Advanced Mechanical Design, University of Rochester
Final Design Report
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MARY CARIOLA DRAWING DEVICE

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ABSTRACT
The purpose of this project is to create a more accessible way for children to draw pictures on paper. In this project, the team attempted to design a device that would allow children of all physical and developmental abilities to draw. The design is a 2D translation stage, powered by two Arduinos and two stepper motors. The design uses 8020 aluminum extrude rails. One rail is stationary and attached to a wooden base, while the other is attached on top of the base rail. The topmost rail translates along the base rail. Each rail has two limit switches attached, one stationary and one adjustable, to define the paper boundary. There are two button inputs, one that moves the top rail up and down (y direction) and one that moves a cart attached to the top rail side to side (x direction). A potentiometer controls the speed of both motors. An adjustable pen holder is attached to the cart, allowing students to use different utensils. The results were a working translation stage powered by inputs from the students, with adjustable speed, paper size, and utensils. The assembly is also equipped with a clear cover for safety, to avoid injuries from the moving pieces while still allowing the students to see the assembly in action.

PROBLEM DEFINITION
The overarching problem is that not all students are able to hold writing utensils on their own to draw on paper. There are a variety of toys that allow students to draw without having to hold a utensil, such as an Etch-a-Sketch, but these devices are not accessible. Some drawing devices require the use of many buttons or knobs, which some children are not able to easily control. This problem is important because children deserve equal opportunities to participate in creative arts. It is especially important to teachers and school faculty who are looking to give children the best possible educational experience, and don't want students to miss out on activities, such as drawing and coloring, simply because the available toys are inaccessible. The purpose of the project is to address this issue and design a drawing device that is operated by buttons provided by the school. The result will be an improvement in the ability for children to create drawings that can be taken home.

REQUIREMENTS, SPECIFICATIONS, DELIVERABLES

Requirement	Description
Device is transportable	Device/assembly can be moved from location to location (most often from one tabletop to another) by one adult.
Compatible with provided buttons	Device must have connections for provided buttons that fit into a 3.5 mm auxiliary port.
Childproof/Includes safety cover	Clear/see through cover that keeps children from being able to touch the mechanism but is easily removable by an adult to change paper.
Paper is easily replaceable	Paper constraint devices can be lifted so paper can be removed and replaced.
Non digital/no screen	Drawing is to be done on physical paper with a drawing utensil of the user's choice. No screen component may be included.
Can hold most standard utensils	Utensils can range from a pencil to a marker, see exact diameter in specifications.
Able to be angled	Device can rest at an angle without slipping from the surface.

Table 1. Requirements for device.

Specification	Description
Paper Width Range	11.5 to 24 inches
Paper Height Range	8 to 18 inches
Base thickness	1/8 inch
Max Weight	20 lbf
Motor Torque	Less than 4.43 lbf*in
Tilt Angle Range	0 to >45 degrees
Power Supply	Output maximum of 5 volts.

Table 2. Specifications for device.

Deliverables	Description
Drawing Device	Physical drawing mechanism. Components include translation stage/electronics, safety cover, pen holder, and stand/base.
Theory of Operation	Written "how to use" guide, including step-by-step instructions and troubleshooting information.
Technical Report	Written summary report including final design, models, simulation results, material list, etc.

Table 3. Deliverables for Capstone Project.

CONCEPTS

Subsystem: Electronics

The electronics subsystem can be broken down into the following: the design, assembly, and wiring of the translation stage using Arduinos, stepper motors, and limit switches, in addition to the provided buttons.

Translation Design and Assembly

The selected design will have two arms made with 8020 rails. The rails will be connected to rollers that are connected to a cart to allow one of the 8020 rails to move along the other. The pen holder will be attached to one of the arms with a bracket and set of rollers. Belts will run across the railing so that the carts will move alongside them.

Wiring and Circuitry

The electronics will be powered by a standard outlet connected to a power supply. The power supply will be connected to an Arduino and stepper motors and will provide power to the whole system.

Coding/Programming

The programming of the Arduino controls the machine. Button inputs result in motion of the stepper motors and the attached pen.

Concept Selection Process Explanation:

Core XY

This concept (Electronics Figure 1) was inspired by the configurations of modern 3D printers. The design below is meant to prioritize speed without hindering the precision of the print, but it is also complicated and contains many moving parts. A design like this would require more intensive troubleshooting and testing.

Diagonal Pulleys

This concept (Electronics Figure 2) is meant for a drawing system that can be hung on a wall. Two motors are attached to belts that are suspended on the wall and are attached to a board. One of the requirements for the design is that it can be transportable, therefore it was not chosen as the concept.

Rotating Arm

This concept (Electronics Figure 3) is simple and contains minimal parts (only two motors and two belts), which makes it ideal for the project. The issue arises when it comes to the programming of the Arduino to run this device. To move in any direction, two motors need to be activated. Any input from the buttons must correlate to two motor outputs. The programming required to achieve this is much more complicated than necessary with another design.

Final Selection: Two Axis Arms

This design (Electronics Figure 4) requires two rails, belts and motors each. The pen holder will be attached to a bracket that connects to a rail and can translate along the rail with the use of rollers. It will be powered by an Arduino. This design was selected mainly for its cost, ease of use, ease of manufacturing, and ease of coding as seen in Figure 1. It will be far easier to code than the other concepts because one input will correspond to one output from one motor rather than the other designs, where, just to move left, right, up, or down, both motors must move at the same time. It also doesn't require as much hardware as some of the other concepts, further influencing the team to pursue this direction.

