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MEMS 411: Mini Test Frame

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FL21 MEMS 411 Mechanical Engineering Design Project

Mini Test Frame

The Mini Test Frame was created during the WashU Senior Design course for use in the Machine Elements course for a future exam where students will design a stucture and are graded on their structure's performance. The Mini Test Frame is a miniaturized compressive testing bench that utilizes dual lead screws to move a crossmember with a load applicator head and force sensor to crush samples.

The project had a budget of 400 dollars and a time frame of a single semester at WashU, which amounts to 14 weeks. Using this time, the team was able to do a simple cardboard and wood mockup to begin design iteration in the first few weeks and then used lessons learned from the initial mockup to apply to the final design. From the interview with the customer, Dr. Potter, customer needs were extrapolated and condensed into a few key design goals based around frame strength, measurement accuracy, weight, and portability.

The team was able to create a final prototype that weighed a total of 15 pounds, could output and withstand a compression force of over 200 lbs, and could execute repeated compression tests on samples in an 8 inch by 8 inch square testing area 9 inches between the load head and the base plate. Several machined aluminum components were manufactured to decrease weight and increase stiffness of the frame by creating unique geometries for clamps and crossmembers not available in off-the-shelf components. Major sensors and actuators in the assembly were sourced as off-the-shelf assemblies for ease of serviceability and replacement if necessary. The system is controlled by an Arduino Uno microcontroller, which are widely available and easy to modify should the customer want to continue to improve on the testing code parameters.

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1 Introduction

In mechanical engineering curricula, students will perform basic material property tests to better understand why materials behave the way they do. Often, this will culminate in a design test of a simple structure of the students' own design. Our client at Washington University in St. Louis needs a cheaper mini test frame for student design competitions instead of purchasing a large test frame from a manufacturer for thousands of dollars.

Our customer needs a small, mobile testing frame that can be carried to class for use in design competitions of vertical structures made of 3-D printed materials or balsa wood. The test frame needs to be able to output 150 pounds of force and measure force and displacement of the machine head. This test frame needs to have an adjustable head and base plate to accommodate different tests and sample fixturing methods.

2 Problem Understanding

2.1 Existing Devices

Influence for the design of new machinery can often be drawn from existing designs. Here are three existing tabletop material testing devices design to execute functions similar to those of the mini test frame.

2.1.1 Existing Device #1: Bionix Tabletop Test Systems

Figure 1: Bionix Table Test Systems (Source: MTS)

Link: https://www.mts.com/en/products/biomedical/biomaterial-test-systems/bionix-tabletop

Description: The bionix tabletop test system tests for tension, compression, flex, bend, shear and kinematics. The machine characterizes the static and dynamic properties of the material it's testing. It has many different attachments for a variety of tests such as grips and fixtures. This machine performs many more tests than the test frame although what it gains in variety it loses in portability.

The tabletop test system is a permanent fixture and can be moved but only while using proper methods of moving it.

2.1.2 Existing Device #2: Mark-10 Test Stand, Hand Wheel Operated

Figure 2: (Mark-10 Test Stand, Hand Wheel Operated Source: Cole-Parmer)

Link: https://www.coleparmer.com/i/mark-10-es20-test-stand-hand-wheel-operated-100-lbf-500-n/5984617?PubID=UX&persist=true&ip=no&gclid=CjwKCAjw7fuJBhBdEiwA2lLMYQuER2fc3KJCHAMK7thpqQXBGIfqvt3iQIXVEfrjqc63im2AdDqGbRoCCPkQAvD_BwE
Description: The table test frame uses the Mark-10 meter to take data. This frame is mainly used to create a control environment that one cannot achieve while using the Mark-10 meter by hand. The stand is best used in a lab setting where it can have a permanent spot. It is not designed for moving.

2.1.3 Existing Device #3: 311 Family Electromechanical Test Machine

Figure 3: (311 Family Electromechanical Test Machine: Test Resources)

Link: https://www.testresources.net/test-machines/universal-testing-machines/300-series-universal-test-machine/
Description: This table top test frame requires less than 3 ft^2 of desk space making it relatively compact while also having the benefit of having a dual column load frame. The test frame focuses on static testing and has oil free electric motors. The device performs creep tests in addition to the same types of tests as the Bionix Table top test system, but it requires less space to operate. The test frame is still difficult to transport because it weights approximately 400 lbs.

2.2 Patents

2.2.1 Precision Force Applicator For Force Transducer Calibration (US20150096348A1)

This patent is an assembly that applies load from the assembly to a part. The assembly included a differential screw connecting between the stationary member and the moving part. This patent is relevant to us because we were also considering to apply the load at the center of the test frame through a modular load applicator. We could reference the patent in making our own design.

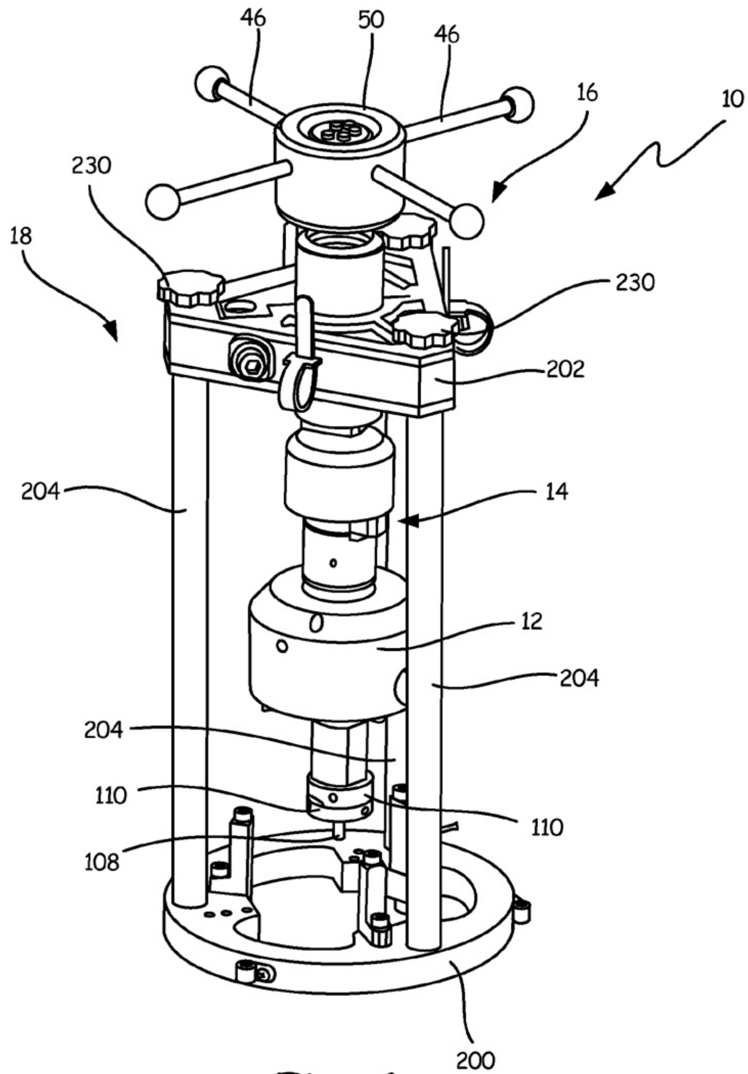


Figure 4: Patent Images for precision force applicator

2.2.2 Displacement measuring device CN105466379B

This is a displacement measuring device in the displacement measuring field. The design featured connecting rods and bearings that amplifies the displacement from the tested material into a large, measurable displacement. This could help reduce the inaccuracy that could arise in measuring small displacements. We believe this patent is relevant since we would be measuring the displacement of the load applicator to calculate the stiffness of the test specimen. The idea of amplifying the displacement, and it's mechanical design could shed light on our design.

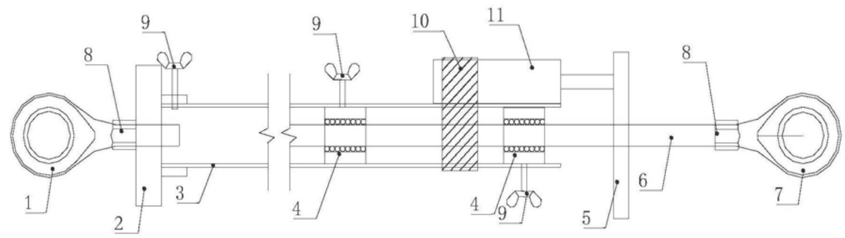


Figure 5: Patent Images for displacement measuring device

2.3 Codes & Standards

2.3.1 Electrics - Power cord plug (NEMA 5)

The NEMA 5 standard defines the three-wire grounding power cable rated for 125V maximum. This standard defines how the power cable and plug should be constructed for safety. This standard is relevant to us because in implementing our test frame, we are considering using an electric servo to drive the push rod to apply the force. Since our maximum force is 150lb, significant power from the servo is required. In addition, our frame is likely made out of aluminum, a conductive material. Therefore, three-wire grounding power cable is needed.

2.3.2 Standard Practices for Force Calibration and Verification of Testing Machines (ASTM E4 21)

This standard describes the procedure of calibrating the force measuring device on a testing machine, and specifies how to verify that the force measured is accurate. This standard is relevant to us because for our test frame, we want to be able to measure how much force was applied onto the model, thereby indicate which of the models is stronger. This standard covers both the compression and tension testing, and the compression part applies to our project.

2.4 User Needs

An interview of the customer was conducted to determine the specific user needs that must be satisfied in the design of the test frame. The test frame is to be used to evaluate the strength-to-weight ratio of 3D printed structures designed by students. The winner will be determined by whoever achieves the highest strength-to-weight ratio.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Jolley Hall 110, Washington University in St. Louis, Danforth Campus
Date: September 10^{th}, 2021
Setting: The customer described the objectives and test methodology of the student competition in which the mini test frame would be used. We inquired about the constraints on the size, weight,

precision and accuracy of measurements for the project, as well as any preferences that may influence the design. This meeting took ∼45 min in total.

Interview Notes:

What should the overall dimensions of the test frame be? (L× W×H)

- Ideally, the frame should be less than 1 ft × 1 ft × 1 ft. An acceptable size would be under 1 ft × 2 ft × 2 ft.

What are the approximate dimensions of the specimens that the frame must be able to perform tests on?

- The specimens will be no more than 8 in × 8 in × 6 in.

What are the structures to be tested made from?

- The specimens are to be 3D printed.

What range of loads must the test frame be able to apply to the test specimens?

- Ideally, the test frame should be able to apply 150 lbs to the specimens. However, at least 100 lbs would be acceptable.

Should the test bed be shielded?

- Yes, but this is of low importance relative to the performance of the machine. If need be, the test bed can be easily shielded with a plexiglass structure.

Is there a minimum or maximum range of displacement that the test frame should be able to measure?

- The frame should measure at least 3 in of displacement.

To what degree of accuracy must the load magnitude and displacement of the load applicator be measured?

- The precision of the measurement is more important than the accuracy, as the students will be scored relative to each other. The force should be measured to the nearest tenth of a pound. Since the students will be scored based on the strength-to-weight ratio of their structure rather than the stiffness, there is no distinct requirement for the precision of the displacement reading.

Can the load be applied manually by the user, or must it be by some mechanical means (i.e. an electric motor attached to a leadscrew)?

- The load can be applied either manually or other electromechanical means.

If operated manually, is there a minimum distance from which the user must be able to stand while operating the test frame?

- No, there is no minimum distance required.

Is there any need for adjustability of any aspects of the test bench?

- Ideally, the fixture method for the test specimen should be modular.

Should the load applicator be modular or be able to be moved?

- The tip of the load applicator should have a small threaded portion to which different tips can be attached. The load applicator does not need to move, as the applied load should be directed downwards over the center of the test bed/specimen.

Does the test frame need to be easy to assemble/disassemble?
- The test frame should not have to be disassembled, so ease of assembly and disassembly is not necessary.

Can the test frame be disassembled for transportation?
- The test frame should remain assembled for transportation.

What is the maximum allowable weight for the test bench required for it to be easily transported?
- The weight of the frame is less important than the overall functionality, but an ideal weight would be less than 15 lbs. Anything less than 30 lbs is acceptable.

What is an appropriate service life for the test frame?
- The frame should be able to withstand approximately 500 test cycles before it breaks.

Must the test frame be battery operated, or run off of a standard wall plug?
- Utilizing AC power would be most convenient.

