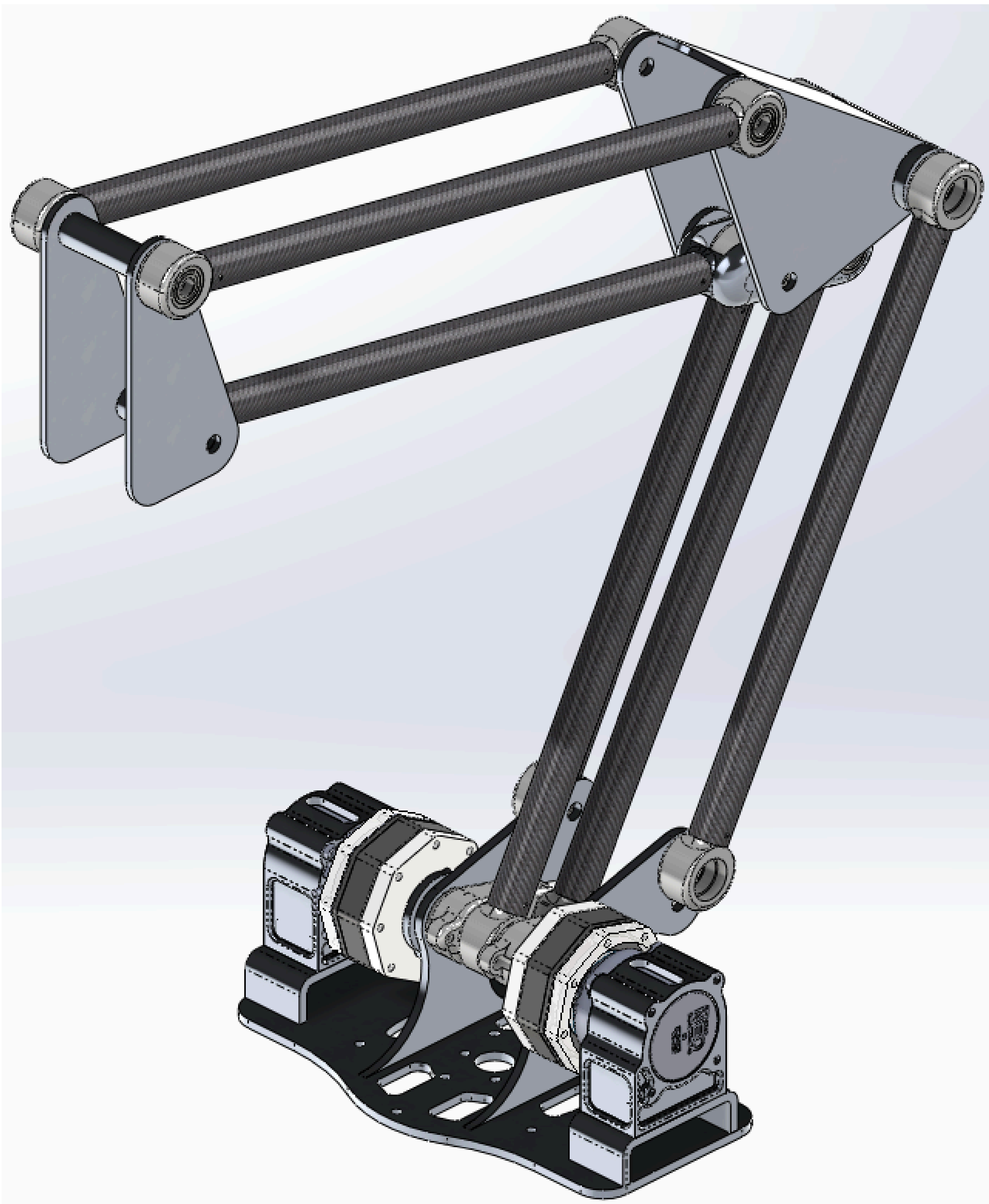
ROVER PANTOGRAPH ARM — SEPTEMBER 2023 - MARCH 2024

I was involved with Titan Rover for my senior design project, and I was in charge, and worked completely alone on the robotic arm. The design took several iterations, and had strict requirements. Although I didn't have time to program the arm due to being stuck in the machine shop, and dealing with my other academic classes, I still believe I outputted a good product, and the analysis that went into it is invaluable, and applicable to other projects.

