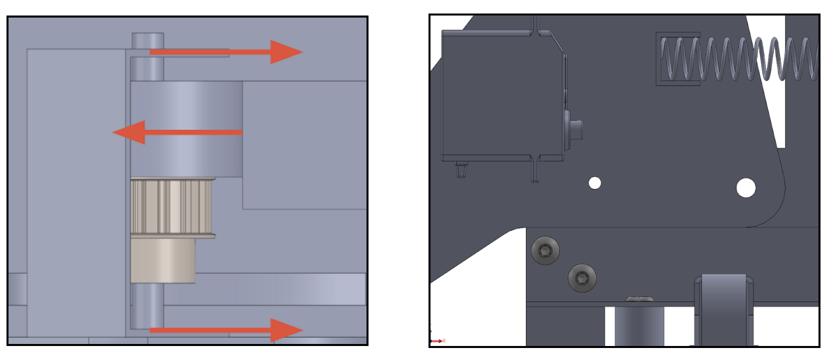


Figure 7 & 8: Free body diagram of bearing (left) and close-up of spring loaded mechanism with pin hole.

The capability of the Spring RC servo producing enough torque to release the pin was calculated. The torque must oppose the frictional force of the delrin.

$\tau = rF_f = r\mu F_N = (0.015)(0.2)(0.66) = 0.002\ Nm$. This is achievable with a Spring RC servo.

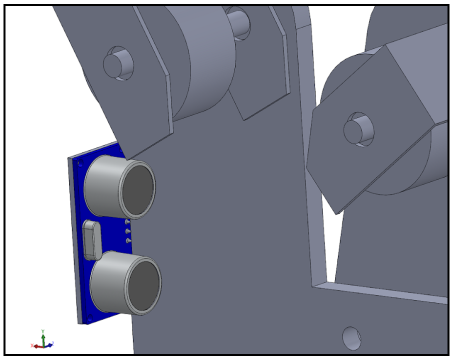


Figure 9: Close-up of ultrasonic sensor on MCM.

An ultrasonic sensor will be placed 2” from where the aluminium extrusion would be sandwiched between the traction wheels. It will be mounted to the side of the stationary piece of acrylic on a plate of sheet metal. It will be connected to an Arduino Nano and carrier board which will be mounted to the back of the MCM. When it senses an object is exactly 2” from it, it will delay 3 seconds and then trigger the servo to release the pin and the motor to drive the traction wheel.

Drive

The drive was designed to allow for precise maneuverability so that Jenny can easily align with the beaver and multiplier hook. The 13.3” x 11.15” chassis is composed of aluminum L-brackets bolted together. Two rear wheels are driven by a 57:1 LDO motor. The wheels are made of delrin and covered with rubber bands. There are two delrin pegs in the front. I selected the 57:1 LDO motor by finding the required torque for each motor $\tau_m = rF_T/2 = (1.57")(��F_N) = 0.294Nm$The 57:1 has $\tau_{max\,power} \approx 0.3$ at 7.4V which is closest to the required 0.294 Nm compared to other available motors.

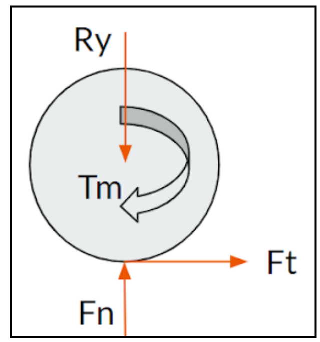


Figure 10: Free body diagram of rear wheel.

To make sure Jenny will not slip or tip going down the ramp I used the conditions:

$$1 > \frac{h}{l g\cos\theta}\left[\frac{\frac{2\tau_{max}}{r} - mg\sin\theta}{m} + g\sin\theta\right]$$

$$\frac{r\mu mg\left[\cos\theta - \frac{(\cos\theta\, l - \sin\theta\, h)}{L}\right]}{2\tau_{max}} > 1$$

