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Portable Multi Metalworking Tool

Daniel Sarkis
Washington University in St. Louis, dsarkis@wustl.edu

Julia Medina
Washington University in St. Louis, julia.medina@wustl.edu

Matt Geiser
Washington University in St. Louis, mjgeiser@wustl.edu

Wilbur Donze
Washington University in St. Louis, wilburdonze@wustl.edu

Kaitlin Kretzler
Washington University in St. Louis, klkzr3@mail.umsl.edu

See next page for additional authors

Authors
Daniel Sarkis, Julia Medina, Matt Geiser, Wilbur Donze, Kaitlin Kretzler, Dale Brodack, Mason Jungels, Gregory Jones, David Cross, and Alex Friedman

Joint Engineering Program
University of Missouri–St. Louis ▪ Washington University in St. Louis
ELEVATE YOUR FUTURE.
ELEVATE ST. LOUIS.

The number of machine shops for students are scarce and the available shops are not open at convenient times. Students want to be able to machine his or her own parts but have to wait to be a member of a school class or company. If only there was a machine that can lathe, mill, and drill press and can be taken anywhere the student desires. Now there is! The Portable Multi Metalworking Tool is a combination machine that can perform lathing, drilling and milling.

JME 4110
Mechanical Engineering
Design Project

Combination Mill/Drill/Lathe

Julia Medina

Wilbur Donze

Gregory Jones

Matt Geiser

David Cross

Kaitlin Kretzler

Daniel Sarkis

Dale Brodack

Alex Friedman

Mason Jungels

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User Needs and Metrics

3.1 Record of the user needs interview

Prompt/Question	Customer Statement	Interpreted Need	Need Importance (1-5)
Can we combine the mill and drill?	Yes.	Mill and drill can be combined for simplicity	3
Is there a preference for mill/drill orientation?	No, but if the spindle moves along a rail it is potentially less accurate.	Orientation can be vertical or horizontal	3
What are the variable speed requirements of the motor?	It needs discrete different speeds; it doesn't need many steps.	Few speed options	2
Is a vertical rise of the stage acceptable as an alternative of the spindle moving downward?	Yes, if it is well made.	Well made raising stage	5
What material are we cutting?	Mild steel will be the hardest (1020 steel).	The tool must be able to cut through mild steel	5
What are the weight limits?	The lifting weight should be no more than 40 lbs.	Portable, but likely on wheels (not carried)	3
How long should it take to assemble the unit?	It shouldn't take longer than 20 minutes to assemble; it shouldn't take more than 3 minutes to switch between functions.	Easy assembly and function change	4
Should we assume that all the tooling is provided by the user and not part of the unit?	No, it should all be in the original purchase.	All tooling included in assembly	5

How will dimensions of cuts be measured?	The distance of movement of the cutting tool should be known when “dialing in”.	An appropriate coordinate system should be provided by the device	3

3.2 List of identified metrics

Based on the interview the following needs were determined

Need Number	Need	Need Importance (1-10)
1	Can achieve 1000 RPM lathing	8
2	Can cut 0.020” at 2” radius	7
3	Chuck can hold: part, spindle, and drill bit	10
4	Fits 22” x 22” x 12”	3
5	Able to carry less than 40 lbs total, max 30 lbs for lathe	3
6	Costs less than $800-$1000	7
7	Easy to Assemble	5
8	Should allow a part with 4” x 4” foot print	10
9	Actual cross slide providing controlled movement in the X, Y, and Z directions	10
10	Mill can cut a groove 0.25” wide	7
11	Mill can cut a groove 0.25” deep	7

12	Mill can cut at a rate of 0.001”/revolution	5
12	If possible, cross slide movements can be electronically controlled	2
13	Should provide force and torque needed to drill at 0.25” hole in mild steel	5
14	Drill should allow 2” of plunge	5
15	Variable speed if possible	3
16	Can cut mild steel	6
17	Can hold a part 4” in diameter and 12” long	7

By determining the needs of our product, a list of metrics was developed to help score each concept.

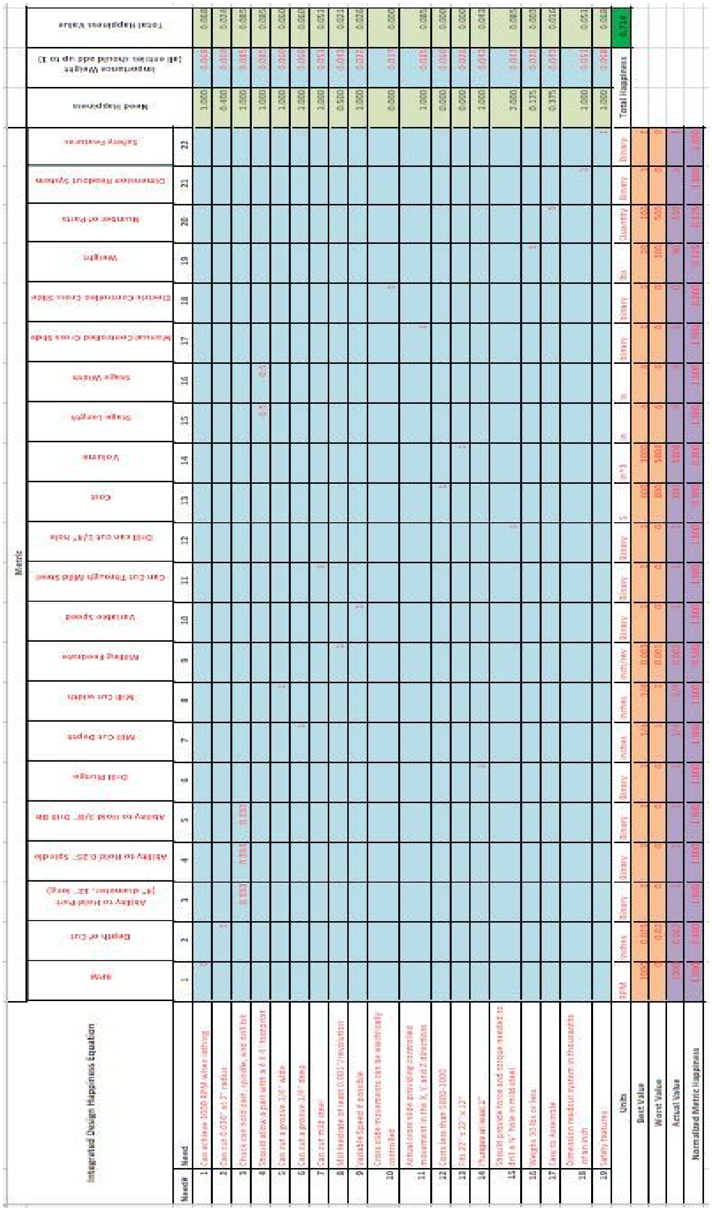
Metric Number	Associated Need Number	Metric	Units	Max	Min
1	1	RPM	rpm	1000	100
2	14	Depth of Cut	inches	2	0
3	17	Ability to Hold Part (4" diameter, 12" long)	binary	1	0
4	3	Ability to Hold 0.25" Spindle	binary	1	0
5	3	Ability to Hold 3/8" Drill Bit	binary	1	0

6	4	Volume	in^3	5,808	0
7	5	Weight	lbs	40	0
8	6	Cost	$	1,000	0
9	6, 7	No. of Parts	Integer	Design Specific	0
10	8	Stage Length	inches	6	4
11	9	Cross Slide Manually Controlled	binary	1	0
12	10	Cutting width	inches	1	0.25
13	11	Cutting Depth	inches	1	0.25
14	12	Cutting speed	in/rev	0.10	0.001
15	9, 12	Cross Slide Electric Controlled	binary	1	0
16	13	Drill can cut ¼” hole in mild steel	binary	1	0
17	14	Drill Plunge	inches	3	2
18	1, 15	Can operate at various speeds	binary	1	0
19	16	Can cut through mild steel	binary	1	0
20	9	Dimension Readout System	binary	1	0

3.3 Table/list of quantified needs equations

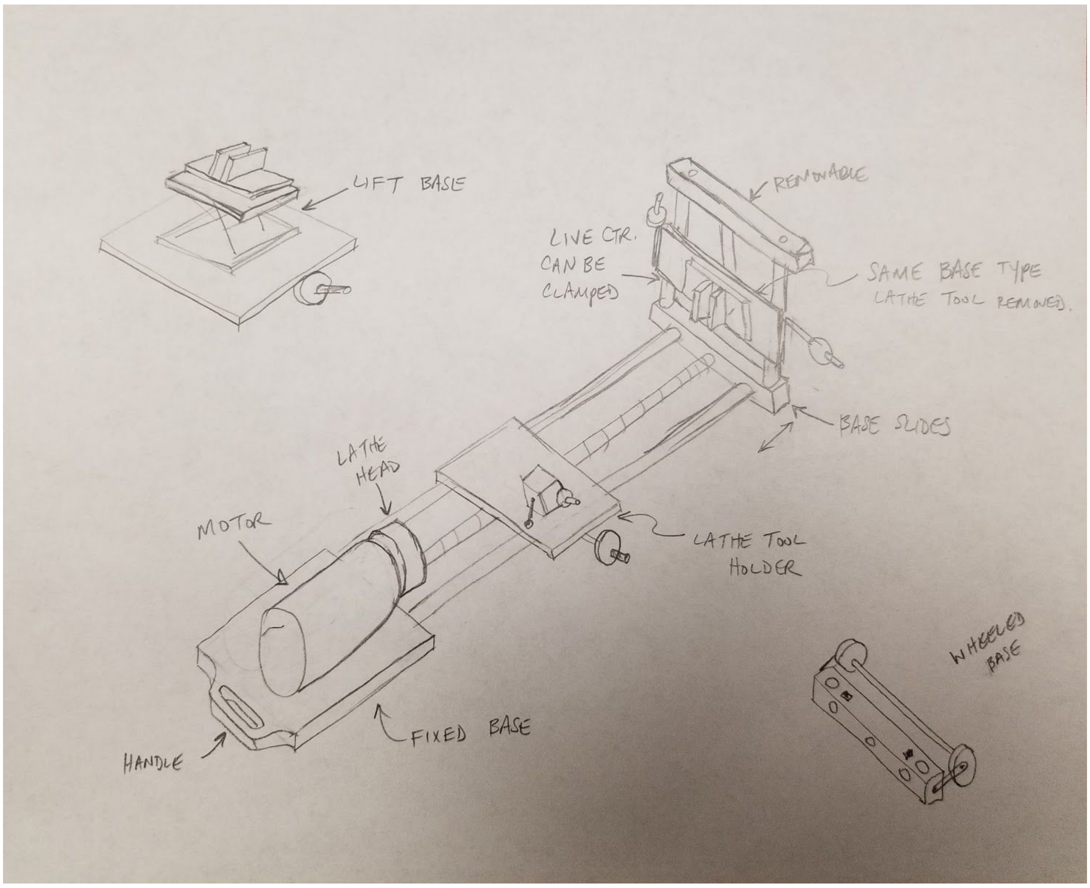
After reviewing each team's ideas for the mill/drill, lathe, and transportation, the group created concept drawings for the overall design. To pick the best concept, a set of user-needs equations was developed and each concept screened according to the needs determined in the interview.

3.3.1 Concept 1



4 INTEGRATED CONCEPT DRAWINGS

4.1 Integrated Concept Drawing



5 CONCEPT SELECTION PROCESS

5.1 Concept scoring (not screening)

5.2 Preliminary analysis of each concept's physical feasibility

For the "portability" aspect of the design, multiple ways were discussed to attach casters (wheels) to the aluminum frame; after going over the pros and cons of each idea, it was decided to use a wooden block to mount the casters onto the frame of our project. This idea was chosen because it is lightweight, less machining is required, and it's able to better absorb any vibrations that would occur as a result of moving it around.

5.3 Final summary statement

The final integrated concept has the motor and lathe head on a fixed base. The lathe cutting tool will be on guide rails that can be hand-cranked in the z-axis. The clamp base will also have a crank for the z-axis and a clamp that will go along the y-axis. All three parts will be on three guide rails. The entire unit would be in an "L" shape. The end with the clamp will have a wheelbase so that the entire unit can flip and roll. That top piece should have a stop or better support when the motor goes vertical. The fixed base with the motor would have a handle for leverage. The transportation/assembly group became integration/transportation because the new design concept does not need a table to condense. The lathe group became headstock and motor. The drill/mill group became the carriage system that incorporates the lathe tool and clamp. The integration/transportation group will assist in the merging of the entire project. Possible changes would probably be moving the handle to another location, adding more weight to the base with the clamp , and determining which base will be officially fixed.

6 Proposed performance measures for the design

7 Revision of specifications after concept selection

Groups changed to headstock, tailstock, and transportation/integration

8 Introduction

8.1 Value proposition / project suggestion

Engineering students are often interested in learning machine shop skills to create things for personal use as well as for school projects. However, with limited space available there often is not enough time or facilities available for students to complete projects in the shop. The goal of this project is to design a portable, three-in-one, mill, drill press, and lathe that students can build on their own.

8.2 List of team members

Julia Medina, Wilbur Donze, Gregory Jones, Matt Geiser, David Cross, Kaitlin Kretzler, Daniel Sarkis, Dale Brodack, Alex Friedman, and Mason Jungels

8.3 Team Organization

The groups had originally decided to divide up into the 3 main functions (lathing, milling, and drilling) of the project; however, as design concepts were being discussed, it quickly became clear that this was not the best way to organize subgroups. Since a combination headstock was chosen for the machine (i.e. one that would rotate lathe workpieces, drill bits, and mill spindles), it felt easiest to assign one group the headstock/motor design, another the carriage, cutting tool, and distance dials, (tailstock) and the last group the transportation and mating assembly.

9 Background Information Study

9.1 Design Brief

In order to give students better access to machine tools, the lathe, drill press, and mill combination machine should be able to fit in a dorm room or on a desktop. The assembly should be collapsible, about the size of large luggage (22” X 22” X 12”), and it should be lightweight enough for a student to move it back and forth from home to the classroom. The assembly should be able to cut/drill metals such as mild steel. The design should meet all of the aforementioned specifications, minimize cost, and maintain simplicity so that any student is able to procure parts and create their own mill-drill-lathe assembly.

9.2 Background summary

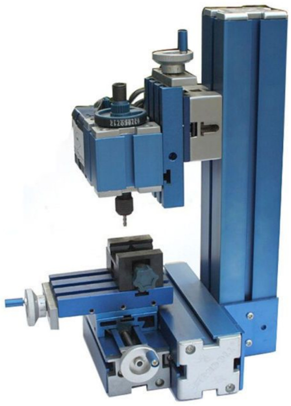
9.2.1 Mill/Drill Background Summary

We plan to complete the design and development of the milling and drilling components of the overall portable 3-in-1 combination system. The milling system will be similar in design to a single mill unit that can be found in a machine shop. The mill will also be able to complete the drilling function that our combination will require. The system should be able to match the functionality of a larger unit, such as being able move in the X, Y, and Z axes. The X and Y axis motion will be accomplished using cranks on the vice, which will be capable of holding a 4 x 4 in object. The Z axis motion will be achieved by moving the machine head itself, rather than having a fixed head with movable vice. As the mill and drill are combining two functions of the system into one component, it must be able powerful enough to work on mild steel, while also being as light and cost effective as possible. Easy movement, setup and safe use by the end user without affecting functionality of the other components will be a paramount concern. Codes and standards will be observed to ensure that a trained user will not come to harm during normal operation of the device.

EXISTING DESIGN 1 - SUNWIN MINI MILL

https://www.ebay.com/i/151575263820?chn=ps

https://www.amazon.com/SUNWIN-Milling-Machine-Woodworking-Student/dp/B01HJNX4KI



SPECIFICATIONS:

- Motor Speed: 20,000rpm
- Headstock speed: 2,000rpm
- Support power: 12VDC/2A/24W
- Slide travel: 35mm and 45mm
- Vice capacity: 25mm×35mm
- The maximum measurements on 3D: 230×200×315mm(LxWxH)
- Quality/Safety Certifications: CE, UL (Transformer)
- Weight: 3.5kg

This mini mill only seems to be available through third party sellers such as eBay and Amazon, and so the only specifications available are those given above. The price for such a unit is in the $200-230 range, meaning that if this device was bought, there is a good chance of staying within the $1000 budget for the whole item. Although the unit specifically states it is used for woodworking, a 2000 rpm headstock should be able to deal with mild steel. The unit is also able to move in X, Y, and Z directions. The change in height is accomplished by moving the mill unit itself, rather than the workbench. If the unit is indeed only 3.5 kg (7.7 lb), as the specifications claim, then this part would be ideal, as it is lightweight enough to remain portable, while leaving a larger weight allowance for other components. The one area this item does not meet the project's specifications is the vice capacity. It needs to be able to hold an item 4 x 4 in (approx. 100 x 100 mm), which exceeds the stock vice's maximum dimensions. If this unit were to be used, it will be necessary to modify or replace the vice with one that can handle a larger object.