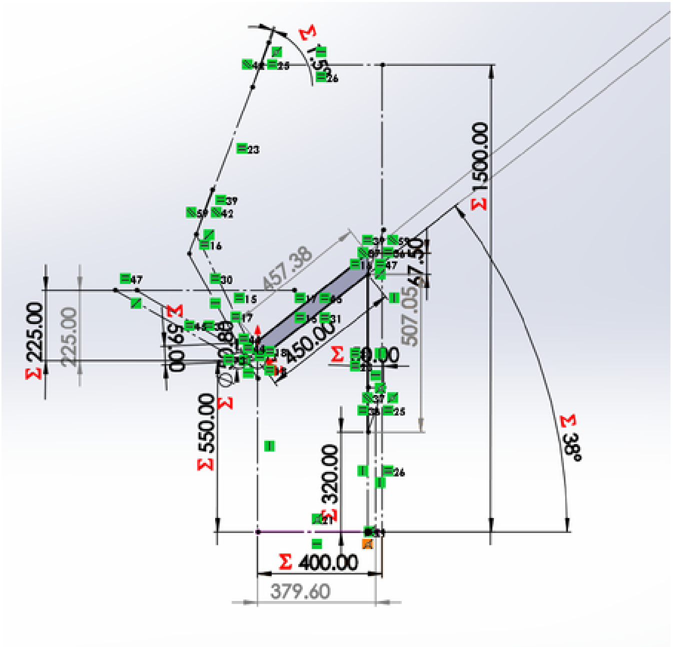
This project primarily focused on 4-bar linkages, and their mechanical advantage. But it also tested my spatial ability, when I tried to balance the arm's range, and robustness, while also trying to get the arm to not run into itself. It also tested my CAD skills, because I ad to design things as if they could be manufactured, and not just 3D printed.

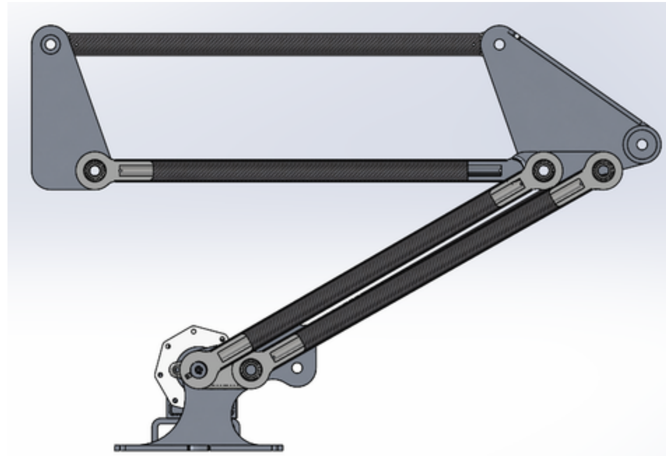
The next few pages will go over in much more detail, all the intricacies of the arm, and the analysis that went into it.



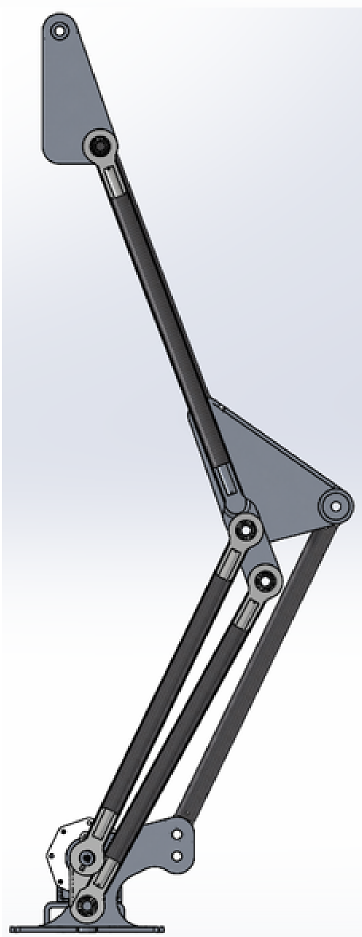
ROVER PANTOGRAPH ARM — RANGE AND COMPACTNESS REQUIREMENTS

The arm had 3 main requirements: It had to be able to easily reach the ground, It had to easily be able to reach 1.5m up from the ground, and it had to fold up when not in use (especially when the rover itself was moving). Those geometric constraints are shown in the sketch below. All subsequent parts and assemblies were defined around that sketch.

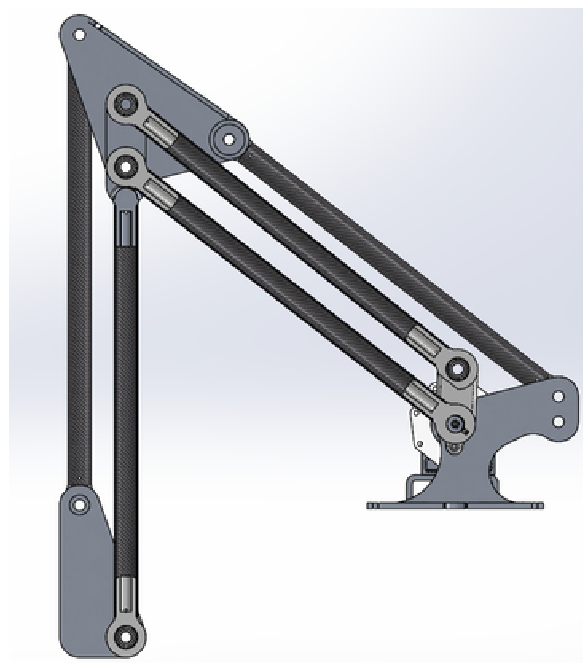




The arm folded up. This moves the center of gravity lower, and closer to the middle of the rover, which would help against tipping over



The arm reaching all the way up. The wrist would have covered the horizontal distance.



The arm reaching down. The wrist would have covered the rest of the distance to the ground. As will be shown later, the wrist's orientation won't be affected by the orientation of the other linkages.