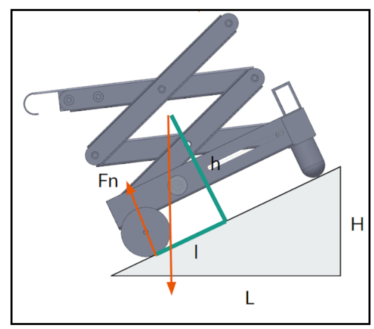
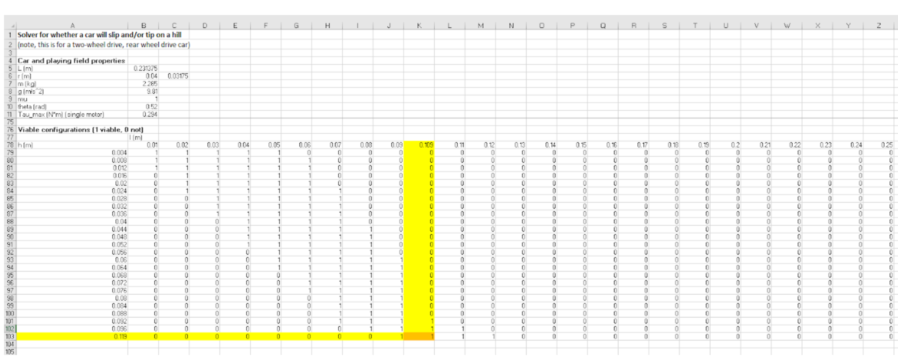


Figure 11: Free body diagram of robot on ramp.

I calculated the center of mass without the MCM at l = 4.29” and h = 4.685”. Plugging these conditions into an excel sheet, I adjusted my drive wheel radius from 1.5” to 1.57” and found parameters that satisfied these conditions.



	A	B	C
1	Solver for whether a car will slip and/or tip on a hill		
2	(note, this is for a two-wheel drive, rear wheel drive car)		
3			
4	Car and playing field properties		
5	L (m)	0.231375	
6	r (m)	0.04	0.03175
7	m (kg)	2.285	
8	g (m/s^2)	9.81	
9	mu	1	
10	theta (rad)	0.52	
11	Tau_max (N*m) (single motor)	0.294	
75			
76	Viable configurations (1 viable, 0 not)		
77		l (m)	

	A	B	C	D	E	F	G	H	I	J	K
78	h (m)	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.109
79	0.004	1	1	1	1	1	0	0	0	0	0
80	0.008	1	1	1	1	1	1	0	0	0	0
81	0.012	1	1	1	1	1	1	0	0	0	0
82	0.016	0	1	1	1	1	1	0	0	0	0
83	0.02	0	1	1	1	1	1	0	0	0	0
84	0.024	0	1	1	1	1	1	1	0	0	0
85	0.028	0	0	1	1	1	1	1	0	0	0
86	0.032	0	0	1	1	1	1	1	0	0	0
87	0.036	0	0	1	1	1	1	1	0	0	0
88	0.04	0	0	0	1	1	1	1	0	0	0
89	0.044	0	0	0	1	1	1	1	1	0	0
90	0.048	0	0	0	1	1	1	1	1	0	0
91	0.052	0	0	0	1	1	1	1	1	0	0
92	0.056	0	0	0	0	1	1	1	1	0	0
93	0.06	0	0	0	0	1	1	1	1	1	0
94	0.064	0	0	0	0	1	1	1	1	1	0
95	0.068	0	0	0	0	0	1	1	1	1	0
96	0.072	0	0	0	0	0	1	1	1	1	0
97	0.076	0	0	0	0	0	1	1	1	1	0
98	0.08	0	0	0	0	0	0	1	1	1	0
99	0.084	0	0	0	0	0	0	1	1	1	0
100	0.088	0	0	0	0	0	0	1	1	1	0
101	0.092	0	0	0	0	0	0	1	1	1	1
102	0.096	0	0	0	0	0	0	0	1	1	1
103	0.119	0	0	0	0	0	0	0	0	1	1
104											
105											

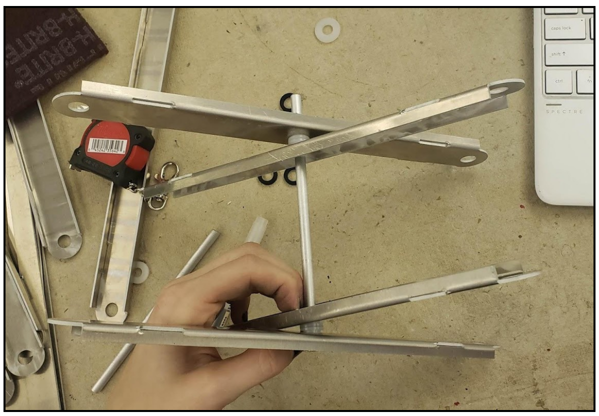
	A	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
78	h (m)	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.2	0.21	0.22	0.23	0.24	0.25
79	0.004	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0.008	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	0.012	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82	0.016	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0.024	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0.028	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0.032	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0.036	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0.044	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0.048	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0.052	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0.056	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	0.064	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95	0.068	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0.072	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	0.076	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
99	0.084	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	0.088	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
101	0.092	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102	0.096	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
103	0.119	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 12: Excel spreadsheet confirming no-slip & no-tip conditions down ramp.