EXISTING DESIGN 2 - GRIZZLY G4015Z - 19-3/16" COMBO LATHE/MILL

http://www.grizzly.com/products/19-3-16-Combo-Lathe-Mill/G4015Z?gclid=CjwKCAjwjZjZBRAZEiwAPeLSKz7LxUIqRHa8AyBuxC6UpRpoEZdGPosyi79A6IMRHJbtVoaFvNTMfRoCwDgQAvD_BwE

The Grizzly Combo Lathe/Mill is covers all the machining specifications of this project. However, at a cost of nearly $1700 and a weight of 475 lbs, the machine is neither portable, not affordable to the average student. The mill component will be able to meet drilling requirements as well, meaning that the drill and mill can be combined into one unit. The vice can accommodate a 4 x 4 in object. The major challenge with the Grizzly is finding a way to miniaturize the design in order to fit in a 22 x 22 x 12 in carry case, and making it light enough to be portable, without sacrificing safety or function of the tool.

9.2.2 Lathe Background Summary

A lathing subsystem will be designed for a 3-in-1 machining system, using similar designs to traditional lathes. In a lathe, the workpiece is held in a chuck and rotated at high rpm. As the part rotates, a cutting tool is brought to the surface of the part and removes material. The rpm necessary to remove material from the part is dependent on the material's "cutting speed" (i.e. the tangential velocity of the part relative to the stationary cutting tool) and the part's size; cutting speed can vary significantly between different materials. Most lathes rotate workpieces about a horizontal axis, though vertical axis lathes do exist (these all seem to have the headstock anchored to the base though). The lathe to be designed will be mechanically compatible with the other teams' subsystems and will use as many common components as possible. This will allow the user to switch between machining modes without having to spend inordinate amounts of time setting up, and minimize cost of the overall apparatus.

Summary of relevant background information (such as similar existing devices or patents, patent numbers, URL's, et cetera)

9.2.3 Transportation/Integration Background Summary

We need to make sure the machine will break down into the project's requested dimensions of 22 x 22 x 12 inches. After researching tables to support the entire design we came up with an adjustable table that is attached to the support pole of the drill press. The table can be adjusted vertically along the pole, as well as have sliders on both sides to extend the X and Y axis. The pole will be supported on wheels to make the entire assembly mobile. Also, the pole that will support the lathe-mill-drill press combo can be adjustable to shrink. This design should fit in the requested dimensions when the user is done. The user should be able to slide the machine down and push the table extensions in.

Welded Machine Table

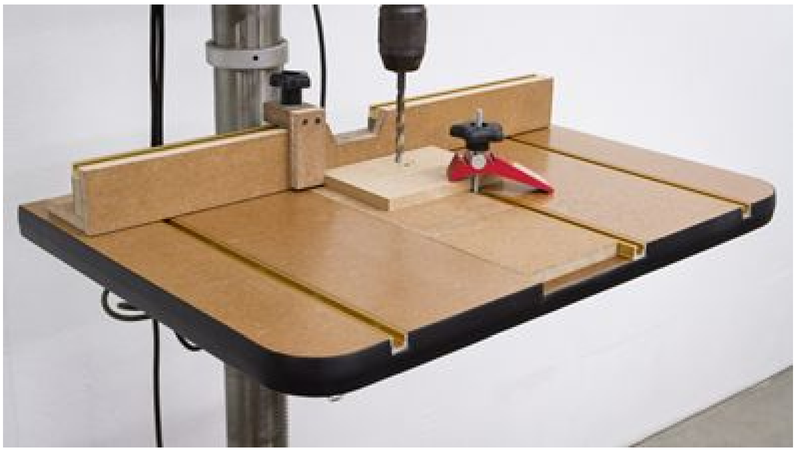
36 x 24 x 30 inches, 103 lbs, $225

https://www.uline.com

**Table is too long to fit in desired dimensions. Also tall but can be modified.

MUST BE ABLE TO SUPPORT THE COMBO DESIGN

Drill Press Table



https://www.youtube.com/

A drill press has a table attached to it on the pole that supports the drill press. This can eliminate the length and width space, as well as help with the height. The pole can slide down for travel use. The table can have sliding extensions to make it longer for lathing.

**The bottom of the drill press can be on wheels to make the entire machine mobile.

Quick-snap adjustment allows you to adjust the width and length from 18" x 18" to 24" x 24"; Weight capacity of 600 lbs; $91.50.

www.grainger.com

**This design looks easy enough to fabricate.

10 Concept Design and Specification

10.1 User Needs and Metrics

10.1.1 Record of the user needs interview

Prompt/Question	Customer Statement	Interpreted Need	Need Importance (1-5)

Can we combine the mill and drill?	Yes.	Mill and drill can be combined for simplicity	3
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What are the weight limits?	The lifting weight should be no more than 40 lbs.	Portable, but likely on wheels (not carried)	3
How long should it take to assemble the unit?	It shouldn't take longer than 20 minutes to assemble; it shouldn't take more than 3 minutes to switch between functions.	Easy assembly and function change	4
Should we assume that all the tooling is provided by the user and not part of the unit?	No, it should all be in the original purchase.	All tooling included in assembly	5
How will dimensions of cuts be measured?	The distance of movement of the cutting tool should be known when "dialing in".	An appropriate coordinate system should be provided by the device	3

10.1.2 List of identified metrics

Based on the interview the following needs were determined

Need Number	Need	Need Importance (1-10)
1	Can achieve 1000 RPM lathing	8
2	Can cut 0.020” at 2” radius	7
3	Chuck can hold: part, spindle, and drill bit	10
4	Fits 22” x 22” x 12”	3
5	Able to carry less than 40 lbs total, max 30 lbs for lathe	3
6	Costs less than $800-$1000	7
7	Easy to Assemble	5
8	Should allow a part with 4” x 4” foot print	10
9	Actual cross slide providing controlled movement in the X, Y, and Z directions	10
10	Mill can cut a groove 0.25” wide	7
11	Mill can cut a groove 0.25” deep	7
12	Mill can cut at a rate of 0.001”/revolution	5
12	If possible, cross slide movements can be electronically controlled	2
13	Should provide force and torque needed to drill at 0.25” hole in mild steel	5

14	Drill should allow 2” of plunge	5
15	Variable speed if possible	3
16	Can cut mild steel	6
17	Can hold a part 4” in diameter and 12” long	7

By determining the needs of our product, a list of metrics was developed to help score each concept.

Metric Number	Associated Need Number	Metric	Units	Max	Min
1	1	RPM	rpm	1000	100
2	14	Depth of Cut	inches	2	0
3	17	Ability to Hold Part (4" diameter, 12" long)	binary	1	0
4	3	Ability to Hold 0.25" Spindle	binary	1	0
5	3	Ability to Hold 3/8" Drill Bit	binary	1	0
6	4	Volume	in^3	5,808	0
7	5	Weight	lbs	40	0
8	6	Cost	$	1,000	0

9	6, 7	No. of Parts	Integer	Design Specific	0
10	8	Stage Length	inches	6	4
11	9	Cross Slide Manually Controlled	binary	1	0
12	10	Cutting width	inches	1	0.25
13	11	Cutting Depth	inches	1	0.25
14	12	Cutting speed	in/rev	0.10	0.001
15	9, 12	Cross Slide Electric Controlled	binary	1	0
16	13	Drill can cut ¼” hole in mild steel	binary	1	0
17	14	Drill Plunge	inches	3	2
18	1, 15	Can operate at various speeds	binary	1	0
19	16	Can cut through mild steel	binary	1	0
20	9	Dimension Readout System	binary	1	0

10.1.3 Table/list of quantified needs equations

After reviewing each team’s ideas for the mill/drill, lathe, and transportation, the group created concept drawings for the overall design. To pick the best concept, a set of user-needs equations was developed and each concept screened according to the needs determined in the interview.

10.1.3.1 Concept 1

Need#	Need	1 RPM	2 Depth of Cut	3 Ability to Hold Part (4" diameter, 12" long)	4 Ability to Hold 0.25" Spindle	5 Ability to Hold 3/8" Drill Bit	6 Drill Plunge	7 Mill Cut Depth	8 Mill Cut width	9 Milling Feedrate	10 Variable Speed	11 Can Cut Through Mild Steel	12 Drill can cut 1/4" hole	13 Cost	14 Volume	15 Stage Length	16 Stage Width	17 Manual Controlled Cross Slide	18 Electric Controlled Cross Slide	19 Weight	20 Number of Parts	21 Dimension Readout System	22 Safety Features	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
1	Can achieve 1000 RPM when lathing	1																						1.000	0.068	0.068
2	Can cut 0.030" at 2" radius		1																					0.400	0.060	0.024
3	Chuck can hold part, spindle, and drill bit			0.333	0.333	0.333																		1.000	0.085	0.085
4	Should allow a part with a 4 X 4" footprint															0.5	0.5							1.000	0.085	0.085
5	Can cut a groove 1/4" wide								1															1.000	0.060	0.060
6	Can cut a groove 1/4" deep							1																1.000	0.060	0.060
7	Can cut mild steel											1												1.000	0.051	0.051
8	Mill feedrate of least 0.001"/revolution									1														0.500	0.043	0.021
9	Variable Speed if possible										1													1.000	0.020	0.020
10	Cross slide movements can be electrically controlled																		1					0.000	0.017	0.000
11	Actual cross slide providing controlled movement in the X, Y, and Z directions																	1						1.000	0.085	0.085
12	Costs less than $800-1000													1										0.000	0.060	0.000
13	Fits 22" x 22" x 12"														1									0.000	0.026	0.000
14	Plunges at least 2"						1																	1.000	0.043	0.043
15	Should provide force and torque needed to drill a ¼" hole in mild steel												1											2.000	0.043	0.085
16	Weighs 30 lbs or less																			1				0.125	0.026	0.003
17	Easy to Assemble																				1			0.375	0.043	0.016
18	Dimension readout system in thousandths of an inch																					1		1.000	0.051	0.051
19	Safety features																						1	1.000	0.068	0.068
	Units	RPM	Inches	Binary	Binary	Binary	Binary	Inches	Inches	Inch/rev	Binary	Binary	Binary	$	in^3	in	in	binary	binary	lbs	Quantity	Binary	Binary	Total Happiness		0.714
	Best Value	1000	0.025	1	1	1	1	1/4	1/4	0.003	1	1	1	600	1000	4	4	1	1	20	100	1	1			
	Worst Value	0	0.02	0	0	0	0	1	1	0.001	0	0	0	800	5000	0	0	0	0	100	500	0	0			
	Actual Value	1000	0.022	1	1	1	1	1/4	1/4	0.002	1	1	1	[illegible]	5000	4	4	1	0	90	350	1	1			
	Normalized Metric Happiness	1.000	0.400	1.000	1.000	1.000	1.000	1.000	1.000	0.500	1.000	1.000	1.000	0.000	0.000	1.000	1.000	1.000	0.000	0.125	0.375	1.000	1.000			

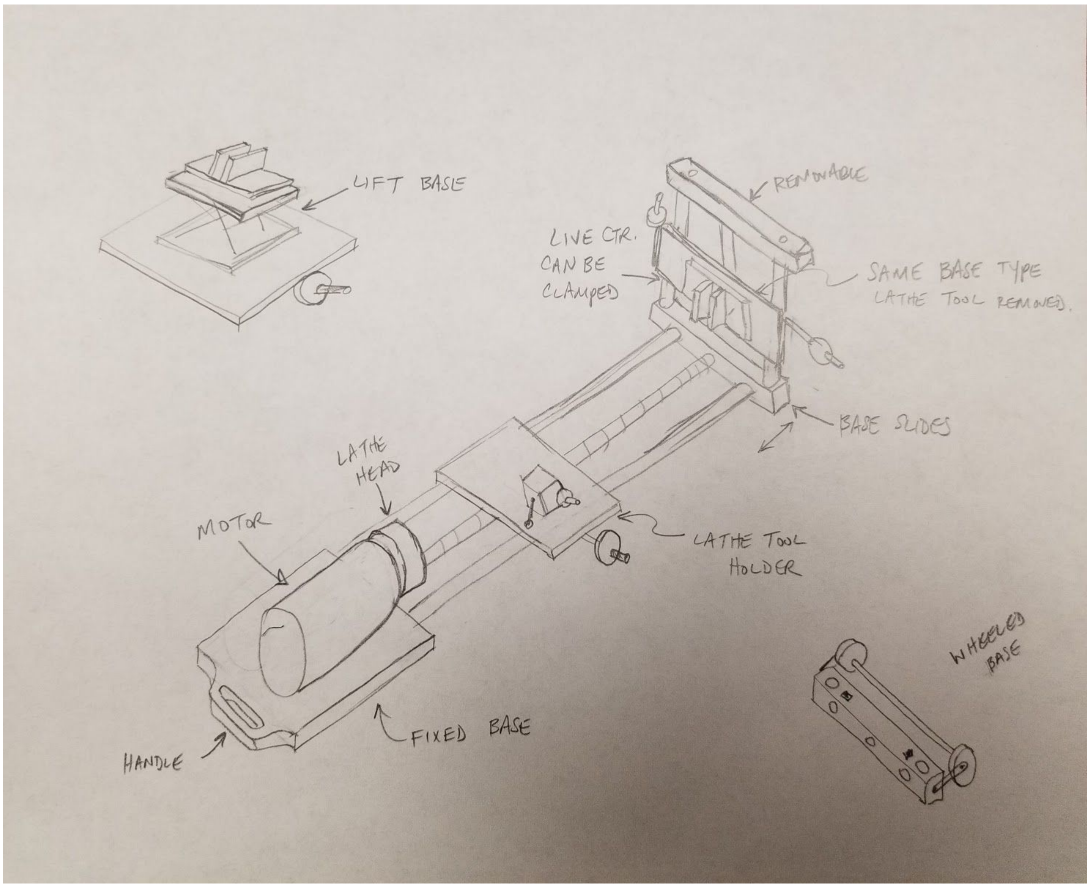
Integrated Design Happiness Equation

10.1.3.2 Concept 2

10.1.3.3 Concept

10.2 Integrated concept drawings

10.2.1 Integrated Concept Drawing



10.3 Concept selection process

10.3.1 Concept scoring (not screening)

10.3.2 Preliminary analysis of each concept's physical feasibility

For the "portability" aspect of the design, multiple ways were discussed to attach casters (wheels) to the aluminum frame; after going over the pros and cons of each idea, it was decided to use a wooden block to mount the casters onto the frame of our project. This idea was chosen because it is lightweight, less machining is required, and it's able to better absorb any vibrations that would occur as a result of moving it around.

10.3.3 Final summary statement

The final integrated concept has the motor and lathe head on a fixed base. The lathe cutting tool will be on guide rails that can be hand-cranked in the z-axis. The clamp base will also have a crank for the z-axis and a clamp that will go along the y-axis. All three parts will be on three guide rails. The entire unit would be in an "L" shape. The end with the clamp will have a wheelbase so that the entire unit can flip and roll. That top piece should have a stop or better support when the motor goes vertical. The fixed base with the motor would have a handle for leverage. The transportation/assembly group became integration/transportation because the new design concept does not need a table to condense. The lathe group became headstock and motor. The drill/mill group became the carriage system that incorporates the lathe tool and clamp. The integration/transportation group will assist in the merging of the entire project. Possible changes would probably be moving the handle to another location, adding more weight to the base with the clamp , and determining which base will be officially fixed.