2.4.2 Interpreted User Needs

Table 1 below outlines the needs of the customer ascertained from the interview, as well as their level of relative importance.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The test frame is lightweight and easy to carry	5
2	The test frame is small	4
3	The test frame can exert loads large enough to break test specimen	5
4	The test frame can precisely measure the magnitude of the applied load	4
5	The test frame can precisely measure the displacement of the applicator	2
6	The test frame does not deform significantly enough to hinder measurements	4
7	The fixture method of the test specimen is modular	4
8	The load applicator is modular	3
9	The test frame applies the load vertically over the center of the specimen	5
10	The test frame is reliable	4
11	The test frame utilizes AC power	4
12	The test frame is easy and comfortable to operate	3
13	The test frame costs less than $400 construct	3
14	The test frame can perform repeated tests with relative precision	5

2.5 Design Metrics

Table 2 gives the target specifications for each quantitative parameter that must be satisfied by the design of the test frame, as derived from the customer interview.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Total weight of apparatus	lbs	< 30	< 15
2	1,2	Overall dimensions (L×W×H)	ft	1×2×2	1×1×1
3	2,3	Bed dimensions (L×W×H)	in	8×8×6	9×9×9
4	4	Maximum applied load	lbs	100	150
5	4,5	Precision of applied load measurement	lbs	±1	±0.1
6	6	Range of displacement measurement	in	3	> 3
7	6,7	Precision of displacement measurement	in	±0.1	±0.01
8	8	Service life	test cycles	> 300	> 500

2.6 Project Management

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

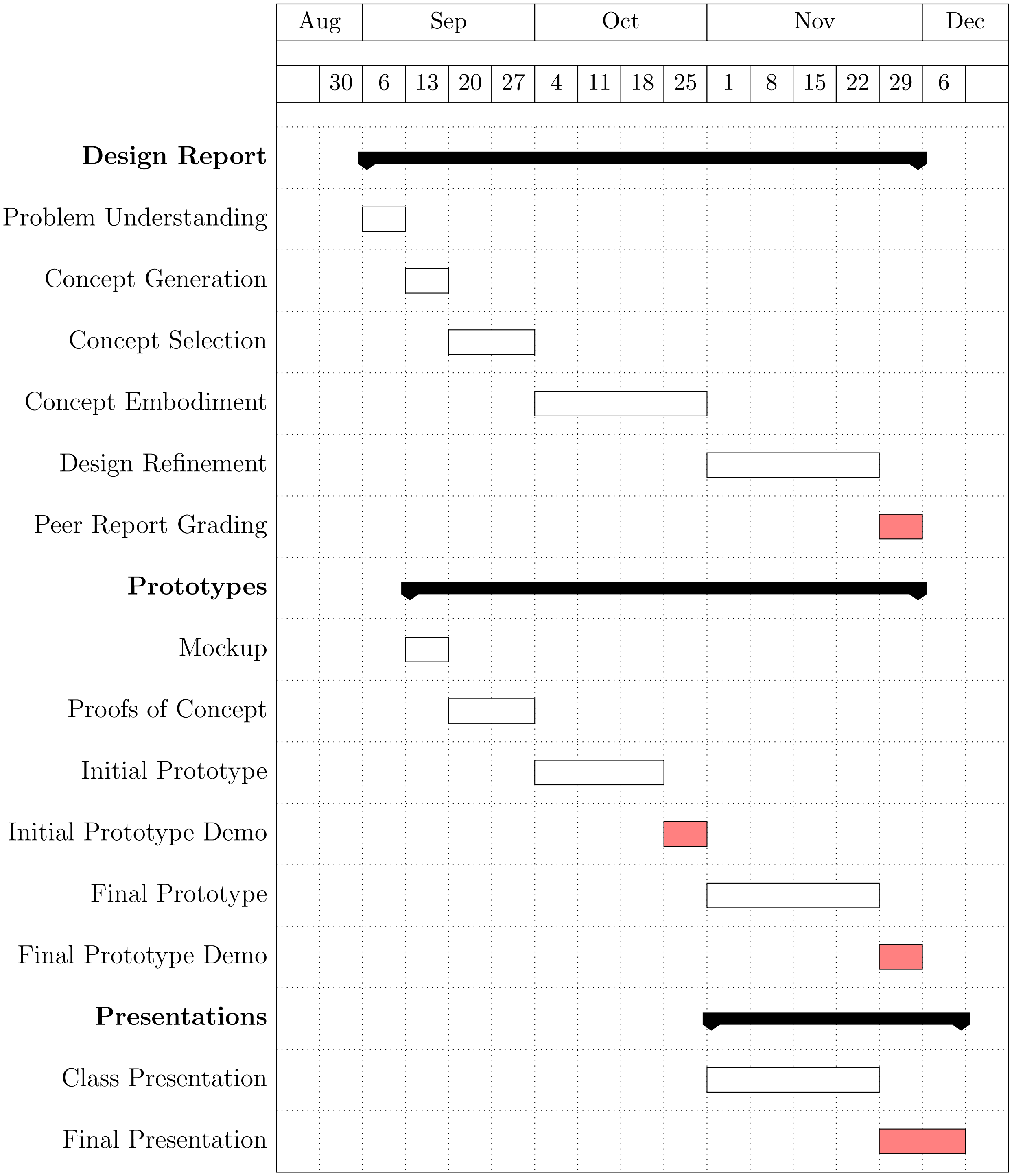


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

The following images show the mockup we made for our test frame project. Prior to constructing the mockup, we did not have a clear vision of the structure of the frame. Since commercially available test frames are expensive and highly precise, we thought making our own test frame would be challenging. Once we started construction, however, we realized the test frame is merely a rigid, solid structure with a force applicator. Upon constructing of our mockup, we realized we could add a few degrees of freedom for the applicator so it could apply force at multiple locations, if the specimen doesn't have its support at the center. We also realized using a motor could simplify our force applying mechanism, reducing the weight on the horizontal member and reduce buckling. The mockup materializes many of our imaginations, and sets a clear path forward for our project.

