ENGINEERING NOTEBOOK

ME 14 Transmission Project

Camilo Garrido

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Problem Statement

5/01 — The objective is to design, fabricate, test, and refine a transmission that achieves the highest score, calculated using the formula:

$$\text{Score} = \frac{\text{max rpm}}{T_{250}}, \quad \text{where } T_{250} \text{ is the time to reach 250 rpm}$$

- We have a $200 budget (not counting taxes or shipping).
- The transmission must fit within a 7" tall by 6" wide by 8" long box and be able to mount onto the testing rig using the provided mounting holes and couplers on the motor and bike axles.
- It must be quickly installable and removable (90 second time limit for each)
- 300 s maximum will be allowed, from the application of power, for evaluating the transmission.

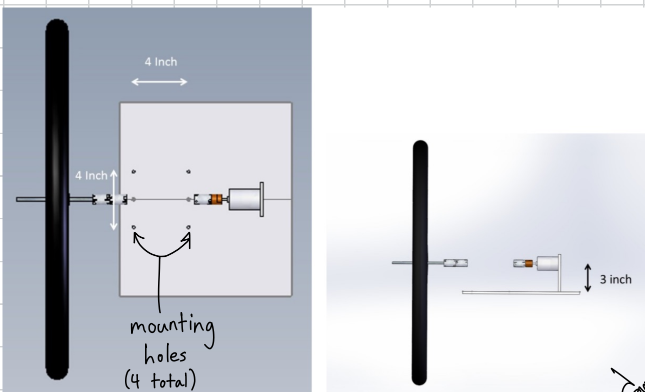


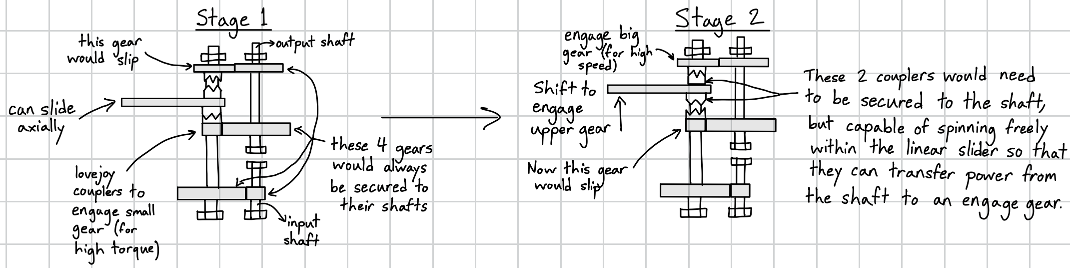
Figure 2 Critical dimensions of the transmission testing apparatus

- These are the critical dimensions of the testing rig, around which we'll design our transmission.

Design Ideation

5/06 – Sebastian proposed that we make a two-stage transmission. We are all on-board, but disputing the best way to go about switching stages.

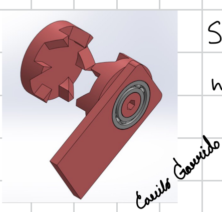
1) Use ~~love-joy~~ lovejoy C.G. couplers and have some sort of linear slider to switch between ~~gear ratios:~~ engaged gears C.G. manually.



This is my favorite. It seems to have the fewest moving components, and seems easiest to assemble.

2) Use 1-way bearings to have two shafts, each with one stage that can either be engaged, or idling, depending on the direction of the input shaft's rotation. Would require some electronics to switch the polarity of the motor for switching directions.

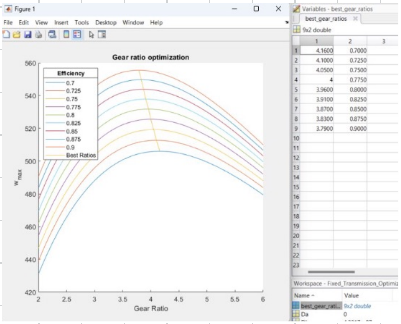
3) Do something similar to method 1, but instead of the lovejoy couplers, use friction pads. We would likely have to machine our own lovejoy couplers if we go with ~~idea~~ method 1 C.G. as we would want triangular ends on the couplers to help with aligning the couplers at high speed. Friction pads could bypass this challenge but create a new one: ~~we~~ they C.G. would need to be held together with a lot of pressure to prevent slipping. Perhaps we can look into springs

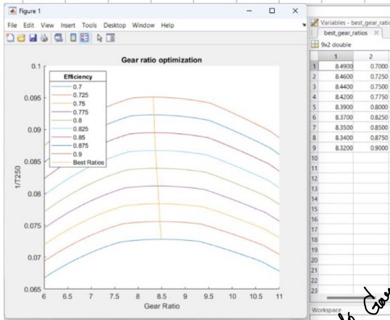
5/08 – 

Sebastian put together this CAD of the lovejoy couplers to help with visualizing method 1.

Design Selection + Justification

5/08 – I was able to get the MATLAB ~~Script Runn~~ script running C.G. and used it to estimate the two gear ratios that would optimize our score

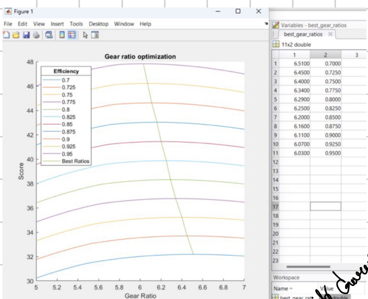




Results

- Best gear ratio for achieving max rpm: ~4:1
- Best gear ratio for achieving lowest T_{250}: ~8.5:1 (though we settled for 8:1 to facilitate finding appropriate gears).

I also checked the best gear ratio for a single-stage transmission and found it to be ~6:1



Using this script, I estimated that a two-stage transmission would offer around a 5-point improvement over ~~a si~~ C.G. an equally efficient single-stage transmission. But, comparing the script's projected scores to the actual transmission scores from 2 years ago, it seems that the script underestimate scores by as much as 50%, so the improvement might actually be ~10 points.

This further convinced us that a two-stage transmission is the way to go. We decided to ~~explore~~ go with one-way bearings as they would spare us from having to design and fabricate an axially sliding clutch. Having an electrical solution for swithing between stages by flipping the polarity of the motor would be much smoother than a manual clutch, and likely safer too.