Notice that tall these arms are in a cut plane view. Take a while to appreciate that the linkages do not run into each other when in these positions. They also never run into each other transitioning between positions.

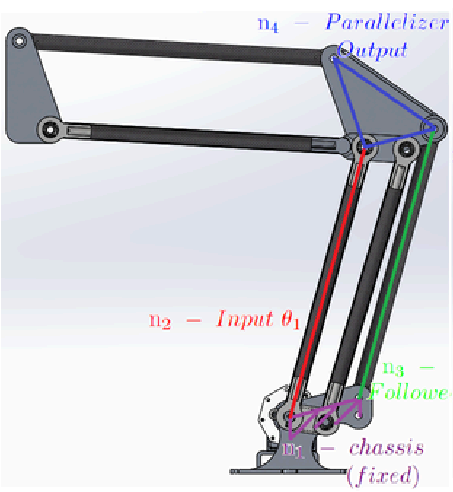
The arm is made of three different 4 bar mechanisms. Shown in the first and second pictures are the parallel arm mechanisms. As shown in the previous page, no matter how the linkages are moved or oriented, the output triangle (at the very tip) always stays parallel to the ground. This is useful, because the wrist was supposed to be mounted onto it. This meant that the wrist's orientation would not be influenced in any way by the position and orientation of the other linkages.

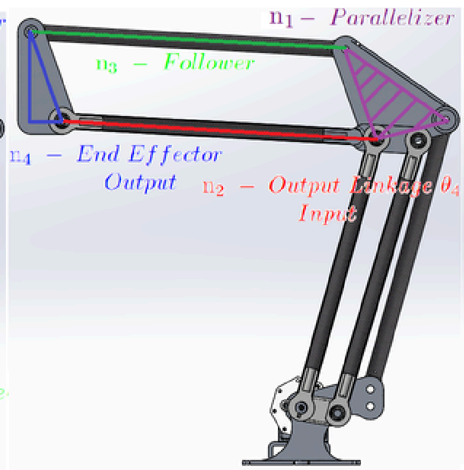
The first picture has a motor that powers theta1. This motor controls the "shoulder" of the arm

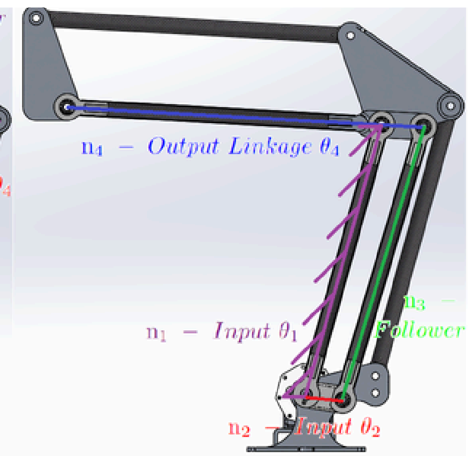
The third picture shows how the "elbow" of the arm is actuated. Instead of having a motor mounted onto the elbow itself, which would cause a heavy mass to hang and swing at a long distance, the vibrations of the motor would have severely amplified the moment put on the arm. This is why the elbow's motor is also placed at the shoulder, at the exact level of the first motor. The elbow motor drives theta2, and through a 4 bar linkage, actuates and changes the angle of theta4.

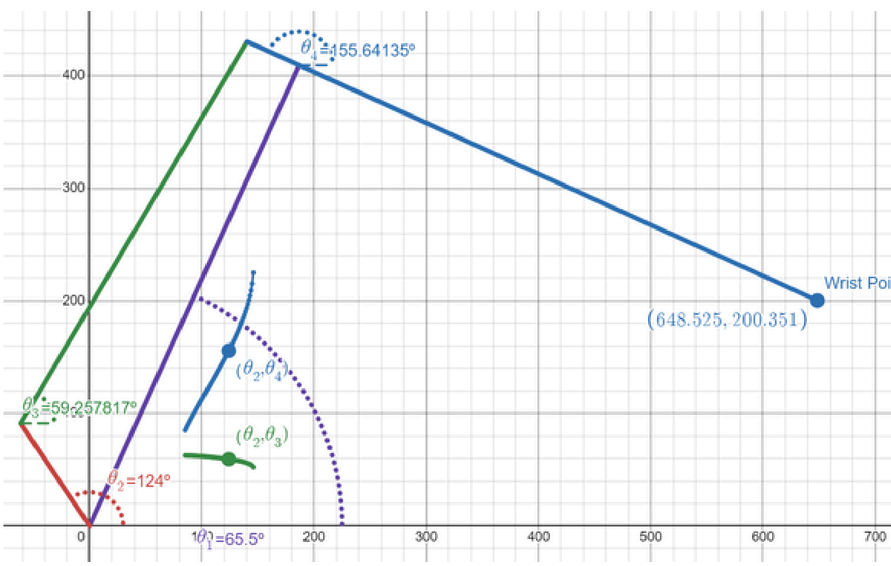
In addition to the range, compactness, and other geometric requirements, I had to consider the mechanical advantage that my 4-bar linkage would produce. While I could theoretically reach anywhere with the longest possible arms, I would also be sacrificing a lot of mechanical advantage, possibly negating any of the precious torque the motors powering it could provide. The nature of it being an arm meant that I was already carrying heavy loads out at a long distance from a pivot, already heavily fighting the torque of the motor.