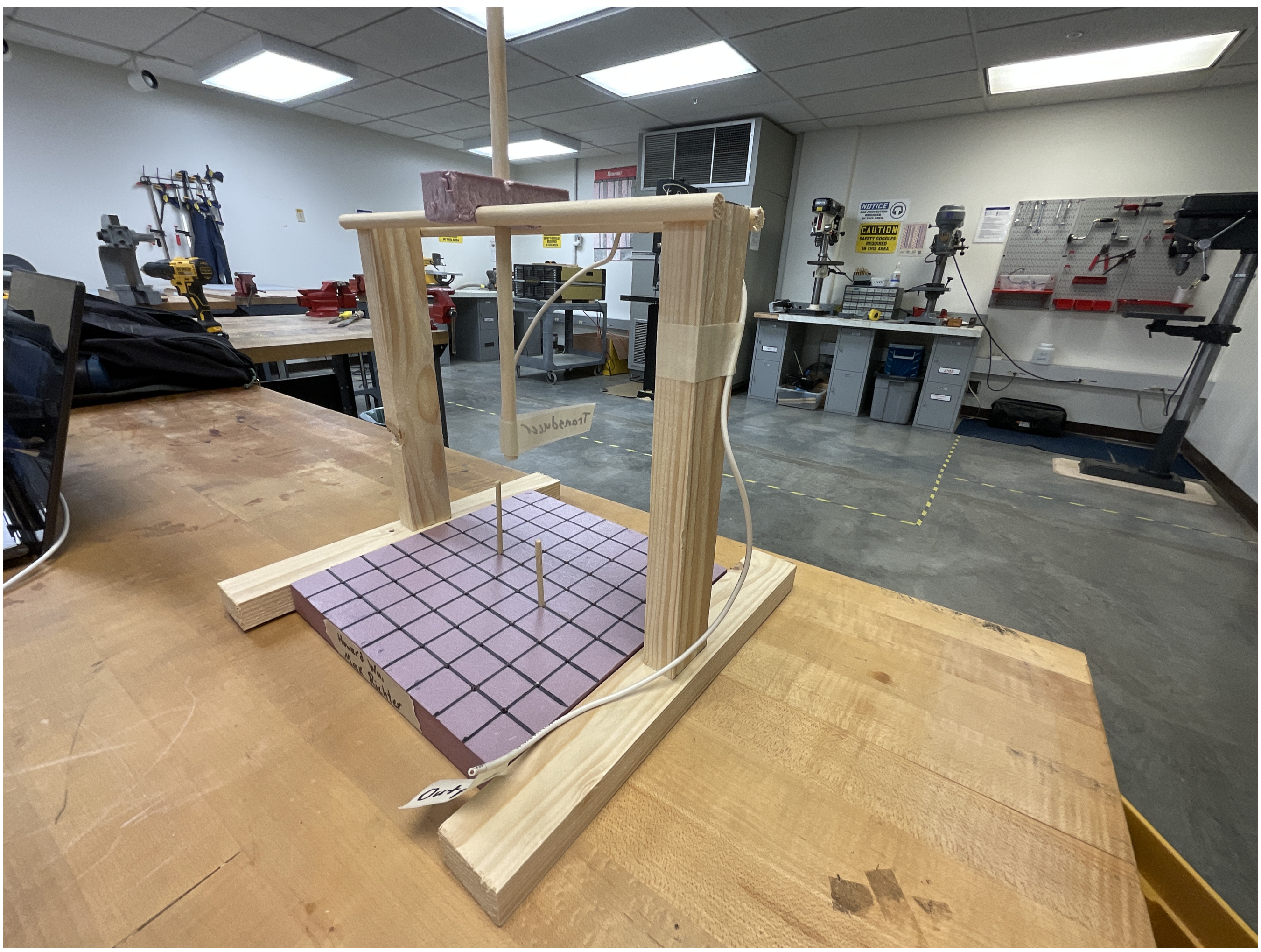


Figure 7: Photo of Mockup 1

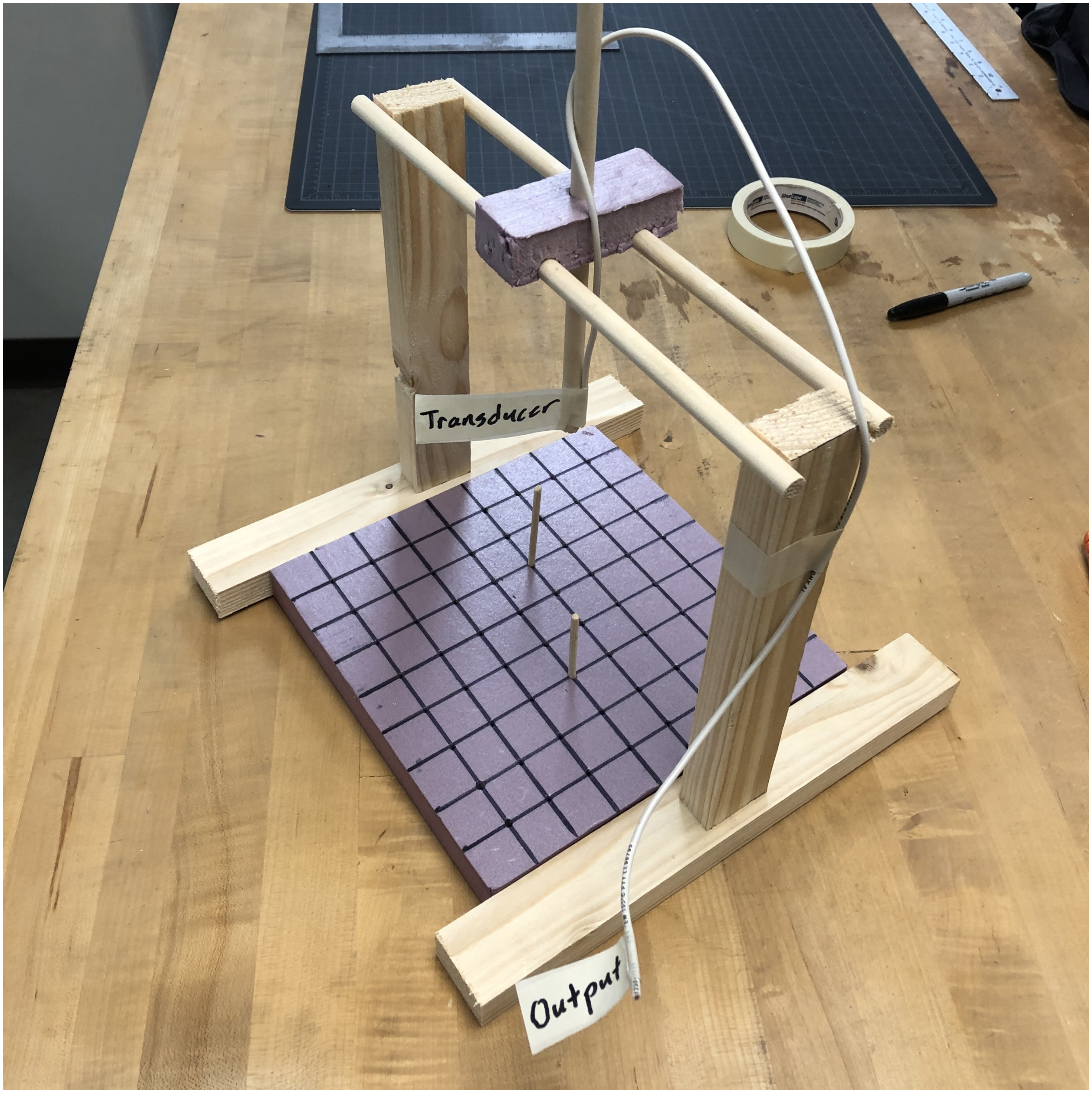


Figure 8: Photo of Mockup 2

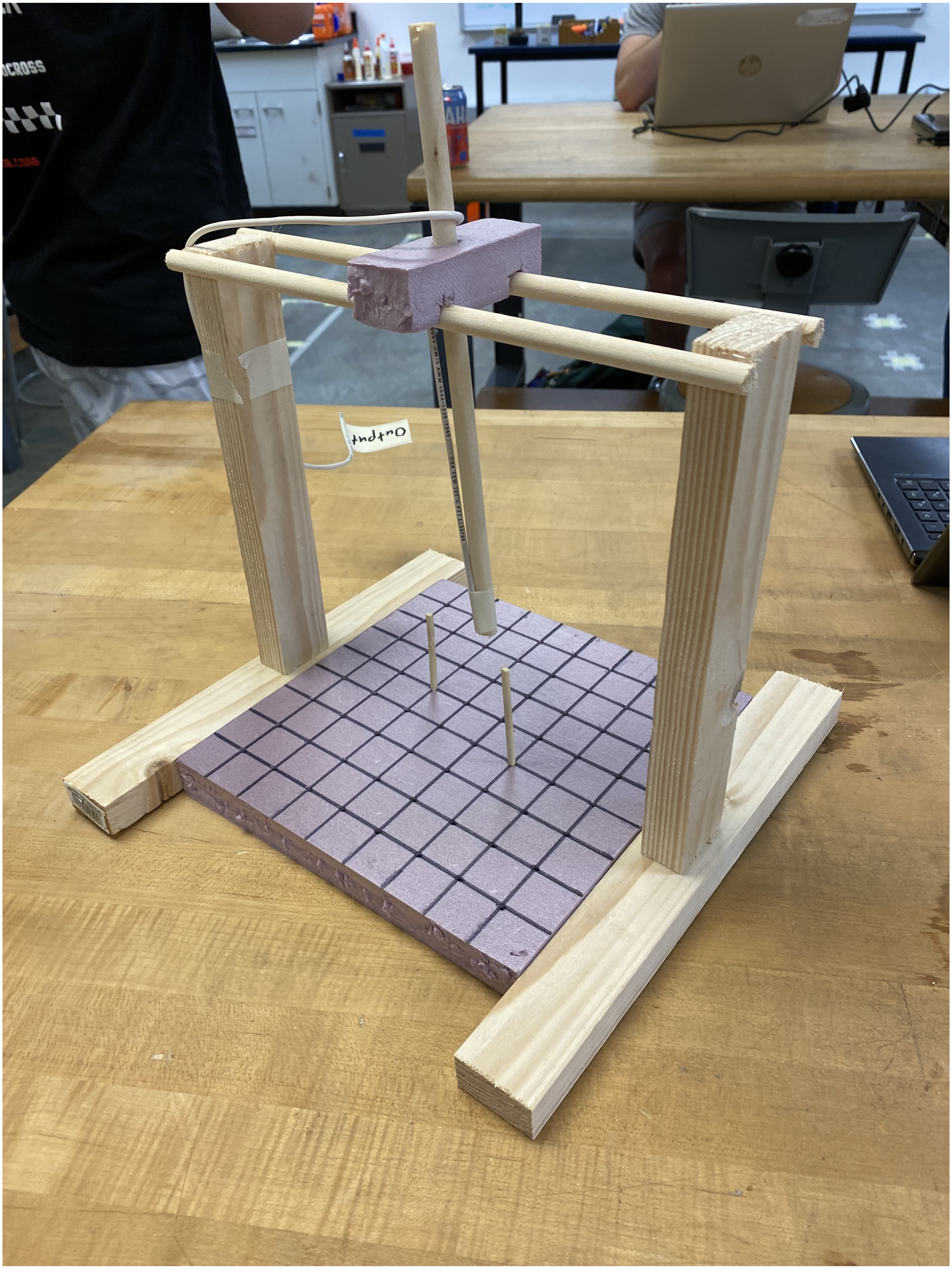


Figure 9: Photo of Mockup 3

3.2 Functional Decomposition

Below is the Function Tree for the Mini Test Frame, expanding on our major customer needs in order to generate specific functions needed for the product. For each function, our team will generate a few concepts of how the system may work, and ultimately we will vet them based on the customer's needs to create the final product.

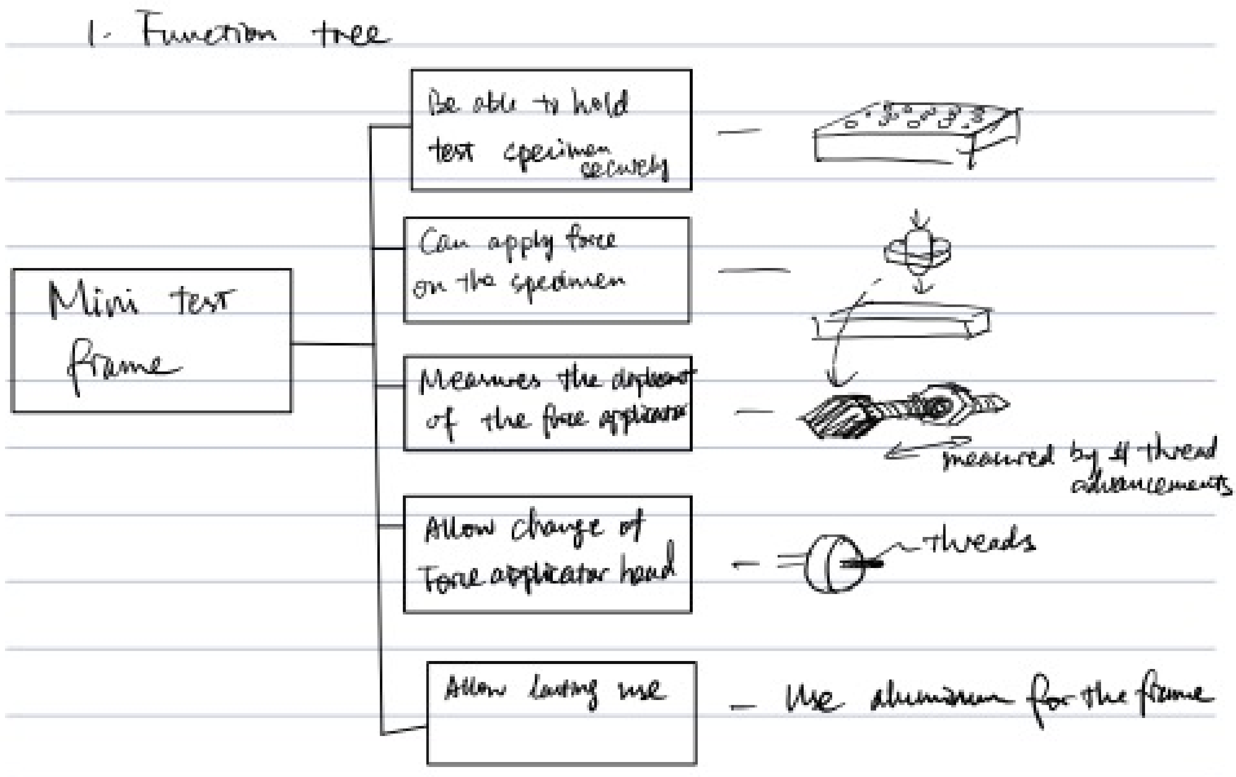


Figure 10: Function tree for the Mini Test Frame, drawn digitally

3.3 Morphological Chart

Below is the Morphological Chart for the Mini Test Frame. Here our team was able to generate several concepts for how each function could be designed. Each concept will be considered with the final customer needs in mind so that no function will compromise or contradict the customer's needs.