10.4 Proposed performance measures for the design

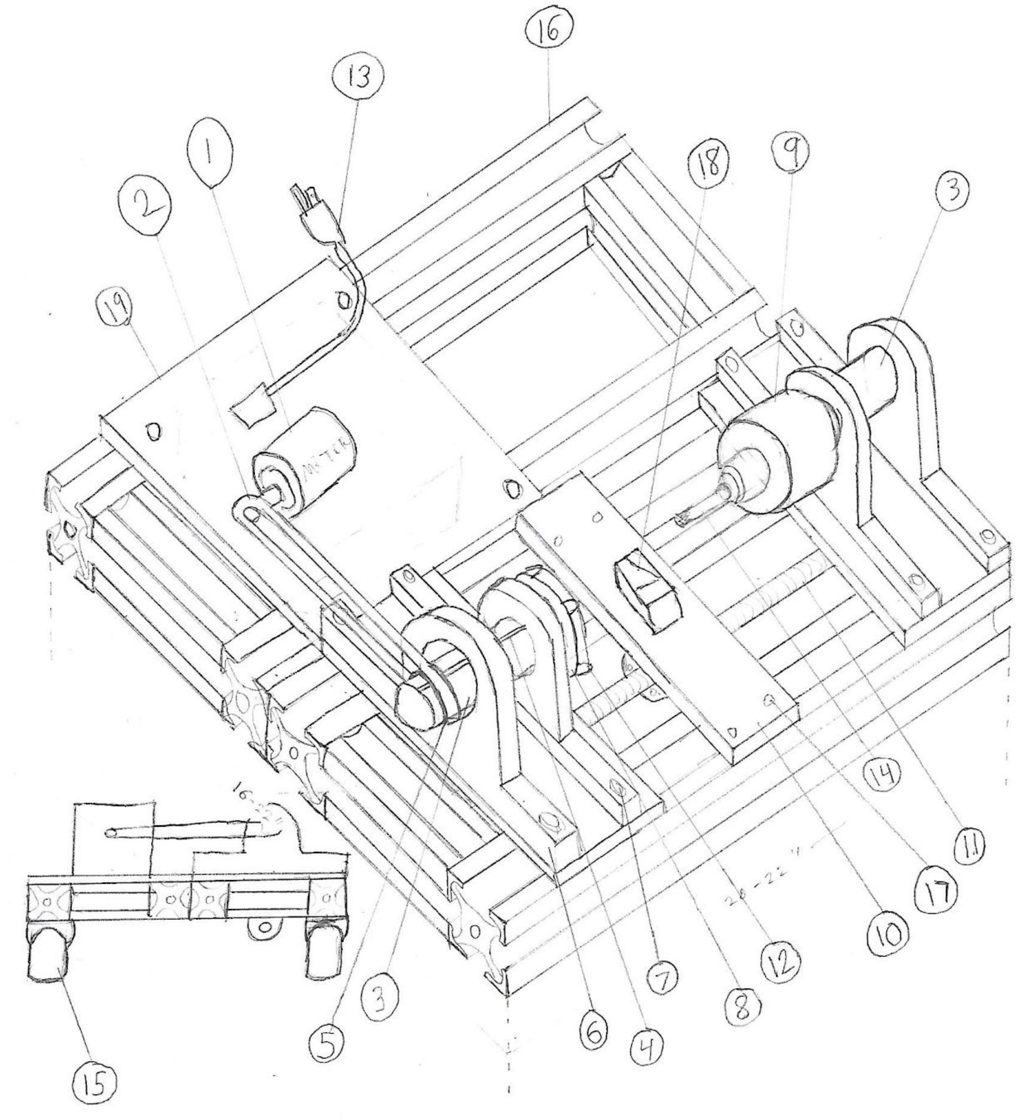
10.5 Revision of specifications after concept selection

Groups changed to headstock, tailstock, and transportation/integration

11 Embodiment and fabrication plan

11.1 Embodiment/Assembly drawing

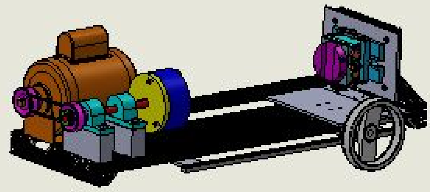
11.1.1 Initial Embodiment Drawing



11.2 Parts List

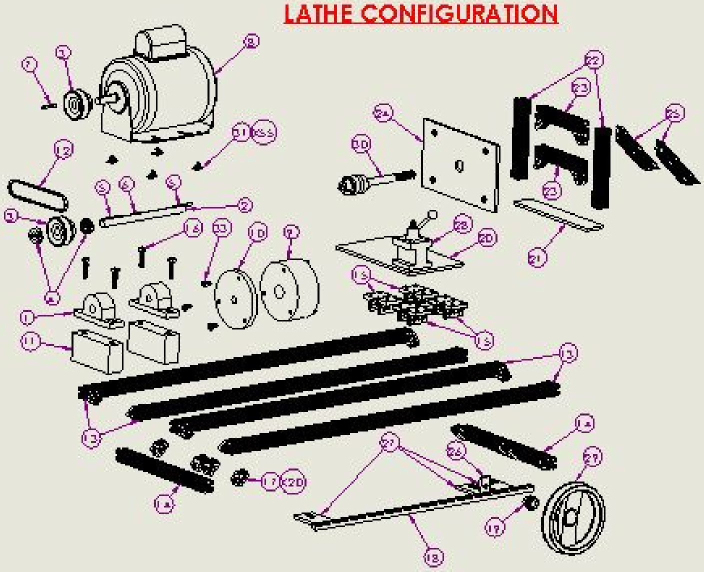
ITEM NO.	PART NUMBER	DESCRIPTION	Mill & Drill QTY.
1	Pillow Block	5" X 1" BASE 5/8" THRU HOLE	2
2	Keyed Shaft	5/8" SHAFT 3/16" X 3/32" KEYWAY	1
3	6204K133	PULLEY WHEEL	2
4	3357K13	SHAFT COLLAR	2
5	Key	3/16" X 3/16" X 2" KEY	2
6	Key	3/16" X 3/16" X 1/2" KEY	1
7	Key	3/16" X 3/16" X 1 1/2" KEY	1
8	MOTOR	1 HP MOTOR	1
9	Chuck	CHUCK	1
10	Mounting Plate	MOUNTING PLATE CHUCK	1
11	Block	BLOCK PILLOW BLOCK ELEVATOR	2
12	Belt	V-BELT	1
13	36 inch (47065T412)	1" X 1" X 36" T-SLOT	4
14	47065T412_ALUMINUM T-SLOTTED FRAMING EXTRUSION	1" X 1" X 12" T-SLOT	2
15	47065T957	MOUNTING PLATFORM T-SLOT	4
16	92190A111	3/8"-16 X 1 1/2" BOLT	4
17	47065T663_T-SLOTTED FRAMING	GUSSET T-SLOT CORNER 1" X 1"	20
18	6295K14	RACK	1
19	6325K13	PINION GEAR	1
20	Clutch base	MOUNTING PLATE TOOL HOLDER	1
21	corner base	MOUNTING PLATE HORIZONTAL TAILSTOCK / COMPOUND VISE	1
22	47065T411	1" X 1" X 7" T-SLOT	2
23	47065T411	1" X 1" X 6" T-SLOT	2
24	base hole	MOUNTING PLATE VERTICAL TAILSTOCK / COMPOUND VISE	1
25	47065T186	45 DEGREE T-SLOT FRAME	2
26	block hole	PINION MOUNTING PLATE	1
27	gear plate	RACK MOUNTING PLATE	3
28	6335K24	RACK & PINION ADJUSTER	1
29	47065T142	T-SLOT MOUNTING SLIDE & BOLT	55
30	91251A537	1/4"-20 X 1/2" BOLT	14
31	92620A578	5/16" - 18 X 1/2" BOLT	3
32	Compound Vise_&	COMPOUND VISE	1

MILL & DRILL CONFIGURATION



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Pillow Block	5" X 1" BASE 5/8" THRU HOLE	2
2	Keyed Shaft	5/8" SHAFT 3/16" X 3/32" KEYWAY	1
3	6204K133	PULLEY WHEEL	2
4	3357K13	SHAFT COLLAR	2
5	Key	3/16" X 3/16" X 2" KEY	2
6	Key	3/16" X 3/16" X 1/2" KEY	1
7	Key	3/16" X 3/16" X 1 1/2" KEY	1
8	MOTOR	1 HP MOTOR	1
9	Chuck	CHUCK	1
10	Mounting Plate	MOUNTING PLATE CHUCK	1
11	Block	BLOCK PILLOW BLOCK ELEVATOR	2
12	Belt	V-BELT	1
13	36 inch (47065T412)	1" X 1" X 36" T-SLOT	4
14	47065T412_ALUMINUM T-SLOTTED FRAMING EXTRUSION	1" X 1" X 12" T-SLOT	2
15	47065T957	MOUNTING PLATFORM T-SLOT	4
16	92190A111	3/8"-16 X 1 1/2" BOLT	4
17	47065T663_T-SLOTTED FRAMING	GUSSET T-SLOT CORNER 1" X 1"	20
18	6295K14	RACK	1
19	6325K13	PINION GEAR	1
20	Clutch base	MOUNTING PLATE TOOL HOLDER	1
21	corner base	MOUNTING PLATE HORIZONTAL TAILSTOCK / COMPOUND VISE	1
22	47065T411	1" X 1" X 7" T-SLOT	2
23	47065T411	1" X 1" X 6" T-SLOT	2
24	base hole	MOUNTING PLATE VERTICAL TAILSTOCK / COMPOUND VISE	1
25	47065T186	45 DEGREE T-SLOT FRAME	2
26	block hole	PINION MOUNTING PLATE	1
27	gear plate	RACK MOUNTING PLATE	3
28	6335K24	RACK & PINION ADJUSTER	1
29	47065T142	T-SLOT MOUNTING SLIDE & BOLT	55
30	91251A537	1/4"-20 X 1/2" BOLT	14
31	92620A578	5/16" - 18 X 1/2" BOLT	3
32	Tool Post	LATHE CUTTING TOOL HOLDER	1
33	chuck_assembly	TAILSTOCK CHUCK	1

LATHE CONFIGURATION

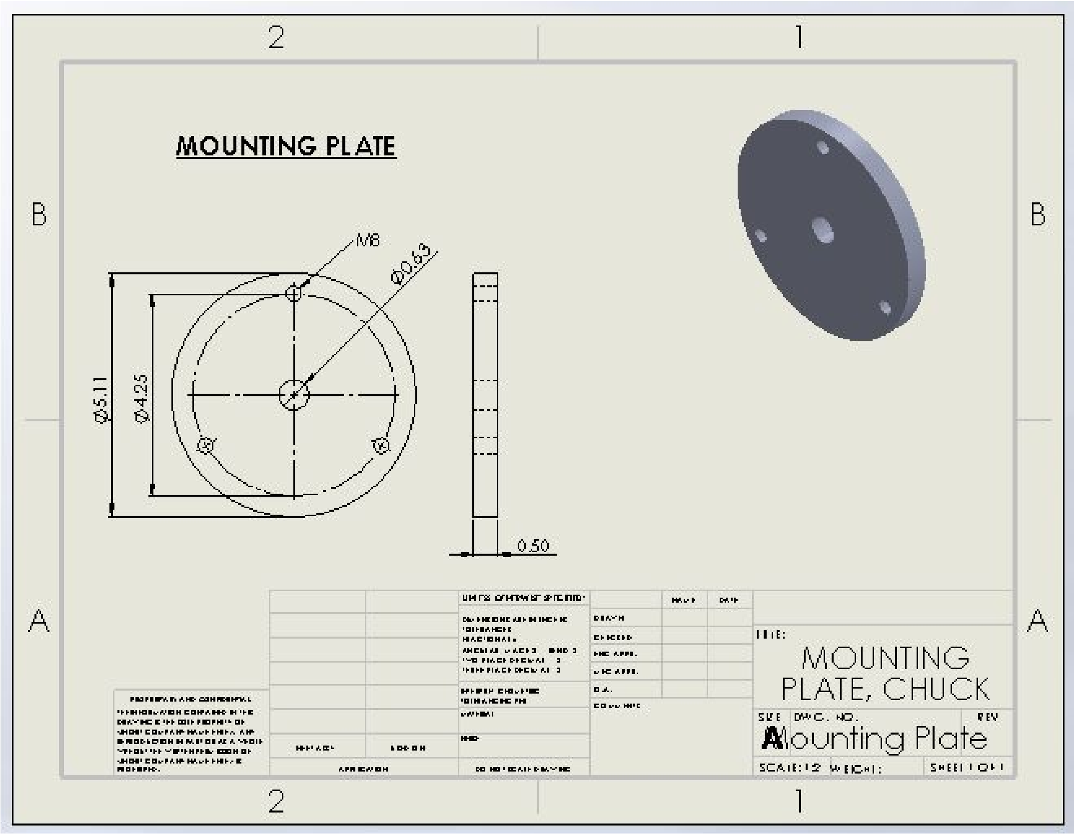


NOT ALL HARDWARE BUBBLED FOR THE SAKE OF CLARITY

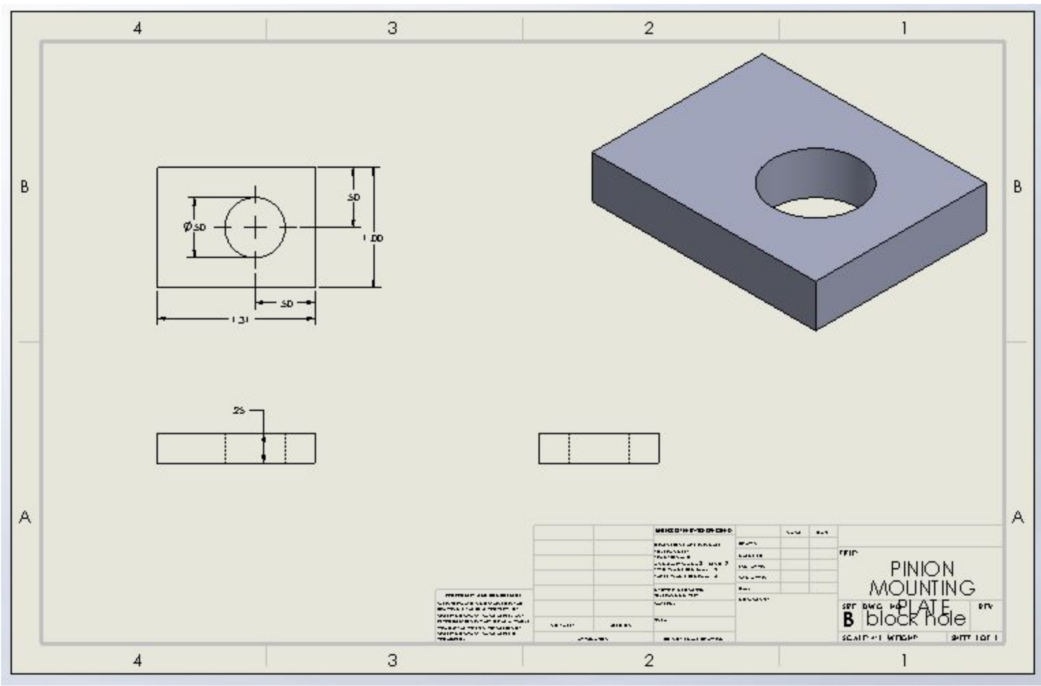
MILL CONFIGURATION ONLY DIFFERS BY:
-NO TOOL POST
-NO TAILSTOCK CHUCK
-ADDED COMPOUND VISE