Multiplier Pull-Up

The goal of the Multiplier Pull-Up mechanism is for Jenny to hook onto the loop of the multiplier and have the scissor lift retract to pull the multiplier to x2.0. This was decided as opposed to pushing because I do not have to worry about the fitting into the space below the multiplier, tipping, or having enough traction and motor torque to push. I also had already fabricated scissor lift members.

The pull-up mechanism consists of parallel scissor lifts with sheet metal members attached with steel rod joints and nylon bushings to minimize friction. Because the hook is 19" off the ground, the scissor lift extends to 19.76" from the ground.



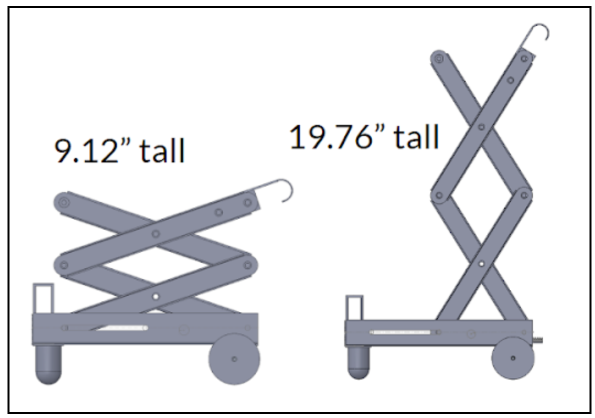


Figure 13 & 14: Fabricated scissor lift assembly (left) and diagram showing height (right).

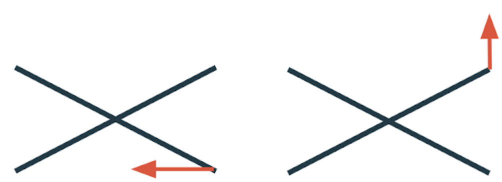


Figure 15: Horizontal actuation (left) and vertical actuation (right) of scissor lift.

Two actuation mechanisms I considered was a horizontal rack and pinion driven at the bottom and a vertical lead screw. According to virtual work the required force to actuate horizontally would be $F = \frac{nF_{load}}{tan(\theta)}$ and with a vertical lead screw $F = nF_{load}$ where theta is the angle between a member from the horizontal and n is the number of cross-linking pairs. It can be observed that vertical actuation requires more force when theta>45. The angle of the multiplier at x2.0 is 56 degrees with the vertical. Geometrically, the scissor lift needs to retract down to a minimum of theta = 49.06 degrees to reach x2.0. Because theta is always greater than 45 degrees, horizontal actuation is best.

Since it takes 14N of vertical downward force to pull the multiplier to x2.0, the maximum applied force on the scissor lift required is $F = \frac{(2)(14N)}{tan(\theta)} = 24.29N$

A 98:1 motor powered by 7.4V was selected for the pinion gear. The smallest pinion radius (½") was selected to minimize torque requirement.

$$\tau_m = rF_A = (0.5"\ pinion)(24N * 1.5\ safety\ factor) = 0.46Nm$$

$\tau_{max\ power} \approx 0.5\ Nm$ for a 98:1 motor at 7.4 V, which is close to 0.46 Nm.

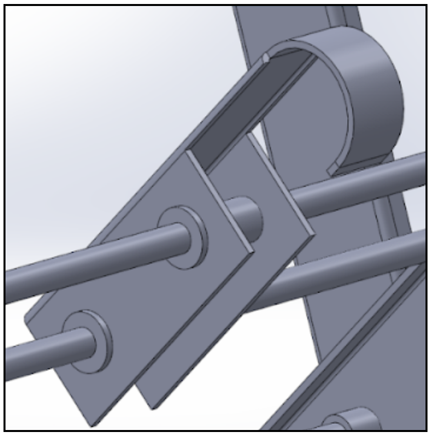


Figure 16: Horizontal actuation (left) and vertical actuation (right) of scissor lift.