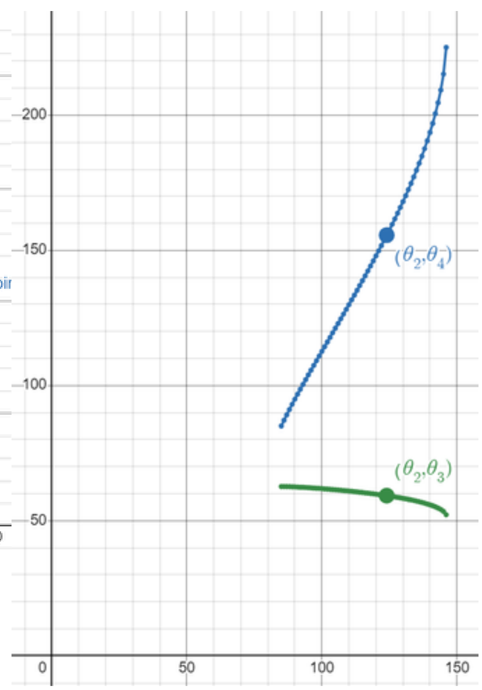
This is why I created a graphing calculator to analyze the 4 bar kinematics (of the third picture) https://www.desmos.com/calculator/s3wx35sbtg





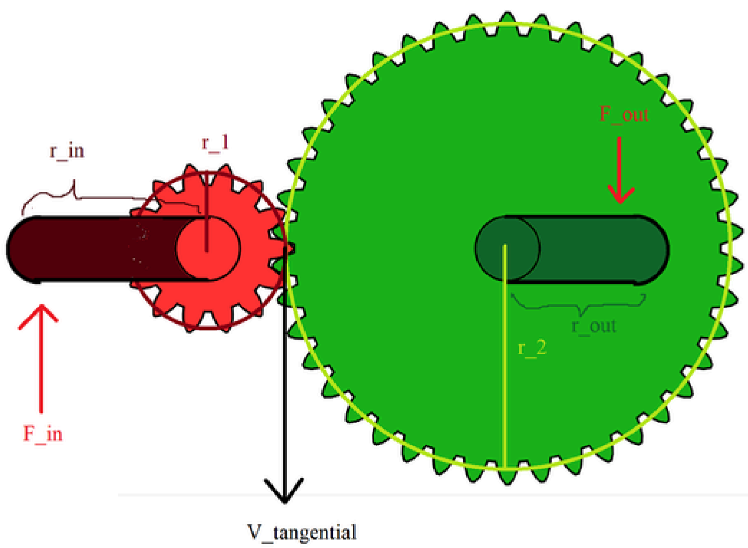






The arm had inputs of torque, but the load it dealt with was a force. Although mechanical advantage is typically used to describe gears and 4-bar mechanisms, they are usually ratios of input force to output force, or input torque to output torque. There is not measurement or term for input torque to output force.

This is why I created my own Mechanical Advantage_forceToTorque number. But to understand it, I want to show how it is derived by first showing how mechanical advantage is derived, using the example of a simple gear pair.



Starting off with the definition of Mechanical Advantage (MA):

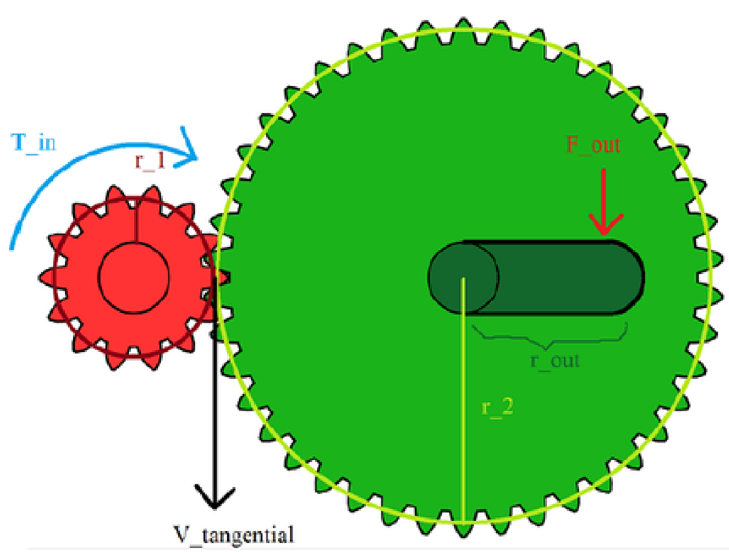
- $MA = \frac{F_{out}}{F_{in}}$
- $MA = \frac{F_{out} \times r_{out}}{F_{in} \times r_{in}} \left(\frac{r_{in}}{r_{out}}\right) = \frac{T_{out}}{T_{in}} \left(\frac{r_{in}}{r_{out}}\right)$

Assuming no losses of power, the power in should equal the power out. Then substitute into MA

- $P_{in} = P_{out} \Rightarrow T_{in}\omega_{in} = -T_{out}\omega_{out} \Rightarrow \frac{T_{out}}{T_{in}} = -\frac{\omega_{in}}{\omega_{out}}$
- $MA = -\frac{\omega_{in}}{\omega_{out}} \left(\frac{r_{in}}{r_{out}}\right)$

Knowing that tangential velocity is equal to angular velocity cross radius (assuming a constant radius, which spur gears don't change radius), and knowing that tangential velocity at the pitch radii of both gears must be the same...