11.3 Draft detail drawings for each manufactured part

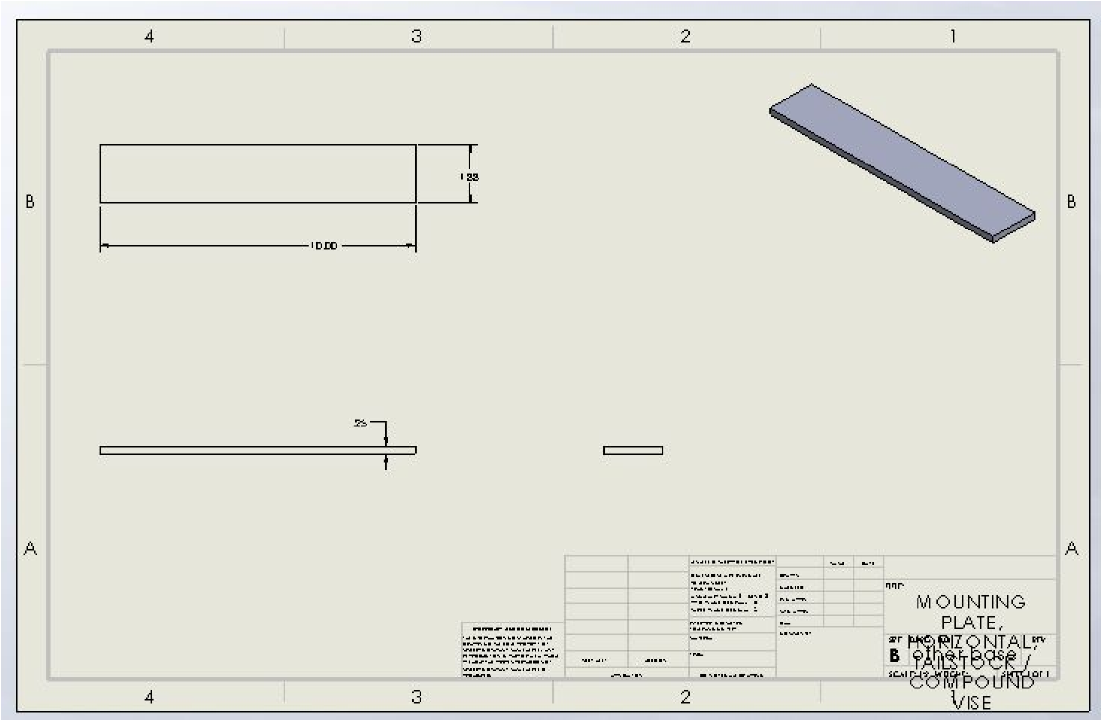
Mounting Plate for Chuck (will be welded to driveshaft)



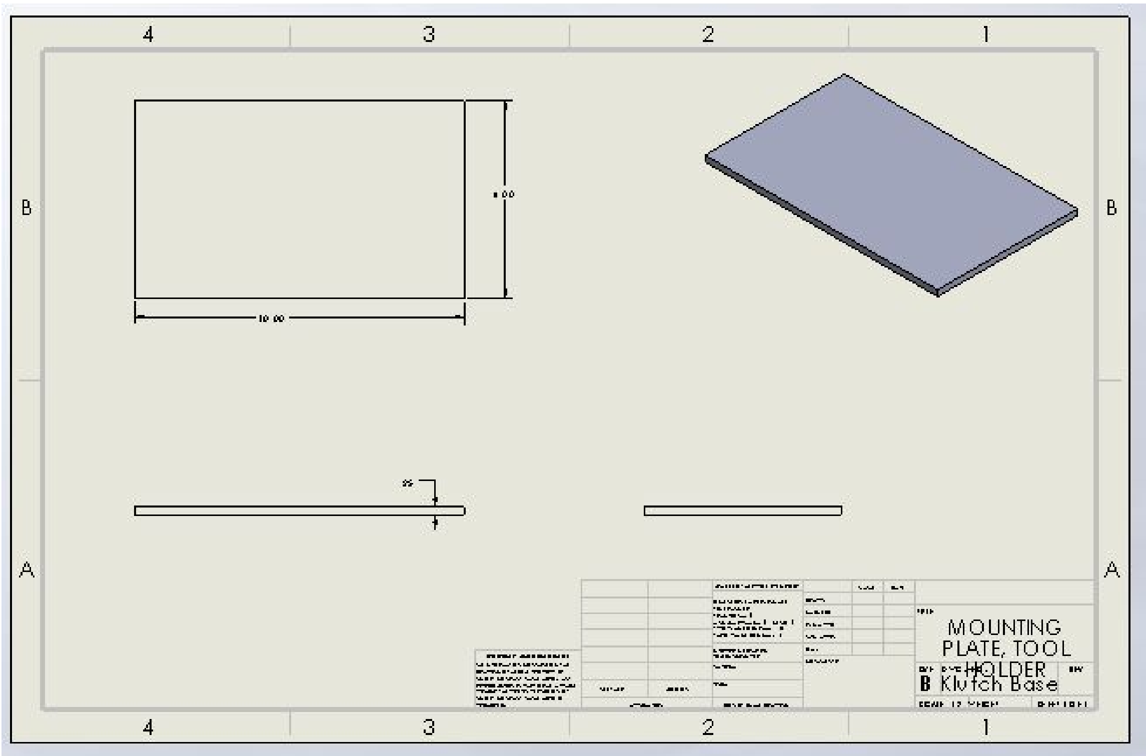
Mounting Plate for pinion gear



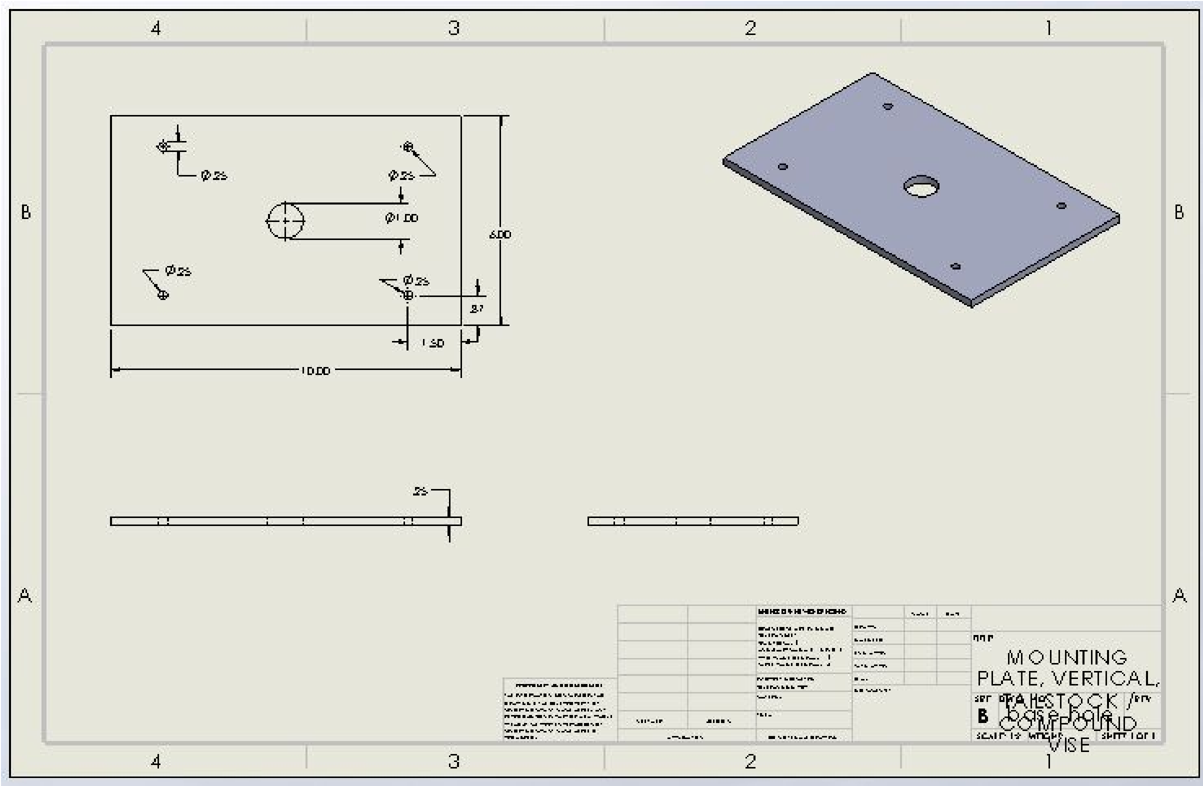
Horizontal Plate for Compound Vise Slide



Mounting Plate for Toolholder



Vertical Mounting Plate for Compound Vise



In many of these drawings, hole positions are either (1) not shown or (2) subject to change. Holes are only shown for the purpose of roughly indicating how/where parts will be mounted to plates. Actual hole positions will be decided when ordered parts arrive and assembly begins.

11.4 Description of the design rationale

Description of the design rationale for the choice/size/shape of each part

1. T-slots
    a. The frame needs to be as light as possible, while still allowing the movement of parts we wanted. Aluminum is a light material, and the type of aluminum we chose gave the required stability and strength we were looking for. The T-slots enable the tools and piece to slide easily into place while keeping the dimensions of the frame as close to the limitations (22 x 22 x 12 inches) as possible.
2. Mounted Flange Bearing
    a. The horizontal-mount flanged bearing will be used to hold the tailstock, headstock, lathe tool, and vise.
    b. The horizontal mounts can slide along the T-slots as needed, but can also be locked into place when necessary.
3. Feed Fasteners
    a. To be purchased from McMaster-Carr, these fasteners will attach components to the rail.
4. Extruded Rails
    a. These T-slotted framing rails will be purchased from McMaster-Carr.
5. Hand Brake
    a. The hand brake will be used to lock the tool head in place

6. AC motor, 1 HP, single phase (5/8" shaft)
    a. The max weight of the working piece and the necessary rpm were considered when calculating the necessary power for the motor. This calculation set a minimum requirement of slightly less than 1 hp . In order to keep the overall weight of the design down, a 1 hp motor was selected
    b. A single phase motor was chosen because we will be plugging the machine into a standard wall outlet.
7. Rack and pinion
    a. It was decided to use a rack and pinion to move the platform (holding the piece being worked on) because it would allow finer control over where the piece is in relation to the mill/drill. It will be mounted underneath the working space, so it doesn't interfere with the piece as it's being worked on.
8. 1/4" 4Fl SE Carbide End Mill
    a. This milling end mill will make the ¼" grooves as desired.
9. Drill/Mill End Mill 3/8" End Mill
    a. This tool has a pointed end to complete the drilling action.
10. Drill/Mill 1/4" Diameter End Mill
    a. This tool has a pointed end to complete the drilling action. It has a ¼" diameter to allow us to drill ¼" holes.
11. Lathe Chuck
    a. The lathe chuck was chosen based upon the maximum and minimum size of the working piece.
12. Lathe tool holder
    a. The lathe tool holder will hold the cutting piece that will perform radial cuts for the lathe.
13. Corner Braces
    a. The corner braces allowed the rails of the frame to attach together in a non-intrusive way.
14. Handle
    a. There will be a handle on the opposite end of the wheels (mill/drill end) used to pull the entire assembly.
15. Wheels
    a. There will be a pair of wheels at the end where the motor and chuck will be since that is where most of the weight is.
    b. Small wheels were chosen to minimize their addition to the total weight of the project, while supporting the weight of the frame and tools.
16. Pillow Blocks
    a. Pillow blocks were chosen based upon the size of the drive shaft. They were chosen to hold the drive shaft so that the lathe would be supported at a reasonable height for the carriage while still allowing rotational motion.
17. Shaft Collar
    a. The shaft collar was chosen based upon the size of the drive shaft. The shaft collars aim to prevent axial motion.
18. Keyed Drive-shaft/Keys
    a. This was chosen to minimize, if not eliminate, any slippage between the driveshaft and the chuck.

b. The keyed drive shaft was chosen so that keys can be inserted at the pulley/drive wheel. This allows the drive shaft to be driven by the crankshaft via the pulleys/V-Belt. The drive shaft was chosen in order to achieve the key powered transmission while remaining cost efficient.

19. Drive Wheel Pulley
    a. The drive wheel pulleys were chosen based upon the size of the drive shaft. They were chosen so that the drive shaft can be driven with the lightweight and low complexity/few part assembly of a pulley system.
20. Mounting Plate
    a. The mounting plate is a machined part that will be welded to the drive shaft and have 4 holes milled into it so that the lathe chuck can be mounted to it.
21. Controller
    a. The controller will allow us to vary the speed of our 1-phase motor to the desired speed required.
    b. The controller was chosen so that it could be used with a 120 V, single phase motor.
22. V-belt
    a. We will use a belt to save space in the assembly. With the belt, we can mount the motor next to drive shaft and power the driveshaft with a pulley.
    b. The length of this belt was chosen based upon the distance between our drive shaft and crankshaft.
23. Morse Taper Live Center
    a. This live center is inexpensive but strong enough to work mild steel as required.

12 Engineering analysis

12.1 Engineering analysis proposal

Each group performed an engineering analysis on their respective sections of the assembly. The tailstock team studied the deflection of the tool bed that will hold the vise, the headstock team examined the keyed drive shaft that will drive the lathe chuck, and the integration/transportation team analyzed the T-slot frame that will hold the assembly together.

12.2 Engineering analysis results

12.2.1 Motivation

12.2.1.1 Tailstock Motivation

The tailstock group will analyze the deflection of the tool bed in regards to milling and drilling operations. The tool bed should be able to withstand the downwards force from drilling and the horizontal force from the end mill. By performing FEA on the tool bed, we can see if the T-slots are a viable option to keep our toolbed stable.

12.2.1.2 Headstock Motivation

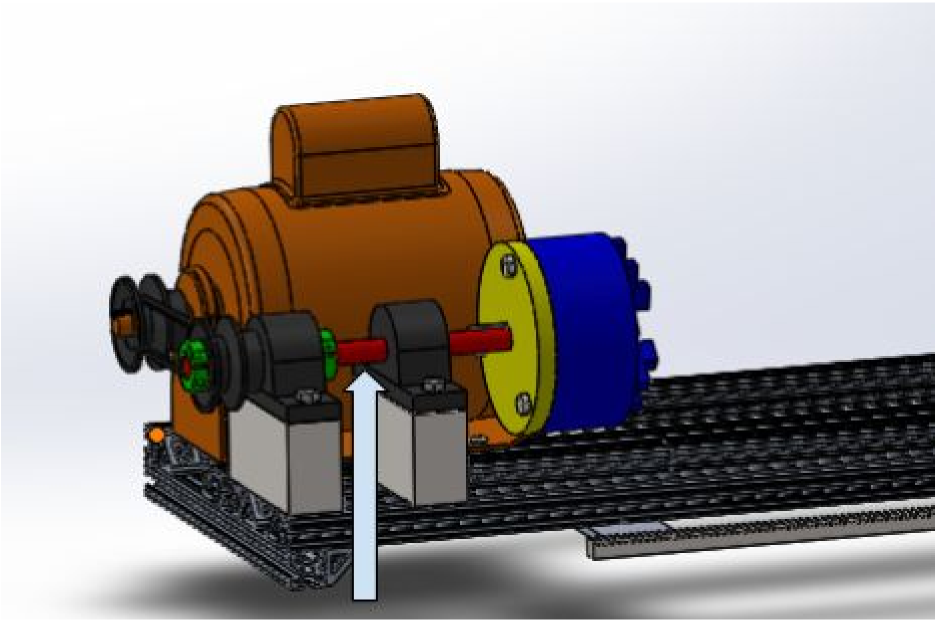


Figure 1: Keyed Shaft Placement in Assembly

In order to induce the rotational movement of the lathe chuck, the chuck is fitted with a shaft and key that is turned by the motor via a belt. The headstock group wanted to make sure that the keyed shaft purchase from Grainger could withstand the torque and forces from the belt and motor.

12.2.1.3 Integration/Transportation Motivation

The integration/transportation group focused on the finite element analysis (FEA) of the t-slot frame. We focused on the area of the t-slot where the lathe cutting tool will be making contact with the part that will be machined on.