Updates to the Concept

The design needs to have 2 Arduinos running simultaneously. Having two motors connected to only one Arduino connects the motors in series, when they should be in parallel; thus, a second one is necessary. If the motors are connected in series, then whenever the two motors are activated, the power is evenly distributed to each motor, essentially making the motors move at half the speed when both buttons are being pressed. Using 2 Arduinos ensures that each motor receives the maximum power they each need regardless of whether the other motor is drawing power as well. Another update to the concept includes using 8020 linear slides instead of carts attached to rollers.

Subsystem: Hardware

The hardware subsystem of the design is divided into 4 major components: the base, safety cover, pen holder, and paper constraint. Each component is explained in more detail below.

Base

The original proposed design was a rectangular sheet (Hardware Figure 1), with dimensions of 18 inches by 24 inches by 1/8 inches. The base was to be made of magnetic material or imbedded with magnetic strips so that it would be compatible with magnets as paper constraints.

Updates to the Concept

Through our design and planning phase, we decided to move away from this concept, due to the weight and cost of a magnetic material. The final design for the base is a ½" thick piece of plywood (Figure 10). This was chosen for simplicity and cost effectiveness. Medium density fiberboard was also considered for the base due to its better resistance to warping, however the cost drove us away from this choice.

Safety Cover

The purpose of the cover is to keep children from being able to touch the mechanism while it is in motion, to prevent injury to the children, and damage to the device. The proposed design (Hardware Figure 3) was a see-through cover with a handle for easy opening and a hinged mechanism to create a lid.

Updates to the Concept

The proposed idea of an all-clear and hinged safety cover was altered in favor of a more cost and time effective cover. The final design (Figure 9) contains only see-through acrylic panels on the front and top sides, with plywood panels on the other 3 sides. The top sheet of acrylic is removeable and slides into a grove in the pieces of plywood, so that the mechanism can be easily accessed.

Pen Holder

The pen holder design will attach the pen to the translation stage. It will be adjustable to hold pens/utensils ranging in size from 0.25 to 0.75-inch diameters. The original proposed design (Hardware Figure 4) has two curved pieces, connected, and adjusted by a screw. This design will be the easiest to manufacture and allow for the most variability in utensil size.

Updates to the Concept

The final design for the pen holder (Figure 12) contained a rotating arm connected to a spring to contact the writing utensil. This was chosen as opposed to the original concept of a screw to contact the utensil as the old design was capable of much more force than necessary. The rotating arm can contact a wide range of utensil sizes. This concept was more difficult to manufacture than the original but was the right design for what was necessary.

Paper Constraint

The constraint needs to hold the paper down so that the force of the moving utensil doesn't also move the paper (paper should not slide). The proposed design (Figure 4) was to embed two magnetic strips in the base plate and use two smaller magnets to hold the paper on.

Updates to the Concept

The original proposal was reconsidered due to its overthought and complexity. Going along with the base selection, the idea of a magnetic material was scraped due to weight and cost, and with it, the magnet idea. We opted to use a clipboard clip in the corner of the base.

MECHANICAL ANALYSIS

Throughout the process many design choices had to be made based on calculations and analysis. Some of these calculations are highlighted in the section below.

Fatigue Analysis of Motor Shaft:

The following is a fatigue analysis of the shaft of the stepper motors. The material is assumed to be 304 stainless steel. Determining S_e ,

$$S_e = k_a k_b k_c k_d k_e k_f S_e' \quad (1)$$

Where k_a is surface factor, k_b is size factor, k_c is loading factor, k_e is reliability factor, k_f is miscellaneous effects factor, and S_e' is the endurance limit for the specimen, S_e is determined to be 6.21 kpsi. The ultimate tensile strength, S_{ult} is 73.2 kspi for 304 stainless steel. Assuming a midrange stress of 50 kspi and an alternating stress of 30 kpsi, according to both Goodman and Soderberg approximations, the motor shaft will fatigue. The Goodman and Soderberg approximation are the following:

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ult}} \geq 1 \quad (2)$$

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_y} \geq 1 \quad (3)$$

Since the fatigue analysis shows that the motor shaft has a finite life, ultimately, the motors will have to be replaced. However, the machine will not be used 1 million times, and does not need to withstand infinite cycling.

Fastener Torque Calculation:

The following analysis is a bolt torque calculation for a 6-32 fastener that is zinc-plated and requires a permanent connection.

This bolt is being used to connect the slide brackets to the belt. Calculating force,

$$F_p = A_t S_p \text{ (4)}$$

where F_p is the force in the bolt and solving for F_i, the preload in the fastener,

$$F_i = \{0.90F_p\} \text{ (5)}$$

the torque can then be calculated,

$$T = kF_i d \text{ (6)}$$

Solving, the torque value required for the screw and fastener is T = 12.418758 $lb_f \cdot in$. The torque value required for the screw is low due to the small size of it. Since the screw is threaded into a bracket and inserted into the belt with washers, there is little concern for the screw torquing out of place.

Tolerance Analysis Calculation (for hole placement on double rail belt mount):
The following is the equation used to determine whether the tolerancing of the hole placement of the double rail belt bracket will pass inspection. The holes passed, as verified using a MATLAB script in Figure 5.

$$diameteral\ error = 2 \times \sqrt{((x_o - x_e)^2 + (y_o - y_e)^2)} \text{ (7)}$$

Spring Sizing:
The spring used in the pen holder assembly needed to produce enough force so that the writing utensil would not slide through when contacted with the ground. To find the minimum spring force needed, a static analysis of the utensil was used. The free body diagram shows a total of 4 forces acting on the utensil: the weight of the pen holder (W_{PH}), force from the spring arm (F_A), normal force from the "V" (N), and the force of friction (F_f) between the utensil and the pen holder. The force of the spring arm depends on two variables,

$$F_A = kx \text{ (5)},$$

where k is the spring constant of the spring and x is the extension distance. The force of friction depends on two factors as well,

$$F_f = N * \mu \text{ (6)},$$

Where μ is the coefficient of friction between the utensil and the pen holder, assumed to be 0.5 for plastic on rubber.
The weight of the pen holder, W_{PH}, is 0.325 lbf. When summing forces F_A=N is found, which can be used to substitute and solve the system of equations for F_A.

$$F_A = \frac{W_{PH}}{\mu} \text{ (7)},$$

Solving this with known values of W_{PH} and μ, it is determined that $F_A \geq 0.65$ lbf. Of the springs available, two were suitable sizes to satisfy this minimum force. The longest of the two springs with an unstretched length of 0.943" and a spring constant of 2.25 lbf/in^2 was chosen. The minimum extension length for the spring is 0.38". This provides a spring arm force of 0.855 lbf, which is more than the minimum required force.