- $V_{tangential} = r_1\omega_{in}, V_{tangential} = -r_2\omega_{out} \Rightarrow -\frac{\omega_{in}}{\omega_{out}} = \frac{r_2}{r_1}$
- $MA = \left(\frac{r_2}{r_1}\right)\left(\frac{r_{in}}{r_{out}}\right)$



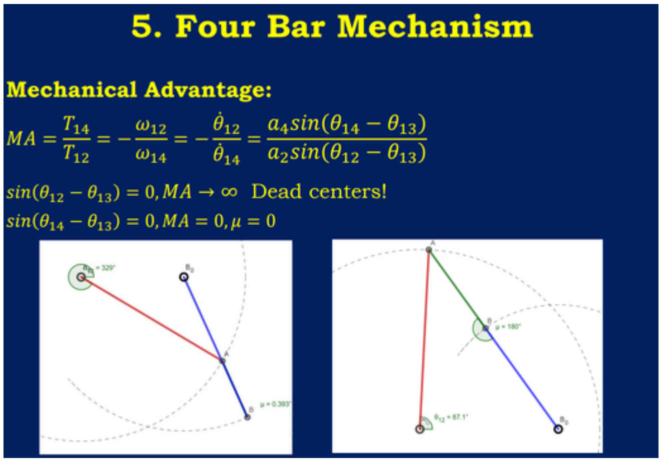
Now, instead of having an input force, we can describe T_in as F_in x r_in, and have an input torque. In order to keep the mathematical ratio of F_out to T_in, if we turn F_out into T_out by multiplying it by r_out, we must also divide by r_out.

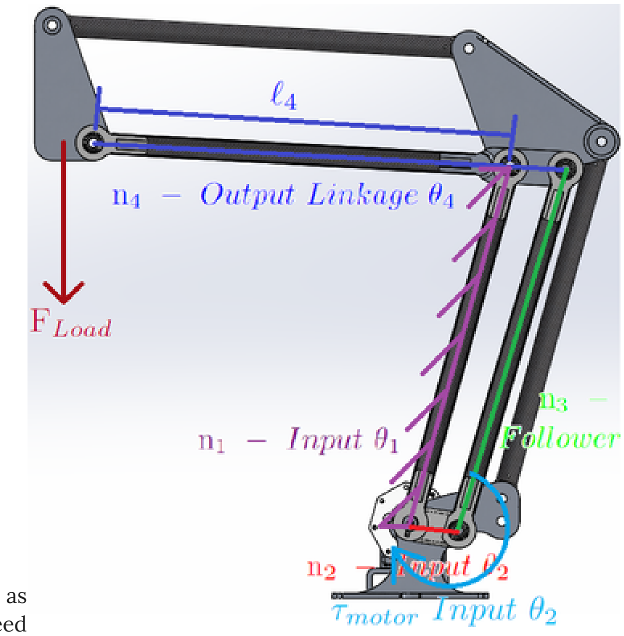
Eventually, the ratio of input torque to output force can be described purely with the geometry of the system: the radii of the gears, compared with the radius of the output lever.

$$MA_{force-to-torque} = \frac{F_{out}}{T_{in}} = \frac{F_{out} \times r_{out}}{T_{in}} \left(\frac{1}{r_{out}}\right) = \frac{T_{out}}{T_{in}} \left(\frac{1}{r_{out}}\right) = -\frac{\omega_{in}}{\omega_{out}} \left(\frac{1}{r_{out}}\right) = \left(\frac{r_2}{r_1}\right)\left(\frac{1}{r_{out}}\right)$$

The concept can now be expanded to the more complex 4-bar mechanism. The input torque, T_motor, which controls theta_2 comes from the elbow motor. The output force is F_Load, which will come from whatever the arm is carrying. The MA_torqueToForce will be the ratio of T_motor to F_Load.

Also shown below is a velocity analysis of any 4-bar linkage. Again, it is defined by the system's geometry. This time however, it is also defined by the system's position itself.





$$-\frac{\omega_{1,2}}{\omega_{1,4}} = \frac{r_4 sin(\theta_{1,4}-\theta_{1,3})}{r_2 sin(\theta_{1,2}-\theta_{1,3})}$$

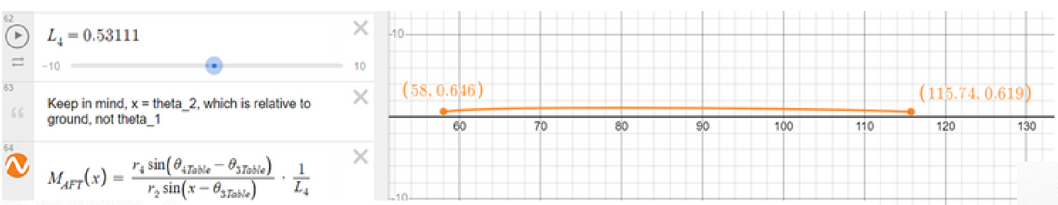
Shown below is the calculation for torque to force. The same logic applies as last time. In the end, the mechanical advantage depends on the actual speed of the linkages themselves. Plugging in the velocity analysis from above, MA is clearly and easily defined.