Because the ¼” steel rods that the hook is mounted on are supporting, at most, the weight of the robot, I wanted to ensure that they would not undergo significant bending. I modelled this as two simply supported beams:

$$P = \frac{W robot}{2} = 11.2N$$

$$I = \frac{\pi r^2}{4} = 7.98 * 10^{-11}$$

$$\Delta = \frac{PL^3}{48EI} = 2.05 * 10^{-4}\ m = 0.08"$$

This amount of deflection is acceptable.

Bill of Materials

Item	Quantity
Sheet Metal	
Acrylic	
6061-T6 12” Aluminum Angle Bar	4
1x3x12” 6063-T6 Aluminum Box Extrusion	1
2”x4” Delrin Rod	4
1”x6” Delrin Rod	4
HDPE Bar	1
2.5” Polypropylene Wheels	2
¼” Diameter 12” T6 Steel Rod	9
Nylon Bushings	27
E-Clips	48
10-32 X ⅜” Round Head Screws	32
10-32 X ½” Round Head Screws	6
10-32 Nuts	38
M3 ⅜” Screws	16

M3 14 mm Screws	4
M3 Nuts	20
Spring RC Servo	1
Spring RC Two-Prong Servo Horn	1
Wire	
57:1 LDO Motor	2
98:1 LDO Motor	2
LDO Motor Mounts	4
Arduino HC-SR04 Ultrasonic Sensor	1
1000 N/m 2” Extension Spring	1
24 Diametric Pitch ½” Pinion Gear	1
24 Diametric Pitch ¼”x¼” Rack Gear	1
Timing Belt	1
Pulley	2

Fabrication

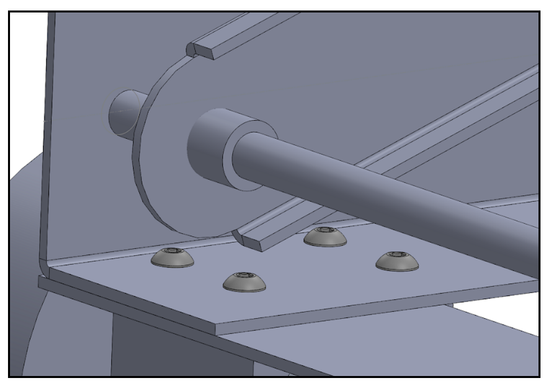


Figure 17: Detail of chassis with M3 bolts.

To fabricate the chassis, first cut 2 11” angle brackets and 2 11 ⅓” sheet metal, one with tabs for additional support. Mill ¼” thick slot into the angle brackets. Laser cut lining for slot and bolt to the side of the angle brackets (this will reduce friction of the steel rods on the slot). Then, drill 4 3mm holes at the ends of each piece. Bolt pieces together with ⅜” M3 screws. Fasten 57:1 LDO motors with polypropylene wheels to the rear with the same bolts. To create front pegs, use the lathe to cut 2 2” delrin rods down to 1.5” and round out the ends. Drill 3 3mm holes into the pegs, thread the holes, and fasten with M3 bolts to front of chassis. Cut a box extrusion to 5.75” and mill 2 0.63” diameter holes on the smaller side. Drill 4 0.19” (~3/16”) holes on the opposing side of box extrusion for 10-32 screws and bolt into the front of the chassis flush against the front edge.

To create MCM, laser cut 2 of the acrylic pieces in the specific shape designed with the ¼” hole for the pivot, pin hole, slot for the motor, and mounting holes for servo and traction wheel. Cut and bend sheet metal into mount for servo and traction wheel bearing support brackets. Cut ¼” steel rod ¾” long and lathe indentations on either end for e-clips. Fasten together two pieces of acrylic with this rod and e-clips.

For traction wheels, cut 2.75” and 2.5” steel rods and lathe indentations for e-clips. Lathe 2” diameter delrin to 2 1.5” diameter wheels that are each ¾” thick. Wrap these wheels in rubber bands. Assemble nylon bushings, e-clips, wheels, bearing supports, and pulley to the steel rods and mount to the acrylic. Fasten bearing support to acrylic using 10-32 ½” screws.