Structural FEA Analysis of Spring Arm:
To determine the proper material for the spring arm, a a finite element analysis was performed. The arm was meshed with a 3D tetrahedral, and the material used was aluminum. An SPC 1,2,4,5 was put within the hole and an SPC 3 on the bottom face to leave one degree of freedom in the rotational Z direction. Another SPC 2 was added at the far end of the arm, where the stopper will contact the arm. The force added to the arm was a 2 lbf load distributed on the face of the cutout for the dowel pin to simulate the force of the spring. The result of this analysis, found in figure 7, gives a maximum displacement of 1.105E-5 inches which is insignificant and signals that aluminum is strong enough for this part.

Material Selection for Spring Arm:
The material selection for the spring arm was based on the structural FEA from the section above. From the analysis, aluminum was shown as a suitable material, however, after repeating the analysis, but using PLA as the material, it seemed 3D printing the arm may be suitable. It was decided to 3D print and test the arm before manufacturing the piece with aluminum. This first prototype failed, leaving aluminum as the material selected for the arm.

Mechanical Analysis:
The design of our translation stage (see in Electronics Figure 4) originally contained a cantilever beam. Deflection in the cantilevered 8020 rail, which the pen holder would move across, would cause the pen holder to not operate smoothly. Using a beam length of 21.5 inches and an end load of 1 lbf, the deflection of the beam was 3.904e-3 inches. While this deflection likely would not have caused significant issues in the pen holder's operation, we opted to include a ball transfer at the far end of the rail as a precaution. The analysis can be found in Figure 8.

MANUFACTURING

Item Manufactured	Material	Method	Justification
Pulley mount	Aluminum	Mill	Easy and fast to make by team
Limit switch mount	Aluminum	Mill	Easy and fast to make by team
Motor mount	Aluminum	Mill	Easy and fast to make by team

Slide bracket	Aluminum	Mill	Easy and fast to make by team
Pen holder assembly	Aluminum, PLA	Bill Mildenberger, 3D printing, Mill	Design is complex and had enough money in budget for Bill to manufacture. Some adjustments needed to be made so 3D printing and milling by team was quicker and cheaper
Base	Plywood	Table saw sanding, hot gluing	Cut base to size on table saw, sanded corners, and hot glued the stopper pieces
Safety Cover	Polycarbonate, plywood	Bill Mildenberger, wood gluing, nail gunning	Paid for Bill to make the cover, due to complexity in solvent welding. The design was changed, so the team added an extra 1 inch to the base to make it taller for time and money reasons

Table 3. Items manufactured, material used, method of manufacture, and justification. A more detailed overview of each manufactured component is listed below.

Hardware Item	Purchased Hardware Cost ($)	Purchased Shop Time ($)	Team Member Manufacturing Time (hours)
Button Head Hex Screw (3/8" length)	10.16		
Ball Transfer	7.28		
1010 8020 (25 in.)	12.04		
1020 8020 (27.5 in.)	39.68		
3676 8020 (T-nuts)	12.60		
5M timing belt	12.99		
20 Tooth 5mm Bore Pulley	6.99		
Micro Limit Switch	5.99		
8-32 Thumb Screw	6.78		
0-80 Button Head Screw	5.72		
#0 Washers	2.45		
¼-20 Hex Nut	8.95		
4mm Shoulder Diameter Screw	6.42		
¼-20 Button Head Screw	11.74		
M3 Pan Head Screw	12.71		
¼" Shoulder Diameter Screw	6.31		
2428 Mount Bracket	14.19		
3386 T-nut and Screw	2.73		
10-32 Thumb Screw	6.78		
10-32 Thumb Screw ½" Head Height	12.52		
5/16" Shoulder Screws	19.52		
Etch-a-sketch	23.95		
Pen Holder Backplate, Back Arm, Stopper	N/A	180	
Safety Cover	N/A	120	
Spring Arm	N/A		2.5
Double V	N/A		1 (3D print)

Arduino UNO Rev3	28.50		
Adafruit Motor shield Rev3	24.99		
Nema 17 Stepper Motor	9.99		
Clipboard Clips	11.99		
Fiberboard 24” x 36”	33.23		
AUX port for buttons	8.99		
Wire sleeves	8.99		
Power Supply	16.99		
Single Rail Slide Bracket	N/A		2
Double Rail Slide Bracket	N/A		2
Pulley Mount Double Rail	N/A		2
Pulley Mount Single Rail	N/A		2
Stationary Limit Switch Mount	N/A		2
Adjustable Limit Switch Mount	N/A		2
Motor Mount Double Rail	N/A		2
Motor Mount Single Rail	N/A		2

Table 4. Purchased hardware cost, purchased shop time, and team member manufacturing time in hours.

Team Member	Development time (SCRUM hours)
Linnea	86
Farhan	99
Tom	82.5
Maya	100.5

Table 5. Development time of team members in hours.

If the system were scaled to 1000 systems, some changes that could be made to improve cost and build time would be to more efficiently produce the parts that were manufactured using the mill. Techniques such as laser cutting and stamping could be used for various components of the pen holder and mounts. These techniques would eliminate mill time and produce these components much faster and cheaper. Individual systems would still need to be assembled by hand, requiring a few hours per system.