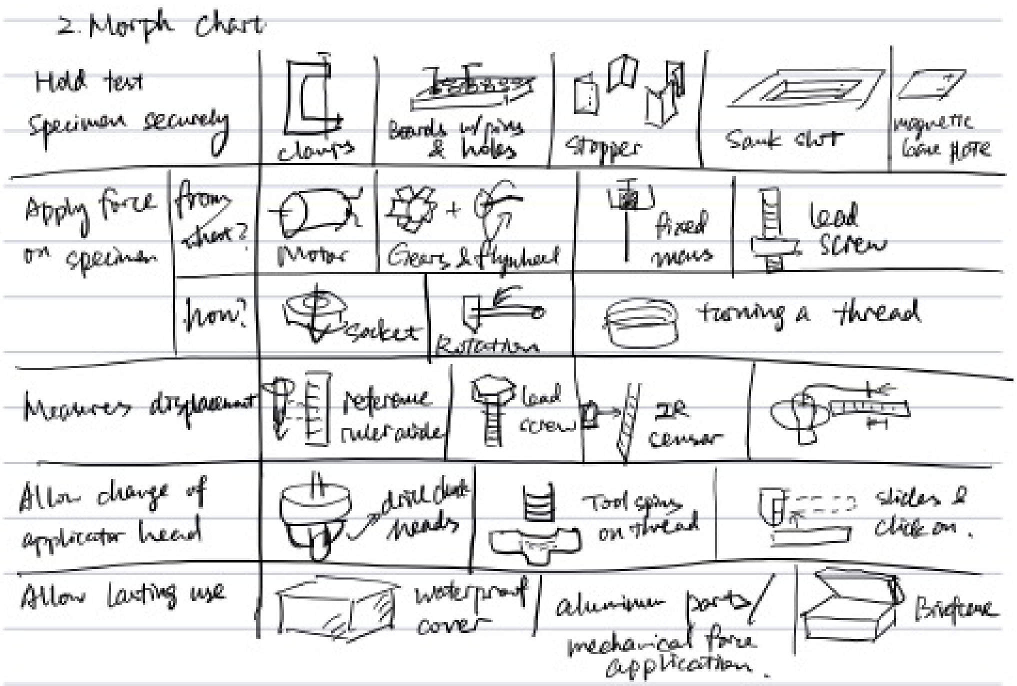


Figure 11: Morphological Chart for Mini Test Frame

3.4 Alternative Design Concepts

3.4.1 Concept 1

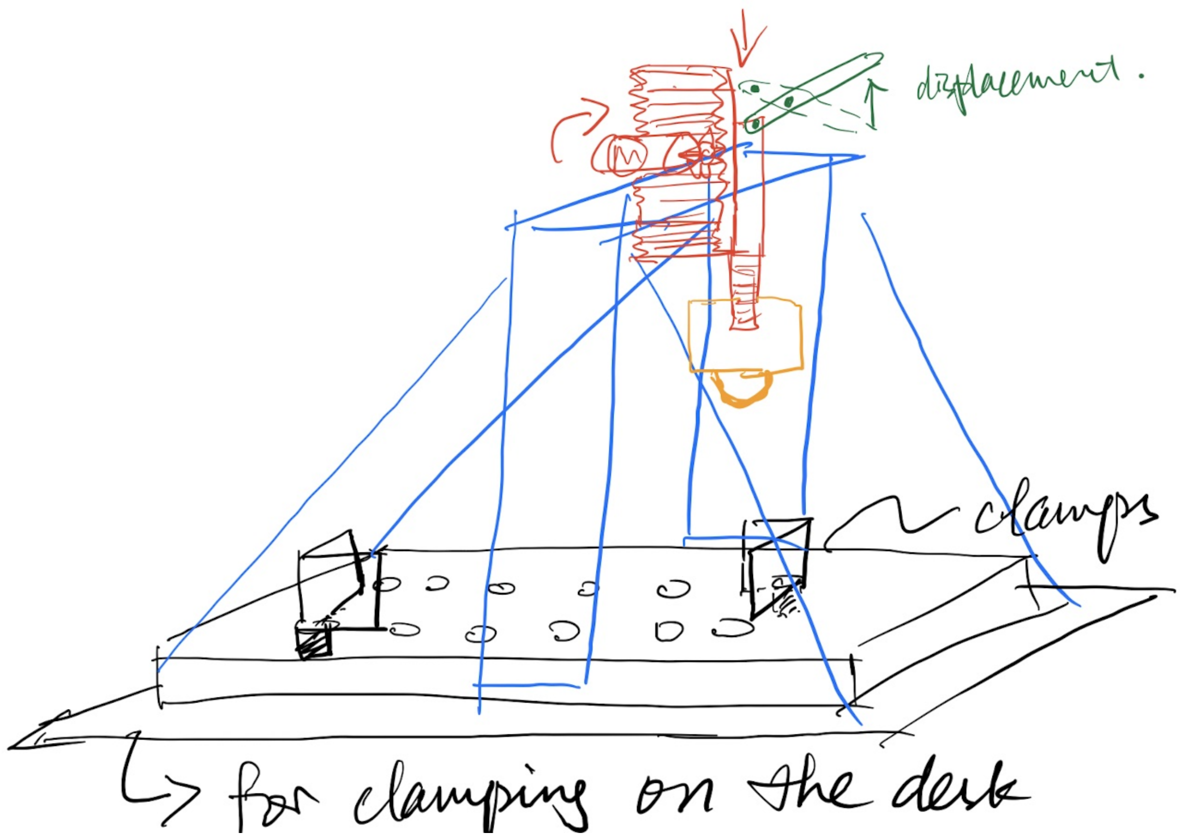


Figure 12: Sketches of Mini Test Frame concept1

Solutions from morph chart:

1. Unit sits on table with extended surface for clamping
2. Board with holes to hold specimen
3. Motor
4. Gear linkage
5. Lever
6. Power cable
7. Threaded end
8. Aluminum parts

Description: A board with holes and pins were used to secure the test specimen. The main frame of the test bench was made in triangular shapes for stability. A motor was used to move the force applicator through gears. The displacement was measured with a lever that amplifies the displacement. The applicator head could be changed by screwing off the tool. The frame shall be made by aluminum for lasting use.

3.4.2 Concept 2

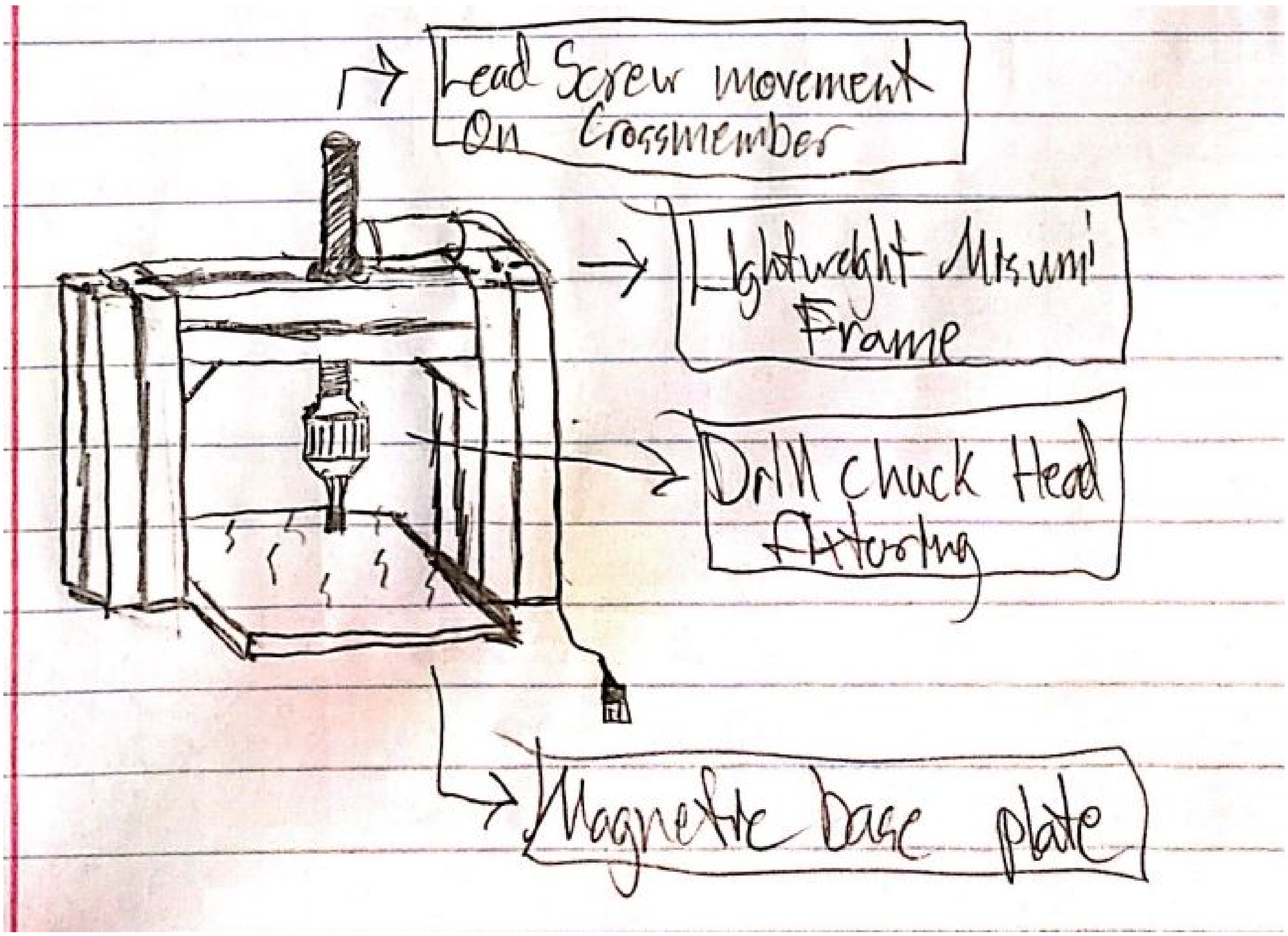


Figure 13: Sketches of Mini Test Frame concept2

Solutions from morph chart:

1. Lead Screw movement on Frame cross-member
2. Lightweight Misumi tube frame
3. Drill chuck head fixturing
4. Magnetic base plate for samples

Description: A stepper motor attached to a lead screw moves the drill chuck attachment downward toward the test sample. The stepper motor is able to measure the force output based on the voltage across the motor and since it is a stepper motor it can easily measure the displacement of the lead screw. The magnetic base plate allows for easy fixturing of samples that have magnets incorporated into the 3-d printed samples. The drill chuck head allows for easy changing of testing heads for different sample types or testing methods.

3.4.3 Concept 3

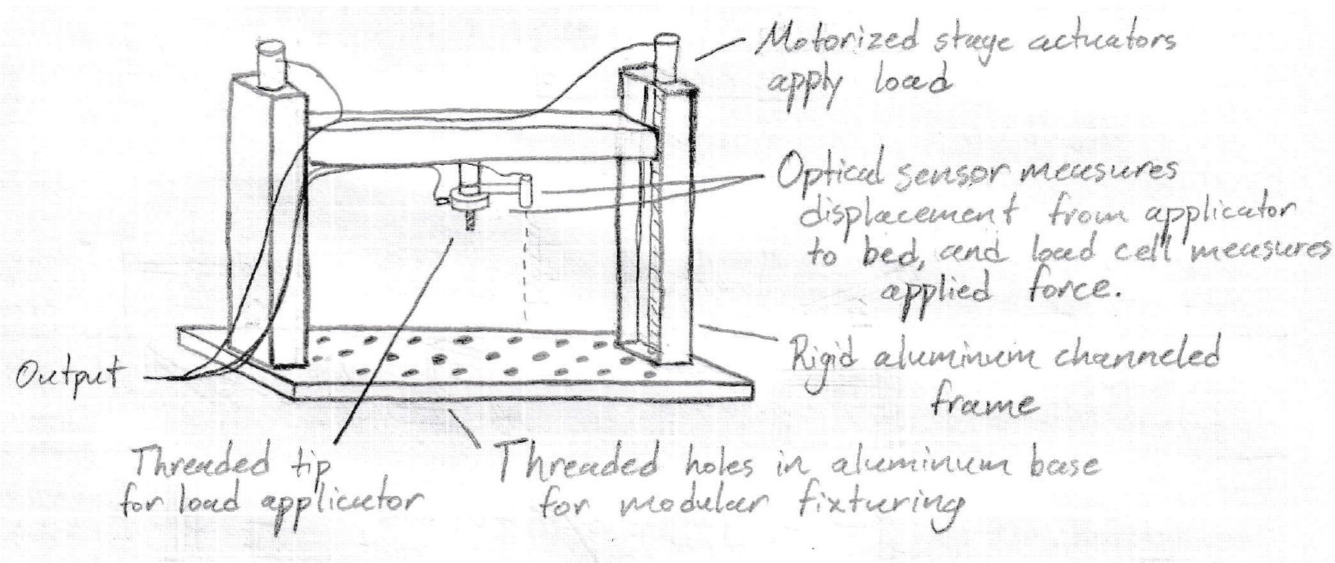


Figure 14: Sketches of Mini Test Frame concept3

Solutions from morph chart:

1. Force applied by motorized lead screws
2. Lightweight, rigid extruded aluminum channel frame
3. Infrared sensor for displacement measurement
4. Threaded holes in testing bed to hold specimen in place
5. Threaded load applicator head

Description: Load is applied to the test specimen through the horizontal cross-member which is actuated by motorized lead screws in the vertical members. The lightweight extruded aluminum channel frame allows for easy transportation, and its rigid structure resists deflection under large loads. The applied force is measured using a small load cell, which is fixed to the horizontal member, and threaded on one side for the use of interchangeable applicator heads. An IR sensor measures the displacement of the load applicator relative to the aluminum test bed, which features threaded holes for modular fixture methods of the specimen.

3.4.4 Concept 4

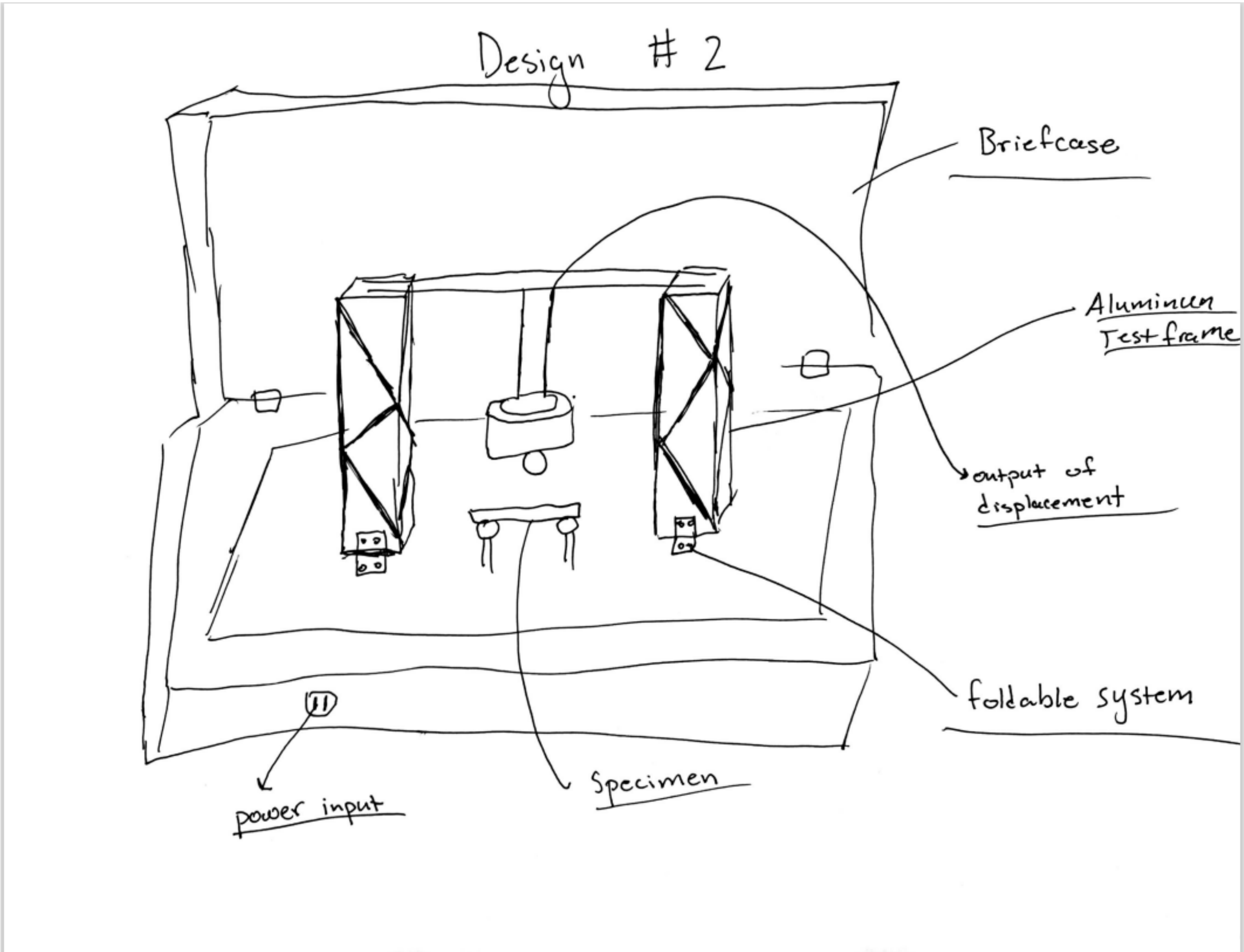


Figure 15: Sketches of Mini Test Frame concept4

Solutions from morph chart:

1. Material: Aluminum
2. Modular/Folding
3. Force transducer
4. Output to pc
5. Easy to transport briefcase

Description: A mini test frame that is modular and folding frame for easy transport. Uses a force transducer to measure displacement using a motor to move the testing apparatus downward.Uses aluminum beams for support and machined so that it could be as light as possible while still keeping its integrity. Can be powered through a plug on the outside of the case so that the test frame can stay in the case.

4 Concept Selection

4.1 Selection Criteria

Figure 16 shows the Analytic Hierarchy Process created to determine the overall weightings of each of our major criteria for the Mini Test Frame.

Criteria	Stiffness	Measurement Accuracy	Weight	Modular Fixturing	Durability	Row Total	Weight/Priority	%
Stiffness	1	0.333	0.333	0.333	0.333	2.333	0.467	20
Measurement Accuracy	3	1	0.333	0.333	0.333	5	1	20
Weight	3	3	1	0.333	0.333	7.667	1.917	25
Modular Fixturing	3	3	3	1	0.333	10.333	1.033	10
Durability	3	3	3	3	1	13	3.25	25

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

4.2 Concept Evaluation

The Weighted Scoring Matrix for the Mini Test Frame shown in Fig. 17 was compiled using the criteria set forth in the Analytic Hierarchy Process.

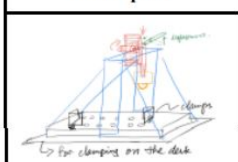
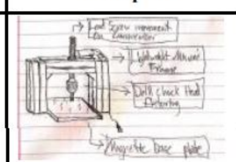
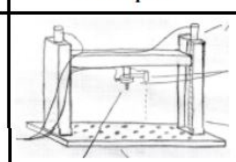
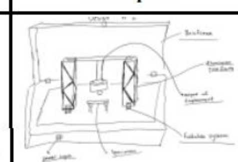
Alternative Design Concepts		Concept #1		Concept #2		Concept #3		Concept #4	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Stiffness	20.00	3	0.60	4	0.80	4	0.80	2	0.40
Measurement Accuracy	20.00	2	0.40	3	0.60	5	1.00	3	0.60
Weight	25.00	4	1.00	2	0.50	3	0.75	5	1.25
Modular Fixturing	10.00	4	0.40	4	0.40	5	0.50	2	0.20
Durability	25.00	3	0.75	5	1.25	4	1.00	2	0.50
	Total score	**3.150**		**3.550**		**4.050**		**2.950**	
	Rank	**3**		**2**		**1**		**4**	

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

4.3 Evaluation Results

Based on the results from the Analytic Hierarchy Process and the resultant Weighted Scoring Matrix, we have come to the conclusion that Concept 3 received the highest score, and shall be the baseline for our concept.

We selected five criterion for our evaluation: stiffness, accuracy, weight, modular fixtures, and durability. Concept 3 should be the stiffest design due to its use of aluminum supporting structures both in the cross member and the vertical members. By measuring the change of distance through a sensor and calculating applied load from motor torque, it is likely to produce the most accurate result. Other design concepts are somewhat rough in specifying these details. This concept might not be the lightest, but that is compensated from its stiffness and accuracy. The base plate fixture is modular and could fit multiple specimen geometries. Due to it's use of aluminum, it is the most durable as well.

4.4 Engineering Models/Relationships

The horizontal cross-member to which the load applicator is affixed can be modeled by a simple beam in bending, as illustrated in Fig. 18. The force F_{Max} applied to the beam represents the reaction force exerted upwards by the test specimen, assuming that the specimen can withstand the maximum load applied by the test frame. The reaction forces on the left and right ends of the cross-member are then given by $F_{Max}/2$, which determine the axial forces that must be carried by the motors and lead-screws within the vertical members. Similarly, the reaction moments on the vertical members are given by $M = F_{Max} \times l$, where $l = L/2$.

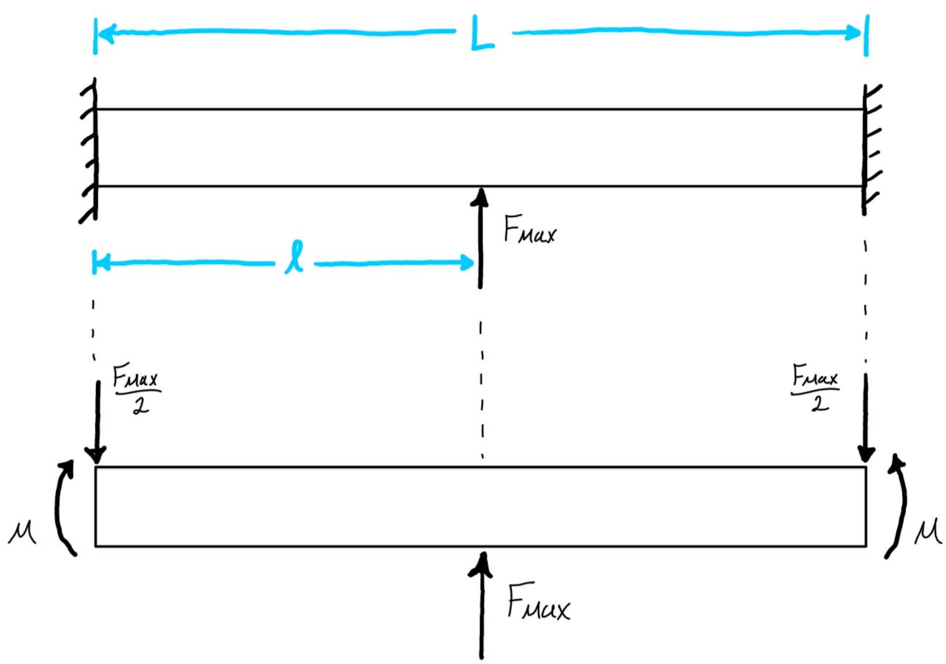


Figure 18: Reaction forces and moments on the horizontal cross-member.

By using the model shown in Fig. 19 we can calculate the deflection of the cross-member using the maximum force that must be applied by the test frame, F_{Max}, again assuming that the test specimen will exert an equivalent reaction force upwards on the frame.

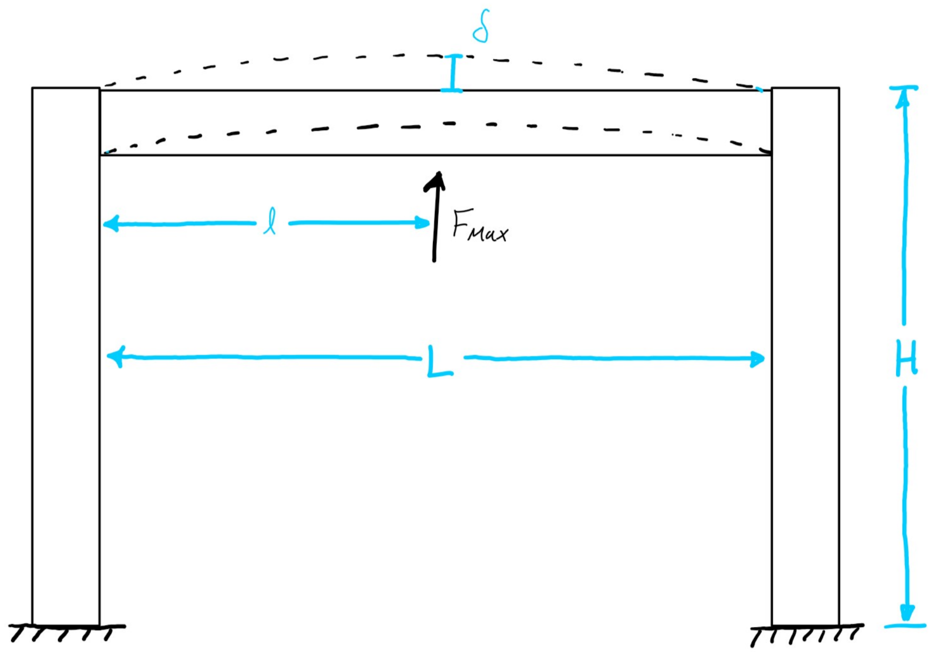


Figure 19: Frame subject to reaction force from test specimen.

The maximum deflection δ_{max} in the beam can be determined from the three-point bending equation, given as follows:

$$\delta_{max} = \frac{F_{Max} L^3}{48EI}.$$

In this case, $L = 2l$ is the beam length, E is the modulus of elasticity of the material, and I is the area moment of inertia of the beam cross-section. Understanding the behavior of the cross-member under maximum loading conditions can assist with both material selection, as well as determining optimal dimensions of the beam cross-section to minimize deflection.

The final model shown in Fig. 27 is that of the load applicator to which the force transducer is attached. It is important to explore the possibility of buckling experienced by the applicator under extreme loading conditions.

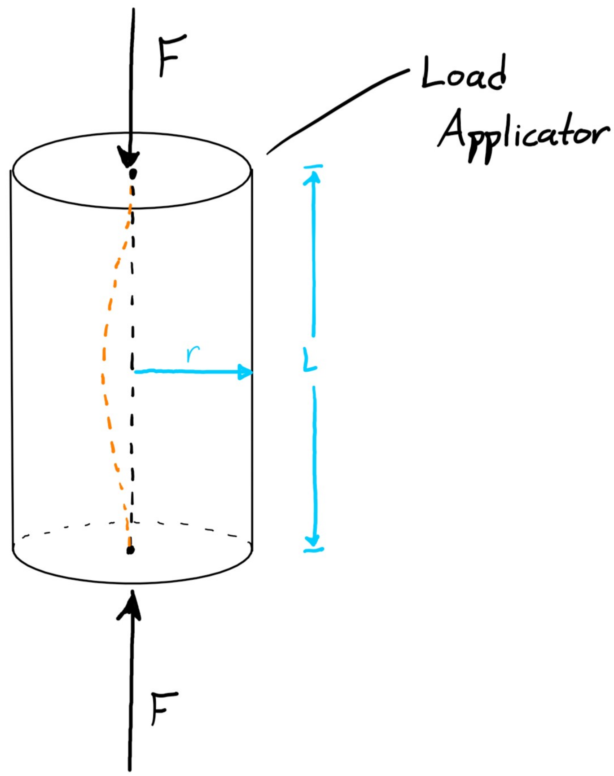


Figure 20: Buckling of the Load Applicator

The critical buckling load, signified by F is given by the expression

$$F = n\frac{\pi^2 EI}{L^2},$$

where again E is the elastic modulus, I is the area moment of inertia of the cross-section, and L is the column length. In this case, the factor n is determined by the end conditions of the column. The area moment of inertia of a cylinder cross-section with radius r is given by

$$I = \frac{\pi}{4}r^4.$$

The specimens that we will be testing likely won't put up much resistance to the force transducer, but using the critical buckling load to determine the optimal dimensions of the load applicator could prevent any damage it might otherwise incur.

