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MEMS 411: Torsion Tester Design Report

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Mechanical Engineering Design Project
MEMS 411, Fall 2022

Torsion Tester

The goal of this project is to provide the customer, Dr. James Jackson Potter, with a lightweight, inexpensive, and accurate alternative to modern, professional torsion-testing machines. The torsion tester developed by this team will be used in a classroom setting for design competitions on 3-D printed ABS plastic torsion bars; therefore the design also accommodate a range of functions which might be useful to the customer during testing competitions, potentially including automatic stopping at failure, a reset function, and the ability to create custom functions which can integrate into the existing function library.
To create a less expensive yet highly accurate alternative to existing machinery, a number of simplifications have been made to the design problem. The torsion testing needs only to function in one direction of rotation. The specimens may be mounted using either an existing style of dog-bone mounting or through a fitted accessory which matches the lateral faces of the specimen. Additionally, the tester needs only to function over a range from 0° to 180° degrees in deformation angle to provide a reasonable range in which both deformation and failure would occur within the specimens.

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1 Introduction

The goal of this design project is to provide Dr. James Jackson Potter with a torsion-testing machine to be used during design competitions in other courses. Torsion testing is a process by which material properties and physical limits of test specimens are determined. In general terms, the steps of executing a torsion test are as follows: a specimen is inserted into the tester gripping mechanism, secured in place for the safety of the operator and spectators, and a known torque is applied to one or both ends of the rod. As the known torque increases, a twist angle (angular deformation) begins to present within the specimen. To determine average material properties, the known torque may be correlated with the angular deformation through constitutive relations such as Hooke's Law. The physical limits of the test specimen are determined based off of the raw values of torsion and angular deformation themselves. The tester itself is assumed to be much stiffer than the specimens and therefore is assumed to be a rigid body during analysis.

This design project does not have the goal of determining material properties; instead, the primary focus is on accurately measuring angular deformation and applied torque on the specimen [1]. This simplifies the project in that the only geometry relevant to testing apparatus design is the outer face geometry with which specimens are mounted. The actual internal structure of the specimens can be completely arbitrary with respect to the apparatus design. There are a number of additional considerations to be made in designing a device which is capable of accurately measuring these two quantities, including portability (bounding box size and weight), accommodation of varying specimen geometry, power sourcing, controller style, domains of torque and angular deformation, unidirectionality, and compatibility with common fitting sizes ($\frac{1}{4}$-20 imperial) [1].

Overall, the customer is seeking a highly portable, cost-efficient yet accurate alternative to professional-grade testing machines. This device will be used for testing on a set of specimens no larger in bounding size than 8"x2"x2" and on materials which will be relatively pliable (much less stiff than hard metals, ex. PLA or ABS) [1].

2 Problem Understanding

2.1 Existing Devices

In researching existing torsion testing machines with similar design parameters, a few specific professional models bear a striking resemblance to some of the requirements outlined by Dr. Potter. These devices are shown below along with parameters which may be useful in this design project.

2.1.1 Existing Device #1: 130AT Axial Torsion Test Machine

Figure 1: 130AT Information Page Image, no higher resolution image provided (Source: TestResources, Inc.)

Link: https://www.testresources.net/literature/130at-axial-torsional-test-machine.pdf
Description: The 130AT test machine features a vertical design with a small horizontal footprint and enables up to 73.75 $lbf \cdot ft$ of torque and up to 2250 lbf of axial force. Both static and cyclic loading styles are enabled by this machine, however customization of loading patterns is not listed as a feature. The 130AT provides high resolution data capture of torque and angular displacement as well as a channel for strain measurement. Despite the parallels in measurement capability requirements between the 130AT and this design project, the vertical footprint of the 130AT is far too large (due to its axial capabilities), its weight is beyond the limits for portability, and the cost associated with the unit is high.

2.1.2 Existing Device #2: MT2 Low Capacity Torsion Testing System

Figure 2: MT2 Information Page Image, no higher resolution image provided (Source: TestResources, Inc.)

Link: https://www.instron.com/-/media/literature-library/products/2013/06/torsion-testing-system.pdf
Description: The MT2 torsion testing system demonstrates a variety of capabilities which would be useful to our customer. The MT2 is capable of exerting 166 $lbf \cdot ft$ of torque (above the customer's requirement) while maintaining a fairly high space efficiency. It uses a chuck design to grip specimens; if efficient, electrically driven, and able to facilitate quick changing of specimens, this design could supersede the fitted mount design (with customer approval). Knowing the importance of quick remove and replacement of specimens may mean that the chuck design, although reliable, would not satisfy the customer. The MT2 also features a range of functions for testing, including not only the general "start," "stop," and speed functions, but also a "reset," and a fatigue analysis mode.

2.1.3 Existing Device #3: 530E2 All-Electric Dynamic Axial Torsion Test System

Figure 3: 530E2 Information Page Image, no higher resolution image provided (Source: TestResources, Inc.)

Link: https://www.testresources.net/literature/530e2-family.pdf
Description: The third device which may be useful when making design decisions is the 530E2 Dynamic Axial Torsion Test System. This system is capable of both axial and torsional testing. Although it focuses much more heavily on the axial component of loading, the design is horizontally space efficient (1 ft^2 footprint), is capable of dynamically changing its load up to 15 times per second, is electrically powered, and may rotate its head up to 20 full revolutions. The extremely high range of motion implies a strong design decision to accommodate it. Dr. Potter is seeking a tester with a range of motion up to 180°, however a higher range could potentially allow for longer specimens as well as more pliable materials, if needed.

2.2 Patents

2.2.1 Pre-existing torsion tester equipped with motion detection and torque measurement capability (US20140208863A1)

Patent US20140208863A1 describes a torsion tester consisting of a series of "driving units" that can interface with three or more input or output shafts of a test device. It specifies that each driving unit is comprised of a drive shaft, a rotation detector, and a torque sensor; this is a setup that our design will most likely share. It also details a controller that is configured to set the rotational frequency and torque of each driving unit individually. While our design will not have multiple driving units, it will require a controller to dictate the use of the machine.

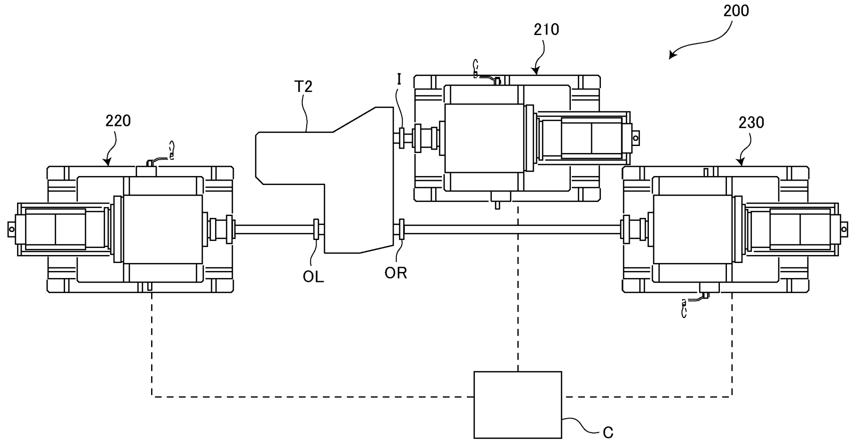


Figure 4: Patent Image for Pre-existing Torsion Tester

2.2.2 Electronic device torsion testing mechanism description and instrumentation guideline (US7454980B2)

Patent US7454980B2 also describes a torsion tester, but goes into further detail about the structure and testing method than the previous patent. Additionally, this patent describes the torsional testing of electronic devices in particular and testing them incrementally as they are being twisted to verify functionality. For the structure of the tester, it describes a base attached to two fixtures, where the second fixture has an attached lever that is pushed by an actuator. It also describes having two rotary bearings that connect the second fixture to the base in order to limit the relative motion between the two fixtures to a fixed line. It specifies using a linear displacement gauge to measure displacement as the electronic device is incrementally twisted.

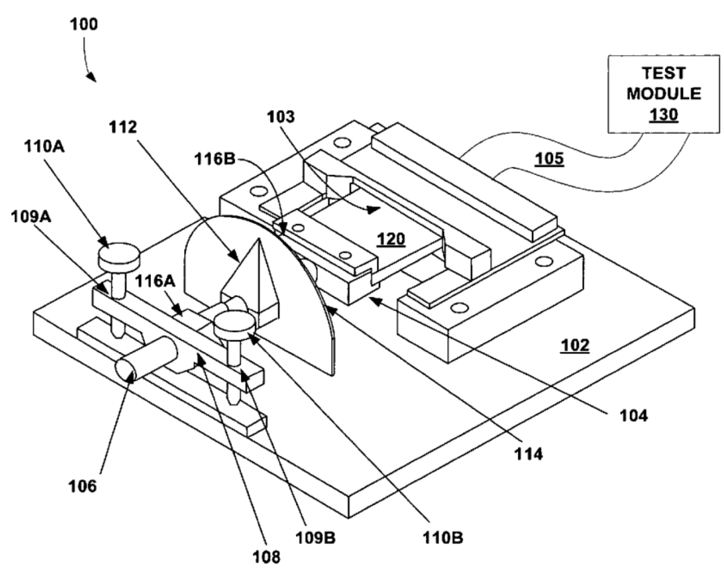


Figure 5: Patent Image for Electronics Torsion Testing Mechanism Description

2.3 Codes & Standards

2.3.1 Torsion Test - Optimal test conditions (ASTM A938)

This international standard sets specifications for a standard torsion test of a metallic wire. It specifies that the grips and/or chuck jaws of the torsion tester should remain coaxial throughout the duration of the test. The standard also provides information regarding optimal specimen length and speeds. While the standard determines success by number of successful revolutions, it will likely still be useful in a smaller scale scenario such as with PLA material. A key aspect of such a test is to ensure that the specimen does not deflect laterally, as this could result in erroneous results. This should be helpful when designing our torsion tester because even though the specifics of the standardized torsion test may not be entirely applicable to a portable environment, the general design concepts can be of great use.

2.3.2 Machines - General requirements (OSHA 1910.212)

This standard sets requirements for all machines, regardless of purpose. This subsection mainly focuses on what types of guards/shielding need to be applied to said machines. Most importantly, a machine which is to modify a material in some capacity should have a guard and or shielding in the so called "danger zone" where potential debris could cause harm to the user. As such, the covering should be implemented at the point of material handling, and in a way that such injuries and hazards can be prevented, while simultaneously not serving as a hazard itself or inhibiting use of the machine. This should be applicable to our portable torsion tester because if the tester is to test until failure, there will need to be some sort of shielding to prevent the scattering of debris.

2.4 User Needs

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Jolley 110, Washington University in St. Louis, Danforth Campus
Date: September 12^{th}, 2022
Setting: We discussed various preliminary aspects of the torsion tester - design constraints, ideal metrics, and concept generation. The whole interview was conducted in the workshop, and took ~40 min. Each of Dr. Potters responses were transcribed below from his point of view.

Interview Notes:
Is there an acceptable weight and size for portability?

- The acceptable weight would be about 20 lbs, ideal would be 10 lbs. I care about it medium. I'd like it to fit in an IKEA bag pretty well.

Is there a specific material these specimens will be made out of?

- Most specimens will be 3D printed out of PLA plastic. 8" by 3" is the largest idea for a specimen, potentially in a dogbone shape.

What shapes/sizes of specimens must we accommodate?

- I'll make the mounting plate for the various shapes of specimens if you can have a threaded holes for the mounting plate to attach to the torsion tester. Specimens will likely be an extruded 2D shape when viewed from above.

What magnitudes of angular deformation are we expecting to track?

- It would be fun to get accurate failure tests. If the specimens were put through SolidWorks, the simulation would definitely stay in the linear regime. I would say 15-20° base, and hope for 180°. 90° would be acceptable.

What is a preffered power source?

- It can be plugged into the wall.

How precise does the instrumentation need to be?

- I care more about accuracy than twisting capability. Assuming that the testing occurs in a small angle domain, about 12 ish degrees or so, 0.1° is the minimum precision, 0.01° would be great.

Are there preferred units for the instrumentation?

- No preference, maybe Imperial out of habit?

Is covering of the mechanism required?

- Not a concern until close to the end of the project if something is dangerous. Doesn't have to be child safe.

How much stiffer than the samples does the device need to be?

- Very very stiff.

Are there any requirements for the digital display?

- Arduino console should be good. The device should be controllable by these buttons I have, but it does not need to be super friendly.

Anything else?

- The bolts for the attachment plate should be $\frac{1}{4}$-20 bolts. The torsion tester also only needs to twist in one direction. A Leonardo for the electronics should work well too.

2.4.2 Interpreted User Needs

The following table details the needs of the customer and their importance to the customer.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	TT is portable	5
2	TT is strong enough to resist torsional loads	5
3	TT is stiff to resist angular deflection	5
4	TT can measure the torque magnitude and angular displacement of the load applicator accurately	4
5	TT's mechanism is covered	1
6	TT is user friendly	2
7	TT is lightweight	3
8	TT is fast	2
9	TT is capable of inducing large torques	2
10	TT is capable of twisting to large angles of deformation	3
11	TT is able to attach a mounting plate to be designed by the customer	5

These interpreted customer needs were then translated to quantifiable design metrics shown in the next section.