12.2.2 Summary statement of analysis done

12.2.2.1 Tailstock Summary

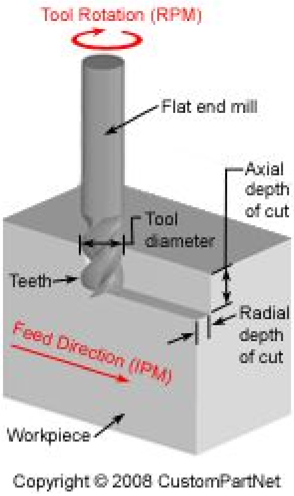


Figure 2: Milling Forces

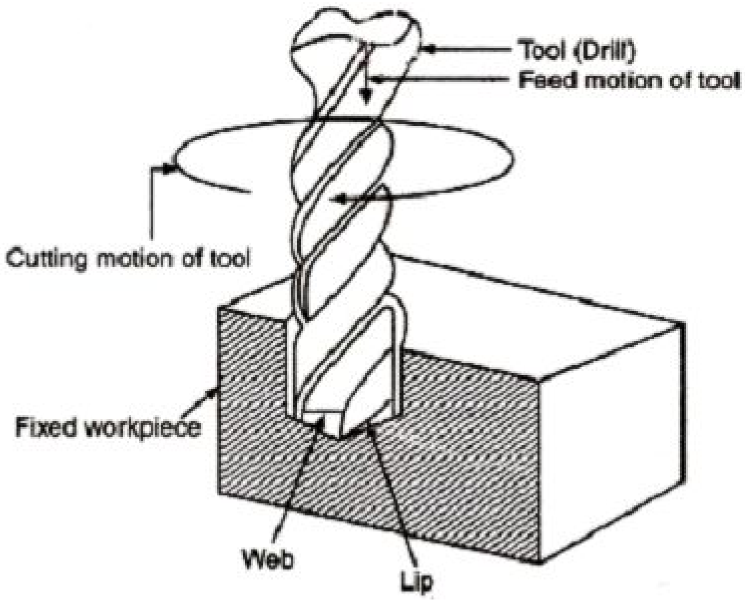


Figure 3: Drilling Forces

12.2.2.2 Headstock Summary

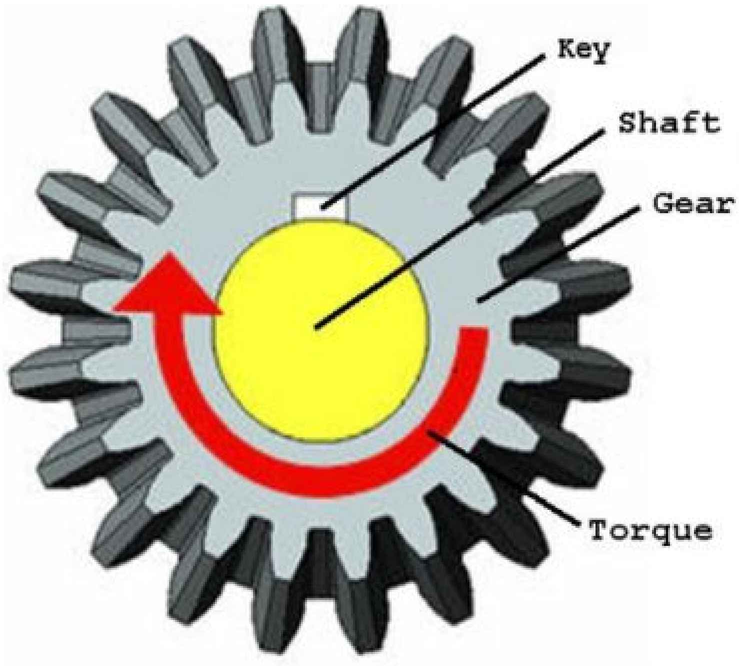


Figure 4: Forces on Keyed Shaft

12.2.2.3 Integration/Transportation Summary

The resulting forces in its three orthogonal components are: feed force F_f , radial force F_p and tangential force F_c. The feed force F_f is oriented in the same direction as the longitudinal axis of the piece, which coincides with the feed direction. The passive force F_p is oriented in radial direction seeking to dismiss the tool, and to depart it from the machined surface. The main cutting force F_c is oriented in the machining direction, being the most important component in size and role. The resultant cutting force can be calculated with the following equation:

$$R = \sqrt{F_f^2 + F_p^2 + F_c^2}$$

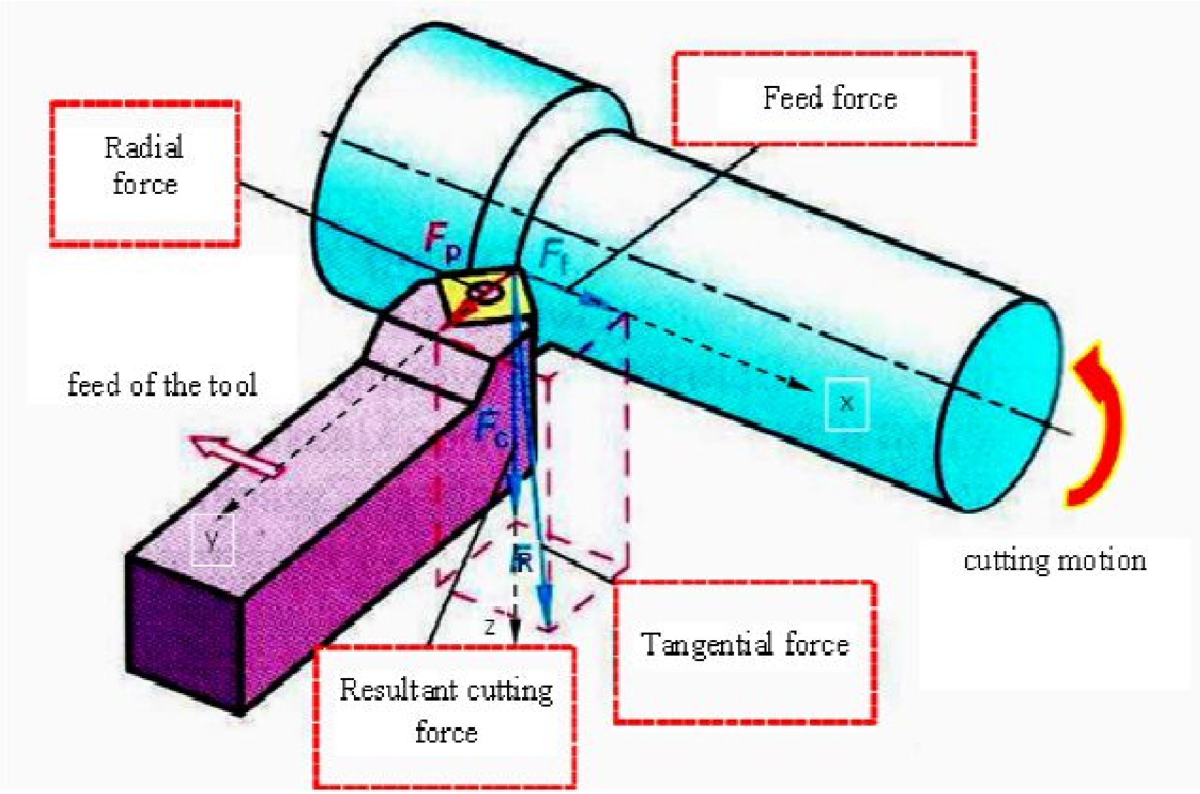


Figure 5: Forces for lathe cutting

The frame should have a vertical force (Main Force F_c) at that general area of contact above the frame. This will let us know if the t-slot will withhold the force from the lathe cutting. Using the table below we determined the main force would be 385 N because it lined up with the speed of the part rotating at 400 rev/min.

No.	Speed n [rev/ min]	Cutting speed v [m/min]	Feed rate f [mm/rev]	Depth t [mm]	Main force F_c [N]	Feed force F_f [N]	Pass. force F_p [N]
1	315	69,24	0,1	1	200	141	58
2			0,2		374	277	135
3			0,315		484	383	139
4			0,4		583	496	167
5			0,63		724	645	177
6			0,8		747	756	185
7	315	69,24	0,2	0,5	475	266	236
8				0,75	682	419	294
9				1	796	520	314
10				1,5	1052	708	327
11	200	43,96	0,2	0,5	460	355	195
12	315	69,24			390	285	165
13	400	87,92			385	280	161
14	500	109,9			370	266	152
15	630	138,47			353	246	138
16	800	175,84			338	228	124

12.2.3 Methodology

All analysis was done through Solidworks Simulation. The T-slots Solidworks files were downloaded from the McMaster-Carr catalog. The T-slot files were used to model the frame. The tool bed will be modeled from aluminum scraps from previous projects, so the tool bed was modeled in Solidworks manually. The keyed drive shaft was modeled based off of dimensions gathered on Grainger's website. Forces were simulated for each case and results were gained for the displacement, Von Mises stress, shear stress, or strain for whichever was relevant in each analysis.

12.2.4 Results

12.2.4.1 Tailstock Results

The results tell us that there will not be much deflection under the milling or drilling forces. The tool bed deflected, at most, .001 inches under the drilling force. From Figure 2 we can see the deflection due to the vertical drilling force.

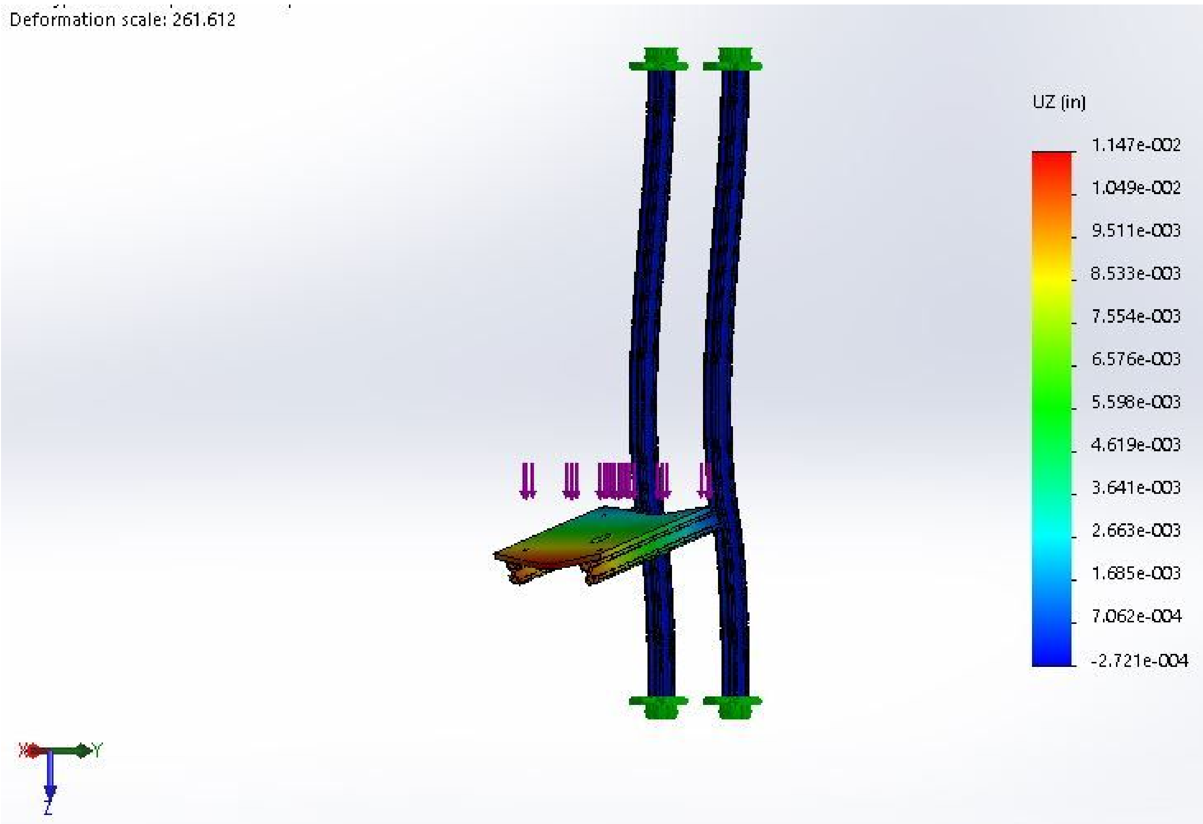


Figure 6: Drilling Force Simulation

Under the horizontal milling force, the tool bed deflected 0.003 inches. Figure 3 shows the deflection from the horizontal milling movements.

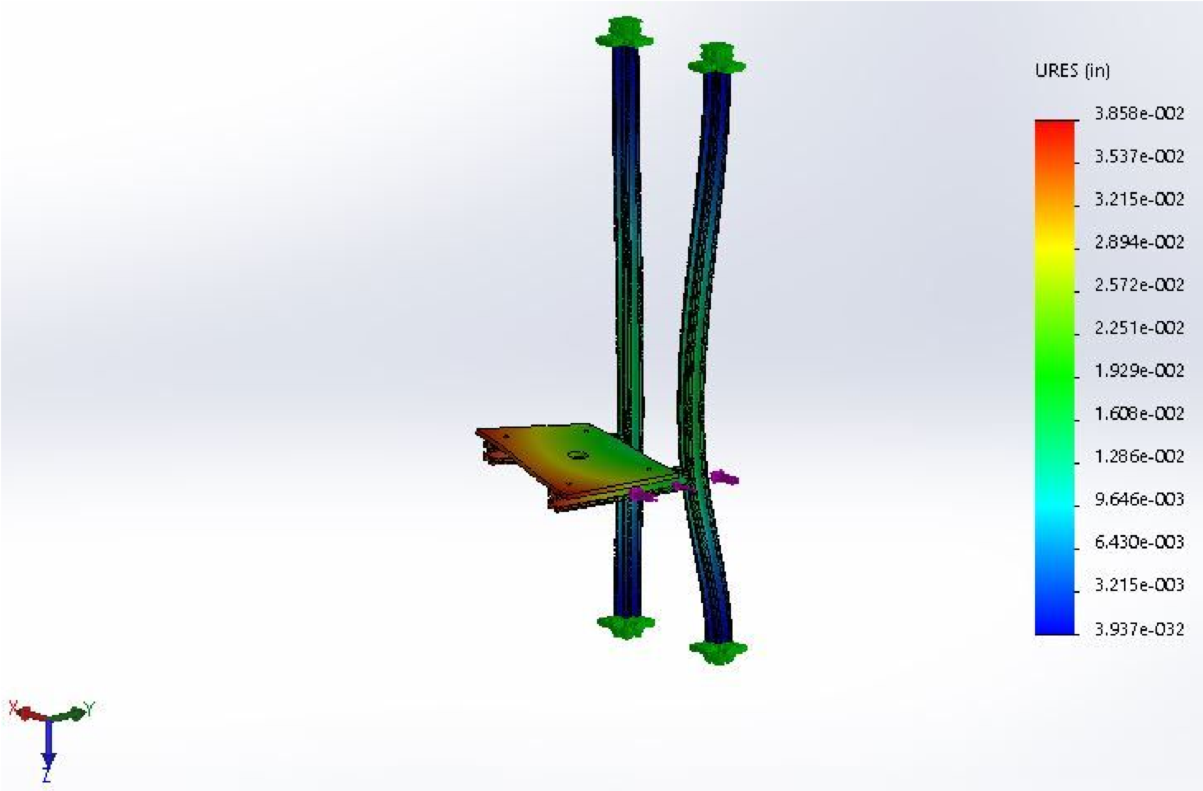


Figure 7: Milling Force Simulation

The figures depict an exaggerated view of how the forces could deflect the table and the extruded T-slots.

12.2.4.2 Headstock Results

Results are documented in Figure 7 and Figure 8 below. Figure 7 depicts the deflection of the beam. At worst the beam only deflects 0.011 inches at the end fitted with the belt. Figure 8 shows the shear stress on the shaft. The greatest shear stress occurs at the bearing that attaches the shaft to the motor, allowing the shaft to turn the lathe chuck. Even the greatest shear stress, 27, 677 psi, does not exceed the shear modulus of the shaft which is 29 x 10^6 psi.