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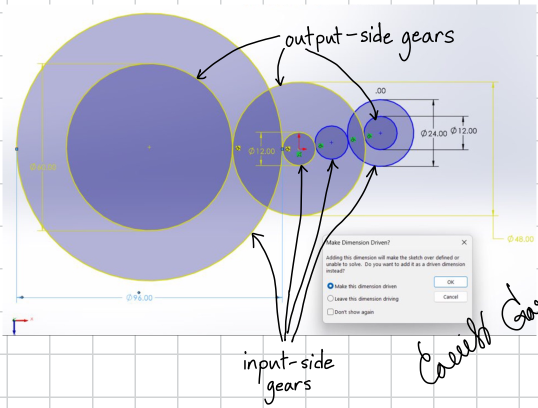
Design Selection + Justification Continued...

One-way bearings also seem more reliable, as they can't wear down like friction pads and they engage/disengage just by switching directions, ~~whereas trying~~ C.G. which seems much more reliable than trying to align the teeth of our custom lovejoy couplers when they are already rapidly spinning.

We initially tried to design the transmission using only spur gears (for their high efficiency).



• However, I found that this was geometrically impossible with less than 8 gears given our desired design constraints (i.e., 4:1 and 8:1 gear ratios and colinear input and output shafts).

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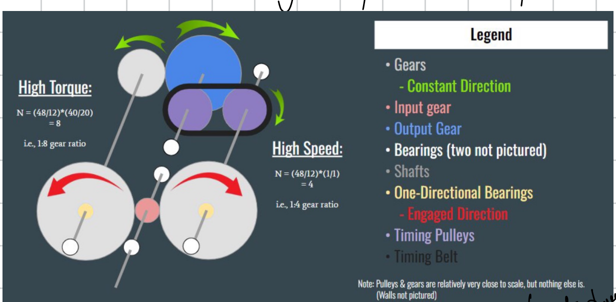
As such I proposed using 5 spur gears and 1-timing ~~belt~~ belt C.G. assembly, figuring that this would offer higher efficiency and less mass by reducing the number of interfacing components compared to an 8+ spur-gear design.



I made this visualization of the design for the PDR.

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Preliminary Component Specification

5/08 – We unanimously agreed to use acetal gears because they are cheaper (and we have to make room in the budget for the additional ~~compe~~ components C.G. needed for a two-stage transmission), quieter, and lighter than metal gears. They ~~are more~~ aren't as C.G. strong as metal gears, but we found that by starting with a 12-tooth, $\frac{1}{4}$" face-width gear, we were able to ~~select~~ find gears with the necessary diametrical pitches and diameters, all $\frac{1}{4}$" face-width, that could achieve our desired gear ratios. We'll have to do the gear stress analysis to be certain, but we feel fairly confident that such thick gears will not break.

The selected gears are all 20° Pressure Angle (the options for 14° Pressure Angle gears were much more limited) and 24 DP to ensure proper meshing. We found the best options on SDP/SI.

1) On the torque stage we have ~~a~~ the C.G. 12T gear powering a 48T gear with ~~the~~ its C.G. shaft connected to a 20T gear which powers the 40T output gear, for a total 8:1 gear reduction
2) On the speed stage we have the 12T ~~ip~~ C.G. input gear powering a 48T gear with its shaft connected to a ~~0.913"~~ 0.935" OD Pulley which powers another 0.935" pulley via a timing belt (whose length we determined by measuring the length of a slot around the pulleys in SOLIDWORKS and rounded up to the closest available).

For the one-way bearings, we went with acetal spring bearings to avoid breaking the bank on just these two pieces (as the steel ones were $20 each). The smallest ones available are 3/8" ID, so we didn't have much of a choice but to go with these. Due to the small size of the 12T input gear, we decided to go with a 1/4" ~~shaft~~ input shaft C.G.. For the rest of the shafts, we hope to use 3/8" keyed shafts provided by the shop.

For the PDR tomorrow, we just selected some wall bearings on McMaster matching our shaft sizes. We'll explore these in more detail later.

We'll be using a toggle switch wired (with alligator clips from the shop) to the motor's H-bridge to quickly flip its polarity. Mo has been working on the preliminary CAD and is almost done with it.

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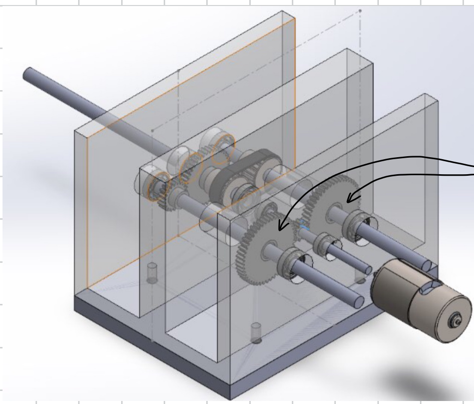
PDR

5/09– I ~~had the~~ got an idea for a contingency plan in case our two-stage transmission, which is C.G. beginning to seem much more involved than any of us had anticipated, doesn't work out. We can buy a 24T and 36T gear (also 24 DP, 20° Pressure Angle, acetal, and 1/4" face width) sold on SDP/SI to replace the 20T and 40T gears (respectively) on the torque-side of our transmission to make it a 6:1 gear reduction. Then, we could disassemble/detach the speed-side of the transmission, thus turning it into a pretty standard transmission.



These two gears are mounted on one-way bearings that engage/slip in opposite directions from each other.

• Mo completed the preliminary CAD, demonstrating that our specified parts should all come together well.

The PDR seemed to go very well. Everyone seems cautiously optimistic about the design. It will be a lot of work but appears to be viable and innovative. Our key takeaways were:

- Investigate the one-way bearing specs with more scrutiny
- Perform stress analysis on the gears.
- Redo the BOM accounting for the prices of items from the shop

Overall, this gave us a lot of confidence to move forward with our idea.