Screw two-prong servo horn into servo. Attach one end of wire to the servo horn and the other end to a small delrin pin created in the lathe of about 3/16” diameter. Create wire loops and push through acrylics to create hooks to mount the extension screw. Create sheet metal mount for ultrasonic sensor and bolt with 10-32 ½” screws at edge of acrylic.

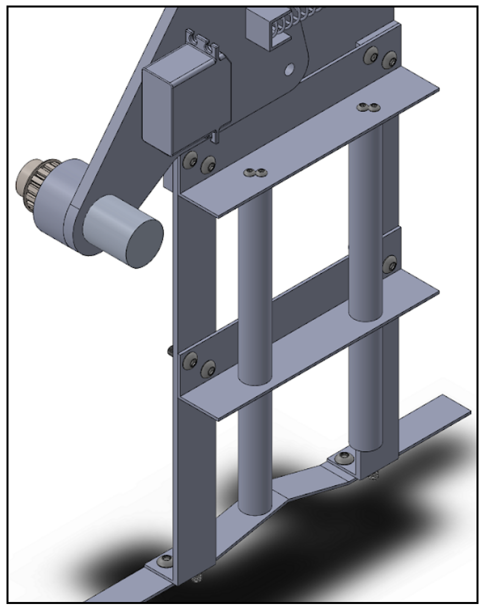


Figure 18: MCM assembly with fasteners.

For lower section of MCM, cut angle bracket into 2 5.75” pieces and drill 0.19” holes as shown in Figure 18. Bolt together with vertical sheet metal pieces using 10-32 ⅜” screws. Bend sheet metal of lower part to fit bottom contour of beaver. Use lathe to cut 1” delrin rods into 2 0.63” diameter 7.45” long rods. Drill 3mm holes into delrin, thead the holes, and fasten with 14 mm M3 screws into angle bracket.

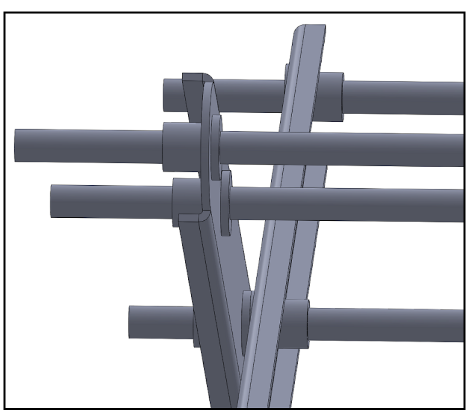


Figure 19: Scissor Lift joint connection detail.

For the Multiplier Pull-Up, cut e-clip incisions into 12” long ¼” steel rods. Waterjet 8 members and bend into trusses using brake. Assemble steel rods to connect members with nylon brushings in the holes and e-clips as fasteners. Mount pinion gear on a 98:1 LDO motor and use M3 screws to attach to motor mount. Mount motor mount to chassis. Mill HDPE to create linear sliding track for rask gear with thickness such that the distance from the bottom of the rack to the center of the pinion is 0.458”. Drill 0.371” holes into sheet metal and bend using brakes into a U-bracket bracket. Fit with nylon brushings and attack to slide that will move along with the rack gear. Bend hook using sheet metal and attach to steel rod at top.

Finally, mount a radio receiver to the main chassis and Arduino Nano and carrier board to MCM. Congratulations, Jenny XJ-9000 is ready to roll!

Reflections

My initial strategy was just to lift the beaver. The design that inspired me was one of the display robots in Pappalardo. While I didn't want to just copy the idea, I also didn't want to waste time and over-plan. I remember an architect who was a guest speaker in the class 4.301 (Intro to Artistic Experimentation) told us that it's best to just get to the shop and start prototyping and building things to get over the hurdle of starting instead of ruminating over every possible option. I also remembered that in high school robotics, we would be building the robot up until the last minute and leave no time for testing. After every competition, I would have this sense of regret where I wished we'd spent less time brainstorming or trying to come up with a fancy design and more time just building because testing is the most essential part! That is where all the iteration happens. I have a tendency to want something to come out unique and impressive-looking, so I will overdo the brainstorming part. But keeping it as simple as possible first, focusing on functionality, and working up to something more ambitious is usually the best route.

So I decided to start fabricating my scissor lift, while of course doing additional analysis on the side. I am glad that I didn't wait to start it because I think physically building got my mind thinking. As I was playing with the scissor lift, I had an epiphany and thought, "if I'm going to actuate this from the top anyway, what if I just removed the lift entirely and have a separate 'lifter' climb the column on its own?" Ironically, this was an idea I sketched at one point in my notebook, but brushed it off as silly and overly-ambitious. But coming to this point in my design thinking was possible because I got my hands dirty.