2.5 Design Metrics

The following table displays the quantifiable design metrics in terms of acceptable and ideal measurements as well as the associated need from Table 1 for each metric.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1,7	TT weight	lb	< 20	< 10
2	1	TT height	in	< 8 (approx)	
3	1	TT base dimesnion	in	<12 x 18 (approx)	
4	8	TT duration of testing	sec	< 20	< 10
5	9	TT maximum induced torque	lb-ft	pending CAD study	50
6	3	TT maximum endured torque	lb-ft	>> 50	
7	10	TT maximum twist angle	deg	< 90	< 180
8	4	TT measurment precision	deg	< 0.1	< 0.01

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

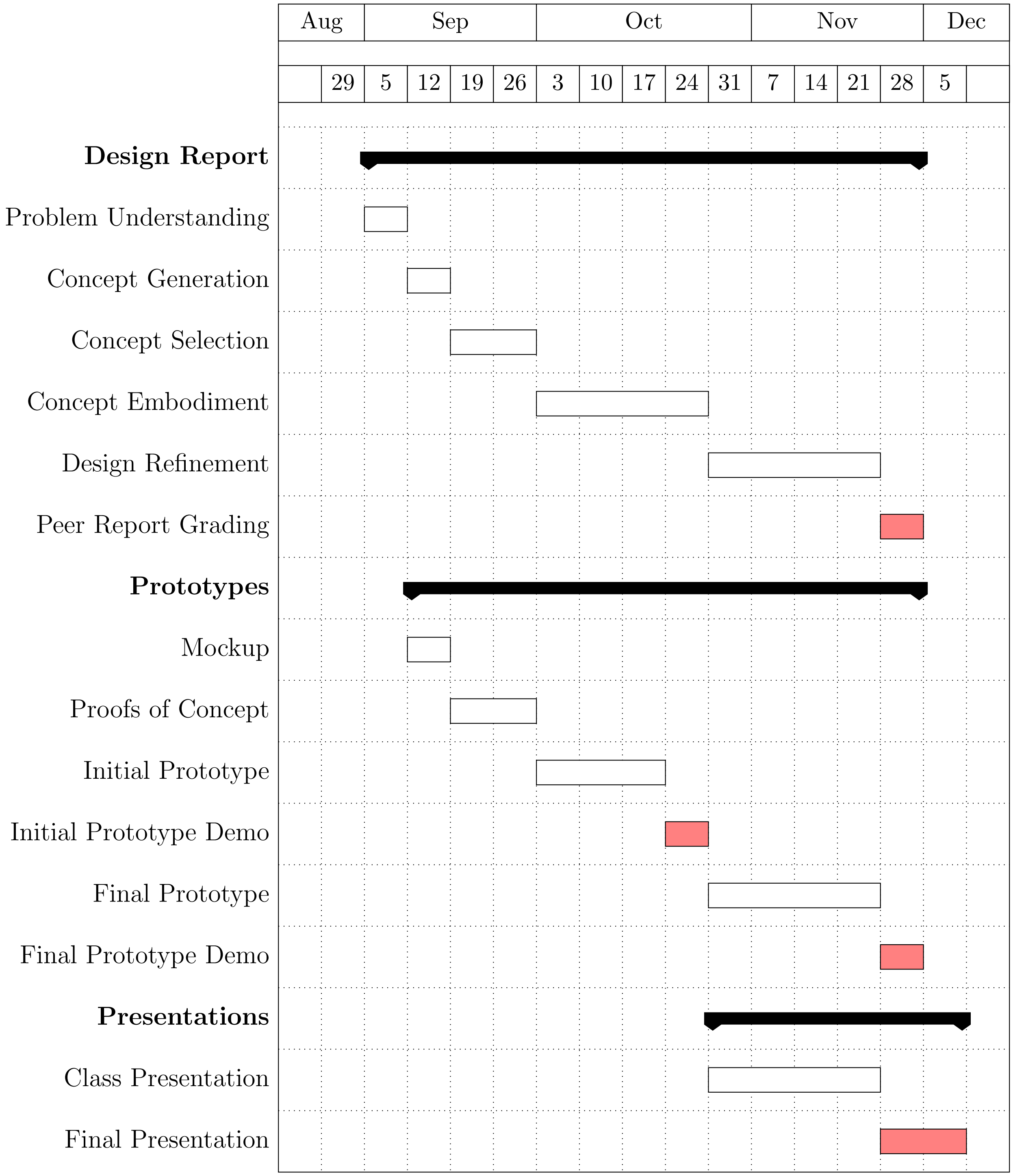


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

A general mockup prototype of the torsion testing machine was created to determine which aspects of the machine would be most feasible, which would be difficult to implement, and how the components would fit together in the most general sense. The mockup shown below in Fig. 7 was build from cardboard sheets, Styrofoam, wooden dowels, and hot glue.

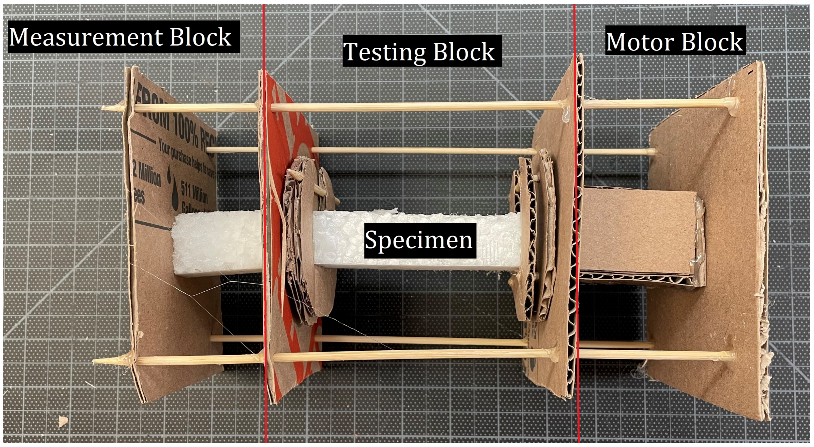


Figure 7: Side view of mockup prototype

The side view shows the general structure of our mockup which is set of three distinct sections: a motor block (right), the testing block (middle), and a measurement block (left). The motor block holds a representation of a motor, gearbox, and Arduino mount; each of these components will be mounted directly to the rigid sides of the motor block and powered through wires which exit the right wall. The motor block will also include a method for measuring angular displacement at high precision. The motor block will be coupled to the right fitted specimen holder using bolts, as can be seen below in Fig. 8

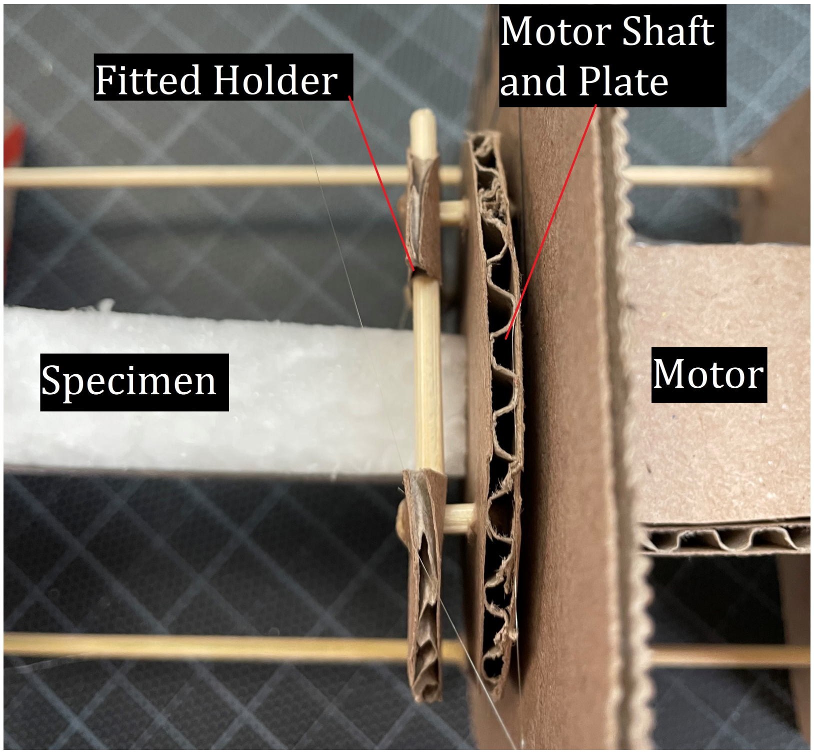


Figure 8: Top view of mockup prototype coupling between motor shaft and fitted holder.

The specimen will be inserted into the fitted specimen holders (one for each side) and a pin (represented by a wooden dowel, as seen in Fig. 8, will be inserted into the fitted holder to keep the specimen secure and safely in place. The opposite side of the specimen is similarly secured into a fitted holder; however this holder is coupled to a shaft which enters the measurement block on the left, represented by the leftmost Styrofoam block, as seen below in Fig. 9. This block is a representation of a collection of machinery which includes a method for measuring torque, either by determining the load distribution along a load cell, or by using an extremely stiff linear-deflection meter matched with an arc length integration.

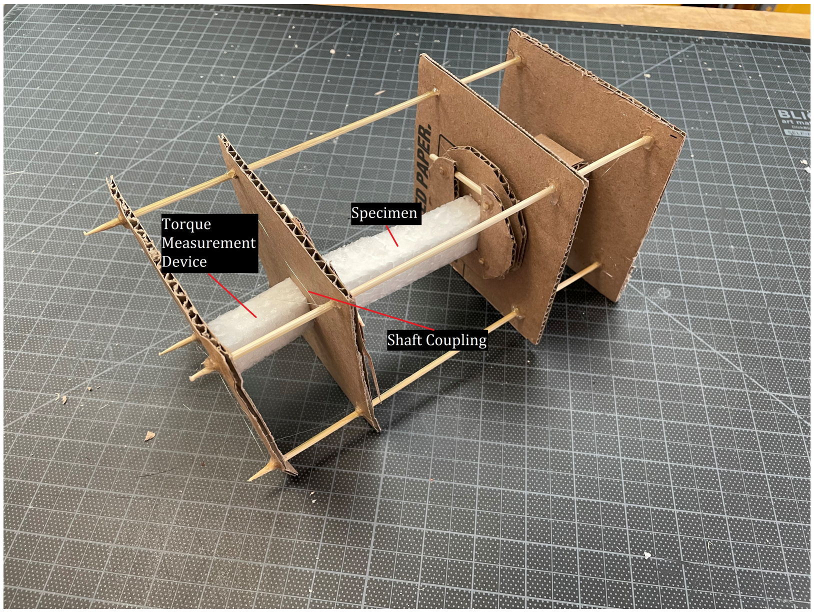


Figure 9: Isometric view of mockup prototype, showing measurement block.

Some additional features, including cross-supports to prevent deflection and twisting of the base, the internals of the measurement and torque-applying devices, as well as wiring have been left out of the mockup due to time and material constraints. The mockup is also at about 3/4 scale relative to the real prototype and its dimensions are not to scale relative to those of the real device.

3.2 Functional Decomposition

Fig. 10 represents the function tree for the portable torsion tester, broken down into its sub-functions. This list of functions is not exhaustive, but comprises most of the main goals and necessities for the customer.

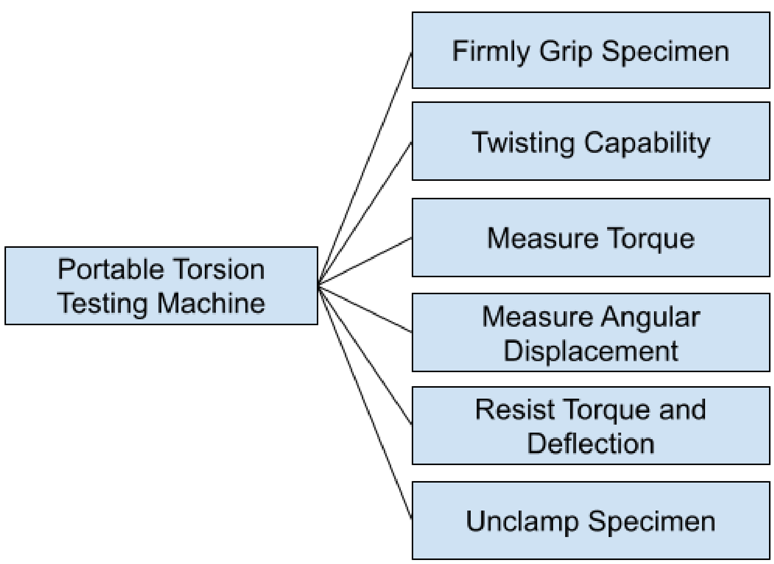


Figure 10: Function tree for the torsion tester.

3.3 Morphological Chart

Shown below in Fig. 11 is our morphological chart for our torsion tester given the six specified functions.