5 Concept Embodiment

5.1 Initial Embodiment

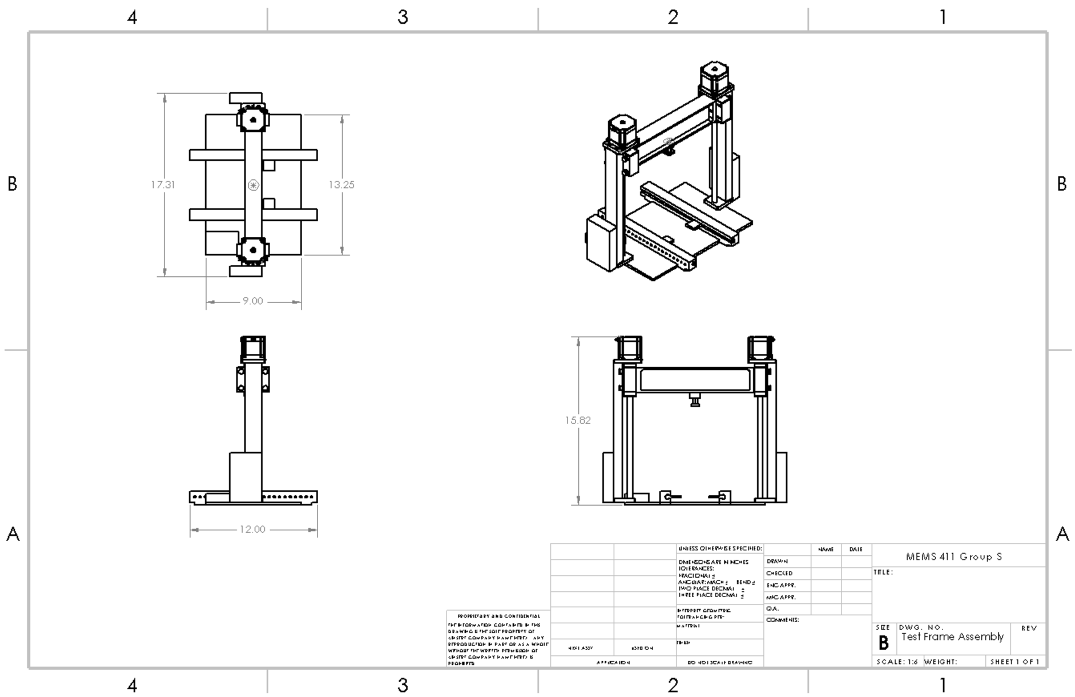


Figure 21: Assembled projected views with overall dimensions

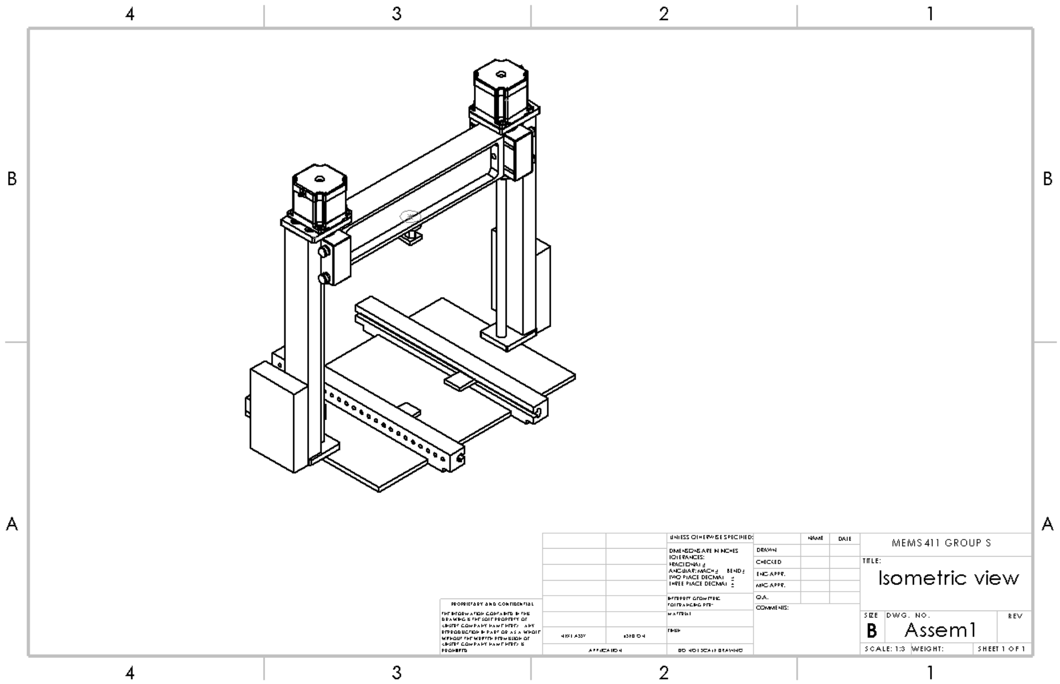


Figure 22: Assembled isometric view

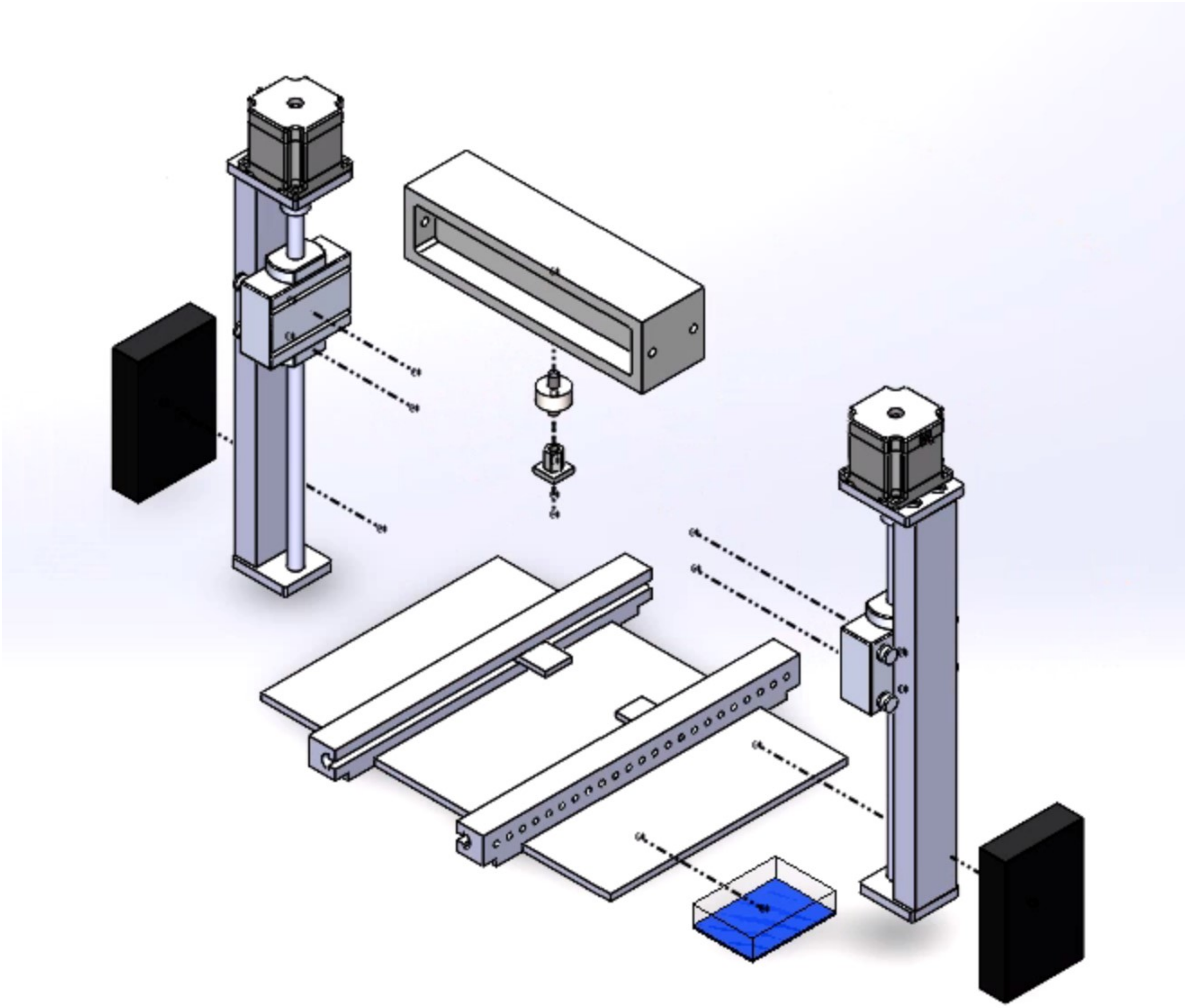


Figure 23: Exploded view

Our performance goals are: 1. Can withstand 100 lbs of force 2. Load applicator moves at 0.25 in/s 3. Measurement of sample displacement and force output 4. Maximum deflection of 0.015in

5.2 Proofs-of-Concept

No physical testing was able to be performed due to delays in parts, however, by drafting up testing procedures, we were able to identify several concerns for design changes. By articulating the testing procedure, we were able to begin drafting code sections that would help with user safety and measurement procedure. We focused on beginning to write code and create wiring diagrams of the experiment setup since most critical parts had not arrived at this point. This allowed us to get a head start and begin testing as soon as motors and sensors arrived.

5.3 Design Changes

There are a few design changes compared to the concept we envisioned before. The base plate was changed after we learned about the stock available at school. We switched to a thinner base plate which could be easily found from the materials from the Machine Shop Practicum course. We also included two clamping rails for holding down the test specimen on the base plate, as it could accommodate specimen of different sizes and shapes. We removed the holes in the base plate as they require specific dimensions to be secured. However, this is still an ongoing design that we might restore for reducing weight.

We also improved our design on the cross member. When we envisioned the concept, we did not have a clear idea of the load the cross member would take, and only drew a generic rectangular bar on the sketch. During prototyping, we realized that a solid rectangular metal cross member would be heavy without improving much on the strength of the piece. We recalled that I-beams have a large moment of inertia with reasonable weight, which is useful to resist bending and save weight in our design. Therefore, we changed our design to an I-beam that could be machined from a rectangular stock. Initial finite element results indicated its rigidity with a maximum deflection result of 0.003 in, which satisfies our prototype performance goal.

We also refined the load applicator section. Having a clearer idea of the load cell we are using, we designed a threaded hole in the I-beam to attach our load cell.

6 Design Refinement

This section presents three theoretical models using our design's actual dimensions to calculate their deformation. They demonstrate the validity for our design and are more concrete than the envisioned models in Section 4.4.

6.1 Model-Based Design Decisions

6.1.1 Beam bending

The cross member could be modeled as a beam under a vertical load which causes it to bend. To save weight without compromising strength, we designed an aluminum I-beam for the cross member. To calculate the maximum deflection of the beam, we are using the beam bending model. While the cross member have flanges for mounting at the end, in the model it is assumed the beam has an I-shaped cross section throughout. The hole for the load cell is also ignored. The calculations are presented in Fig. 24. An illustration of the cross section is shown in Fig. 25. Solidworks program was used to find the moment of inertia of the cross section.