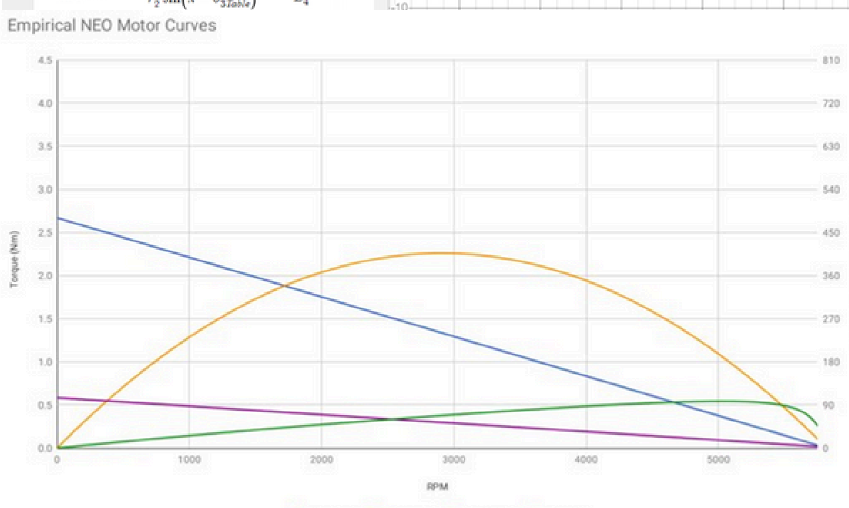
It can be seen that the MA changes as the position of the arm changes. The graphing calculator also keeps track of that,

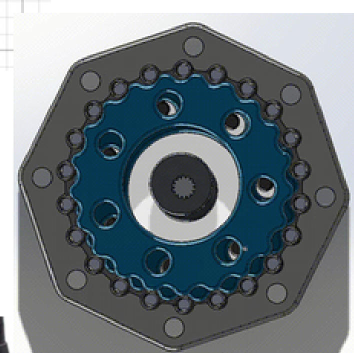
$$MA_{force-to-torque} = \frac{F_{load}}{T_{in}} = \frac{F_{load}\times\ell_4}{T_{in}}\left(\frac{1}{\ell_4}\right) = \frac{T_{out}}{T_{in}}\left(\frac{1}{\ell_4}\right) =-\frac{\omega_{in}}{\omega_{out}}\left(\frac{1}{\ell_4}\right) =-\frac{\omega_{1,2}}{\omega_{1,4}}\left(\frac{1}{\ell_4}\right)$$

$$MA_{force-to-torque} = \frac{r_4 sin(\theta_{1,4}-\theta_{1,3})}{r_2 sin(\theta_{1,2}-\theta_{1,3})}\left(\frac{1}{\ell_4}\right)$$

This became useful when sizing the gearbox around the motors.

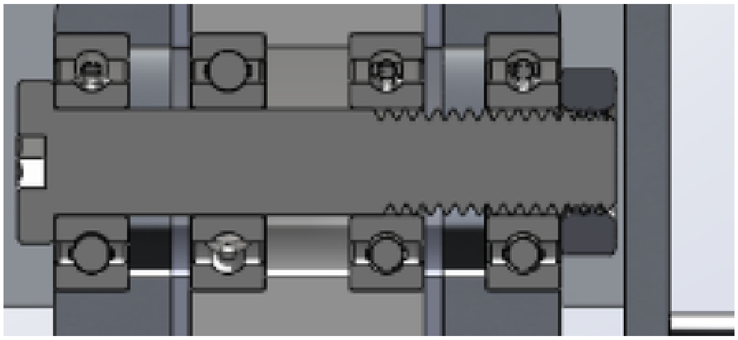






ROVER PANTOGRAPH ARM — SCREWS AS AXLES AND BEARING CREATIVITY

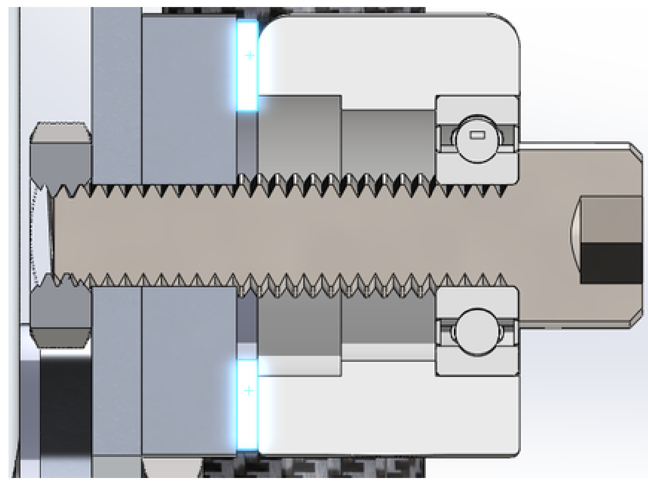
I thought it would be efficient to use heavy M12 screws as both a way to secure parts together, as well as an axle. Normally, tightening something would make it resistant to movement, and would add heavy friction. However, I did some creative things to get around this.