Pen holder:
For the pen holder, there were 5 major components to be manufactured. The backplate, both arms and the stopper needed to be made from aluminum, due to the high stresses through them and overall durability concerns. The backplate and back arm had features with tight tolerances, so we opted to have Bill Mildenberger manufacture them for us. The stopper and front arm had fewer complex geometries, so we manufactured them in Rettner with the lathe and mill, respectively. The “V” piece is not expected to experience high stresses, and it has a rather complex geometry that was necessary to optimize through several trials. For these reasons it was opted to 3D print this part.

Base
The base was made using a table saw and a piece of plywood and sanded. The “stopper” pieces were made by cutting a thin strip of the same material into properly sized cubes. Hot glue was used to attach the stoppers to the wooden base. There was much discussion surrounding the material for the base. Originally, medium density fiberboard was proposed, as it is stronger than plywood and does not warp, but it was ultimately determined to be an unnecessary expense. The amount of warp the plywood would undergo was negligible and unlikely to cause failure.

Safety cover
The safety cover had many specifications, mainly that it had to be clear and cover the whole mechanical assembly. The original design was to have a box with all sides made of acrylic, and the top panel attached to a hinge to be opened and closed. The design was to be made by Bill Mildenberger, as it would require acrylic solvent welding, a skill that was beyond the team’s ability. Discussions with Bill lead to design changes to provide more structural support to avoid the collapse or twisting of the box, which would be achieved by using wooden sides and supports. The original cover made by Bill was 4-sided wood, and the top panel polycarbonate. However, this did not fit with the specifications of the sponsor, so the design was modified, and the front wood panel was replaced with polycarbonate to allow for more visibility of the assembly.

Mounts/Brackets

Custom designed plates and brackets, including pulley mounts, motor mounts, limit switch mounts, and slide brackets were made. These items were unable to be purchased as they are custom parts with specific locations for mounting holes. The manufacturing for these items was within the skill level of the team, as they just needed to be cut to size and have some holes drilled and tapped.

Non-manufactured Items

Purchased/non manufactured items included 8020 rails, carts, pulleys, limit switches, t-nuts, screws, etc. They were purchased instead of made by the team for a variety of reasons, including time to make, and skills required to make. Additionally, some items needed to be very high quality and have perfect tolerancing (for example, the cart must be able to slide and fit perfectly on the rails, otherwise the assembly would not function). Another component purchased was the pulleys and belts, which needed to be high quality since they will be getting used a lot.

TEST PLAN AND RESULTS

Specification	Required Value	Measured Value	Pass/Fail	Test Method
Paper Width Range	11.5 to 24 inches	11.5 to 22 inches	Fail	Tape Measure
Paper Height Range	8 – 18 inches	8 – 17.5 inches	Fail	Tape Measure
Base thickness	1/8 inch	½ inch	Fail	Tape Measure
Max Weight	20 lbf	29.8 lbf	Fail	Digital Scale
Tilt Angle Range	0 to >45 degrees	0 to 70 degrees	Pass	Tilt Test
Motor torque	< 4.43 lbf*in		Pass	
Power supply	Output of 5 volts		Pass	

Table 6. Specification Pass/Fail

INTELLECTUAL PROPERTY

The overall design with all its components could be considered patentable. However, the design is composed of unpatentable or previously patented components. The base and safety cover are not novel; there are many existing covers with sliding lids, and the base is simply a piece of plywood equipped with some stoppers. The 8020 rail, motor, belt, and pulley system are a more in-depth design done by the team, but this sort of translation stage already exists in 2D and 3D. For example, the 3D printer [1] contains a 2D translation stage, which by itself is not patentable, but is as an assembly. The only piece of the assembly that could be considered patentable is the adjustable pen holder, because it was completely designed by a member of the team. It was designed especially to be compatible with the 8020 sliding carts, fit the height envelope of the base and safety cover, and be adjustable for the specified range of pen diameters.

SOCIETAL AND ENVIRONMENTAL IMPLICATIONS

The main societal impact of this project is increasing accessibility for students. Accessibility is an ongoing issue in the United States, and across the world. While there are laws in place, such as the Americans with Disabilities Act (ADA) [2], which mandate accessibility for a wide array of disabilities, there are still areas that need improvement. One such area is children's access to toys that are usable to them, regardless of their physical abilities or developmental level. The societal impact of this drawing device is relatively small, as it specifically helps one school, however, there is potential for devices like this to become more common, as well as more easily and widely manufactured.

The environmental impact is relatively low. The product is made with very readily available components made mostly from common materials. Some small pieces were 3D printed, which creates some plastic waste, so using a different material for those components would be an opportunity to further limit environmental impact. Plywood is used for the base and part of the cover, which requires cutting down trees, so there is potential to use a greener material. The device requires power, which is currently being supplied by a standard wall outlet, so there is potential for using a renewable energy source such as solar or wind power.

RECOMMENDATIONS FOR FUTURE WORK

With more time or opportunities for this project, a focus would be to work on making the assembly quieter. Since the device is meant to serve children with some sensory needs, it is an issue that the device is loud during operation. A lot of progress has been made in limiting the noise by reducing slop in as many areas as possible. Further work to mitigate noise could include soundproofing the safety cover.

