DESIGN AND DEVELOPMENT OF A 2-AXIS SERVO TRAINER

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And the

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Author’s Declaration

We hereby declare that we are the sole authors of this report.

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Abstract

Servo motors are complex electro mechanical units that allow their rotational position, velocity, acceleration, and many other aspects to be controlled very accurately. Specialized control modules and programming is required for these motors to exhibit desired behavior. Both factors vary drastically between competing companies such as Bosch Rexroth and Allen Bradly.

These motors and drives are used extensively in industrial settings, which are very costly and hazardous settings to learn their functionality. For this reason, Bosch Rexroth develops servo trainers that replicate industrial processes at a desk sized scale to render learning safer and cheaper. This project resulted in the design and manufacturing of a trainer system, which consists of two portable units: The electrical controls (Alpha Prototype), and the emulation of an industrial flying saw (Beta Prototype).

An extensive concept generation phase was deployed for both modules of the project starting at the component level, combining them into sub-systems, followed by their interactions at the system level. In addition to functionality, ease of access and aesthetics were also considered throughout the design, which ultimately brandishes see through panels of Plexiglas.

In addition to the designing and manufacturing of the trainer, thorough documentation of the learning process was generated throughout the project with respect to the Bosch Rexroth products. This was a key aspect of the project and was requested by Bosch as part of their quest to for more user-friendly products.

The project delivers on the controls and application modules that are ready for educational purposes. The controls system allows for a total of four drives to be mounted, while the flying saw application provides two servo axes to control via IndraDrive. These axes allow for the exploration of synchronous motion, accurate positioning, and torque sensing. The unit is also capable of expanding to two more axis without the addition of a third or fourth drive.

Control over the drives and motors was carried out using IndraWorks Engineering, Bosch Rexroth’s proprietary software. Within the software, programs can be written using the

CODESYS V3 to provide control while utilizing Bosch Rexroth's products to their full potential. The programs can be created through a variety of methods including structured text, functional block diagrams, and ladder diagrams.

The total time spent to complete this project as well as the documentation is approximately 1200 hours total, which is split among the three group members.

A final technical presentation of this project was delivered on May 9, 2018, and the final report submitted on May 11, 2018.

Acknowledgments

This project would not have been possible if it had not been for the support from the following parties:

Bosch Rexroth Canada for supplying the IndraDrive units and funding the project.

Greg Filek, our industry sponsor, for all the extra hours he put in helping us troubleshoot the plethora of problems encountered, and his unwavering enthusiasm for the project.

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Chapter 1 - Introduction

Automation requires a series of actions to occur in a timed and specific manner to carry out its intended function. This requires the collection of information from various input such as motors, sensors, and the positioning of an object to be aware of what is going on during a process. At the heart of all this is a master motion control drive, which collects and analyses the information to decide an appropriate response as defined by the programmer. Learning and troubleshooting the design and development of a process should be done prior to its implementation, so Bosch Rexroth offers training platforms to give their customers a means to develop an understanding of their products functionality.

The project will be split into two sections: One, the Alpha Prototype, which will house two IndraDrive Cs control units and all the accompanying electronics. Two, the Beta Prototype, which will be the 'works like' trainer and emulation of an industrial controls application at a desk top scale.

1.1. Problem Statement

While training platforms already exist, Bosch Rexroth is seeking to understand the design and learning process from the perspective of individuals that are not already familiar with their products and software. Their goal is to identify any gaps that exist in their instructional database and record the process of carrying out the development of a trainer.

1.2. Objectives

The objective is to design and build a small-scale system (referred to as a trainer) that utilizes Bosch Rexroth motors and motor controllers. This trainer will allow customers to learn and experiment with the functionality of the IndraDrive Cs system in a controlled environment. The three main functions of interest are:

- Accurate positioning
- Torque sensing
- Synchronized motion.

The trainer would allow the customer to explore their programming interface platform, learn and develop motion control, and diagnose and determine solutions for faults that may occur.

In the process of carrying out the creation and use of a trainer platform, the goal is to identify any difficulties or shortcomings that arise in the process. To improve customer experience, Bosch Rexroth is interested in any trouble that we, as mock customers, encounter through the development and implementation process. This reporting will be a key aspect of the project.

1.3. Scope

Bosch Rexroth manufactures high-quality products for controlling motion in industrial applications. To make these products more appealing and far-reaching, the company wishes to have available trainers for engineers and programmers to learn the functionality of Bosch Rexroth components, coupled with the IndraDrive Cs system, without major investment or downtime. The three key features of the IndraDrive Cs system that have been highlighted are:

- Positioning
- Torque Sensing
- Synchronous motion.

This project emulates the common industrial application of controls: a flying saw. It entails the design and manufacture of an Alpha and Beta Prototype, documentation of trials and tribulations experienced with the IndraDrive Cs System, and programming of the final trainer in all three of the IndraDrive Cs' available programming methods:

- Instruction List
- Function Block Diagrams
- Ladder Diagrams
- Structured Text
- Sequential Function Chart.

The project will have the following set of deliverables:

- Wiring diagrams
- Bills of materials
- Solid models
- Manufacturing and assembly drawings
- Manufactured trainer
- Technical report including instructions

The project has the following set of limitations and exclusions:

- Pen-like end effector
- Non-scalable design
- Only consider Bosch Rexroth controls/actuators
- Electrical power only
- No structural analysis

1.4. Product Background

Bosch Rexroth has a variety of training systems, or trainers, that they provide to their clients. This is to allow the client to learn how to use the equipment in a controlled environment and achieve progressive goals of motion and control. The trainers come in a wide variety of configurations which ultimately allows the client to learn exactly what they need.

Possible industrial applications that could be emulated for a 2-axis servo trainer are:

- Flying Saw
- Bolt Tightening Device
- Robotic Gripper
- 2D Plotter

1.4.1. Flying Saw

The flying saw, also known as a cold saw carriage, is a machine that allows for material to be cut while it moves. This can allow for a precise cut without requiring the material to be stationary. It is commonly found in a variety of manufacturing environments making HVAC ducts, pipes, tubes. [1]

Figure 1.1 - A flying saw produced by Scontor [2]

The motions found in the flying saw application are linear for the carriage system. There can also be rotational motion which could be used to drive the material forward. These two motions must also be synchronized for the cut to not only be straight but also avoid binding of the saw blade.

1.4.2. Bolt Tightening Device

A bolt tightening mechanism can be found in any application that has automated assembly of any machine with bolts. It simply ensures that the bolt is properly fastened and hasn't simply stripped or become misaligned. In this case, there is rotational motion for the action of tightening the bolt and linear to raise and lower the bolt.

1.4.3. Gripper

Grippers are commonly used in robotics and automated assembly lines. They are used to manipulate objects by being able to lift, rotate, and move. Their variations of motion can be achieved with any number of linear and rotational motions. [3]

Figure 1.2 - A typical robotic arm with gripper found in industry [3]

1.4.4. 2D Plotter

2D plotters come in all shapes and sizes depending on the application. They can be quite small for additive manufacturing processes such as 3D printers, or quite large for CNC laser or waterjet cutters used for sheet metal. They all move in a single plane using Cartesian coordinates.

Figure 1.3 - The flat plane that material lies on to be cut by the CNC laser [4]

1.5. Quality Function Deployment (QFD) Analysis

To make the product more appealing to our customer base, we quantified their needs into designable parameters using the QFD. This QFD looks at the entire 2-axis servo unit, this means we are considering both the Alpha Prototype and Beta Prototype.

Our project sponsor was very adamant that the key goal of this project was to serve as a learning experience for us as students, with that experience well documented. The QFD highlighted the importance of this, as it was the largest weighted average by a factor 3.

Following documentation, the three other main contributing factors of the design are mass, size, and number of coded languages. As a portable device that must fit on an engineer's desk, the first two of these make sense. This product is intended as a learning platform to teach engineers the functionality and capabilities of the Rexroth-Bosch motor controller. To be effective, it must be capable of functioning in several coding languages, as electrical, mechanical, and other engineers tend to use different coding platforms.

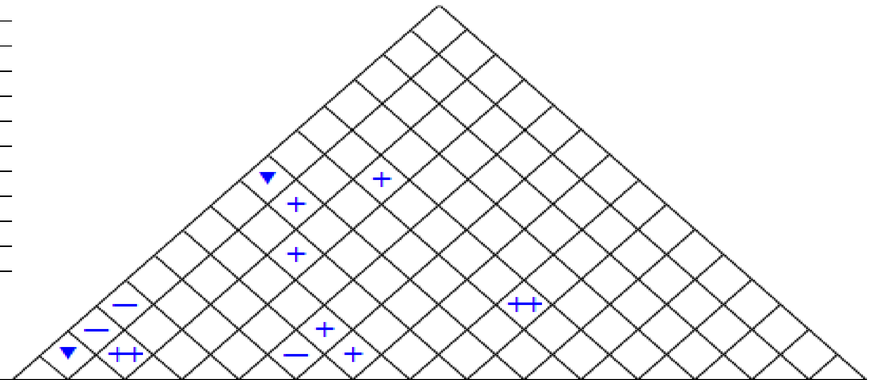
These key components were carried forward into the design phase of both modules of the project to ensure it satisfies our prospective clients

Title: ______

Author: ______

Date: ______

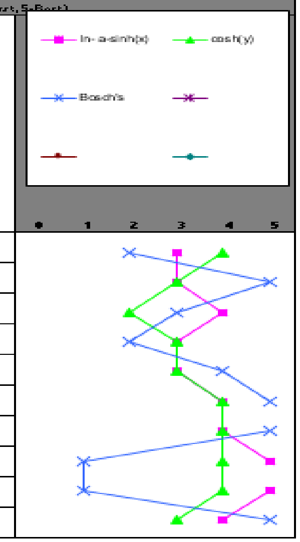
Notes: ______



Legend

Symbol	Meaning	Value
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
X	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)		
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▼	▼	▲	▲	▲	▼	▼	▼	▼							
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Cost	Mass	Size	Plug quantity	Number of coded languages	Number of coded routines	Topics documented	Footprint	Number of parts	Setup time	Longest length					ln- a-sinh(x)	cosh(y)	Bosch's
1	9	5.7	2.0	Low Cost	Θ	Θ	▲	▲					▲							3	4	2
2	9	11.4	4.0	Portable	O	Θ	Θ					▲			O					3	3	5
3	3	8.6	3.0	Good looking	O															4	2	3
4	9	11.4	4.0	Intuitive operation				Θ	O	O	Θ			▲						3	3	2
5	9	5.7	2.0	Easy to setup (Plug and Play)				Θ			▲			Θ						3	3	4
6	3	14.3	5.0	Utilizes torque sensing, accurate positioning, synchronous motion					▲	O	▲									4	4	5
7	9	8.6	3.0	Coded in mutliple languages					Θ	▲	▲									4	4	5
8	9	11.4	4.0	Comprehensive manual							Θ									5	4	1
9	9	14.3	5.0	Process documentation							Θ									5	4	1
10	9	8.6	3.0	Take up minimal space on desk			O					Θ			▲					4	3	5
				Target or Limit Value	<15000 $	<20 kg	0.6 m^3	<2	>2	>4	>10	a	<200	<10 minutes	< 1m							
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	1	4	3	1	8	9	5	4	4	3	2							
				Max Relationship Value in Column	9	9	9	9	9	3	9	9	1	9	3							
				Weight / Importance	111.4	154.3	134.3	160.0	125.7	85.7	362.9	88.6	5.7	62.9	42.9							
				Relative Weight	8.4	11.6	10.1	12.0	9.4	6.4	27.2	6.6	0.4	4.7	3.2							



Powered by QFD Online (http://www.QFDOnline.com)

Table 1.1 - QFD

1.6. Discussion

After careful consideration and consultation with Greg Filek, the Flying Saw industrial application was ultimately selected. This is because of how common of a practice it is, and how well it targets the three features of the IndraDrive Cs System that the desired trainer is to utilize. In addition, with the material stationary, it could also double as a 2D plotter. Finally, with another 2-axis servo team working in tandem with Bosch Rexroth, their selection of the bolt tightening device will be adequately different in function from the flying saw.

Chapter 2 - Alpha Prototype

The Alpha Prototype is a portable structure that holds all the electrical and controls aspect of the 2-axis servo trainer project. It contains electrical safety components such as circuit breakers and emergency stops, as well as buttons and distribution wiring so that all mounted IndraDrive units could be powered up. The client requested that the structure allow for mounting of 3-4 drives at any one time and allow for varying sizes of drives (eg. IndraDrive HCS01 and HCS02).

In addition, this aspect of the project would need to be present on a programmer's desk or at least within their office. For this reason, size is an important factor.

2.1. Concept Generation

Due to the availability of 45mm X 45mm and 45mm X 90mm aluminum extrusion, most of the generated concepts to utilize those materials. Each concept tried to further reduce the footprint, deviate from the existing Bosch designs, and increase aesthetic appeal.

2.1.1. Alpha 1

The initial concept was to have the drives secured to the aluminum extrusion through sliding t-nuts. While this design was simple and light, it did not allow for drives of different heights to be mounted beside one another on the main racking.

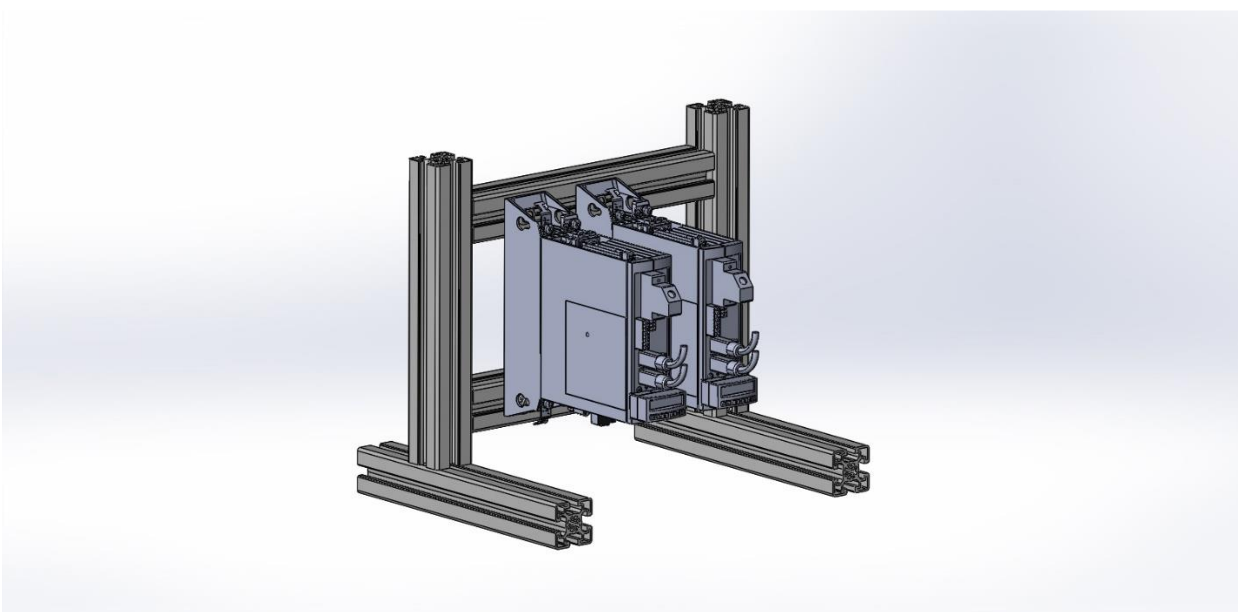


Figure 2.1 - Alpha Prototype 1

2.1.2. Alpha 2

Building off the Alpha 1 design, the bulk of the mass in the drives themselves, the feet of the device were moved forward to allow a user to push the back flush against a wall. Joining brackets and mock accessories were also added to get a better feel of the layout.

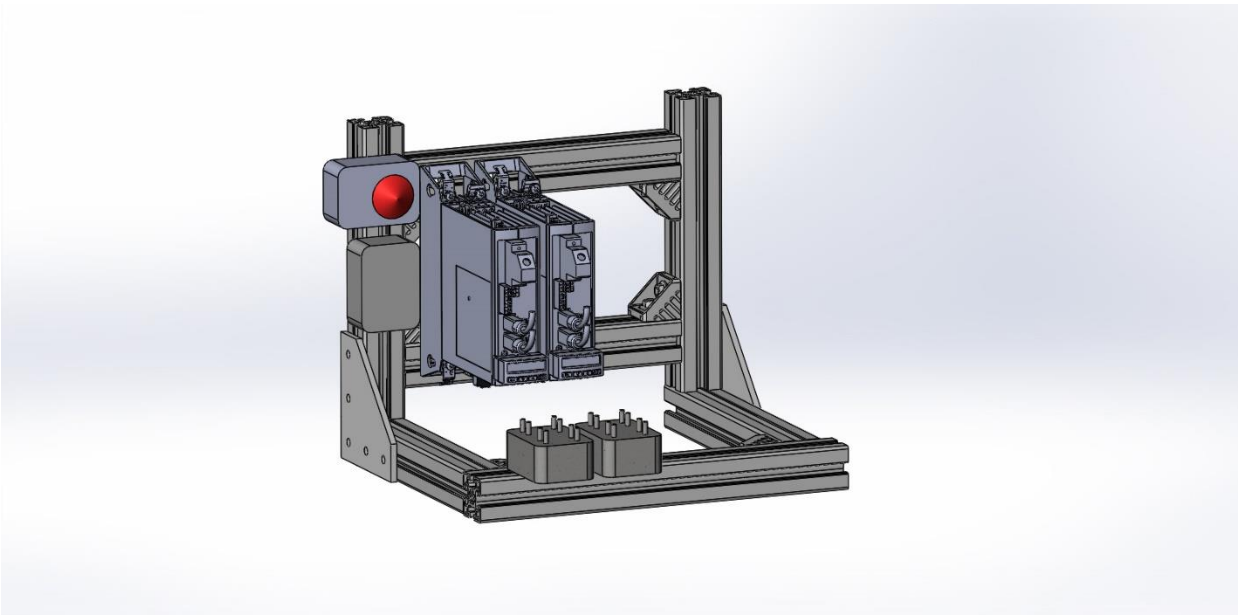


Figure 2.2 - Alpha Prototype 2

2.1.3. Alpha 3

This prototype moved away from the lateral aluminum extrusions for mounting to a center aluminum plate. The plate would have a hole and slot configuration and utilized the vertical support beams allowing for drives of different sizes while keeping the overall width small. An aesthetic Plexiglas plate would be used to allow the electrical connections, relays, etc… to be visible to the user while not being too openly exposed and therefore susceptible to snagging or contact. This concept drastically deviates from the typical box shape designs that Bosch typically offers, while minimizing its footprint.

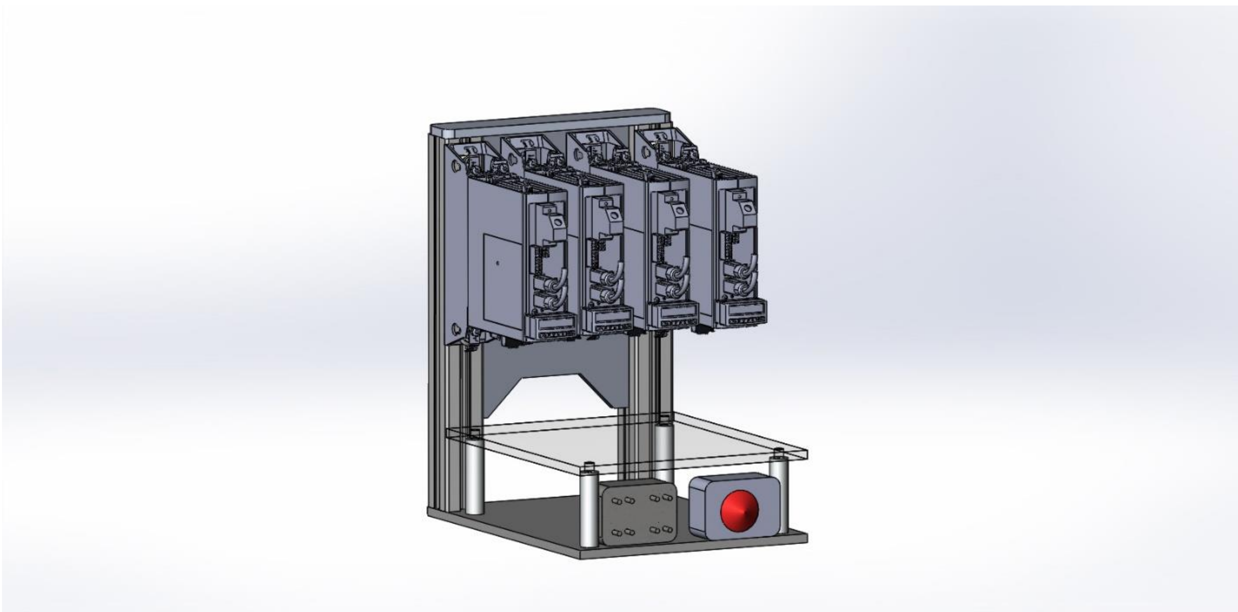


Figure 2.3 - Alpha Prototype 3

2.1.4. Alpha 4

Building off Alpha 3, this prototype has increased strength at the lower corners. The use of four aluminum spacers was reduced to two, and instead, the Plexiglas plate is supported in part by the brackets on the aluminum extrusion while the front is tightened down with wingnuts. The back plate was updated to show the slots and a handle was added for carrying.

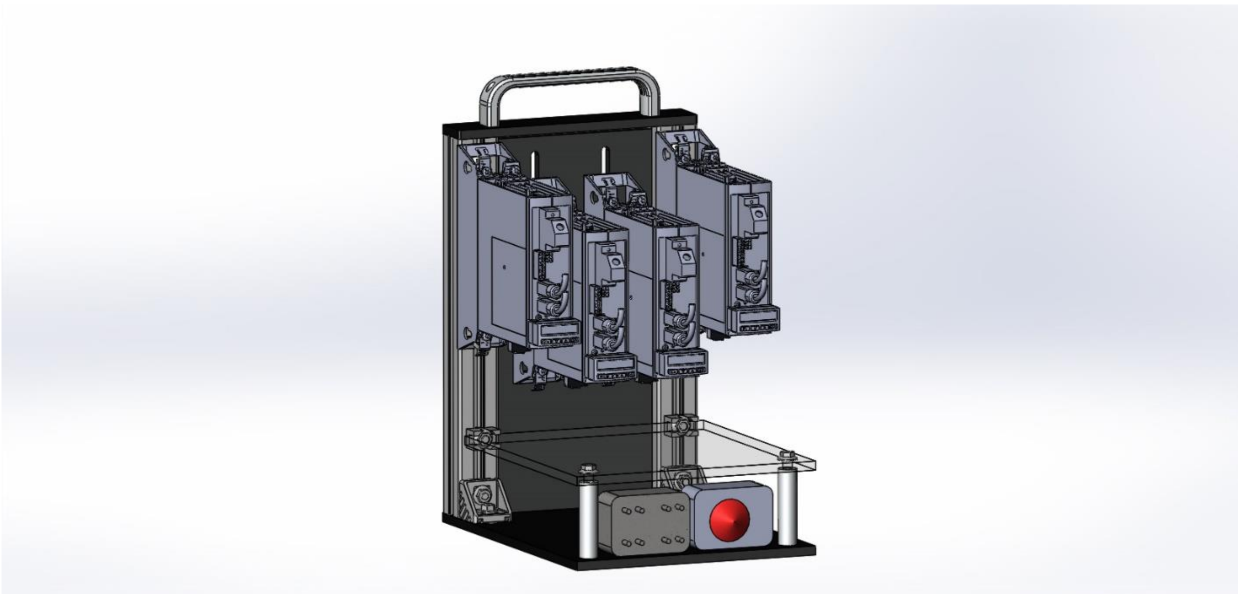


Figure 2.4 - Alpha Prototype 4

2.2. Final Design

The final design appears quite like the fourth design iteration. The drives are mounted on a vertical plate and are separated from the electrical components by a sheet of Plexiglas, but there are several minor changes to help improve functionality and aesthetics.

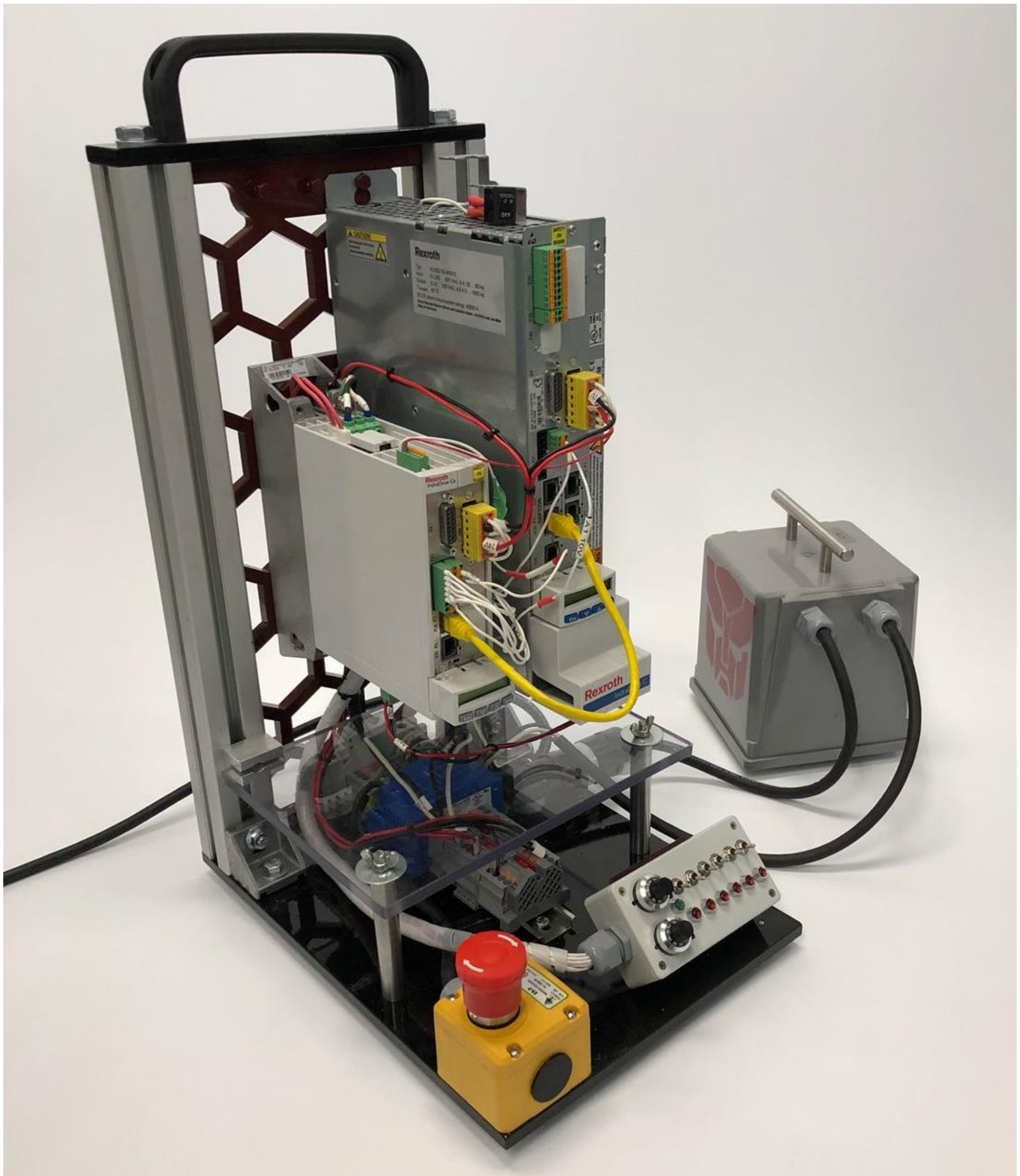


Figure 2.5 - The completed Alpha Prototype.

2.2.1. Button mounting

The first of these changes was the shortening of the Plexiglas cover, this allows for novel orientations of the E-stop and switch box. The E-stop is now mounted with its back to the bottom plate, which allows for more convenient access regardless of the user's position. The switch box is also mounted at a 45° using magnets, which allows the user to both freely move to where it's desired or view it from its mounting location regardless if they are standing or seated. This new configuration of buttons is shown in Figure 2.6.

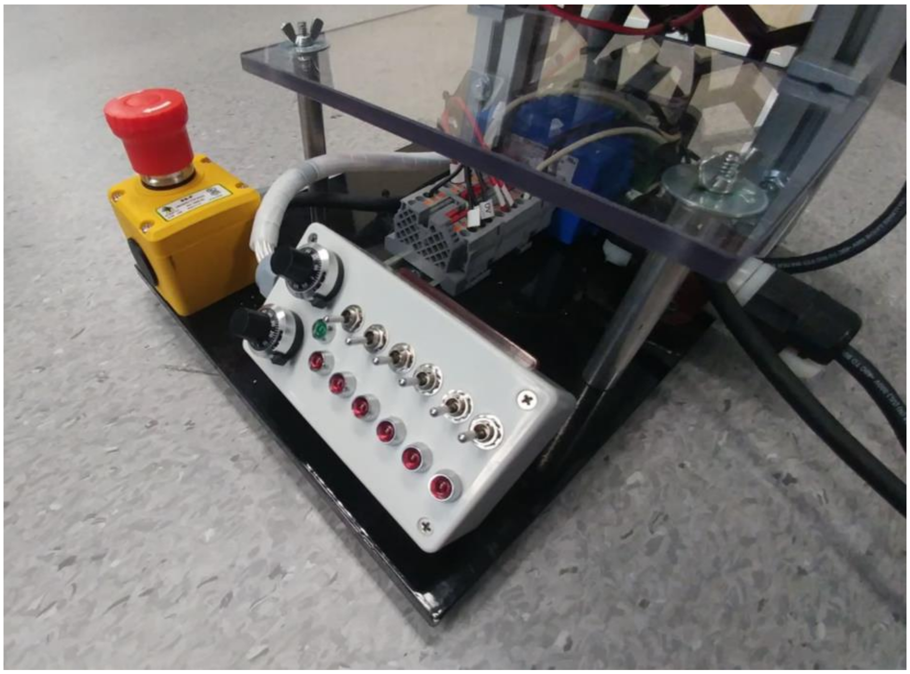


Figure 2.6 - The final mounting of the E-stop and control box.

2.2.2. Electronics

Not displayed in any of the CAD concepts, the electronics mounted to the drive consist of a transformer for 24V DC, a breaker, and multiple terminal blocks and grounding blocks. These electronics were all mounted to din rail for easy modification and can be seen in Figure 2.7.

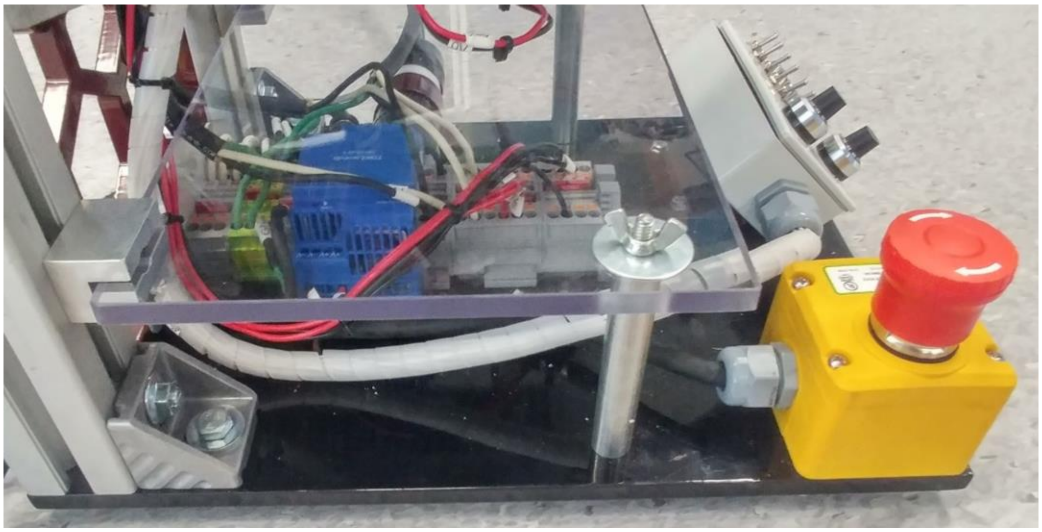


Figure 2.7 - The electronics required for operation.

2.2.3. Transformer

The Alpha now has an accessory box with a 240-volt transformer mounted inside, which was required to operate because of a change to a more advanced master motor controller. This accessory for the Alpha can fortunately be disconnected for easier transportation due to the implementation of a plug for power going into the transformer and its output simply needing to be plugged into the drive. The plugged-in transformer can be seen in Figure 2.8.

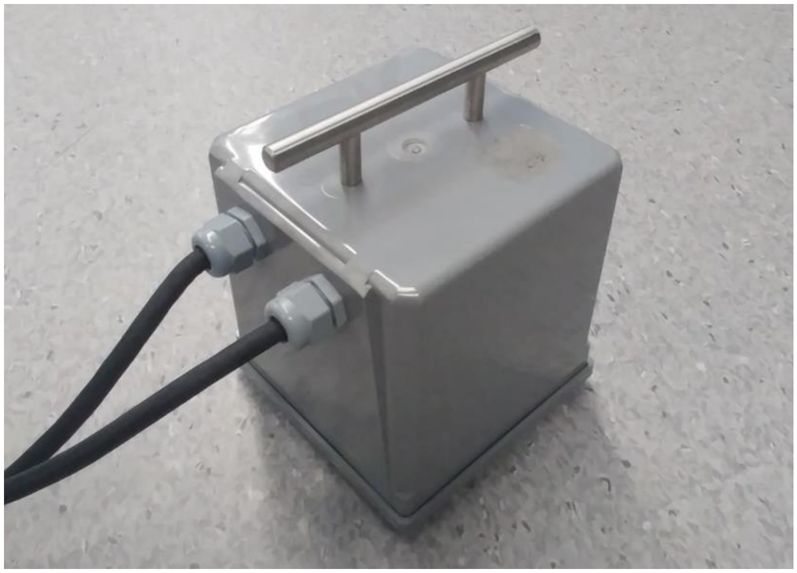


Figure 2.8 - The transformer required for the Alpha Prototype.

2.2.4. Back Plate

The back plate had material removed to help improve portability. This was done with a water jet cutter, and the pattern was picked due to it being aesthetically pleasing. The design was created in SolidWorks and converted to a DXF file, which is required for use of the water jet cutter. The completed cut is shown in Figure 2.9.

Figure 2.9 - The back plate of the Alpha Prototype.

2.2.5. Discussion

Overall, the final design of the Alpha Prototype works very well for its intended purpose. It is user friendly and takes up a relatively small footprint on a desk. The electronics are visible yet tucked away to prevent accidental contact and the breaker remains accessible due to the cut-outs of the back plate. To provide the Alpha Prototype with a finished look, the non-aluminum extrusions were powder coated. The completed Alpha Prototype is shown in Figure 2.5.

The one drawback to the Alpha Prototype is its weight is less than ideal. While it is still portable, reducing the weight would make it easier to carry, especially since there is now a transformer that needs to be carried around with it. This reduced weight could be achieved by using a thinner piece of sheet metal for the back plate and bottom plate.

Chapter 3 - Beta Prototype

The Beta Prototype is the module of the project, where an industrial application is embodied in a scaled down version. The industrial application being emulated is that of a flying saw. The flying saw will require 3 forms of motion:

1. Parallel motion, depicted below by the green rails
2. Perpendicular motion, depicted below by a blue rail on a gray carriage
3. Linear motion of a sheet, depicted below by the red rollers (that would have a cellophane belt wrapped around them).

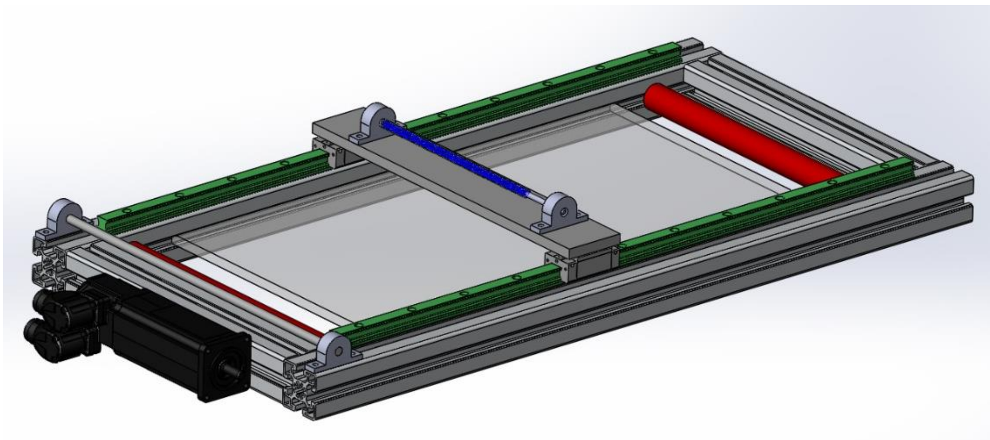


Figure 3.1 - Preliminary flying saw layout

3.1. Component Level Design

To avoid getting fixated on specific methods of accomplishing the end goal of a flying saw, the key mechanical features were considered separately. These key features of the Beta Prototype are:

- General Layout
- Creating Motion
- Constraining Motion

This approach is like that of a morphology.

3.1.1. General Beta Layout

The layout depicted above in Figure 3.1 is considered the 2D layout, as it only uses aluminum extrusions connected in a single plane. A 3D layout was also considered that had the advantage of mounting all components underneath the writing surface, but the size and weight disadvantages deemed it unnecessary.

	2D	3D
Pros	Less Material Less Mass Components Exposed More Stable	Smaller Footprint More Mounting Space Variable orientation possible
Cons	Larger Footprint	More Material More Mass More Expensive

Table 3.1 - Considerations for a 2D or 3D layout of the Beta Prototype

3.1.2. Creating Motion

Linear motion is not novel and has many ways of being generated, Table 3.2, outlines the pros and cons in our application.

Methods of creating Linear Motion

	Pros	**Cons**
Leadscrew	Mechanical advantage	Intolerant of misalignment
	Bosch has one lying around	
Rack and Pinion	Few parts	Motion creating motor must move
		No mechanical advantage
		Intolerant of misalignment
Belts and Pulleys/	Cheap	Less precise
Chain and Sprocket	Tolerant to misalignment	No mechanical advantage
	Both directions of motion can be generated without moving either motor (Core XY or Etch-a-sketch)	Lots of parts
Linear Actuator	Simple to use	Expensive
		Very long
Linear Motor	Simple to use	Expensive
		Dangerous
Predesigned linear stage	Plug and play	Very Expensive

Table 3.2 - Methods of creating linear motion

Our project sponsor notified us early in the project that linear motors can be dangerous if they are accidentally powered up without a load. Combined with their high cost, they were removed from consideration. The sheer cost of Bosch's linear stages disqualified the method from consideration. The use of a rack and pinion was removed due to the necessity of the motor also needing to move as part of the carriage to keep the parts within the frame. This unnecessary movement of mass should be avoided.

3.1.2.1. Torque Considerations

To determine the amount of torque required from the motor to move the carriage via leadscrew or belt, an acceleration needed to be agreed upon. Utilizing the simple trapezoidal velocity profile, shown in Figure 3.2, an approximately expected acceleration for the desired constant linear velocity (0.55m/s) of the roller was calculated. A speed simply defined as adequate by the design team.

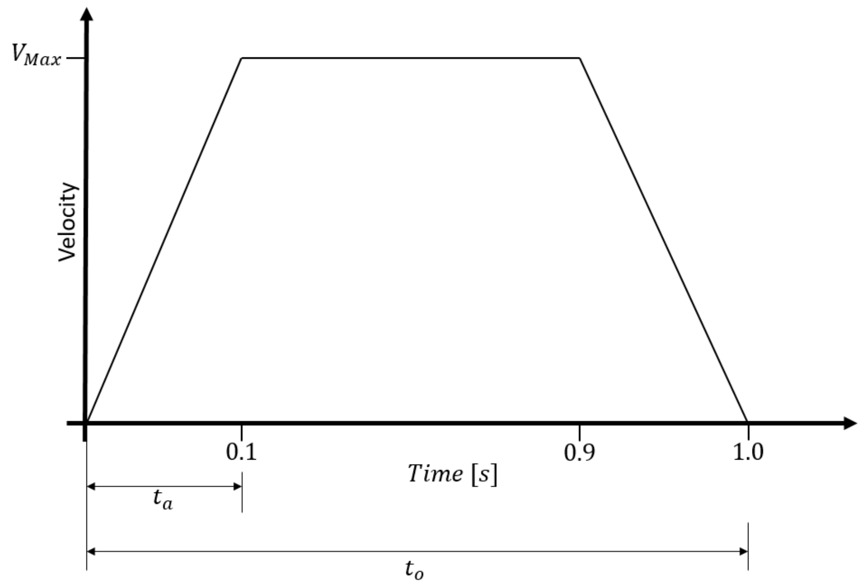


Figure 3.2 - Parallel motion velocity profile

$$V_{max}t_o - V_{max}t_a = L$$

$$Vmax = \frac{L}{t_o - t_a} = \frac{0.5m}{(1-0.1)s} = 0.55m/s$$

$$a = \frac{V_{max}}{t_a} = \frac{0.55m/s}{0.1s} = 5.5m/s^2$$

$$\alpha = \frac{5.5m}{s^2}\left(\frac{0.2rev}{1mm}\right)\left(\frac{1000mm}{1m}\right)\left(\frac{2\pi rad}{1rev}\right) = \frac{6911rad}{s^2}$$

By investigating the approximate mass of all the components expected to reside on the carriage, the overall mass of the carriage was determined to be approximately 1.37kg.

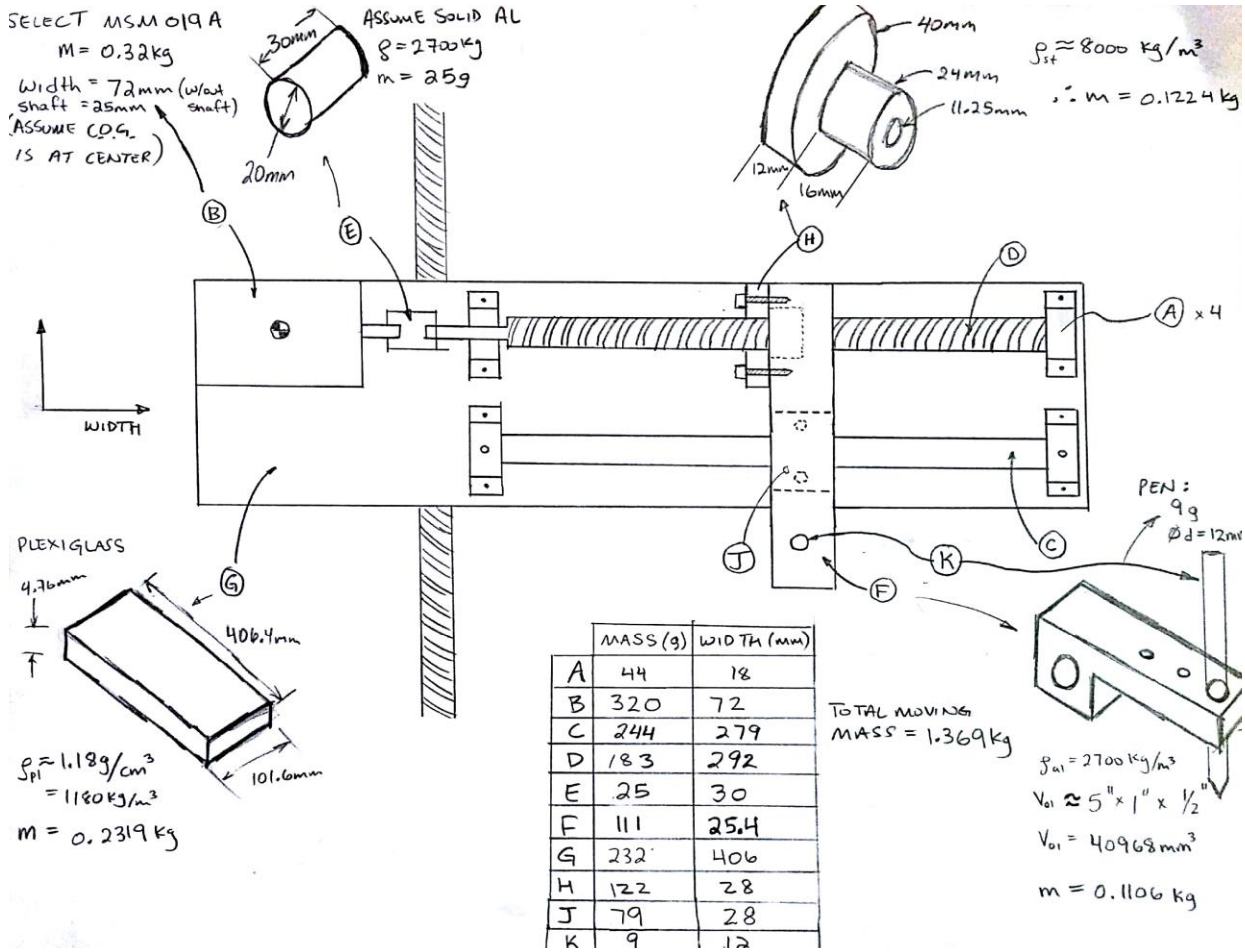


Figure 3.3 - Approximate carriage mass

With the acceleration and mass of the carriage, calculations for the torque requirement for the leadscrew and belt drive methods were done.