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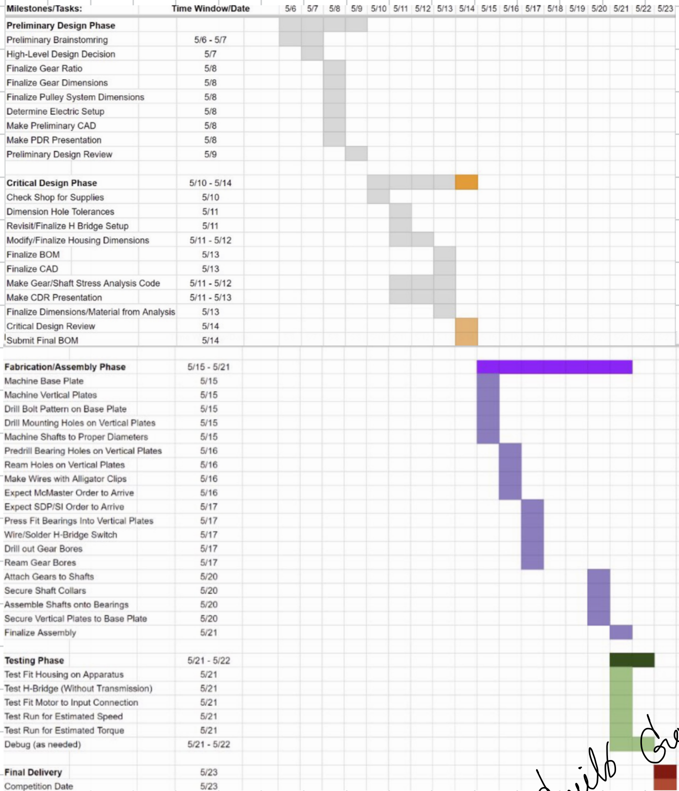

Milestones/Tasks:	Time Window/Date
Preliminary Design Phase	
Preliminary Brainstomring	5/6 - 5/7
High-Level Design Decision	5/7
Finalize Gear Ratio	5/8
Finalize Gear Dimensions	5/8
Finalize Pulley System Dimensions	5/8
Determine Electric Setup	5/8
Make Preliminary CAD	5/8
Make PDR Presentation	5/8
Preliminary Design Review	5/9
Critical Design Phase	5/10 - 5/14
Check Shop for Supplies	5/10
Dimension Hole Tolerances	5/11
Revisit/Finalize H Bridge Setup	5/11
Modify/Finalize Housing Dimensions	5/11 - 5/12
Finalize BOM	5/13
Finalize CAD	5/13
Make Gear/Shaft Stress Analysis Code	5/11 - 5/12
Make CDR Presentation	5/11 - 5/13
Finalize Dimensions/Material from Analysis	5/13
Critical Design Review	5/14
Submit Final BOM	5/14
Fabrication/Assembly Phase	5/15 - 5/21
Machine Base Plate	5/15
Machine Vertical Plates	5/15
Drill Bolt Pattern on Base Plate	5/15
Drill Mounting Holes on Vertical Plates	5/15
Machine Shafts to Proper Diameters	5/15
Predrill Bearing Holes on Vertical Plates	5/16
Ream Holes on Vertical Plates	5/16
Make Wires with Alligator Clips	5/16
Expect McMaster Order to Arrive	5/16
Expect SDP/SI Order to Arrive	5/17
Press Fit Bearings Into Vertical Plates	5/17
Wire/Solder H-Bridge Switch	5/17
Drill out Gear Bores	5/17
Ream Gear Bores	5/17
Attach Gears to Shafts	5/20
Secure Shaft Collars	5/20
Assemble Shafts onto Bearings	5/20
Secure Vertical Plates to Base Plate	5/20
Finalize Assembly	5/21
Testing Phase	5/21 - 5/22
Test Fit Housing on Apparatus	5/21
Test H-Bridge (Without Transmission)	5/21
Test Fit Motor to Input Connection	5/21
Test Run for Estimated Speed	5/21
Test Run for Estimated Torque	5/21
Debug (as needed)	5/21 - 5/22
Final Delivery	5/23
Competition Date	5/23

Enzo put together this preliminary timeline for us.

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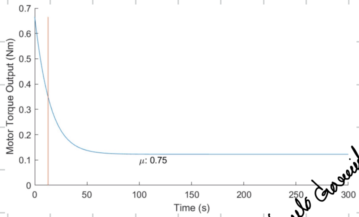
Analysis for the CDR

5/11 — 

Luis used the MATLAB script to estimate the maximum torque the motor would output, with a lower bound efficiency of ~0.75. It came out to be ~0.7 Nm (this occurs when ~~on~~ C.G. our torque-oriented stage with the 8:1 gear reduction is engaged).

Enzo is working on writing a MATLAB script from scratch that can quickly compute the Von Mises failure criteria of all of our gears and then estimate the factor of safety of each gear using this max input torque and material properties of the gears found online.

5/12 — We briefly met as a team. We think we should use a P7/h6 Interference Fit for pressing the bearing into the housing as the "Engineering Fundamentals" table suggested this force fit when special pressure requirements aren't known. We decided to make it a short meeting as there isn't much we can do today. Enzo will keep working on the gear stress analysis, and I will go to the shop tomorrow morning to consult Paul about the one-way bearing's requirements, as well as to see if we can find any of the parts in our BOM down there and claim them at half-price.

5/13 — Paul Stovall said that there isn't really a way to measure the smoothness of a shaft, but we could just grind and polish a shaft on the lathe and hope it gets close enough to the 16 μin smoothness spec called out on the one-way bearing's McMaster page. I suggested to the team that switching all our shafts to 5/16" to save on mass and reduce the number of gears and pulleys whose inner holes we'd have to bore out to 3/8" (as most of the items had 5/16" or smaller stock bore sizes). I found plenty of 5/16" ID set-screw shaft collars (more than we'd need — I claimed 4), as well as ~~the~~ a 1/4" D-shaped steel shaft (~6" long) that would work perfectly as C.G. our input

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shaft. I also found and claimed:

(4) 0.3125"×0.5"×0.1562" unopened, very smooth-running, flanged, high-precision ball-bearings that we were very lucky to find as getting them at half-price saved us $13.52

(2) 1/4" sealed ball-bearings that are also 0.5" diameter, which will make machining the holes for bearings in the walls very easy as all but two will have the same OD and thus the same fit.

(2) Set-screw shaft collars for 1/4" diameter (to secure the input shaft axially).

These were really great finds, as after our PDR, we were worried that our BOM ~~a~~ C.G. would go over-budget because we had counted some items as being "free" when they actually weren't, but because of ~~this~~ C.G. these savings, our total cost actually went down over $25.