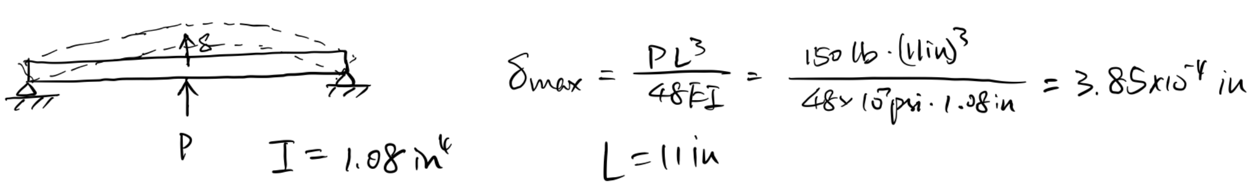


Figure 24: Calculations for actual cross member bending

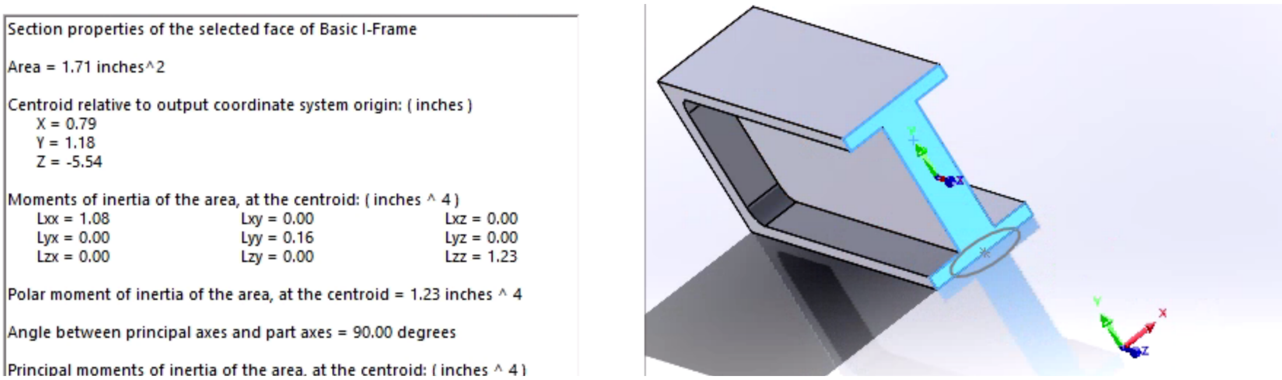


Figure 25: Cross section of the cross member

According to beam bending equations with the actual dimensions of the prototype, the maximum deflection at the center of the beam is only 3.85×10^{-4} in at the designed maximum load of 150 lb, which is hardly observable. Note that in the model, it is assumed the beam has simply supported boundary conditions. In reality, four fasteners secure the cross member on each side. This resembles more to a clamped boundary condition. However, even assuming the simply supported boundary yields a negligible deflection. Therefore, the deflection of the cross member would be smaller and could be ignored.

6.1.2 Load cell axial deformation

The second model describes the deformation of the load cell. The load cell consists of a sensor and two mounting screws on the top and bottom of the sensor. The model predicts the axial deformation of the load cell under maximum load. It is assumed that the sensor does not readily deform due to its large cross sectional area. The screws experience higher stresses which are likely to deform more. The threads are assumed negligible in affecting the screws' deformation. Two screws are combined in calculating the total axial deformation. The screws are made out of steel. The calculations are presented in Fig. 26.

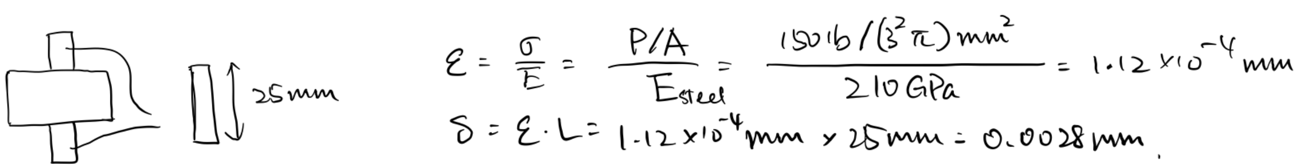


Figure 26: Calculations for load cell axial deflection

6.1.3 Support channel buckling

Our third model predicts whether the supporting channels for the stepper motor will buckle under maximum load. The support consists of a rectangular aluminum bar and a steel lead screw. There are cut channels on the aluminum bar which has been ignored in calculating the critical buckling load. The threads on the lead screw are also ignored to simplify the model. The support is assumed to have a free end at the top and a clamped boundary at the bottom, where the stepper motor assembly is firmly attached to the base plate. Figure 27 presents the calculations.

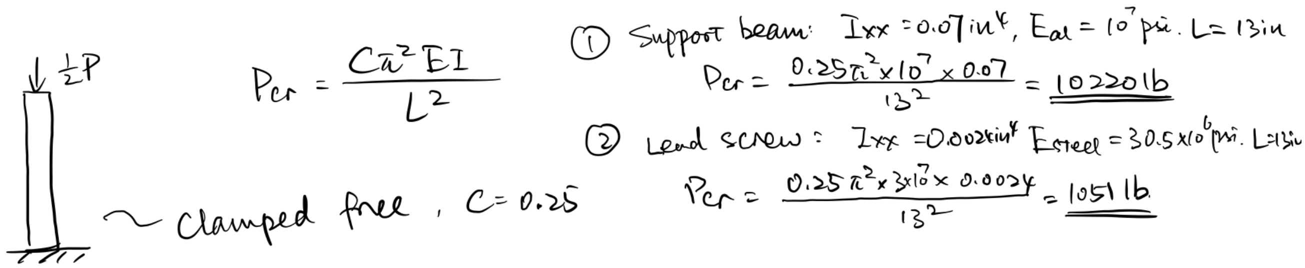


Figure 27: Calculations for support channel buckling

The critical buckling load from either the lead screw or the support beam is significantly higher than the maximum load possible for the applications of our test frame. Consequently, the assumptions should not affect the concluding evidence that the supports are significantly stronger and will not fail under normal operations.

6.2 Design for Safety

In designing our prototype, we considered multiple potential danger in using our device. We have came up with the following solutions to address the most prominent three risks: finger jamming, flying debris, and sharp corners

6.2.1 Risk #1: Finger jamming

Description: In our prototype, the test frame moves up and down with two stepper motors. Fingers could be jammed between the specimen and applicator head, and in the stepper motor lead screws.

Severity: The severity is **catastrophic**. Jamming the fingers with moving parts could seriously hurt the user.

Probability: This could happen **frequently** without proper training. It is easy for user to forget and leave their hands in the way of the machine.

Mitigating Steps: We will include reminders to stay clear of the machine when the program starts. We will also mount clear plastic boards to the sides of the stepper motor to prevent hands from gripping onto them, which could touch the moving lead screw.

6.2.2 Risk #2: Flying debris

Description: During testing, debris could fly out from the test specimen from cracking or extensive compression.

Severity: The severity is **critical**. Flying debris could be sharp and fast, which could struck viewers which cause harms.

Probability: This is **likely** to happen. This could occur very frequently as each test specimen is crushed.

Mitigating Steps: In our program to apply load, we will stop the motors once a sudden decrease in force is detected. This prevents additional pressure to the specimen which could cause debris to fly out. We also will warn the user on starting to stay away from the machine while moving.

6.2.3 Risk #3: Sharp corners

Description: There are sharp corners on the base plate and the cross member. They could hurt the user if one accidentally touches these corners.

Severity: The severity is **marginal**. This is only causing skin damage which is likely to heal in a short period of time. Nevertheless, this is still a damage to the body and is not desired.

Probability: This could happen **occasionally**. It is possible that users forget and touch the sharp corners from time to time.

Mitigating Steps: We will round the corners and fillet the base plate to eradicate the possibility to hurt people.

6.2.4 Risk #4: Electric shock

Description: There are multiple power chords and cables in our test frame, which could be an electrical hazard for users.

Severity: The severity is **critical**. Our maximum voltage in the device is 24V but the power chord to the wall socket is at 110V. Both could be damaging to the body.

Probability: This is **unlikely** to happen. Cables should not be touched during normal operations, and even they are touched, the 24V cables are more likely to be exposed than the 110V cables.

Mitigating Steps: Bare wires are wrapped with insulation tapes to prevent direct contact with people.

6.2.5 Risk #5: Accidental tip over

Description: The test frame could be dragged to the ground when someone accidentally kicks the power cable. The test frame have sharp edges which could harm the surrounding people.

Severity: The severity is **marginal**. It is unlikely that people get seriously hurt from getting hit by the frame, and it is likely people could escape from the falling frame.

Probability: This is **unlikely** to happen.

Mitigating Steps: Our power cables are connected through a connector to the motor controller. The connector has loose connections which could easily detach when someone kicks the cable.

After reviewing the risks using the Risk Assessment spreadsheet, we realize that the risks are more to less severe with the rank: finger jamming, flying chips, sharp corners, electric shock and accidental tip over. Therefore, preventing finger jamming is the highest priority, then followed by flying chips and sharp corners. Electric shock and tip over prevention are of the lowest priority. This informs us that merely providing warnings before the machine starts might not be sufficient to prevent finger jamming given its importance. We are also considering to include additional training for the user before operating the test frame. This also reduces our emphasis on electrical hazards, and wrapping the cables should be sufficient.

Severity of risk	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
Catastrophic		Finger jamming			
Critical		Chips fly out			Electric shock
Marginal			Sharp corners		Accidental tipover
Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial					

Figure 28: Heat map of risks generated

6.3 Design for Manufacturing

There are 13 theoretical necessary parts to build the Mini Test Frame. It requires 2 linear actuator assemblies, base plate, 4 plate clamps, cross member, load cell, load head, 2 Stepper motor drivers, Arduino Uno micro-controller, and a computer to run the test programs. There are a total of 20 M6 fasteners in the final assembly, not including the fixture method.

The base plate and cross member are two theoretically necessary components(TNC). They must be separate in this device since machining was required to make these components as light and strong as possible. Integrating these parts into other would compromise the weight and strength of the parts. The linear actuator assemblies are also TNCs. They needed to be integrated separately since they were purchased items and could not be engineered from scratch given our time and budget constraints. Our team could not have engineered a lead screw bearing system given the tools and budget provided to make sure the system operated smoothly. The micro-controller needs to be its own separate part because we cannot engineer our own PCBs and circuits to create a micro-controller from scratch. the TNC count could be decreased with bespoke PCB design to condense the stepper motor drivers and micro-controller into a single board so that space could be saved and wiring would be simpler. There are two clamps in securing the linear actuators to the base plate on each side. These clamps could be redesigned into a single clamp per actuator. However, it may require disassembly of the linear actuator to install the part.

There were several required changes in our design in order to machine the components. Several radii were changed to accommodate end mill sizes. Manufacturing tolerances were also lowered so that the system would not be over-defined and impossible to machine within a tolerance that was too tight to execute on a manual milling machine.

6.4 Design for Usability

6.4.1 Vision impairment

Vision impaired people will not be affected from using the device. Our device is operated from running codes on the computer, which does not cause trouble for color blindness. Presbyopia persons should not have any issue operating the device either, if they have their appropriate lenses, which is commonly prepared by presbyopia people.

6.4.2 Hearing impairment

Hearing impaired people will not be affected from using our device. Our device does not produce any sounds for instructions, so it does not bar hearing impaired people to use the device. Even those with presbycutia could still operate the device. More over, the device is designed for instructors for classroom experiments, and the target users are not likely to have presbycutia.

6.4.3 Physical impairment

Physical impaired people could be affected with our device. Our device is relatively heavy due to extensive use of machined aluminum and steel parts. They could cause issues for muscle weak people or limb immobilized people to carry and use. However, once the device is properly set up, physical impaired people could easily use the device with a computer, which does not require much physical motions. We could improve our device by changing for lighter but strong materials like carbon fiber.

6.4.4 Control impairment

Control impaired people are likely be affected from using our device. Operation of our device require attention so that hands are not jammed in the device which cause injuries. Control impaired people have worse situational awareness, which could prevent them from keeping themselves safe. A better alternative to our design is to include a lockable casing for the test frame. The test only starts after the casing is locked. In this way, all injuries could be potentially prevented.

7 Final Prototype

7.1 Overview

We successfully developed our final prototype using the stepper motors, the cross member, the load cell, the base plate, and the control modules. Figure 29 is a picture of our final prototype.

We were able to achieve all our design goals. The final prototype is $13 \times 9.5 \times 18.5in$, which is within the tolerance from the customer interview. We were able to extract a force output larger than 150 lbs, with very minimal deflections of the cross member. The load and displacement are displayed on the smartly developed Arduino program, and the load applicator could move at variable speeds thanks to the design adopting the stepper motors.