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[1] United States Patent, US 10,232,603 B2, *Three-Dimensional Printer*, Hartmann, Mar. 19, 2019. https://patentimages.storage.googleapis.com/5a/af/cd/33c346b0ff601e/US10232603.pdf

[2] U.S. Department of Justice, Civil Rights Division, *Americans with Disabilities Act*, 2010. https://www.ada.gov/

APPENDIX

Electronics	Core XY	Diagonal Pulleys	2 Axis Arms	Rotating Arm
Novel	0	+	0	+
Cost	0	+	+	0
Manufacturing	0	+	+	-
Transportability	0	-	0	+
Ease of use/safety	0	0	+	-
Total	**0**	**2**	**3**	**0**

Figure 1: Translation Stage Pugh Matrix

Safety Cover	**Plexiglass Box**	Removeable Cover	No Cover
Novel	0	+	-
Cost	0	-	+
Ease of Use	0	+	+
Safety	0	0	-
Total	**0**	**1**	**0**

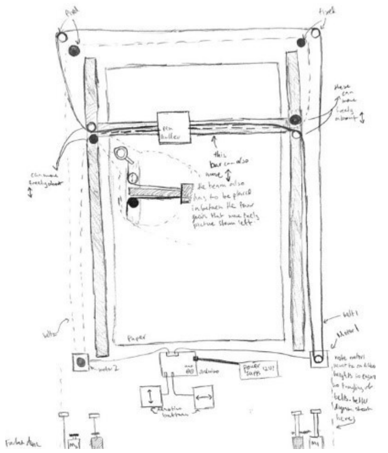
Figure 2: Safety Cover Pugh Matrix

Pen Holder	**3 Point Constraint**	Tube w/ Screw	Clamp
Novel	0	+	+
Cost	0	-	-
Manufacturability	0	-	-
Size Range	0	-	-
Total	**0**	**-2**	**-2**

Figure 3: Pen Holder Pugh Matrix

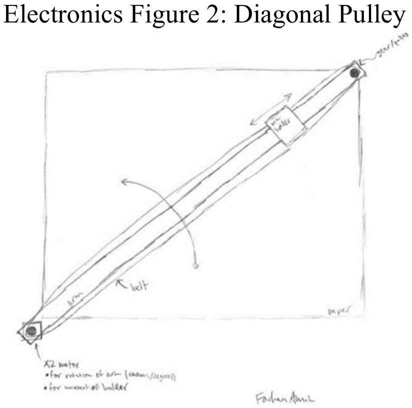
Paper Constraint	**Paper Weight**	Magnets	Clip on Sliders	Accordion
Novel	0	0	+	+
Cost	0	0	-	-
Manufacturability	0	0	-	-
Compatibility	0	-	-	-
Functionality on Angle	0	+	+	+
Total	**0**	**0**	**-1**	**-1**

Figure 4: Paper Constraint Pugh Matrix

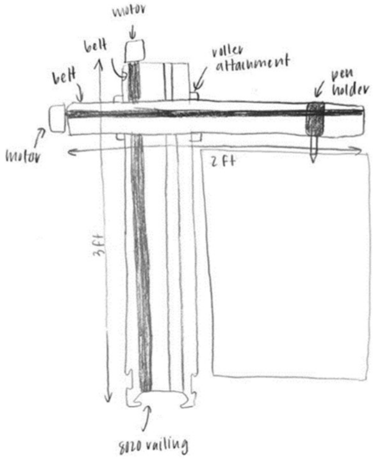


Electronics Figure 1: Core XY Concept

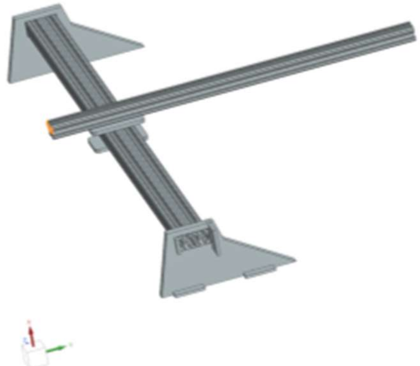
Electronics Figure 2: Diagonal Pulley Concept



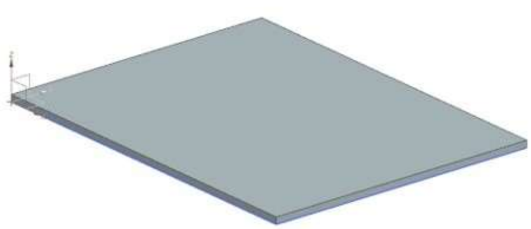
Electronics Figure 3: Rotating Arm Concept