I also emailed McMaster to get the manufacturer's spec sheet for the one-way bearings as well as the smoothness of their shafts. They* provided the spec-sheet and it revealed that in addition to the 16 μin smoothness requirement, the bearings require a shaft hardness of at least Rockwell C58. It also provided the housing bore and shaft diameter sizes, 0.6245"–0.6255" and ~~0.3475~~ ~0.3745" C.G. to 0.375" (respectively). They** also claimed their polished shafts all have 10 μin surface finishes, so we can directly use them for the one-way bearings.

* I received this email from chi.sales@mcmaster.com

** I received this email from cle.sales@mcmaster.com

<u>Group Meeting</u>: I shared the information from Paul Stovall and McMaster to the team and searched for appropriate shafts. Sebastian is working on updating the BOM. Enzo shared the results of his gear-stress-analyzing

MATLAB script. Its results seem unreasonable—it's claiming that our gears will have factors of safety with O.o.M. as high as 10^3. Mo is working on updating the CAD. I found nitride-coated, 3/8" steel shafts with HRC60, 10 μin surface finish, and a tight diametrical tolerance that would at ~~most~~ worst C.G. be smaller than the one-way bearing's minimum shaft size by only 0.0005". We can order 3, 12"-long shafts to improve the odds that at least one is properly within spec, and to have some extra in case anything goes wrong during machining. Luis checked Enzo's script and found some mistakes that ultimately brought the factors of safety of the gears down to much more reasonable numbers, ranging from 2.10–24.6. While the rest of us worked on the slides for the CDR, Enzo worked on a script to analyze the torsion of our shafts—mainly to see if we could use a 5/16" keyed aluminum shaft from the shop for our output shaft to save on mass and machining time (we wouldn't have to bore out the 40T output gear). As we intuitively suspected, the factor of safeties for the shafts were just fine, with the lowest being 3.62.

5/14— I remembered that ~~our~~ the C.G. smallest ID one-way bearings were 3/8", so we went back to 3/8" shafts.* Luckily, I checked with Paul Stovall and it seems that we can keep using the 5/16" bearings that I found in the shop yesterday by just turning down the OD of our 3/8" shafts down to 5/16". Even more luckily, I found several more of the 0.3125"×0.5"×0.1562" flanged high-precision ball-bearings, so I claimed 2 more. Thus, we were able to get all 8 of our wall ball-bearings at half-price from the shop. I also found some 3/8" shaft collars in the shop and claimed four of them. With our leftover budget we added backup gears for the 40T and 20T gears which had the lowest factors of safeties, as well as for the 12T gear which is the smallest one and is super critical to the transmission (as it is the input gear). With these updates we finalized our slides for the CDR.

* for the 2 nitride-coated shafts

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CDR

Like the PDR, we feel that our CDR went very well. There were some mistakes in the CAD but Mo said that those will be easy fixes. We'll also double-check all of our fits with Paul tomorrow before we machine all of the housing for the transmission.

Finalized BOMs:

	A	B	C	D	E	F
1	Item	Qty	Price	Total	Source	Half-Priced
2	Rocker Switch	1	$12.50	$12.50	https://www.mcmaster.com/7395K61/	
3	12 Tooth Gear	2	$3.54	$7.08	https://shop.sdp-si.com/a-1m-2-y24012.html	
4	48 Tooth Gear	2	$4.33	$8.66	https://shop.sdp-si.com/a-1m-2-y24048.html	
5	20 Tooth Gear	2	$3.84	$7.68	https://shop.sdp-si.com/a-1m-2-y24020.html	
6	40 Tooth Gear	2	$4.16	$8.32	https://shop.sdp-si.com/a-1m-2-y24040.html	
7	24 Tooth Gear	1	$3.91	$3.91	https://shop.sdp-si.com/a-1m-2-y24024.html	
8	36 Tooth Gear	1	$4.10	$4.10	https://shop.sdp-si.com/a-1m-2-y24036.html	
9	Belt Pulleys	2	$14.59	$29.18	https://shop.sdp-si.com/a-6a-3-15df03712.html	
10	Belts	1	$6.60	$6.60	https://shop.sdp-si.com/a-6r-3-028037.html	
11	One Way Bearings	2	$13.09	$26.18	https://www.mcmaster.com/2489K23/	
12	3/8" Shaft Clamping Collars	2	$6.00	$12.00	https://www.mcmaster.com/6436k13/	
13	3/8 Nitride-Coated Steel Shaft (12 in)	3	$7.36	$22.08	https://www.mcmaster.com/5936K62/	
14						
15	MATERIALS FROM LAB					
16	5/16" Open Wall Bearings	4	$3.34	$13.36	Closest Equivalent: https://www.mcmaster.com	
17	5/16" Shielded Wall Bearings	2	$3.34	$6.68	Closest Equivalent: https://www.mcmaster.com	
18	1/4" Wall Bearings	2	$2.85	$5.70	https://www.mcmaster.com/57155K323/	
19	3/8" Shaft Collars (Black-Oxide)	3	$1.01	$3.03	https://www.mcmaster.com/9414T8/	
20	3/8" Shaft Collars (Zinc-Plated)	4	$1.11	$4.44		
21	5/16" Shaft Collars	2	$0.91	$1.82	https://www.mcmaster.com/9414T7/	
22	1/4" Shaft Collars	2	$0.89	$1.78	https://www.mcmaster.com/9414T6/	
23	1/4" D Shaft (6 in.)	1	$3.92	$3.92	https://www.mcmaster.com/1327K72/	
24	3/8" Keyed Shaft (6 in.)	1	Provided	$0.00	Provided Materials	
25	12 mm Acylic Sheet	6 x 24 in.	Provided	$0.00	Provided Materials	
26	10-32 Screws	16	Provided	$0.00	Provided Materials	
27	Set screws	10	Token Fee	$2.00	Shop Materials	
28	Washers	2	Token Fee	$0.25	Shop Materials	
29	Wiring		Token fee	$1.00	Shop Materials	
30	Loc-Tite	minimal (if any)	Token Fee	$1.00	Shop Materials	
31						
32	Total			$193.27		

This is our complete BOM. It includes the half-priced items from the shop, including token-fee items.