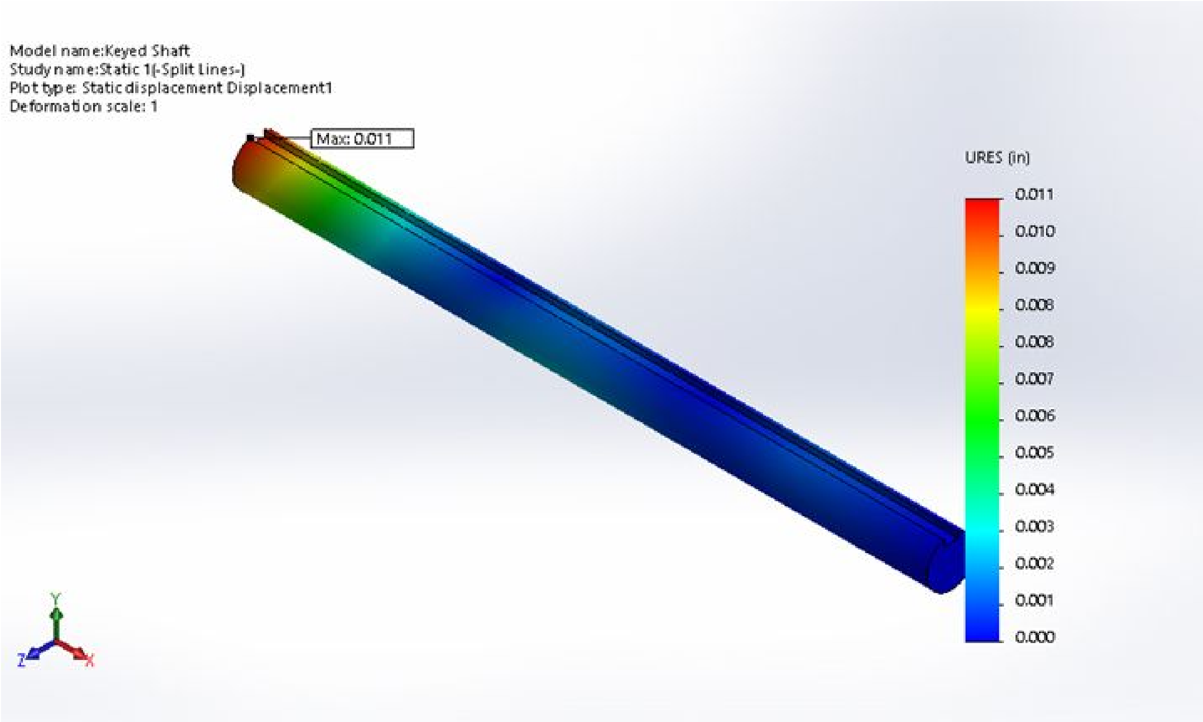


Figure 8: Deflection Results

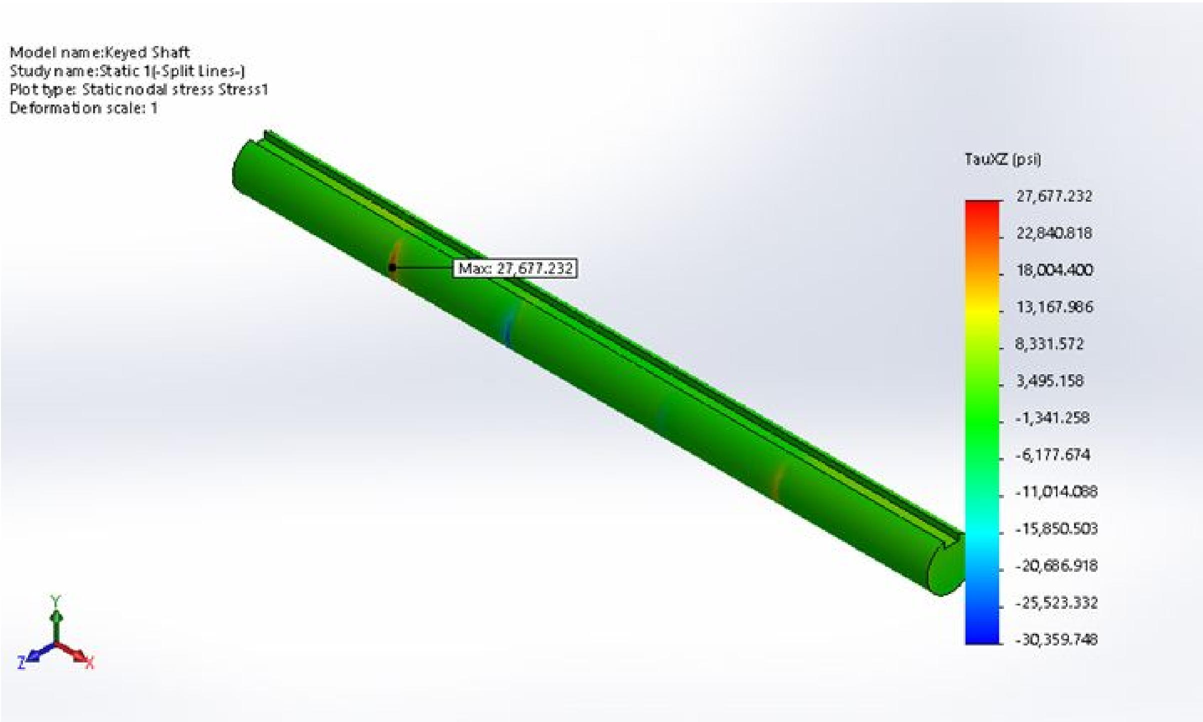


Figure 9: Shear Stress Results

These results are as expected because the end of the driveshaft that is attached to the motor will experience the most vibration as the shaft is turned. The vibrations from the motor will cause slight deflections and shear stress.

12.2.4.3 Integration Results

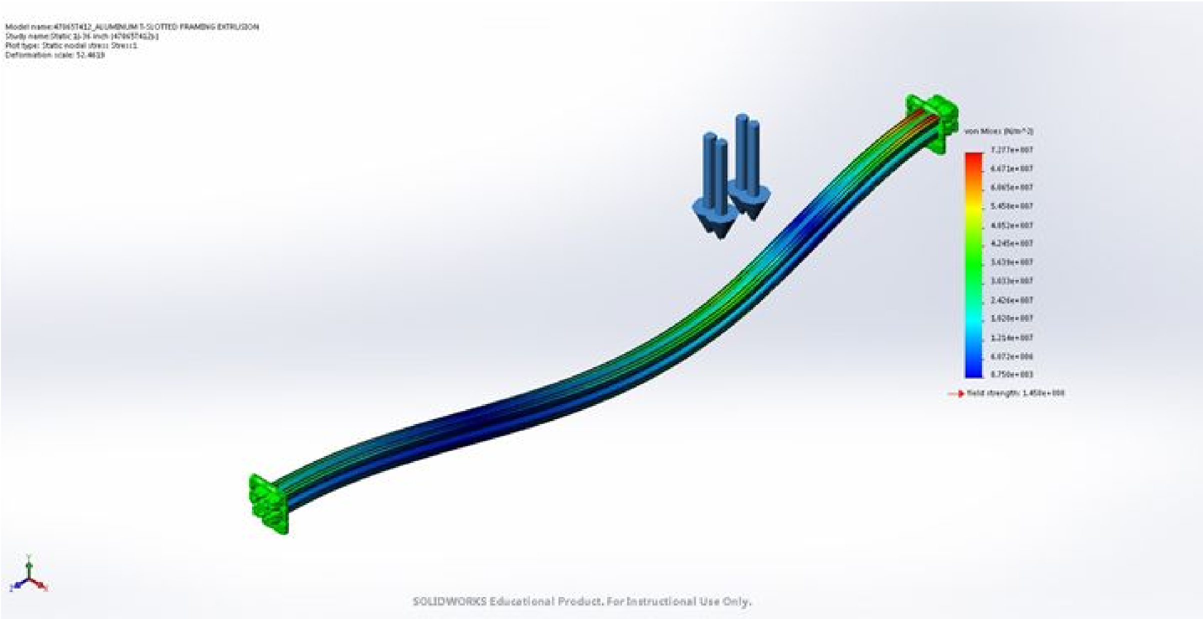


Figure 10: Von Mises Stress

The stress test had a maximum Von Mises stress of 7.277e+007 N/m^2 and minimum of 8.750e+003 N/m^2.

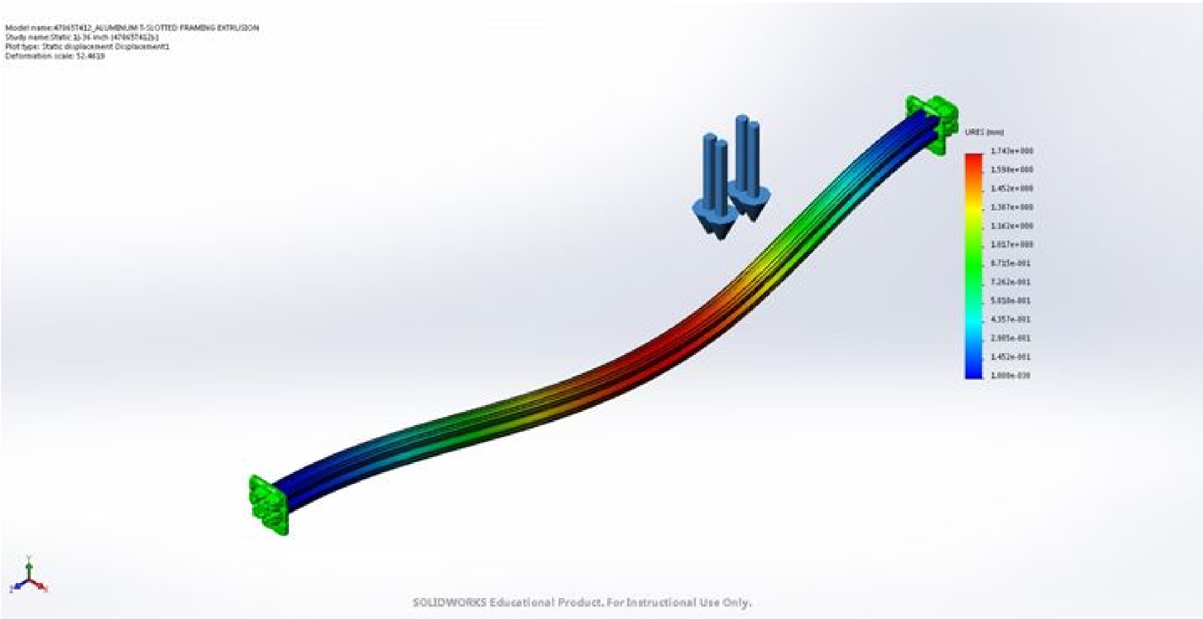


Figure 11: Displacement

The displacement test had a maximum resultant displacement of 1.743 mm and minimum of 0 mm.

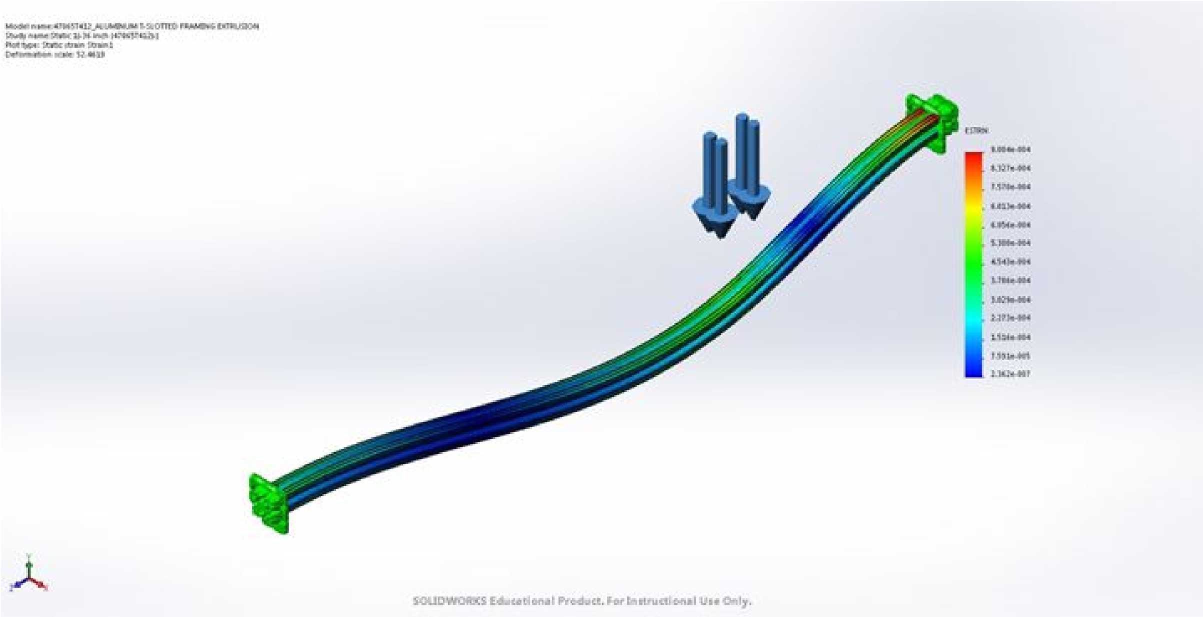


Figure 12: Strain

The strain test had a maximum equivalent strain of 9.084e-004 and a minimum of 2.362e-007.

The overall results are great because there will only be a slight displacement from the calculated force of 385 N. The force was attached at the frame, which, according to our design, the force will actually be a few centimeters above the frame. So the results should be condensed a bit.

12.2.5 Significance

12.2.5.1 Tailstock Significance

Since our results are positive we will go ahead with the aluminum T-slots and use them in the final prototype. The dimensions and material will not change, as we adequately provisioned for possible deflections in the initial design.

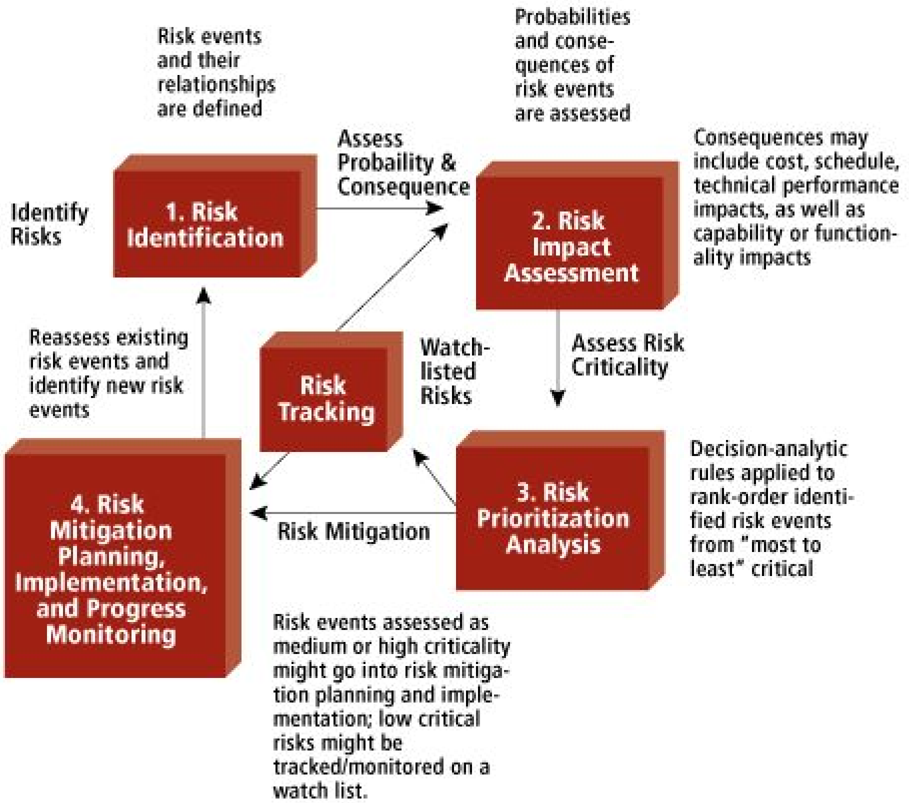
12.2.5.2 Headstock Significance

These results convinced us that the keyed drive shaft would be able to withstand the torque and resulting forces from the motor. The shaft will be purchased from Grainger in the 304 Stainless Steel material and mounted to the chuck lathe.

12.2.5.3 Transportation/Integration Significance

These results help us realize that the T-slot frame will be a good support for the entire assembly. The T-slot material is Aluminum 6063-T5. The difference between the embodiment drawing and the CAD drawing is that the design in CAD had extended T-slots (36 inches), there is a backboard-plate that supports the tailstock, and the rack and pinion were added with the turning wheel for the movable plates. The frame needed to be extended because the motor and chuck assembly along was 12 inches in length. The backboard-plate will help with operating the tailstock without having two pillow blocks and another shaft. The embodiment drawing originally had a pinion rod but we found an easy to assemble rack and pinion design.

13 Risk Assessment



13.1 Risk Identification

When designing any machine tools there is certainly safety risks involved. The combination mill/drill/lathe design poses further risks as the design will be more complex. Other risks involved in the design of the assembly include sticking to a budget, completing the project on schedule, and achieving the performance desired from the tools.