Electronics Figure 4: Two Axis Arm Concept

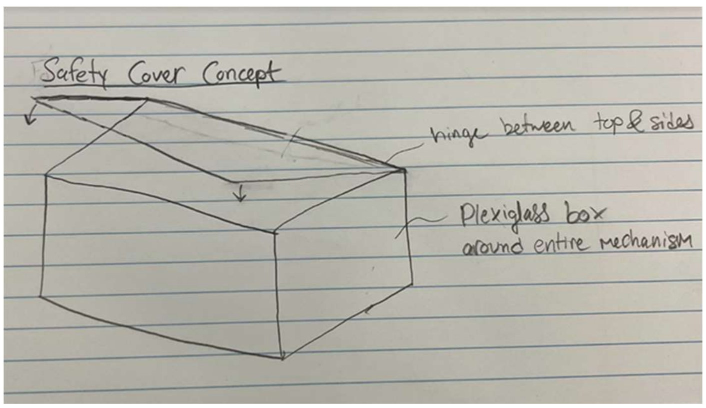


Electronics Figure 5: Translation Stage Assembly

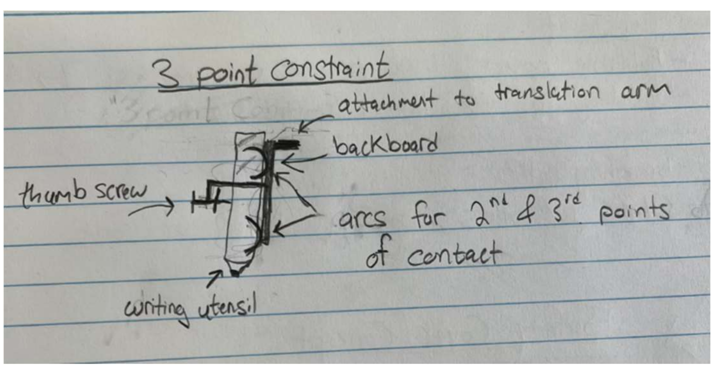


Hardware Figure 1: Base NX Model

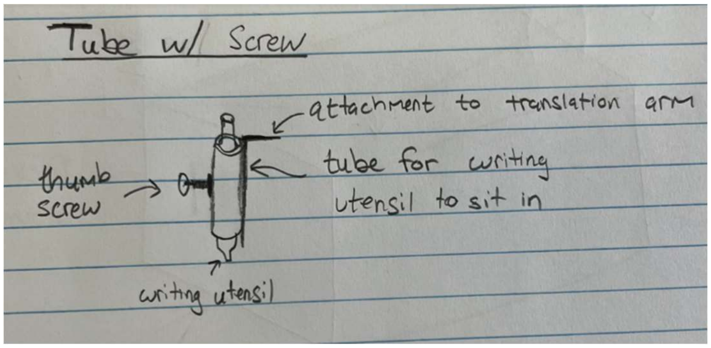
Hardware Figure 2: Safety Cover Plexiglass Box Concept



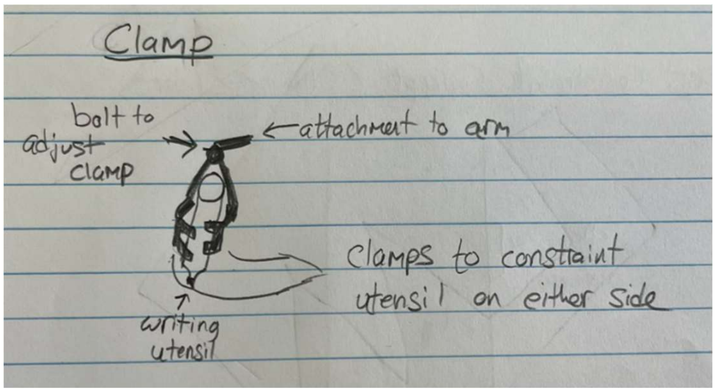
Hardware Figure 3: Safety Cover Plexiglass Box with Hinged Lid Concept



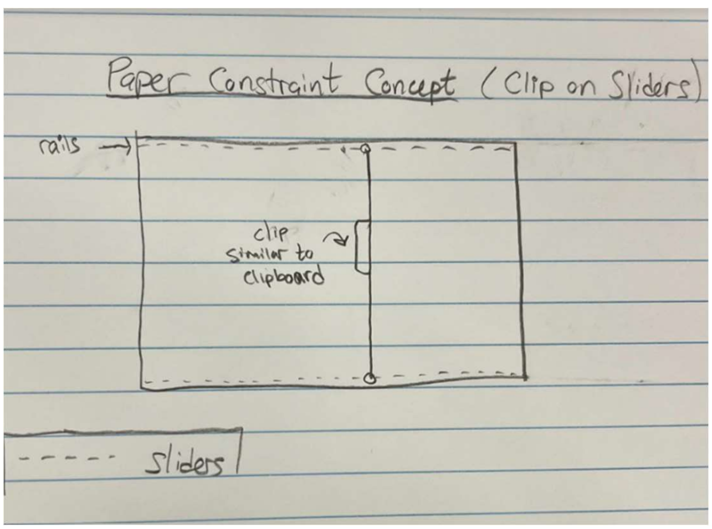
Hardware Figure 4: 3-Point Constraint Pen Holder Concept



Hardware Figure 5: Tube with Screw Pen Holder Concept



Hardware Figure 6: Clamp Pen Holder Concept



Hardware Figure 7: Clip on Sliders Paper Constraint

```matlab
%Tolerance Analysis of Double Rail Belt Mount

pos = 0.06; %diameter of hole in question
bonus = 0.005; %tolerances on dimensions
allowed = pos+bonus; %calculate allowed dimensions
r_error = sqrt((.77-.775)^2+(.515-.520)^2); %error calculation
d_error = 2*r_error; %diametral error calculation
if d_error <allowed
    disp('PASS')
else
    disp('FAIL')
end
```