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~~These are~~ This is C.G. the BOM we submitted for ordering from SDP/SI and McMaster:

	MEMBERS	TEAM #	PART #	DESCRIPTION	QTY	INDIVIDUAL COST	SUBTOTAL	TOTAL	URL
SDP_SI ORDER	Sebastian, Banuelos Mohammad, Arbab Enzo, Celis Camilo, Garrido Luis, Calyeca	2	1M 2-Y240	12 Tooth Gear	2	$3.54	$7.08	$75.53	https://shop.sdp-si.com/a-1m-2-y24012.html
		2	1M 2-Y240	48 Tooth Gear	2	$4.33	$8.66		https://shop.sdp-si.com/a-1m-2-y24048.html
		2	1M 2-Y240	20 Tooth Gear	2	$3.84	$7.68		https://shop.sdp-si.com/a-1m-2-y24020.html
		2	1M 2-Y240	40 Tooth Gear	2	$4.16	$8.32		https://shop.sdp-si.com/a-1m-2-y24040.html
		2	1M 2-Y240	24 Tooth Gear	1	$3.91	$3.91		https://shop.sdp-si.com/a-1m-2-y24024.html
		2	1M 2-Y240	36 Tooth Gear	1	$4.10	$4.10		https://shop.sdp-si.com/a-1m-2-y24036.html
		2	3-15DF0	Belt Pulleys	2	$14.59	$29.18		https://shop.sdp-si.com/a-6a-3-15df03712.html
		2	6R 3-0280	Belt	1	$6.60	$6.60		https://shop.sdp-si.com/a-6r-3-028037.html
		2					$0.00		
		2					$0.00		
		2					$0.00		

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	MEMBERS	TEAM #	PART #	DESCRIPTION	QTY	INDIVIDUAL COST	SUBTOTAL	TOTAL	URL
MCMASTER-CARR ORDER	Sebastian, Banuelos Mohammad, Arbab Enzo, Celis Camilo, Garrido Luis, Calyeca	2	7395K61	2D2T Switch	1	$12.50	$12.50	$83.80	https://www.mcmaster.com/7395K61/
		2	2489K23	Clutch Bearings	2	$13.09	$26.18		https://www.mcmaster.com/2489K23/
		2	6436K13	Shaft Clamps	2	$6.00	$12.00		https://www.mcmaster.com/6436K13/
		2	5936K62	3/8 Shaft	3	$11.04	$33.12		https://www.mcmaster.com/5936K62/
		2					$0.00		
		2					$0.00		
		2					$0.00		
		2					$0.00		
		2					$0.00		
		2					$0.00		
		2					$0.00		

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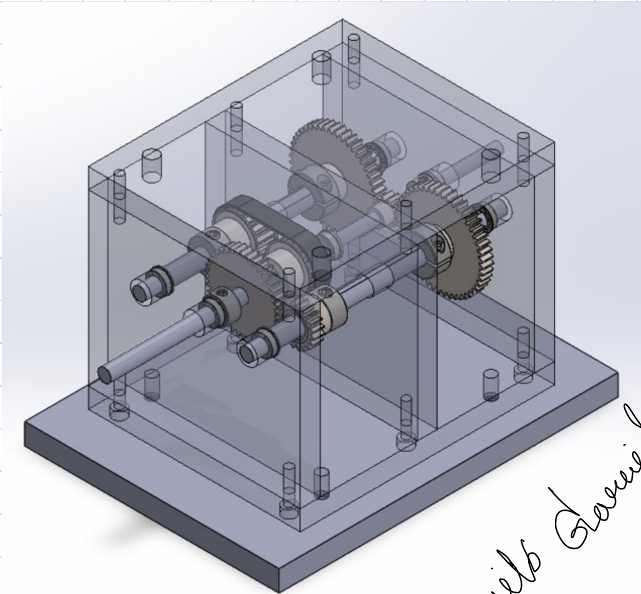

Mo completed the CAD. Here's the isometric view.

Our timeline hasn't changed since the PDR.

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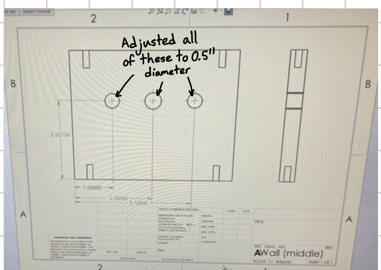
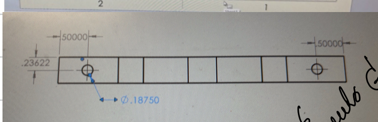
Machining

5/15 — Paul actually suggested using a U8/h5 fit for the bearings into the walls. Regardless, we would've used the same drill and reamer (there are only so many options). Also, Luis and I ~~sought~~ consulted C.G. Paul Stovall~~'s~~ C.G. about the best way to machine the walls of the transmission down to ~~side~~ C.G. the exact same size (as best as possible) to have accurate and congruent datums for the final assembly. He suggested clamping the walls together and using a flycutter to quickly cut them all at once. We used a vise stop to maintain coincident datums between the walls, floor, and ceiling to ensure proper alignment of all the components. I wrote a program on the conversational to quickly and repeatably set the positions for drilling and reaming the holes for the bearings in the walls. We used a vice stop to set the program relative to a common datum for all of the walls. However, when edge-finding the first wall, Luis and I forgot to account for the 0.1" radius of the edge-finder, causing them to be offset. Luckily we had ~~an~~ C.G. enough room on the acrylic wall to re-make the holes on a different side such that they would be properly positioned. For aesthetics, we could mill out a through-slot through the misaligned holes later on. This process took longer than expected, so we will have to make the bolt holes tomorrow.





Camilo Garrido

I used this drawing to make the mill program. For any missing dimensions, I went off of the CAD. Note that these dimensions are nominal. For the bearing holes I used the U8/h5 fit to select the reamer and drill.

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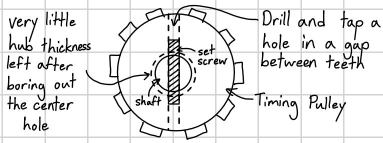
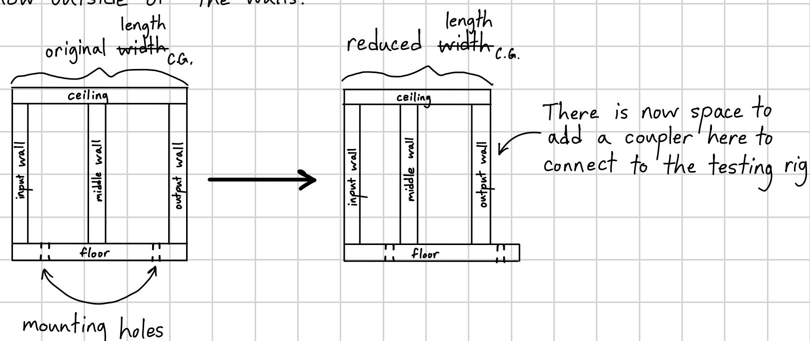
Small Design ~~Change~~ Changes C.G.