While I didn't get to spend much time fabricating, for the little time I did, I noticed that building, feeling, and even just seeing your plan come to life will change how you approach it, especially since I don't have extensive shop experience. Because I can't necessarily visualize how something will be built until I ask a shop staff, some of my preconceptions about the design will change. For example, when I was building the scissor lift, I first imagined that I can just put the brushings on, secure them with e-clips, and call it a day. When I first waterjet my pieces, I realized my brushings were not fitting snug. While it seemed to not make a huge difference, assembling multiple linkages together proved that this wobbliness intensified. I had to waterjet again with smaller holes and painstakingly bore them out just enough to get the brushings in. When I put them together, I then noticed that they joints did not move smoothly at all. I then had to take apart my assembly and scotch-brite each of my steel rods to reduce the friction. From this, I learned that fabrication takes longer than expected, especially when there is a learning curve!

Another important lesson that I learned is how iterative design is. I noticed that every time I made a change in my design, I would have to redo some analysis from before. For instance, changing a wheel size to fix a power issue with the driving motor will in turn affect the center of mass, which would then affect the no-tip and no-slip conditions going down the ramp. A helpful tool to manage these specs is CAD. By just creating a CAD, I don't have to keep track of individual dimensions for every change I make. It also gives me a better spatial understanding of my robot. For example, the CAD made me realize that my wheel was interfering with the placement of my rack and pinion motor. By CADing first, I could work out how all the components will come together, and automatically track things like center of mass and weight.

While I had some familiarity with CAD before, 2.007 really helped me sharpen my skills! Something I wish we could have taken advantage of is more FEA and simulation analysis, since I've never really used these tools before. It seems as though there is no particular structure to teaching CAD in the engineering curriculum at MIT even though it's a very important vocational skill. More workshops and written homeworks in CAD would help, as opposed to some of the topics covered in written homeworks which I feel most students have already learned before.

Another tool I wish I had used that I've seen others use is MATLAB. While I do believe I have ample training in it through classes like 2.086 and 2.004, I found it brilliant that some other students were using it to generate code for motor selection and plotting power curves. Since I am a bit old-fashioned (scared of code) and enjoy drawing, sketching, and going straight into building over numerical analysis or computer generated design, I think stepping out of my comfort zone and doing something more computational would have been helpful. However, I do think one of the upsides of the quarantine is that I was forced to do more in-depth analysis. Looking back on design I did in high school robotics, I have no idea how I was able to do it without having an understanding of basic principles like torque-speed relationships and material mechanics! 2.007 has definitely taught me to take a more logical, analytical, and procedural approach to design.

With respect to the design process, I found the "milestone" structure extremely effective. It kept me on track, forced me to document my work properly (which I'm thankful for now, while writing the final report), but still allowed some flexibility for me to do my own thing while being held accountable with everyone else. I will likely use milestones in future UROPs, jobs, or independent projects I do to make sure I am on task. In design projects, it is really easy to get caught up on one detail and spend way too much time on it.

Another design principle that will stick with me is the separation of defining the problem, strategy, and design conceptualization. The lecture discussion of figuring out how to remove snow from MIT gave me a good understanding of this. I am a very visual person and I am often quick to see and problem and immediately picture what the solution would look like without first defining the parameters and weighing different strategies. Breaking down the problem in this way will help me brainstorm solutions for future projects and assignments as a mechanical engineer.

In summary, some changes that I think would improve the course would be more training in CAD that tends to the varying levels of experience students have, especially with simulations analysis. More of a focus on on-the-job skills and basic shop knowledge would be helpful. For example, I appreciated the instructions on proper engineering drawings and dimensioning to a datum. However, I think a crash course on basic shop information like how screws, drill bits, and gears are dimensioned and named, and the names of certain tools, machines, and metalworking techniques. Instead of written homeworks expanding on stuff we learned in 8.01, 2.001, and 2.003, I think 2.007 being a class for uniquely hands-on engineering knowledge would fill a gap in a practical understanding of fabrication and the industry, whether it be computational software like Solidworks or how to make decisions when making stuff and shop lingo. Perhaps this is just something we lacked because of the quarantine.