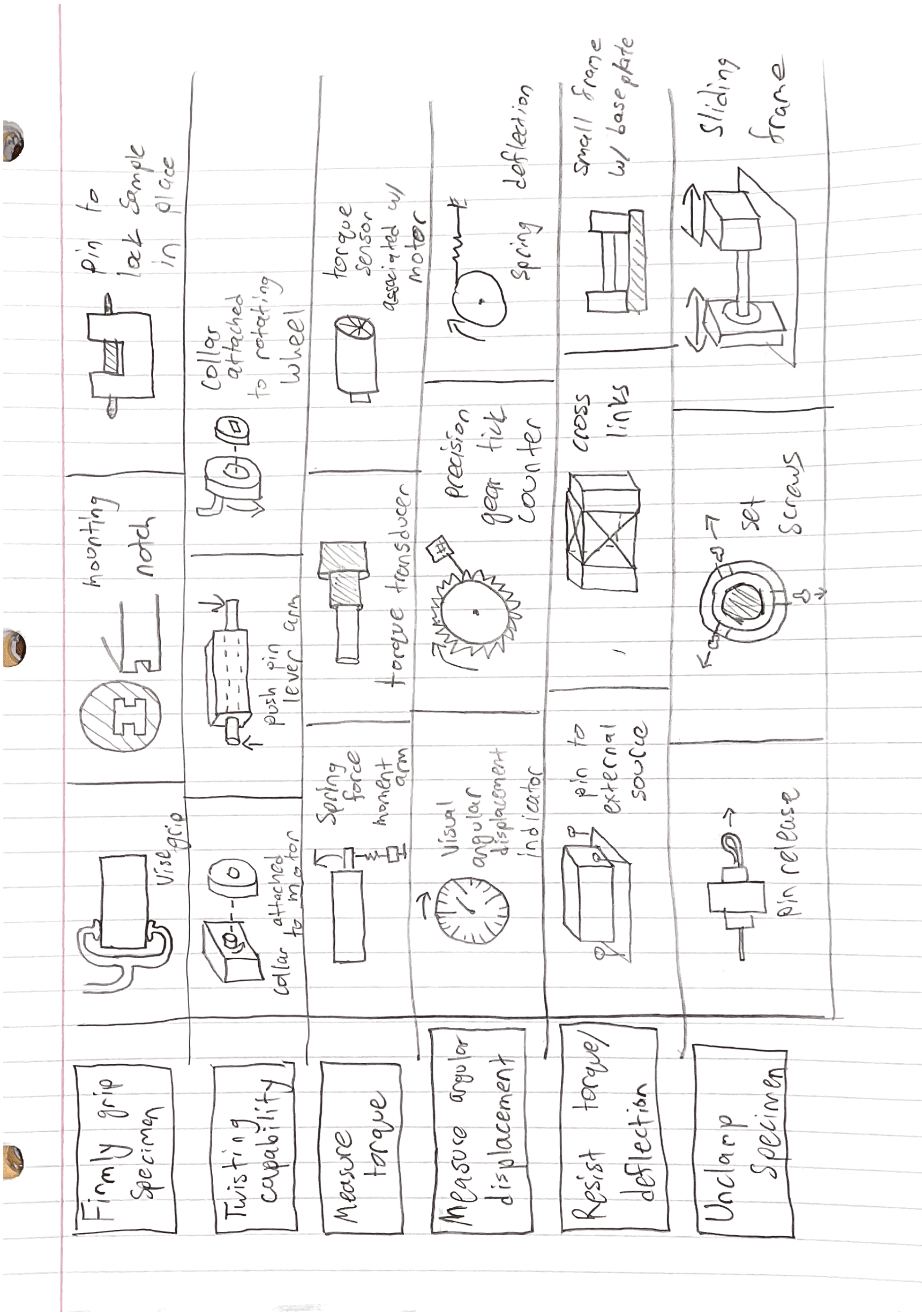


Figure 11: Morphological Chart for Torsion Tester

3.4 Alternative Design Concepts

3.4.1 Concept #1: Spring Cleaning

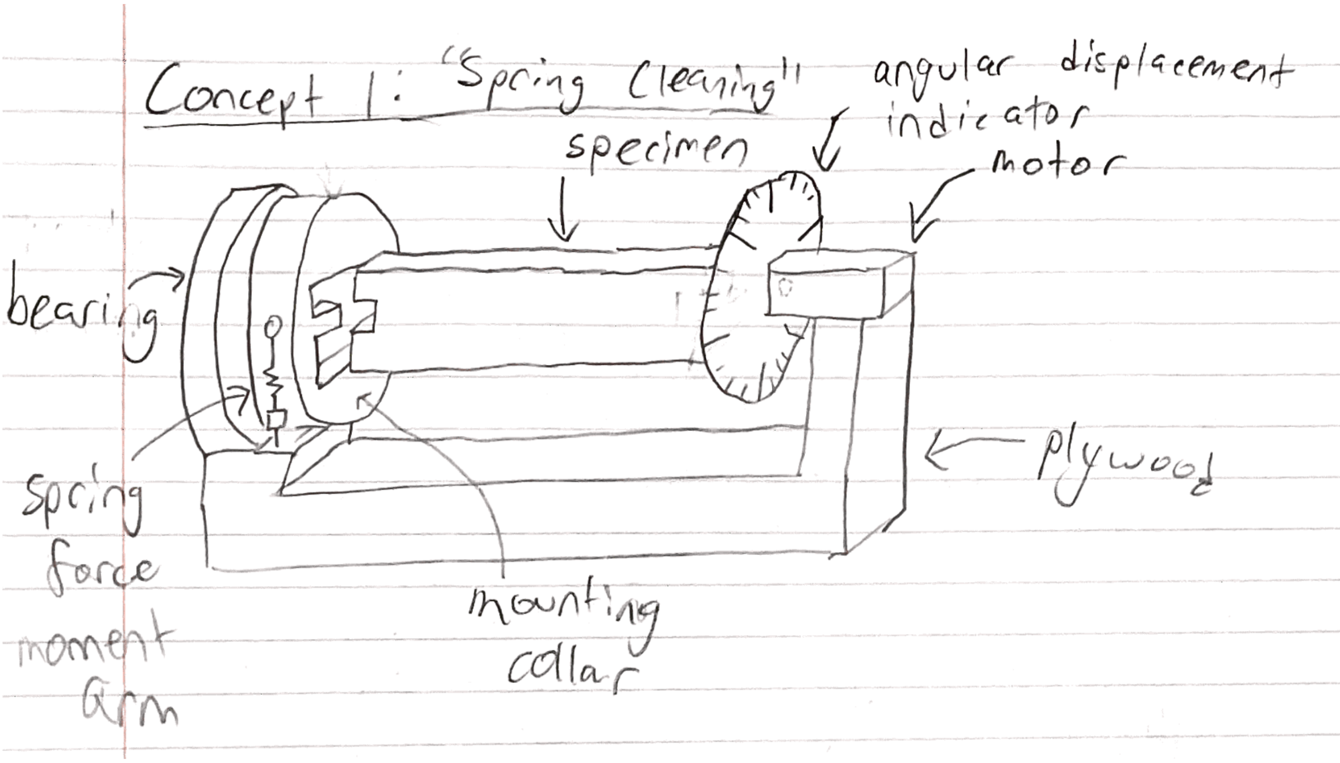


Figure 12: Concept 1: Spring Cleaning

Description: The first concept utilizes a spring force moment arm to calculate the torque. The other end is where the motor mount attaches directly to the specimen attachment plate to twist the specimen while an angular displacement indicator allows for visual inspection of the angular displacement of the specimen. The specimen is mounted to the system via a notch in the specimen attachment plate.

3.4.2 Concept #2: Rack + Pinion Internal Systems

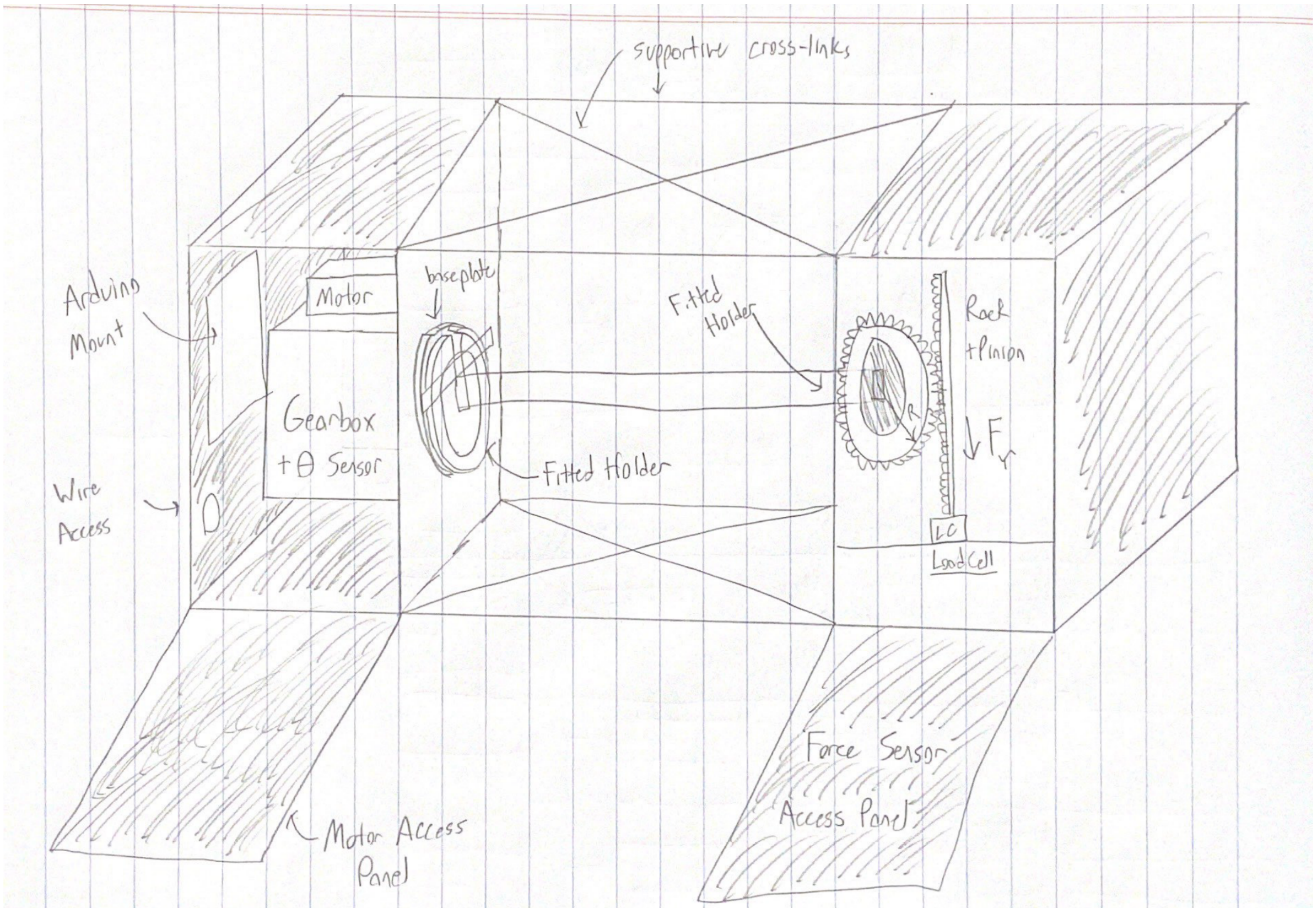


Figure 13: Rack + Pinion Internal Systems

Description: This second concept measures the torque via a load cell attached to a rack + pinion mechanism, which connects to a gear at the end of the specimen holder attachment. The specimen is inserted into the holder by a notch that cuts through the holder, and the holder is connected to a separate baseplate that connects to the gearbox. All of the systems are covered by walls and the two blocks of machinery are connected by supportive cross-links.

3.4.3 Concept #3: Collapsible Supports

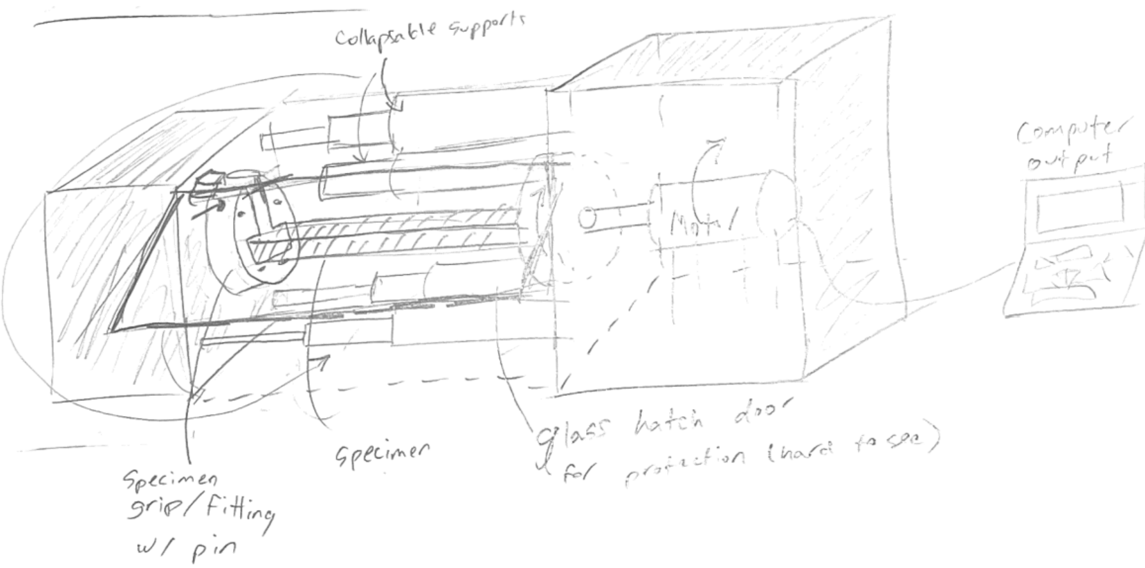


Figure 14: Collapsible Supports

Description: The third concept utilizes collapsible supports to insert specimens of different sizes into the machine. To secure the specimen in place, this concept utilizes a pin to ensure the specimen is fixed. Additionally, this concept relies on the motor output to measure torque and angular displacement, which is connected to a computer to output data.