3.1.2.2. Leadscrew

This calculation analyzes the required torque to generate parallel motion via leadscrew.

$$Assume\ Pitch\ (P) = \frac{0.2rev}{1mm} = \frac{0.2rev}{10^{-3}m}$$

$$J_T = J_{Motor} + J_{Coupling} + J_{Screw} + J_{LoadRef}$$

$$J_{Coupling} = \frac{1}{2} m_{Coupling} r_{Coupling}^2 \qquad J_{Screw} = \frac{1}{2} m_{Screw} r_{Screw}^2$$

$$J_{LoadRef} = \frac{w_{Load} + W_{Carriage}}{g} * \frac{1}{(2\pi P)^2 \epsilon}$$

$$J_T = 0.0000025 + \frac{1}{2}(0.025)(0.01)^2 + \frac{1}{2}(0.183)(0.006)^2 + 1.37kg * \frac{1}{\left(2\pi \frac{0.2}{10^{-3}m}\right)^2}$$

$$= 7.91 * 10^{-6} kgm^2$$

$$T = J\alpha = (7.91 * 10^{-6} kgm^2)\left(\frac{6911rad}{s^2}\right) = 0.055Nm$$

$$Apply\ a\ S.F.\ of\ 2\ to\ account\ for\ efficiencies\ and\ friction \therefore \boldsymbol{T_{Screw} = 0.110Nm}$$

3.1.2.3. Belt

This calculation analyzes the required torque to generate parallel motion via belts.

$$Assume\ Gear\ Ratio\ for\ belt\ (N) = \frac{1rev}{2\pi(20mm)}\left(\frac{2\pi}{1rev}\right)\left(\frac{1000mm}{1m}\right) = \frac{50rad}{m}$$

$$J_T = J_{Motor} + J_{Coupling} + J_{LoadRef}$$

$$J_{Coupling} = \frac{1}{2} m_{Coupling} r_{Coupling}^2$$

$$J_{LoadRef} = \frac{w_{Load} + W_{Carriage}}{g} * \frac{1}{(N)^2 \epsilon}$$

$$J_T = 0.0000025 + \frac{1}{2}(0.025)(0.01)^2 + 1.37 * \frac{1}{(50)^2} = 5.55 * 10^{-4} kgm^2$$

$$T = J\alpha = (5.55 * 10^{-4} kgm^2)\left(\frac{6911rad}{s^2}\right) = 3.84Nm$$

$$Apply\ a\ S.F.\ of\ 2\ to\ account\ for\ efficiencies\ and\ friction \therefore \boldsymbol{T_{Belt} = 7.67Nm}$$

The motors under considerations are Bosch's MSM019A and MSK030C, producing 0.16Nm and 0.8Nm of torque respectively. Either of these motors is more than adequate to drive the carriage via leadscrew. However, neither of these motors produce adequate torque, without the addition of a gearbox, to drive the carriage via belts. Due to the high cost of gearboxes, and the availability of leadscrews, a belt driven carriage was removed from consideration.

3.1.3. Constraining Motion

Leadscrews are not designed to support radial loads; they are strictly for generating axial force. For this reason, the system will need supports to both bear the weight of the carriage, as well as act as a torque arm to resist the lead nut from simply rotating as the leadscrew turns. Table 3.3 outlines various methods of guiding motion.

Methods of guiding motion and bearing weight

	Pros	**Cons**
Linear Rails (Round)	Cheap Constrains translation in 2 axis	Lots of parts Constrains rotation in 2 axis
Linear Rails (Other)	Constrains rotation in 3 axis Constrains translation in 2 axis	Bulky Expensive
Extrusion Slides	Cheap Few parts Constrains roll in 3 axis Constrains translation in 2 axis Low mass Utilizes existing structure	Possible binding Possible friction concerns
Extrusion Rollers	Cheap Low mass Utilizes existing structure	Constrains motion Constrains translation in 1.5 axes* Constrains roll in 1 axis* (*With few parts, they can constrain more but it requires lots of parts)

Table 3.3 - Methods of guiding motion and bearing weight

3.1.3.1. Radially Loaded Circular Cross Sections

Linear bearings with circular cross sections are not designed to take large radial loads. To check the viability of this method, the required rod diameter was analyzed to keep the deflection of the guide rails below 1mm. Material properties are outlined in the table below [5].

Geometric and Mass Properties			
Total Carriage Mass	Worst Case load Fraction	Carriage Mass	Rod Length = 2L
[kg]		[kg]	[mm]
1.4	0.75	1.05	900

Material Properties		
Yield Strength	Elastic Modulus	Density
[Mpa]	[Mpa]	[kg/m^3]
560	190000	8050

Table 3.4 - Radially loaded beam properties

3.1.3.1.1. Preliminary

To determine an adequate diameter to support the carriage, the expected deflection and bending stresses experienced by the rod needed to be investigated. The following conservative loading arrangement was used:

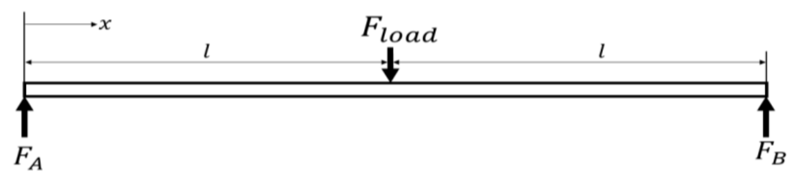


Figure 3.4 – Preliminary beam loading diagram

With the derivation available in Appendix C.1.1, the following parametric solutions were obtained:

$$Maximum\ Displacement\ (y_{\max}) = \frac{F_{load} l^3}{6EI}$$

$$Bending\ Stress\left(\sigma_{bending}\right) = \frac{2lF_{load}}{\pi r^3}$$

In place of a safety factor, this calculation is using a worst-case load fraction, which is representing the maximum load of the carriage expected to be supported by a single rail. Since the design has two rails and a leadscrew under the motor, this should be far more than adequate.

These equations were solved in excel using various diameter rods.

Shaft Diameter	Shaft Diameter	Moment of Inertia	Shaft Mass	Force applied	Bending Stress	Deflection
[in]	[mm]	[mm^4]	[kg]	[N]	[Mpa]	[mm]
0.250	6.350	79.811	0.229	12.551	112.344	12.571
0.375	9.525	404.045	0.516	15.365	40.749	3.040
0.500	12.700	1276.982	0.918	19.304	21.598	1.208
0.625	15.875	3117.632	1.434	24.368	13.959	0.625
0.750	19.050	6464.721	2.065	30.558	10.130	0.378

Table 3.5 - Excel calculations for the support of the carriage via circular cross-section

3.1.3.1.2. Refined

A more accurate model of the radial loading conditions was created to reduce the potential for drastically over-engineered rods which would be heavier and costlier.

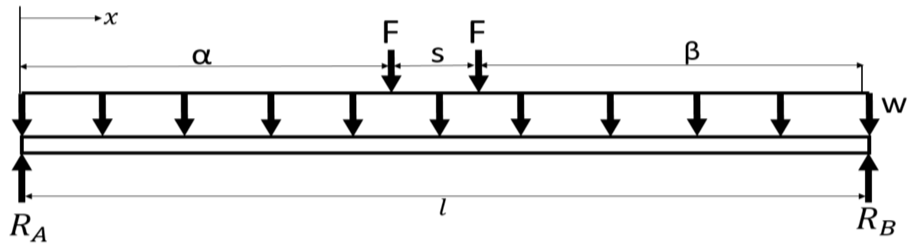


Figure 3.5 - Refined beam loading diagram

Where:

α is the position of the carriage along the rail
s is the width of the carriage
l is the length of the linear rail

The following Macaulay function was derived to describe the loading:

$$M = R_A < x - 0 >^1 - \frac{w}{2} < x - 0 >^2 - F < x - \alpha >^1 - F < x - (\alpha + s) >^1$$

Maple was used to integrate this moment function twice (to obtain an equation for displacement) and solve for boundary conditions. A 3D plot was generated to determine how the loading conditions will change over the carriages' traversing and confirm that the maximum deflection of the beam would be obtained while the carriage is perfectly straddling the middle of the beam. The Maple code for this analysis is available in Appendix C.1.2

Trying different common linear rail diameter sizes around the concluded 5/8 inch from the preliminary testing yielded the following results.

Diameter (in)	Maximum Displacement (mm)	
	Preliminary	Refined
3/8	3.040	2.634
1/2	1.208	0.988
5/8	0.625	0.486

Table 3.6 - Radially loaded circular cross-section maximum displacement

Keeping to our below 1mm deflection specification, the refined loading arrangement yields a less conservative but more realistic requirement of the rods being 1/2in in diameter.

3.2. Subsystem Level Design

This section considers how each constraining method may be used to guide both parallel and perpendicular motion, as well as how the linear motion from the rollers may be approached.

3.2.1.1. Parallel Motion Concepts

Figure 3.6 shows the use of extrusion sliders to restrain motion and bear load, while the motion itself is generated via leadscrew.

Figure 3.7 depicts the use of extrusion rollers to restrain motion and bear load. The additional width of the wheels could give additional room for perpendicular motion motors.

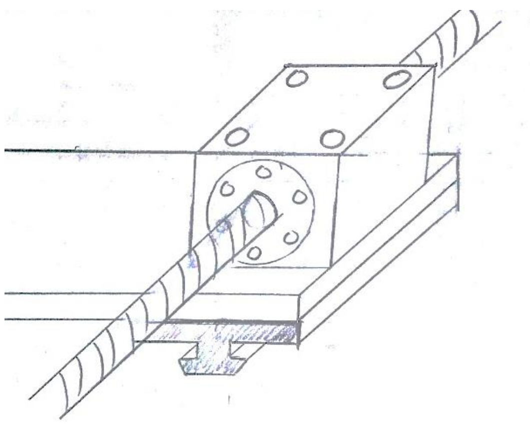


Figure 3.6 - Slider and leadscrew

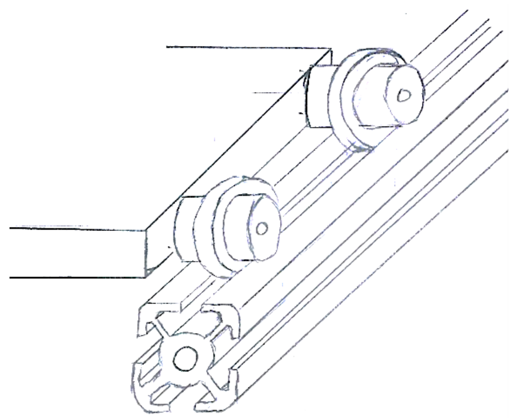


Figure 3.7 - Roller carriage

Figure 3.8 shows a method of using a leadscrew to generate motion while completely concealing the leadscrew inside of an aluminum extrusion and utilizing magnets.

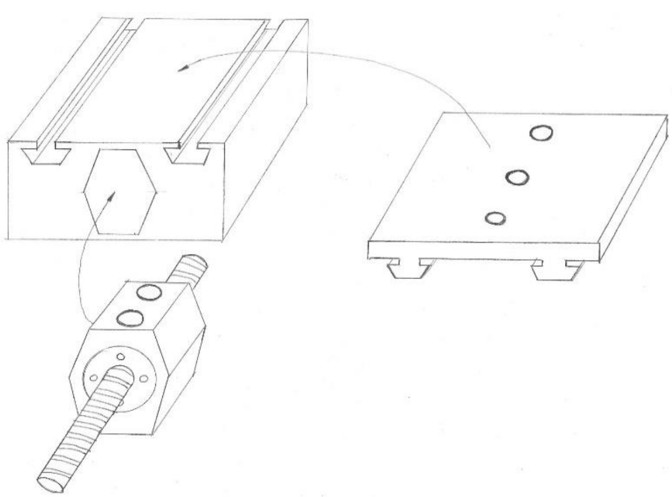


Figure 3.8 - Magnetically couple slider leadscrew

3.2.1.2. Perpendicular Motion

This axis of motion moves very little mass and spans less than 11 inches. For this reason, radial loading of the leadscrew and supporting rails are less important. The use of a leadscrew was preferred due to spare parts that the project sponsor had on hand.

Figure 3.9 depicts a cross slide that utilizes a round linear rail to guide the perpendicular motion. The carriage itself could be made of transparent polycarbonate or acrylic. This allows for a less obstructed viewing of the writing surface.

Figure 3.10 shows one way that rollers could be used to constrain motion. The depicted method has many parts, making for an overly complex solution.

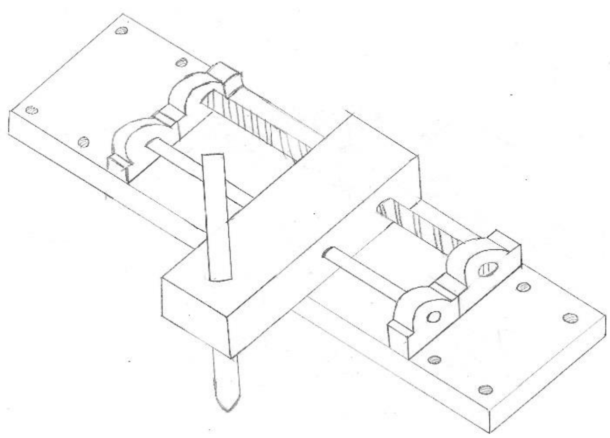


Figure 3.9 - Round linear rail guided perpendicular motion

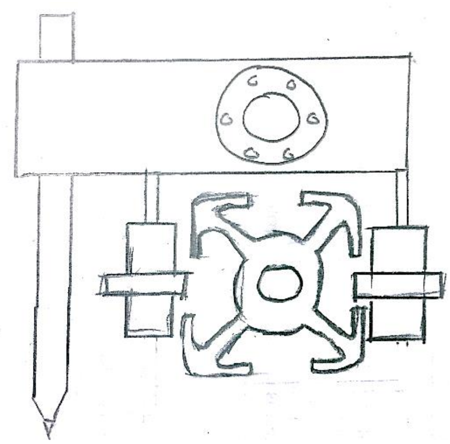
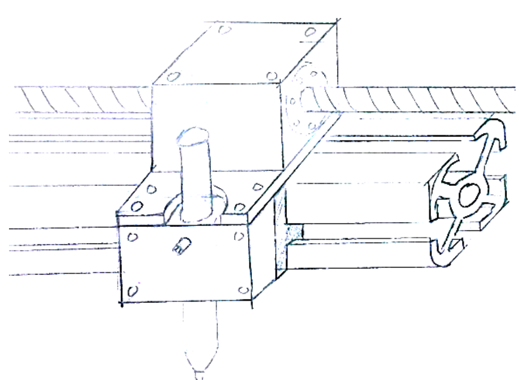


Figure 3.10 - Roller constrained perpendicular motion

Figure 3.11 and Figure 3.12 show how a piece of aluminum extrusion could be used with sliders to restrain motion and allow for driving via leadscrew. With this type of configuration, the action of sliding could also be used, in conjunction with the twisting of the leadscrew, to lift the end effector off the writing surface.



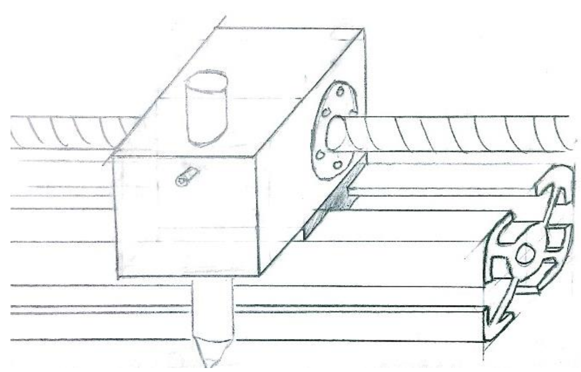


Figure 3.11 - Side slide guided perpendicular motion

Figure 3.12 - Top slide guided perpendicular motion

3.2.1.3. Linear Motion of Sheet

Since the use of extrusion rollers and slides requires the top of the extrusion to be unobstructed, the support for the cellophane sheet must come from below that point. One concept, depicted in Figure 3.13, is to support the writing surface backer with a plate that seats into the side of the extrusions that make up the frame. It can be built up to suit the elevation requirements of the roller position.

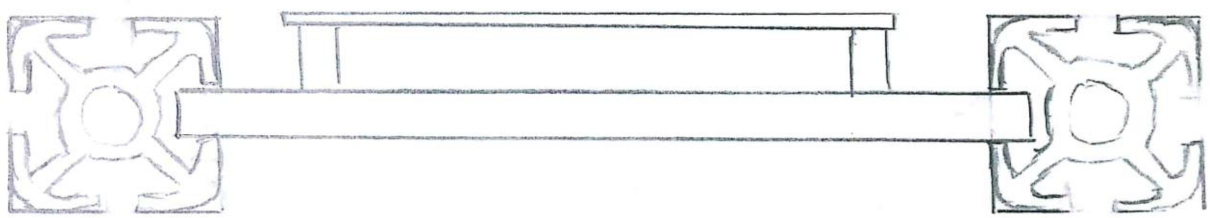


Figure 3.13 - Side extrusion channel supported writing backer

The rollers themselves could be mounted on top of the extrusion, seen below in Figure 3.14. This mounting method was originally considered before the extrusion motion constraint methods were considered. This method would require the writing backer to require an additional extension, and the carriage to be elevated but could allow for the driving motor to be mounted, and therefore better protected, inside the frame. Alternatively, a flange style bearing or bushing would yield the opposite result.

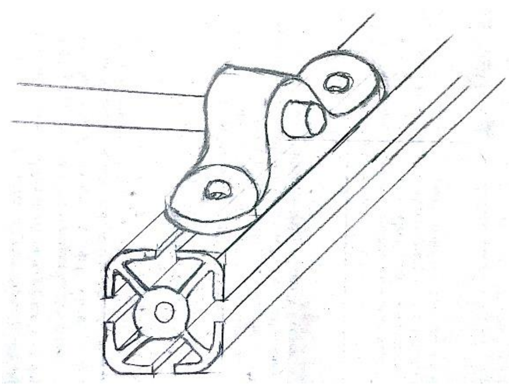


Figure 3.14 -Pillow block supported roller

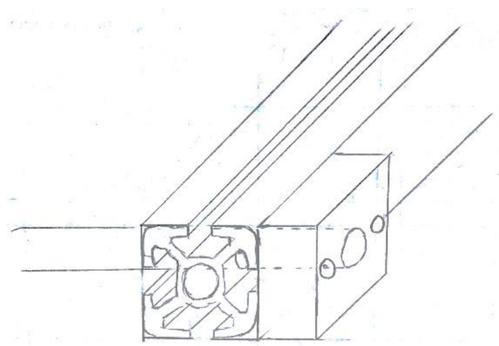


Figure 3.15 - Flange style bearing or bushing supported roller

3.2.2. Proof of concepts

Many of the methods for creating and constraining motion came with unknowns regarding their manufacturability and effectiveness. To remedy this uncertainty, various proof of concepts were created and tested.

3.2.2.1. Extrusion Slider Concept

This low-cost test investigated the potential for binding when the carriage is trying to slide. The goal was to have a leadscrew drive the slider inside of the 45x90mm aluminum extrusion. The leadscrew would be positioned symmetrically between the two tracks of the double slider (left-hand side of Figure 3.16), and the secondary slider connected to the 45x45mm slider would simply be a guide track.

The sliders were made using a unique process coupling 3D printing and resin casting. Only the exterior walls of the slider were printed, which then acted as a mold to cast a resin in. This was done to achieve a homogenous part while cutting down on print time and cost.

When testing, the team found that the concept worked fine when the vertical load was zero and it was pushed a certain way, but the effects of binding were quite prominent under normal conditions and it was deemed unviable.

Figure 3.16 - Slider proof of concept

3.2.2.2. Magnetic Slider Concept

Based on the vision of having linear motion without the visibility of the driving mechanism, the leadscrew would run inside of the aluminum extrusion with a magnet mounted to the lead nut block. Another magnet would be connected above the magnet pictured below, and the carriage would slide from their related force. Both the concept of south-south and south-north were considered in this design. The advantage of the south-south being that the repulsive force would reduce the normal force, therefore reducing the drag friction force from sliding.

Even with the repulsion setup of the magnets, the design suffers from an inherent lag in the nonrigid connection. The magnetic connection acts like a spring which caused the carriage to lag or lead as a function of the force being applied to it. This means that the position an encoder on the leadscrew would read during acceleration and deceleration (due to additional inertia forces) would be off from the true location. The idea was ultimately discarded due to this innate inaccuracy.

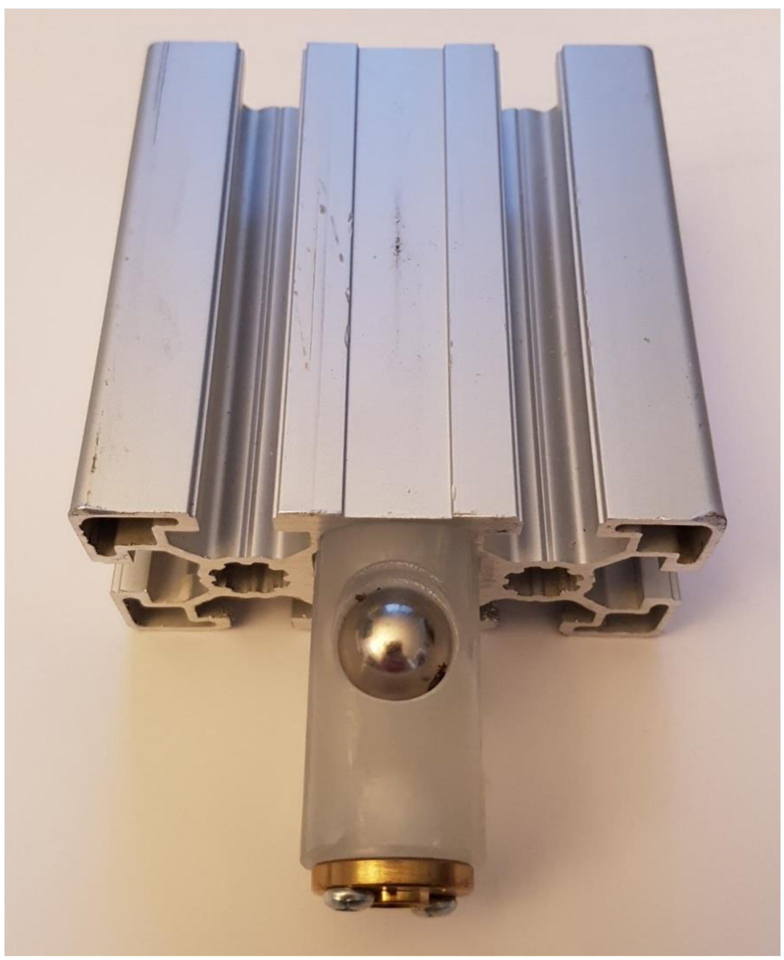


Figure 3.17 - Magnetic linear motion coupling

3.2.2.3. Radially Loaded Circular Cross Section

A pick and place PLC trainer produced by Festo Didactic was used as confirmation for the viability of the round linear rail design. Utilizing two linear rails with a leadscrew in the middle to guide the motion and an accompanying aluminum extrusion slider to support the carriage load at the other end. Comparing to our extrusion slider proof of concept, the fit between the extrusion and the slider must be very loose to avoid the binding issue.

Figure 3.18 - Festo Didactic's carriage motion system

Figure 3.19 - Close up of motion guiding from Festo Didactic

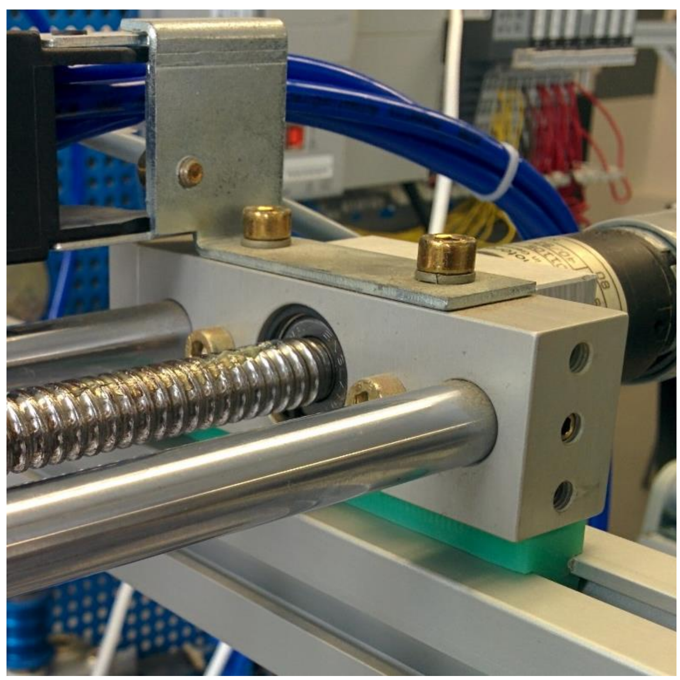


Figure 3.20 - Close up of aluminum extrusion based motion guide from Festo Didactic

After further consultation with Dr. Vahid Askari, a professor at BCIT, this style of motion guiding was ultimately selected as the best option of those tested.

3.2.2.4. Carriage Concept

The carriage style was chosen to utilize a leadscrew and rail provided by our project sponsor. Connecting them is a 3D printed part that overhangs a pencil. The pencil in this design is fixed to a particular height, which would not allow for the operator to lift it off the writing surface.

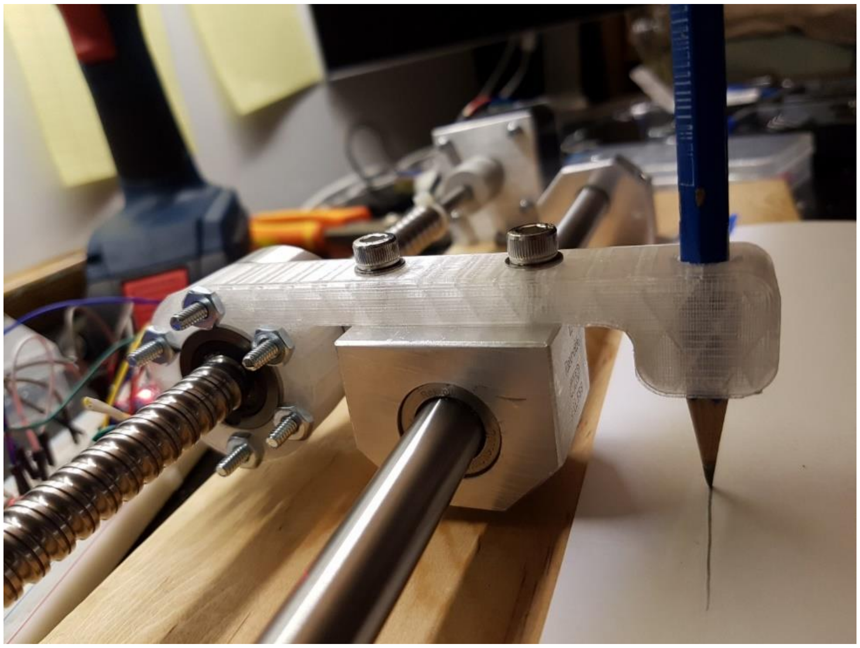


Figure 3.21 - Carriage proof of concept

3.2.2.5. Roller Tensioning Concept

This concept fixes one roller in place while allowing the other to slide freely by mounting the bearing onto a slider for the 45x45 aluminum extrusion. Springs mounted inside the rail will push one roller apart from the other, tensioning the cellophane that is wrapped around them. Obtaining equal spring force is simply done through feel or trial and error. In addition, this design has the versatility to be used with the spring in tension or compression depending on access.

Figure 3.22 - Spring tensioner for rollers

Two fixed roller designs were considered, one containing two locking t-nuts, the other with one t-nut and a slider. The advantages of the two-bolt design was ease of printing, reduced material, and ease of disassembly. It may pose a problem of access to the interior bolt when fully assembled. The one bolt design utilizes a profile that slides in the extrusion. It has the advantage of fewer parts but cannot be removed without unbolting the aluminum frame.

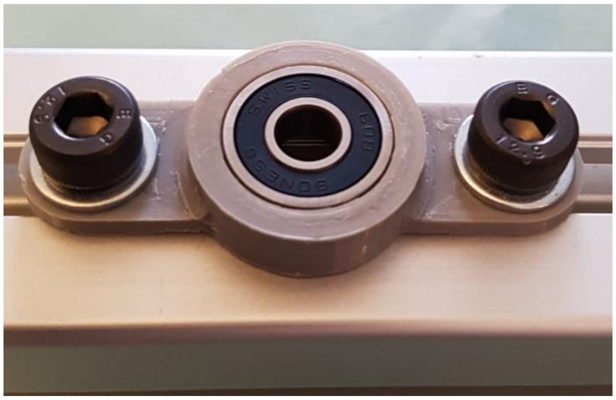


Figure 3.23 - Two-bolt flange bearing

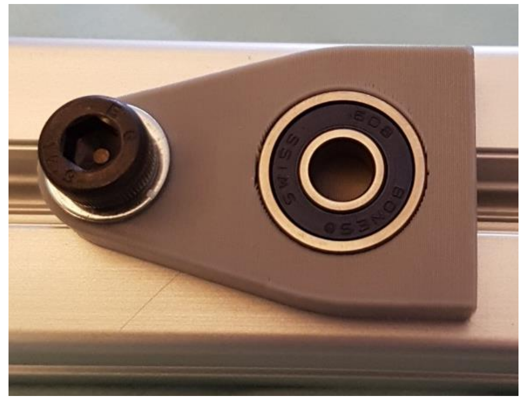


Figure 3.24 - One-Bolt Slider Bearing

3.3. System Level Design

All the subsystems of a machine must work in tandem with one another for it to function properly. Through careful consideration and iteration, the subsystems components are pieced together to form the trainer design.

At this design stage most dimensions were unknown, so a skeletal layout was developed in SolidWorks, depicted in gray in Figure 3.25. This worked off a desired writing surface of 8.5inches by 2ft, in which the cutting action would be performed.

All components of later designs were then added to the skeletal layout as new layers, with corresponding parts deriving key parameters from this master sketch file. Depicted below, in orange and blue are two such layers corresponding to the carriage and parallel motion assemblies. This method allows for parametric modification of the model throughout iterations and minimized the amount of remodeling required per iteration. This method proved critical in ensuring that all the components lay within the footprint of the aluminum extrusion.

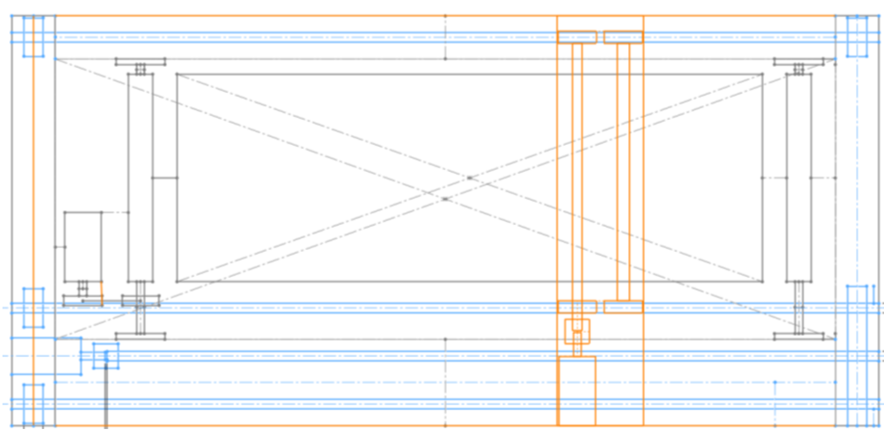


Figure 3.25 - SolidWorks Skeletal Layout

3.3.1. Preliminary Design

The Beta Prototype requires three motors to emulate a flying saw. The first motor is attached to a pulley, which spins a piece of cellophane over the center platform to act as a moving writing surface. The second motor tracks the carriage along in the same direction as that of the cellophane. The third motor performs the “cut”, in which it drives a pen across the platform to write on the surface of the cellophane. Together the three perform a flying-saw application.

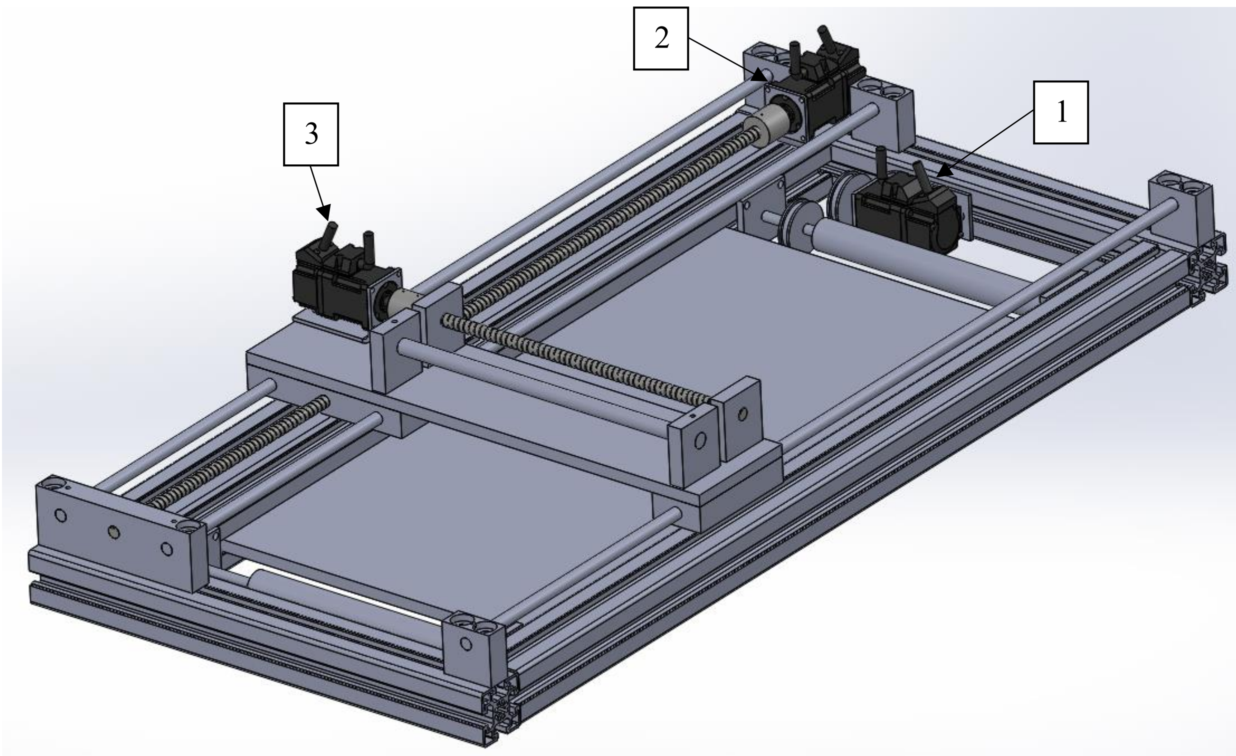


Figure 3.26 - Beta Prototype concept

3.3.1.1. Redesign for Assembly

Two aspects of the Beta design were considered from an assembly point of view. The first being the radially loaded circular cross-section proof of concept, and the second being the outer frame connections.

3.3.1.1.1. Parallel Motion

With the use of a leadscrew finalized, the purpose of this design for assembly is restricted to the supporting rails, which will be referred to as the guide system. Please note that this analysis was done both using software and by hand, as the team wanted to verify the results and their understanding of the software usage, all of which is available in Appendix C.2.1.

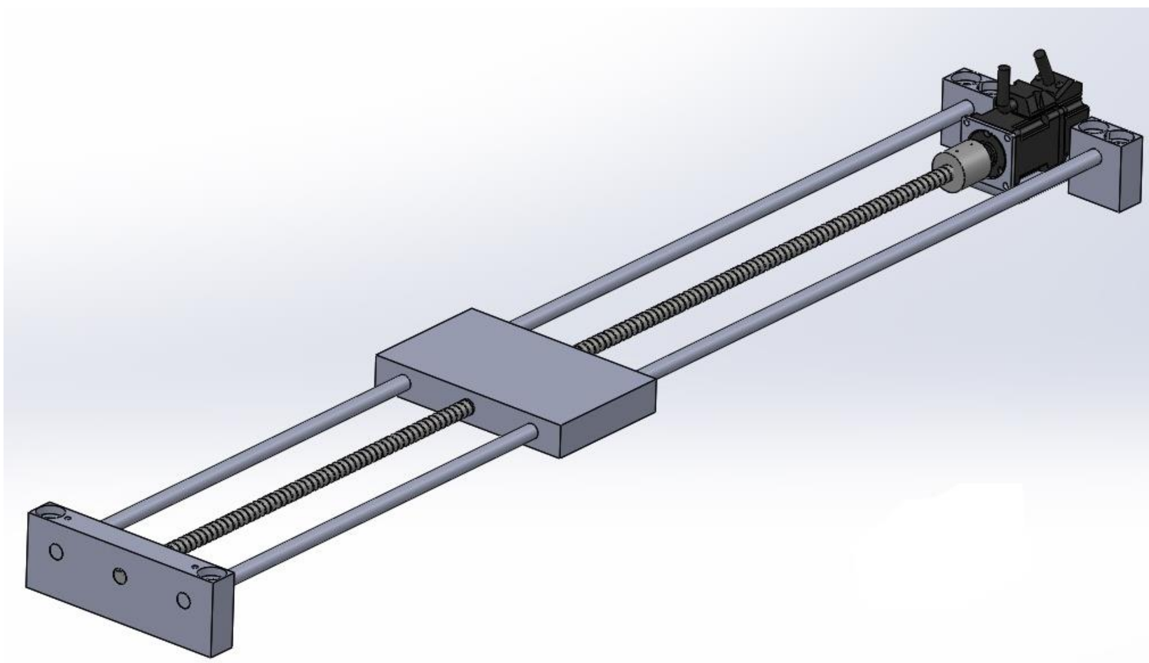


Figure 3.27 – Original parallel motion guide assembly

3.3.1.1.1.1. Original Design

The exploded view of the guiding system is shown below. Since we are using aluminum extrusion as the frame of the structure, the fasteners that are readily available and provided by our sponsor are t-nuts and bolts. This design was chosen due to price constraints. It is recognized that this design is not optimal, but calculations ensuring that the deflection of the carriage is tolerable during the range of motion of the carriage may be found in subsystem section regarding radially loading circular cross-sections.

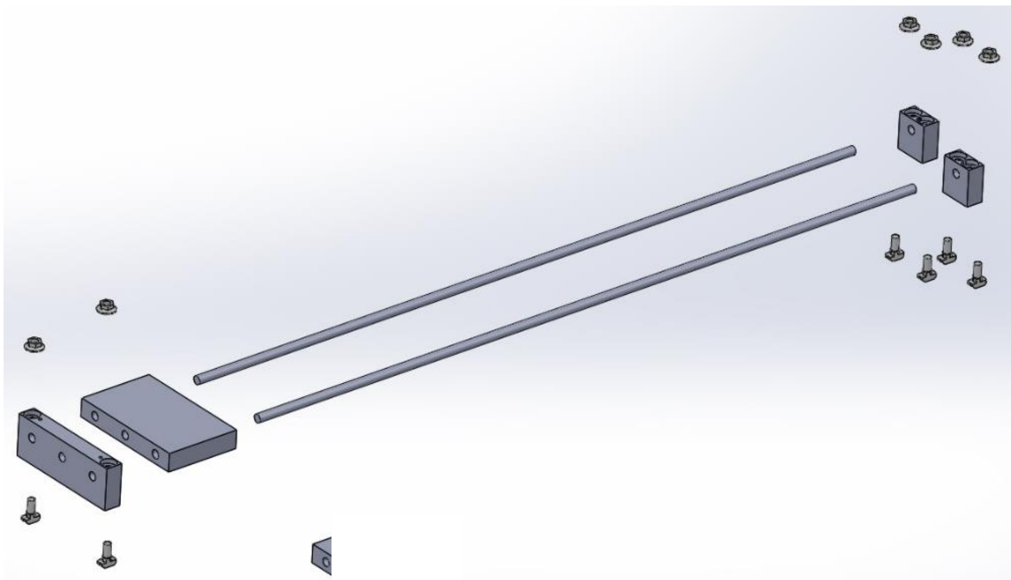


Figure 3.28 - Original parallel motion guide assembly (Exploded View)

3.3.1.1.1.2. Redesigned System

The redesigned system utilizes a one-piece linear rail system in place of the supporting rods. This design does not require the end blocks to support the rail, which will save time and resources in the manufacturing process. The use of this system has increased the design efficiency from 2.64% to 10.9%, an increase of over 4 times. It has the added benefit of reducing the weight, the cost, and has mitigated the issue of deflection the other design had.

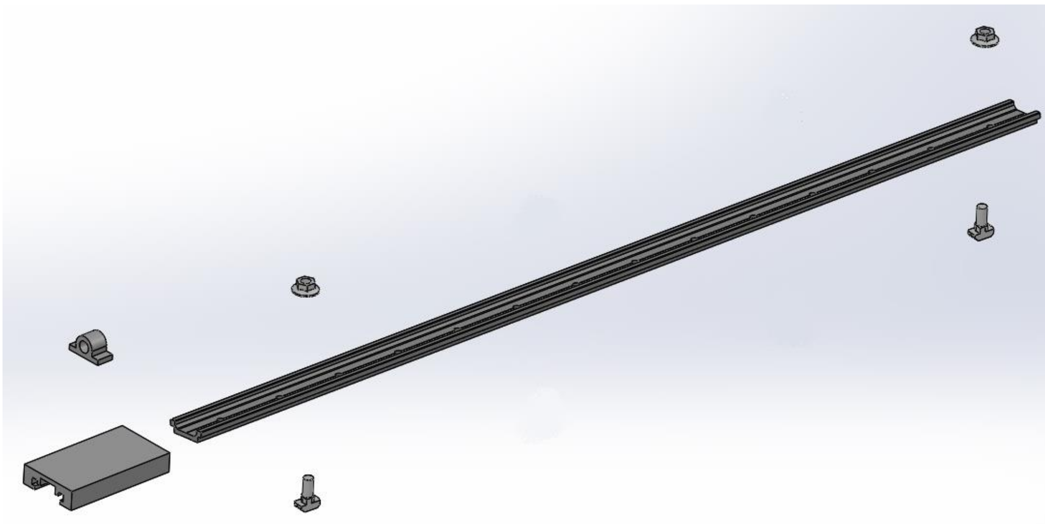


Figure 3.29 - Parallel motion guide redesign 1

This option was possible and ultimately selected due to the sponsorship of IGUS.

3.3.1.1.1.3. Alternative Optimal Design

The analysis indicated that we only need one part to carry out our function. This design can be visualized below, where a carriage will utilize the aluminum profile to both allow movement and constrain the system from rotation. Although this design is optimal, a proof of concept of this design, found earlier in this chapter, highlighted the very real issues of binding or loss of positional accuracy if the fit is too loose.

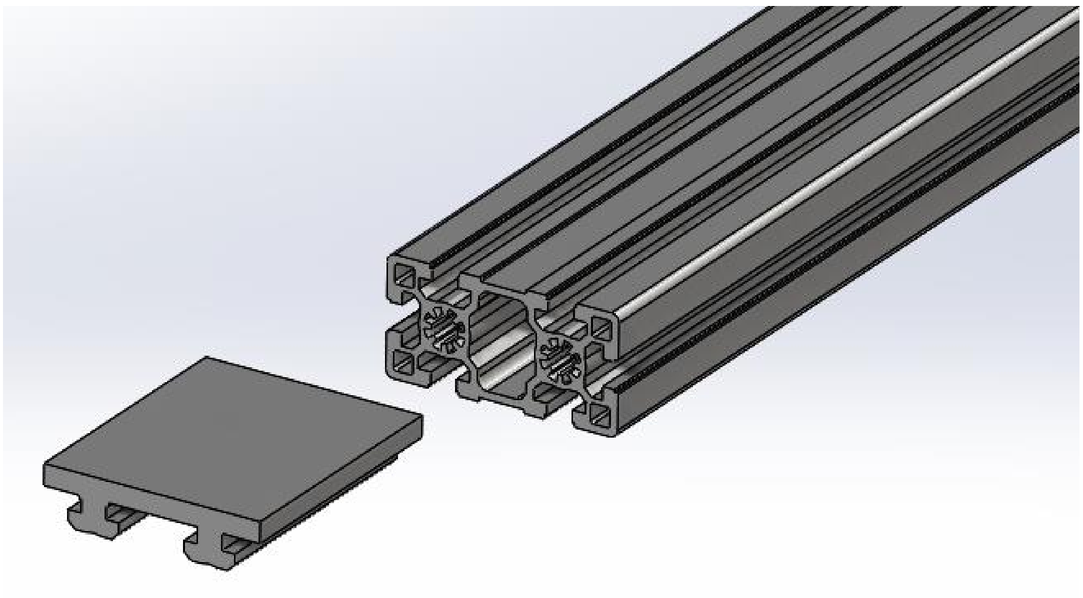


Figure 3.30 - Parallel motion guide redesign 2

3.3.1.1.1.4. Design Conclusion

As seen in the DFA Appendix, the carriage system utilizing the aluminum profile is an ideal way to minimize the number of parts, handling and assembly time, and cost of the guiding system. If manufacturing of a larger scale was considered, this design should be analyzed and iterated to the point that it worked. Since this is a one-off prototype we are creating, the redesign utilizing the single support rail is the best option. It utilizes components from a trusted company and will ensure that our project functions as intended. Although the optimal design, depicted in Figure 3.30, would have further reduced our part count and assembly time the failure modes and effects analysis, described later in this report, made the optimal design undesirable due to its higher potential for binding.

3.3.1.1.2. Frame Gusset

Since the Beta Prototype is to be portable, a frame to hold all the components together and in their correct locations is required. This frame needs to be a ridged with all the pieces of the aluminum extrusion frame at 90 degrees to adjacent pieces.

3.3.1.1.2.1. Original Design

The original design, a 5 bolt 90 degree gusset plate, which would be implemented at all four corners of the frame, is shown below in Figure 3.31 and Figure 3.32.