Safety

- Dangers of debris breaking off of machined parts
- Potential of entanglement in lathe

Budget

- Use of entire budget before project completion

Schedule

- Project not assembled by due date
- Parts arrive too late

- Required parts are not ordered

Performance

- Lathe chuck does not turn
- Machine is unable to cut mild steel
- Assembly is too heavy
- Assembly is too large to fit in dorm/apartment
- Assembly cannot withstand machining forces

13.2 Risk Analysis

Risk	Probability	Impact	Analysis
Debris breaking off of machined parts	High	Medium	Users should wear safety glasses, long pants, and closed-toe shoes when operating the lathe/mill/drill.
Entanglement in lathe	Medium	High	The lathe chuck should be fitted with a guard to prevent entanglement in the rotating motion of the lathe. Users should also take care to not wear loose fitting clothing or jewelry while working with the assembly.
Use of entire budget before completion	Medium	High	A parts list with costs should be created before purchasing materials.
Project not assembled by due date	Medium	High	Parts should be ordered as soon as possible to start building the prototype.
Parts arrive too late	Medium	High	Parts should be ordered from a reliable source as soon as possible.
Required arts are not ordered	Medium	High	Team members should be responsible for parts in their section of assembly.
Lathe chuck does not turn	Low	High	Finite Element Analysis completed on drive shaft to make sure it can withstand forces from motor.
Machine unable to cut mild steel	Low	High	
Assembly is too heavy	High	Low	If the assembly is too heavy, it loses its portability aspect. Overall assembly should not weigh more than 40 lbs.
Assembly does not fit in dorm/apartment	Medium	Medium	Assembly should be 22” x 22” x 12”.

Assembly cannot withstand machining forces	Medium	High	Finite Element Analysis completed on the T-slot framing and on tool bed to make sure deflections are not too high.

13.3 Risk Prioritization

The high probability risks took first priority when designing the assembly. The assembly weight was thought of when designing the frame. Aluminum T-slots were chosen because they are lightweight. When using the assembly group members wore safety glasses, long pants, and closed-toe shoes to avoid being hurt by debris from machined tools. In order to avoid using the budget before project completion, a parts list was created with prices. We tried to stay under budget so we could afford last-minute purchases. We also made use of scraps from previous projects to save money. We made sure that our assembly would perform as desired by performing engineering analyses on the frame and driveshaft. The analyses came back positive, so we are confident in our design.

14 Codes and Standards

14.1 Identification

OSHA 29 CFR 1910.212(a)(1), Machinery and Machine Guarding - General Requirements for all machines.

OSHA 29 CFR 1910.216, , Machinery and Machine Guarding - Mills and calenders in the rubber and plastics industries.

ANSI B11.6, Safety Requirements for Manual Turning Machines with or without Auto Control

ANSI B11.8, Safety Requirements for Manual Milling, Drilling, & Boring Machines with or without Automatic Control

14.2 Justification

For this design, the codes and standards for multiple machines were considered. Regulations issued by various institutions were considered in order to understand the full scope of design regulations. The OSHA standards are considered because these outline codes are used for a wide range of machines. Setup and operation of the mill will have to conform to OSHA standards concerning mills (1910.216) and ANSI standards B11.6 and B11.8. The OSHA standards require guarding and emergency stop mechanisms for all machines and have no guidelines specific to lathes and mills. ANSI B11.6 should also be referenced for more detailed standards. These standards set forth guidelines for manual turning machines.

Electrical standards that should be considered when designing all machine components include emergency stop, anti-restart, and other safety trip controls. Although guarding is required by most standards, a chuck shield that is electrically interlocked with the automatic stop is not.

14.3 Design Constraints

The referenced standards place constraints on the design by requiring additional safety features. All design additions are required for operator safety. All lathes and mills should include an emergency stop as well as an anti-restart feature, but only lathes need to have a guard that will cover the machine part that spins the workpiece. A guard that would cover the lathe chuck and workpiece when in motion should be implemented for operator safety.

14.4 Significance

Budget and time constraints interfered with the fulfillment of the standards. In order to satisfy the emergency stop and anti-restart requirements, the electrical motor controls would have needed to have been upgraded to a more sophisticated system. Furthermore, the emergency stop, as well as the chuck guard, would have also required additional parts to incorporate or materials to fabricate.

15 Working prototype

15.1 prototype Photos

Figure 13: Entire Assembly on Motor Side

The first picture shows the overall assembly from the motor side. The motor is operated by a dimmer switch plugged in from an outlet. The frame is made of aluminum t-slots that make moving components convenient. A last minute decision for mobility was adding four casters to a block of wood that was easily mounted to the t-slot. On the other side the vise is mounted on a plate which is also mounted on four sliders. The vise holds the lathe cutting tool and tailstock. The entire piece slides forward toward the chuck for milling. If the user wants to drill then the part will be mounted on the vise and the drill chuck will be mounted in the chuck.

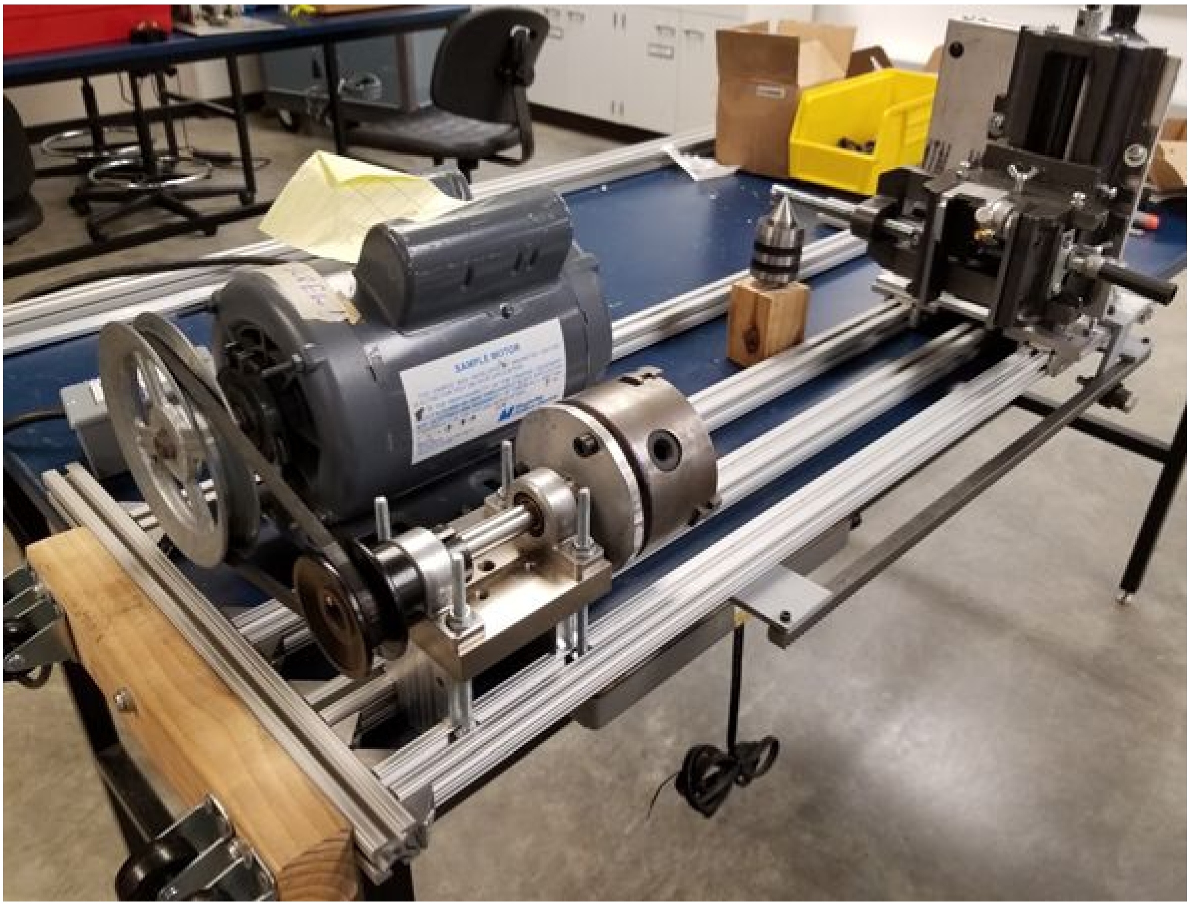


Figure 14: Entire Assembly on Chuck Side

This side shows the belt connecting the motor to the collar shaft and chuck. At first the motor was turned the opposite way because of fear of the vise hitting the motor. This had to be changed because the distance between the chuck and tailstock/vise was one inch. The vise had to be the mobile tool, especially since the motor has to stay mounted in one spot, unless the user wants to disassemble the motor and shaft collar/chuck repeatedly. This view also shows the vise/tailstock being guided with a rack and pinion.

15.2 Working Prototype Video

https://youtu.be/C3KcML7IIEQ

15.3 Prototype components

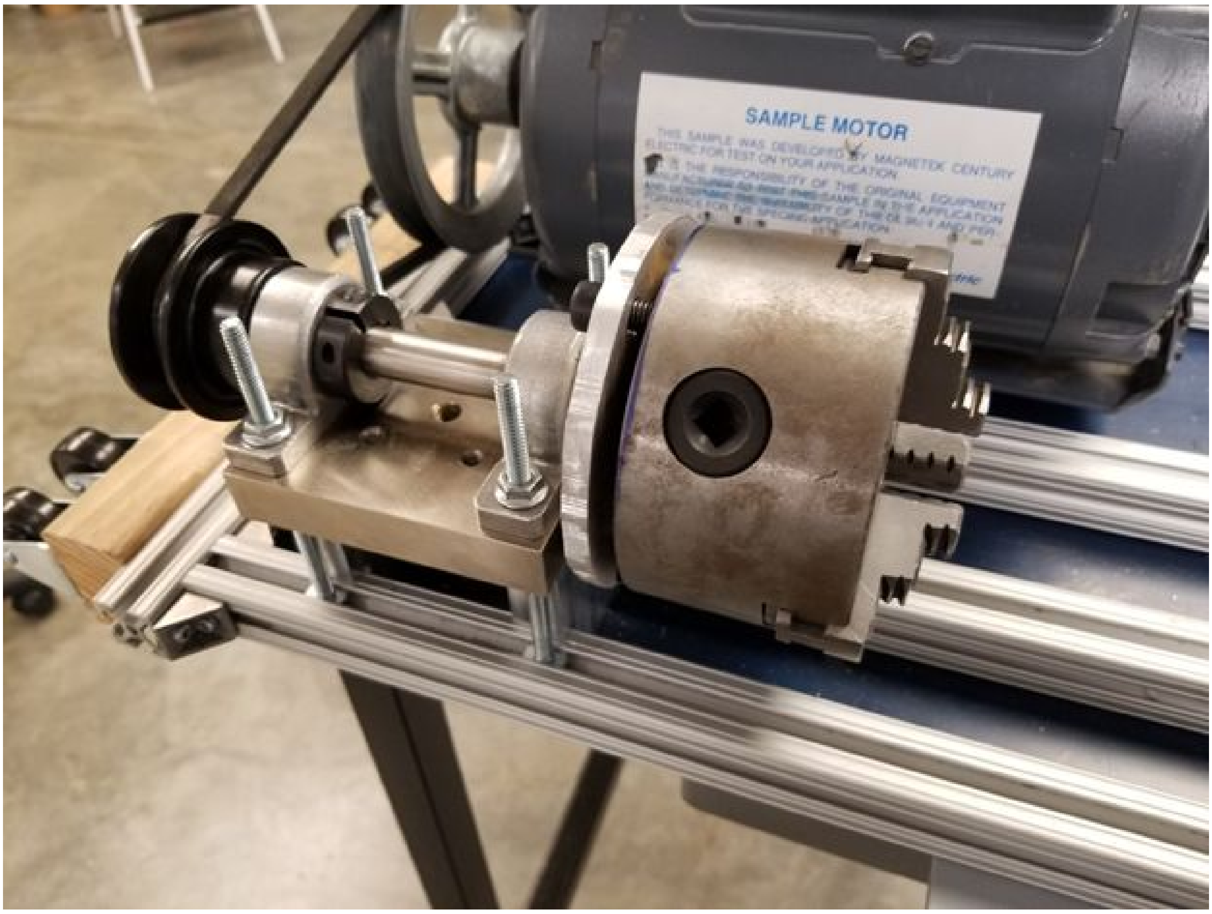


Figure 15: Chuck Assembly

There was vibration in the chuck which is dangerous for cutting and precision so we had to make sure everything was balanced. The steel plate had to be machined and was the third try. A shaft bearing was placed in between the chuck and plate because there was still vibration. Another shaft bearing next to the pillow block helped the shaft from rocking horizontally. After many small adjustments the chuck had minuscule vibration and was quieter.

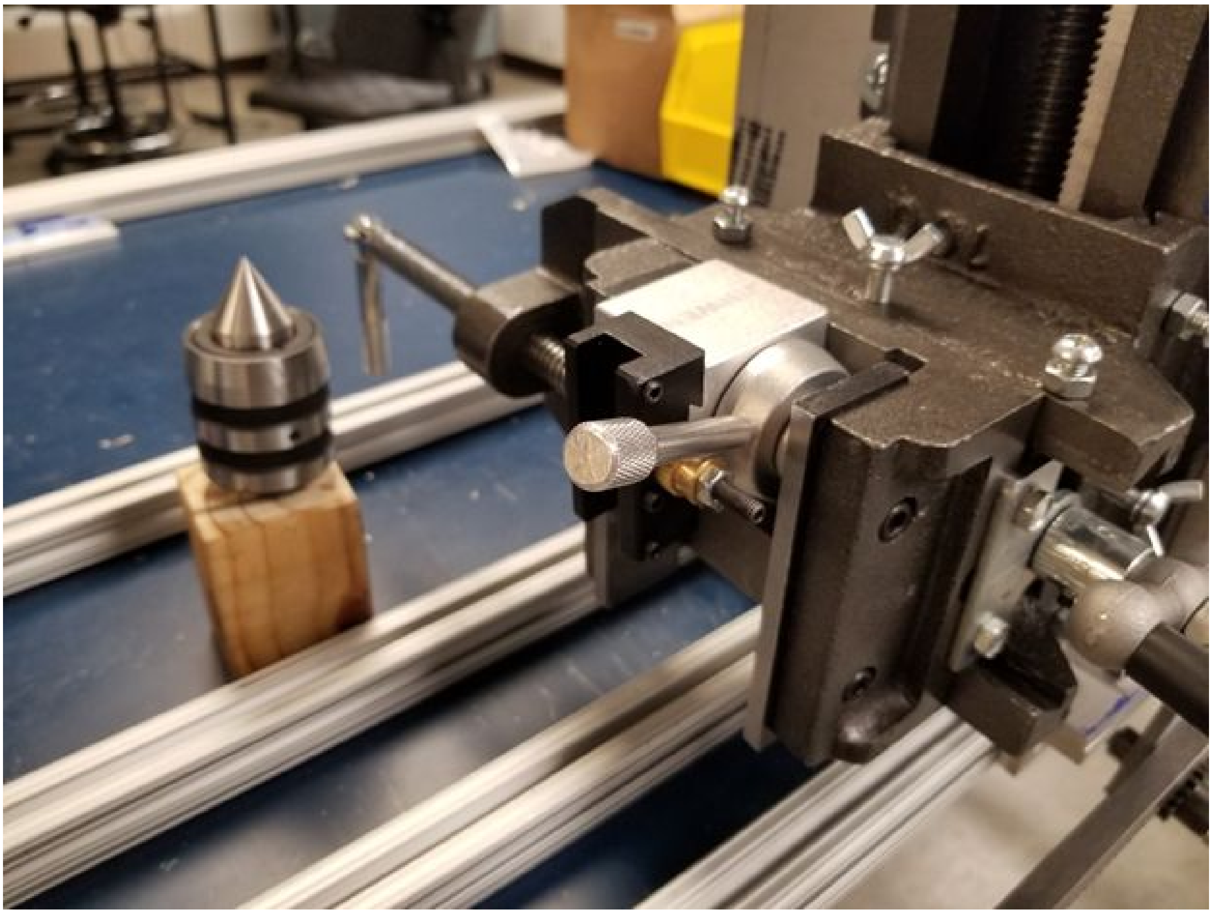


Figure 16: Lathe Cutting Tool and Vise Assembly

We unfortunately ran out of time in the machine shop to make a plate for the lathe cutting tool, so we decided to have the entire vise be mobile. With limited time and equipment we remounted the entire vise on the four sliders. If the user wants to lathe, he or she can slide the vise and lathe cutting tool toward the object in the chuck and start trimming; same procedure for the tailstock. If the user wants to drill then he or she can mount the object in the vise, mount the drill chuck in the chuck, and start drilling.