3.4.4 Concept #4: Torsion Gauge with Double Plates

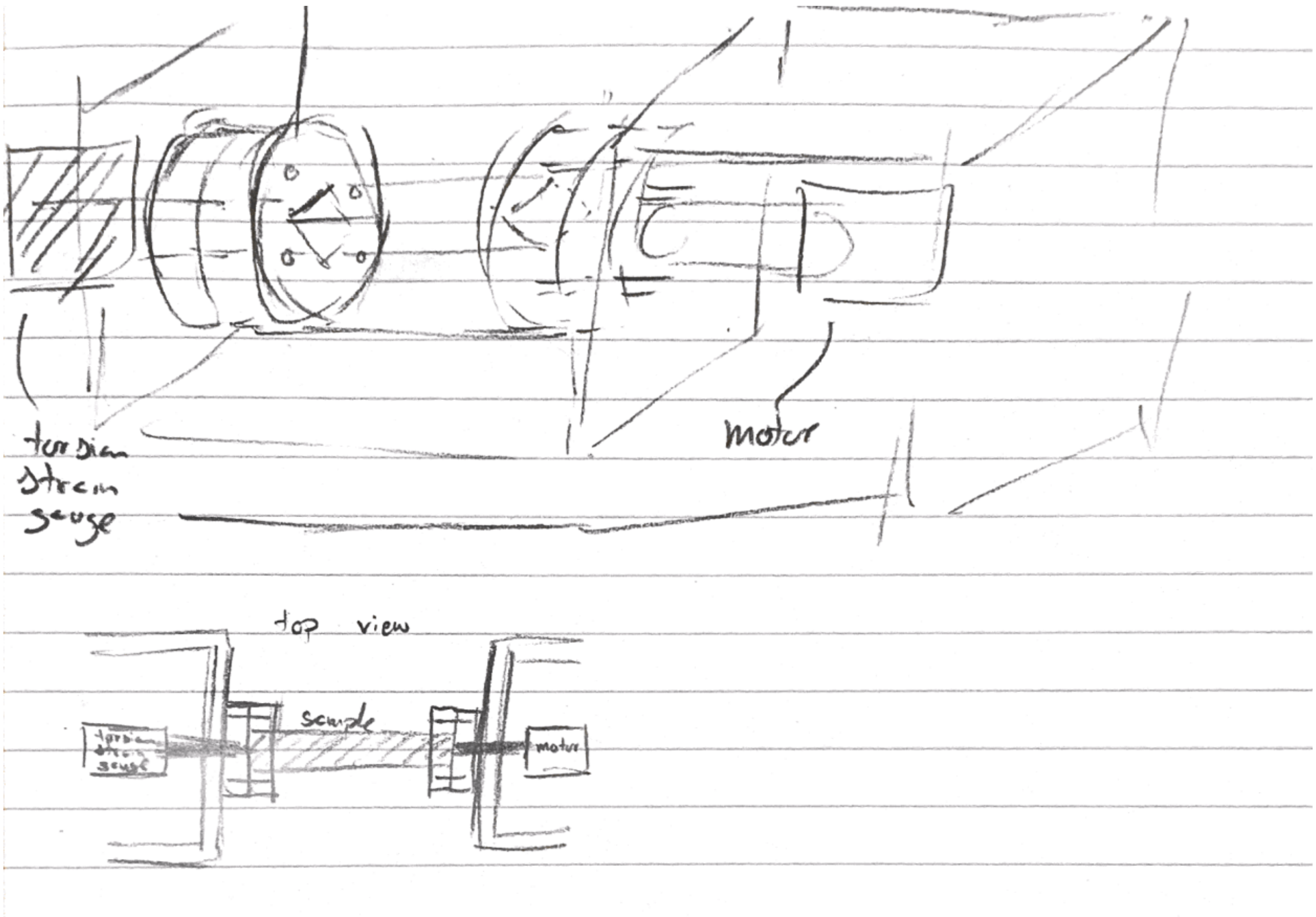


Figure 15: Torsion Gauge with Double Plates

<u>Description</u>: This fourth concept utilizes a torsion strain gauge mounted to a wall and attached to the central rotary shaft of the system to measure torque and angular displacement. This central rotary shaft is connected to the first of two plates. This first plate is bolted to a second plate, which is not connected directly to the central rotary shaft but instead holds the specimen. This setup is mirrored on the opposite side to attach the motor to a separate central rotary shaft.

4 Concept Selection

4.1 Selection Criteria

Shown below in Fig. 16 is the Analytic Hierarchy Process that we used to determine the weights for our weighted scoring matrix. The chosen descriptors in this process cover the most important characteristics that we want included in our final product.

	Portable	Stiff	Precise	Torque Range	User-Friendly		Row Total	Weight Value	Weight (%)
Portable	1.00	0.20	1.00	0.33	3.00		5.53	0.13	12.83
Stiff	5.00	1.00	3.00	3.00	5.00		17.00	0.39	39.41
Precise	1.00	0.33	1.00	1.00	5.00		8.33	0.19	19.32
Torque Range	3.00	0.33	1.00	1.00	5.00		10.33	0.24	23.96
User-Friendly	0.33	0.20	0.20	0.20	1.00		1.93	0.04	4.48
						Column Total:	**43.13**	**1.00**	**100.00**

Figure 16: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Shown below in Fig. 17 is the Weighted Scoring Matrix that we used to decide which design we would be pursuing for our prototype.

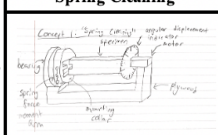
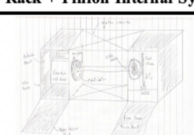
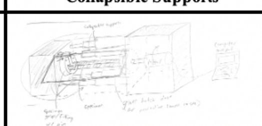
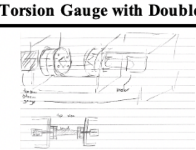
Alternative Design Concepts		**Spring Cleaning**		**Rack + Pinion Internal Systems**		**Collapsible Supports**		**Torsion Gauge with Double Plates**	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Portable	12.83	3	0.38	2	0.26	4	0.51	2	0.26
Stiff	39.41	3	1.18	5	1.97	3	1.18	4	1.58
Precise	19.32	3	0.58	3	0.58	3	0.58	4	0.77
Torque Range	23.96	3	0.72	4	0.96	3	0.72	4	0.96
User-Friendly	4.48	3	0.13	3	0.13	2	0.09	3	0.13
	Total score	**3.000**		**3.900**		**3.083**		**3.699**	
	Rank	**4**		**1**		**3**		**2**	

Figure 17: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

For this concept evaluation, the "Spring Cleaning" torsion tester was selected as a baseline for evaluation due to its simplicity in design, as well as ability to satisfy all criteria well. Out of the other three designs, the "Rack and Pinion" design scored the best in the weighted scoring matrix. Compared to the "Spring Cleaning" design, this tester was less portable due to the larger number of internal components which contribute to a greater size. These extra parts, however, contribute to a very high stiffness (the highest amongst all the models). The precision of this design was about even with the baseline design. For the winning design, the torque produced is calculated based on the measured force from the rack and pinion system, allowing easier use of a load cell. However, there could be some discrepancy between the true torque and the calculated torque due to the geometry of the rack-and-pinion system. Once again, the size and stiffness of this winning design contributes to the greater range of torque values that it can measure and withstand, ultimately proving more valuable in meeting the customer's needs. Finally, in terms of user-friendliness, this design is about as functionally intuitive as the baseline design; the operation of the torsion tester is no more complicated than the baseline nor are the inputs complex. Other designs did have standout performances in other areas, such as the "Collapsible Supports" design's increased portability, or the "Torsion Gauge with Double Plates" design's increased precision in torque measurement. However, due to the substantially larger importance of stiffness and torque range to a design, the "Rack and Pinion" design proved the most effective design.

4.4 Engineering Models/Relationships

4.4.1 Model 1: Load Cell Calibration by Geometry

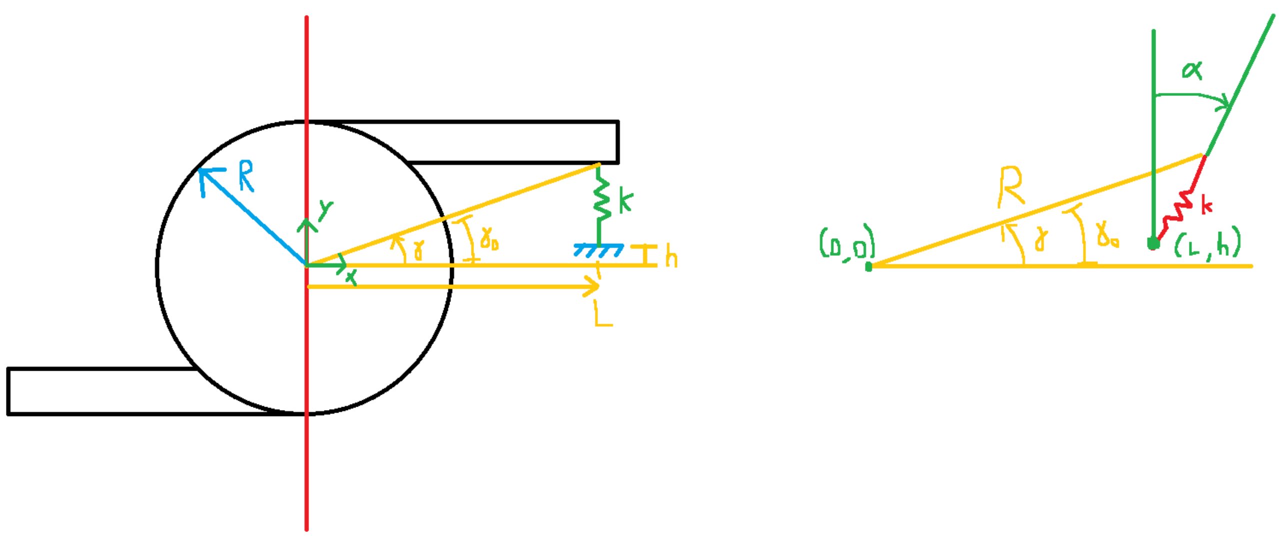


Figure 18: Graphical representation of Load Cell Calibration

$$\alpha = \arctan\left(\frac{R \cdot sin(\theta) - h}{R \cdot cos(\theta) - L}\right) \tag{1}$$

$$F_{ky} = F_k \cdot cos(\alpha) = (\delta_0 - \delta)k \cdot cos(\alpha) \tag{2}$$

$$F_{ky} = \left(\delta_0 - \left\| \begin{bmatrix} cos(\gamma) & -sin(\gamma) & 0 \\ sin(\gamma) & cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ h \\ 0 \end{bmatrix} \right\| \right) k \cdot cos \left(\arctan \left(\frac{R \cdot sin(\theta) - h}{R \cdot cos(\theta) - L} \right) \right) \tag{3}$$

This model describes the load experienced by the load cell in the original axial direction of the spring. This accommodates for the potential slight rotation of the loading arm with respect to the original load cell location. This will help us attain the 0.01° precision hoped for by the customer.

4.4.2 Model 2: Torsion Beam Model

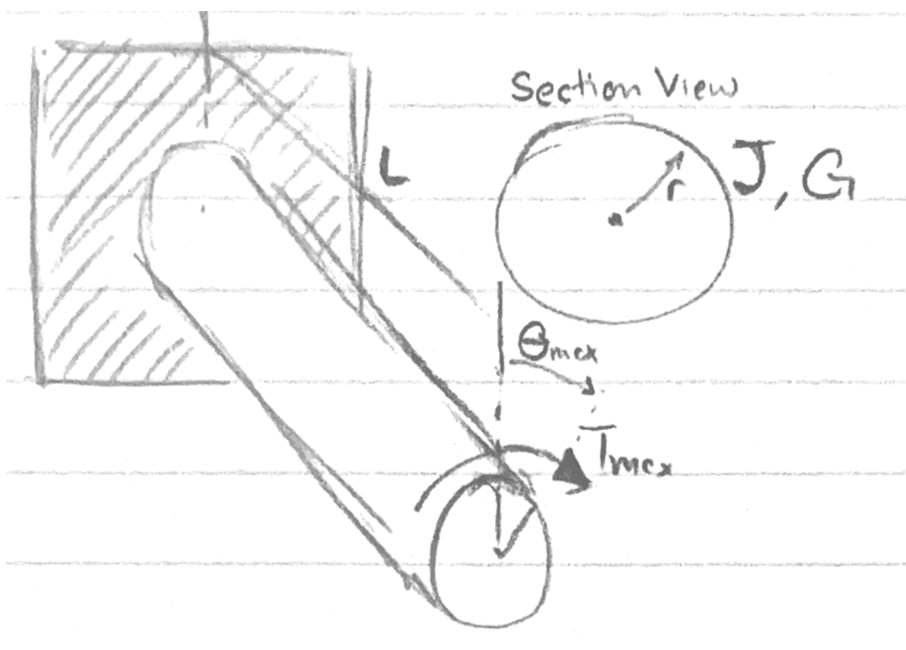


Figure 19: Simplified beam torsion model, representative of the specimen's experienced torsion attached to a fixed end

$$T_{max} = \frac{\tau_y J}{r} \tag{4}$$

$$\theta_{max} = \frac{T_{max} L}{GJ} \tag{5}$$

This model describes the maximum torque T_{max} and angular displacement θ_{max} the specimen can experience before yielding, modeled as a solid cylindrical beam, with the following given properties: yield shear stress τ_y, polar moment of inertia J, radius (location of material furthest from central axis) r, length of specimen L, and shear modulus G.