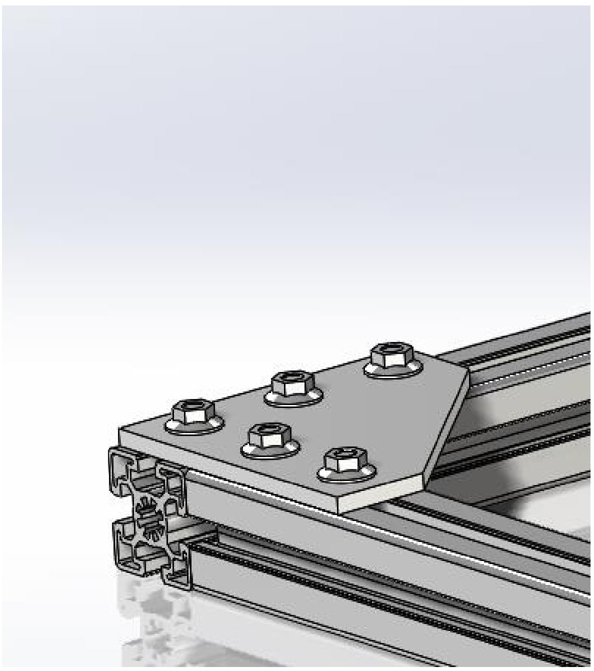


Figure 3.31 - Gusset Frame Connection

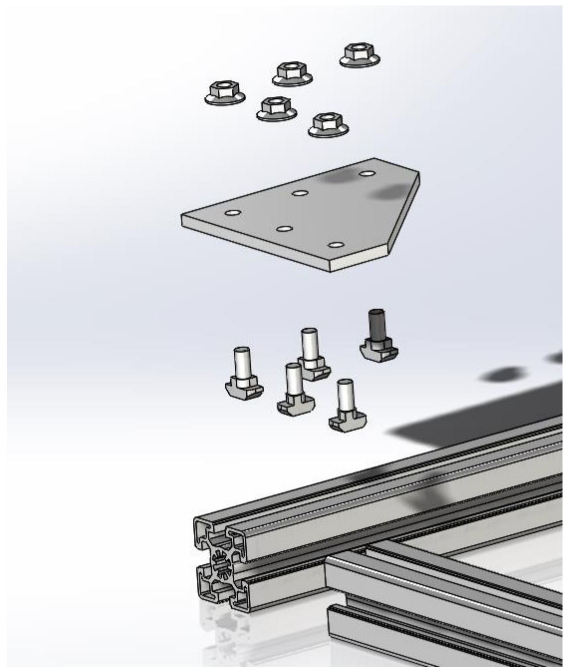


Figure 3.32 - Gusset Frame Connection, Exploded View

Utilizing DFA Product Simplification 10.0 software by Boothroyd Dewhurst, we obtained various recommendations whose printout is available in Appendix C.2.2.1. Naturally, the software highlighted the multiple redundant fasteners utilized and suggested various possible redesign considerations (see Appendix C.2.2.1.2)

3.3.1.1.2.2. Redesign

The connection was redesigned to simply use one bolt that will pass through a drilled hole in the aluminum extrusion, demonstrated below in Figure 3.33 and Figure 3.34.

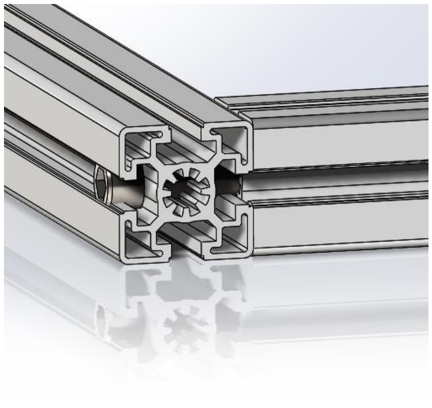


Figure 3.33 - Frame Connection Redesigned

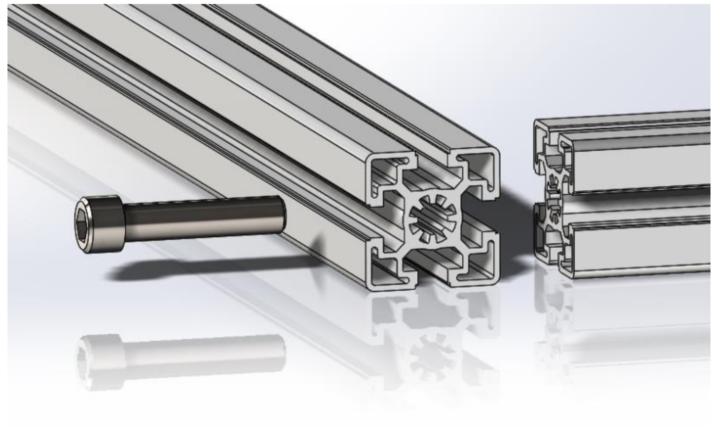


Figure 3.34 - Frame connection redesigned, Exploded View

3.3.1.1.2.3. Design Conclusion

The Boothroyd Dewhurst method was used to analyze both connection methods, ultimately reducing assembly time by 100 seconds and number of parts from 13 to 3, as outlined in the software output available in Appendix C.2.2.2. Though not rigorously analyzed, the redesign should reduce the Beta Prototype in both size and mass, two of the more highly valued aspects discovered in the QFD analysis.

3.3.1.2. Linear Motion of Sheet

Due to the availability of only two drives, we are, by extension, restricted to being able to control only two Bosch Rexroth motors with IndraDrive. To work around this, our third linear motion of the roller will be generated with a simple stepper motor, whose velocity with vary under the control of a potentiometer. This changing voltage from the potentiometer will also signal to IndraDrive so it can determine the velocity of the linear motion.

To generate the transfer function to describe the voltage to linear velocity, the RPM of the stepper motor to linear velocity first needs to be established. As outlined earlier, we want a maximum linear velocity of 0.55m/s, which in RPM of the roller is:

$$\omega_{roller} = \frac{v}{\pi D} = \left(\frac{0.55m}{s}\right)\left(\frac{1}{\pi(1.25in)}\right)\left(\frac{1in}{25.4mm}\right)\left(\frac{1000mm}{1m}\right)\left(\frac{60s}{1min}\right) = 330.84RPM$$

The stepper motor was tested for a maximum RPM which ended up being 180RPM. Thus if a 1:2 gear ratio is used, the stepper motor need only spin at:

$$\omega_{stepper} = \frac{\omega_{roller}}{N} = \frac{330.84RPM}{2} = 165.42RPM$$

Which is below the tested maximum RPM of the stepper motor. The torque required to drive the motors will be minimal due to the use of bearings and lightweight materials for the rollers themselves.

3.3.2. Modified Design

Considering the design for assembly analysis and sponsorship from IGUS, the resulting iteration is depicted in Figure 3.35 below. This design utilizes a double rail on the driven side of the carriage, and a single looser rail on the following side. With the frame held together by a single bolt that threads into the hole in the middle of the extrusion profile.

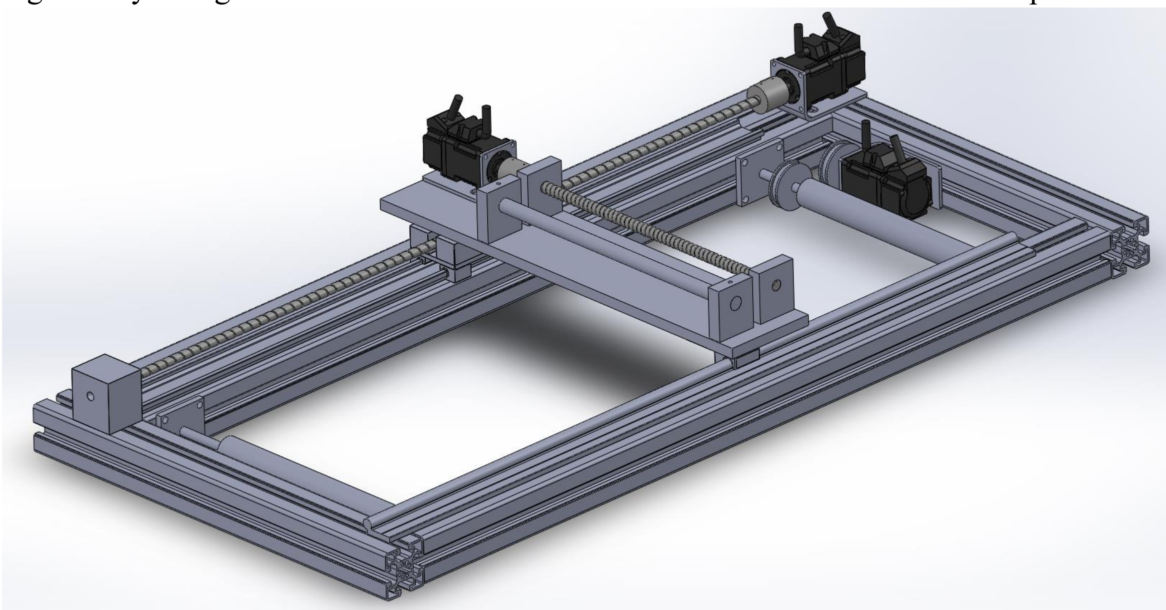


Figure 3.35 - Beta Concept 2

The double rail on the lead screw side of the parallel motion does more than reduce the number of parts and assembly time. It alleviates concerns of carriage binding due to the cantilever inertial loading, and misalignment. IGUS stresses a 2:1 rule depicted in Figure 3.36.

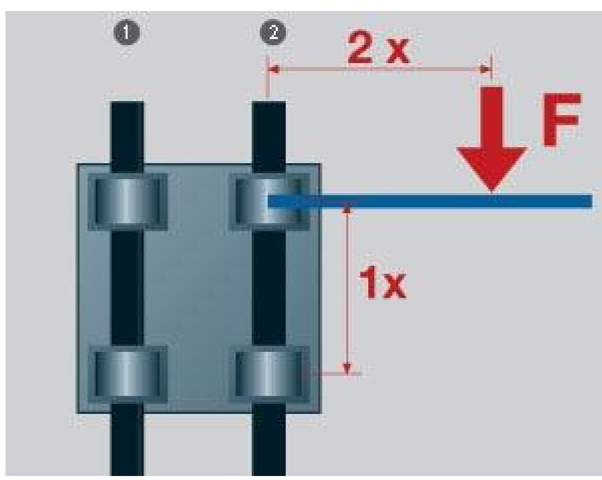


Figure 3.36 - Linear bearing sets supporting a cantilever load recommendations [6]

With a carriage length of approximately 400 mm, and the bulk of the carriage mass residing in the motor positioned almost directly above the bearing, our center of gravity should be less than half of our carriage length. This means we simply need to ensure that the bearings are spaced approximately 100mm apart in the direction of travel.

3.4. Final Product

The most drastic change between the Final Design and the Modified Beta Design are larger motors. The originally specified MSM019A were not available to Bosch Canada so larger MSM031B motors were implemented into the final design. The increased center height of the motor lifted the carriage and required larger brackets. The final footprint of the Beta Prototype is approximately 475mm by 900mm with all components other than cables residing within.

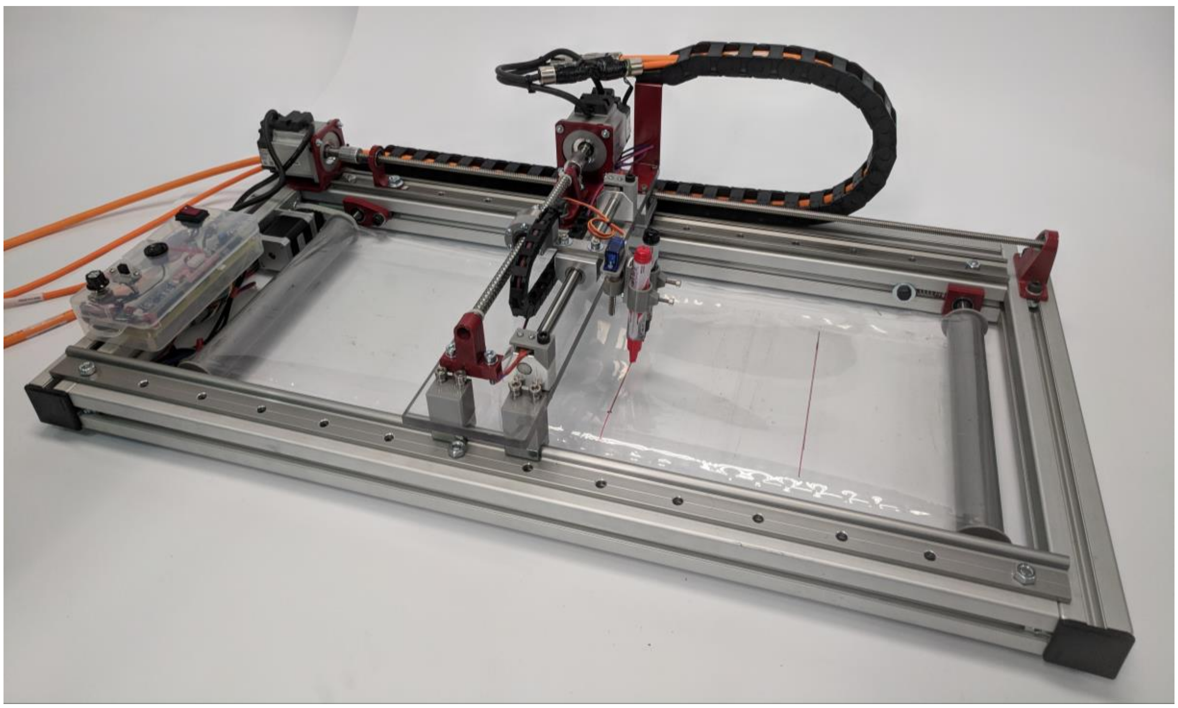


Figure 3.37 - Final Beta Prototype product

3.4.1. Roller Motion

The cellophane sheet used as the moving material ultimately had a width of 11 inches instead of the designed for 8.5 inches. This was easily compensated for by simply extending the extrusion profiles that run parallel to the rollers and widening the rollers themselves. Additional spacing for ease of access had also been designed in and was reduced somewhat to accommodate the additional 2.5 inches.

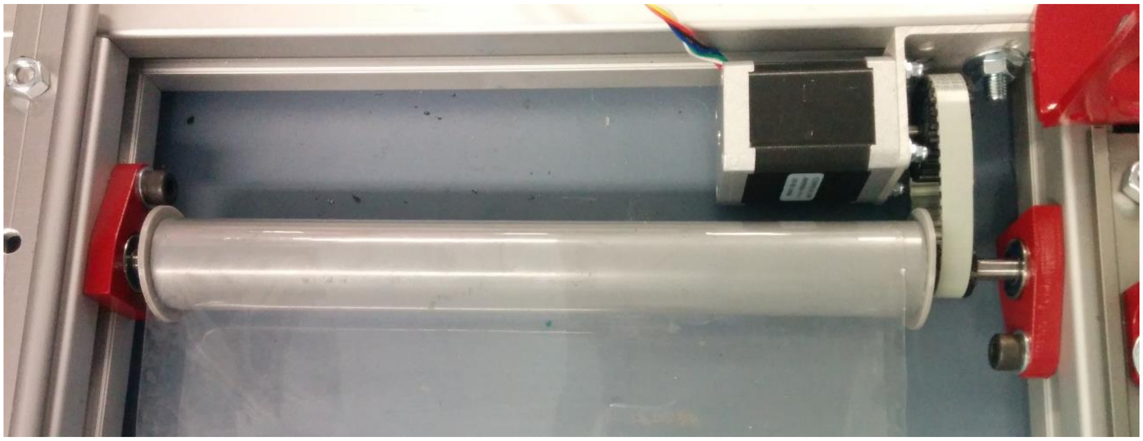


Figure 3.38 - Final driven roller layout

The spring tensioned slider system proved to be very effective in taking up slight variations in the cellophane surface and ensuring that the cellophane tracks properly.

Figure 3.39 - Final spring roller tensioner

3.4.2. Perpendicular Motion

The perpendicular motion is generated via ball screw and constrained with a round profile linear rail. Other than the center height of the ball screw due to the change in motor, the design remained nearly identical to that in the proof of concept.

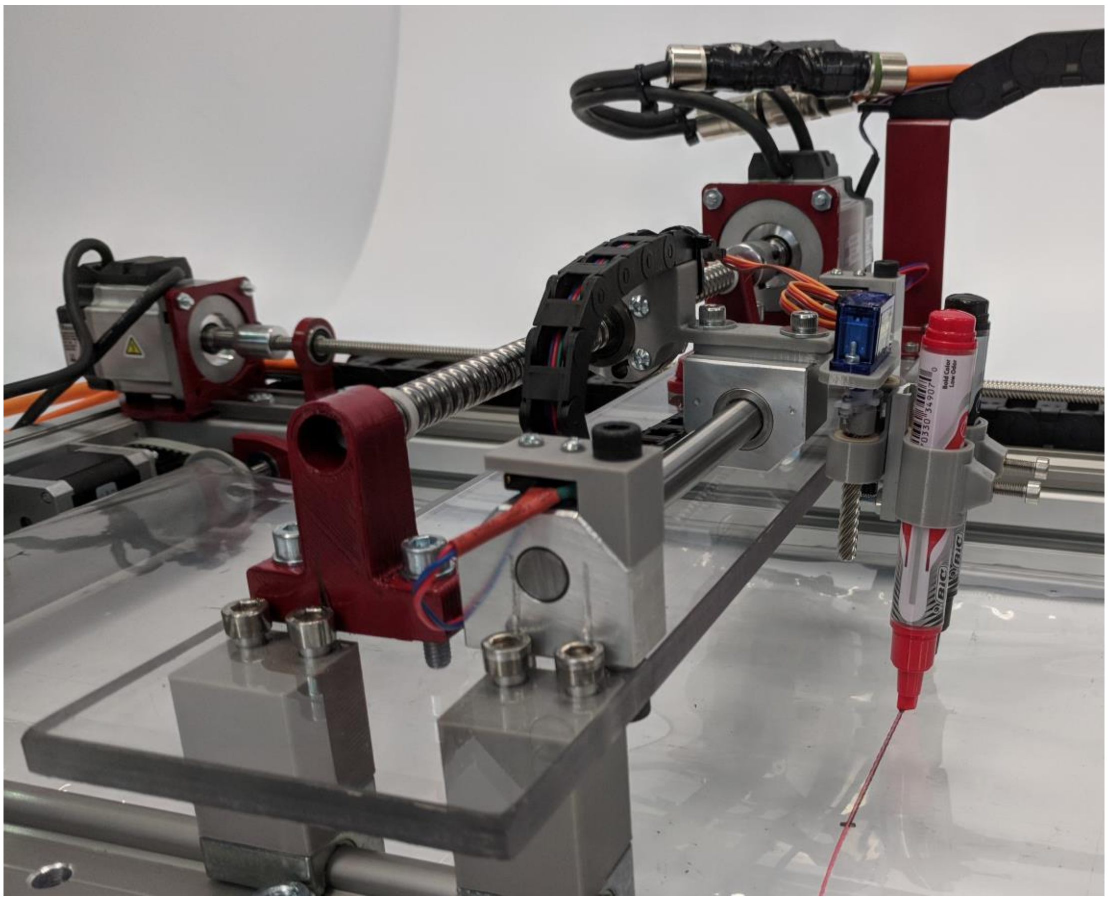


Figure 3.40 - Final perpendicular motion

3.4.3. End Effector

The pen effector is driven by a 180-degree servo motor attached to an eight-start lead screw. The servo has two positions available, “pen up “and “pen down”. In addition, the pen needs to maintain contact with an uneven writing surface throughout the tracking motion. To accomplish this, the pen is attached to a slider and is free to slide up and down. At the base of this slider is a bolt that prevents it from sliding all the way off, which is where it rests in the up position.

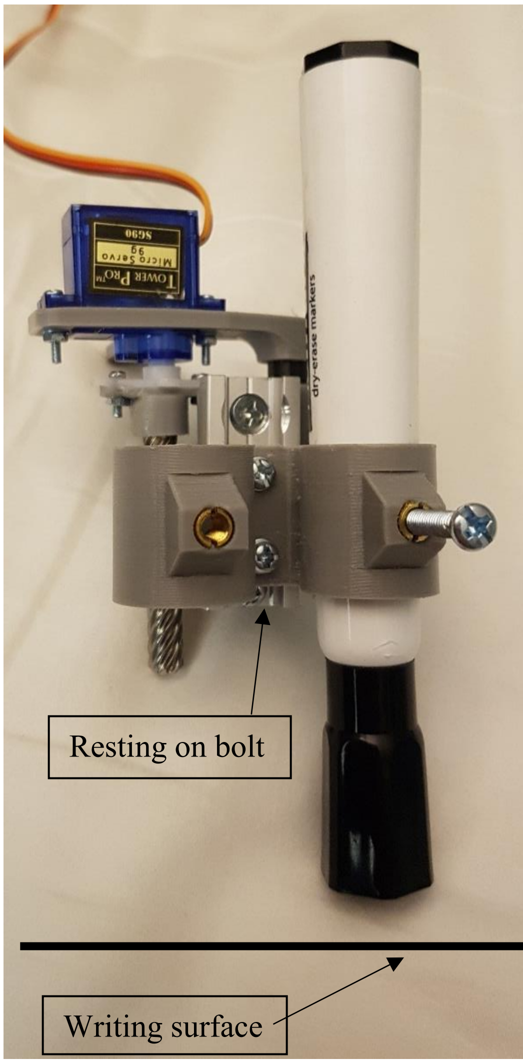


Figure 3.41- End effector UP position

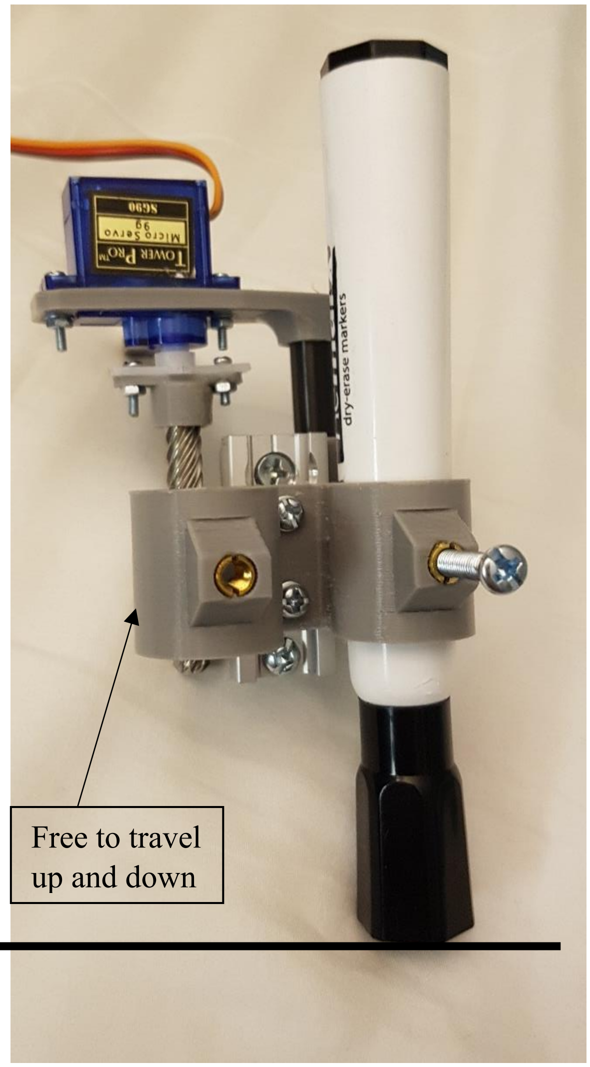


Figure 3.42- End effector DOWN position

3.4.1. Parallel Motion

A double 6mm square rail from Igus with an accompanying 100mm wide slider set is used to guide the motion while a lead screw generates the axial force to create the motion.

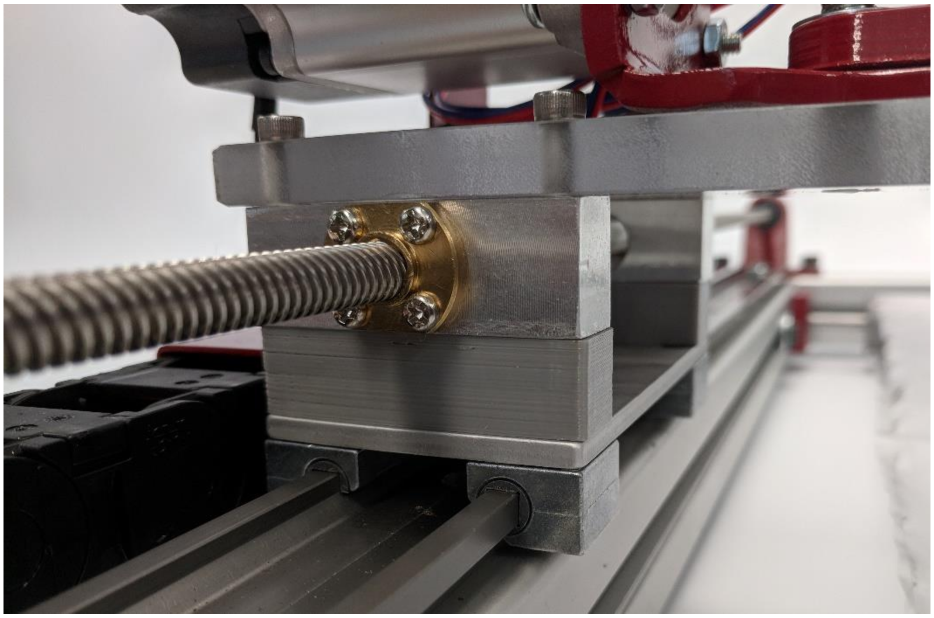


Figure 3.43 - Parallel motion driven side linear bearing set

The guiding rail on the opposite side uses a 10mm diameter single rail with an accompanying bearing that has variable preloading (highlighted in yellow below). This variable preloading allows the effects of binding to be explored with the unit, and thus torque sensing of the drive.

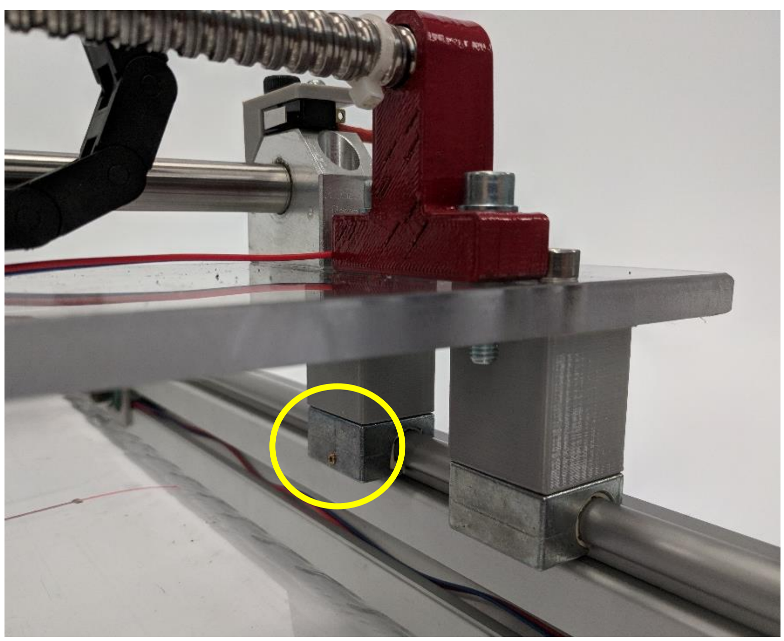


Figure 3.44 - Parallel motion following side linear bearings

3.4.2. Discussion

Many of these changes occurred after the modified design was thought to be finalized. This is a testament to the adaptability and versatility of the design, which could be scaled larger and smaller with minimal effort.

3.5. Programming

To develop a full-fledged training platform for electric motors, programs must be developed for their respective drives. To program a Bosch Rexroth drive, their proprietary software, IndraWorks, must be used.

3.5.1. IndraWorks

IndraWorks is a PLC based program that can commission the drives. It has project functionality, allowing for the proper planning of various projects in industry. The project tree, shown in Figure 3.45 allows for intuitive navigation of the current project, and can access the majority of readily used task windows and right clicking items for additional options. It also has functional toolbars and drop-down menus.

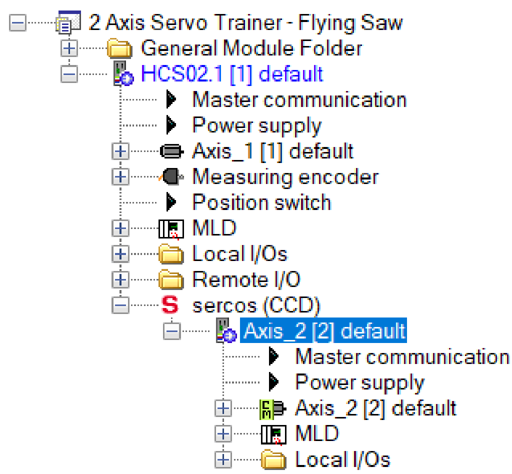


Figure 3.45- Project tree within IndraWorks

It uses CODESYS V3, which is a software platform used for industrial automation technology. CODESYS V3 allows device manufacturers, like Bosch Rexroth, to custom build their own control software, and for this project, requires learning the associated program language, application and debugging.

There are multiple options in terms of the style of program; they are:

- Instruction List
- Function Block Diagrams
- Ladder Diagrams
- Structured Text
- Sequential Function Chart

Only one of these options are required to be used, but all programs can be used to achieve the same results, just with varying ease of implementation and trouble shooting.

IndraWorks functions during programming by changing the bits within parameters. Each bit corresponds to a change in the operation of the drive, and of its peripherals. There are thousands of parameters and have functionalities such as setting the upper limit for the velocity of a motor, changing the communication protocol between master and slave drive, or even what type of optional safety features are available. The drive can, through changing values or toggling options, commission the system to the desired functionality for the required program.

3.5.2. Commissioning

To commission the drive for the flying saw, the first step is to set up the IP address of the drives and computer using IndraWorks. For the computer, the IP address should be set to a known value. This can be by accessing the Ethernet properties, then editing the properties of Internet Protocol Version 4 (TCP/IPv4) as shown in Figure 3.46. For IP address, the fields should be 192.168.XXX.YYY where XXX represents the value to be used for all devices, and YYY represents a value used to distinguish each device. The Subnet mask and Default gateway can be left as is.

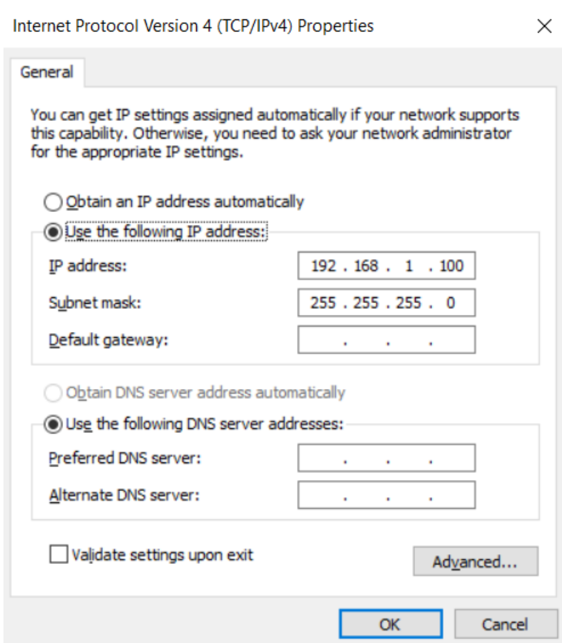


Figure 3.46 - Editing the IP address of the computer

Since the computer will be connected via Ethernet cable to the master's port X26, the IP address of this port will need to be configured. This is achieved through the physical display on the drive. By using the arrows, find Ethernet, then X26 and set IP address to 192.168.XXX.ZZZ so the third field matches the computer and the fourth field is unique from the computer. Additionally, the communication protocol of the master will also need to be set to Ethernet/IP. This allows IndraWorks to find the master after scanning for a device on the start page.

At this stage, there may need to be some changes to parameters if there are any error messages that appear once the drive is connected. This trouble shooting process is done by checking the display on the drive for the error code, and using the Trouble Shooting Guide – R911297319 to see potential causes and remedies. The parameters also have an associated description that is accessed by first opening the parameter editor, entering the parameter's ID, and then left-clicking the question mark. This description can include the purpose of the parameter, what the various bits of the parameter do, and how it's identified within IndraWorks.

Once the master has connected, the slave can be connected using Cross Communication Drive (CCD), which uses SERCOS, another communication method similar to Ethernet/IP. The first step is to configure the master for multi-axis, done through right click on the master in the project tree, and selecting Basic Configuration / Functional Packages. The Device Use should be set to Multi-axis Motion Control (MLD-M) as shown in Figure 3.47.

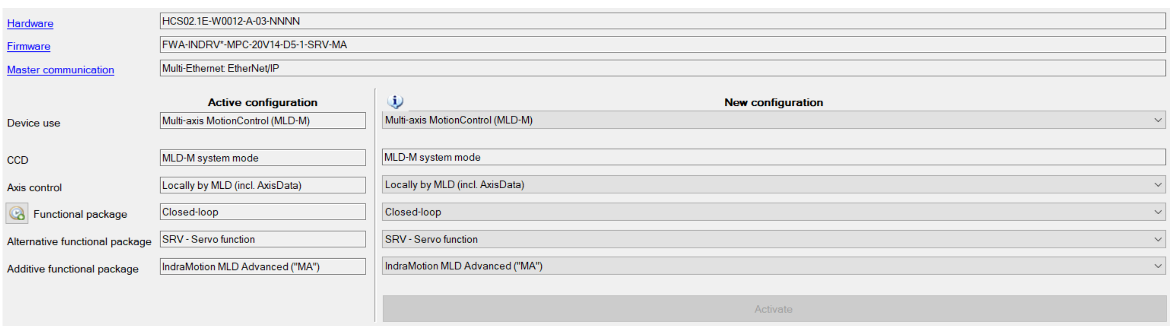


Figure 3.47 - Configuring the master for mult-axis motion

The slave must have its communication protocol set to SERCOS for CCD to work. The IP addresses also need to be configured for X24-25 for the master and slave using the same convention described earlier for the master's X26. CCD can now be enabled in the task window for the basic settings of CCD as shown in Figure 3.48. The master must also be set to MLD-M System Mode. The connection of a slave could produce additional errors, so trouble shooting may be required again.

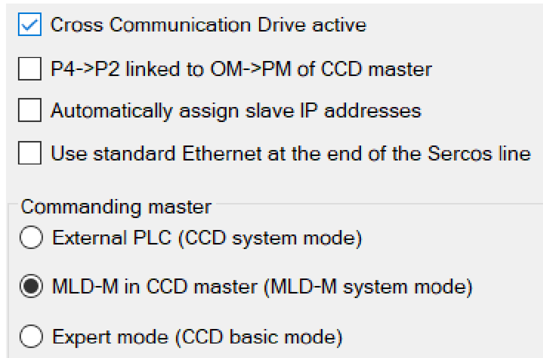


Figure 3.48 - Enabling CCD in the Basic Settings task window

With the commissioning complete, the status of both axis can be checked using MLD status, if both drives are error free and in operation mode, this window should appear as shown in Figure 3.49Figure 3.48. At this stage, drive can now have programs written to execute the required actions to emulate a flying saw.

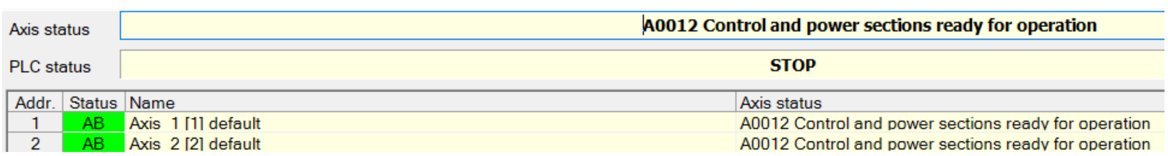


Figure 3.49 - MLD status for the master and slave drives

3.5.3. Programming Flowchart

For the programming of the flying saw, there is a need for consideration of the variety of motors used and the order they must be operated in. This last point is crucial for it to properly emulate a flying saw. To ensure the program is created exactly as intended, a flowchart was created to highlight the pseudo code and demonstrate the thought process. This flow chart is shown in Figure 3.50.

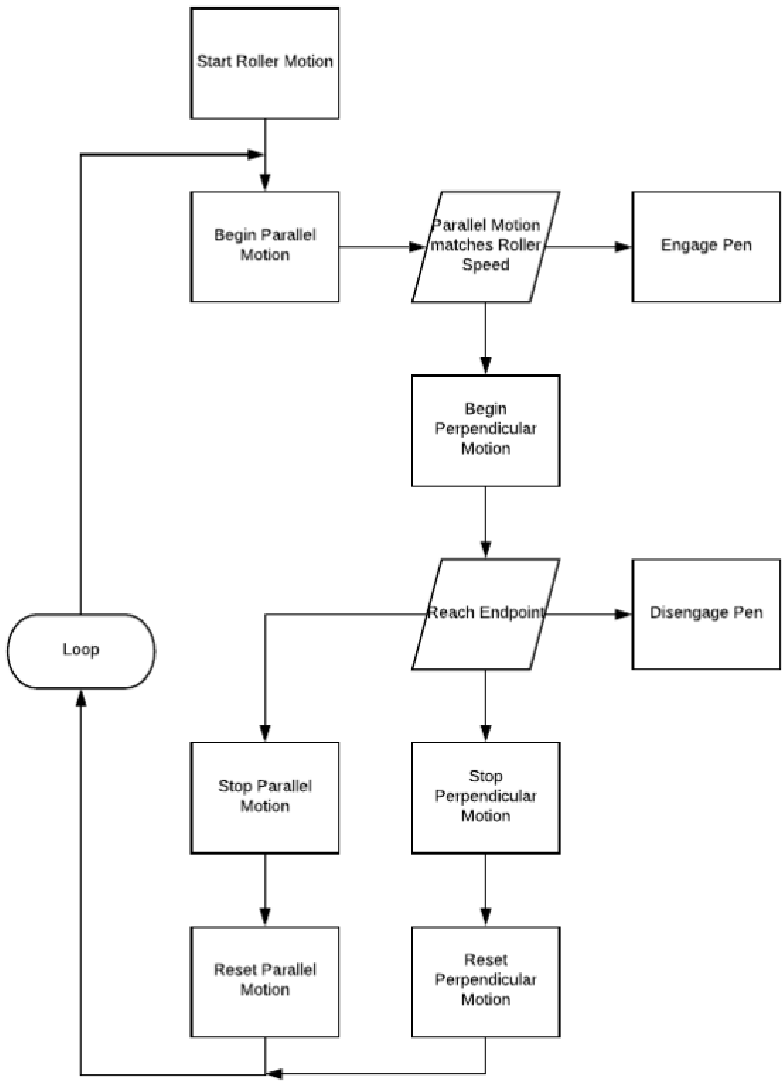


Figure 3.50 - Flowchart for the flying saw

The flying saw will first start by having the rollers get up to speed. After the desired value is reached, the motor controlling parallel motion will begin operating, bringing the carriage up to speed. Once the carriage speed has matched that of the roller, the motor controlling perpendicular motion will begin while the pen is simultaneously engaged to emulate the act of cutting. Once the endpoint is reached, the pen is disengaged while both motors stop and reset. This process will then repeat for the designated number of times.

3.5.4. Ladder Diagram

With pseudocode in the form of a flow chat, it can now be used to create the program. Programs are created by double clicking on Logic, this prepares the drive for programming. To create a program, right click on application, go to add, and select POU (Program Organization Unit). Within this window, the method programming can be selected from the implantation language drop down menu, as shown in Figure 3.51. Due to time constraints, only Ladder Diagrams will be used to create the program.

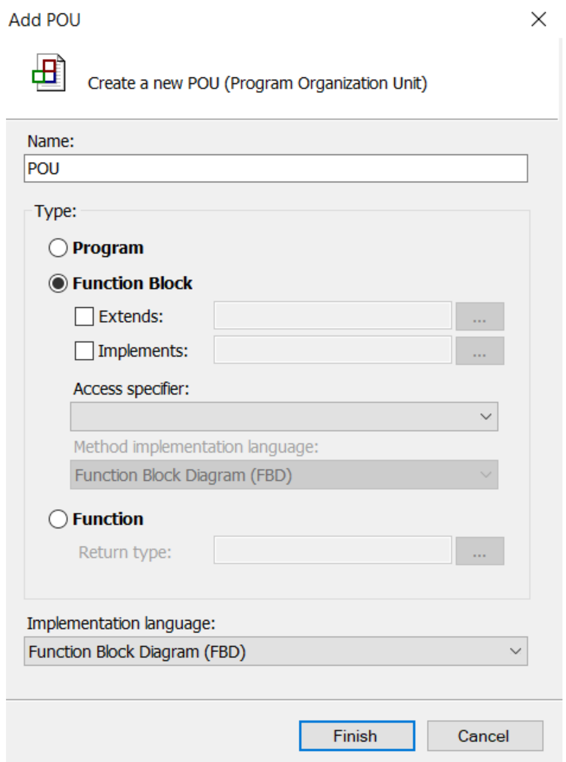


Figure 3.51 - Creating a POU to program in

Ladder Diagrams get their name from the fact that there are two vertical lines representing power, and they are joined by rungs of code. In IndraWorks, these rungs are generated by inserting networks, and these networks will have function blocks, simply called blocks, inserted in them. The function blocks control motion, power and can even be user defined. When a block is inserted, a window is opened that allows the user to choose from premade function blocks, for this application only the Motion blocks found in MX_PLCopen will be used, as shown in Figure 3.52.

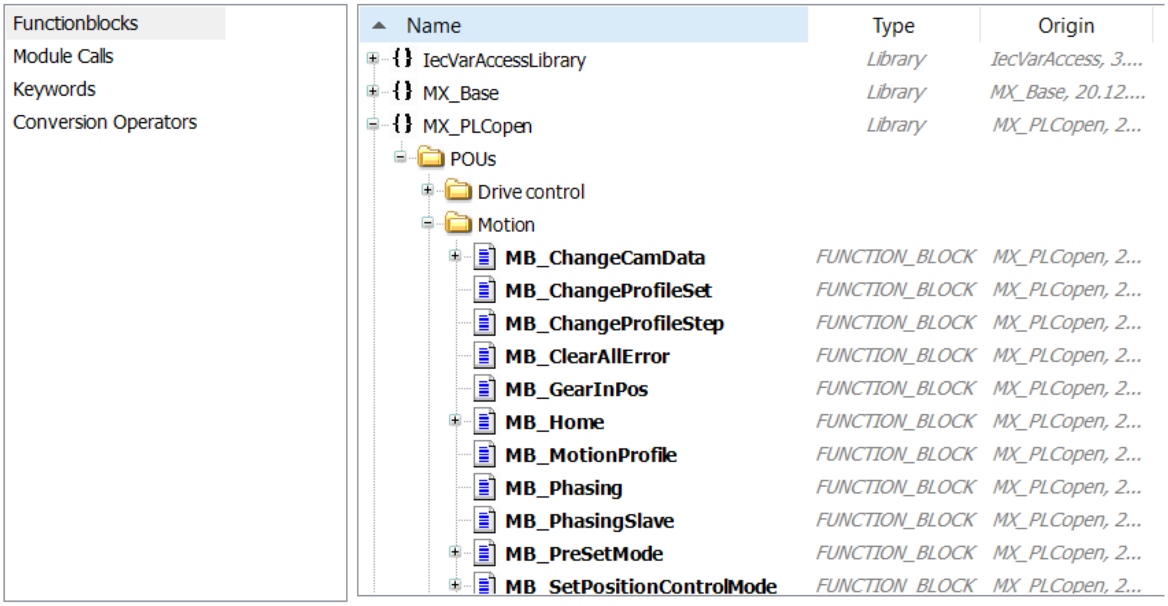


Figure 3.52 - Accessing the motion function blocks

For the Flying Saw, the only two function blocks used are MC_Power and MC_MoveRelative. The first two networks are simply used to provide power to both axes. The inputs and outputs for each function block must be set, which can be done simply through the Auto Declare window that appears when exiting each field. An example of this Auto Declare window is shown in Figure 3.53.

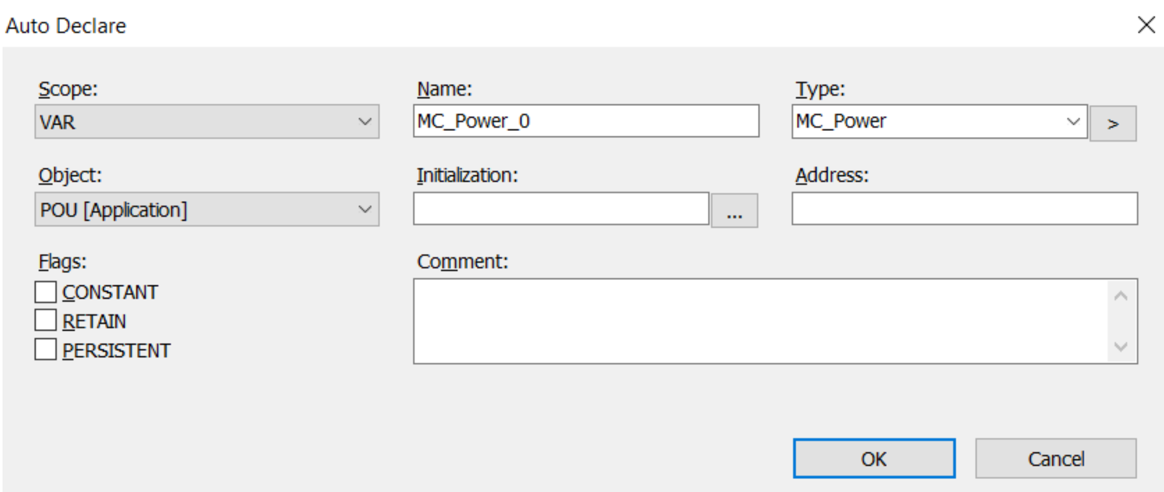


Figure 3.53 - The Auto Declare window which makes declaring variables a simple process

An example of these two function blocks is shown in Figure 3.54.