Figure 5: MATLAB Script for Tolerance Analysis

```
PASS
     0.0141
```

Figure 6: MATLAB Output for Tolerance Analysis

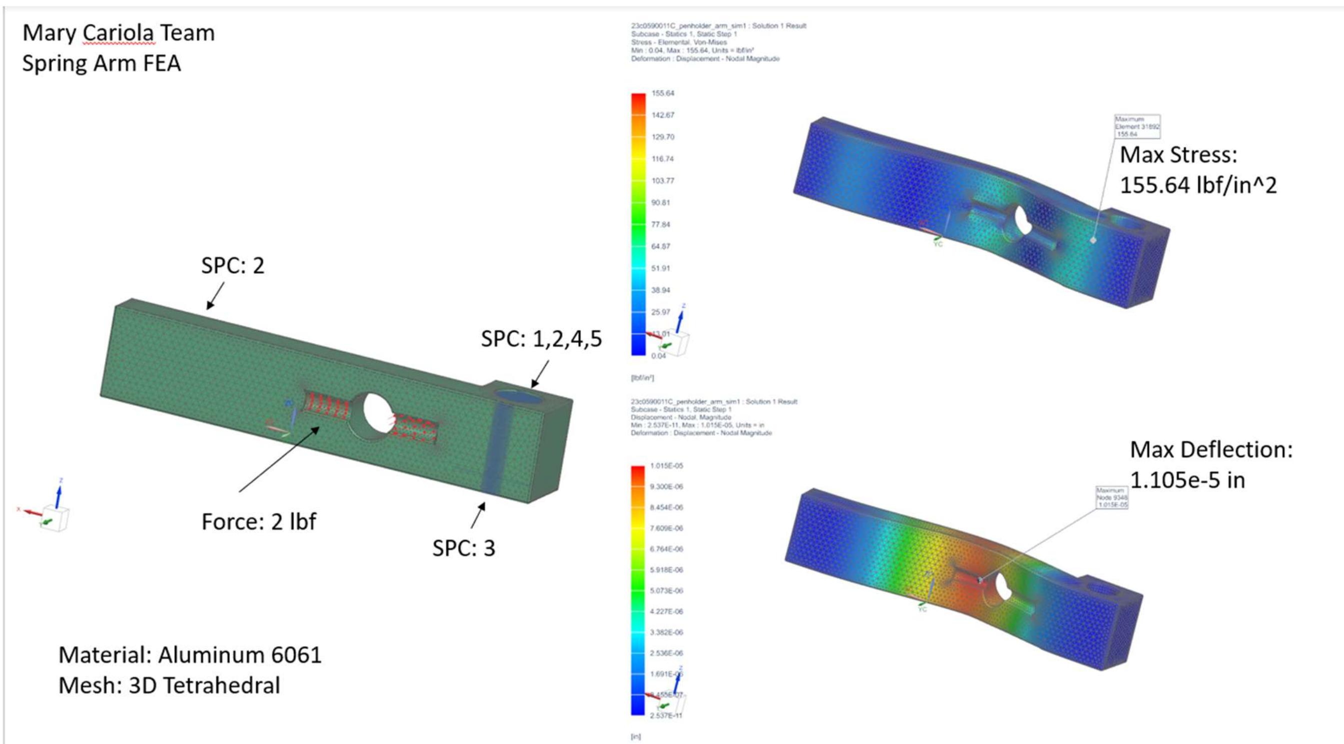
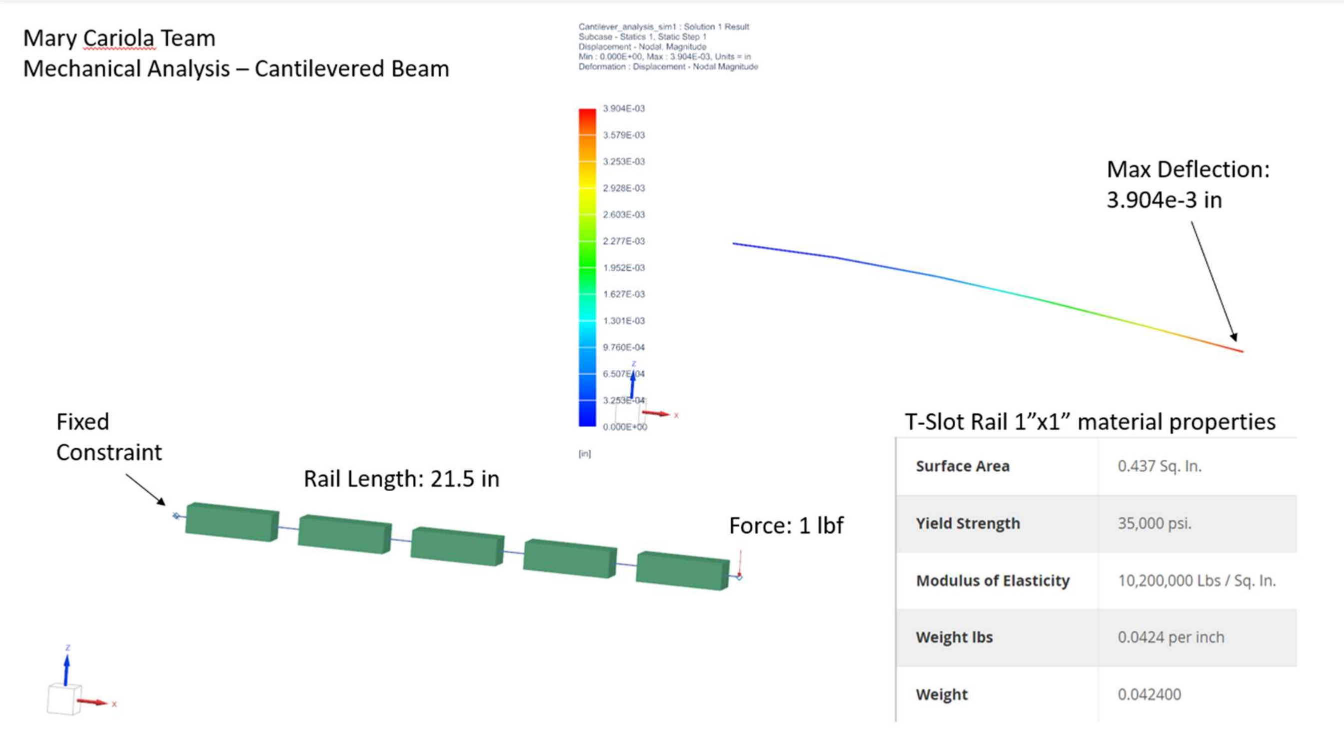


Figure 7: FEA analysis of spring arm



Surface Area	0.437 Sq. In.
Yield Strength	35,000 psi.
Modulus of Elasticity	10,200,000 Lbs / Sq. In.
Weight lbs	0.0424 per inch
Weight	0.042400