05/15 — The instructor, Dr. Mello, informed us that ~~our~~ the C.G. metal pulleys we had selected in our BOM were out of stock on SDP/SI. Luckily, we found a plastic version that had identical specs except for a smaller bore size (1/4" instead of 5/16"). We had initially chosen the metal ones over these because we saw on the CAD that when we bore one of these pulleys out to 3/8", there wouldn't be much material left on the hub to hold a set-screw. there appear to be some solutions to ~~that~~ this C.G. issue, such as drilling a set screw in between teeth of the timing pulley and through the shaft:

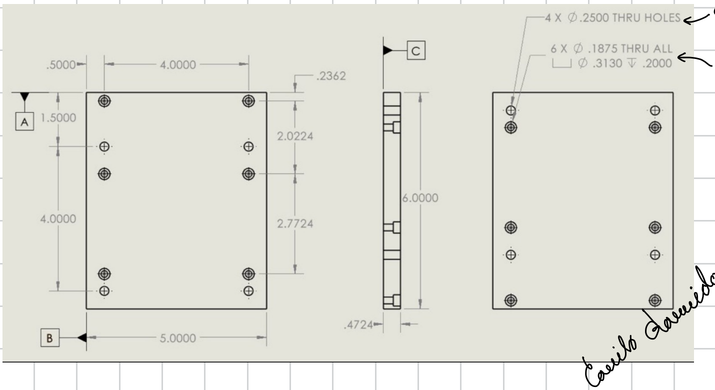


Cross-sectional Drawing

5/16 — Right before Mo and I were going to start drilling the assembly and mounting bolt holes in our transmission's housing, Sebastian pointed out an issue with our design that had flown under ~~the~~ our C.G. radar. With our current design, our transmission would have fit within the 7" tall by 6" wide by 8" long box, but would not have room to couple with the output shaft when the transmission is ~~mounted~~ bolted C.G. into the mounting holes on the testing rig because our output-facing wall sticks out too much. So, we reduced the space between our walls and shifted the mounting holes such that the two closer to our output side are now outside of the walls.



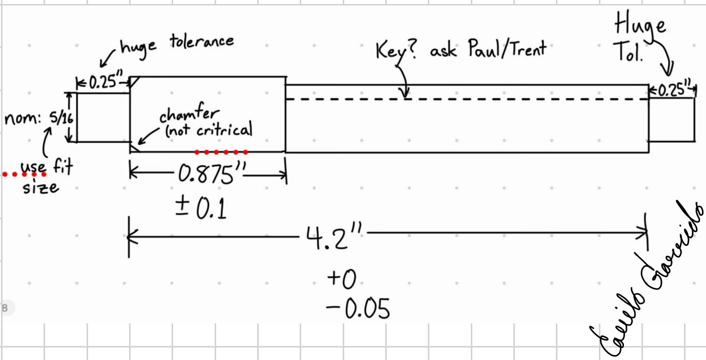
Unfortunately, this change to the housing broke many of the mates in the CAD. So, to have a reference for machining the holes into the ~~fo~~ C.G. floor and ceiling, I made this CAD drawing:



callout for the 4 mounting holes

callout for the 6 holes for the bolts to secure the walls (only need to be counterbored on the floor, not the ceiling).

I made this quick sketch of what the nitride-coated shaft's ~~should~~ C.G. important dimensions and tolerances were (since our CAD doesn't provide much detail on how to machine them) and sent it to Enzo since he'll be machining on the lathe tomorrow.



It isn't to scale or anything, but I explained the drawing to him in person to make sure we're on the same page about all of the dimensions.

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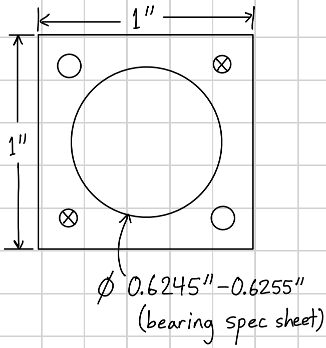
Machining Continued...

5/16 — Using the drawing on the previous page (for the floor and ceiling) and the wall drawing on page 13, I wrote a program to facilitate drilling, tapping, and reaming the holes for the mounting and assembly bolts and once again used a vise stop to ensure proper alignment. Mo assisted me throughout the machining process, and we didn't have any issues this time. The ordered parts have yet to arrive, so we can't machine anything else today.
Update: The McMaster parts have arrived, but we're still going to pause machining until tomorro

5/17 — Enzo and Sebastian turned down the ends of our 3/8" ~~nickel~~ C.G. nitride-coated steel shafts so that they would fit into the 5/16th bearings. Then they started boring out the inner holes of our gears to their respective shaft sizes. Enzo said he would wire up the electronics for quickly switching the polarity of the motor.

It turns out boring out the gears to size is much more difficult than we anticipated. Even when using a center-finding gauge on the mill as Trent Wilson had suggested to Sebastian, the shaft hole wasn't sufficiently concentric with the gear ring after being drilled and ream. We'll have to come up with a new procedure.

5/20 — Sebastian and I talked to Paul Stovall, and the best course of action for boring out the gears is to ~~use~~ C.G. insert precision gauge pins into the holes of the gears with a slight interference fit, then insert ~~some~~ C.G. part of the pin into a collet in the lathe. Then, cover ~~part o~~ C.G. the gear's hub in ~~sha~~ C.G. Sharpie ink and gently cut light passes axially along the hub until the Sharpie layer is fully removed (thus making the hubs concentric to the inner hole). Then we insert the hub into the collet of another lathe on which we drill and ream the center hole out to our desired size. The same procedure works for boring out the pulleys. Sebastian and I worked together to get this done quickly. For one of the 48T gears, we were unable to use this procedure because Sebastian had already tried to bore out ~~th~~ C.G. its center hole on the mill but it came out crooked, so we didn't have a good reference-center ~~for the~~ in which to insert a C.G. precision gauge pin. Sebastian and Luis will try to bore it out more carefully on the mill. We also asked Paul about the best way to secure each of the 48T gears onto a one-way bearing. We were hoping that it would be as easy as using Loc-Tite between the gears inner surface and the outer cage of the one-way bearing, but Paul asserted that the better solution would be to make a hub out of ~~stock~~ C.G. scrap aluminum that press-fits onto the outer cage of the one-way bearing and is secured onto the side of the gear (since plastic deforms more easily, having the acetal gear directly press-fit and glued to the one-way bearing could lead to concentricity issues). Sebastian worked with Paul to come up with this design for the aluminum hub:



Legend

○: hole for dowel pin (for locational accuracy)

⊗: tapped hole for 6-40 screw (for axially securing onto the gear).