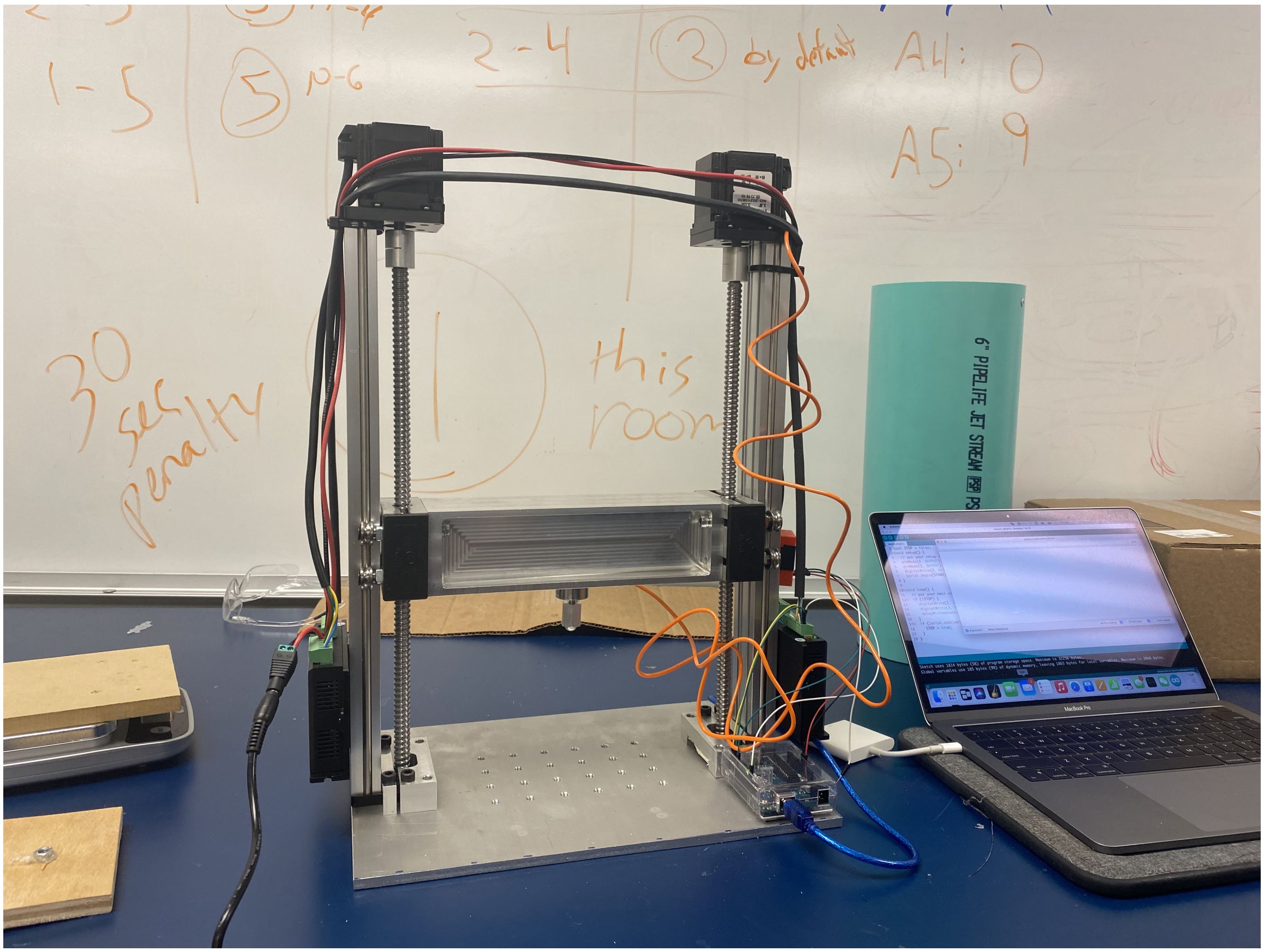


Figure 29: Final prototype of our test frame

A Software Code - Arduino

```
#include <HX711_ADC.h>
#if defined(ESP8266)|| defined(ESP32) || defined(AVR)
#include <EEPROM.h>
#endif

float failPercent = 0.5;
float crackPercent = 0.8;

enum States {  READY, TESTING, STOP  };

//pins:
const int HX711_dout = 4; //mcu > HX711 dout pin
const int HX711_sck = 5; //mcu > HX711 sck pin

//HX711 constructor:
HX711_ADC LoadCell(HX711_dout, HX711_sck);

const int calVal_eepromAdress = 0x00;
unsigned long t = 0;
States state = READY;
bool testing = false;
long steps = 0;
bool resetPosition = false;
bool cracked = false;
bool started = false;
float load = 0;
float helperLoad[20];
int loadIndex = 0;
bool calibrated = false;
bool firstPass = false;
long stepCount = 0;
bool touching = false;

// Function declarations:
void stateREADY();
void stateTESTING();
void stateSTOP();

void setup() {
  pinMode(2, OUTPUT);
  pinMode(3, OUTPUT);
  digitalWrite(2, HIGH);
  Serial.begin(9600); delay(10);
  //  Serial.println("***The super mini testframe***");
  delay(500);
  Serial.println("Confirm the test frame is at initial position. Type r to ...
      reset. Type anything else to skip");
  while (!(Serial.available() > 0)) {}
  if (Serial.available() > 0) {
    String reset = Serial.readString();
    reset.trim();
    if (reset == "r") {
      resetPosition = true;
      stateREADY();
```

```
    }
  }
  digitalWrite(2, LOW);
  Serial.println("Reset complete!");

  LoadCell.begin();
  unsigned long stabilizingtime = 2000; // preciscion right after power-up can ...
      be improved by adding a few seconds of stabilizing time
  boolean _tare = true; //set this to false if you don't want tare to be ...
      performed in the next step
  LoadCell.start(stabilizingtime, _tare);
  if (LoadCell.getTareTimeoutFlag() || LoadCell.getSignalTimeoutFlag()) {
    Serial.println("Timeout, check pin designations");
    while (1);
  }
  else {
    LoadCell.setCalFactor(1.0); // user set calibration value (float), initial ...
        value 1.0 may be used for this sketch
  }
  while (!LoadCell.update());

  Serial.println("Calibrate load cell? y/n You don't need to if you've ...
      calibrated it.");
  while (!(Serial.available())) {}
  String response = Serial.readString();
  response.trim();
  if (response == "y") {
    calibrated = true;
    calibrate();
  }
}

void loop() {
  // Reading in STATES
  if (state == TESTING) { // Emergency STOP
    if (Serial.available() > 0) {
      // Stop
      state = STOP;
      Serial.println("Stopped");
    }
  }
  else {
    Serial.println("Enter 'start' to run the test. Enter any input to interrupt ...
        the test.");
    while (!(Serial.available() > 0)) {}
    String input = "";
    input = Serial.readString();
    input.trim();
    if (input == "start") {
      Serial.println("Test start in 3... Please keep moving space clear.");
      state = TESTING;
      started = true;
      touching = false;
      for (int j = 0; j < 20; j++) {
        helperLoad[j] = 0;
      }
```

```
      loadIndex = 0;
      if (!calibrated) {
        LoadCell.tareNoDelay();
      }
      steps = 0;
      stepCount = 0;
      delay(3000);
    }
    else if (input == "reset") {
      Serial.println("Resetting test frame in 3... Please keep moving space ...
         clear.");
      state = READY;
      resetPosition = true;
      delay(3000);
    }
    else {
      Serial.println("Try again.");
      state = READY;
      resetPosition = false;
    }
  }

  if (state == READY) {
    stateREADY();
  } else if (state == TESTING) {
    stateTESTING();
  } else if (state == STOP) {
    stateSTOP();
  }
}

void stateREADY() {
  while (resetPosition) {
    steps = 0;
    stepCount = 0;
    digitalWrite(2, HIGH);
    Serial.println("The motor will move up. Type in anything to stop.");
    delay(1000);
    while (!(Serial.available() > 0)) {
      digitalWrite(3, LOW);
      digitalWrite(3, HIGH);
      delayMicroseconds(600);
      if (Serial.available()) {
        Serial.println("Type c to continue. Type anything else to confirm this ...
           starting location.");
        delay(1000);
        Serial.read();
        while (!(Serial.available())) {}
        delay(1000);
        while (Serial.available() > 0) {
          String stopReset = Serial.readString();
          stopReset.trim();
          if (stopReset == "c") {
            Serial.println("The motor will move up. Type in anything to stop.");
            continue;
          } else {
```

```
            resetPosition = false;
            steps = 0;
            break;
          }
        }
      }
      if (!resetPosition) {
        break;
      }
    }
  }
}

void stateTESTING() {
  if (started) {
    digitalWrite(2, LOW);
    delay(1000);
    cracked = false;
    stepCount = 0;
  }
  started = false;

  while (!(Serial.available() > 0)) {
    steps += 1;
    if (cracked) {
      digitalWrite(3, LOW);
      digitalWrite(3, HIGH);
      delayMicroseconds(6000);
    } else {
      digitalWrite(3, LOW);
      digitalWrite(3, HIGH);
      delayMicroseconds(600);
    }

    if (Serial.available() > 0) {
      state = STOP;
      Serial.println("Stopped.");
      break;
    }

    if (steps % 200 == 0) {
      float i = 0;
      static boolean newDataReady = 0;
      const int serialPrintInterval = 0; //increase value to slow down serial ...
         print activity

      // check for new data/start next conversion:
      if (LoadCell.update()) newDataReady = true;

      // get smoothed value from the dataset:
      if (newDataReady) {
        if (millis() > t + serialPrintInterval) {
          i = LoadCell.getData();
          Serial.print("Load_cell output val: ");
          Serial.println(i);
          newDataReady = 0;
```

```
          t = millis();
        }
      }

      load = i;
      if (load > 1) {
        touching = true;
        float averageLoad;
        helperLoad[loadIndex] = load;
        if (loadIndex == 19) {
          loadIndex = 0;
        } else {
          loadIndex += 1;
        }

        if (firstPass) {
          averageLoad = 0;
          for (int j = 0; j ≤ loadIndex; j++) {
            averageLoad += helperLoad[j];
          }
          averageLoad /= loadIndex;
        } else {
          averageLoad = 0;
          for (int j = 0; j < 20; j++) {
            averageLoad += helperLoad[j];
          }
          averageLoad = averageLoad / 20.0;
        }

        if (steps > 200) {
          if (load < failPercent * averageLoad) {
            state = STOP;
            Serial.println("Failure detected.");
            Serial.print("Max force: "); Serial.println(averageLoad);
            Serial.print("Displacement: "); Serial.println(stepCount * 0.005);
            break;
          } else if (load < crackPercent * averageLoad) {
            cracked = true;
            Serial.println("Crack detected.");
          }
        }

        if (averageLoad > 150) {
          state = STOP;
          Serial.println("Maximum required load reached");
        }
      }

      if (touching) { stepCount += 1; }
    }
  }
}

void stateSTOP() {
  // STOP the motor
}
```

```
void calibrate() {
  Serial.println("***");
  Serial.println("Start calibration. Remove any load on the load cell.");
  Serial.println("Send 't' to set the tare offset.");

  boolean _resume = false;
  while (_resume == false) {
    LoadCell.update();
    if (Serial.available() > 0) {
      if (Serial.available() > 0) {
        char inByte = Serial.read();
        if (inByte == 't') LoadCell.tareNoDelay();
      }
    }
    if (LoadCell.getTareStatus() == true) {
      Serial.println("Tare complete");
      _resume = true;
    }
  }

  Serial.println("Hang a known mass on the loadcell.");
  Serial.println("Send the weight of this mass (i.e. -100.0).");

  float known_mass = 0;
  _resume = false;
  while (_resume == false) {
    LoadCell.update();
    if (Serial.available() > 0) {
      known_mass = Serial.parseFloat();
      if (known_mass != 0) {
        Serial.print("Known mass is: ");
        Serial.println(known_mass);
        _resume = true;
      }
    }
  }

  LoadCell.refreshDataSet(); //refresh the dataset to be sure that the known mass is measured correct
  float newCalibrationValue = LoadCell.getNewCalibration(known_mass); //get the new calibration value

  Serial.print("New calibration value has been set to: ");
  Serial.println(newCalibrationValue);
  Serial.print("Save this value to EEPROM adress ");
  Serial.print(calVal_eepromAdress);
  Serial.println("? y/n");

  _resume = false;
  while (_resume == false) {
    if (Serial.available() > 0) {
      char inByte = Serial.read();
      if (inByte == 'y') {
#if defined(ESP8266)|| defined(ESP32)
        EEPROM.begin(512);
```

```
#endif
        EEPROM.put(calVal_eepromAdress, newCalibrationValue);
#if defined(ESP8266)|| defined(ESP32)
        EEPROM.commit();
#endif
        EEPROM.get(calVal_eepromAdress, newCalibrationValue);
        Serial.print("Value ");
        Serial.print(newCalibrationValue);
        Serial.print(" saved to EEPROM address: ");
        Serial.println(calVal_eepromAdress);
        _resume = true;

      }
      else if (inByte == 'n') {
        Serial.println("Value not saved to EEPROM");
        _resume = true;
      }
    }
  }

  Serial.println("End calibration");
  Serial.println("***");
}
```