Figure 8: Mechanical Analysis for Cantilevered Beam

Figure 9: Assembled Safety Cover


Figure 10: Plywood Base

Figure 11: Base and Cover Assembly

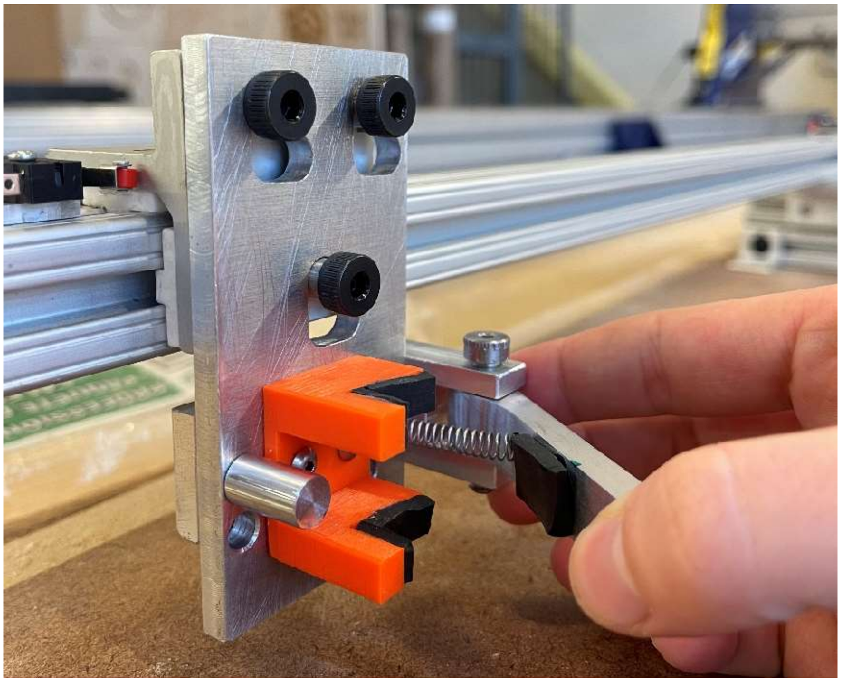


Figure 12: Pen Holder Assembly

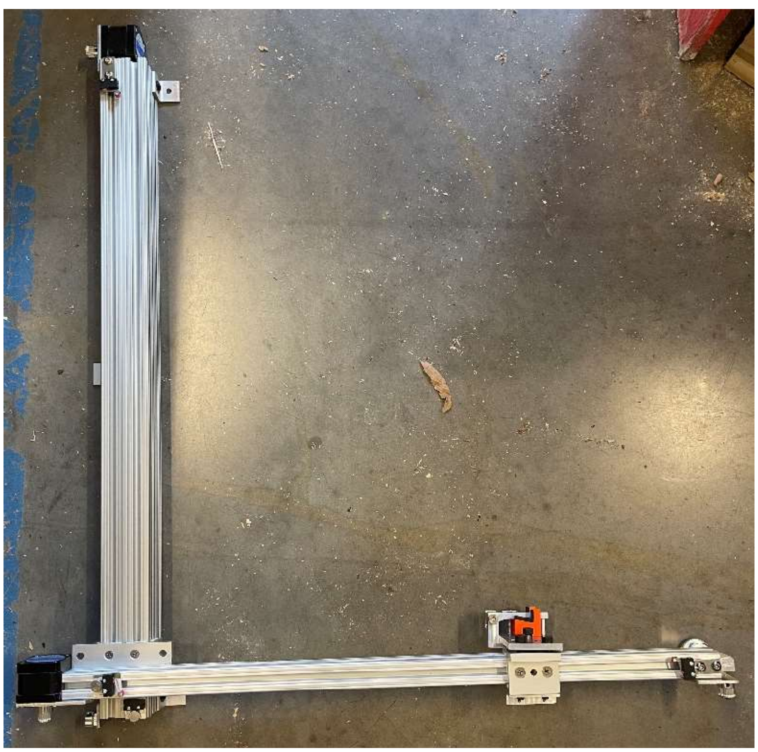


Figure 14: Translation Stage Assembly

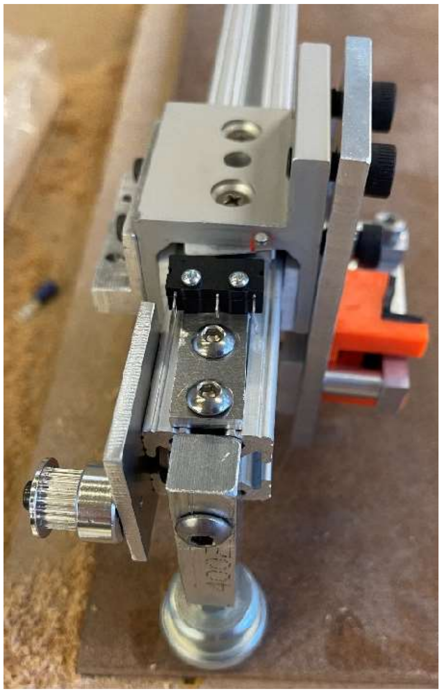


Figure 15: Limit Switch Mount

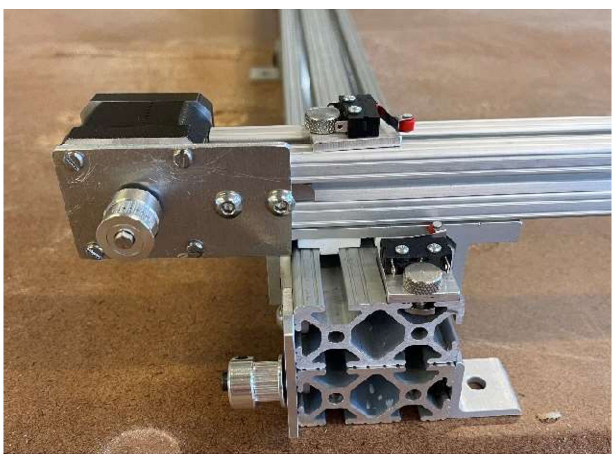


Figure 16: Stepper Motor Mount