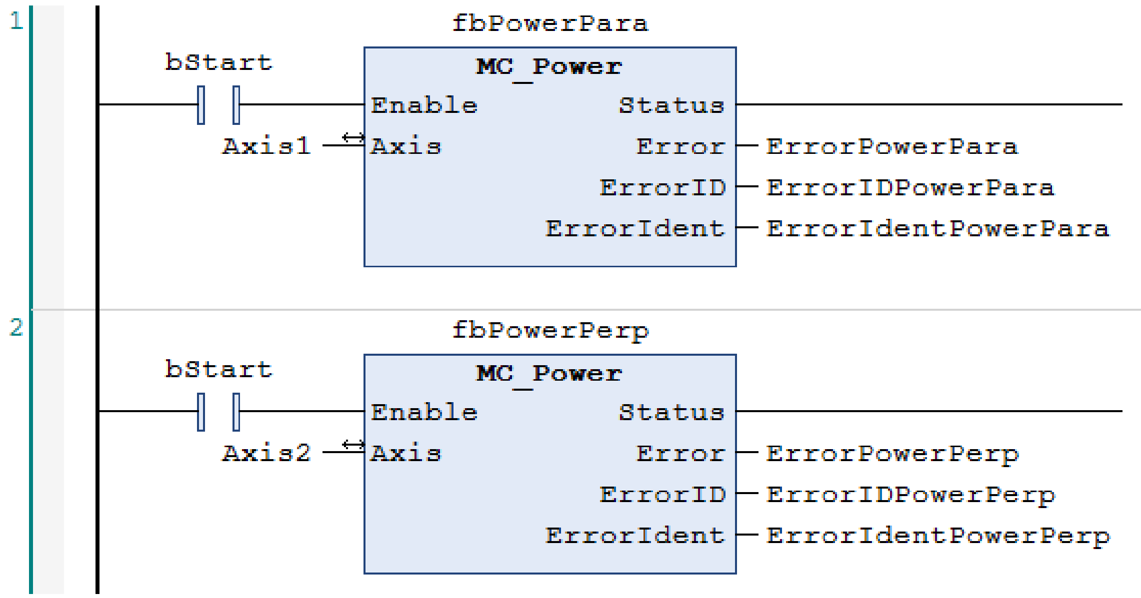


Figure 3.54 - The function blocks required to power both motors

Once power is supplied to both drives, motion can now be created. As a simple starting point, the motion will be created using MC_MoveRelative. MC_MoveRelative causes the motor to move a relative, set distance from its initial condition. To get the flying saw to motion through the two controlled axis, the outputs of the function blocks will need to be used as inputs for following motion commands. An example of this is shown in Figure 3.55. The perpendicular motion for this begins once the output from the initial parallel motion becomes true. This example program could be expanded to also perform an additional cutting action which returns the perpendicular axis to its original position.

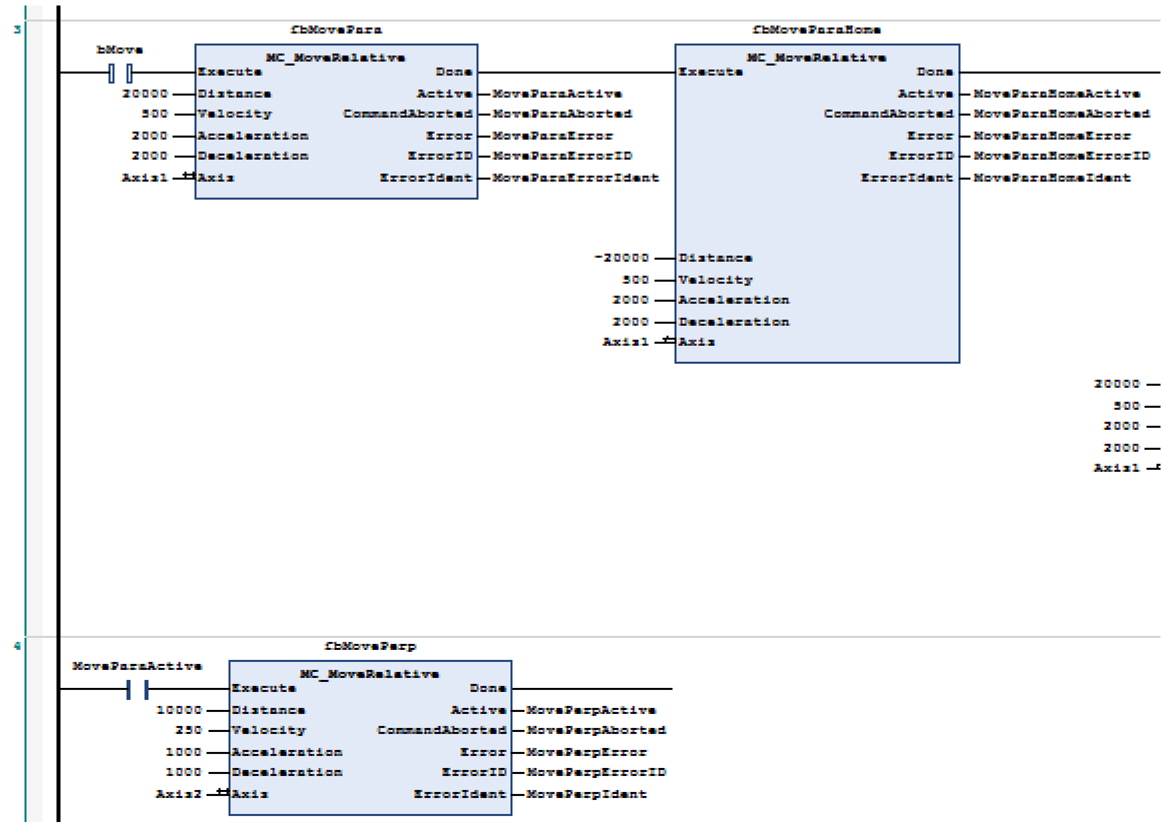


Figure 3.55 - An example of ladder logic being used to control parallel and perpendicular motion

3.5.5. Implementation of Additional Axes

The circuit board's function is to control the third and fourth axis of motion of the flying saw, which is the roller motion and pen's engagement with the cellophane. The roller motion is driven by a stepper motor via an EasyDriver and the pen engagement is driven by a 180-degree servo. An Arduino Nano is utilized to control the two motors, however it has been designed such that the Arduino can be removed and the extra set of pins (pin 6 in Figure 3.59) can be used to control the stepper motor via IndraDrive. These functions are controlled from the three switches and a potentiometer mounted to the top of the control box depicted in Figure 3.56

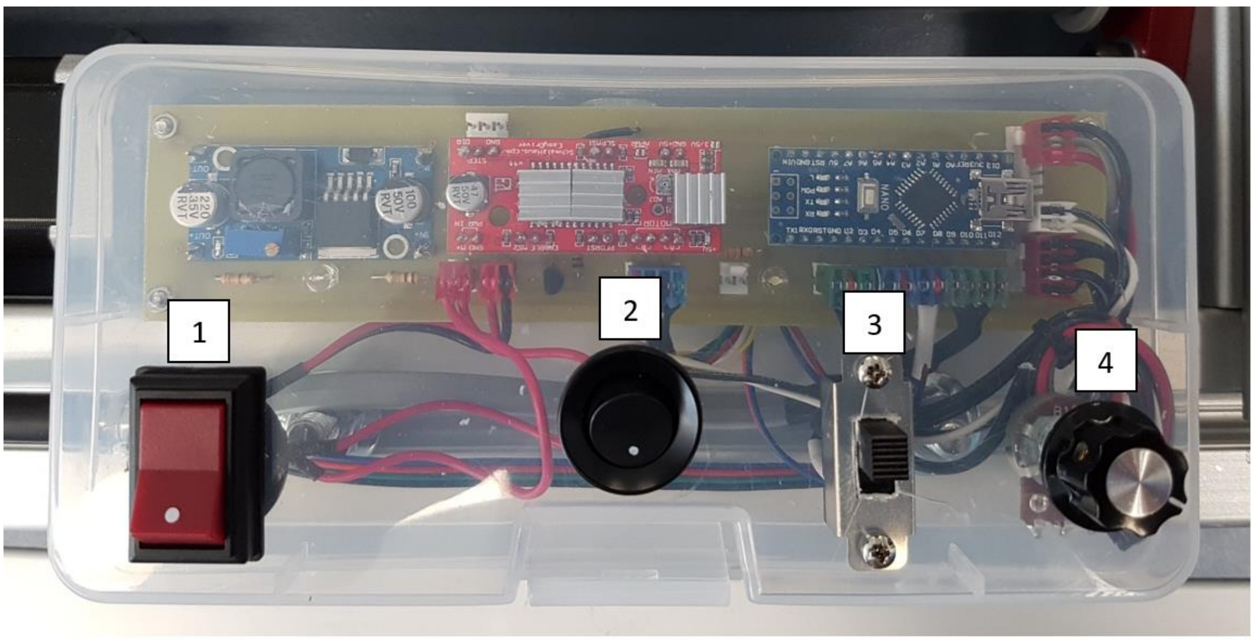


Figure 3.56 - Control Switches

Four limit switches have been incorporated into the ends of the parallel and perpendicular lead screw limits. These switches can be implemented in one of two ways:

By connecting the four pairs of wires (one pair per limit switch) to the Arduino. In this configuration, if any of these limit switches are triggered, a white led will illuminate on the circuit board (as seen in Figure 3.58) and the two pins beside it will change from 0 to 18 volts. This single signal can then be sent to the IndraDrive unit through the I/O and coded to halt the program.

Alternatively, the four pairs of wires from the limit switches can be directly connected to the I/O ports on the IndraDrive system which gives more precise information on what axis has encountered which limit specifically.

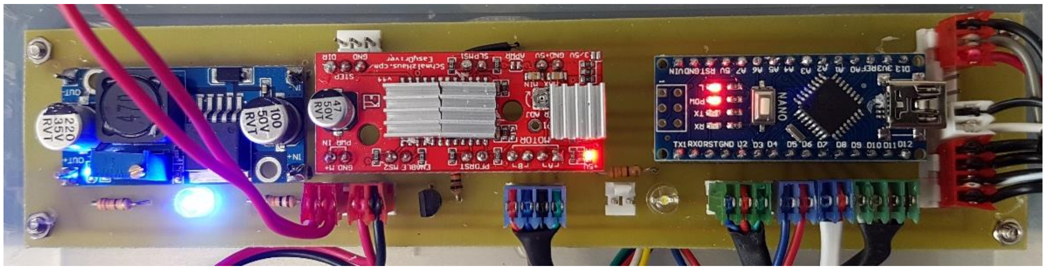


Figure 3.57 - Circuit Board Powered (Regular Operational Mode)

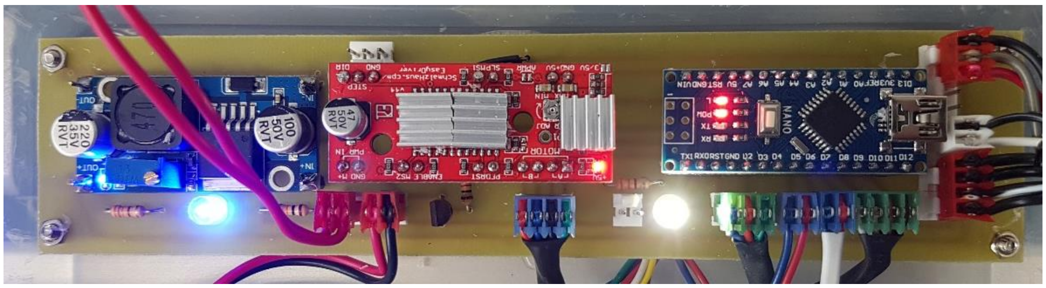


Figure 3.58 - Circuit Board Powered (Limit Switch Activated)

The connections to the circuit board are outlined in Table 3.7 below, where the connection number corresponds to the numbers found on Figure 3.56 and Figure 3.59.

Connection Number	**Number of Pins Used**	**Description**
1	2	Power switch
2	2	Activates pen effector up or down
3	4	3-position switch (Forward-Float-Backward)
4	3	Potentiometer – Controls speed when switch 3 is in position forward or position backward
5	2	19V power line
6	4	Stepper Motor
7	3	Pen effector Servo
8	8 (2x4)	Four Limit Switches
9	2	Optional pins to read position of the potentiometer (Signal and Ground pin)

10	3	To externally drive to stepper motor using easydriver but without Arduino (position, step, ground)
11	2	19V signal pins to alert Indradrive of Limit switch activation (Led will illuminate)
12	0	Blue light to indicate healthy 5V signal supplied to components

Table 3.7 - Circuit board connection descriptions

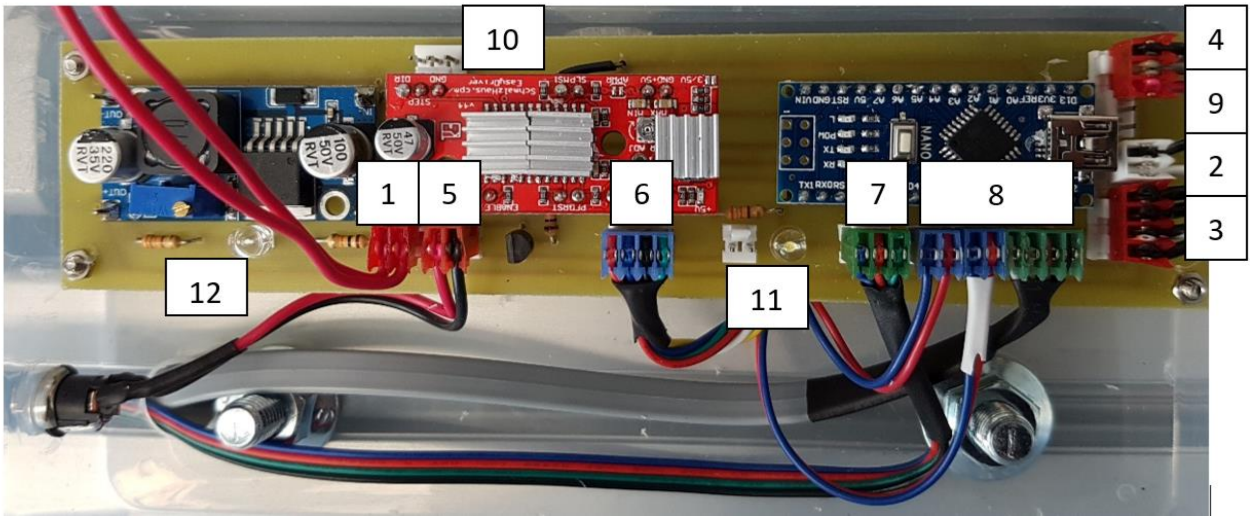


Figure 3.59 - Circuit Board Layout

3.5.5.1. Transfer Functions

The linear velocity of the cellophane varies between 0 and 180RPM as the potentiometer goes from 0V to 5V. Thus a transfer function can be created to determine the resulting roller velocity and corresponding RPM of the other axis required to make a proper cut.

$$Voltage(TF)(N)(\pi D)\left(Lead_{parallel}\right) = RPM_{parallel}$$

$$\left(RPM_{parallel}\left(Lead_{parallel}\right)\left(\frac{1}{l_{parallel}}\right)\right)^{-1} = Cut\ Time[min]$$

$$\left(Cut\ Time\ [min]\left(\frac{1}{l_{Perpendicular}}\right)\left(Lead_{perpendicular}\right)\right)^{-1} = RPM_{perpendicular}$$

Variable descriptions and original values are described in Table 3.8 below.

Symbol	Value	Description
Voltage	N/A	This is the voltage detected by the analogue to digital converter corresponding to the potentiometer.
TF	$\left(\frac{\frac{180rev}{min}}{5V}\right)$	This is the transfer function coded into the Arduino to convert voltage to stepper motor RPM
N	$\frac{1}{2}$	Toothed belt gear ratio between stepper motor and roller
D	29.31mm	Diameter of roller
$Lead_{parallel}$	$\left(\frac{8mm}{rev}\right)$	Parallel motion lead screw lead
$RPM_{Parallel}$	N/A	The RPM the parallel motion motor needs to be set to
$l_{parallel}$	510mm	Total length of travel for the parallel motion
$l_{perpendicular}$	210mm	Total length of travel for the perpendicular motion
$Lead_{perpendicular}$	$\left(\frac{5mm}{rev}\right)$	Perpendicular motion lead screw lead

$RPM_{perpendicular}$	N/A	The RPM the perpendicular motion motor needs to be set to.

Table 3.8 - Roller motion transfer functions variables

Chapter 4 - Reliability

4.1. Failure Modes and Effects Analysis (FMEA)

This section looks into potential modes of failure of the 3-axis servo trainer at a design-level, using the FMEA method. The criteria pertaining to Severity, Occurrence, and Detection, is outlined in Appendix D.1, D.2, and D.3.

The project has two critical functions relating to the flying saw: Linear motion (both Parallel and Perpendicular) and Roller motion. The FMEA analysis of these components can be seen in Table 4.1 - FMEA Analysis.

All our RPN (Risk Priority Numbers) fall below our organizations' 500 immediate action criteria, however, we recognize that our critical concerns are with:

- Parallelism of our two guiding rails
- The alignment of the rollers
- The roller profile.

These are potential failure causes with the highest corresponding RPN values. They were watched throughout the design process to minimize the occurrence of their corresponding failure modes.

FAILURE MODE AND EFFECTS ANALYSIS

Item:		Responsibility:	Curtis From	FMEA number:	1
Model:		Prepared by:	Matt Vickars	Page :	1 of 1
Core Team:	Curtis From, Matt Vickars, Dean Tamboline			FMEA Date (Orig):	2018-03-20 Rev: 1

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results: Actions Taken	Sev	Occ	Det	RPN
Linear Motion (Parallel)	Binding	Loss of function	8		Loose driven side, tight following side	4	Prototype Tests	2	64	Tighten driven side, Widen carriage contact points, Loosen following side	Dean Tamboline, May 216, 2018					0
					Rails out of parallel (assembly)	9	Measuring Stick	2	144	Create alignment jig	Matt Vickars, May 19, 2018					
	Slop	Inability to draw a straight line	5		Loose driven side, loose following side	5	Prototype Tests	2	50	Reduce tolerances on guide components	Dean Tamboline, May 16, 2018					0
	End stop collision	Broken mounts	7		Coding Error	6	Field testing	2	84	Have team step through coding to ensure logic	Matt Vickars, May 19, 2018					0
					Encoder Failure	1	Trusting Bosch	8	56	None at this time	N/A					0
Roller Motion	Cellophane tears	Loss of function	8		Over tightened during manufacturing	5	Field testing, spring tensioning prototype	2	80	Continue with spring loaded proof of concept	Curtis From, May 20, 2018					0
	Cellophane tracks off rollers	Damage to cellophane	6		Rollers out of alightment	7	Field testing	4	168	Create alignment jig, Profile roller for self alignment	Matt Vickars, May 19, 2018					
					Roller not machined with proper profile	5	Prototype Tests	7	210	None at this time	N/A					0
	Cellophane slips	not able to perform flying saw function	3		under tightened during manufacturing	5	Field testing, spring tensioning prototype	2	30	Continue with spring loaded proof of concept	Curtis From, May 20, 2018					0

Table 4.1 - FMEA Analysis

4.2. Fault Tree Analysis (FTA)

The fault tree analysis investigates all the potential failure modes and associated causes that would yield a symptom of the system's cut-line not being perpendicular to the material. This symptom is very ambiguous and has many causes that could lead to it including, electrical, physical, and manufacturing issues. The fault tree can be seen below in Figure 4.1 and Figure 4.2.

No Cut-set or Path-set analysis was required since all the logic operators used were ORs. This effectively means that any of the causes at the bottom of the tree will directly result in the issue of the drawn line not being perpendicular to the material. Due to a lack of data regarding the probability of failure of each cause, we are unable to conduct a quantitative analysis of the fault tree.

The realized causes from the fault tree analysis were considered and referred to throughout the design process to design around and minimize the potential for as many of the effects as possible.

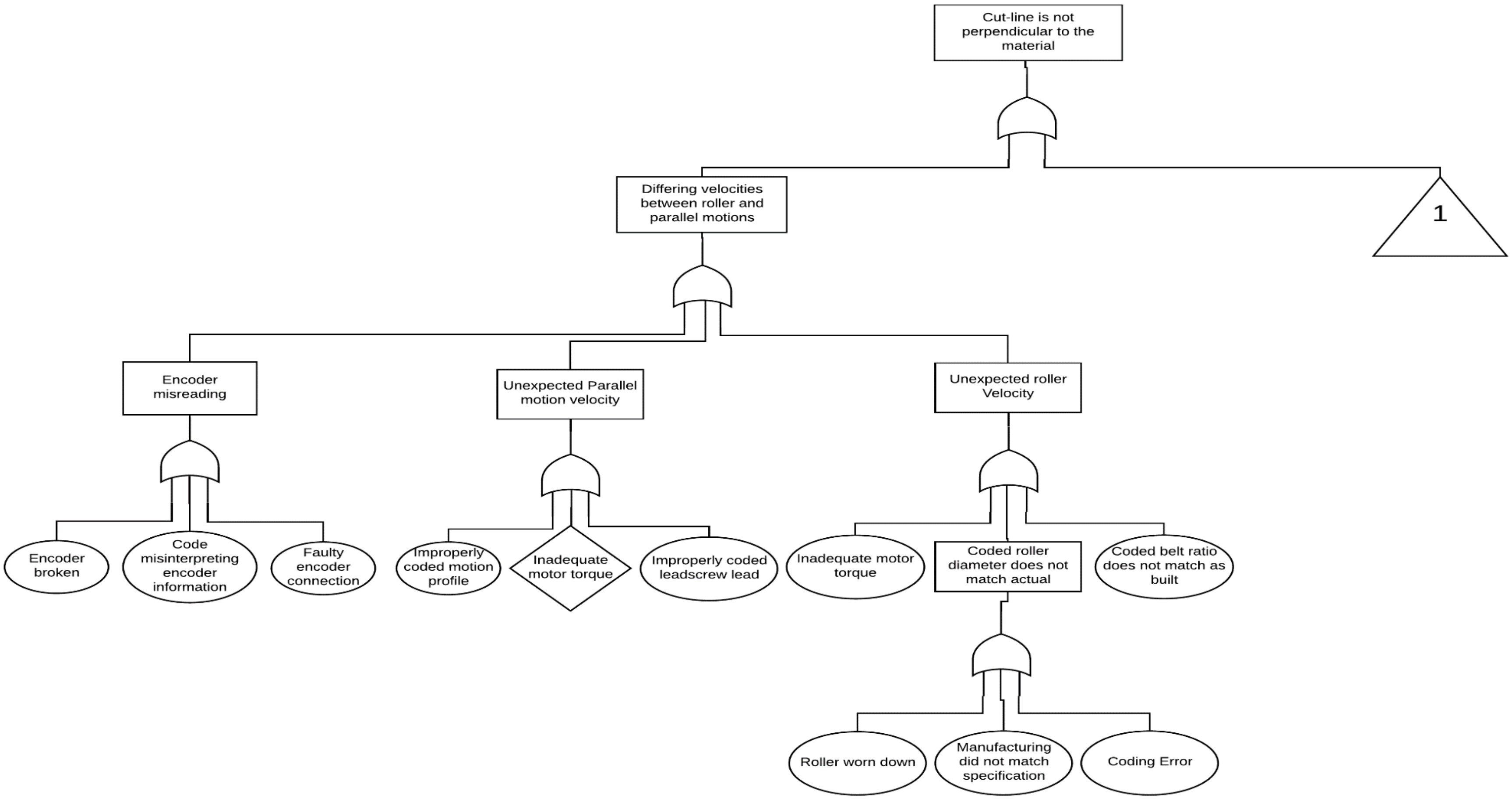


Figure 4.1 - Fault tree analysis (page 1)

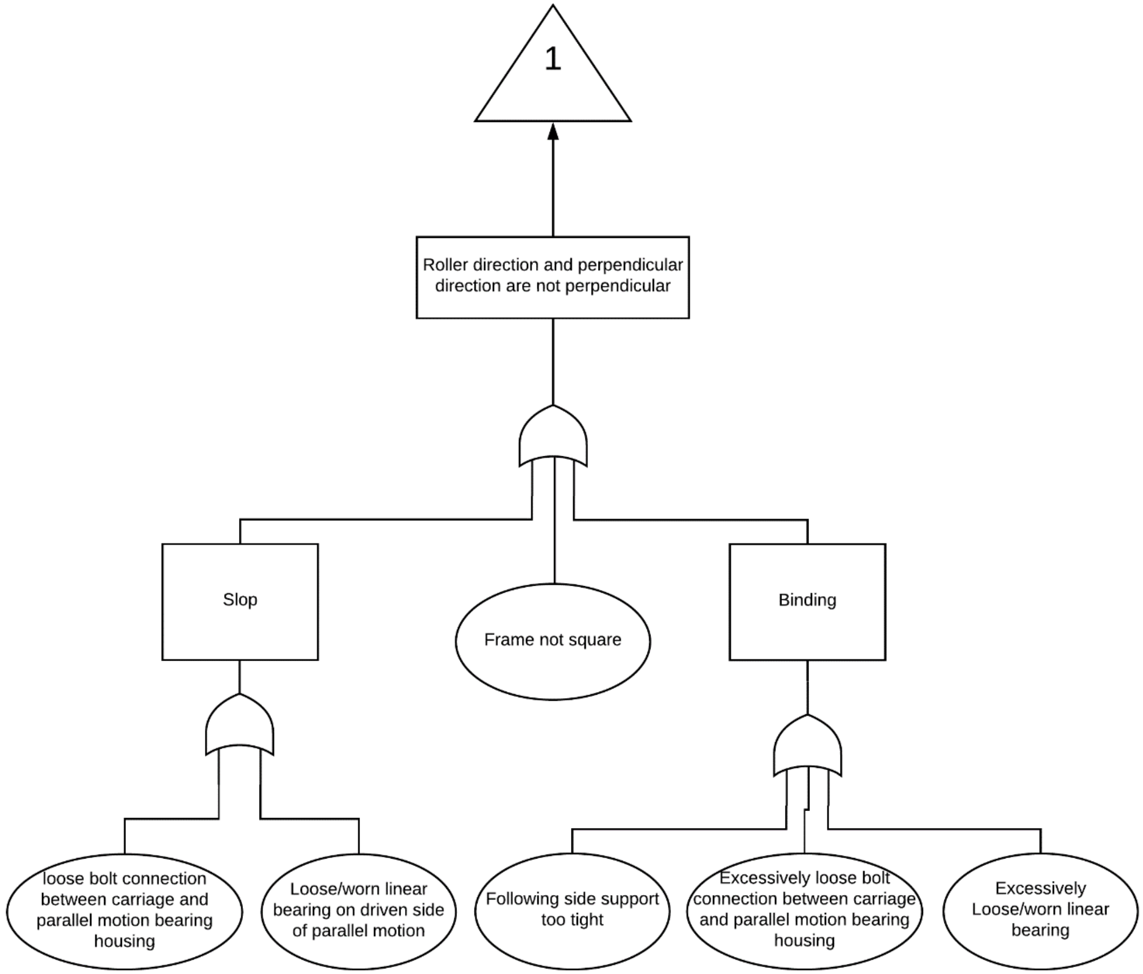


Figure 4.2 - Fault tree analysis (page 2

Chapter 5 - Learning Challenges

5.1. Wiring Diagram Issues

Ultimately, we would like to see something like a printer "easy setup guide" for a given Bosch Rexroth product to make it more user-friendly. The group found the documentation for the IndraDrive Cs system convoluted, overly complicated and generally fragmented, requiring multiple resources to obtain a complete outline. In addition, tracking down the correct manual proved tedious and sometimes impossible.

5.1.1. Port X3

Available IndraDrive manuals clearly describe how to connect port X3 for three-phase power (typical of industrial application), there is however little documentation for single phase. The groups were able to deduce proper wiring of X3 but we were unable to find any documentation that explicitly stated a method.

5.1.2. Port X47

Port X47 was the source of great confusion for both groups. One group interpreted the mention of a "Bb relay contact" such that it should be connected from control lines to a relay that terminated power to the system.

With both groups working together, X47 was simply connected to the 24V DC supply under the idea that it was simply checking the availability of the supply voltage. This too was flawed and would have caused a short circuit in the system.

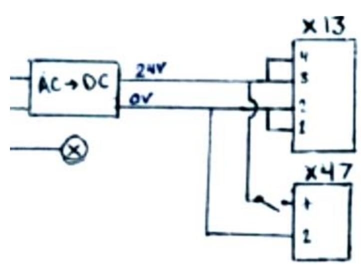


Figure 5.1 - Flawed connection of port X47

After consulting our sponsor, Greg Filek, we were enlightened that X47 is simply a health check, typically used for PLCs. Our application will not be using a PLC system but X47 must be connected regardless. Greg suggested that we may connect a light to it to show the health status of the drive to the user (personal communication, Greg Filek, November 15, 2017). When the light is "On", the system will be notifying the user that the drive is healthy.

5.1.3. Port X49

The IndraDrive Cs manual, states that port X49 is optional safety technology for the Safety On Board features. With no other resources found on the port and the manual's use of the word "optional", both groups decided that the port did not need to be wired until the feature would be used. Greg Filek informed us that X49 is indeed for safety onboard but must be wired for the system to output to its drive.

5.1.4. PORT X13

We initially wired this port on intuition with +12V going to port 2 and -12V to port 1, tracking this down due to short-like symptoms. Though proper wiring is clear in the manuals, we find ourselves wondering why these ports aren't simply labeled +V and -V.

5.2. IndraSize

The software is outdated and hard to navigate. When I attempt to leave a page by going to the "home" icon, it will not allow me to and a pop-up window tells me to "kindly select the product step by step". It turns out you must scroll down a very small increment to the cancel icon at the bottom. Although it should be able to fit the whole page when put it into full screen, the working panel does not change size and white space is simply added.

During the drive selection process for an axis, the save option opens a window that saves the axis as an .ipl file. From the "Start Project Manager" page, the same axis will save as an .isa file instead. I believe that one of these saves the file as an axis and the other as a project but was unsure about what to save as.

Entering working parameters of an axis to determine the appropriate motor was hard to navigate as well. Once entered, I noticed that some of the selection boxes were there for you to select a motor yourself, whereas I expected that providing it with a working torque would provide me with suitable motors. Instead, once I selected a motor (that may or may not be suitable for the axis) the software told me the drives that are compatible with it.

5.3. Alpha Prototype switch box

The switch box for the Alpha Prototype is intended to allow the end user to use a variety of switches to control aspects of the final product. One switch could, for example, cause one motor to jog at a pre-determined speed, while another would cause a different motor to go to its home location. There are also LEDs that would provide feedback to the user as well a potentiometer that could be used to dial in a motor to a certain speed. The completed switch box is shown below in Figure 5.2.

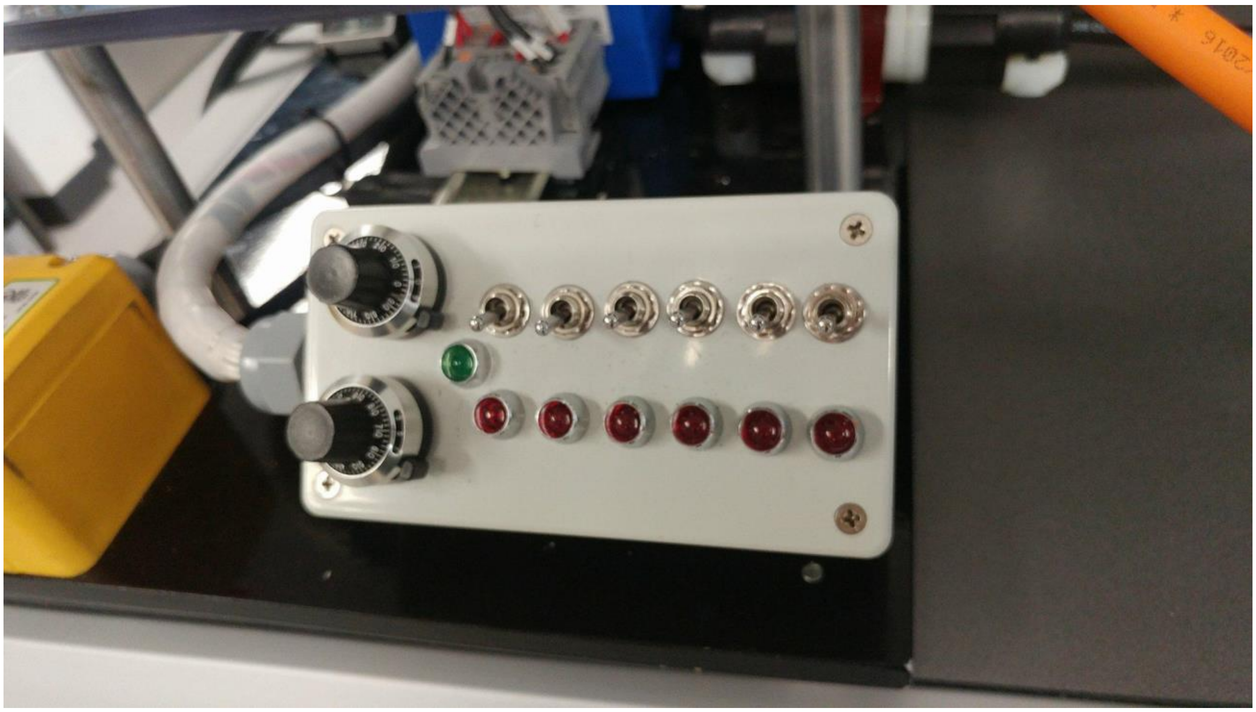


Figure 5.2 - The switch box for the Alpha Prototype

Unfortunately, getting the switch box to full functionality has been a difficult task. To start out, when the switch box was initially connected to the drive through the I/O ports, nothing happened; flipping switches would produce no signal that the drive could detect. This was monitored through IndraWorks status window for inputs and outputs shown in Figure 5.3. However, the drive was detecting a change in voltage for the potentiometer, but the range it went through was magnitudes smaller than what was expected.

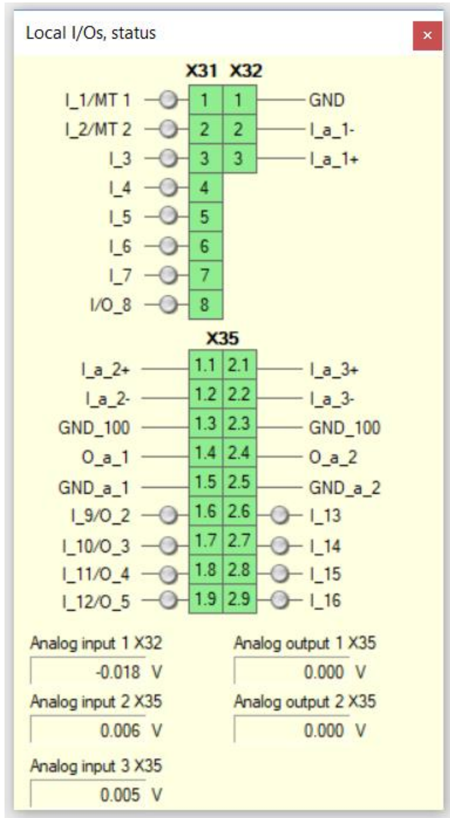


Figure 5.3 – Status window of Inputs and Outputs in IndraWorks

To trouble shoot this problem, additional testing was needed. During this testing, the drive did receive some signals from the switches, but there was little logic as to when it would work, and when it would not. When one switch was flipped on its own, it behaved exactly as expected. But as soon as multiple switches were flipped, it would only receive all the signals some of the time, and when all six were flipped, some of the signals would disappear.

To try and understand what was happening, a multi-meter was used to verify there was a sufficient voltage going to the switch box, which there was. Then came the process of checking the voltage during each switch flip. It was then that it was realized the switch box was incorrectly wired. A schematic of the wiring is shown in Figure 5.4.

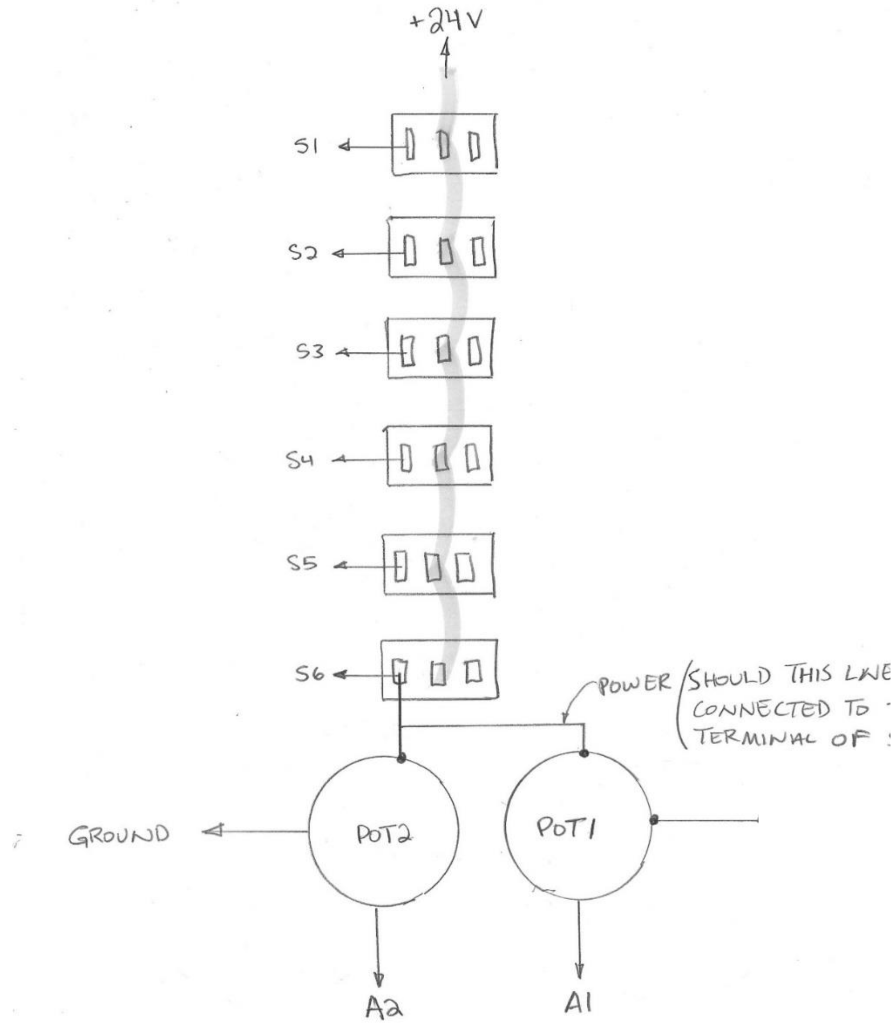


Figure 5.4 - Wiring of the switches within the switch box

The problem was that the 24V wire connected to the middle terminal of the six switches also needed to be connected to the two potentiometers. This was causing the signal to behave unexpectedly. After re-soldering the connection, the multi-meter was reading that the switches were working as intended, but the drive was still not receiving the signal as expected. There was also still the problem that the potentiometers were not producing the expected voltage range. In addition, the sixth switch had the 24V signal running to the wrong node, and caused that switch to enable or disable power further down the line.

At this point, the project was given back to the sponsor, Greg Filek, as this problem was beyond the expertise of the team. Greg did more troubleshooting and concluded that the control board of the master drive had been fried, potentially due to the drive having the I/O being wired incorrectly, or that it tried to send and receive a signal through the same port.

5.4. Power for Slave Drive

Providing adequate power to the slave drive proved to be a challenge. Initially, the drive was assumed to be an HCS01.1E-XXXXX-A-02 drive, which was consistent with the drive that the other Bosch Rexroth received. This drive only requires 1-phase AC between 110 and 230V. With this assumption, the drive was wired to provide it with 120V AC.

Under this wiring configuration, the drive produced error F2816 - Softstart fault power supply unit. This error indicated there were problems with the DC Bus Voltage, a problem with the main voltage, or the drive was defective. After consulting with Greg Filek and Peter Gu, a Bosch Rexroth Application Specialist, it was revealed that our drive was actually an HCS01.1E-XXXXX-A-03, meaning it required 3-phase AC between 200 and 500V. Peter also mentioned that this drive could be 'tricked' into thinking it received 3-phase, when it in fact only received 1-phase power. This could be achieved by selecting Converter in invertor mode in the Power Supply dialogue for the slave as shown in Figure 5.5.

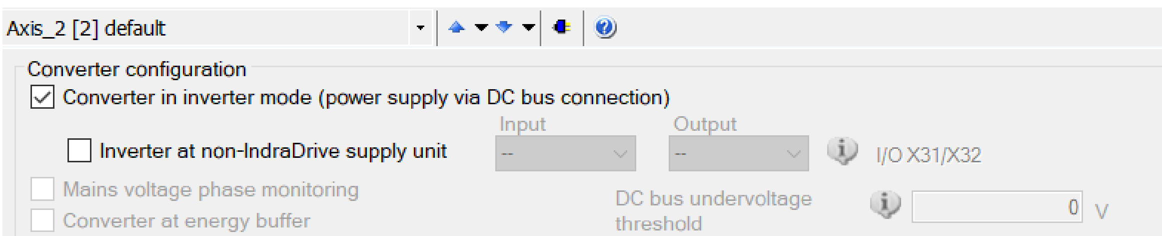


Figure 5.5 – The 'trick' for pretending 1-phase AC is 3-phase AC

With the wiring changed to provide the higher voltage, and the 'trick' implemented, the slave was booted up only now, it produced a new error F2818 - Phase Failure. This error referenced main voltage again, which points to the 'trick' not working.

To get past this new error, a new work around was found. When the slave is booted up, go to the same Power Supply dialogue shown in Figure 5.5, except deselect both Converter in inverter mode and Mains voltage phase monitoring. Deselecting the phase monitoring provides a warning, which is accepted. Once this is done, start easy startup mode and clear the error. This will clear the error and bring the drive to A0012 - Control and power sections ready for operation.

5.5. IndraWorks

Working with IndraWorks proved to be a difficult obstacle in the way of completing this project. There were two versions of IndraWorks used, IndraWorks DS and IndraWorks Engineering; the Engineering version was the source of trouble and henceforth, all mentions of IndraWorks refers to the Engineering version.

IndraWorks itself is an enormous program with an enormous potential due to the vast amount of functionality. This represents the first learning challenge however, as such a large program requires significant time to learn and familiarize oneself with. Learning what parameters are, which ones can be changed, and how they interact with each other was an ongoing process. Additionally, learning how to navigate the program and where to access specific dialogues took significant time as well.

5.5.1. Internet Protocol

The first challenge associated with IndraWorks was learning and configuring Internet Protocols (IP) as this is required to connect IndraDrive with IndraWorks. Greg Filek initially explained the process, but it still took time to become familiar with. The IP addresses used by the computer and the master drive are shown in Figure 5.6 and Figure 5.7, respectively.

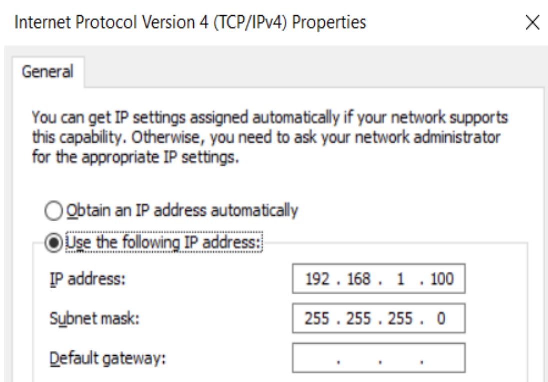


Figure 5.6 - The IP configured for the computer

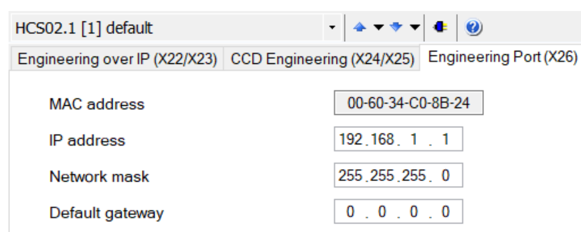


Figure 5.7 - The IP address of the master drive

5.5.2. Cross Communication Drive

The Cross Communication Drive (CCD) is what allows the master drive to communicate with the slave. For this to become active, the master first needed to be configured using the functional package for Multi-Axis Motion Control (MLD-M) and the slave needed to be set to SERCOS as its communication protocol, after which CCD could be enabled.

Achieving communication between slave and master using CCD was a major challenge at first, primarily due to the lack of available documentation. Greg Filek provided a document initially, but the document was for MLC drives, whereas the drives provided used MLD. The difference between these two types of drives is quite substantial, which rendered this document useless. Additionally, documents to help initiate this process were difficult to find using the Bosch Rexroth website's Media Directory as there was nothing listed under Tutorials and Learning Materials shown in Figure 5.8.

Figure 5.8 - The lack of available learning materials on Bosch Rexroth's website

In order to find documents that would help with learning, Google was used instead. Google searches resulted in the Getting Started – R91131930 document dedicated to MLD, but it was from 2006 and referenced a much older version of IndraWorks.