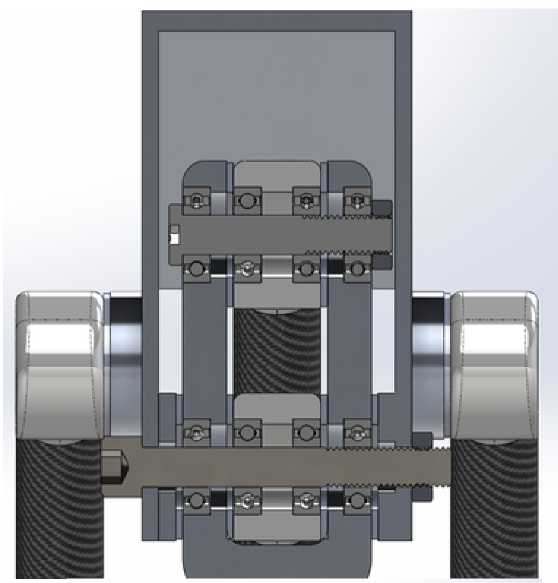


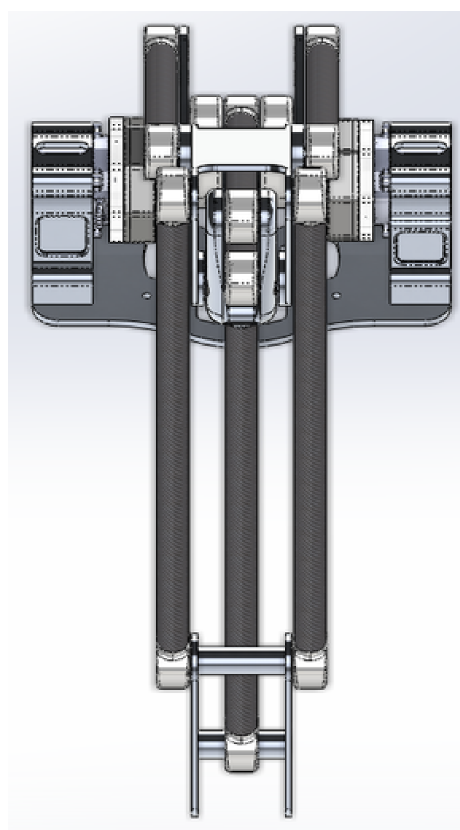
As can be seen to the left, the head of the screw, and the nut only touch the inner race of the bearing, while the outer race of the bearing is firmly embedded into the linkage. The bearings are prevented from sliding inwardly die to the "shelves", and are kept in place from sliding outwardly via the screw and nut. This therefore also keeps the linkages in place.

Think of it this way: The screw and nut are so tight, that they prevent the inner race from moving. However, the outer race is still free to move. And because it is embedded into the piece, the piece is also able to freely move around the bearing.

In cases where linkages and joints must "rub" on each other, I was still able to tighten them together axially, while allowing them to rotate freely and easily. Highlighted in blue are thin thrust needle bearings. Even if the two faces that rub on the bearing move at different speeds, there will still be smooth motion, as the needles will roll in between them with (negligible) slipping. (Negligible because they are cylindrical bearings, instead of cone shaped, meaning the radius of the rolling circle doesn't match the radius it is rolling around the screw).



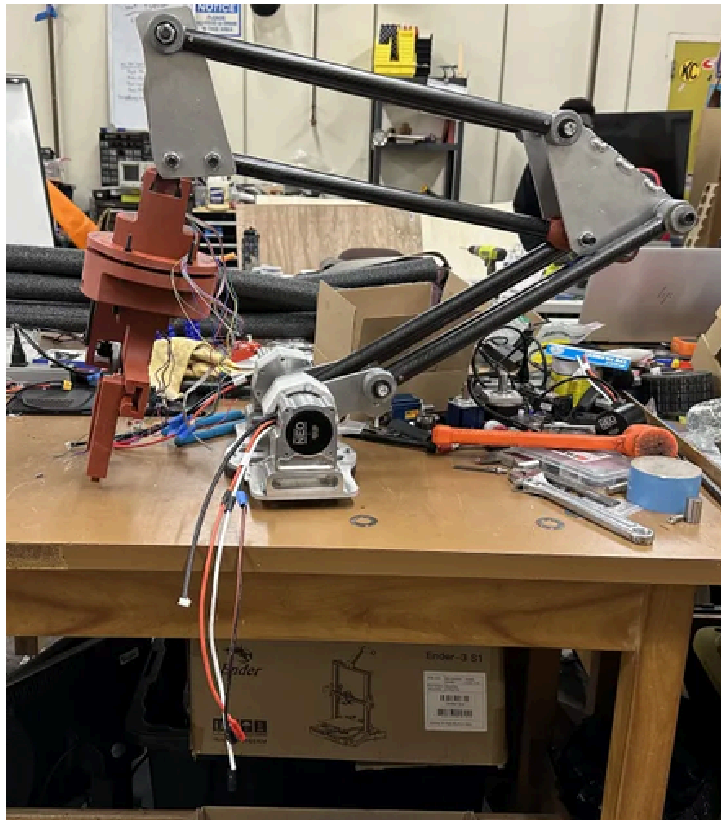




Shown to the left are screenshots of the arm's linkages not running into each other, and having ample freedom and space to move, while still being compact and organized.