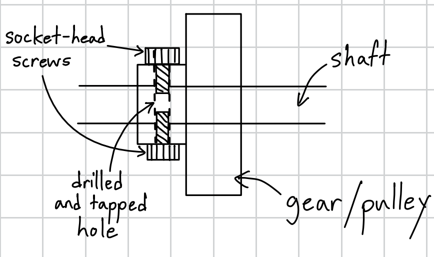
Note: the hub will be 3/8" thick, since the stock hub of the gear was 3/8", and we will mill it down to make room for this new one.

Luis and Sebastian will fabricate and assemble these today. Mo is cutting our 1/4" steel input shaft and 5/16" aluminum output shafts on the lathe.

This is the finished product! Sebastian and Luis tested it on the nitride-coated shaft and it seems to work really well. They will make the other one tomorrow.

Camilo Garrido

5/21— Enzo is flattening a section of the nitride-coated shafts according to the dimensions I called out in the sketch on page 15 (we decided to go with a flat instead of a key since its simpler to machine and we really only need it for set-screw shaft collars). Sebastian is reproducing the one-way bearing/48T gear hub, Mo is milling the ceiling down to its reduced length so that it becomes flush with our inner and outer walls after we moved them closer together (see "Small Design Changes"), and I am boring out the contingency gears so that they fit onto their respective shafts in case we decide to go with that backup plan. Sebastian tested the second 48T gear + aluminum hub assembly. Unfortunately, C.G. there are still some concentricity issues with the gear that had to be bored out on the mill, and it's pretty badly binding with our input gear as a result. I moved onto machining the (purely aesthetic) slot through the 3 bearing holes that had been misaligned on one of the walls. Mo volunteered to help me. Enzo started drilling and tapping the holes through the other gears and pulleys at their final positions on the shafts (which we had marked). At Paul's advice, we decided to ~~use~~ switch to using C.G. two small socket head screws at either side of ~~the~~ each C.G. hub to secure them to the shaft, instead of set one set screw down the middle, which wouldn't have had anything stopping it from loosening out axially due to vibrations.



Sebastian, Luis, and I finished drilling + tapping these holes for the remaining gears and pulleys. We then fully assembled the transmission

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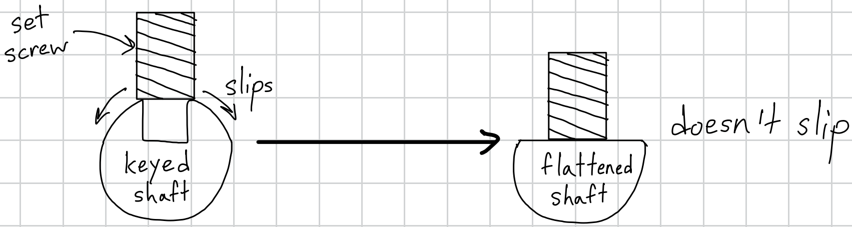
Testing

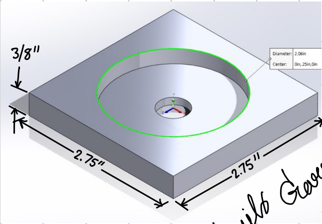
We successfully tested the transmission on the testing rig. Nothing broke! We were able to easily switch between stages, although we noticed that the switch we got from McMaster doesn't live up to its product description and lags a little when switching positions, causing the transmission to visibly slow down when switching directions. Enzo will reach out to Dr. Mello to see if we can still get the toggle switch we initially intended to buy. ~~The~~ C.G. Also, the binding between the 12T and 48T gears is very apparent and loud when the transmission is in its speed stage. We'll see if we can improve this tomorrow. We also noticed that the lovejoy coupler that ~~atach~~ C.G. attaches onto our output shaft is prone to slipping because it is tightening onto the top of the keyed shaft. Flattening the section of the shaft where this coupler sits should increase the contact area of the set-screw and resolve this issue.



We were using slo~~w~~ C.G. -mo on our cameras to count the revolutions of the output shaft to estimate our max rpm, but realized that the bike-wheel seemed to be slipping from its shaft and we don't want to mess with the testing rig to try and fix it.

Camilo Garrido

Machining Continued...



Camilo Garrido

I designed this mount that we could secure into the vice on the mill, and interference fit the gear into, to then redrill its center hole and mounting holes (for the dowels and bolts), relative to the center of the circular pocket, which we know because we machine that pocket ourselves. I consulted Paul about this, and he agreed that it could help improve the concentricity of the gear and the one-way bearing. So, Enzo, Sebastian, and I machined this mount out of scrap aluminum and redid the gear's mounting holes. However, even after reassembling everything ~~with~~ using C.G. these new holes, the gear was still binding significantly. So, I decided to also redo the hub using some more scrap aluminum from the shop and the same exact drill pattern program we had just used to make the center, bolt, and dowel holes on the 48T gear. I had help from Luis and later from Sebastian when remachining the hub. This time, when we reassembled everything, the binding was vastly reduced (though still a little noticeable).

Enzo flattened the end of our output shaft to prevent the lovejoy coupler from slipping. Also, our new switch arrived, and he wired it up.

We reassembled the transmission, and prepared to test it again.

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Testing (Round 2)

- The transmission sounded much quieter this time, indicating that the gear-binding is indeed reduced.
- The TA's came by and re-tightened the bike wheel on the testing rig so that it no longer slips, meaning that we can now get more accurate estimates of ~~a~~ C.G. our transmission's max-rpm using slo-mo to count revolutions of the output shaft.
  - We estimated $\omega_{max} \approx 485$ rpm
  - We don't have a good way to measure T_{250} without the sensor data, but if we guess it to reasonably be around 6-7 seconds, our score would range from around 69-81, which we're satisfied with. Clearly the binding is still causing substantial efficiency losses, but at this point we've already sank dozens of hours into improving it.