Through the use of this document and the examples contained within, progress was slowly made. Some of the issues encountered during the process of enabling CCD were the address of slave and drive, as well as the parameters for CCD. The issue regarding the addresses was due to both the master and slave having the same address; it took some time to understand these addresses corresponded the number displayed on the control panel of the drive, and it was not their IP address. The parameters related to CCD ranged from P-0-1600 to P-0-1999, and some of these parameters needed to be configured. An example of this was parameter P-0-1601 and P-0-1603 which referenced the address of the slave. Initially, the values within the parameters did not match, but they needed to be for the slave to fully connect to the master. The corrected parameters are shown in Figure 5.9 and Figure 5.10.

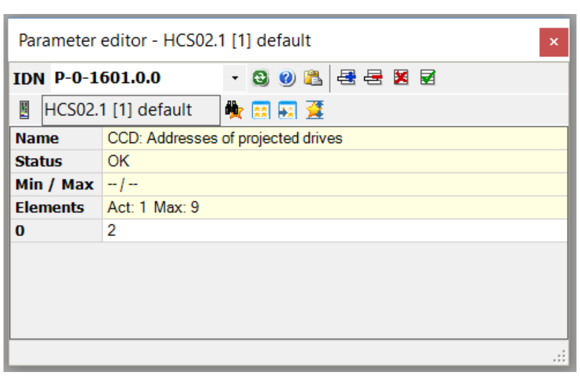


Figure 5.9 – Parameter P-0-1601

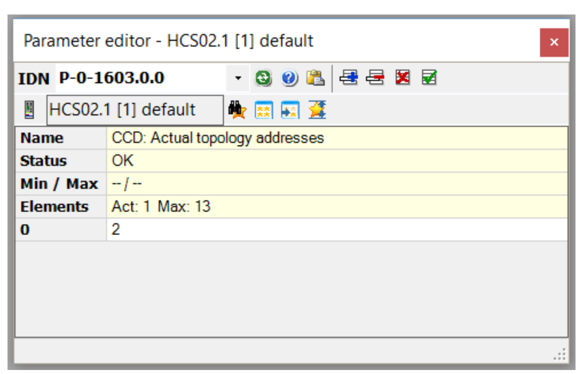


Figure 5.10 – Parameter P-0-1603

Even after having all the parameters set up and the master and slave connected for the first time, there were still issues associated with CCD. The Getting Started document described how CCD could be used to map any I/O signals from the slave to the master, since the master's I/O no longer worked. The document described this being done through the I/O Configuration, shown in Figure 5.11, and would allow for any peripherals of the slave to be used by the master.

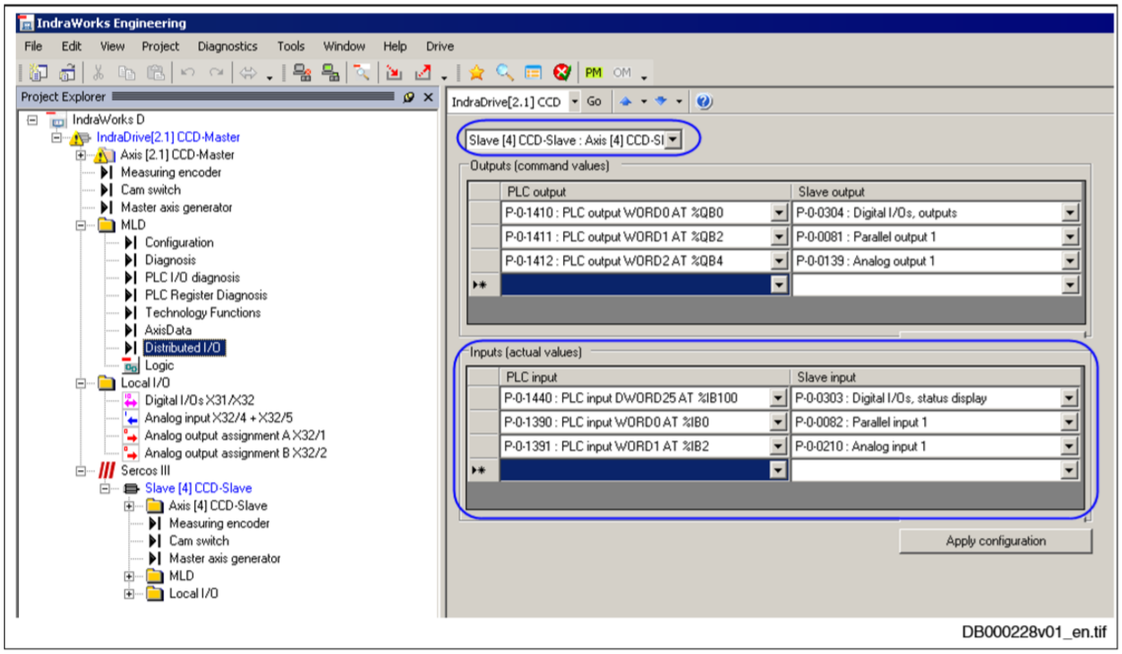


Figure 5.11 - The I/O Configuration dialogue

This dialogue did not appear to exist in the current version of IndraWorks. However, a look alike was found in the Free Process Data dialogue and is shown in Figure 5.12. Even though they did appear to do the same function, the team could not get the slaves peripherals to be copied to the master using this and have not been able to find another method of doing so.

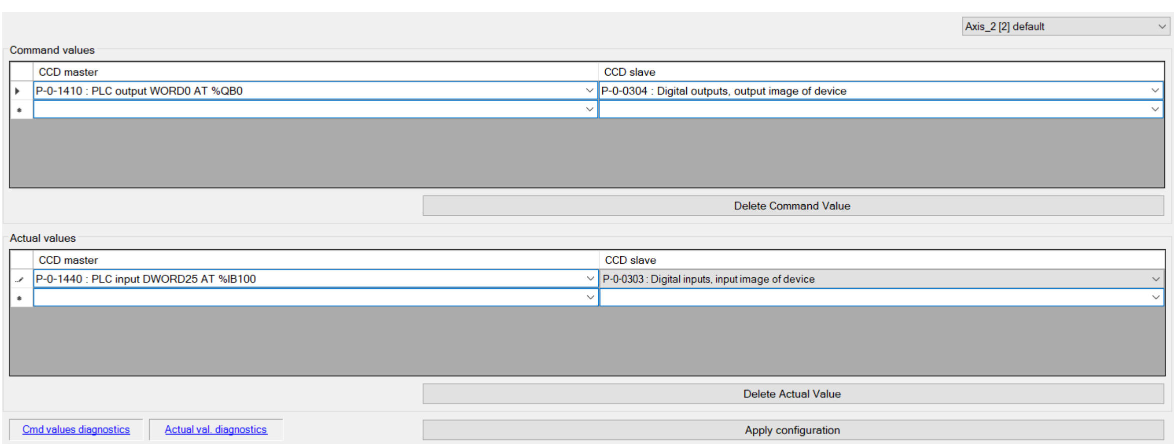


Figure 5.12 - The Free Process dialogue

5.5.3. Programming

There was a multitude of learning challenges associated with programming IndraWorks. The first of these was simply how difficult it was to actually start programing. The fact that the project tree had to be navigated to Logic, which then had to be double clicked to activate this key feature is unintuitive and was only discovered after using the Getting Started document mentioned earlier.

A major challenge associated with programming was the process associated with creating a new program. This was done by right clicking application, and adding a new Program Organization Unit (POU). Everytime a new POU was added, more and more of the window would dissappear, until nothing remained. This appears to be a very serious bug, as this seems to be the only method to actually create a program. An example of this is shown in Figure 5.13.

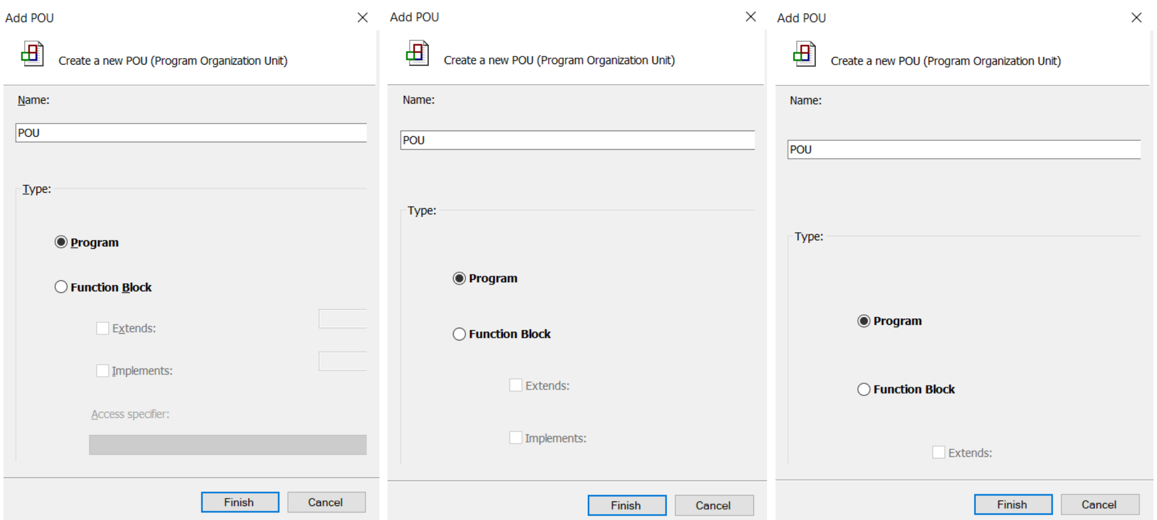


Figure 5.13 – The bug associated with adding a POU causes the available fields to disappear

The language required for programming in structured text was also a learning challenge, as it is done using CODESYS V3, which was a brand new language for the team. This meant learning the syntax required and involved learning how the different function blocks were used for programming.

5.5.4. Troubleshooting

Any troubleshooting that needed to be done through IndraWorks was a lengthy and complicated process, mostly due to the lack of information available. To start, there are a plethora of potential error codes and each of these error codes can correspond to a variety of potential causes. Bosch Rexroth did not appear to have any document on their Media Directory for these error codes, so Google search was instead relied upon again. A Google search produced the Trouble Shooting Guide – R911297319, which contained a better description of error code and even included potential causes and remedies. Without this document, trouble shooting would have been impossible.

Trouble shooting the function blocks used for programming was rather difficult at times. When the function block produced an error, it would refer to an error table. Finding these tables was unintuitive as the error simply mentioned a table, but there was no mention of where to find these tables. This took lots of searching until the tables were discovered within the parameter description window. Even after knowing where to find the tables and searching for them in the parameter description window doesn't yield the best results. A prime example is when the INDRV_Table is searched for, and its exact name is used, it's listed as the fourth result which makes it easy to miss. This is shown in Figure 5.14.

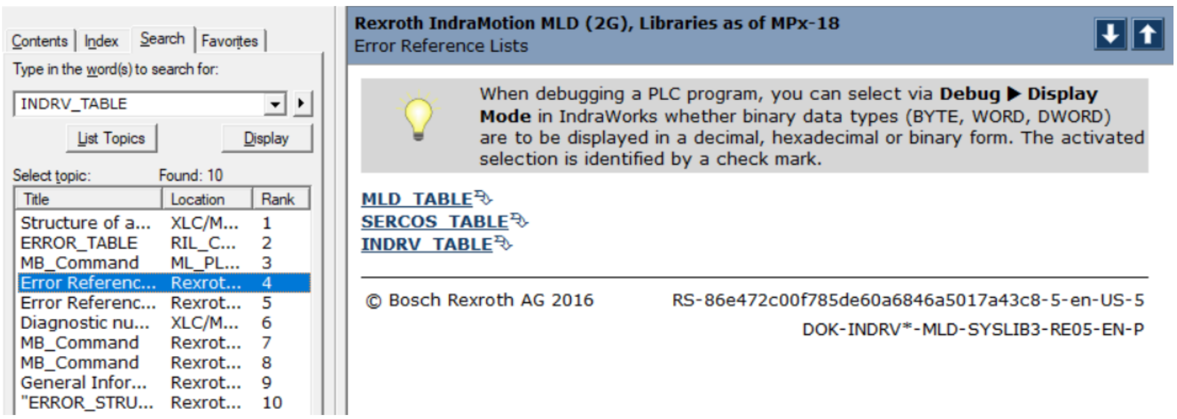


Figure 5.14 – The unintuitive search results for error tables

In addition to the tables being difficult to find, the INDRV_Table was not a helpful reference for trouble shooting errors. As shown in Figure 5.15, the table isn't actually a table, and instead refers the user to separate document. There is no description of how to access this document and searching through Bosch Rexroth's website and using Google searches provided no such document.

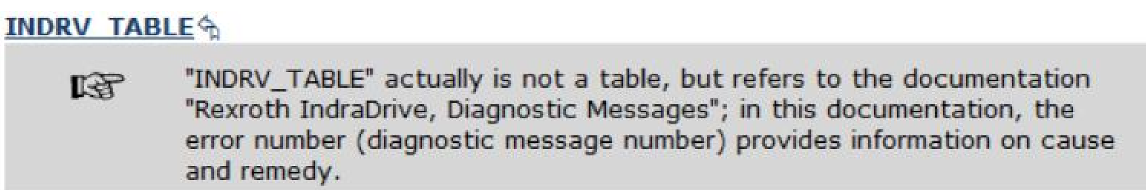


Figure 5.15 – The INDRV_Table

Searches in the parameter description window for Rexroth IndraDrive, Diagnostic Messages also proved futile as it only brought up results for either diagnostics or messages, and nothing for the combination of the two.

5.5.5. *Other IndraWorks Challenges*

Another rather interesting challenge with IndraWorks arose after communication between the slave and master was initially achieved. What happened is, the master cannot be found by searching for device while the slave receives control voltage. Even when the drives are not connected by an Ethernet cable, this problem persists. The exact cause of it is undetermined due to difficulty associated with trouble shooting when the drive is not connected.

Once the slave has no control voltage and nothing else has changed, the master is found by IndraWorks and functions normally. At this point, the control voltage could be supplied to the slave, which will also work as intended.

The Parameter Description window also proved to be quite difficult to navigate due to the sheer number of parameters available. This made it incredibly difficult to look for a single parameter description through navigation, and often the search function returned a multitude of results that were sometimes just as difficult to sift through. There were even occasions where this window was blank apart from a single link to another parameter description and had no other useful information. It would have also been ideal to have multiple parameter descriptions open to enable side by side comparisons, rather than simply relying on memory or being forced to screen shot everything.

5.6. Documentation

As alluded to in the wiring diagram section and the trouble shooting section for IndraWorks, the related documentation for this project was quite difficult to manage at times. There were over 20 separate documents that were used extensively during this project, and even more that were referenced for particular details. This proved to be a major challenge, as trying to find the right piece of information in the right document often felt like trying to find a needle in a haystack.

The documentation for the drives felt rather incomplete at times, as demonstrated by our difficulty in wiring the drives initially. There was often a lack of a full description the functionality of each port. The team would instead rely on Greg's description of the port to get a full understanding of what port did, how it was to be wired, and potential issues and remedies associated with it.

During commissioning there was always 6-7 documents being used simultaneously to effectively gather all the required information necessary to learn, implement and trouble shoot. This is incredibly inefficient as what often happened was the necessary information was hidden in one document, but time was spent reading the others as they referenced small pieces that appeared relevant at the time.

Documentation for programming was also lackluster in some aspects. The document containing a full description of each function block was useful, but that was the only useful document found. A more in-depth description about POU's, how to use global variables, among others would have been incredibly useful. There was simply a lack of in-depth description for every aspect required for comprehensive program that utilized IndraWorks to its full capacity.

To make the documentation more user friendly, having everything laid out in Bosch Rexroth's Media Directory on their website in a easier to find manner would be incredibly useful. Within this platform, having a summary of everything contained in the document would allow users to find the exact document needed without having to use trial and error. Currently, the media directory is mostly filled with posters and brochures, which isn't useful for someone looking for actual documentation, especially since it's listed under documentation and resources on the website.

Chapter 6 - Future Work

Like any good project, the deliverables came down to the wire. This was primarily due to the complexity and challenges faced with programming the IndraDrive unit. There are many aspects of the project that could be improved upon in the future:

The additional axes (pen effector raise and lowering, and roller motion) were implemented via Arduino due to a variety of drive errors and programming troubles. Since the IndraDrive units can transmit a PWM signal through its I/O, the printed circuit board made to control these motions was designed for easy transfer of control from the Arduino to IndraDrive once the I/O issues are sorted out.

IndraWorks can utilize five different programming methods, and it would be ideal to have the flying saw coded using all five methods. A walkthrough for new users to follow along with would be ideal.

The Beta Prototype currently uses several 3D printed parts, some of which are acting as bearings, which are expected to wear out quickly. These should be redesigned to incorporate bearings before becoming a production unit.

The parallel and perpendicular motor mounts were manufactured by waterjet cutting a 3/16 inch steel plate and using a hydraulic press to give a 90 degree bend. The problem with this is that the center height of the two mounts vary by almost 2mm. This means that the motor and lead screw supports are not concentric, putting unnecessary stress on the couplers and motor. These components should be properly machined to ensure concentricity.

In getting the drive up and running, we encountered catastrophic failure when the carriage was accidentally actuated in the wrong direction, crashing into a bearing block that has since been removed. This event destroyed the lead screw bearing mount opposite to the motor on the parallel motion and the motor coupler. The beta prototype has limit switches which were originally envisioned as features controlled by IndraDrive. Since this device is a learning tool, they should instead be wired into a contact relay that will kill power to the drives should a new user make the same mistake we did. It should be noted that in the collision, the parallel lead screw became slightly bent causing it to vibrate during motion around 2000RPM. This lead screw should be replaced ideally one with a 10mm lead and a larger diameter as originally intended.

Future users may also wish to explore backlash control with this unit in the parallel lead screw.

It would be our recommendation that Bosch substitute the drives currently on the alpha prototype for single phase 120VAC units. This should eliminate a multitude of overwhelming error codes for first-time IndraDrive users.

Chapter 7 - Conclusion

IndraWorks is not an intuitive program and is not user friendly to users with no experience in industrial controls. This hinderance severely strained the completion of the project down to 2 hours before its exposition on May 9, 2018. Having said that, the result is spectacular, working exactly as envisioned. Never, has the team seen a more beautifully drawn straight (though somewhat wiggly) line. The unit highlights some of the basic drive capabilities, and acts as a sturdy and untapped platform for users to explore programming of a flying saw in the IndraWorks environment.

The Alpha Prototype manages to pack on four drives within a miniscule footprint and is aesthetically pleasing due to its novel design.

The Beta Prototype successfully emulates the principles of a flying saw. It supplies new users with an apparatus to explore three key motor controller features: Accurate Positioning, Torque Sensing, and Synchronous Motion. Additional work is required to prevent new users from inadvertent articulations of the primary two axes. Programming was only achieved in Ladder Logic, though there are more than four other methods that it may be programmed through. This could be explored as future work. It was envisioned that the apparatus would come with a walkthrough to get the flying saw running.

The flying saw 2-axis servo trainer was completed on time, on budget, within the defined scope, and with no time loss accidents. The project was officially completed upon submission of this document on May 11, 2018. All of the deliverables, documentation, Alpha Prototype, and Beta Prototype has been handed over to Greg Filek and Bosch Rexroth.

Chapter 8 - Bibliography

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Chapter 9 - Glossary

Alpha Prototype	The portable structure that holds all the electrical and controls aspect of the 2-axis servo trainer project.
Beta Prototype	The aspect of the project that emulates the industrial application of a flying saw that someone can learn to program.
Carriage	The platform upon which the parallel motion is mounted and of which is moved linearly by the perpendicular motion.
IndraDrive	An industrial servo drive unit manufactured by Bosch Rexroth.
IndraWorks	Bosch Rexroth's proprietary software for commissioning and programming their drives.
Function Blocks	Function Blocks are a method of programming that provides a visual representation. It connects inputs and outputs, both denoted as lines.
Parallel Motion	The linear motion of the flying saw that acts parallel to the roller motion.
Perpendicular Motion	The linear motion of the flying saw that acts perpendicular to the roller motion.
Roller Motion	The linear motion of the product being "cut" by the flying saw. This is represented by the sheet of cellophane that the pen draws the "cut" line upon.

Trainer	A device for learning how to program and operate Bosch Rexroth products.

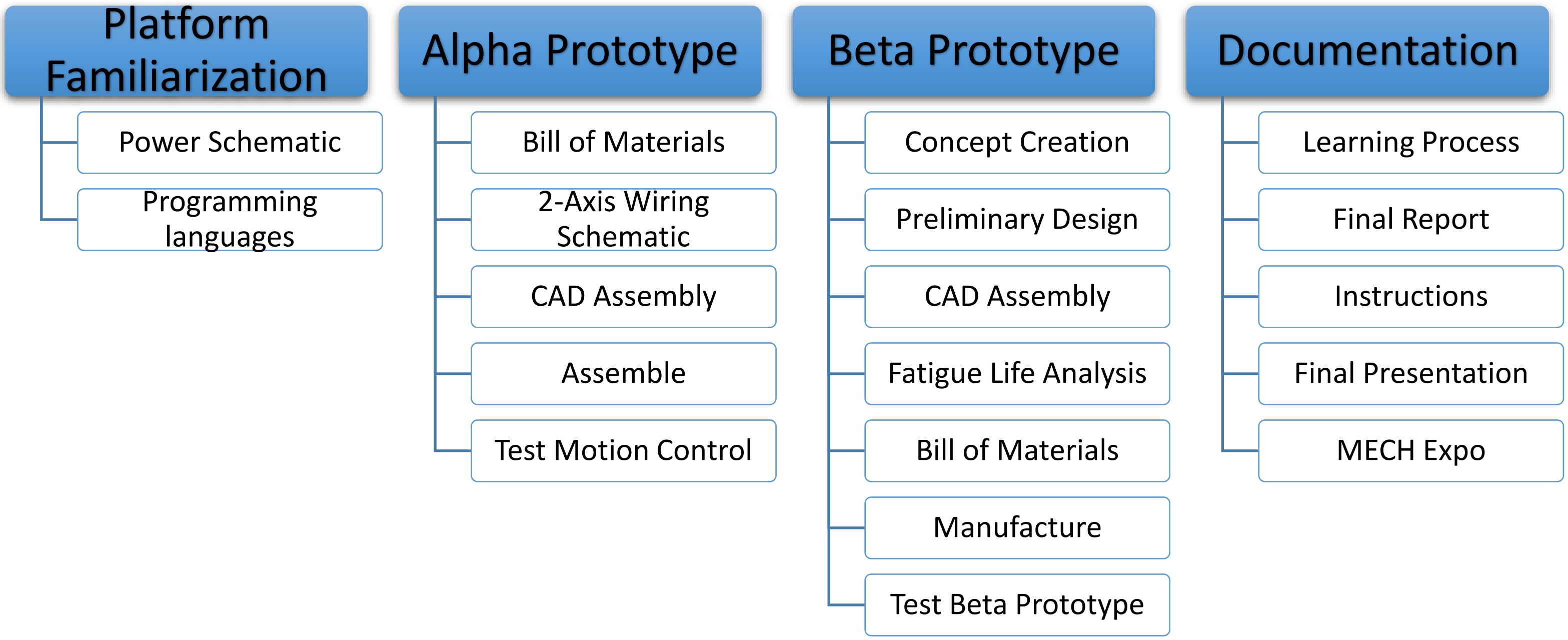
Appendix A Project Management

A.1 Responsibility Matrix

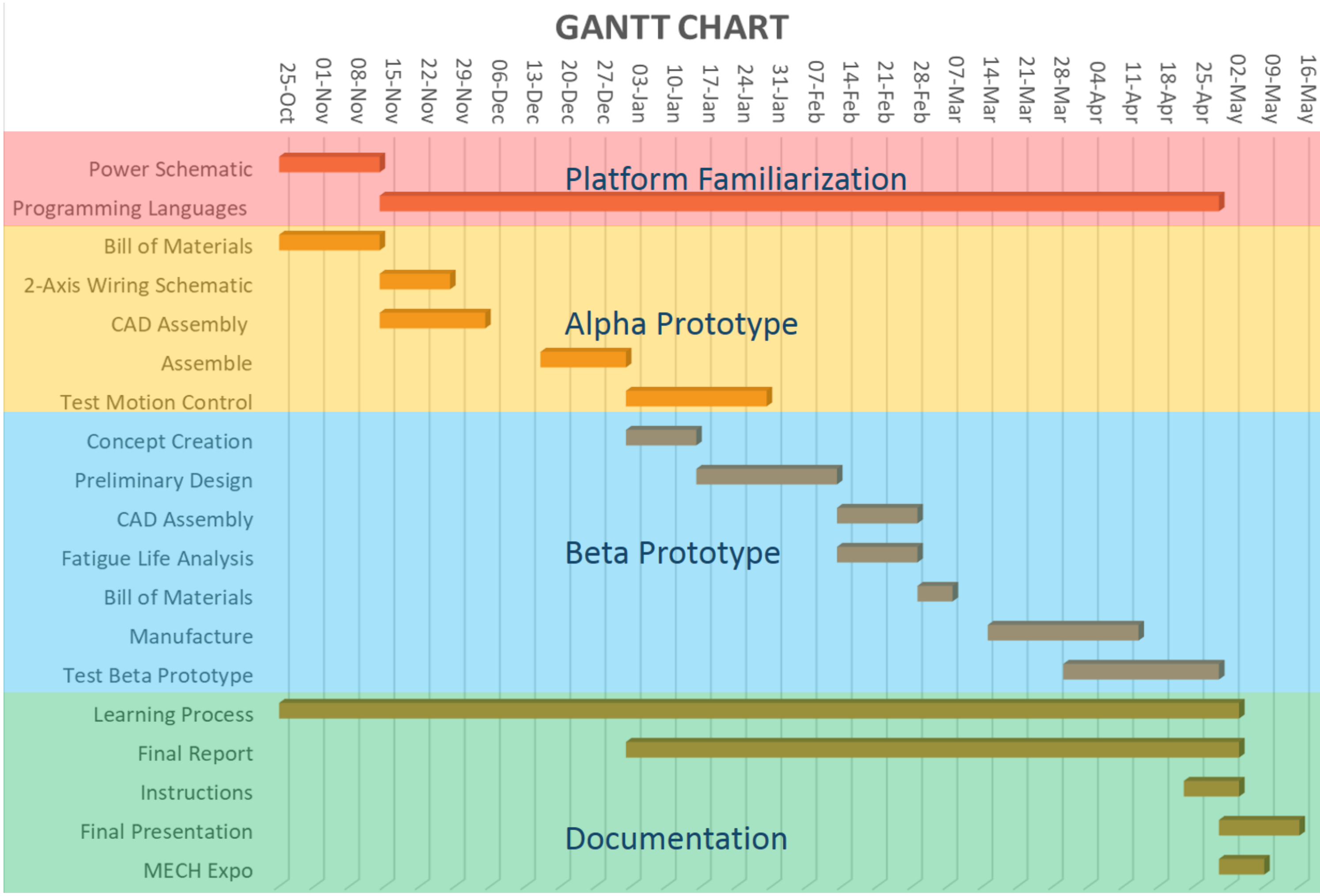
		Platform Familiarization		Alpha Prototype					Beta Prototype							Documentation				
		Power Schematic	Programming Languages	Bill of Materials	2-Axis Wiring Schematic	CAD Assembly	Assemble	Test Motion Control	Concept Creation	Preliminary Design	CAD Assembly	Fatigue Life Analysis	Bill of Materials	Manufacture	Test Beta Prototype	Learning Process	Final Report	Instructions	Final Presentation	MECH Expo
In-A-Sinh(Eng.)	Curtis From	R	A	C	R	R	A	A	R	R	A	A	C	A	A	R	A	A	A	R
In-A-Sinh(Eng.)	Matt Vickars	A	A	R	A	C	R	A	A	A	R	A	C	R	A	A	R	C	A	A
In-A-Sinh(Eng.)	Dean Tamboline	A	R	C	A	C	A	R	A	A	A	R	R	A	R	A	A	R	R	A
Stakeholders	Greg Filek	C	C	I	C	I	I	I	I	C	I	C	C	I	I	C	C	C	I	I
Stakeholders																				
Stakeholders	Johan Fourie	I	I	I	I	I	I	I	C	C	I	C	I	I	I	I	C	I	I	I

R = Responsible **A = Accountable** **C = Consultant** **I = Inform**

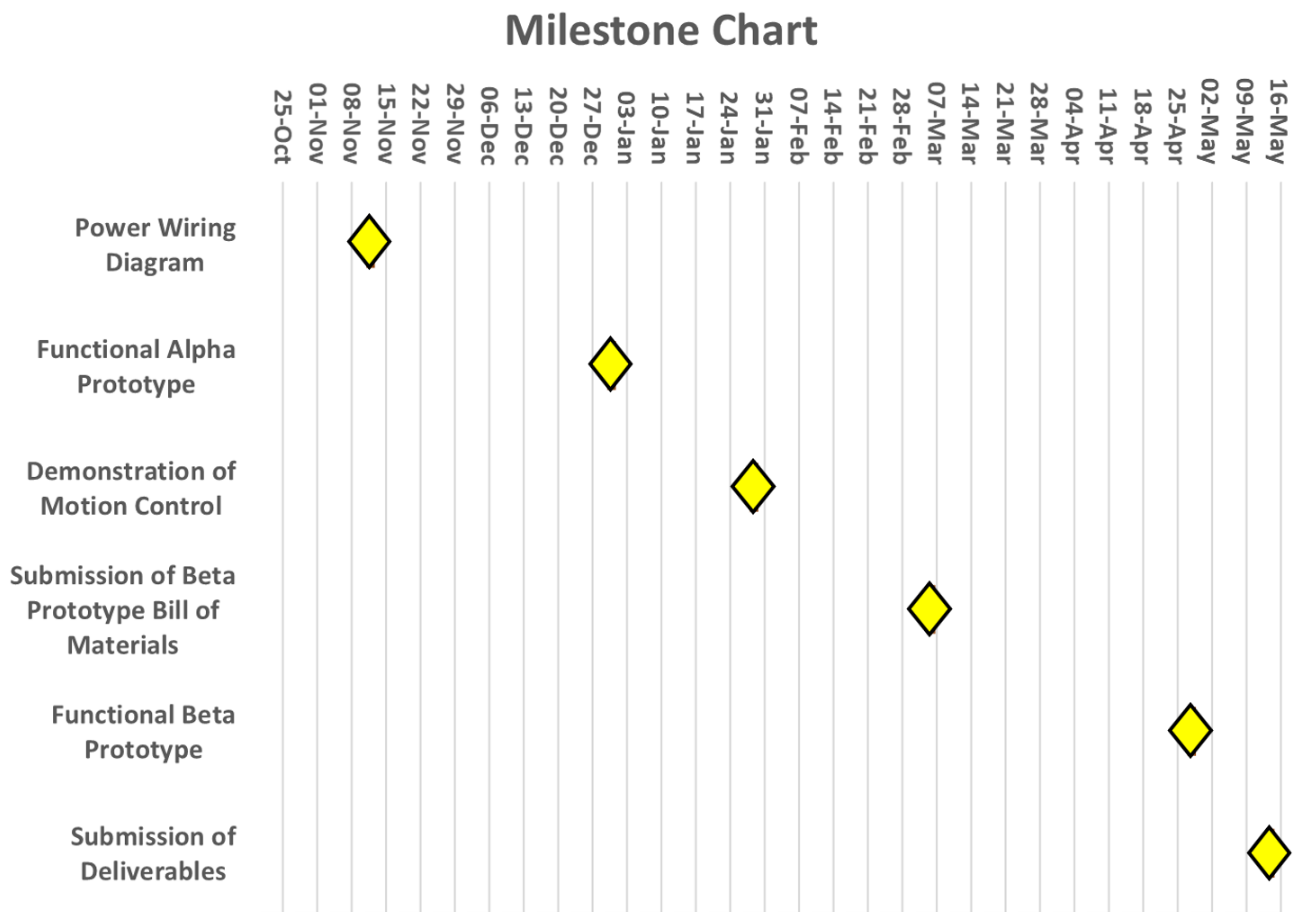
A.2 Work Breakdown Structure



A.3 Gantt Chart



A.4 Milestones Chart



A.5 Technical Requirements

A.5.1 Task 1

The flying-saw emulator will accomplish the task of writing a line perpendicular to the direction of the cellophane roller under the following conditions

a. Cellophane velocity = 0.4m/s

A successful attempt will include

a. The pen effector passing over the cellophane in the length of 650mm, which is the maximum travel distance parallel to the cellophane's direction of motion
b. Line to within 2 degrees of perpendicular to cellophane direction
c. Pen marking is continuous for entire duration of activation

Appendix B Alpha Prototype

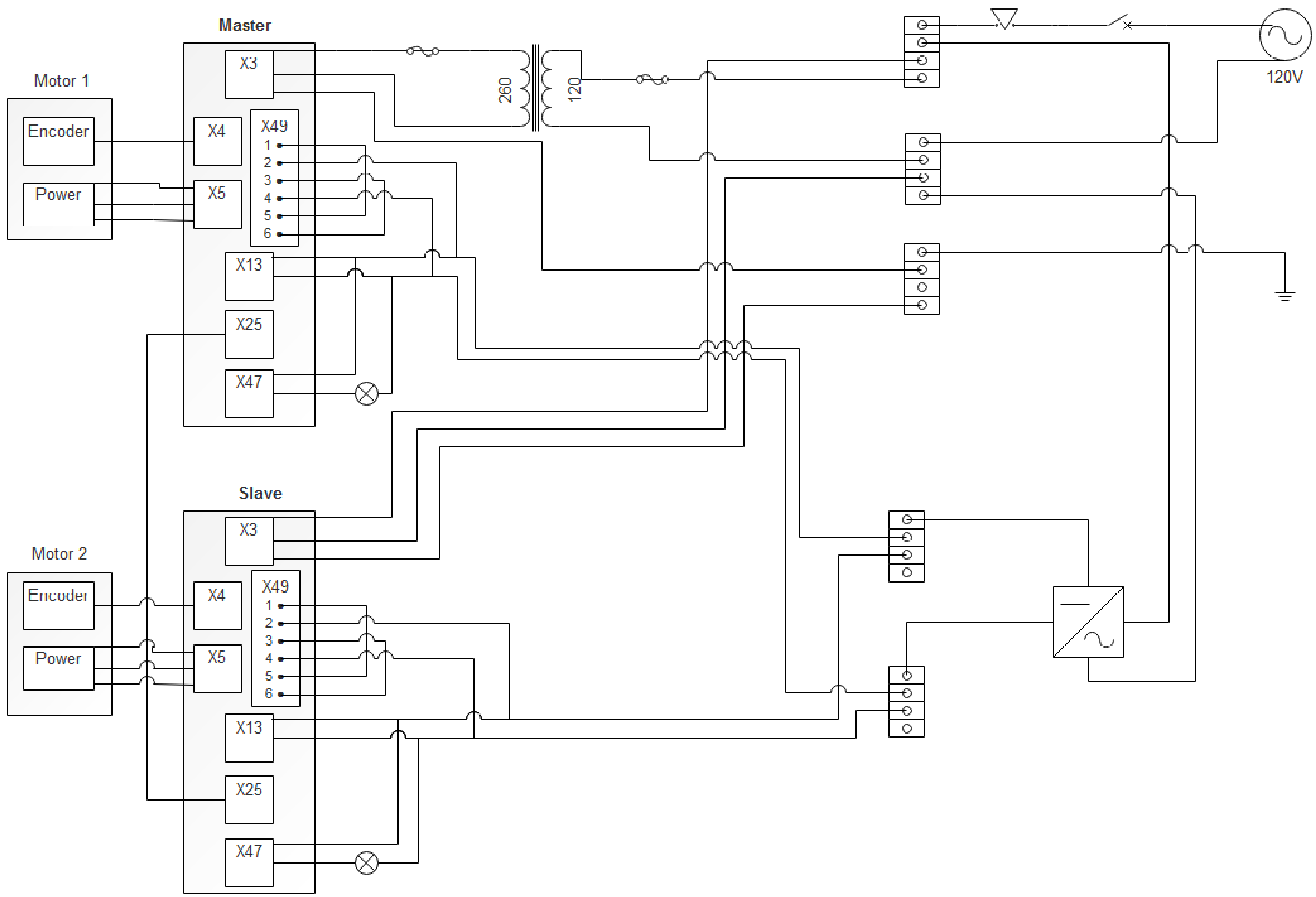
B.1 Alpha Prototype Boot Process

The Alpha Prototype can be readied for operation through the following steps:

WARNING: ENSURE THAT THE DEVICE IS UNPLUGGED, E-STOP IS ACTIVATED, AND BREAKER IS IN THE OFF POSITION BEFORE STARTING.

1. Insert the three-pronged male electrical plug from the transformer into its female counterpart, which can be found rigidly mounted to the right side of the Alpha Prototype's base plate.
2. Connect the 2nd cable from the transformer, with a green plug, to X3 located on the bottom of the larger, master drive.
3. Plug in the power cord into a 120V supply.
4. Flip the breaker switch to the on position.
5. Deactivate the E-STOP by twisting it counter clockwise.
6. The drives are now receiving power and should have BOOT displayed on the font hat.
7. After going through the required booting processes, the drives are ready for operation.

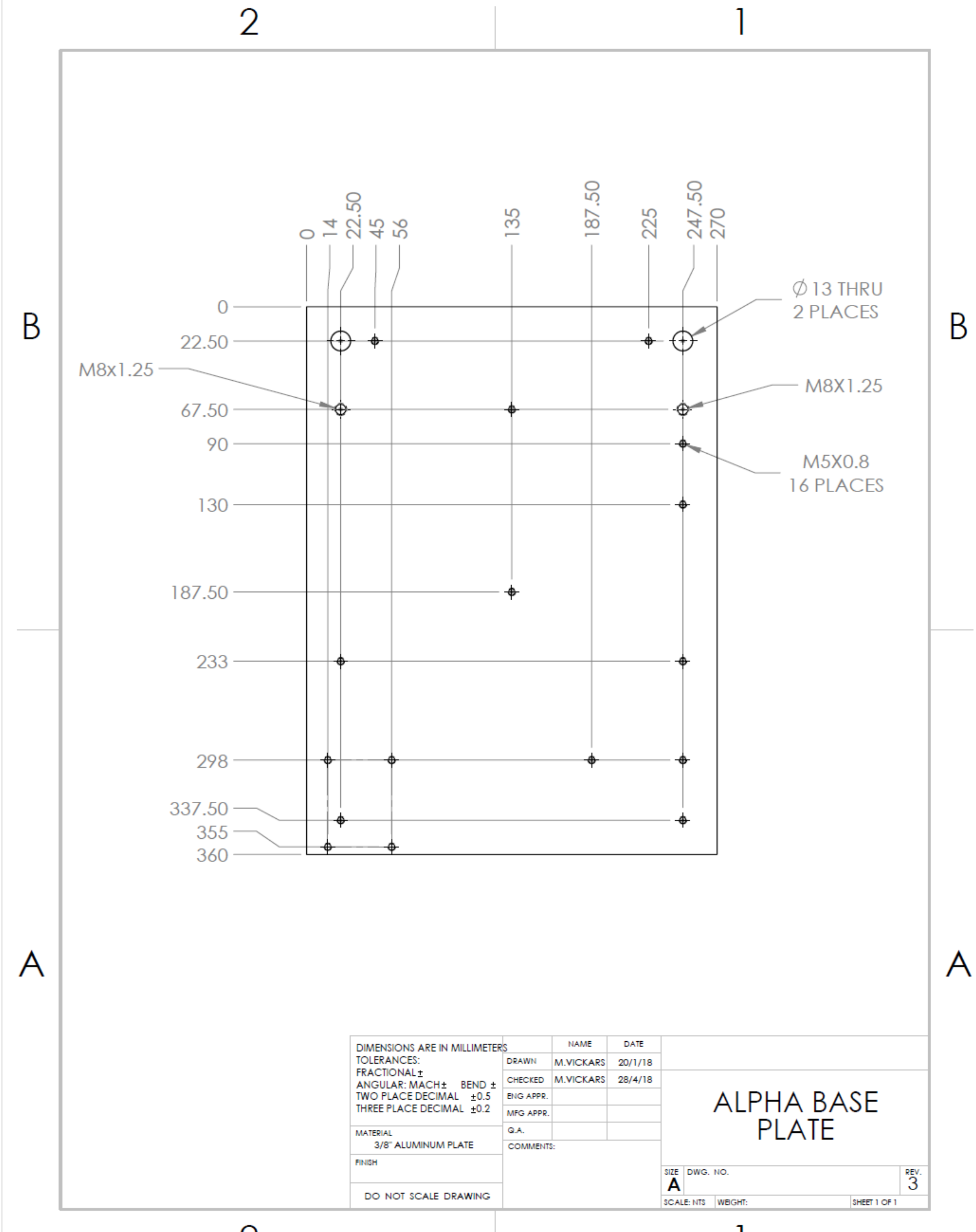
B.2 Wiring Diagram

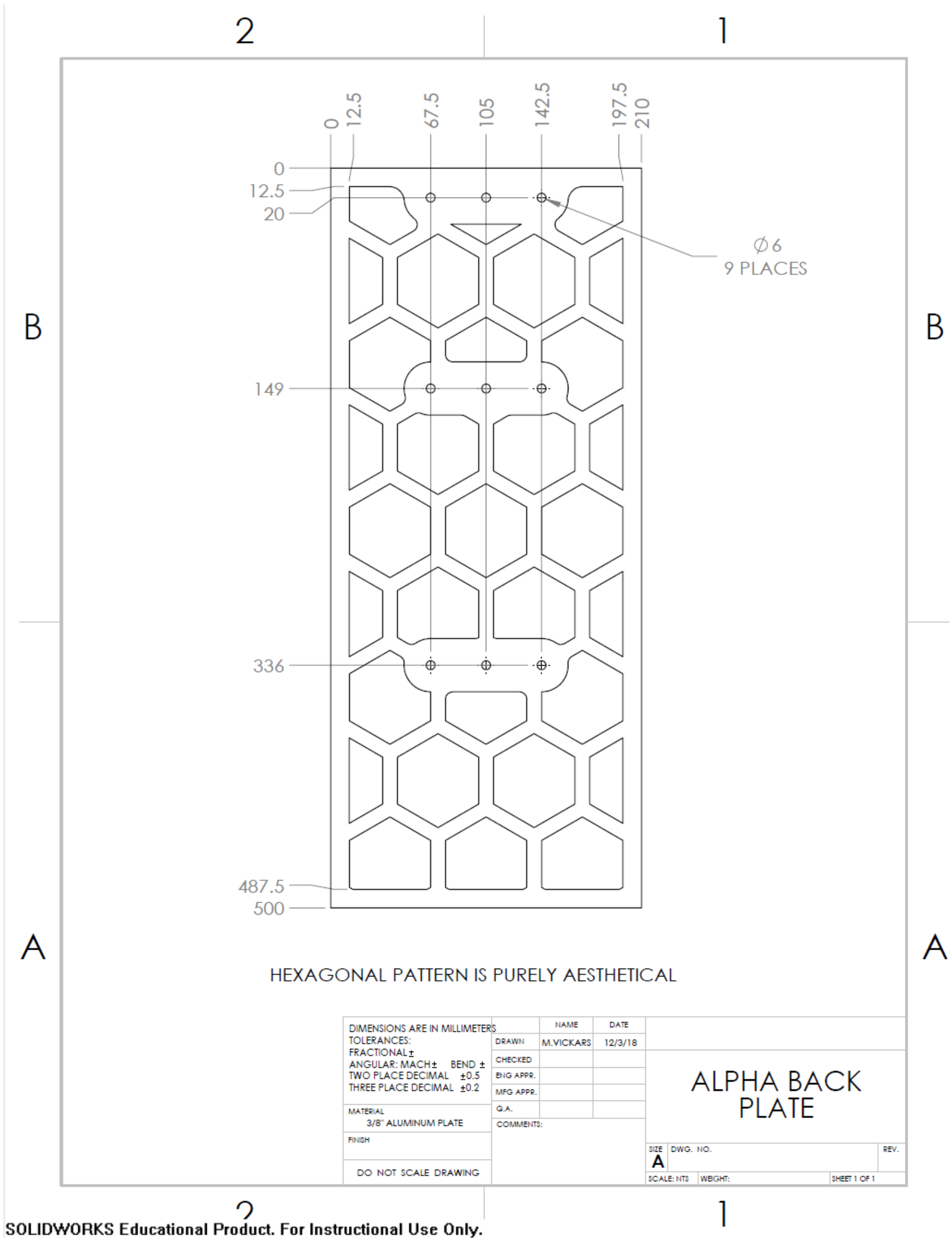


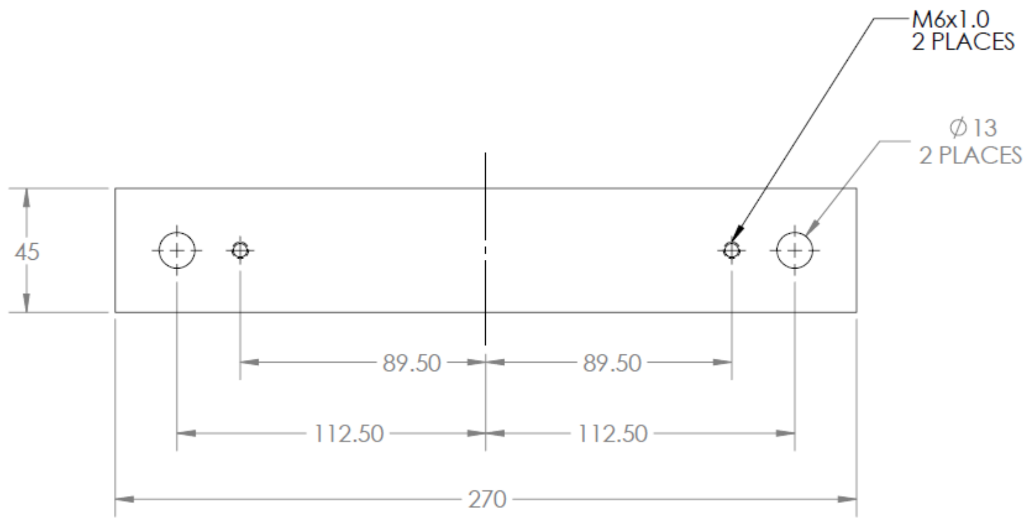
B.3 Bill of Materials

	Bill of Materials for Alpha Prototype		
	Name	**Specifications**	**Quantity**
Electrical	Power Plug	Male, 3 wire, 120V, 15A	1
	Breaker	15A, 125V	1
	Converter	120VAC to 24DC	1
	Transformer	120 to 240VAC	1
	E-Stop Button	15A, 120V	1
	Power Wire	14 gauge, 3 wire	2m
	White Control Wire	20 gauge, Solid	3m
	Black Control Wire	20 gauge, Solid	3m
	Electrical Tape		1
	I/O box	6 Switches, 6 Red Lights, 2 Potentiometers, 1 Green Light	1
	Din Rail		0.2m
	Terminal Blocks, Ungrounded		12
	Terminal Blocks, Grounded		3
	Terminal Block Jumpers	2 prong	6
	Terminal Blocks End Plate		5
	Ferrules	Assorted sizes for 28gauge-12gauge wire	
	Master Drive (Compact converter)	HCS02.1E-W0012-A-03-NNNN	1
	Master Drive (Control Unit ADVANCED)	CSH02.1B-CC-EC-ET-L3-NN-NN-FW	1
	Slave Drive	HCS01.1E-W0006-A-02-B-ET-EC-NN-NN-NN-FW	1
Mechanical	Aluminum Extrusion Posts	45mm x 45mm Aluminum Extrusion, Length 500mm	2
	Aluminum Base Plate	3/8" Thick Aluminum Plate, 270mm x 360mm	1
	Aluminum Mounting Plate	3/8" Thick Aluminum Plate, 210mm x 500mm	1
	Polycarbonate Plate	3/8" Thick Polycarbonate, 270mm x 300mm	1
	Aluminum top plate	3/8 Thick Aluminum Plate, 270mm x 45mm	1
	Aluminum Block	1" x 1" x 6"	1
	Aluminum Round stock	3/4" Diameter	0.3 m
	Rubber Feet		4
	Aluminum Spacers	ID 6.3mm, OD 13mm, Length 80mm	2
	Redirod	M6, Length 1m	1
	Thumb Nut	Stainless steel M6 thumb nut	2
	Magnets	D=3/8in x 1/4in	4
	Cental Bolt	8 981 021 302	4
	Bracket 45/45 Brace, Set(standard)	3 842 523 561	2
	Large Strap Handle	3 842 525 766	1
	Tnuts, Slot 10, Threads M8	8 981 019 580	10