ROVER PANTOGRAPH ARM — IN REAL LIFE

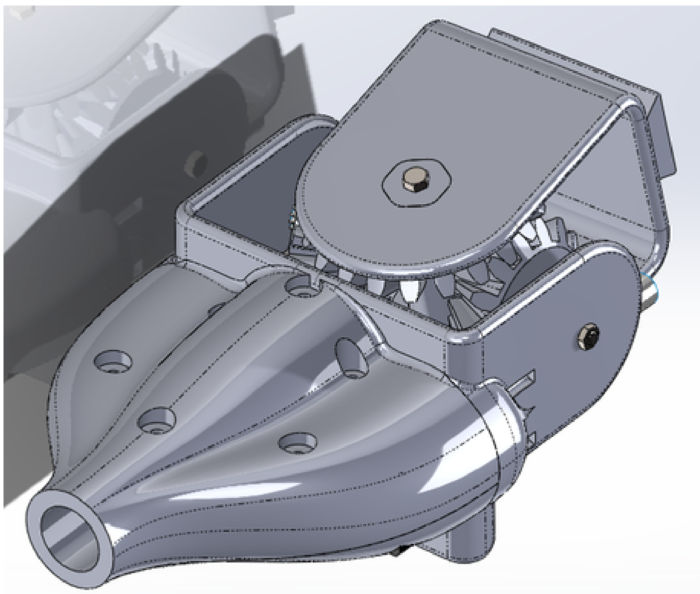
Below are pictures of the actual made product, as well as its individual components.

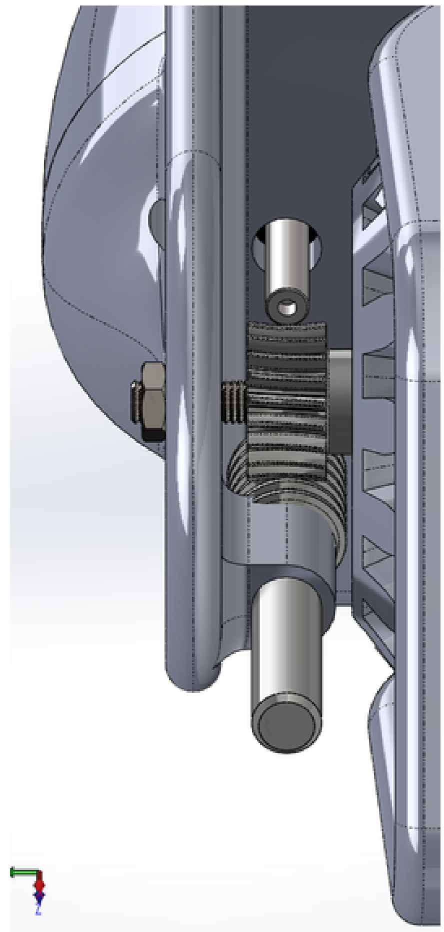


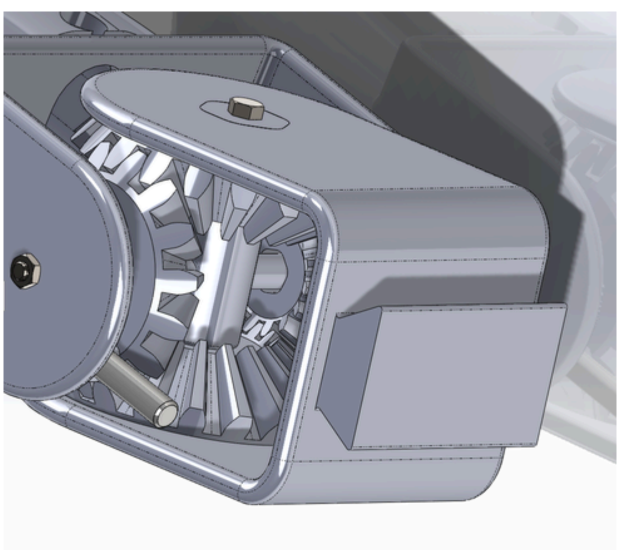
Shown below was an idea for the wrist. This is known as a differential bevel joint. It works like a car differential, but in reverse. Two side bevel gears are spun, and they output the speed and orientation of the dovetailed prong. If they move in opposite directions at equal magnitude speeds, the output (the dovetailed piece) will yaw. If they move both in the same direction at the same speed, the output will pitch. This is a nice compact way to get two axes of rotation centered at the same point. Two motors are still used, but this configuration is much more compact.

They were supposed to be driven by worm screws, to prevent back driving (so the load wouldn't fall), and a high reduction (so the wrist could lift load).

Unfortunately, there just wasn't enough time to implement this wrist.







Shown below are screenshots of me learning to use fusion 360 to mill solid stock of aluminum in HAAS CNC machines. I learned about speeds and feeds, and creative ways to set up workpieces.