- We also noticed that we get this highest speed of 485 rpm only with the ceiling off. Having the ceiling on seems to reduce ω_{max} by ~10 rpm. I tried ~~mill~~ C.G. drilling out slightly larger clearance holes for the bolts in the ceiling using the mill, ~~so~~ C.G. thinking that perhaps the tight clearance holes were creating some over-constraints, but even this didn't fix the issue. So, we're just going to run the transmission without the ceiling tomorrow.

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Competition Day

Enzo asked Trent Wilson if the shop had lubricant for acetal gears, but it did not. So, we left the transmission exactly as it was.

First run – We decided to wait until our rpm plateaued on the first (high-torque) stage before switching, to build up as much angular momentum in the wheel ~~before~~ C.G. to reduce the amount of work the speed-oriented second stage has to do to reach the max rpm. The transmission exceeded our own expectations, achieving a time-to-250 rpm of only 5.8 seconds. There was a lot of noise in our rpm graph, possibly because of the binding gears causing mechanical chatter. The TA's applied a filter to "de-noise" our results, and with that we got a max rpm of 491 rpm, for a score of 84.66!

After the success of our first run, we felt we had a comfortable enough lead over the other teams to risk a modification between runs. In an effort to reduce the gear binding, I carefully shaved down the teeth on the problematic 48T gear ever so slightly. Weirdly, this made ~~the transmission~~ C.G. it feel like the transmission was sometimes running perfectly, but periodically, it would sometimes bind even worse than before. Perhaps some of the teeth were shaved unevenly or had some burs I didn't notice that would occasionally cause this binding

Second run – Our second run did not perform as well as the first, primarily because our time to 250 rpm was over 7 seconds this time around. We can't know for certain what caused this, but I suspect that it was related to shaving down the teeth on the 48T gear between rounds, as we didn't make any other intentional modifications to the transmission between runs.

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Pictured here: "Five Guys," Dr. Mello, and our transmission as it was on the day of the contest.
(Photo credit: Mabel Lu)

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Design Review/Reflection

Going into the PDR, we knew that a two-stage transmission would not offer enormous score benefits over a single-stage transmission, especially if fabrication imperfections had led to major efficiency losses. We took the risk anyway and put in the extra work because we wanted to make an innovative design that would demonstrate that, even after all of the years that this project has been around, there are still new ideas to explore. I feel that by going the extra mile — dissecting the MATLAB script, studying the one-way bearing spec sheet and combing through product descriptions on SDP/SI for appropriate parts, and consulting Trent Wilson and Paul Stovall at length about the complex machining procedures that our design required — I learned much more than I would've if we'd designed a single-stage transmission whose components required little-to-no modification and achieved a higher score than our two-stage transmission (it certainly would've been possible). ~~Our~~ On its first run, our C.G. transmission ~~was~~ achieved C.G. within the range of scores that we predicted early on. I just wish we'd bought a backup 48T gear so that we could've avoided the binding issues that hindered transmission, but we couldn't afford to buy a backup for every single gear and we couldn't have known that we would run into this problem. I'm extremely proud of my team! Our hard work paid off.

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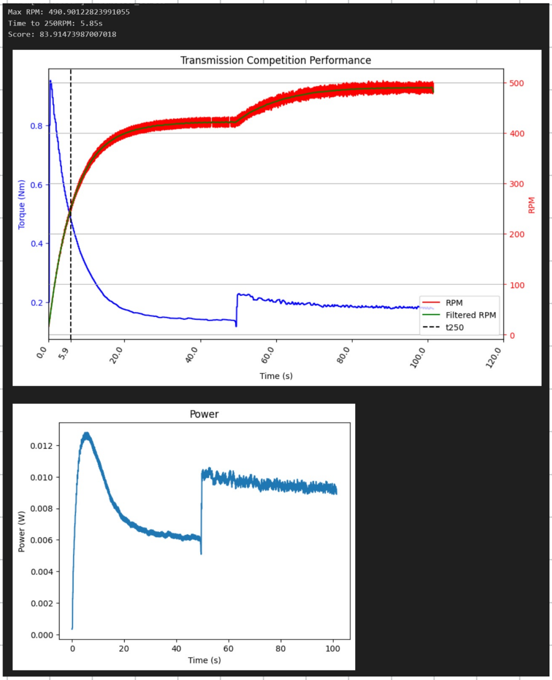
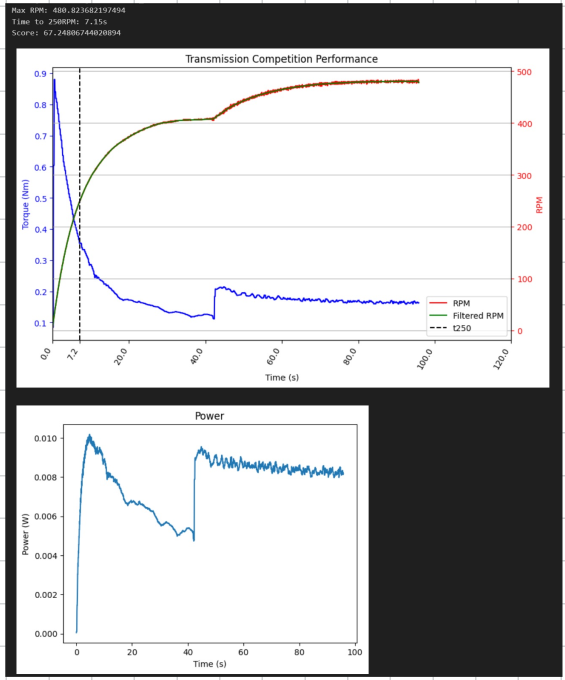
Competition Result Plots

The competition result plots were released today. You can clearly see the "boost" in rpm from when we switched to our second stage in each trial:

Trial 1



Trial 2



You can see that ~~our power~~ the transmission's C.G. output power was overall lower on our second run, but also that there was less noise in the data. My hypothesis is that shaving down the teeth of the 48T gear reduced the binding which in turn reduced the oscillations in our output power, but might've ~~caused~~ introduced C.G. some new source of inefficiency that reduced the overall magnitude of the output power (or perhaps we just didn't align the transmission as well as we did on the first run).