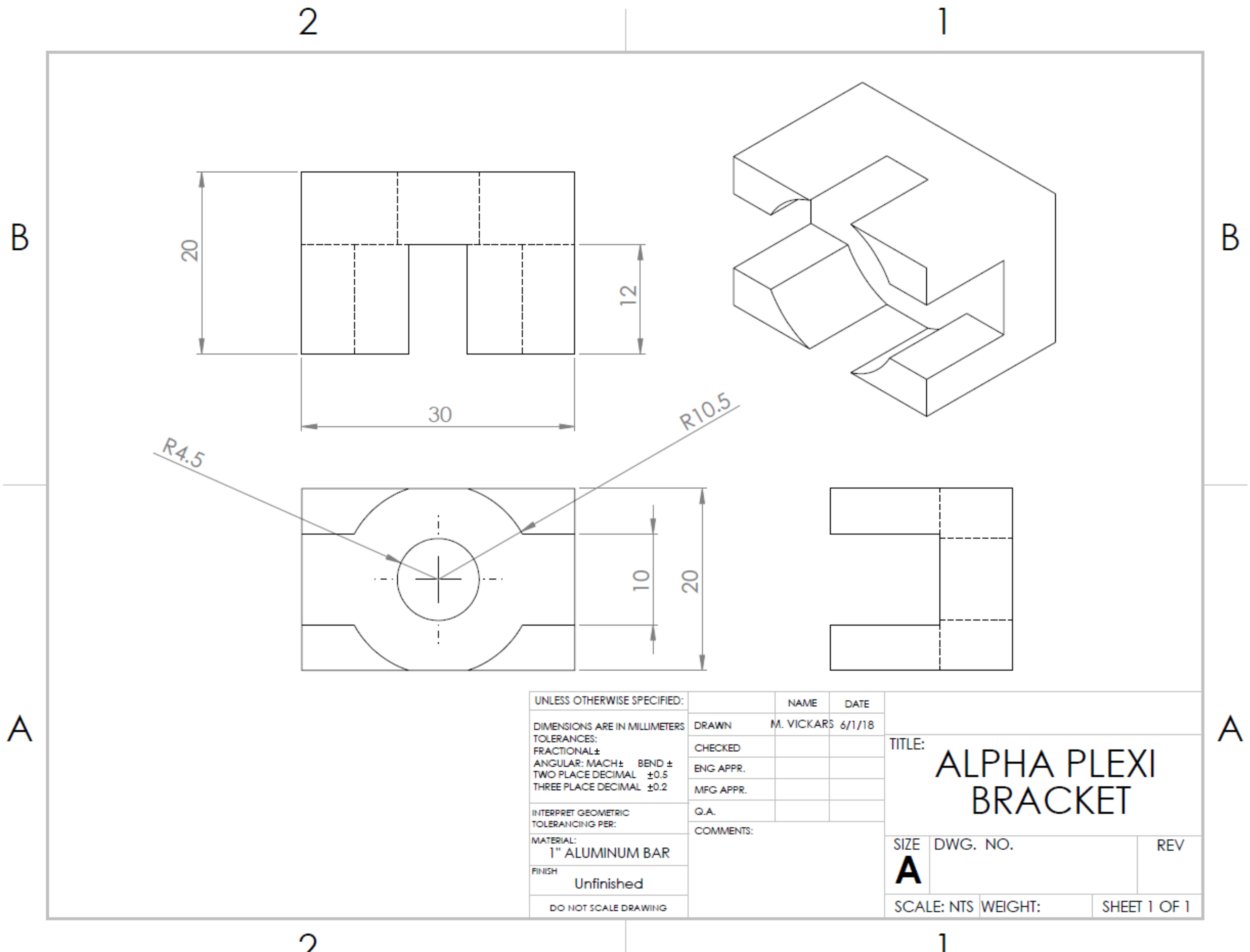
B.4 Shop Drawings

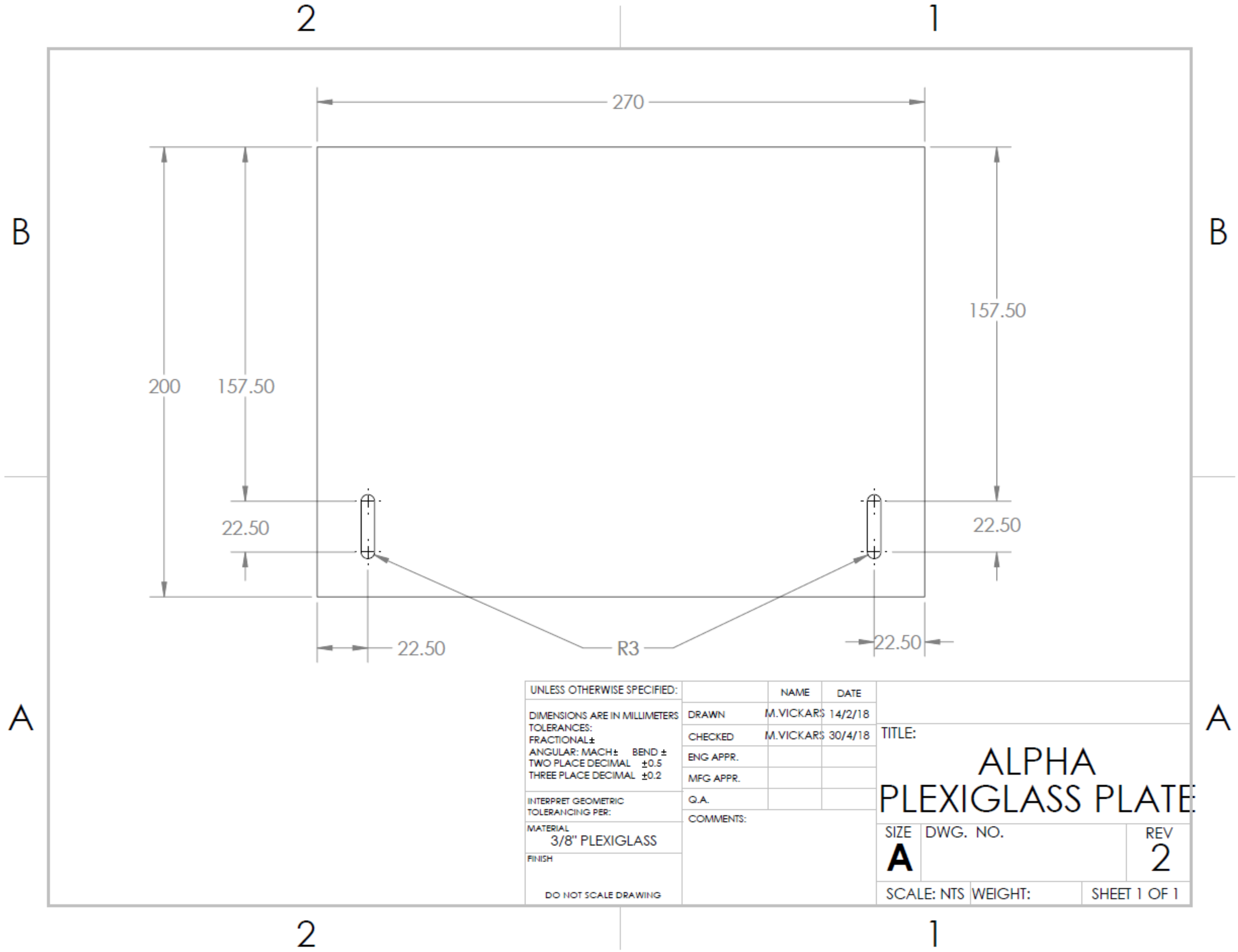



0
12.5
67.5
105
142.5
197.5
210
0
12.5
20
149
336
487.5
500
∅6
9 PLACES
HEXAGONAL PATTERN IS PURELY AESTHETICAL
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.5
THREE PLACE DECIMAL ±0.2
MATERIAL
3/8" ALUMINUM PLATE
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
M.VICKARS
12/3/18
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
ALPHA BACK PLATE
SIZE
A
DWG. NO.
REV.
SCALE: NTS
WEIGHT:
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MILLIMETERS TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ±0.5 THREE PLACE DECIMAL ±0.2	DRAWN	M. VICKARS	10/1/18	TITLE:
	CHECKED			ALPHA HANDLE SUPPORT
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL 3/8" ALUMINUM PLATE	COMMENTS:			SIZE A · DWG. NO. · REV
FINISH				
DO NOT SCALE DRAWING				SCALE: NTS · WEIGHT: · SHEET 1 OF 1


2
1
B
A
20
12
30
R4.5
R10.5
10
20
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.5
THREE PLACE DECIMAL ±0.2
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL:
1" ALUMINUM BAR
FINISH
Unfinished
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
M. VICKARS
6/1/18
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
ALPHA PLEXI BRACKET
SIZE
A
DWG. NO.
REV
SCALE: NTS
WEIGHT:
SHEET 1 OF 1


270
200
157.50
157.50
22.50
22.50
22.50
R3
22.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.5
THREE PLACE DECIMAL ±0.2
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
3/8" PLEXIGLASS
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN M.VICKARS 14/2/18
CHECKED M.VICKARS 30/4/18
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
ALPHA PLEXIGLASS PLATE
SIZE A
DWG. NO.
REV 2
SCALE: NTS
WEIGHT:
SHEET 1 OF 1

B.5 Arduino Code

```
//Note a Portion of this code is based off an example from
//www.schmalzhaus.com/EasyDriver/Examples/EasyDriverExamples.html

#include <AccelStepper.h>
#include <Servo.h>

Servo myservo;
AccelStepper stepper1(1,5,4);
  //1 indicates I am using a EasyDriver
  //5 is the STEP Pin
  //4 is the DIR Pin

#define  INDRASIGNAL  2
#define  SERVO 3
#define  LIMIT1   6
#define  LIMIT2   7
#define  LIMIT3   8
#define  LIMIT4   9
#define  SERVOSWITCH   10
#define  FORWARD   11
#define  BACKWARD   12
#define  NOHOLDINGTORQUE  13
#define  SPEED_PIN 0
#define  MAX_SPEED 6000
#define  MIN_SPEED 0.1

void setup() {
  stepper1.setMaxSpeed(10000.0); //must set this to a value > MAX_SPEED
  stepper1.setEnablePin(NOHOLDINGTORQUE); //enable means disable power to
motors
```

```
  pinMode(FORWARD, INPUT_PULLUP);
  pinMode(BACKWARD, INPUT_PULLUP);
  pinMode(SERVOSWITCH, INPUT_PULLUP);
  pinMode(LIMIT1, INPUT_PULLUP);
  pinMode(LIMIT2, INPUT_PULLUP);
  pinMode(LIMIT3, INPUT_PULLUP);
  pinMode(LIMIT4, INPUT_PULLUP);
  pinMode(INDRASIGNAL, OUTPUT);
  digitalWrite(INDRASIGNAL,LOW);
  myservo.attach(SERVO);
  Serial.begin(9600);//for serial output of pot value for troubleshooting
stepper speed
}


void loop() {
  static float current_speed = 0.0;         // Holds current motor speed in
steps/second
  static int analog_read_counter = 1000;    // Counts down to 0 to fire
analog read
  static char sign = 0;                     // Holds -1, 1 or 0 to turn the
motor on/off and control direction
  static int analog_value = 0;              // Holds raw analog value.



  // If a switch is pushed down (low), set the sign value appropriately
  if (digitalRead(FORWARD) == 0) {
    stepper1.disableOutputs();
    sign = 1;
  }
  else if (digitalRead(BACKWARD) == 0) {
    stepper1.disableOutputs();
```

```
    sign = -1;
  }
  else {
    sign = 0;
    stepper1.enableOutputs();
  }



if (digitalRead(LIMIT1)==0 || digitalRead(LIMIT2)==0 ||
digitalRead(LIMIT3)==0 || digitalRead(LIMIT4)==0){
  digitalWrite(INDRASIGNAL,HIGH);
}
   else {
    digitalWrite(INDRASIGNAL,LOW);
}


if (digitalRead(SERVOSWITCH)==0) {
    myservo.write(179);
}
else {
  myservo.write(1);
}


  // We only want to read the pot every so often (because it takes a long
time we don't
  // want to do it every time through the main loop).
  if (analog_read_counter > 0) {
    analog_read_counter--;
  }
  else {
    analog_read_counter = 3000;
    // Now read the pot (from 0 to 1023)
```

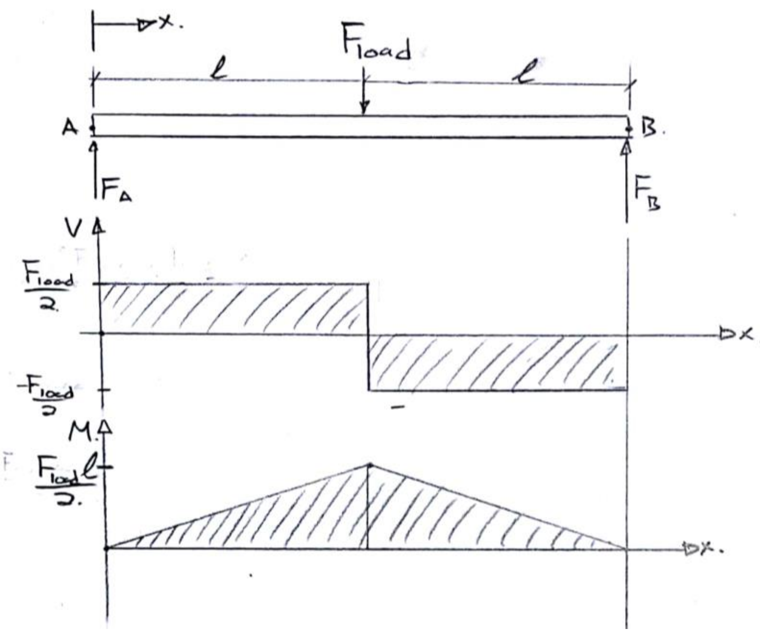
```
    analog_value = analogRead(SPEED_PIN);
    // Give the stepper a chance to step if it needs to
    stepper1.runSpeed();
    //  And scale the pot's value from min to max speeds
    current_speed = sign * (((analog_value/1023.0) * (MAX_SPEED - MIN_SPEED))
+ MIN_SPEED);
    // Update the stepper to run at this new speed
    stepper1.setSpeed(current_speed);
     Serial.println(current_speed);//for serial print diagnostics
  }


  // This will run the stepper at a constant speed
  stepper1.runSpeed();
}
```

Appendix C Beta Prototype

C.1 Radially Loaded Circular Cross Sections

C.1.1 Preliminary



$$\omega = F_A \langle x-0\rangle^{-1} - F_{load}\langle x-\ell\rangle^{-1}$$

$$V = F_A \langle x-0\rangle^{0} - F_{load}\langle x-\ell\rangle^{0}$$

$$M = F_A \langle x-0\rangle^{1} - F_{load}\langle x-\ell\rangle^{1}$$

$$EI\frac{d\theta}{dx} = \frac{F_A}{2}\langle x-0\rangle^{2} - \frac{F_{load}}{2}\langle x-\ell\rangle^{2} + C_1$$

$$EI\,y = \frac{F_A}{6}\langle x-0\rangle^{3} - \frac{F_{load}}{6}\langle x-\ell\rangle^{3} + C_1 x + C_2$$

<u>Boundary Conditions</u>

$@\,x=0 \quad y=0 \rightarrow EI(0) = \frac{F_A}{6}\langle 0-0\rangle^3 - \frac{F_{load}}{6}\langle 0-\ell\rangle^3 + C_1(0) + C_2$

$$C_2 = 0$$

$@\,x=2\ell \quad y=0 \rightarrow EI(0) = \frac{F_A}{6}\langle 2\ell-0\rangle^3 - \frac{F_{load}}{6}\langle 2\ell-\ell\rangle^3 + C_1(2\ell)$

$$C_1(2\cancel{\ell}) = \frac{F_{load}}{6}\ell^{\cancel{3}\,2} - \frac{F_A}{6}8\ell^{\cancel{3}\,2}$$

$$C_1 = \frac{F_{load}\ell^2 - 8F_A\ell^2}{12} = \frac{F_{load}\ell^2 - 4F_{load}\ell^2}{12}$$

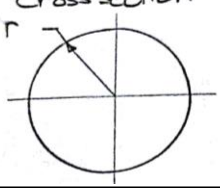
$$C_1 = -\frac{F_{load}\ell^2}{4}$$

<u>Evaluate</u>

$@\,x=\ell \rightarrow EI\,y = \frac{F_A}{6}\langle \ell-0\rangle^3 - F_{load}\cancel{\langle \ell-\ell\rangle^3}^{\,0} - \left(\frac{F_{load}\ell^2}{4}\right)\ell$

$$EI\,y = \frac{F_{load}\ell^3}{12} - \frac{F_{load}\ell^3}{4} = \frac{F_{load}\ell^3}{6}$$

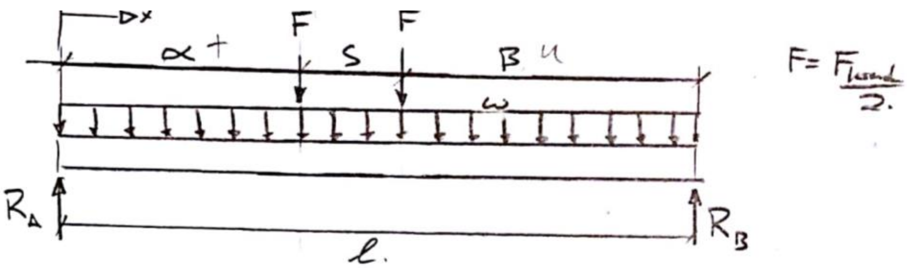
Cross section $\quad Y_{max} = \frac{F_{load}\ell^3}{6EI} \quad \left[\frac{N\,mm^3}{N\,mm^{-2}\,mm^4} = mm\right]$



$$\sigma_{bending\,max} = \frac{MC}{I} = \left(\frac{F_{load}\ell}{2}\right)\left(\frac{r}{1}\right)\left(\frac{4}{\pi r^4}\right) = \frac{F_{load}\ell\,2}{\pi r^3} \quad \left[\frac{N\,mm}{mm^3}\right] = [MPa]$$

Shaft Diameter	Shaft Diameter	Moment of Inertia	Shaft Mass	Force applied	Bending Stress	Deflection
[in]	[mm]	[mm^4]	[kg]	[N]	[Mpa]	[mm]
0.250	6.350	79.811	0.229	12.551	112.344	12.571
0.375	9.525	404.045	0.516	15.365	40.749	3.040
0.500	12.700	1276.982	0.918	19.304	21.598	1.208
0.625	15.875	3117.632	1.434	24.368	13.959	0.625
0.750	19.050	6464.721	2.065	30.558	10.130	0.378

C.1.2 Refined



$$\overset{+}{\circlearrowleft}\Sigma M_B = F\beta + F(\beta+s) + \omega\ell\left(\frac{\ell}{2}\right) - R_A\ell$$

$\frac{Kg}{m^3}\left(\frac{1m}{1000mm}\right)^3$

$$R_A = \frac{\omega\ell}{2} + F(2\beta+s)$$

$$M = R_A\langle x-0\rangle^1 - \frac{\omega}{2}\langle x-0\rangle^2 - F\langle x-\alpha\rangle^1 - F\langle x-(\alpha+s)\rangle^1$$

$$EI\frac{dy}{dx} = \frac{R_A}{2}\langle x-0\rangle^2 - \frac{\omega}{6}\langle x-0\rangle^3 - \frac{F}{2}\langle x-\alpha\rangle^2 - \frac{F}{2}\langle x-(\alpha+s)\rangle^2 + C_1$$

$$EIY = \frac{R_A}{6}\langle x-0\rangle^3 - \frac{\omega}{24}\langle x-0\rangle^4 - \frac{F}{6}\langle x-\alpha\rangle^3 - \frac{F}{6}\langle x-(\alpha+s)\rangle^3 + C_1x + C_2$$

C.1.2.1 Maple code

restart

System Properties

$MassOfCarriage := 1.4$ **kg**

1.4

$s := 90$ **mm**

90

$l := 900$ **mm**

900

$LengthRelations := l = \mathrm{alpha} + s + \mathrm{beta} :$

$F := \frac{MassOfCarriage \cdot 9.81}{2}$ **N**

6.867000000

Beam Properties

$Diameter := \frac{1}{2} \cdot 25.4$ **mm**

12.70000000

$Density := 8050 \cdot \left(\frac{1}{1000}\right)^3$ **kg/mm^3**

$\frac{161}{20000000}$

$E := 190000$ **MPa**

190000

$w := \frac{\mathrm{Pi} \cdot Diameter^2}{4} \cdot Density \cdot 9.81 :$ **N/mm**

$AMInertia := \left(\frac{\mathrm{Pi} \cdot Diameter^4}{64}\right) :$ **mm^4**

Solving System

$R_A := \frac{w \cdot l}{2} + \frac{F \cdot (2 \cdot \mathrm{beta} + s)}{l}$: **N**

beta := *solve*(*LengthRelations*, beta) :

$M := R_A \cdot (x) \cdot \mathrm{Heaviside}(x) - \frac{w}{2} \cdot (x)^2 \cdot \mathrm{Heaviside}(x) - F \cdot (x - \mathrm{alpha}) \cdot \mathrm{Heaviside}(x - \mathrm{alpha}) - F \cdot (x - (\mathrm{alpha} + s)) \cdot \mathrm{Heaviside}(x - (\mathrm{alpha} + s))$:

$EIdydx := int(M, x) + C1$:

$dydx := \frac{EIdydx}{E \cdot AMInertia}$:

$EIy := int(EIdydx, x) + C2$:

$y := \frac{EIy}{E \cdot AMInertia}$

ApplyBoundary Conditions

LeftBoundaryCondition := 0 = *subs*(*x* = 0, *y*) :

C2 := *solve*(*LeftBoundaryCondition*, *C2*) :

RightBoundaryCondition := 0 = *subs*(*x* = *l*, *y*) :

C1 := *solve*(*RightBoundaryCondition*, *C1*) :

Solving a specific point of interest

SingleLocationOfInterest := $\frac{(l - \mathrm{s})}{2}$:

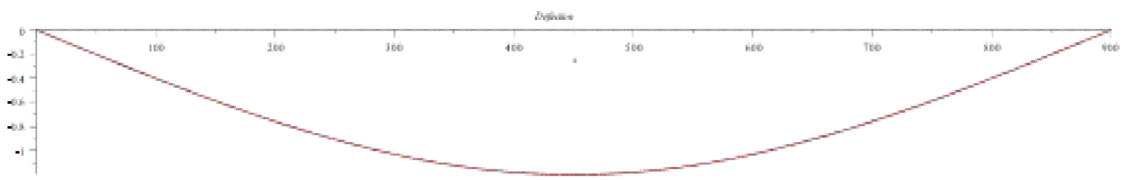
SingleCarriageLocationDeflection := *subs*(alpha = *SingleLocationOfInterest*, *y*) :

SingleCarriageLocationSlope := *subs*(alpha = *SingleLocationOfInterest*, *dydx*) :

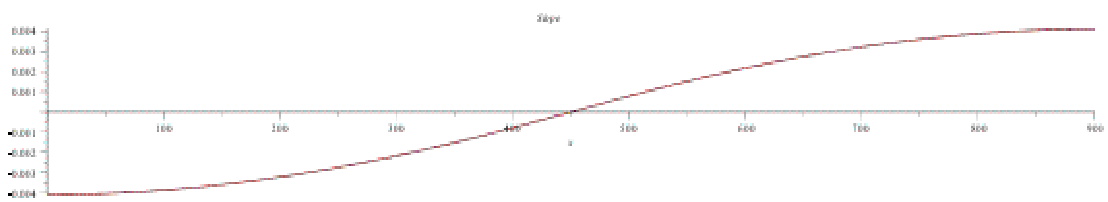
SingleCarriageLocationMoment := *subs*(alpha = *SingleLocationOfInterest*, *M*) :

Plotting point of interest

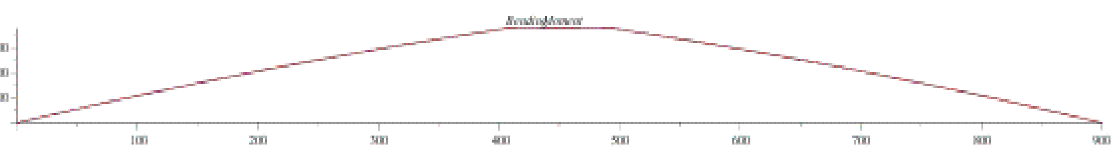
$plot(SingleCarriageLocationDeflection(x), x = 0..l, title = Deflection)$



$plot(SingleCarriageLocationSlope(x), x = 0..l, title = Slope)$

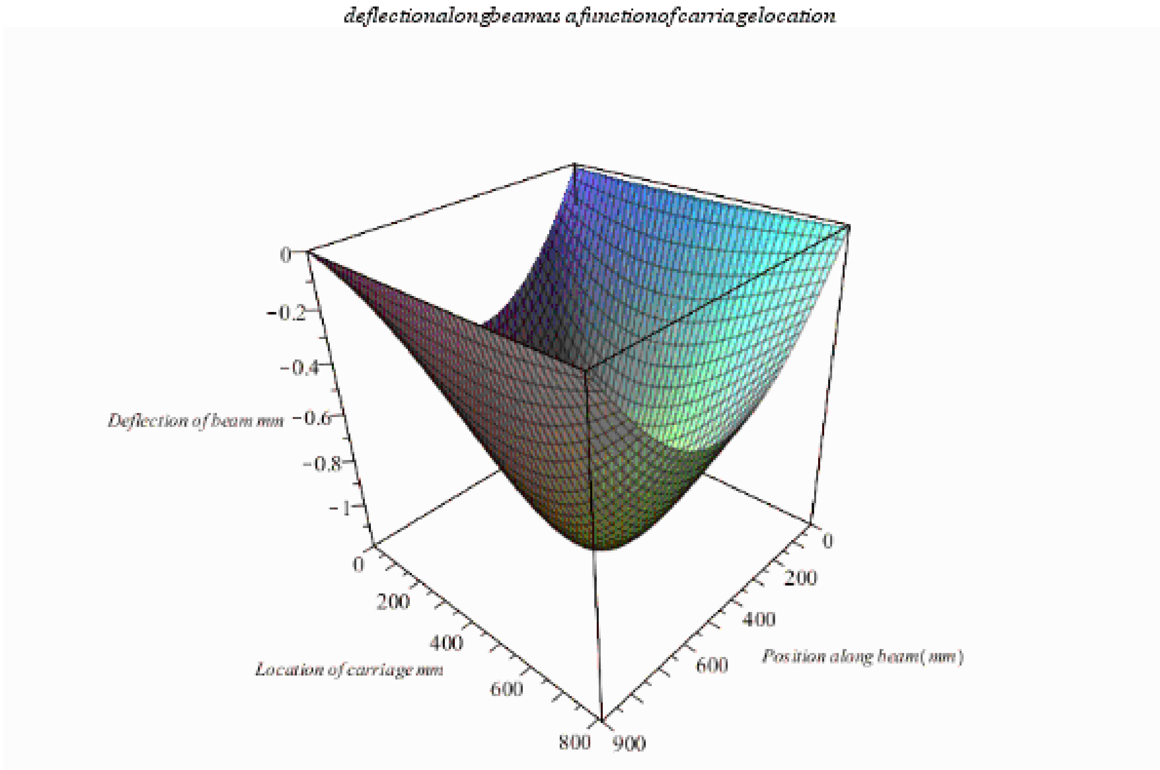


$plot(SingleCarriageLocationMoment(x), x = 0..l, title = Bending\,Moment)$



Plotting deflection as a function of position along beam and location of carriage

$plot3d(y(x), x = 0..l, \text{alpha} = 0..l - s, title = deflection\ along\ beam\ as\ a\ function\ of\ carriage\ location, projection = 0.7, labels = [Position\ along\ beam(mm), Location\ of\ carriage\ (mm), Deflection\ of\ beam\ (mm)], grid = [200, 200])$



C.2 Design for Assembly

C.2.1 Parallel Motion

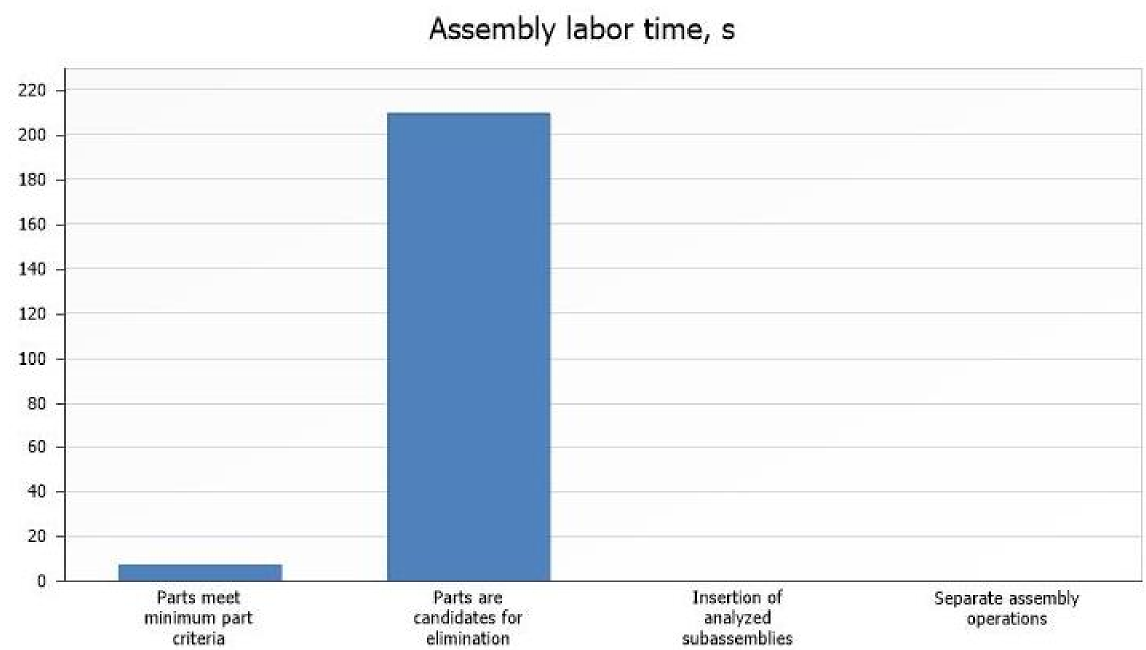
C.2.1.1 Original Design (Two Round Rails)

C.2.1.1.1 Design for Assembly (Manual)

1	2	3	4	5	6	7	8	9			
Part I.D. No.	number of times the operation is carried out consecutively	two-digit manual handling code	manual handing time per part	two-digit manual insertion code	manual insertion time per part	operation time (seconds)	operation cost (cents)	figures for estimationof theoretical minimum parts	Parallel Guide Motion		
1	6	20	1.8	0.0	1.5	19.8	7.92	0	t-nuts		
2	1	30	1.95	0.0	1.5	3.45	1.38	0	Supporting block bearing		
3	2	0.0	1.13	38	6	14.3	5.7	0	Bolt		
4	2	0.0	1.13	1.0	2.5	7.26	2.9	0	Linear rod		
5	1	20	1.8	0.0	1.5	3.3	1.32	1	Carraige		
6	2	20	1.8	1.0	2.5	8.6	3.44	0	Linear rod support		
7	4	0.0	1.13	38	6	28.5	11.4	0	Bolt		
8	4	0.0	1.13	38	6	28.5	11.4	0	set screws		
						114	45.5	1			
						TM	CM	NM	Design Efficiency	=	**2.64%**

C.2.1.1.2 Design for Assembly Analysis (Boothroyd Dewhurst)

Entries including repeats	Original
Parts meet minimum part criteria	2
Parts are candidates for elimination	20
Analyzed subassemblies	0
Separate assembly operations	0
Total entries	22
Assembly labor time, s	
Parts meet minimum part criteria	6.86
Parts are candidates for elimination	209.38
Insertion of analyzed subassemblies	0
Separate assembly operations	0
Total assembly labor time	216.24
Design efficiency	
DFA Index	3.06



C.2.1.1.3 Redesign Suggestions from Boothroyd Dewhurst

Category 1 suggestion: Eliminate the highlighted items by incorporating features into other parts that serve the function of these highlighted items. These suggestions will typically result in the largest improvements in your product design because any associated fasteners, connectors, and joining operations will also be eliminated when the separate part is eliminated. These suggestions should have the highest priority and should always be considered first before continuing on to the Category 2 and then Category 3 suggestions.

Name	Notes	Part number	Total quantity	Process time per product, s	Parent assembly
linear rod		4	2	11.48	Untitled

Category 2 suggestion: Incorporate integral fastening elements into functional parts, or change securing methods, to eliminate as many as possible of the highlighted separate fasteners. The design improvements which are realized by following Category 2 suggestions are somewhat smaller than those realized from the Category 1 suggestions. For that reason, these suggestions should only be considered after all practical Category 1 suggestions have been exhausted.

Name	Notes	Part number	Total quantity	Process time per product, s	Parent assembly
nut		7	4	69.38	Untitled
set screw		8	4	58.62	Untitled
nut		3	2	36.14	Untitled

Category 2 suggestion: Combine connected items or attempt to rearrange the structure of the product to eliminate the highlighted items whose function is solely to make connections. The design improvements which are realized by following Category 2 suggestions are somewhat smaller than those realized from the Category 1 suggestions. For that reason, these suggestions should only be considered after all practical Category 1 suggestions have been exhausted.

Name	Notes	Part number	Total quantity	Process time per product, s	Parent assembly
t-bolt		1	6	25.32	Untitled
linear rod support		6	2	8.44	Untitled

Category 3 suggestion: Reduce difficulties associated with handling and inserting the highlighted items. The design improvements realized by following a Category 3 suggestion are typically the smallest. No parts or separate operations are eliminated and the product structure is not simplified. Only existing parts are made easier to assemble. For this reason, Category 3 suggestions should be the lowest priority of all redesign suggestions.

Name	Notes	Part number	Total quantity	Handling or insertion difficulties	Process time savings, s	Parent assembly
nut		7	4	Restricted vision	16.00	Untitled
nut		3	2	Restricted vision	8.00	Untitled
t-bolt		1	6	Alignment	6.00	Untitled
set screw		8	4	Careful handling	3.00	Untitled
linear rod support		6	2	Alignment	2.00	Untitled
lin support block bearing		2	1	Alignment	1.00	Untitled

C.2.1.2 Redesign 1 (Linear Profile)

C.2.1.2.1 Design for Assembly (Manual)

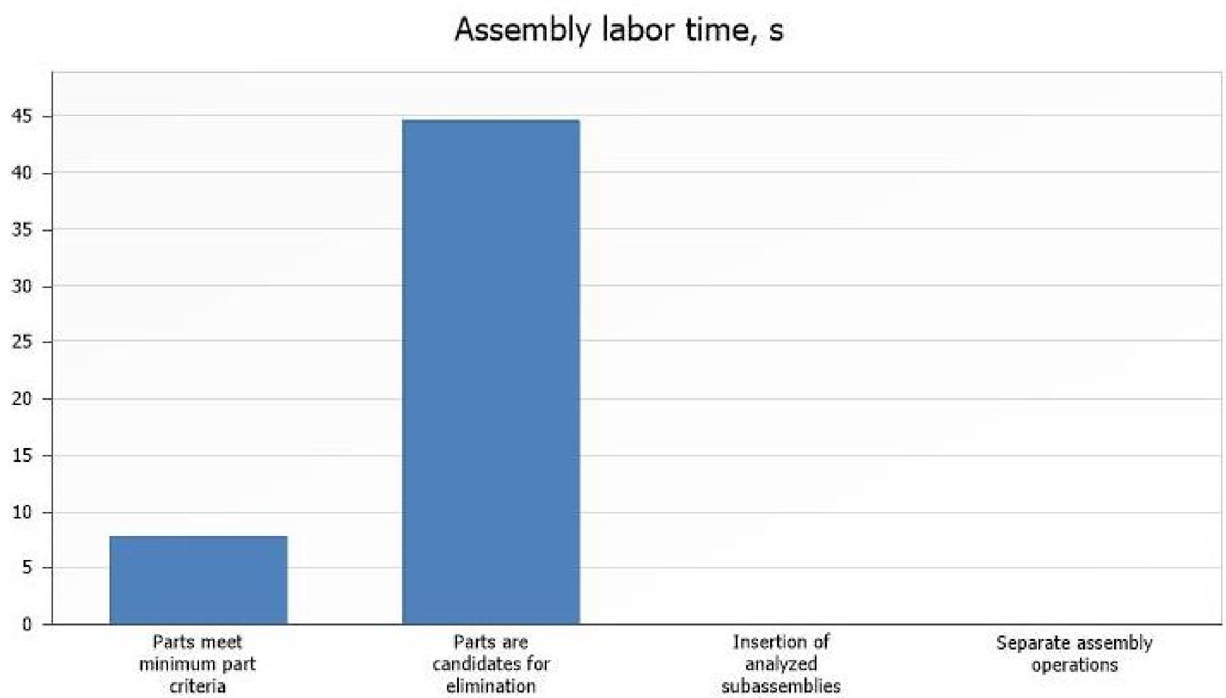
1	2	3	4	5	6	7	8	9				
Part I.D. No.	number of times the operation is carried out consecutively	two-digit manual handling code	manual handing time per part	two-digit manual insertion code	manual insertion time per part	operation time (seconds)	operation cost (cents)	figures for estimation of theoretical minimum parts	Parallel Guide Motion			
1	2	20	1.8	0.0	1.5	6.6	2.64	0	t-nuts			
2	1	20	1.8	0.0	1.5	3.3	1.32	0	Igus Linear Rail			
3	2	0.0	1.13	38	6	14.3	5.7	0	Bolts			
4	1	20.0	1.8	0.0	1.5	3.3	1.32	1	Carriage			
						27.5	11	1				
						TM	CM	NM	Design Efficiency		=	**10.92%**

C.2.1.2.2 Design for Assembly Analysis (Boothroyd Dewhurst)

Entries including repeats	Redesign
Parts meet minimum part criteria	2
Parts are candidates for elimination	4
Analyzed subassemblies	0
Separate assembly operations	0
Total entries	6

Assembly labor time, s	
Parts meet minimum part criteria	7.77
Parts are candidates for elimination	44.58
Insertion of analyzed subassemblies	0
Separate assembly operations	0
Total assembly labor time	52.35

Design efficiency	
DFA Index	12.65



C.2.1.2.3 Redesign Suggestions from Boothroyd Dewhurst

Category 2 suggestion: Incorporate integral fastening elements into functional parts, or change securing methods, to eliminate as many as possible of the highlighted separate fasteners. The design improvements which are realized by following Category 2 suggestions are somewhat smaller than those realized from the Category 1 suggestions. For that reason, these suggestions should only be considered after all practical Category 1 suggestions have been exhausted.

Name	Notes	Part number	Total quantity	Process time per product, s	Parent assembly
nut		3	2	36.14	Untitled

Category 2 suggestion: Combine connected items or attempt to rearrange the structure of the product to eliminate the highlighted items whose function is solely to make connections. The design improvements which are realized by following Category 2 suggestions are somewhat smaller than those realized from the Category 1 suggestions. For that reason, these suggestions should only be considered after all practical Category 1 suggestions have been exhausted.

Name	Notes	Part number	Total quantity	Process time per product, s	Parent assembly
t-bolt		1	2	8.44	Untitled

Category 3 suggestion: Reduce difficulties associated with handling and inserting the highlighted items. The design improvements realized by following a Category 3 suggestion are typically the smallest. No parts or separate operations are eliminated and the product structure is not simplified. Only existing parts are made easier to assemble. For this reason, Category 3 suggestions should be the lowest priority of all redesign suggestions.