4.4.3 Model 3: Simply Supported Overhang Model

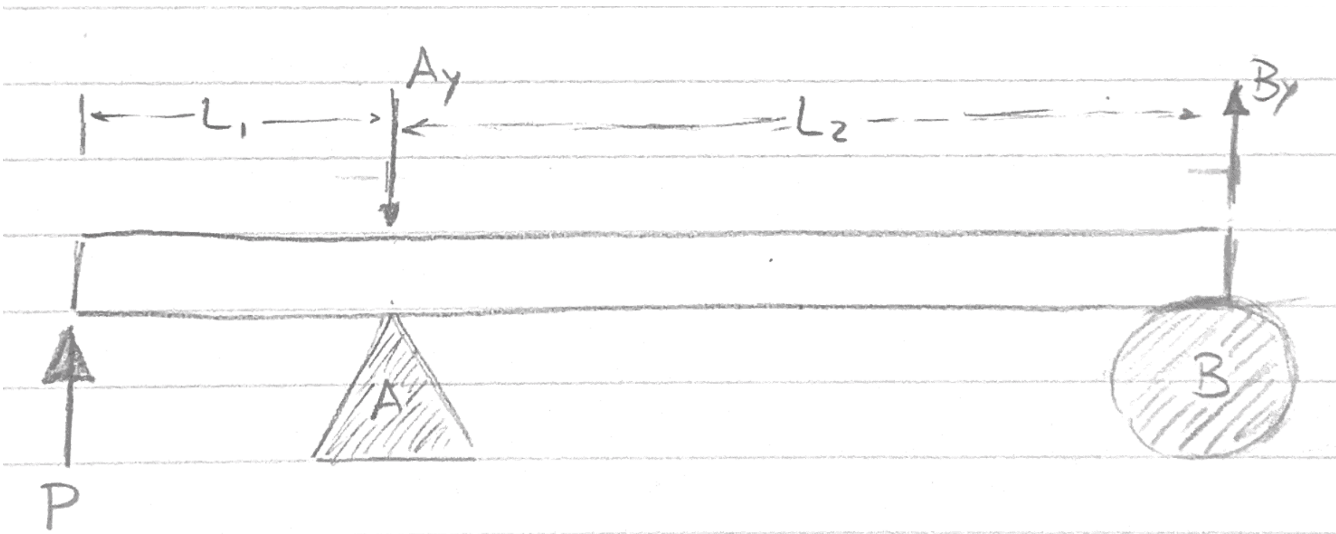


Figure 20: Simplified overhanging simply supported beam system, representing the specimen/axle system as a beam supported by the wall structures as fixtures

$$A_y = \frac{L_1 P}{L_2} \tag{6}$$

$$B_y = P\left(\frac{L_1}{L_2} - 1\right) \tag{7}$$

This model describes the axle/specimen system as an overhang simply supported beam structure if the gearbox motor applies torque by vertical force to one side of the axle system, causing a vertical loading on the system. This loading is represented with load P, and the wall ball bearings are represented with fixtures A and B, and this model determines the vertical reactions at the fixtures A_y and B_y to find the loads experienced by the walls of the system. L_1 is the length between the applied load P and the fixture A; L_2 is the length between fixtures A and B.

5 Concept Embodiment

5.1 Initial Embodiment

Figure 21 shows front, top, and right views of the torsion tester prototype along with some overall dimensions. Figure 22 shows a large isometric view of the prototype. Figure 23 shows an exploded view of the prototype along with a Bill of Materials.

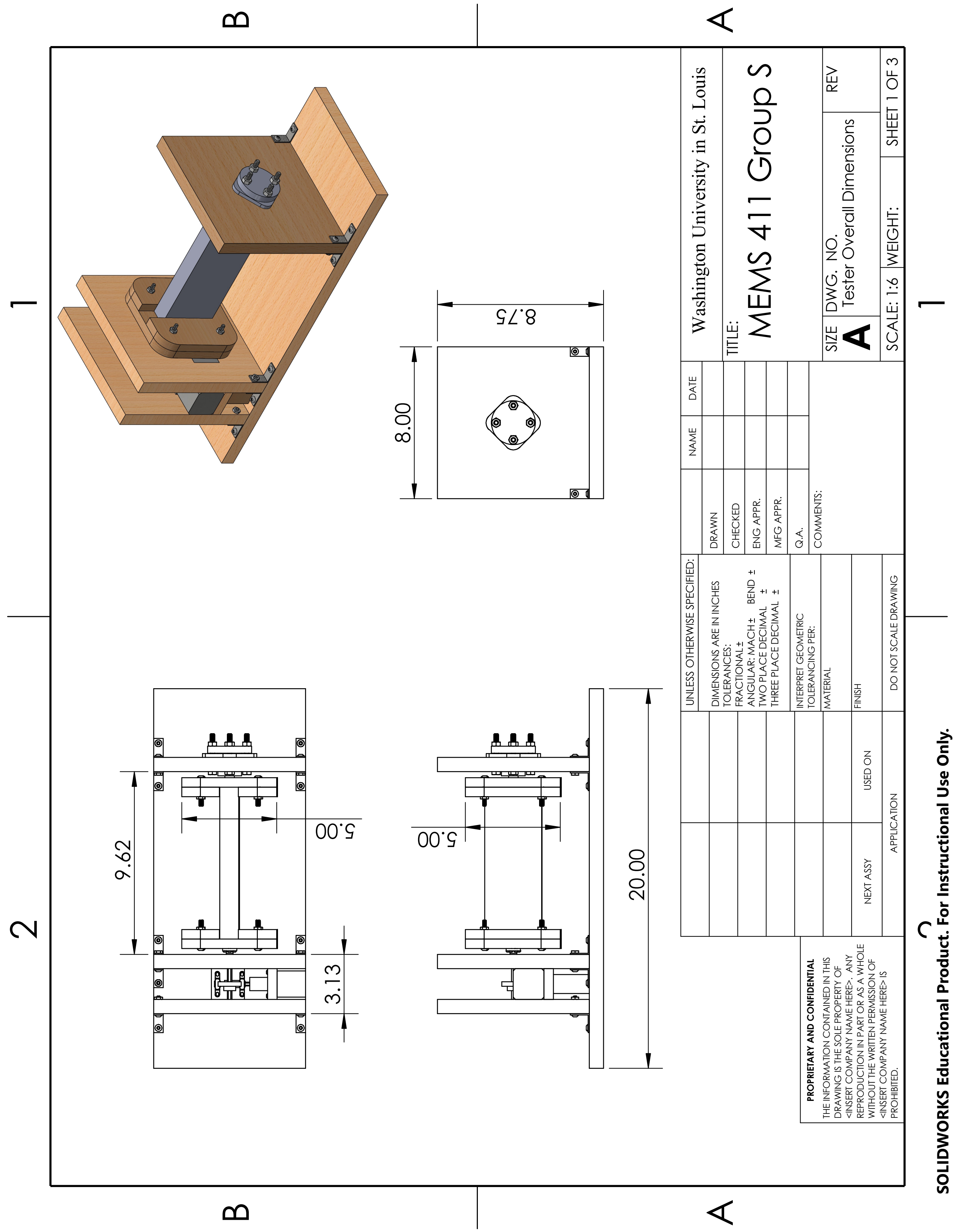


Figure 21: Assembled projected views with overall dimensions

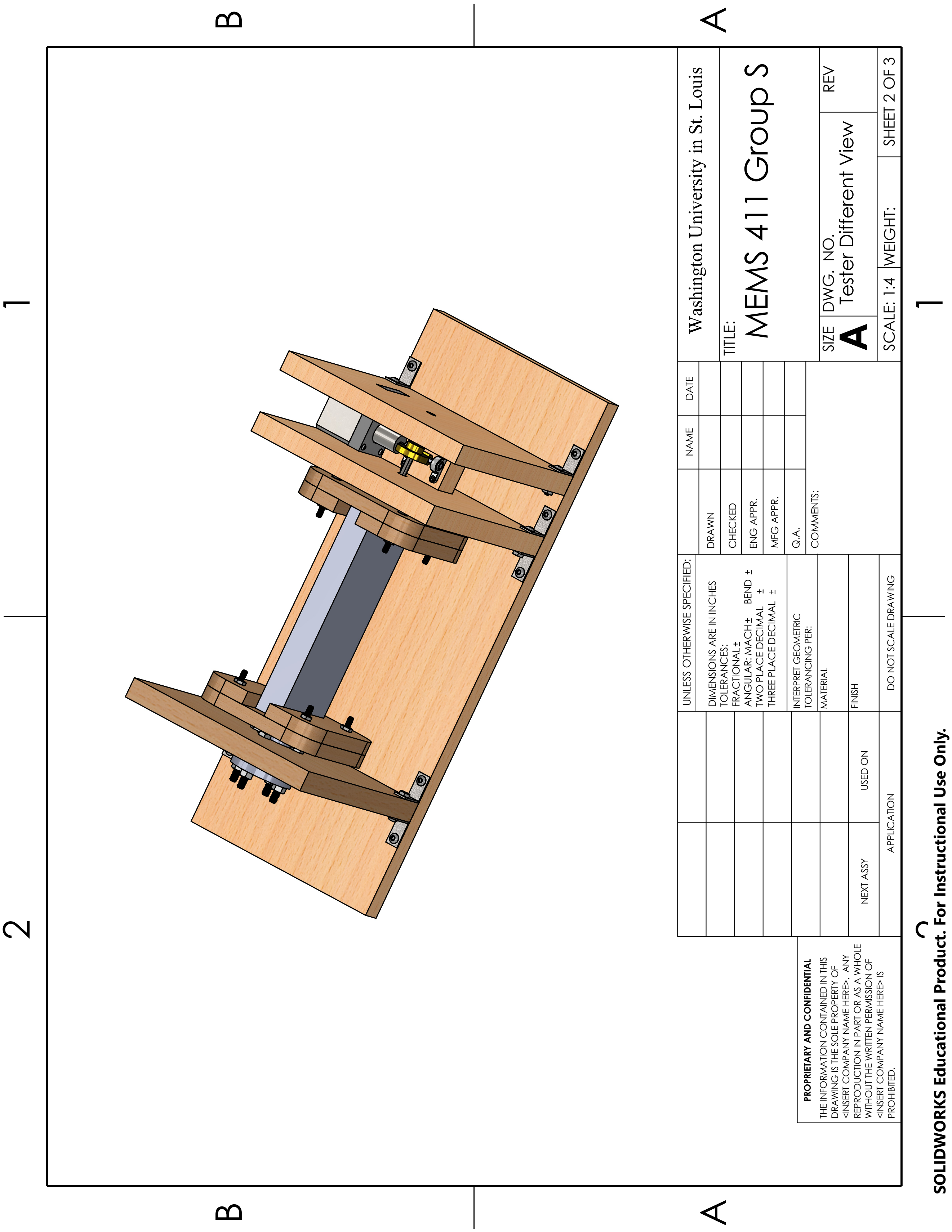
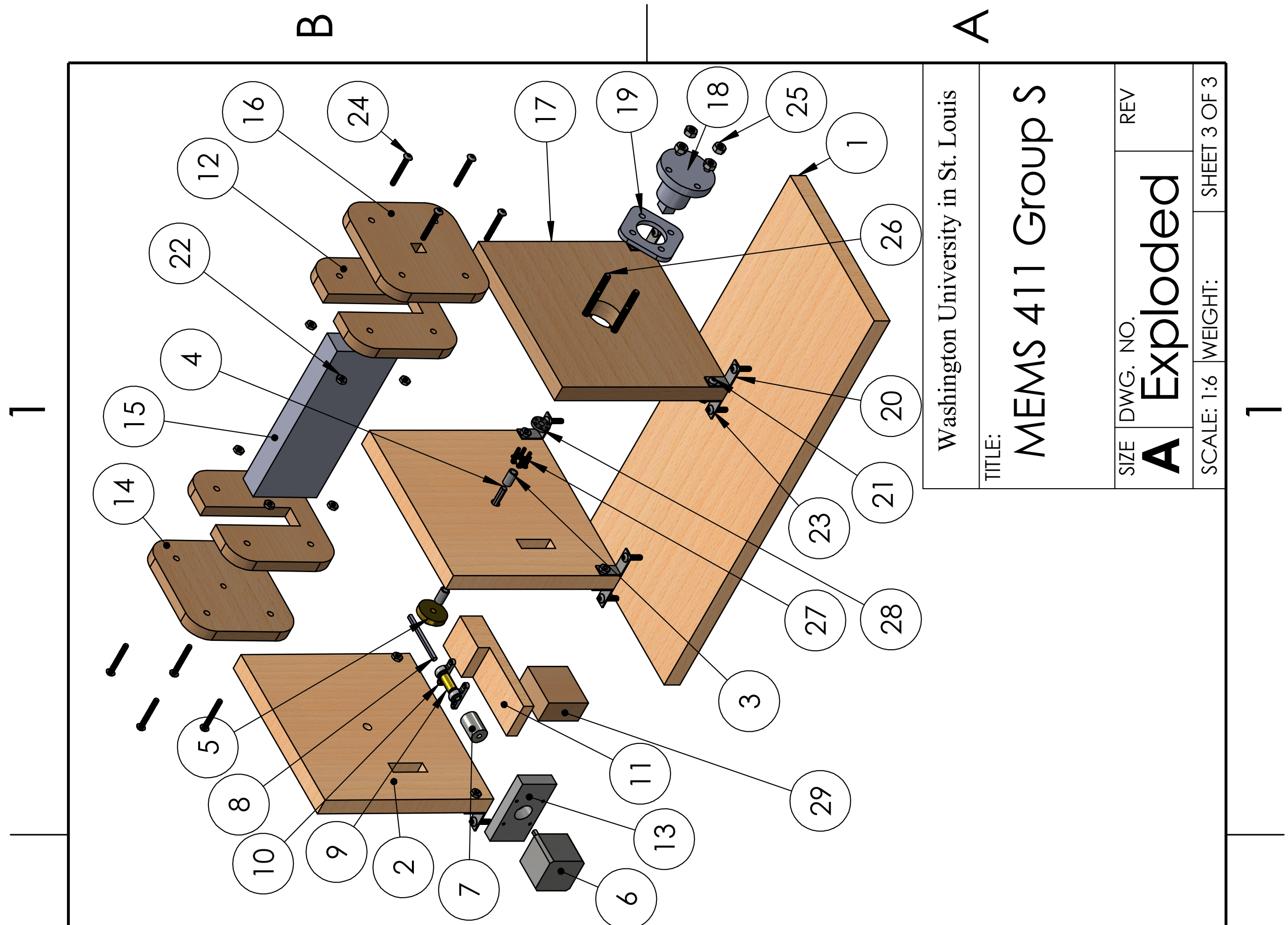


Figure 22: Assembled isometric view



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Baseplate		1
2	Motor-side Wall		2
3	6658K123	Oil-Embedded 841 Bronze Sleeve Bearing	2
4	6mm D-Cut Shaft		1
5	Major Gear		1
6	Motor		1
7	5mm Coupler		1
8	5mm D-Cut Shaft		1
9	Worm Gear		1
10	6687K31	Dry-Running Mounted Sleeve Bearing	2
11	Motor Base Block		1
12	Chuck Plate		2
13	Motor Mount		1
14	Chuck Holder	Motor-side	1
15	Specimen		1
16	Chuck Holder	Sensor-side	1
17	Sensor-side Wall		1
18	Torsion Sensor		1
19	Sensor Mount		1
20	L-Bracket		10
21	92949A247	18-8 Stainless Steel Button Head Hex Drive Screw	6
22	90480A011	Low-Strength Steel Hex Nut	14
23	92949A269	18-8 Stainless Steel Button Head Hex Drive Screw	10
24	92949A251	18-8 Stainless Steel Button Head Hex Drive Screw	8
25	95462A029	Medium-Strength Steel Hex Nut	4
26	92240A550	18-8 Stainless Steel Hex Head Screw	4
27	97763A421	18-8 Stainless Steel Button Head Hex Drive Screws	10
28	Pololu Mount		1
29	Supporting Block		1

Figure 23: Exploded view with callout to BOM

This prototype was created in an attempt to fulfill three performance goals:

– Possess a range of motion exceeding 90 degrees of rotation about axis of the specimen's length

– Measure the angular deformation of the specimen within 0.1 degrees

– Exert 20 ft-lbs of torque on the specimen and measure it accurately to 0.1 ft-lbs.

These goals allow for a full functionality analysis of the prototype.

5.2 Proofs-of-Concept

For the proof-of-concept, the main goals were to create a structurally solid frame for the torsion tester and chuck grips for the specimens. While the proof-of-concept did not incorporate any torsional measurement, it did prove that an infinite range of rotation was possible and would be relatively easy to incorporate into the prototype. The proof of concept also influenced the design of the prototype's structure. A similar wall design to the proof-of-concept was used in the prototype, aside from the outer measuring-block wall. Since the torsion sensor was able to mount to a single wall securely, the fourth wall became unnecessary. The diagonals, which were meant to help support torsional loads, were a component of the proof-of-concept design (although they were not implemented due to time and material constraints). The final prototype used a thick baseplate to resist torsional deformation instead of a set of diagonals. As detailed in the next section, this cut material costs and increased the material and weight efficiencies of our device.

The circular chuck grips with a rectangular cut-out functioned as expected, ensuring that the rectangular specimen did not move around within the grip. However, these were later changed for the prototype to instead take a square shape with rounded corners. This change was made because it made manufacturing these chucks substantially easier. Essentially, the prototype took the structural design of the proof-of-concept and incorporated the motor and worm gear system on one wall to apply torque, and the torque sensor on the other to measure said torque.

5.3 Design Changes

There were a few design changes made between the "Rack + Pinion Internal System" concept and initial prototype. The base of the initial prototype was required to withstand 20 ft-lbs of torque and deflect minimally. However, this requirement was achieved in the prototype without the use of closed outer-housings for the motor and measurement blocks (components of the concept design). Additionally, the diagonals which connected the two blocks were removed in favor of a single, thick baseplate. This was done because the diagonals were found to provide relatively little increased rigidity with respect to the material used, while the baseplate provided immense structural rigidity in comparison.

The motor block and gearbox were not fully fleshed out in the conceptual design, leading to slight changes in the initial prototype. The gearbox was replaced with a worm-gear set with a gear-ratio of 60:1. The motor was additionally rotated and mounted against an elevator connector from the base-plate instead of being connected to the inner motor-block wall. Additionally, the conceptual design assumed that the gearing system would mesh with a mechanical limit sensor to detect the angle of rotation of the specimen relative to rest. Instead, by assuming that the stepper-motor never skips a step before breakage of the specimen, the number of motor microsteps was counted in the Arduino program and relayed, scaled by a gearing-ratio and angle-per-step, to the user as an angular displacement. This removed unnecessary complications from the final product.

Additionally, the measurement block was refined during the design and creation of the initial prototype. The previously-designed rack-and-pinion load-cell system was scrapped in favor of a prefabricated torsional load cell, which allowed measurement of the applied load over the required domain. This also removed the necessity for an outer measurement-block wall, as full stabilization of the load cell could be achieved by mounting it to the inner wall.

Beyond possessing a more open design, the initial prototype possesses slightly different specimen-holders than the conceptual design. For ease of production, the holders were manufactured to be square with a fillet on each corner for safety. Additionally, the pin shown in the conceptual design was scrapped from the final design, as the friction generated between the specimen and holder was more than adequate to hold the specimen in place relative to the insertion axis. The pin was also deemed to not contribute to safety post-breakage, as the specimen would immediately lose its axial constraint and therefore not be limited in motion by the pin.

6 Design Refinement

6.1 Model-Based Design Decisions

6.1.1 Model 1: Shear Forces on Shafts

As a result of the large axial load exerted on the motor, the initial prototype was unable to achieve the desired torque. In remodelling the final version of the torsion tester, a new gearing system is present, requiring a new model. The model below describes the (double) shear load on each of the system shafts.

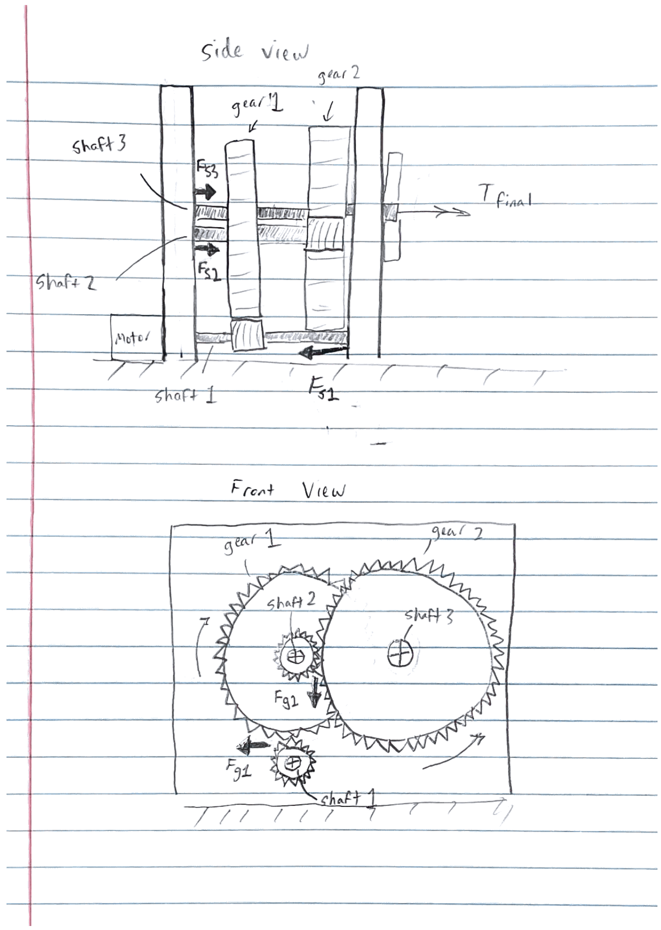


Figure 24: Free Body Diagram of Forces in Gear-Shaft System

where shafts 1, 2, and 3 are shown along with the forces exerted between the gears, F_{g1} and F_{g2} (equal and opposite forces to these are omitted) and the forces exerted on the ends of the shafts to maintain their boundary conditions, F_{S1}, F_{S2}, and F_{S3}. Note that F_{S1}, F_{S2}, and F_{S3} are directed in and out of the plane of the page. Additionally, note that none of the forces in the system are axial in the direction of the motor-shaft length. This obviates the issue with the previous iteration, which was the lack of constraints on the motor relative to the massive applied force. In this model, the torque is never exerted axially on any member.

6.1.2 Model 2: Determining Angular Deformation by Step Count

To determine the angular deformation of the specimen at all times, a *microStepCount* variable is maintained in the code. This variable represents the number of times that the motor has microstepped since the test began. Knowing that the motor is being run at a relatively low pace, assuming the stepper motor never stalls or skips a step is relatively safe. Therefore the following relation can be made to determine the angular deformation of the specimen:

$$\theta = \gamma s \tag{8}$$

$$\gamma = \epsilon \Delta_\phi \tag{9}$$

$$\Delta_\phi = \frac{360°}{ab} \tag{10}$$

where θ represents the angular deflection of the specimen, γ represents the degrees of angular deformation of the specimen per motor-microstep, and s represents *microStepCount*. The value of γ is defined by the degrees of motor angular displacement per microstep (Δ_ϕ) multiplied by the gearing ratio (ϵ, 1:60). The degrees of motor angular displacement per microstep can be defined by taking the steps per revolution of the motor (a, given in the technical sheet) by the microstep-per-step count b (8, as set on the driver). In total, these equations can be simplified to the following:

$$\theta = \frac{360\epsilon s}{ab} \tag{11}$$

Evaluating this for the values listed above, the final result becomes:

$$\theta = \frac{360s}{96000} = 0.00375s \ degrees \tag{12}$$

This final equation allows the number of steps counted in the program to be able to determine the angular displacement of the specimen relative to rest. In making the assumption that the motor never skips a step, the machine was also simplified, in that another sensing apparatus and gearing system were no longer required to fulfill the customer needs. Additionally, this model confirmed an angular discretization with accuracy well beneath 0.1 degrees.

6.1.3 Model 3: Torsion Beam Model for Rectangular Cross Section

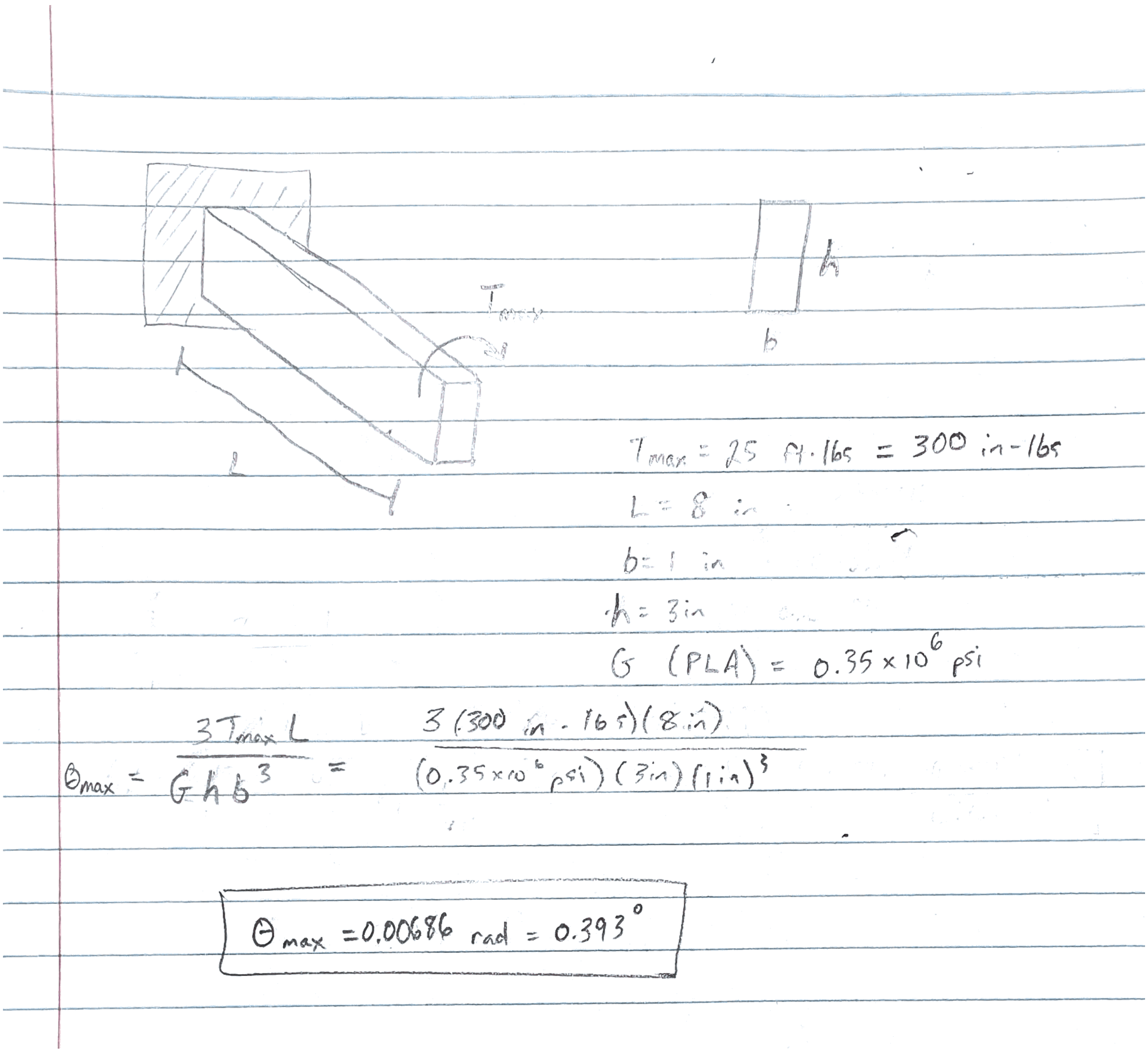


Figure 25: Theoretical maximum deflection angle for PLA specimen

This model calculation updates the previously shown circular beam torsion to account for the rectangular cross section of the specimens. Due to the fact that plane sections no longer remain plane when torque is applied to a rectangular cross section, the equation for the maximum angle of twist must change. The new equation is given by the following:

$$\theta = \frac{3TL}{Ghb^3} \tag{13}$$

Where θ is the angle of deflection, T is the applied torque, L is the length of the beam (specimen), G is the shear modulus of the material, and b and h are the base and height of the cross section.

For this analysis, it was assumed that the cross section of the specimen is perfectly rectangular, disregarding the additional rectangular "ears" on the actual specimens. Additionally, the specimen was assumed to be perfectly fixed by the opposite chuck grip. The PLA specimens can rotate around 0.393º when the maximum torque of 25 ft-lbs is applied. With this maximum deflection angle calculated proves useful in establishing the precision of angular measurement for the torsion tester.

6.2 Design for Safety

Every design bears some risk of breaking or behaving improperly which can be dangerous to users and property. Outlined below are five different risks of malfunction for our torsion tester and what can be done to mitigate them.

6.2.1 Risk #1: Specimen fracture

Description: Upon loading the specimens, they could twist past failure and send fragments everywhere.
Severity: Marginal
Probability: Likely
Mitigating Steps: Set up transparent walls around the tester that can be temporarily removed for specimen insertion and removal.

6.2.2 Risk #2: Motor burnout

Description: Motor failure caused by over torquing. Could potentially produce excessive heat/flames.
Severity: Critical
Probability: Seldom
Mitigating Steps: Program the motor to stop applying torque upon stalling. Additionally, have fire safety equipment available, and keep extra motors on hand.

6.2.3 Risk #3: Frame yielding/fracture

Description: If the specimen, gears motor are stronger than the frame, the frame could yield or fracture depending on the material chosen. Excessive splintering could harm user.
Severity: Critical
Probability: Unlikely
Mitigating Steps: Use strong material that doesn't splinter for frame of tester. Make walls and base of tester excessively thick.

6.2.4 Risk #4: Appendage twisting

Description: A finger or hair could get caught in the gears or the twisting chuck plates which would cause bodily harm.
Severity: Catastrophic
Probability: Seldom
Mitigating Steps: Employ an emergency stop button in the motor's programming if such an incident occurs. Only design for small torques/angular displacements so the potential damage is minimal.

6.2.5 Risk #5: Movement while in use

Description: Tester could move relative to table from motor rotation while in use.
Severity: Negligible
Probability: Unlikely
Mitigating Steps: Make tester heavy, clamp it while in use, use low rotation speeds.

Shown below in Fig. 26 is a heat map associated with this risk assessment to determine which risks are most important to account for when designing our torsion tester.

		Probability that something will go wrong				
	Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Severity of risk	**Catastrophic**				Appendage Twisting	
	Critical				Motor Burnout	Frame Yielding/Fracture
	Marginal		Specimen Fracture			
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial					Movement While in Use

Figure 26: Risk Assessment Heat Map

As shown by the heat map, our highest priority risk is Appendage Twisting. This makes sense as this risk is the only potentially catastrophic danger that our machine poses. Given the relatively low amount of torque we are currently capable of producing, this likely wouldn't result in the loss of a finger or hair, but it could still cause serious pain for the user should it occur. As of now, we currently have an emergency stop button in place to mitigate this risk. Our next two risk priorities are Specimen Fracture and Motor Burnout. Specimen Fracture is a risk that poses little real danger, and wearing eye protection alone should be enough to fully mitigate the potency of the shards, but since it is likely to happen, this is a higher priority risk. Unlike Specimen Fracture, Motor Burnout is less likely to happen, but if it were to happen, this would require an expensive motor replacement. However, since we have complete control over the motor, we can use our emergency stop button when we hear or see the motor stalling so that it never burns out. Last on our list of risk priorities are Frame Yielding and Movement While in Use. These two risks are incredibly unlikely which makes them less important to account for. During the design process, we did choose thick materials for the walls and base to alleviate these risks, but beyond that, not much was done.

6.3 Design for Manufacturing

Excluding the electronic components, the design consists of 43 individual parts comprising structural walls, the motor system, gear-shaft components, and the sensor system. The design also consists of 65 threaded fasteners and 30 associated threaded nuts. The five Theoretically Necessary Components of the design are as follows with visual aids in Fig. 27:

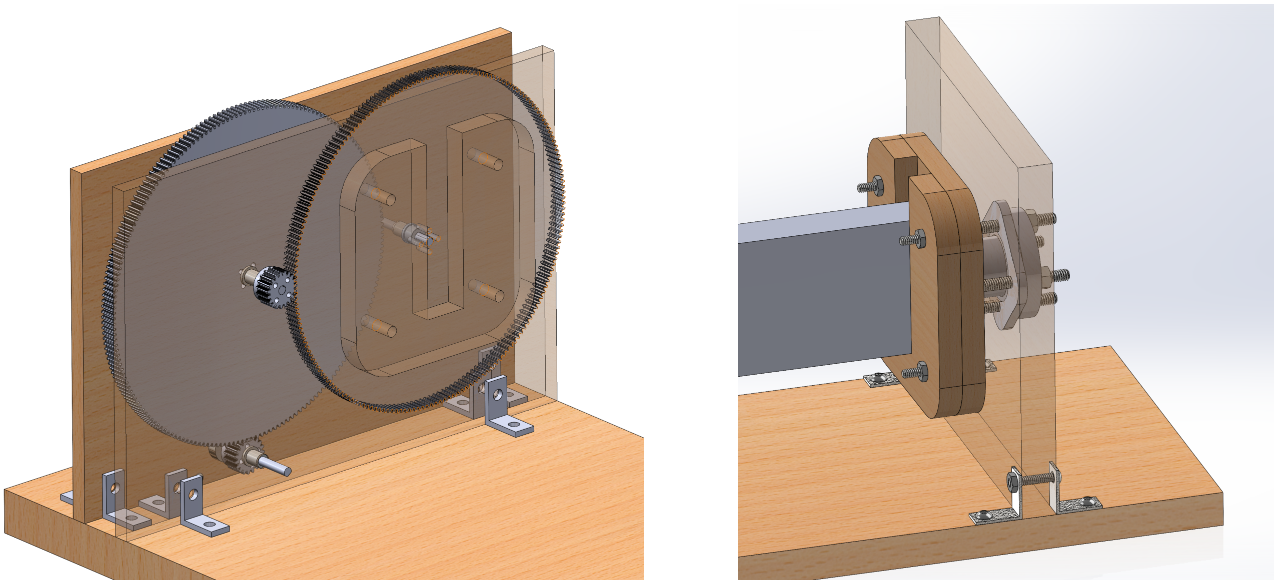


Figure 27: Images of the final CAD model for both sides of the structure. The Motor-side structure is shown left and the sensor-side structure is shown right. Parts have been made transparent for easier viewing of the internal assembly.

1. Static Structure

The static structure consists of the baseplate, the basswood walls, and all fasteners that secure the walls to the baseplate. The static structure is necessary as all other components must move relative to the static structure. Additionally, the loads the system experiences are transferred through the static structure to the surface clamped below the structure.

2. Motor Shaft

The motor shaft system consists of the small gear and its associated connections to the shaft that is connected to the motor. This component is necessary as it transmits the motor power to other moving parts of the system and thus cannot be removed from the system. This component can be seen at the bottom left of the motor-side image in Fig. 27.

3. Intermediary Shaft

The intermediary shaft connects the motor shaft to the central axis shaft and takes advantage of the gearing to transmit higher torque to the central axis. The intermediary shaft is seen in the top left of the motor-side image in Fig. 27 and consists of a larger gear, smaller gear, shaft, and associated connections that allow the shaft to rotate freely within the two walls of the static structure. The component is theoretically necessary to increase the torque output of the central axis but could hypothetically be removed if the gearing ratio between the motor shaft and the central axis is increased to provide a satisfactory torque and/or the motor power is increased.

4. Central Axis Shaft

The central axis shaft receives power from the intermediary shaft through the gearing and holds the torqued specimen in place. The shaft consists of a large gear, the connected wood chuck plate, and associated connections to the shaft that allow free rotation of the chuck plate. This component is necessary as it transmits torque to the specimen via the chuck plate.

5. Sensor Chuck Plate

The sensor chuck plate on the right of Fig. 27 consists of the two wooden plates fastened together. The chuck plate holds the specimen and interfaces with the torque sensor to transmit torque to the sensor. The component is necessary to be able to restrain the specimen and transmit torque to the sensor for the purpose of the device.

Of the five listed Theoretically Necessary Components, identified by their ability to move independently with respect to each other and/or compose different materials, only the intermediary shaft can be theoretically removed without disrupting the main objectives of the device.

6.4 Design for Usability

There are a number of different impairments which might impact how a user can interact with the device. With this in mind, this section details four different impairments and corresponding potential accommodation methods which might aid impaired users.

6.4.1 Impairment 1: Vision Impairment

Example(s): colorblindness, presbyopia

Design Accommodation(s): To accommodate for users who might have a visual impairment, the input buttons could additionally be labelled in braille or designed with different geometries. Additionally, sound cues could be used to indicate what state the machine is in and what command it is currently receiving. In conjunction with these steps, a delay could be imposed between the pressing of the start button (and sound cue) and the actual starting of the motor. This could potentially obviate dangers associated with mistaken pressing of the command keys. To further avoid potential issues with erroneous commands, an operator-presence control switch could be used so that if the user let go of the device, all motion would halt.

6.4.2 Impairment 2: Hearing Impairment

Example(s): sensorineural, conductive, or mixed hearing loss

Design Accommodation(s): To accommodate for users who might have an auditory impairment, the input buttons (and device) could be fitted with LED lights which indicate the state of the machine and the command issued. Additionally, it may be difficult for those with hearing impairment to recognize motor stall or burnout, so an additional sensor could be used to determine if the machine reaches stall for a prolonged period and engage an emergency stop. This would obviate many of the potential dangers associated with the current design for a hearing-impaired user.

6.4.3 Impairment 3: Physical Impairment

Example(s): arthritis, muscle weakness, limb immobilization

Design Accommodation(s): For a user with a physical impairment, the device is already very usable. The specimen can be entered into the slot without any pressing at all, and all functions of the machine are executed through a system of commands of buttons, which can be made large with little required actuation force. The only aspect of the machine which might pose difficulties to a physically impaired user is transport. To resolve this, a cart could be built to roll the device during transport. Additionally, any maintenance tools could be given longer handles to increase moment-arm length and internal safety keys and pins could be made more easily accessible to the external user.

6.4.4 Impairment 4: Control Impairment

Example(s): fatigue, distraction, intoxication

Design Accommodation(s): For a user with control impairment, emergency sensory systems could be implemented into the machine. For example, for a user who faints, the operator-presence control described earlier could engage a machine shutdown before the user has any chance to be injured by the moving parts. In addition, distraction could be mitigated in much the same way as was described for hearing impairment. Bright LEDs and piezo-electric buzzers could be used to flash or buzz when an error has occurred to ensure that the user notices and addresses it. A sensor for prolonged motor stall could also be implemented to prevent a distracted or impaired user from continuing to use the machine in an unsafe manner.

7 Final Prototype

7.1 Overview

Our final prototype was a success by many measures, but it also had some flaws that could easily be improved upon if given more time. Upon doing final testing, our device worked as expected until reaching an induced torque of approximately 3 ft·lbs. At this point, our motor became unable to overcome to frictional forces within the system and stalled.

When looking at our prototype performance goals, our final prototype was very successful. Our device displayed an infinite range of rotation, and we were able to measure the angular deformation and torque on the specimen to the nearest 0.0045 degrees and 0.01 ft·lbs respectively. The only performance goal we failed to achieve was applying a torque of 20 ft·lbs to the specimen.