Name	Notes	Part number	Total quantity	Handling or insertion difficulties	Process time savings, s	Parent assembly
nut		3	2	Restricted vision	8.00	Untitled
t-bolt		1	2	Alignment	2.00	Untitled

C.2.1.3 Redesign 2 (Extrusion Slider)

C.2.1.3.1 Design for Assembly (Manual)

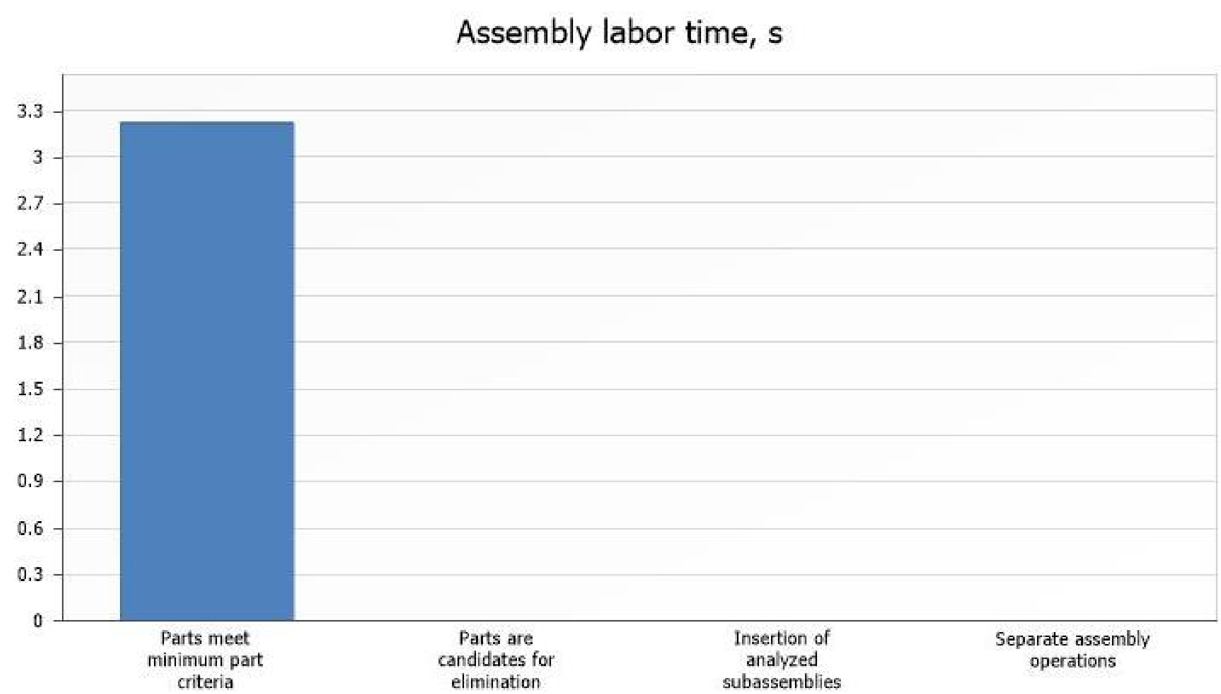
1	2	3	4	5	6	7	8	9				
Part I.D. No.	number of times the operation is carried out consecutively	two-digit manual handling code	manual handing time per part	two-digit manual insertion code	manual insertion time per part	operation time (seconds)	operation cost (cents)	figures for estimation of theoretical minimum parts	Parallel Guide Motion			
1	1	20.0	1.8	0.0	1.5	3.3	1.32	1	Carriage			
						3.3	1.32	1				
						TM	CM	NM	Design Efficiency		=	**90.91%**

C.2.1.3.1 Design for Assembly Analysis (Boothroyd Dewhurst)

Entries including repeats	**Redesign2**
Parts meet minimum part criteria	1
Parts are candidates for elimination	0
Analyzed subassemblies	0
Separate assembly operations	0
Total entries	1

Assembly labor time, s	
Parts meet minimum part criteria	3.22
Parts are candidates for elimination	0
Insertion of analyzed subassemblies	0
Separate assembly operations	0
Total assembly labor time	3.22

Design efficiency	
DFA Index	90.99



C.2.2 Frame Gusset

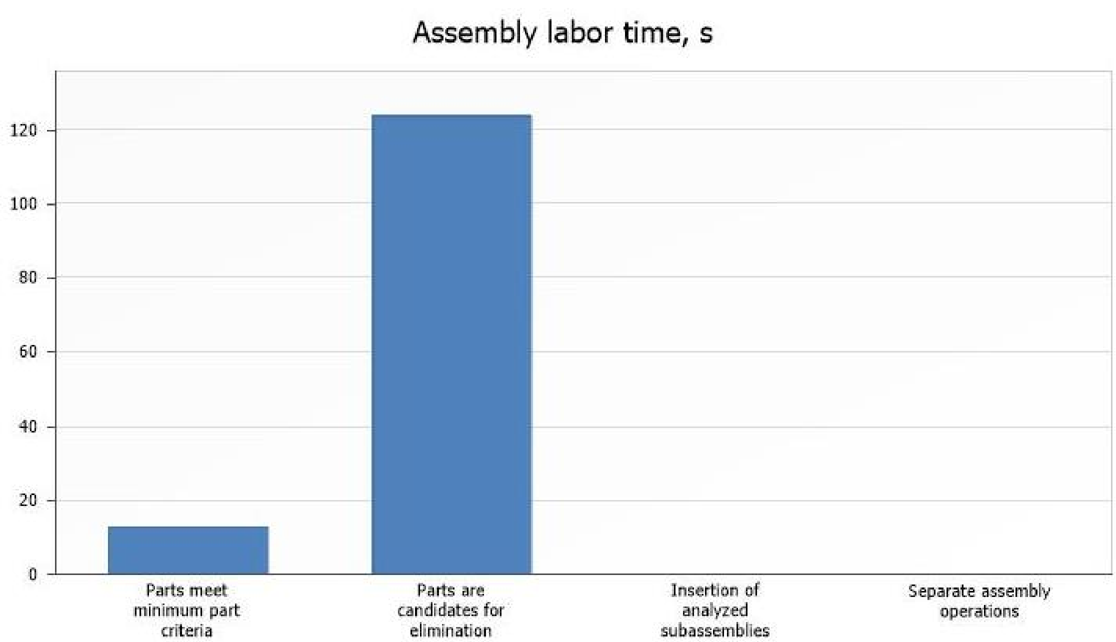
C.2.2.1 Original Design (Gusset Plate)

C.2.2.1.1 Design for Assembly (Boothroyd Dewhurst)

Entries including repeats	Original
Parts meet minimum part criteria	2
Parts are candidates for elimination	11
Analyzed subassemblies	0
Separate assembly operations	0
Total entries	13

Assembly labor time, s	
Parts meet minimum part criteria	12.58
Parts are candidates for elimination	123.72
Insertion of analyzed subassemblies	0
Separate assembly operations	0
Total assembly labor time	136.30

Design efficiency	
DFA Index	4.86



C.2.2.1.2 Redesign Suggestions from Boothroyd Dewhurst

Category 2 suggestion: Incorporate integral fastening elements into functional parts, or change securing methods, to eliminate as many as possible of the highlighted separate fasteners. The design improvements which are realized by following Category 2 suggestions are somewhat smaller than those realized from the Category 1 suggestions. For that reason, these suggestions should only be considered after all practical Category 1 suggestions have been exhausted.

Name	Notes	Part number	Total quantity	Process time per product, s	Parent assembly
Nut			6	102.62	Untitled

Category 2 suggestion: Combine connected items or attempt to rearrange the structure of the product to eliminate the highlighted items whose function is solely to make connections. The design improvements which are realized by following Category 2 suggestions are somewhat smaller than those realized from the Category 1 suggestions. For that reason, these suggestions should only be considered after all practical Category 1 suggestions have been exhausted.

Name	Notes	Part number	Total quantity	Process time per product, s	Parent assembly
T-Bolt			5	21.10	Untitled

Category 3 suggestion: Reduce difficulties associated with handling and inserting the highlighted items. The design improvements realized by following a Category 3 suggestion are typically the smallest. No parts or separate operations are eliminated and the product structure is not simplified. Only existing parts are made easier to assemble. For this reason, Category 3 suggestions should be the lowest priority of all redesign suggestions.

Name	Notes	Part number	Total quantity	Handling or insertion difficulties	Process time savings, s	Parent assembly
Nut			6	Restricted vision	24.00	Untitled
T-Bolt			5	Awkward, Alignment	5.00	Untitled
Extrusion Base			1	Difficult grasp	0.90	Untitled

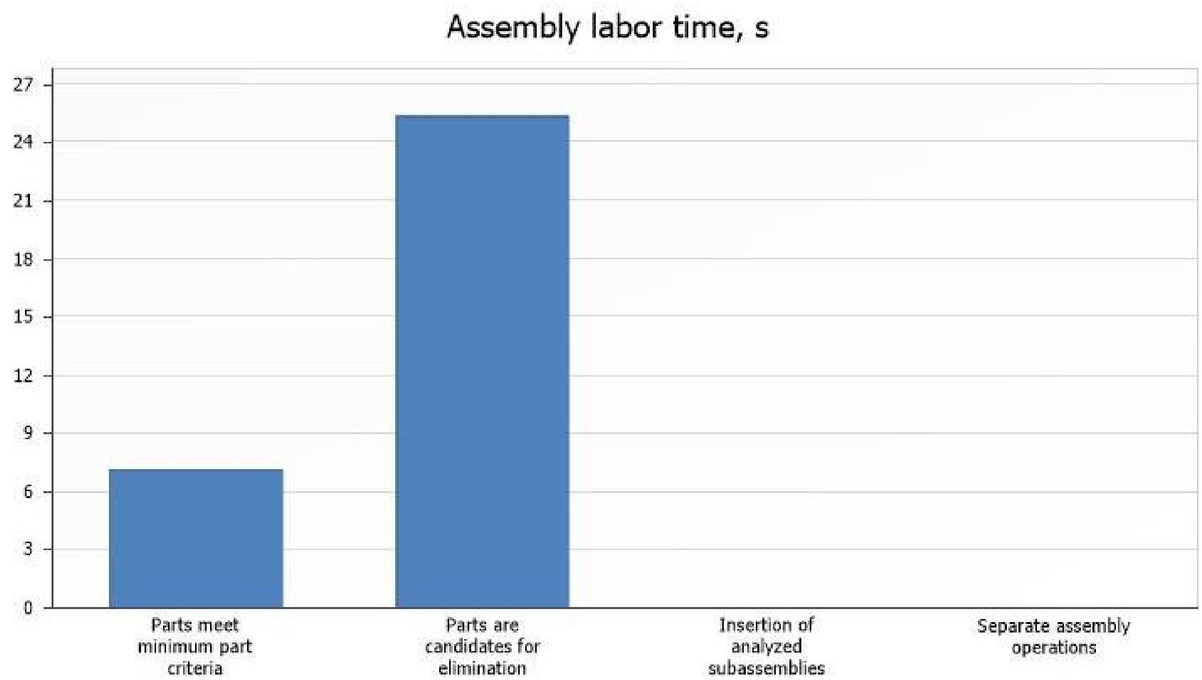
C.2.2.2 Redesign (End Bolt)

Design for Assembly Analysis (Boothroyd Dewhurst)

Entries including repeats	Redesign
Parts meet minimum part criteria	2
Parts are candidates for elimination	1
Analyzed subassemblies	0
Separate assembly operations	0
Total entries	3

Assembly labor time, s	
Parts meet minimum part criteria	7.08
Parts are candidates for elimination	25.32
Insertion of analyzed subassemblies	0
Separate assembly operations	0
Total assembly labor time	32.40

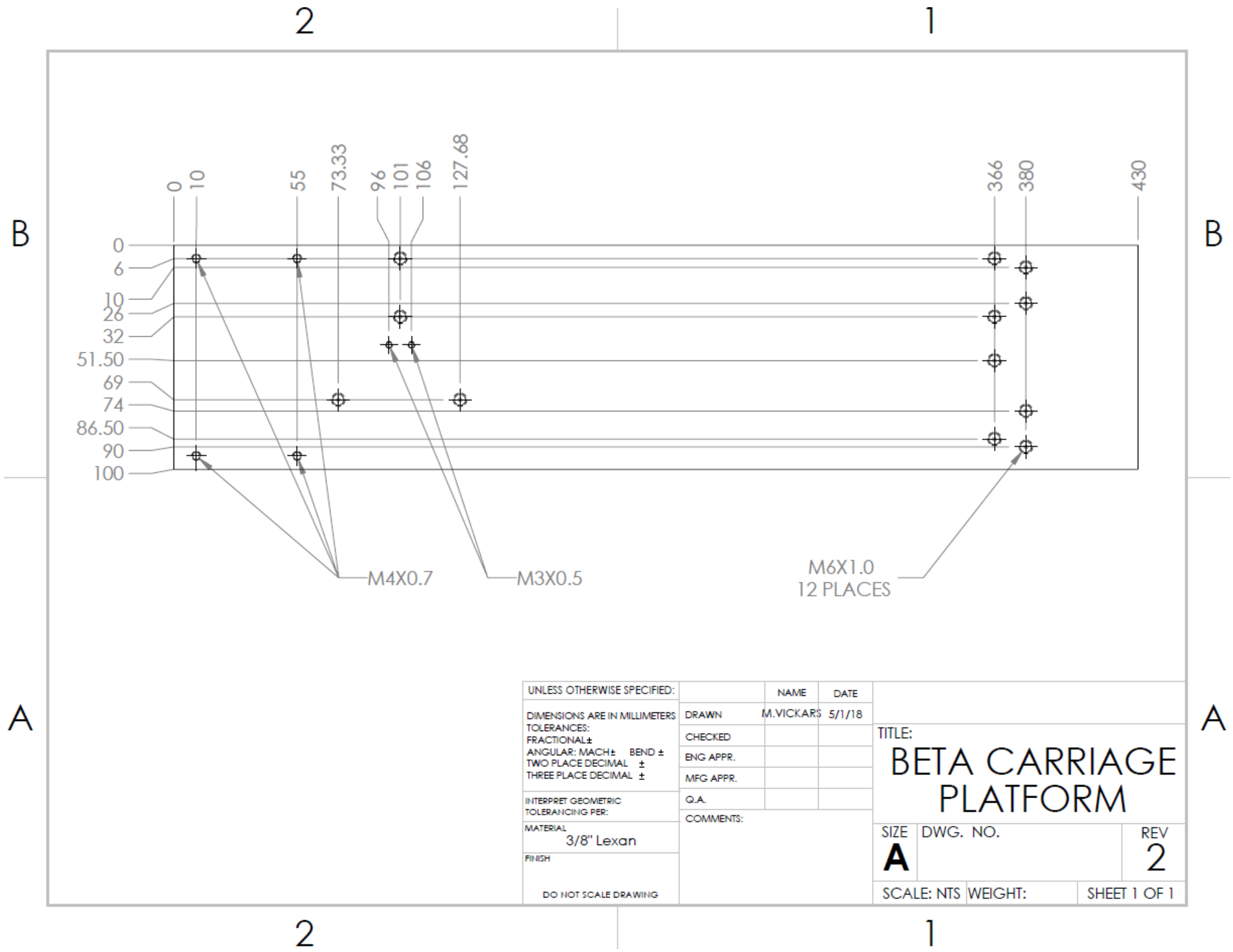
Design efficiency	
DFA Index	20.43



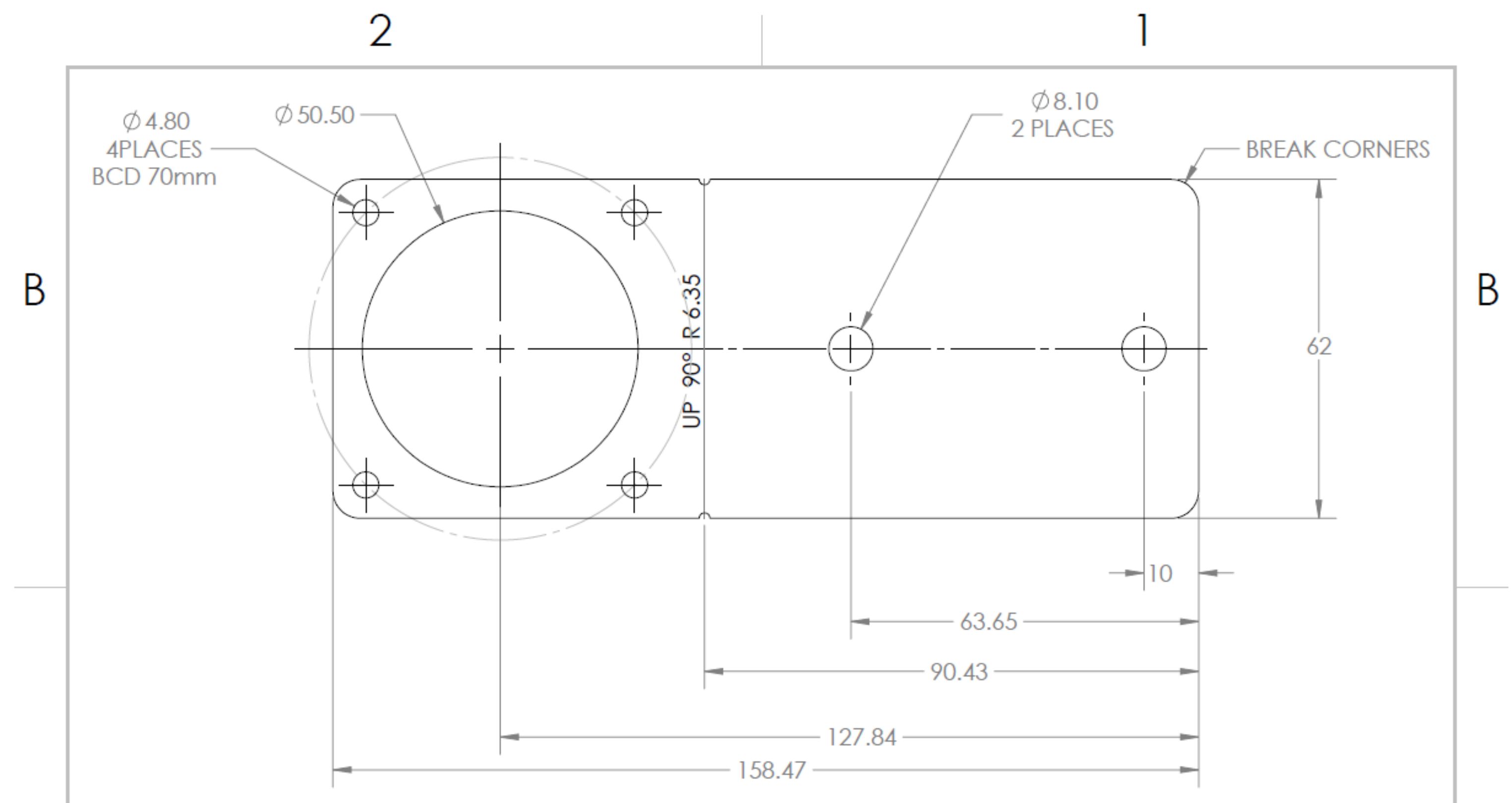
C.3 Bill of Materials

	Bill of Materials for Alpha Prototype		
	Name	**Specifications**	**Quantity**
Electrical	Power Cable	5m	2
	Encoder Cable	5m	2
	Motors	MSM031B	2
	Cable Track	B15i-025-075-0 Plus Brackets 1025-34PZ	1m
	Drag Chain	DRAGCHAIN-0707	1m
	Arduino Nano	V3.0 ATmega328P 5V	1
	Stepper Motor	Nema17 Stepper Motor	1
	Stepper Driver	EasyDriver Shield V44 A3967	1
	Potentiometer	20kOhm	1
	Toggle Switch	2 position	2
	Toggle Switch	3 position	1
Mechanical	Aluminum Extrusion	45mmx45mm x815mm	1
		45mmx45mm x475mm	2
		45mmx90mm x815mm	1
	Central Bolt	M12	4
	Anti Torsion Element	10mm Slot	4
	Couplers	Flexible Couplings 6.35mm to 11mm	1
	Couplers	Flexible Couplings 8mm to 11mm	1
	Steel tubing	25mm diameter x 280mm	2
	Ground Steel Rod	8mm diameter	1m
	Bearings	608ZZ	6
	Steel Plate	3/16" - 200mm x 200mm	1
	Aluminum Flatbar	1" x 4" x 130mm	1
	Lead Screw (parallel)	4 start 8mm pitch	1m
	Lead Nut	4 start 8mm pitch	1
	Lead Screw (perpendicular)	5mm Pitch (Ball Screw)	1
	Linear Rail	12mm Dia. (BLANK Length)	1
	Linear Bearing	R065801200 (Bosch)	1
	Rail supports	R105801200 (Bosch)	2
	Double Rail (6mm square)	WSQ-06-30-850 (Igus)	1m
	Square Rail Carriage (6mm)	WW-06-30-100 (Igus)	1
	Single Rail (10mm diameter)	WS-10 (Igus)	1m
	Single Rail Bearing (10mm diameter)	WJ200UM-01-10 (Igus)	2
	Plexiglass	3/8" - 100mm x 480mm	1
	Toothed Belt	T5 Series, 200m long	1
	Cellophane	10.75 in wide	2m

C.4 Shop Drawings



2
1
B
A
0
10
55
73.33
96
101
106
127.68
366
380
430
0
6
10
26
32
51.50
69
74
86.50
90
100
M4X0.7
M3X0.5
M6X1.0
12 PLACES
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
3/8" Lexan
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
M.VICKARS
5/1/18
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
BETA CARRIAGE PLATFORM
SIZE
A
DWG. NO.
REV
2
SCALE: NTS
WEIGHT:
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.5
THREE PLACE DECIMAL ±0.2

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
3/16" MILD STEEL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	M.VICKARS	05/04/18
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

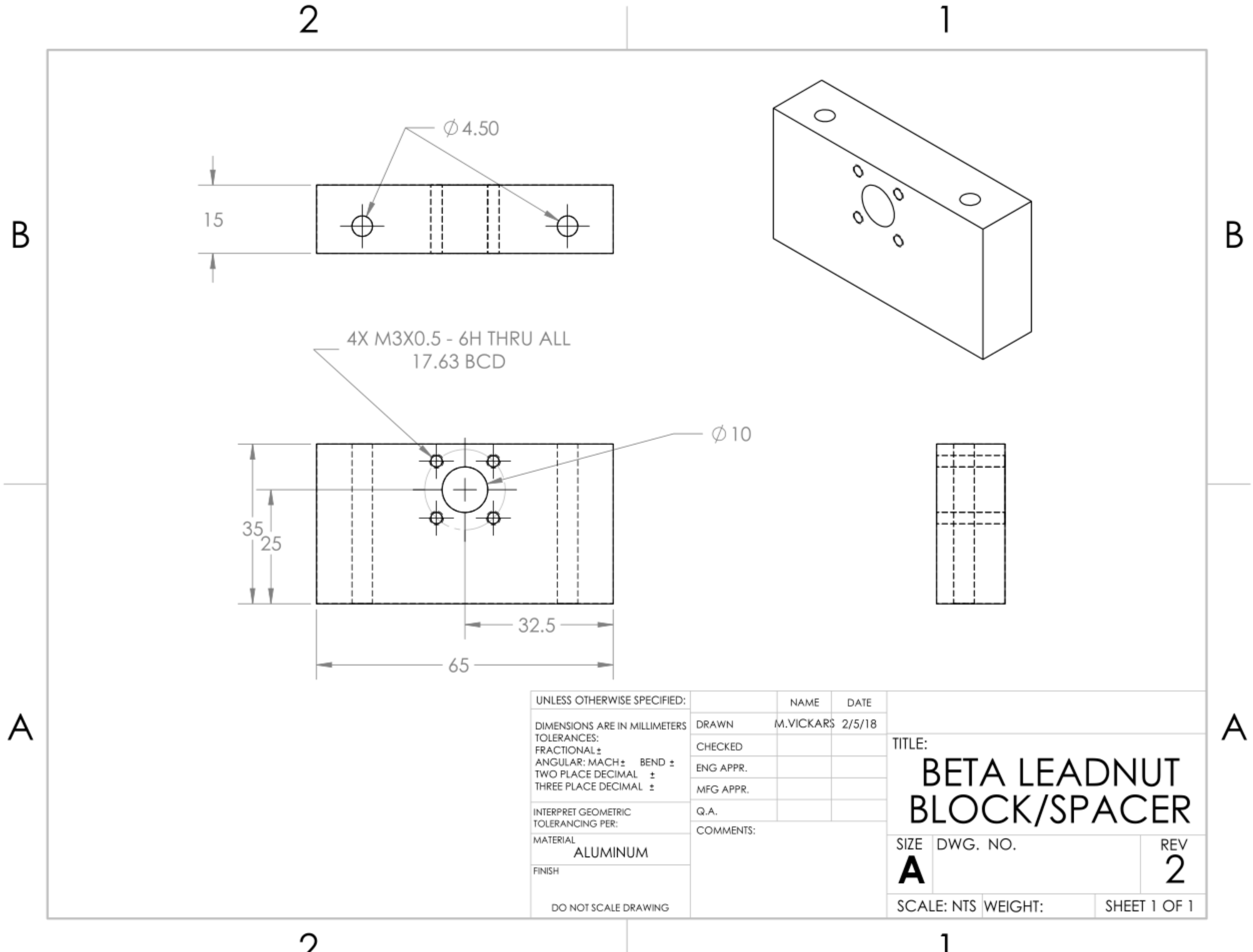
COMMENTS:

TITLE:

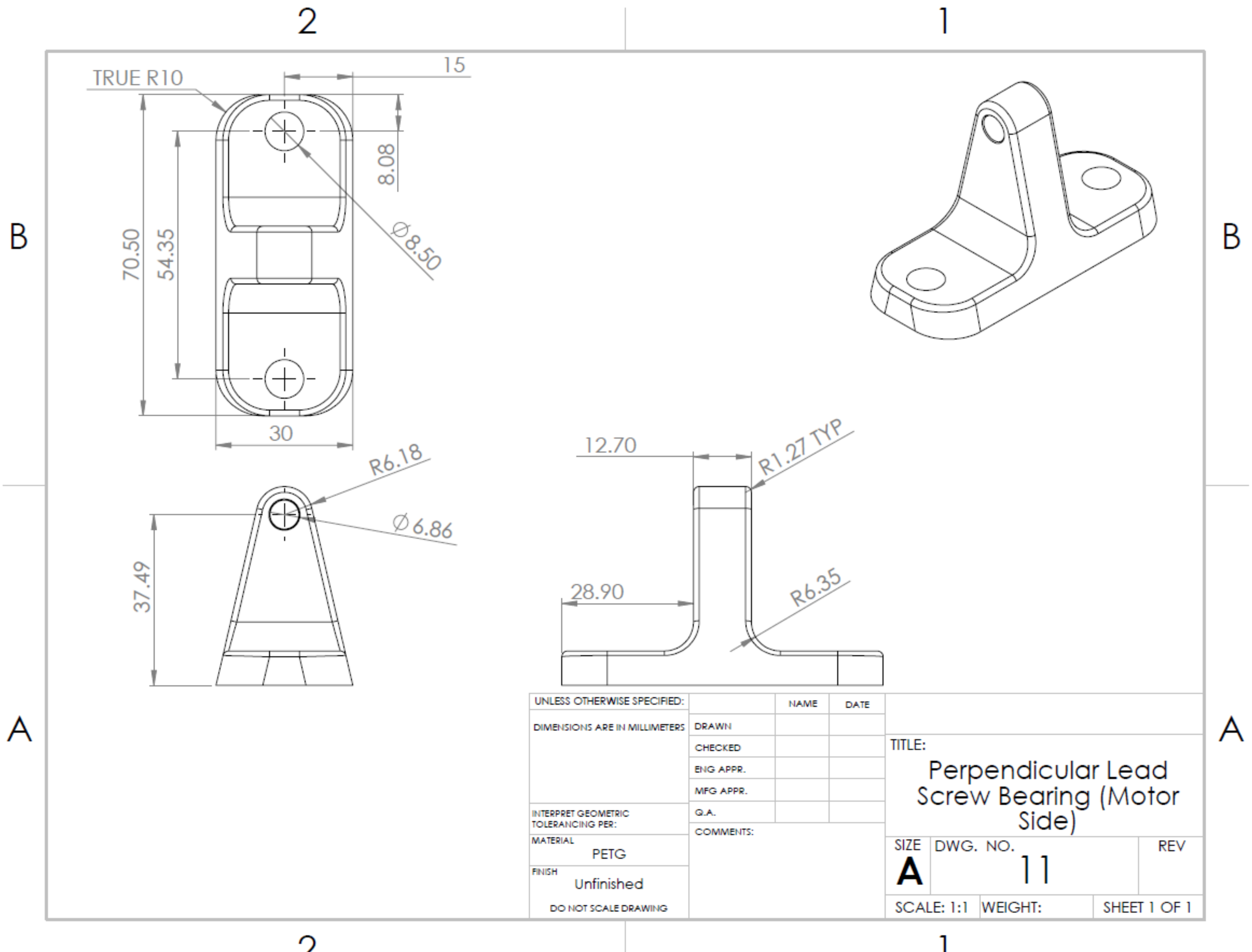
MOTOR MOUNTS

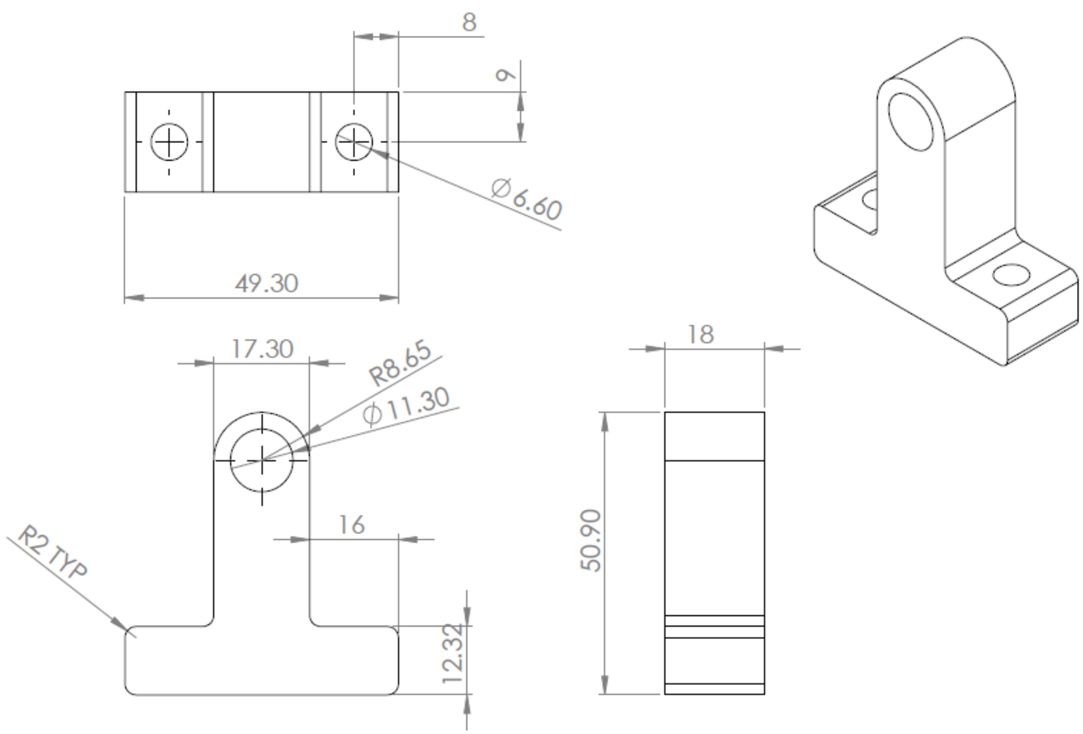
SIZE A | DWG. NO. | REV 2

SCALE: NTS | WEIGHT: | SHEET 1 OF 1


Ø 4.50
15
4X M3X0.5 - 6H THRU ALL
17.63 BCD
Ø 10
35
25
32.5
65
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
M.VICKARS
2/5/18
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
BETA LEADNUT BLOCK/SPACER
SIZE
A
DWG. NO.
REV
2
SCALE: NTS
WEIGHT:
SHEET 1 OF 1

C.5 3D Printed Parts


2
1
B
A
TRUE R10
15
8.08
Ø8.50
70.50
54.35
30
R6.18
Ø6.86
37.49
12.70
R1.27 TYP
28.90
R6.35
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PETG
FINISH
Unfinished
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Perpendicular Lead Screw Bearing (Motor Side)
SIZE
A
DWG. NO.
11
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

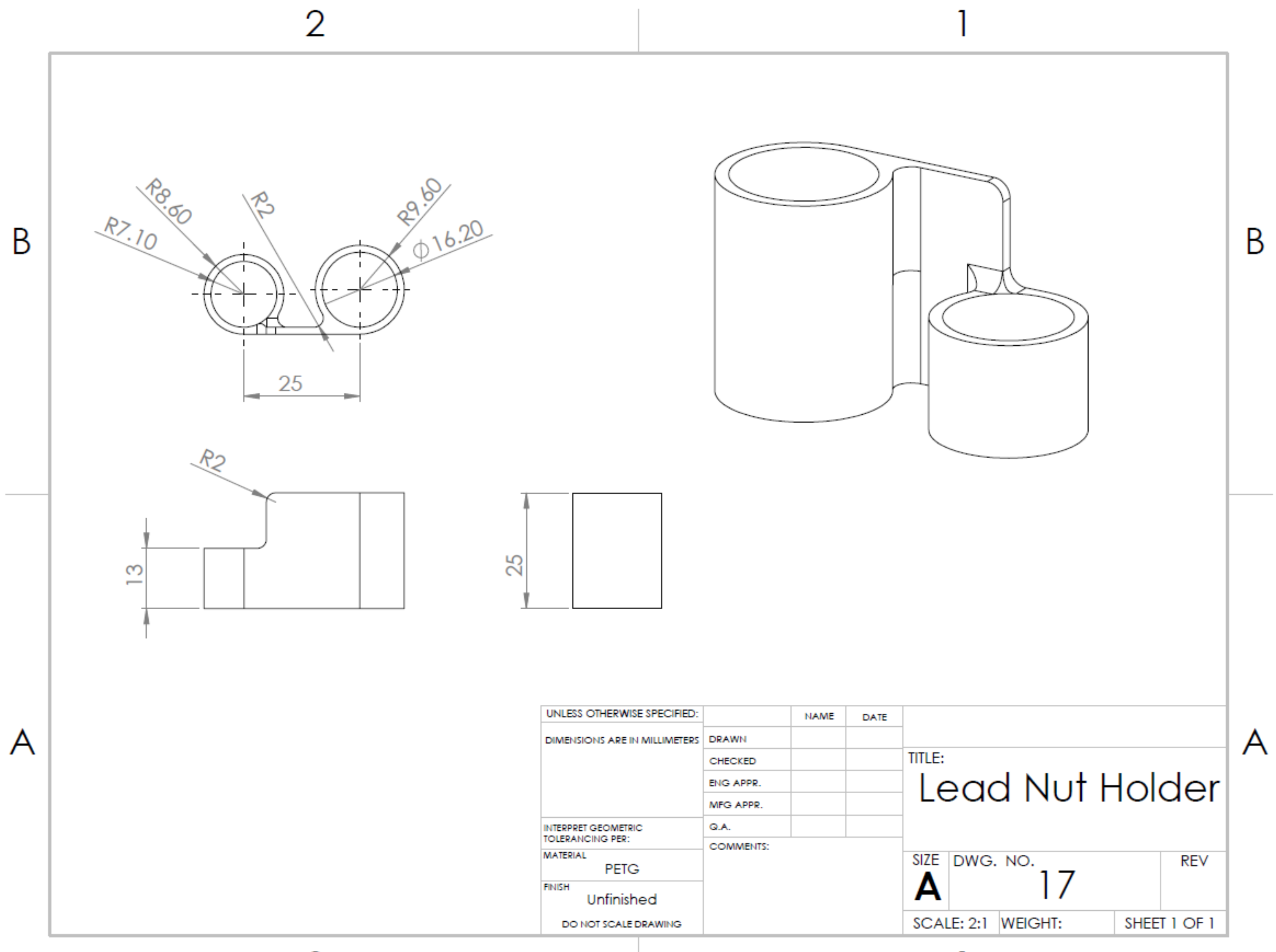


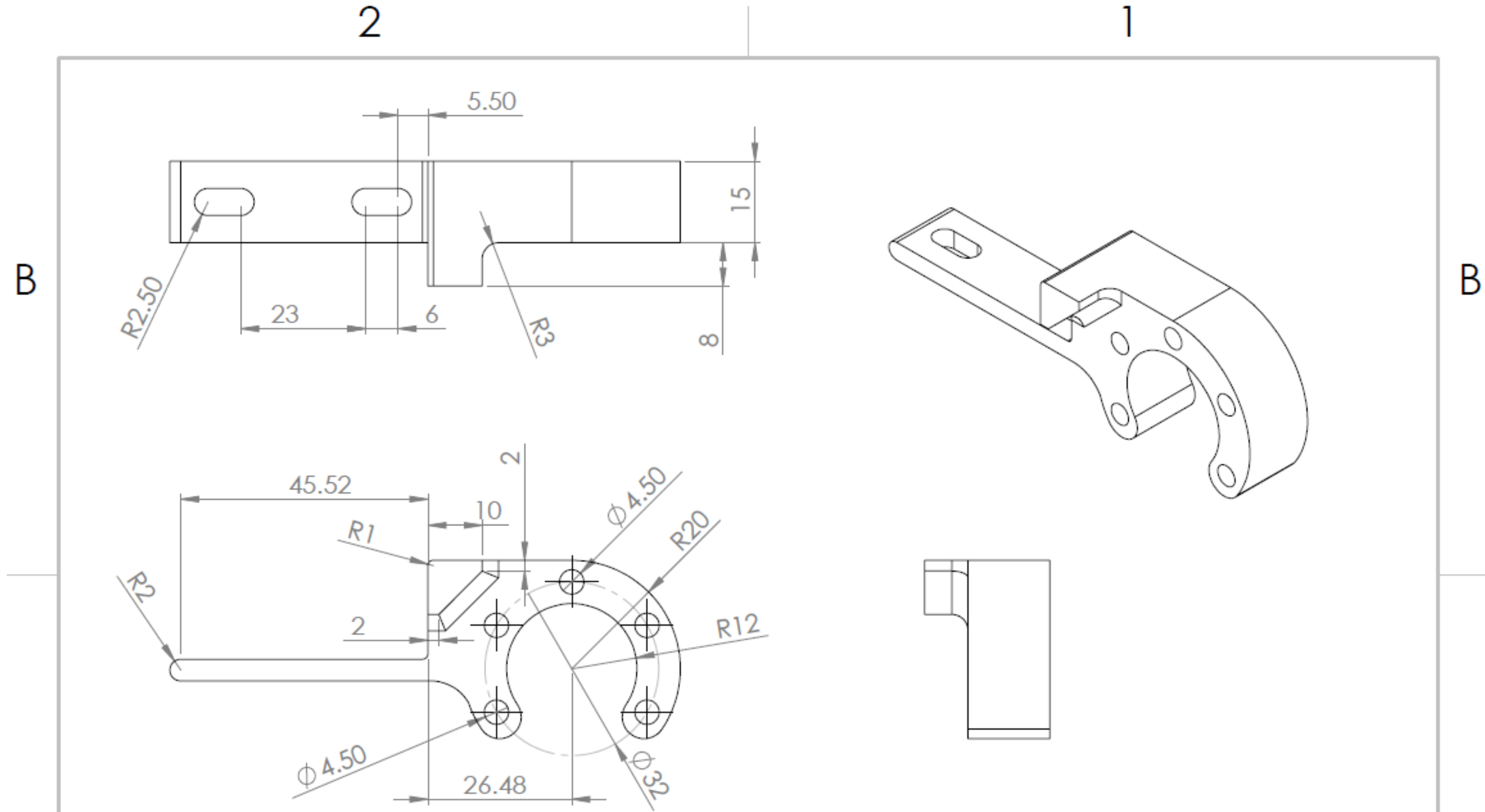
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MILLIMETERS	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL PETG	COMMENTS:		
FINISH Unfinished			
DO NOT SCALE DRAWING			

TITLE:

Perpendicular Lead Screw Bearing (Far Side)

SIZE	DWG. NO.	REV
A	10	
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1


2
1
B
A
R8.60
R7.10
R2
R9.60
ϕ16.20
25
R2
13
25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PETG
FINISH
Unfinished
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Lead Nut Holder
SIZE
A
DWG. NO.
17
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MILLIMETERS	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL PETG	COMMENTS:		
FINISH Unfinished			
DO NOT SCALE DRAWING			

TITLE:

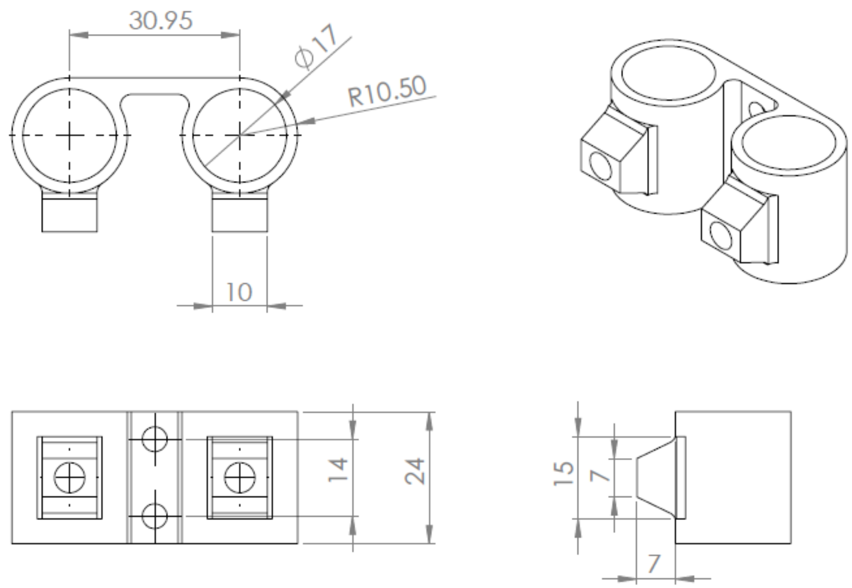
Lead Screw Bridge

SIZE	DWG. NO.	REV
A	16	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

2 1

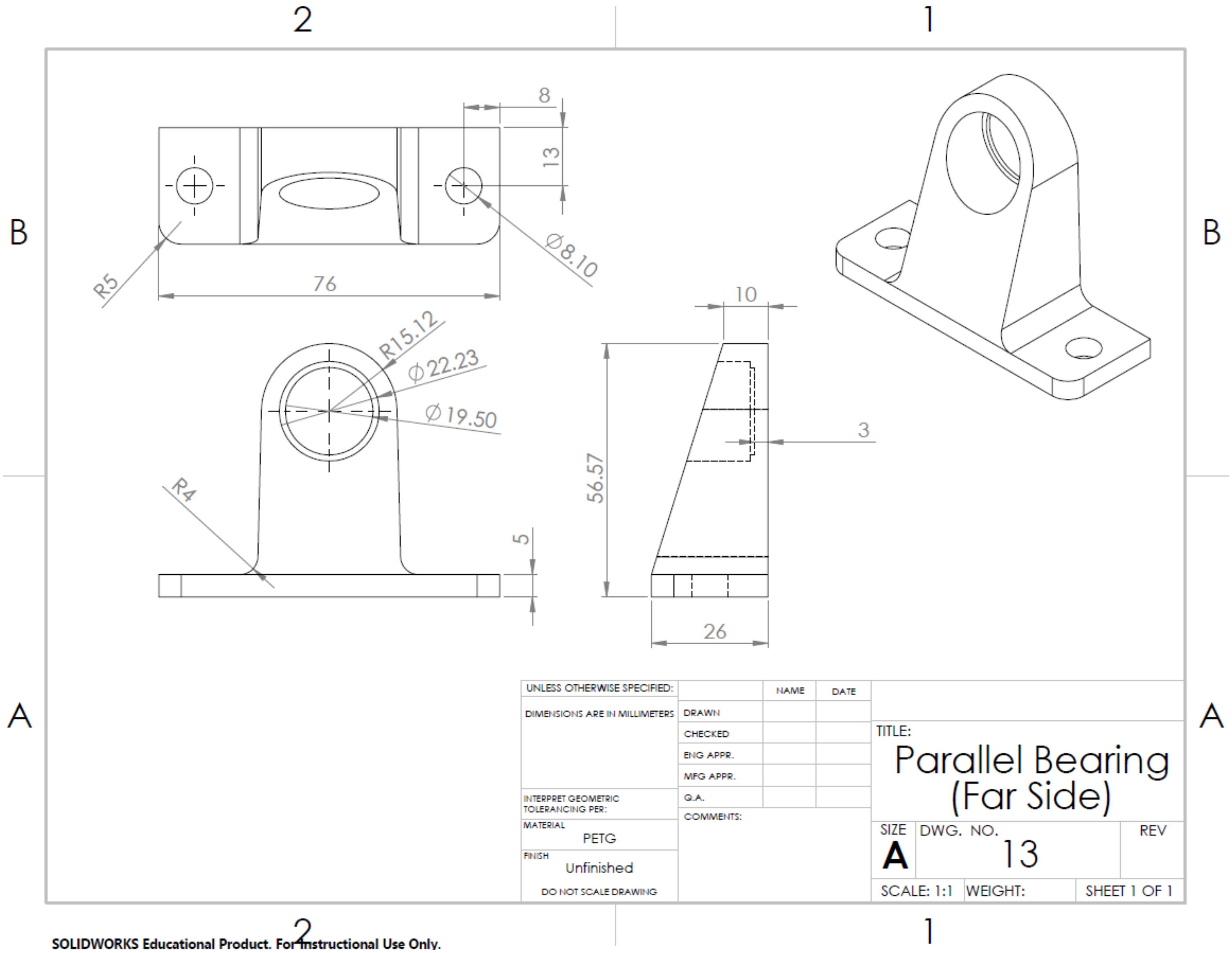
B B



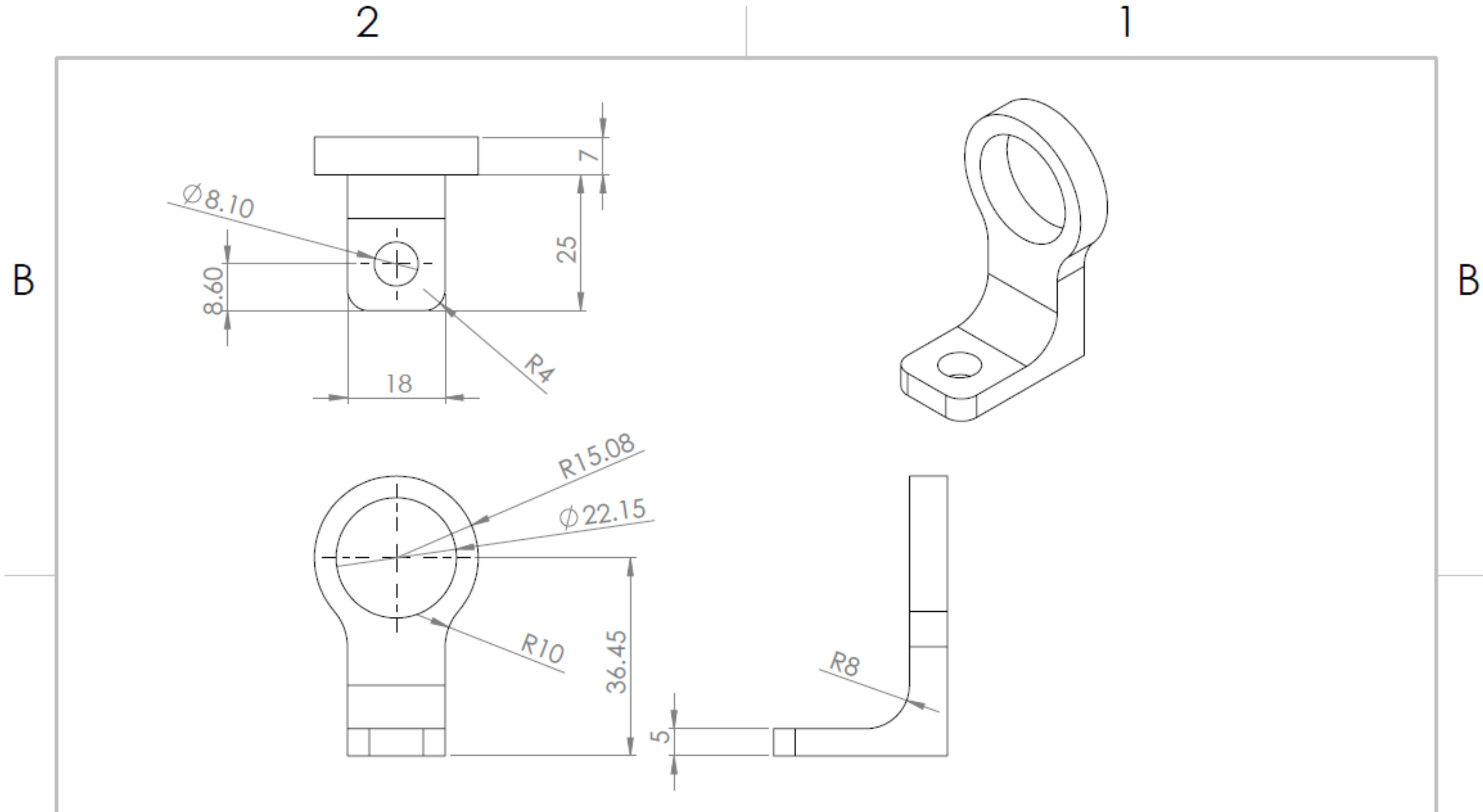
A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MILLIMETERS	DRAWN			TITLE: Pen Holder
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL PETG	COMMENTS:			SIZE A · DWG. NO. 18 · REV
FINISH Unfinished				
DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1