Upon dissecting why our device could not apply the theoretically possible 26 ft·lbs that we expected, there are a couple main possibilities. The first possibility is that our motor is simply not as strong as its published strength. This discrepancy could arise from some unknown component damage or simply the age of the motor. Another possibility is that the walls of our device were putting the rotating shafts under undue stress. When manufacturing the wall that the motor is mounted into, we noticed it began to bow fairly significantly. This deflection caused the rotating shafts to interface with the walls at a slight angle rather than being perfectly perpendicular. We think this added significant friction to the system and caused our motor to stall earlier than expected.

Despite failing the torque requirement, our redesigned prototype improved upon the original in a multitude of ways. By redesigning the gearing system, we were able to remove the large axial load being applied to the motor which allowed us to more than double our applied torque. Additionally, our decision to laser cut acrylic gears for the final prototype proved to be both cost-effective and entirely functional as we experienced no gear slip in the final testing. Similarly, laser cutting an acrylic chuck plate to interface with the torsion sensor reduced the overall amount of play in the system. Lastly, the combination of our gear system redesign and having gears exposed inadvertently gave our final prototype a ”reset mechanic” where the user is able to realign the chuck plates vertically after a test simply by hand spinning the exposed gears in reverse.

With more time and funding, there are several aspects of this device we would continue to improve. First, we would purchase a higher-powered motor and metal pinion gears to more easily achieve the torque requirement. Second, we would redesign the free-standing walls surrounding the gearing system to instead be a single, fixed support system to prevent any undue bowing or other deformations. Third, we would spend more time in post-processing: sanding all components and making the design more aesthetically pleasing. Lastly, we would design an enclosure for our breadboard or look into designing a PCB to prevent wires from unplugging or being damaged.

7.2 Documentation

Shown below are a couple images of our final prototype in its entirety.

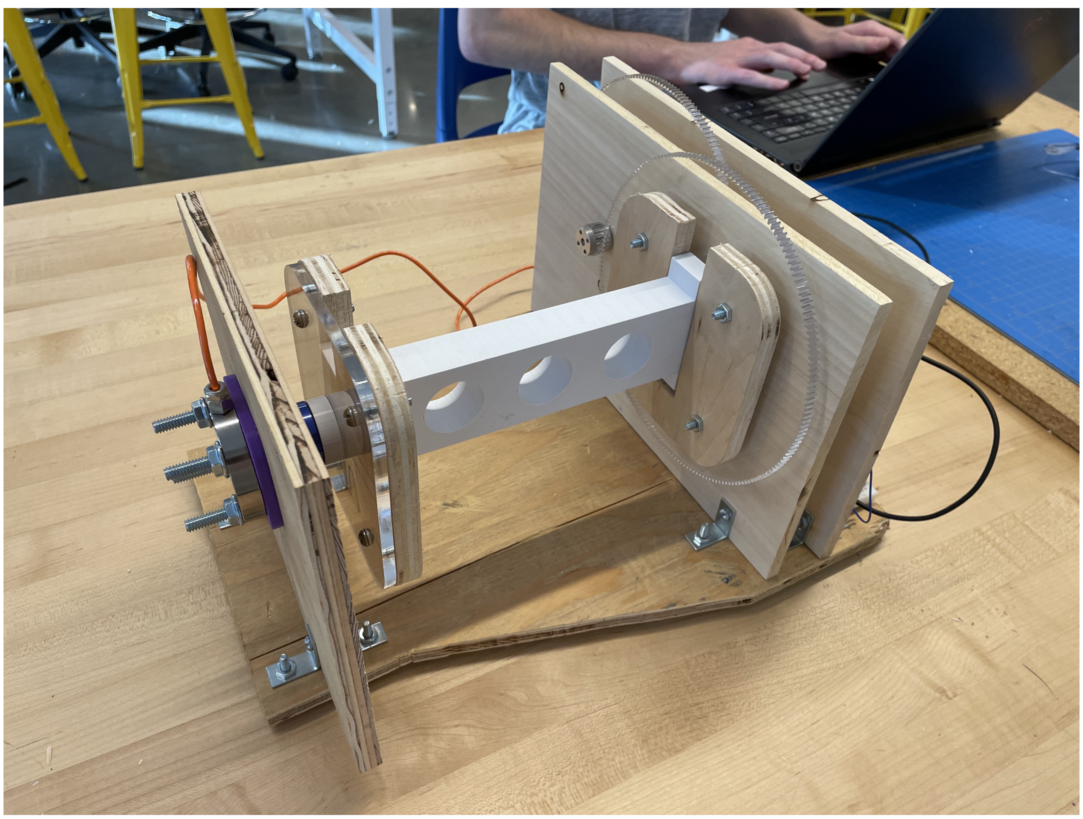


Figure 28: Sensor-side image of the final prototype.

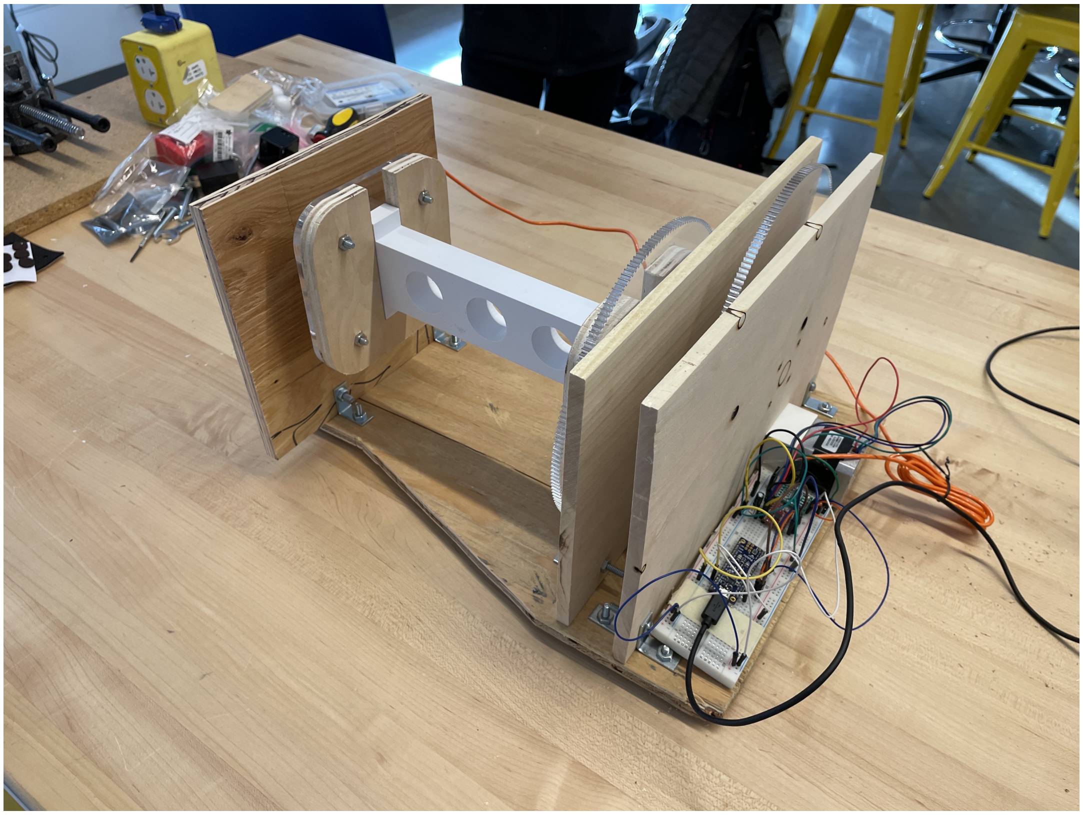


Figure 29: Motor-side image of the final prototype.

Bibliography

[1] J.J Potter et al. *Mechanical Engineering Design Project Interview.*

A Software Code - Arduino

```
#include "HX711.h"

HX711 scale(4, 5);
float calibration_factor = 60433.0;//27.1*2230.0;

// Main settings... up to 3 rev/sec works but has low torque without skipping steps
const float revPerSec = 8.0;
const int stepsPerRev = 200*8;  // will be larger if you use microstepping

const float motorDegPerStep = 360.0/stepsPerRev;
const float gearing_ratio = 100.0;
const float specDegPerStep = motorDegPerStep/gearing_ratio;

// To turn driver on, some drivers require enable pin to be high, some low...
// "true" assumes that it should be high for driver to work
const boolean driverOn = true;
const boolean driverOff = !driverOn;

// Derived quantities
const float stepPerSec = revPerSec*stepsPerRev;
const float secPerStep = 1.0/stepPerSec;
const int microSecPerHalfStep = round(0.5*1000000*secPerStep);

int totalSteps;
int increment;

const float failureConst = 0.75;
float currentTorque = -1;
float lastTorque = -1;
float currentAngle = -1;
float lastAngle = -1;
float playAngle = 0;

float minTorqueReadVal = 0.2;


// Pins
const int enablePin = 12;
const int stepPin = 11;
const int dirPin = 10;

// Variables
boolean dirToggle = true;   // Direction toggle
boolean result = false;
boolean playReached = false;

int comm = 0;
int mid_comm = 0;

// Communication Vals
int start_val = 111; // "o"
int emergency_stop_val = 115; // "s"
int pause_val = 112;  // "p"
int quit_val = 113; // "q"
```

```
int plus_val = 43; // +
int minus_val = 45; // -

// Custom microsecond delay function that can handle longer delays than builtin ...
    "delayMicroseconds()"
void DelayMicroSec(long dt_delay) {
  long t_start = micros();
  while (dt_delay - (micros() - t_start) > 10000) {
    delayMicroseconds(5000);
  }
  delayMicroseconds(dt_delay - (micros() - t_start));
}


// Run once
void setup() {
  pinMode(enablePin, OUTPUT);
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);

  digitalWrite(enablePin, driverOff);
  digitalWrite(stepPin, LOW);
  digitalWrite(dirPin, dirToggle);
  dirToggle = !dirToggle;
  digitalWrite(dirPin, dirToggle);
  Serial.begin(9600);
}


boolean runMotor(int revs) {

  // Set Scale
  scale.set_scale();
  scale.tare();  //Reset the scale to 0
  long zero_factor = scale.read_average(); //Get a baseline reading

  // Enable Motor
  Serial.println("Enabling Motor");
  digitalWrite(enablePin, driverOn);


  // Check for Runcase
  if (revs == -1) {
    totalSteps = 5; // Large Value
    increment = 0;
  }
  else {
    totalSteps = revs*stepsPerRev;
    increment = 1;
  }

  // Loop for Revolving
  Serial.println("Starting Revolutions");

  int step = 1;
  while (step <= totalSteps) {
```

```
    scale.set_scale(calibration_factor);
    // Step
    digitalWrite(stepPin, HIGH);
    DelayMicroSec(microSecPerHalfStep);
    digitalWrite(stepPin, LOW);
    DelayMicroSec(microSecPerHalfStep);

    currentAngle = specDegPerStep * step;
    currentTorque = scale.get_units(), 10;
    if (playReached) {
      Serial.print("Measured Torque: ");
      Serial.print(currentTorque);
      Serial.print(" lbft; ");
      Serial.print(currentAngle - playAngle);
      Serial.println(" Deg; ");
    }
    //Serial.print(" calibration_factor: ");
    //Serial.print(calibration_factor);
    //Serial.print(" Zero Factor: ");
    //Serial.println(zero_factor);
    if ((abs(currentTorque) > minTorqueReadVal) && !playReached){
      Serial.println("PLAY REACHED");
      playAngle = currentAngle;
      playReached = true;
    }

    if ((abs(currentTorque) ≤ 7/8 * abs(lastTorque) * failureConst) && ...
        (abs(currentTorque) > 100000)) {
      Serial.println("FAILED");
      Serial.print("Max Torque: ");
      Serial.print(lastTorque);
      Serial.println();
      Serial.print("Max Angle: ");
      Serial.println(lastAngle - playAngle);
      return false;
    }

    lastTorque = currentTorque;
    lastAngle = currentAngle;
    step += 1;

    // Look for Interrupting Command
    if (Serial.available() > 0) {
      mid_comm = Serial.read();
      if (mid_comm == plus_val) {
        calibration_factor += 1000;
        Serial.print(" calibration_factor: ");
        Serial.print(calibration_factor);
      }
      if (mid_comm == minus_val) {
        calibration_factor -= 1000;
        Serial.print(" calibration_factor: ");
        Serial.print(calibration_factor);
      }
      // Emergency Stop
      if (mid_comm == emergency_stop_val) {
```

```
        Serial.println("EMERGENCY STOP");
        digitalWrite(enablePin, driverOff);
        return false;
      }

      // Pause
      else if (mid_comm == pause_val) {
        Serial.println("Pausing Motor");
        while (Serial.read() != pause_val) {}
      }

      // Reset Command Value
      mid_comm = 0;
    }
  }
  // Disable Motor
  digitalWrite(enablePin, driverOff);
  return true;
}

void loop() {
  // Look for Command
  if (Serial.available() > 0) {
    comm = Serial.read();
  }

  // Start Command
  if (comm == start_val) {
    runMotor(20000);
  }

  // Quit Command
  else if (comm == quit_val) {
    Serial.println("Quitting");
    digitalWrite(enablePin, driverOff);
  }

  // Reset Command Value
  comm = 0;
}
```