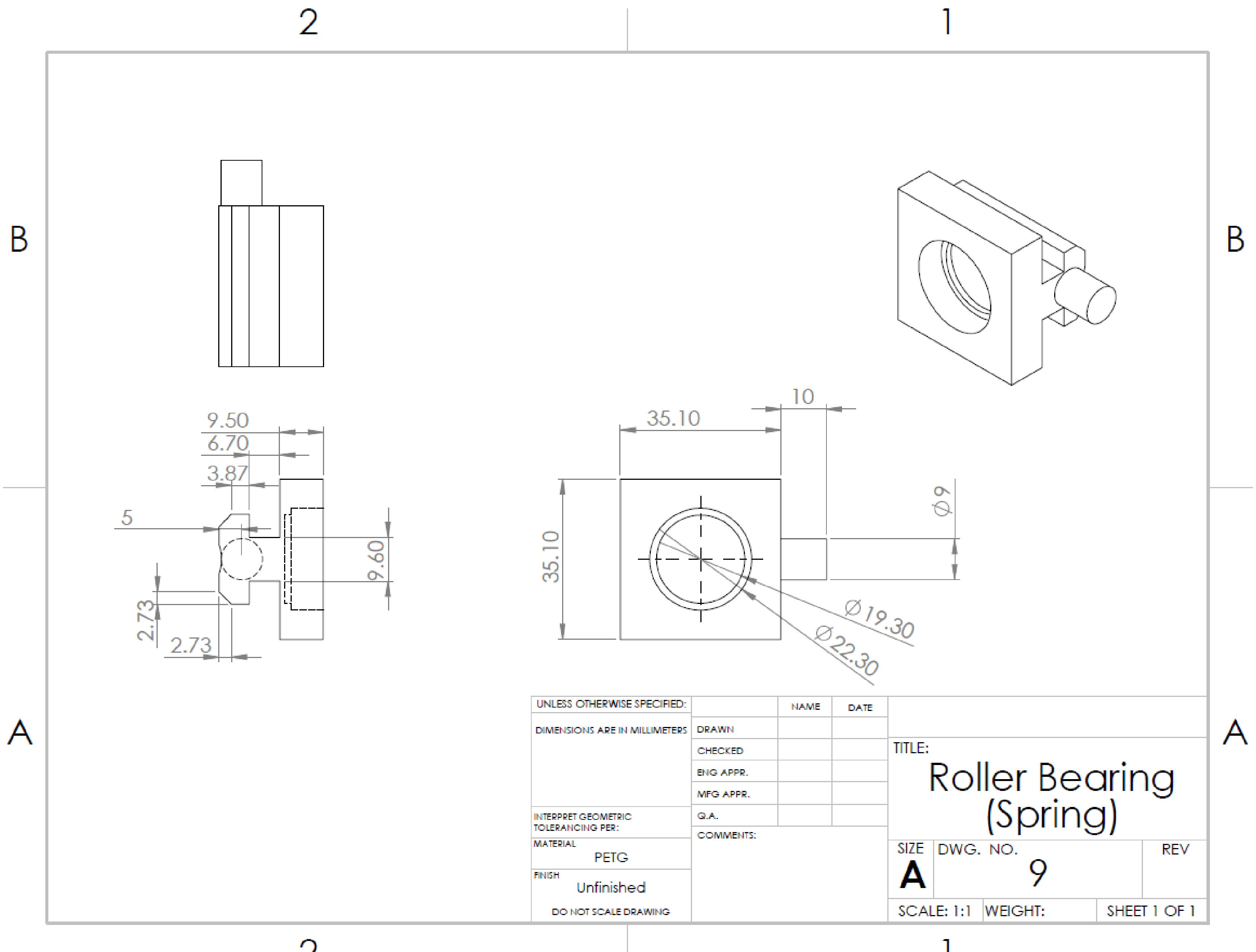
2 1

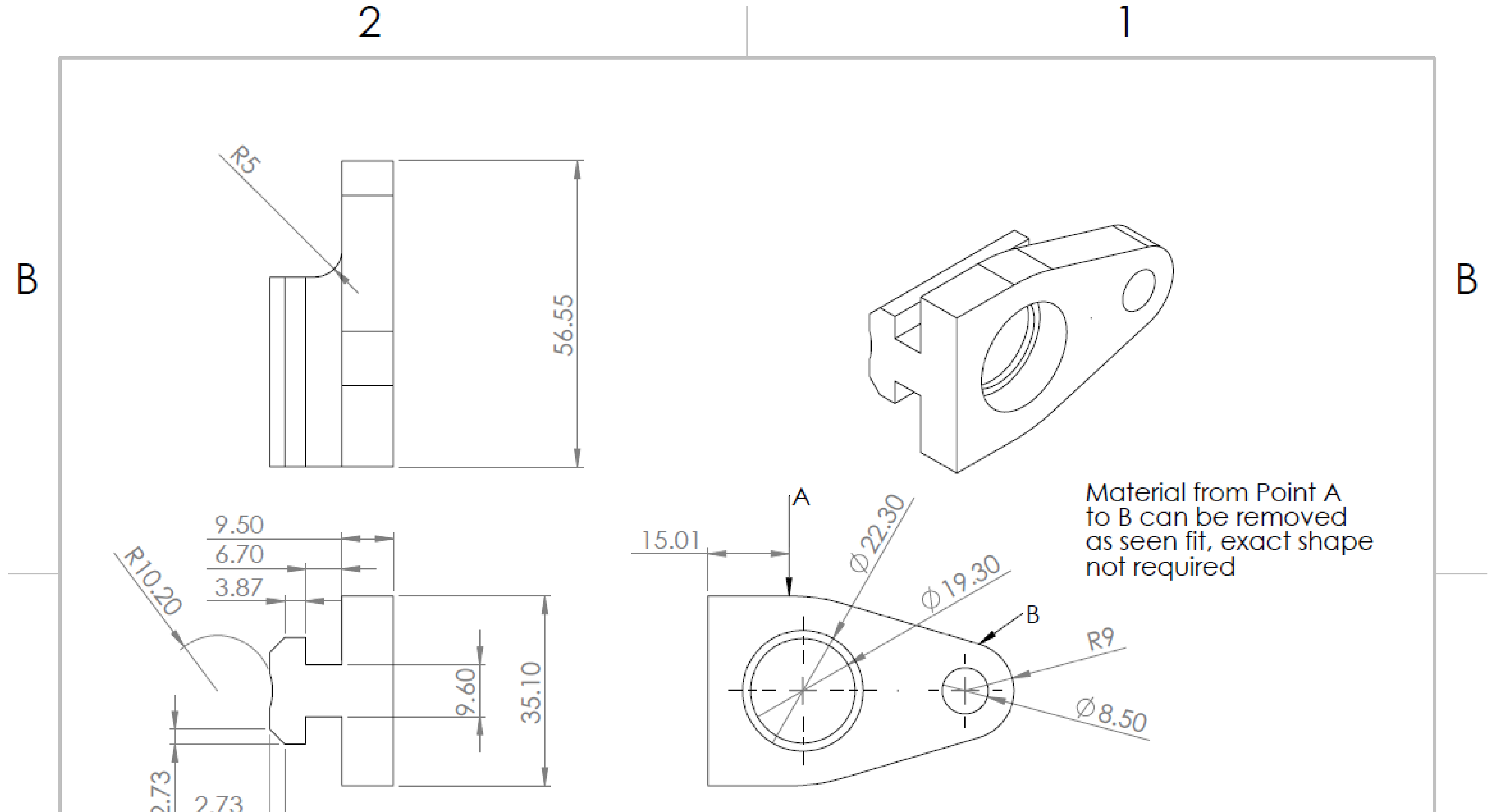


2
1
B
A
8
13
Ø8.10
R5
76
10
R15.12
Ø22.23
Ø19.50
3
R4
5
56.57
26
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PETG
FINISH
Unfinished
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Parallel Bearing (Far Side)
SIZE
A
DWG. NO.
13
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

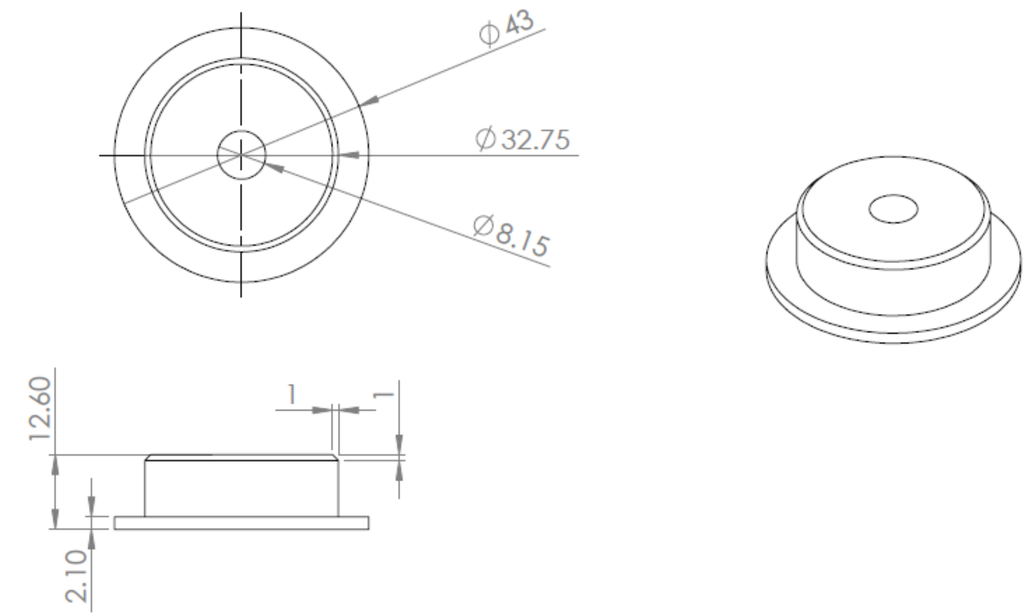


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MILLIMETERS	DRAWN			
	CHECKED			TITLE: Parallel Bearing (Motor Side)
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL PETG	COMMENTS:			SIZE A · DWG. NO. 12 · REV
FINISH Unfinished				
DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1

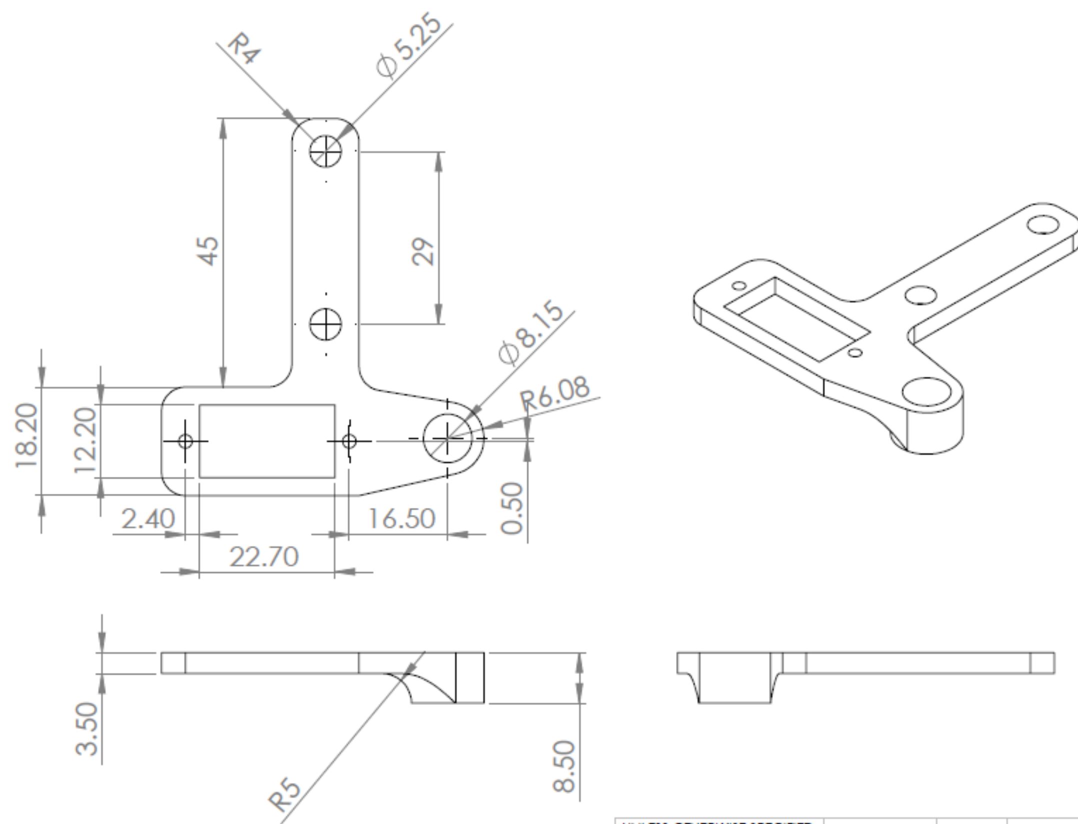

2
1
B
A
9.50
6.70
3.87
5
9.60
2.73
2.73
35.10
10
35.10
Ø9
Ø19.30
Ø22.30
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PETG
FINISH
Unfinished
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Roller Bearing (Spring)
SIZE
A
DWG. NO.
9
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MILLIMETERS	DRAWN			TITLE: Roller Bearing (Stationary)
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL PETG	COMMENTS:			SIZE A — DWG. NO. 8 — REV
FINISH Unfinished				
DO NOT SCALE DRAWING				SCALE: 1:1 — WEIGHT: — SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN MILLIMETERS	DRAWN			TITLE:	
	CHECKED			Roller Insert	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL PETG	COMMENTS:			SIZE A	DWG. NO. 7 / REV
FINISH Unfinished					
DO NOT SCALE DRAWING				SCALE: 1:1 / WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL PETG

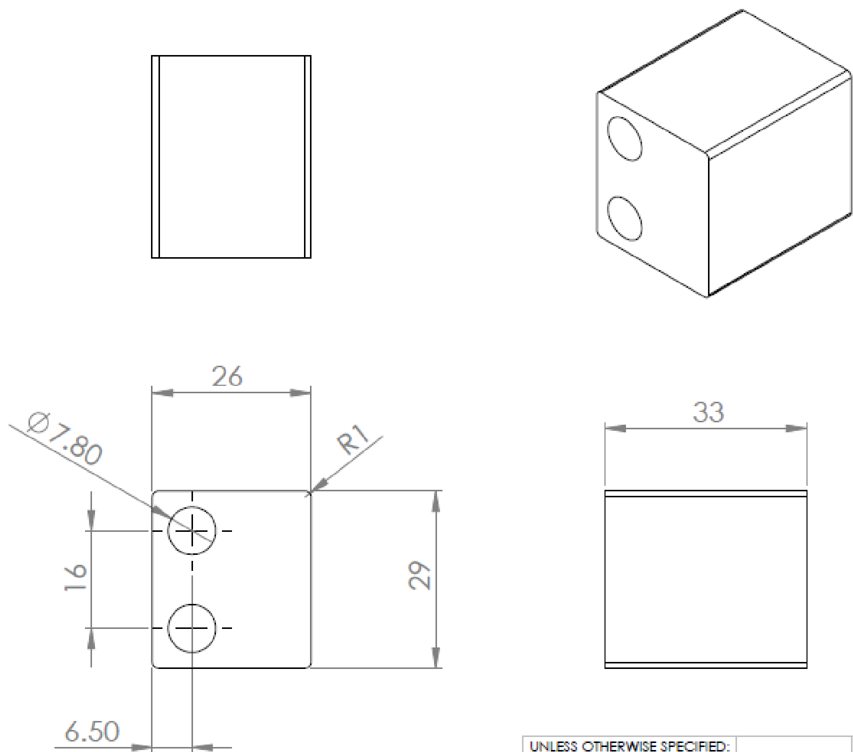
FINISH Unfinished

DO NOT SCALE DRAWING

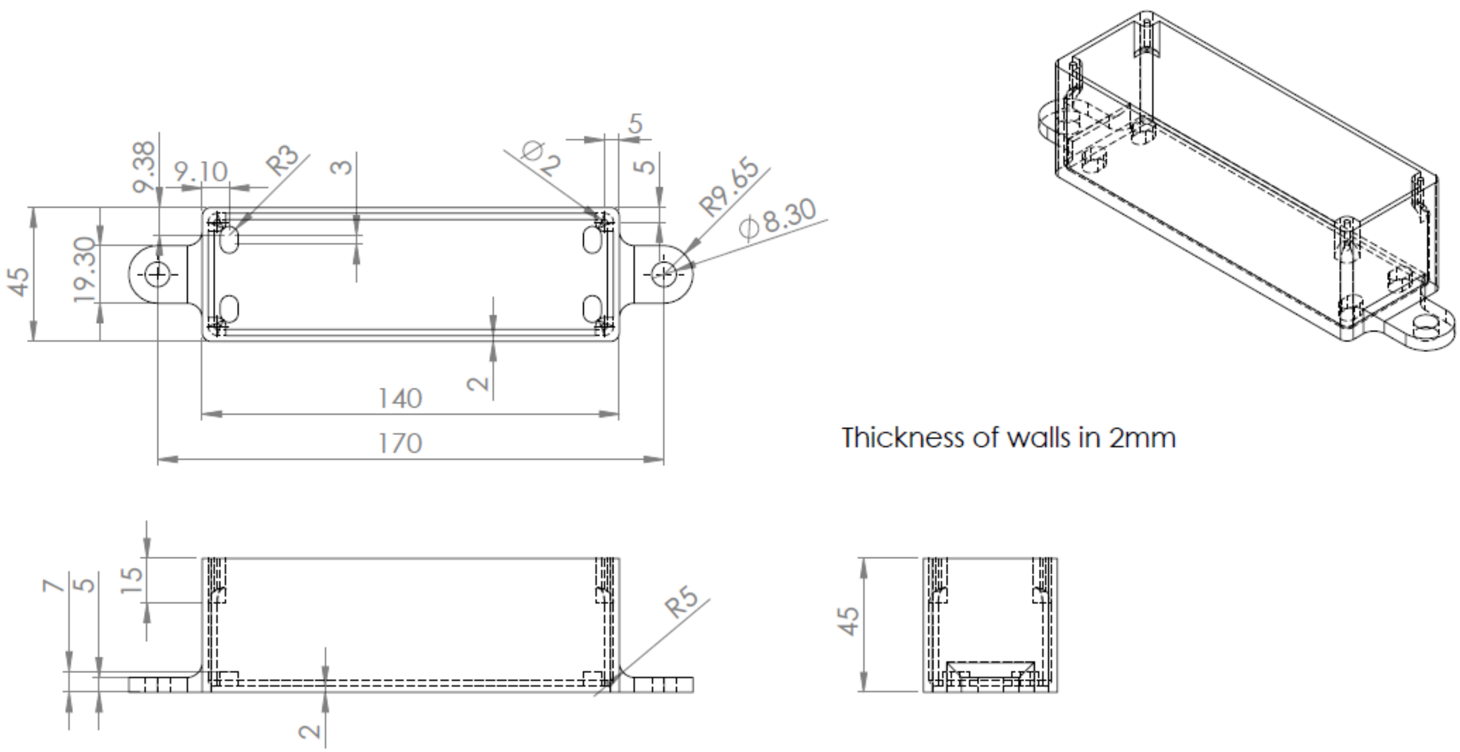
TITLE: Servo Holder

SIZE A DWG. NO. 19 REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MILLIMETERS	DRAWN			TITLE: Spacer (Follow Side)
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL PETG	COMMENTS:			SIZE A · DWG. NO. 5 · REV
FINISH Unfinished				
DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MILLIMETERS	DRAWN			
	CHECKED			TITLE: Circuit Box
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL PETG	COMMENTS:			SIZE A · DWG. NO. 15 · REV
FINISH Unfinished				
DO NOT SCALE DRAWING				SCALE: 1:2 · WEIGHT: · SHEET 1 OF 1

Appendix D Failure Modes and Effects Analysis Criteria Tables

D.1 Severity Criteria

Effect	Criteria: Severity of Effect	Ranking
Hazardous-without-warning	Potential failure mode affects safe system operation and/or involves noncompliance with government regulation without warning.	10
Hazardous-with-warning	Potential failure mode affects safe system operation and/or involves noncompliance with government regulation with warning.	9
Very High	System inoperable, with loss of primary function.	8
High	System operable, but at reduced level of performance. End-user dissatisfied.	7
Moderate	System operable, but comfort/convenient item(s) inoperable. End-user experiences discomfort.	6
Low	Item operable, but comfort.convenience item(s) operable at a reduced level of performance. End-user experiences some dissatisfaction.	5
Very Low	Fit and finish/squeak and rattle, item does not conform. Defect noticed by most customers	4
Minor	Fit and finish/squeak and rattle, item does not conform. Defect noticed by average customers	3
Very Minor	Fit and finish/squeak and rattle, item does not conform. Defect noticed by discriminating customers	2
None	No effect.	1

D.2 Occurrence Criteria

Probability of failure	**Probability of occurring**	**Ranking**
Very High: Failure is almost unavoidable	100% chance of the failure occurring	10
	90% chance of the failure occurring	9
High: Failure is likely	80% chance of the failure occurring	8
	70% chance of the failure occurring	7
Moderate: Failure is possible	60% chance of the failure occurring	6
	50% chance of the failure occurring	5
	40% chance of the failure occurring	4
Low: Failure is unlikely	30% chance of the failure occurring	3
	20% chance of the failure occurring	2
Remote: Failure is extremely rare	10% chance of the failure occurring	1

D.3 Detection Criteria

Detection	Criteria: Likelihood of detection by design control	Ranking
Absolute Uncertainty	The design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode: or there is no design control.	10
Very Remote	Very remote chance that the design control will detect a potential cause/mechanism and subsequent failure mode.	9
Remote	Remote chance that the design control will detect a potential cause/mechanism and subsequent failure mode.	8
Very Low	Very low chance that the design control will detect a potential cause/mechanism and subsequent failure mode.	7
Low	Low chance that the design control will detect a potential cause/mechanism and subsequent failure mode.	6
Moderate	Moderate chance that the design control will detect a potential cause/mechanism and subsequent failure mode.	5
Moderately High	Moderately high chance that the design control will detect a potential cause/mechanism and subsequent failure mode.	4
High	High chance that the design control will detect a potential cause/mechanism and subsequent failure mode.	3
Very High	Very high chance that the design control will detect a potential cause/mechanism and subsequent failure mode.	2

Almost Certain	The design control will almost certainly detect a potential cause/mechanism and subsequent failure mode.	1

Appendix E Request for Proposal

October 17th, 2017
Request for Proposal: Bolt Tensioning Mechanism

To all interested pursuants,

Background

Rexroth-Bosch is designing a machine that will chip logs for the manufacturing of oriented strand board (OSB). Due to the sheer volume of chips being produced and logs being processed, the blades on the machine will need to be frequently changed. This request for proposal (RFP) is to automate the loosening and tightening of the bolts that mount these blades.

Project Outline

This project will focus exclusively on the mechanism for tightening and loosening the bolts. The proposed project will be required to interface with Rexroth-Bosch equipment in order to automate the tightening of one inch bolts. The system must have the following capabilities:

- Accurate bolt tensioning (within 10lbs)
- Misalignment detection
- Cross thread and compromised thread detection
- Over torque prevention.

The complete mechanism must stay within a 2ft x 2ft x 2ft envelope.

Coding for each capability must be modular and conform to Rexroth-Bosch coding practices found in Rexroth IndraMotion MTX Programming Manual – Rexroth-Bosch.

Deliverables

Project completion will require:

- Manufacturing drawings for all components of the final design
- All code required for full operation of the mechanism
- Full documentation of development
- Operating instructions
- Fully functional device.

All deliverables must be received by Rexroth-Bosch **no later than May 11th, 2018**.

Rexroth
Bosch Group

Proposal Submission Guidelines

Proposal reports will be evaluated based on:

- Corporate Profile and Expertise
- Team Member Qualifications and Experience
- Philosophy, Approach, and Methodology
- Project Objectives
- Work Breakdown Structure
- Schedule (including Milestones)
- Costing Plan
- Estimated budget required for project completion.

Proposals must be submitted in pdf form to ProjectManager@Bosch-Rexroth.com by **November 1st, 2017**. If you have any questions, do not hesitate to contact the office of the project manager, Jonathan Murphy, at (778) 713 0977.

Appendix F Design Review Package

FINAL ALPHA DESIGN REVIEW
&
PRELIMINARY BETA DESIGN REVIEW
OF A 2-AXIS SERVO TRAINER

by

Curtis From

Dean Tamboline

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A report presented to

Bosch Rexroth Canada Corporation Inc.

And the

British Columbia Institute of Technology

in partial fulfilment of the requirement for the degree of

Bachelor of Engineering (Mechanical)

Industry Sponsor: Greg Filek

Bosch Rexroth Canada Corporation Inc.

Faculty Advisor: Johan Fourie, Ph.D., P.Eng

Burnaby, British Columbia, Canada, 2018

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Background

Bosch Rexroth has tasked In-A-Sinh(x) Engineering, with designing and producing a training system. This training system will teach engineers motion control using Bosch Rexroth products through emulating the motion of a flying saw, a motion commonly found in industry.

This trainer will focus on three main functions: accurate positioning, torque sensing, and synchronized motion. The trainer will allow the user to progressively learn the three functions while also exploring the software. An important fact is that this design is only for a pen-like end effector and is not a scalable design. It also only considers Bosch Rexroth controls and actuators and will only utilize electrical power.

The design review for the Bosch Rexroth Training System has two separate components: A final design review and a preliminary design review. The final design review is on the Alpha Prototype, which will encompass the mounting of the drives and various electronic components. The preliminary design review is for the Beta Prototype, which is the device that is emulating the Flying Saw motion.

Bosch Rexroth currently produces a training system for material transport as seen in Figure 1, but nothing quite like the flying saw. There is also another training system being developed that has a focus on the same three elements of accurate positioning, torque sensing, and synchronized motion, but to achieve this with a bolt tightening mechanism.

Figure 1 - Bosch Rexroth training system which focuses on material transportation

Alpha Prototype Final Design Review

The Alpha prototype successfully carries out its function as a portable platform to mount IndraDrive motor controllers, all associated electrical components, and auxiliary switches.

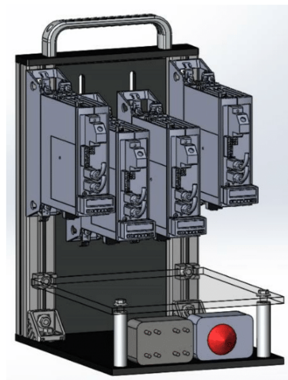


Figure 2 – Alpha Prototype

The Alpha prototype weighs more that we intended. Since only a small portion of the back plate needs to be there for the drives to mount to, we intend to do material removal to lighten the design. If further reduction of weight it deemed necessary, the bottom plate will be investigated for optimization.

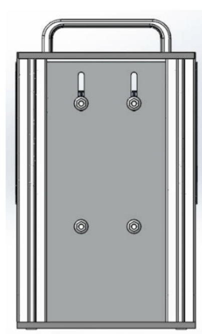


Figure 3 - Current back plate

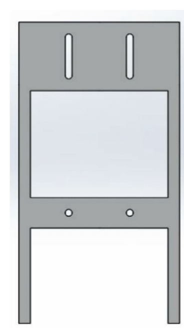


Figure 4 - Optional cut out of back plate

An unexpected (or designed for) transformer was necessary to supply the advanced modular IndraDrive controller with 240 volts. We had considered mounting it somewhere on our current prototype or constructing a separate box to contain it, the latter seemed more appropriate as it kept the terminal blocks enclosed.

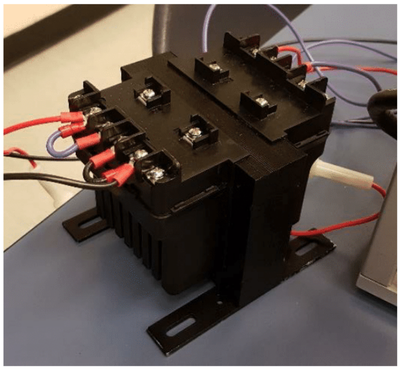


Figure 5 - Transformers

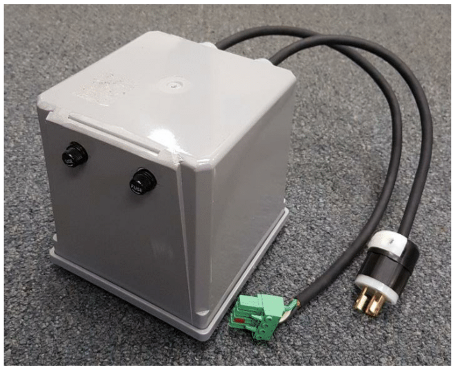


Figure 6 - Transformer Housing

We have considered a few options for ways to mount the Plexiglas plate. The first mounted at four locations on the base plate. The second mounted at two spots on the base, and two on the extrusion rails. The idea is to have it be somewhat easy to remove, and the use of 2 wingnuts at the front and slots in the back is currently the plan.

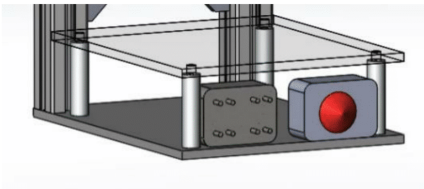


Figure 7 - Plexiglas mounted by four aluminum spacers

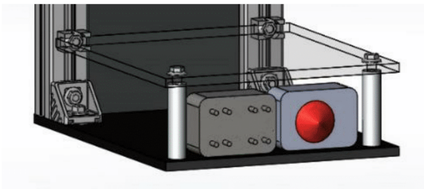


Figure 8 - Plexiglas mounted by two aluminum spacers

Above, the emergency stop and switches are depicted as fixed to the front. A consideration is to have them on an electrical tether to allow them to extend outwards so the user can conveniently position the buttons outside the footprint.

Beta Prototype Preliminary Design Review

General Beta Layout

The flying saw will require 3 forms of motion:

1. Parallel motion, depicted below by the green rails
2. Perpendicular motion, depicted below by a blue rail on a gray carriage
3. Linear motion of a sheet, depicted below by the red rollers (that would have a cellophane belt wrapped around them).

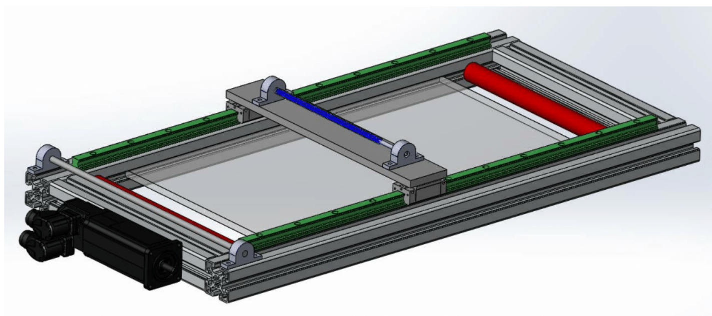


Figure 9 - Preliminary flying saw layout

The layout depicted above is considered the 2D layout, as it only uses aluminum extrusions connected in a single plane. A 3D layout was also considered that had the advantage of mounting all components underneath the plotter but the size and weight disadvantages deemed it unnecessary.

	2D	3D
Pros	Less Material Less Mass Components Exposed More Stable	Smaller Footprint More Mounting Space Variable orientation possible
Cons	Larger Footprint	More Material More Mass More Expensive

Creating and Constraining Motion

Methods of creating Linear Motion		
	Pros	**Cons**
Lead Screw	Mechanical advantage Bosch has one lying around	Intolerant to misalignment
Rack and Pinion	Few parts	Motion creating motor must move No mechanical advantage Intolerant to misalignment
Belts and Pulleys/ Chain and Sprocket	Cheap Tolerant to misalignment Both directions of motion can be generated without moving either motor (Core XY or Etch-a-sketch)	Less precise No mechanical advantage Lots of parts
Linear Actuator	Simple to use	Expensive Very long
Linear Motor	Simple to use	Expensive Dangerous
Predesigned linear stage	Plug and play	Very Expensive

Table 1 - Methods of creating linear motion

Our project sponsor notified us early in the project that linear motors can be pretty dangerous if they are accidentally powered up without a load. Combined with their high cost, they were removed from consideration.

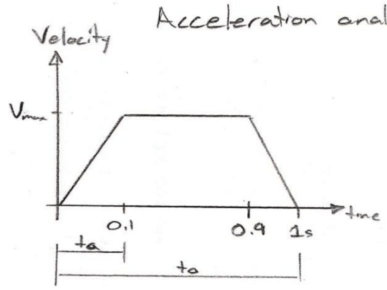
We had our project sponsor look into Bosch's linear stages since we will basically be reinventing the wheel, but the cost was too high and the method was removed.

The use of a rack and pinions was removed due to the necessity of the motor also needing to move as part of the carriage to keep the parts within the frame. This is unnecessary movement of mass.

The concept of non-moving motors has also been disregarded because it would involve a system that would not be intuitive to the user, which is a quality the project sponsor mentioned.

This leaves us with lead screw, and belts and pulleys. In order to decide between lead screw and belt, the following calculations determine if either method can accommodate the supplied torque from the desired motor, thus we need the acceleration:

Acceleration analysis (Assume Trapezoid Profile)



$$V_{max} t_o - V_{max} t_a = L$$

$$V_{max} = \frac{L}{t_o - t_a} = \frac{0.5m}{1s - 0.1s} = 0.55 \, m/s$$

$$a = \frac{V_{max}}{t_a} = \frac{0.55 \, m/s}{0.1s} = 5.5 \, m/s^2$$

Lead screw vs Belt

$$Motor\ is\ Bosch\ Rexroth\ \ MSM019A-0300-NN$$

$$Assume\ required\ acceleration\ (a)=\frac{5.5m}{s^2}$$

$$\alpha=\frac{5.5m}{s^2}\left(\frac{0.2rev}{1mm}\right)\left(\frac{1000mm}{1m}\right)\left(\frac{2\pi rad}{1rev}\right)=\frac{6911rad}{s^2}$$

Lead Screw:

$$Assume\ Pitch\ (P)=\frac{0.2rev}{1mm}=\frac{0.2rev}{10^{-3}m}$$

$$J_T=J_{Motor}+J_{Coupling}+J_{Screw}+J_{LoadRef}$$

$$J_{Coupling}=\frac{1}{2}m_{Coupling}r_{Coupling}^2 \qquad J_{Screw}=\frac{1}{2}m_{Screw}r_{Screw}^2$$

$$J_{LoadRef}=\frac{w_{Load}+W_{Carriage}}{g}*\frac{1}{(2\pi P)^2\epsilon}$$

$$J_T=0.0000025+\frac{1}{2}(0.025)(0.01)^2+\frac{1}{2}(0.183)(0.006)^2+0.321*\frac{1}{\left(2\pi\frac{0.2}{10^{-3}}\right)^2}=7.25*10^{-6}kgm^2$$

$$T=J\alpha=(7.25*10^{-6}kgm^2)\left(\frac{6911rad}{s^2}\right)=0.0501Nm$$

$$Apply\ a\ S.F.of\ 2\ to\ account\ for\ efficiencies\ and\ friction\ \therefore T_{Screw}=0.100Nm$$

Belt:

$$Assume\ Gear\ Ratio\ for\ belt\ (N)=\frac{1rev}{2\pi(20mm)}\left(\frac{2\pi}{1rev}\right)\left(\frac{1000mm}{1m}\right)=\frac{50rad}{m}$$

$$J_T=J_{Motor}+J_{Coupling}+J_{LoadRef}$$

$$J_{Coupling}=\frac{1}{2}m_{Coupling}r_{Coupling}^2$$

$$J_{LoadRef}=\frac{w_{Load}+W_{Carriage}}{g}*\frac{1}{(N)^2\epsilon}$$

$$J_T=0.0000025+\frac{1}{2}(0.025)(0.01)^2+0.321*\frac{1}{(50)^2}=1.32*10^{-4}kgm^2$$

$$T=J\alpha=(1.32*10^{-4}kgm^2)\left(\frac{6911rad}{s^2}\right)=0.912Nm$$

$$Apply\ a\ S.F.of\ 2\ to\ account\ for\ efficiencies\ and\ friction\ \therefore T_{Belt}=1.824Nm$$

The larger of the two motors under consideration could only supply a peak torque of 0.8Nm, while the desired smaller motors supply 0.16. This means that the belt drives are not a feasible method with a reasonably sized motor.

Methods of guiding motion and bearing weight		
	Pros	**Cons**
Linear Rails (Round)	Cheap Constrains translation in 2 axis	Lots of parts Constrains rotation in 2 axis
Linear Rails (Other)	Constrains rotation in 3 axis Constrains translation in 2 axis	Bulky Expensive Heavy Lots of parts
Extrusion Slides	Cheap Few parts Constrains roll in 3 axis Constrains translation in 2 axis Low mass Utilizes existing structure	Possible binding Possible friction concerns
Extrusion Rollers	Cheap Low mass Utilizes existing structure	Constrains motion Constrains translation in 1.5 axis* Constrains roll in 1 axis* (*With few parts, they can constrain more but it requires lots of part)

Table 2 - Methods of guiding motion and bearing weight

Due to mass concerns and the possibility of utilizing the existing structure to constrain and guide motion, the team is in favor of both extrusion options while still considering the round linear rails for perpendicular motion. The non-round linear rails have too many outlined cons to be considered any further.

The following motion concepts have taken into consideration the above mentioned guiding motion, bearing weight and generation motion methods.

Parallel Motion Concepts

Figure 10 shows the use of extrusion sliders to restrain motion and bear load, while motion is generated via leadscrew. The team is considering driving only one side of the carriage. Consultation with Steven McMillan has lead us to consider a 2:1 connection to the lead screw vs the width of the carriage. This will require testing. This slide method could easily be adapted to pulley driven motion.

Figure 11 depicts the use of extrusion rollers to restrain motion and bear load. Either lead screw or pulleys could drive this method. The additional width of the wheels could give additional room for perpendicular motion motors.

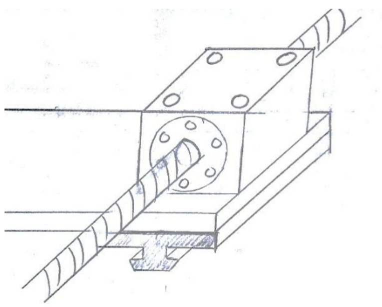


Figure 10 - Slider and lead screw

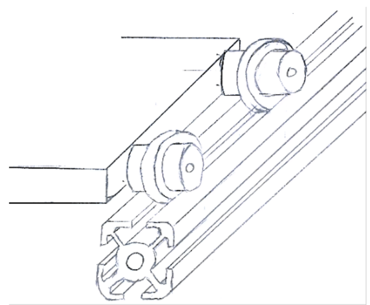


Figure 11 - Roller carriage

Figure 12 shows a method of using lead screws to generate motion while completely concealing the driving pulley or lead screw. This method could be used to drive either slider or roller constrained motion and bearing.

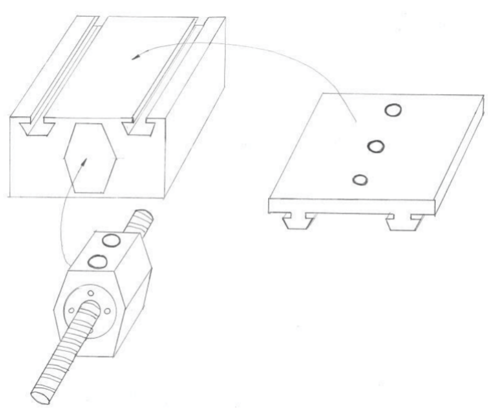


Figure 12 - Magnetically couple slider leadscrew

Perpendicular Motion

Currently, lead screw motion is preferred due to the availability of it from our project sponsor. This axis of motion does not conflict with the McMillan 2:1 rule, nor are the loads particularly large. For this reason, one constraint location is being considered as acceptable.

Figure 13 depicts a cross slide that utilizes a round linear rail to guide the perpendicular motion. In addition, the carriage itself is to be made of transparent polycarbonate or acrylic. This would allow for a less obstructed viewing of the writing surface.

Figure 14 shows one way that rollers could be used to constrain motion. The depicted method has many parts, making for what the team believe is an overly complex solution.

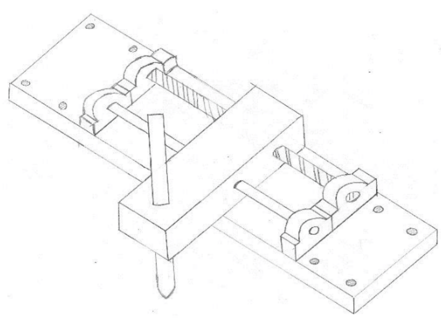


Figure 13 - Round linear rail guided perpendicular motion

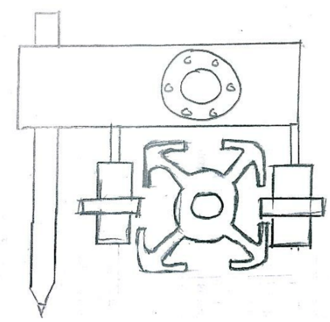


Figure 14 - Roller constrained perpendicular motion

Figure 15 and Figure 16 show how a piece of aluminum extrusion could be used with sliders to restrain motion and allow for driving via lead screw. With this type of configuration, the action of sliding could also be used, in conjunction with the twisting of the lead screw, to lift the end effector off the writing surface. This concept would require proof of concept prototypes to verify its viability.

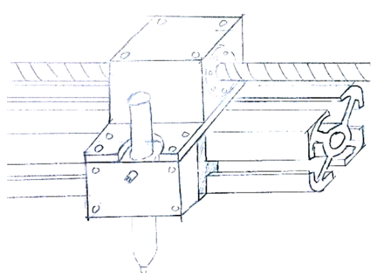


Figure 15 - Side slide guided perpendicular motion

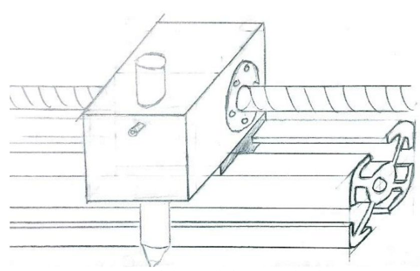


Figure 16 - Top slide guided perpendicular motion

Linear Motion of Sheet

Since the use of extrusion rollers and slides requires the top of the extrusion to be unobstructed, the support for the cellophane sheet must come from below that point. One concept, depicted in Figure 17, is to support the writing surface backer with a plate that seats into the side of the extrusions that makeup the frame. It can be built up to suit the elevation requirements of the roller position.

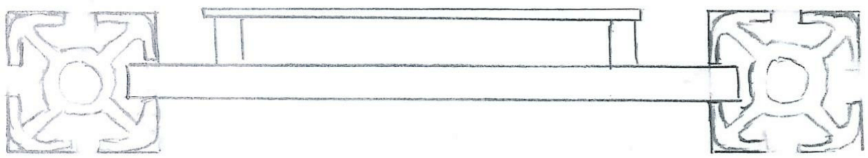


Figure 17 - Side extrusion channel supported writing backer

The rollers themselves could be mounted on top of the extrusion, seen below in Figure 18. This mounting method was originally considered before the extrusion motion constraint methods were considered. This method would require the writing backer to require additional extension, and the carriage to be elevated, but could allow for the driving motor to be mounted, protected, inside the frame. Alternatively, a flange style bearing or bushing would yield the opposite result.

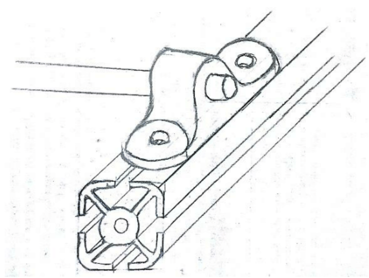


Figure 18 -Pillow block supported roller

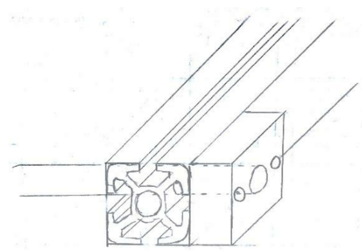


Figure 19 - Flange style bearing or bushing supported roller

The roller drive belt path and overall profile should be considered. The current idea is to have the motor, bearings, and rollers mounted in-plane and within the footprint of the aluminum frame.

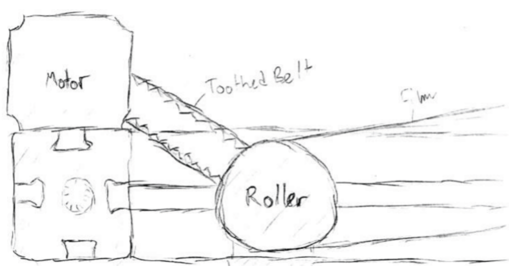


Figure 20 - Motor mounting to roller location consideration