Figure 17: Vise and Rack and Pinion Assembly

As mentioned before, the vise is mounted to the vertical plate, which is mounted to another plate on four sliders. The aluminum t-slots held the weight very well. The rack and pinion was tricky to get working but makes sliding the vise more convenient. The little plates holding the rack and pinion were 3D printed.

Figure 18: Tailstock Assembly

The tailstock assembly was a last minute decision. All of the parts ordered were a week in a half late so the day we received the parts was the day this all came together. We didn't have time to order or create some tough holder for the tailstock so some cut a piece of would and wedged the tailstock inside. It actually holds pretty well but we obviously don't recommend performing this way. A big flaw for this is limited accuracy.

16 Design documentation

16.1 Final Drawings and Documentation

16.1.1 Engineering Drawings

See Appendix C for the individual CAD models.

Here include a set of the final engineering drawings for your prototype. Include units on all CAD drawings.

16.1.2 Sourcing instructions

7.2 Final Presentation

https://youtu.be/C3KcML7IIEQ

8 Teardown

9 Appendix A - Parts List

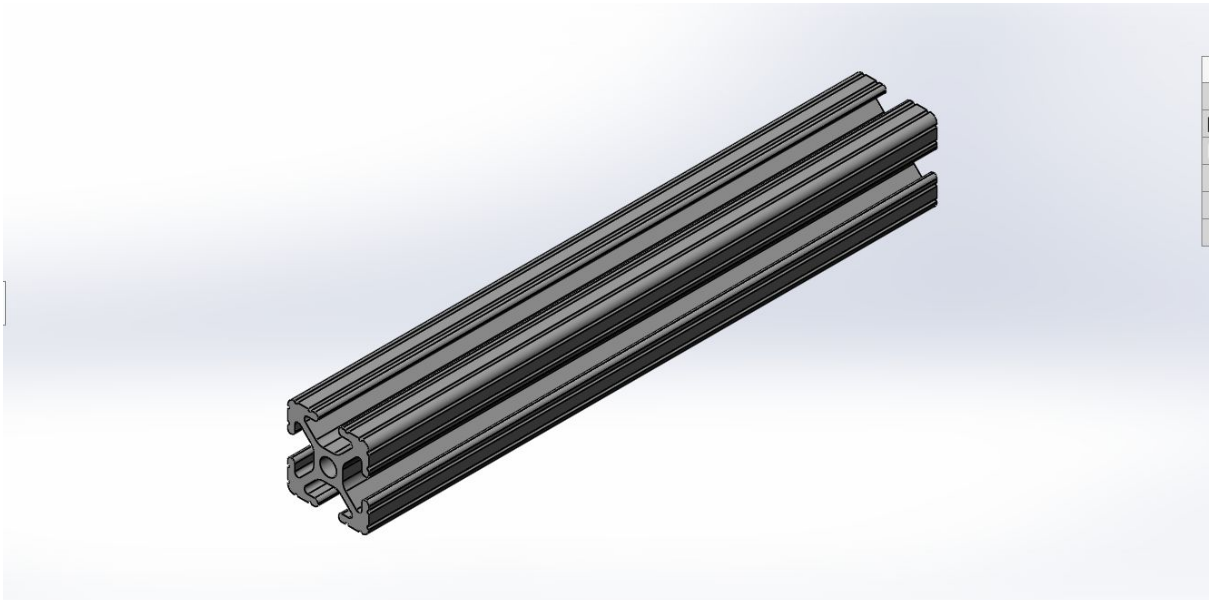
General Bill of Materials	Cost	Weight (lbs)	Catalog #	Location
AC motor, 1 HP, single phase (5/8" shaft)	$0.00	35		Morgue
v belt (29")	$6.77		7881K31	https://www.mcmaster.com/#7881k31/=1dqu8me
keyed driveshaft (5/8" x 6"; keyway: 3/16" x 3/32")	$22.85		30F869	https://www.grainger.com/category/keyed-shafts/power-transmission-accessories/motor-supplies/motors/ecatalog/N-19ep
key (3/16" x 3/16" x 12")	$1.19		98491A117	https://www.mcmaster.com/#98491a117/=1dqq4fq
drive wheel, pulley (5/8", 3/16"x 3/32" keyway) [x2]	$24.16		6204K133	https://www.mcmaster.com/#6204k133/=1dqptde
pillow blocks 5/8" (x2)	$28.00	5.6	645638704588	https://www.amazon.com/2x-UCP202-10-Pillow-Block-Bearing/dp/B078TRWD2Y/ref=sr_1_1_sspa?ie=UTF8&qid=1531783480&sr=8-1-spons&keywords=pillow+block+bearing+5%2F8&psc=1
Bolt Size: 3/8" inch ($3.64 each)	$29.12		92190A111	https://www.mcmaster.com/#92190a111/=1dquujc
Shaft Collar (x2) (5/8" ID, 3/16" x 3/32" keyway)	$32.24		3357K13	https://www.mcmaster.com/#3357k13/=1dqq0d0
controller, 120 V, single phase, > 6 A (resistance controller)	$19.99	1.06	80005NW	https://www.amazon.com/CastleGreens-Variable-Controller-Inline-Exhaust/dp/B07CNPZ8NC/ref=sr_1_7?ie=UTF8&qid=1531376053&sr=8-7&keywords=120v+motor+speed+controller
1/4" 4Fl SE Carbide End Mill	$14.49	0.06	E700-1/4	https://www.amazon.com/gp/product/B01LZGBGBV/ref=s9_acsd_simh_hd_bw_b2bDZY3_cr_x__w?pf_rd_m=ATVPDKIKX0DER&pf_rd_s=merchandised-search-3&pf_rd_r=QEYYS0PSA4TVBQMED14X&pf_rd_t=101&pf_rd_p=735c36d0-fe09-5a98-a44d-b6875f971900&pf_rd_i=2382225011
Drill/Mill End Mill 3/8" Mill diameter	$20.58		2957A13	https://www.mcmaster.com/#2957a13/=1dpors0
Drill/Mill 1/4" mill diameter	$20.58		2957A13	https://www.mcmaster.com/#milling-drills/=1dpotih
Wheels ($10.65 each)	$21.30		47065T336	https://www.mcmaster.com/#47065t336/=1dqsjem
T-Slots	$16.50	0.94	45-4545-Lite	https://8020.net/shop/45-4545-lite.html
Fastener ($2.3 for 4)	$4.60		47065T142	https://www.mcmaster.com/#47065t142/=1dok5k8
Lathe tool holder	$29.80	1.5	4089902	https://www.amazon.com/Jinwen-Tooling-Package-Holders-Multifid/dp/B018QMTXB0/ref=sr_1_5

				?s=power-hand-tools&ie=UTF8&qid=153118309 1&sr=1-5
Silver Gusset Bracket (x8)	$52.32			https://www.mcmaster.com/#47065t663/=1dscj2b
Horizontal-Mount Flanged Bearing (x4)	$184.64			https://www.mcmaster.com/#47065t959/=1dscdex
Total	$344.49	44.1572		

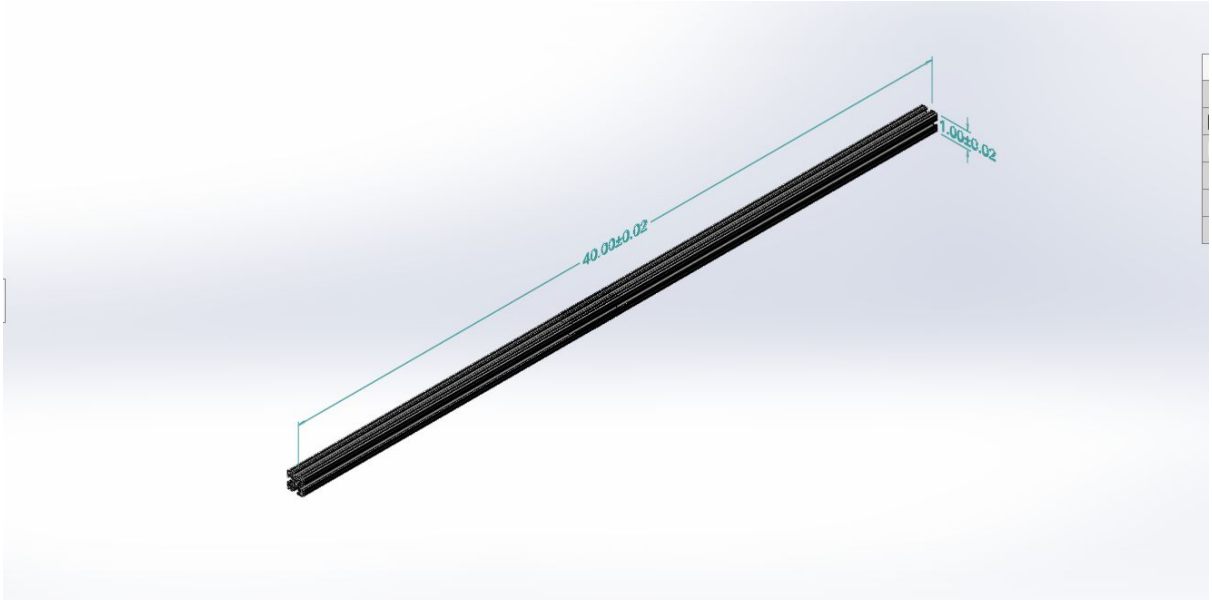
10 Appendix B - Bill of Materials

See Appendix A

11 Appendix C – Complete List of Engineering Drawings



6 47065T411_ALUMINUM T-SLOTTED FRAMING EXTRUSION



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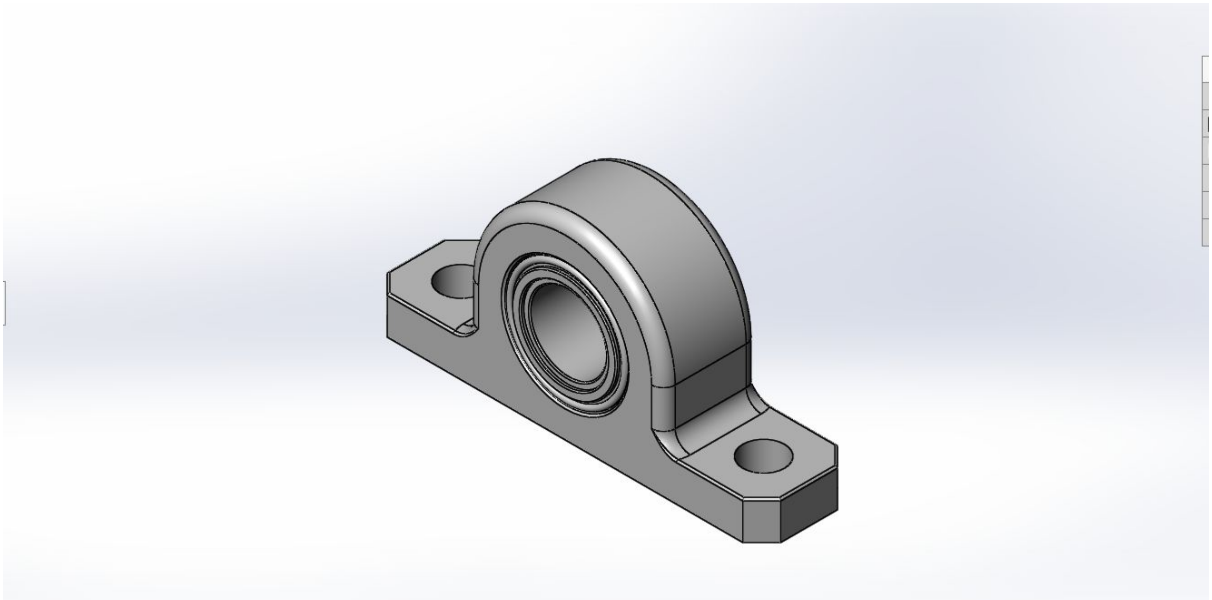
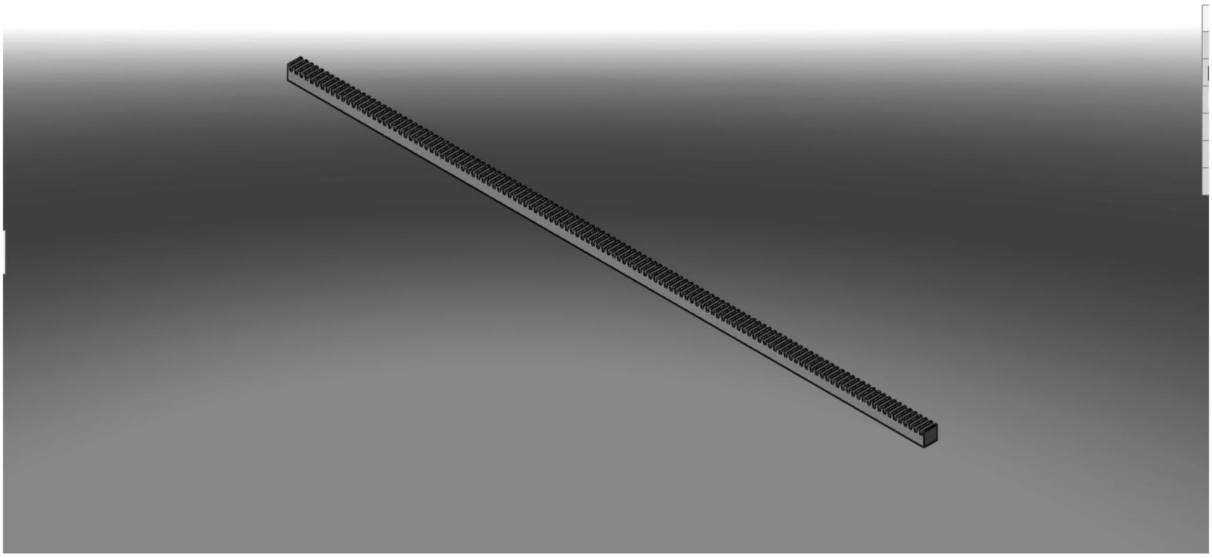
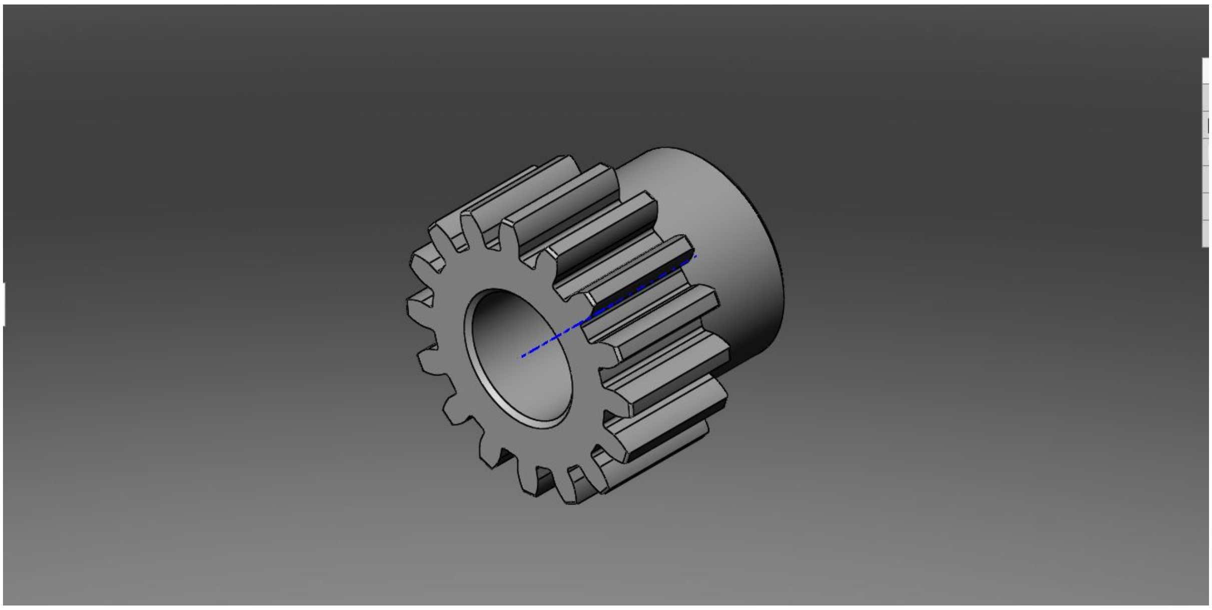


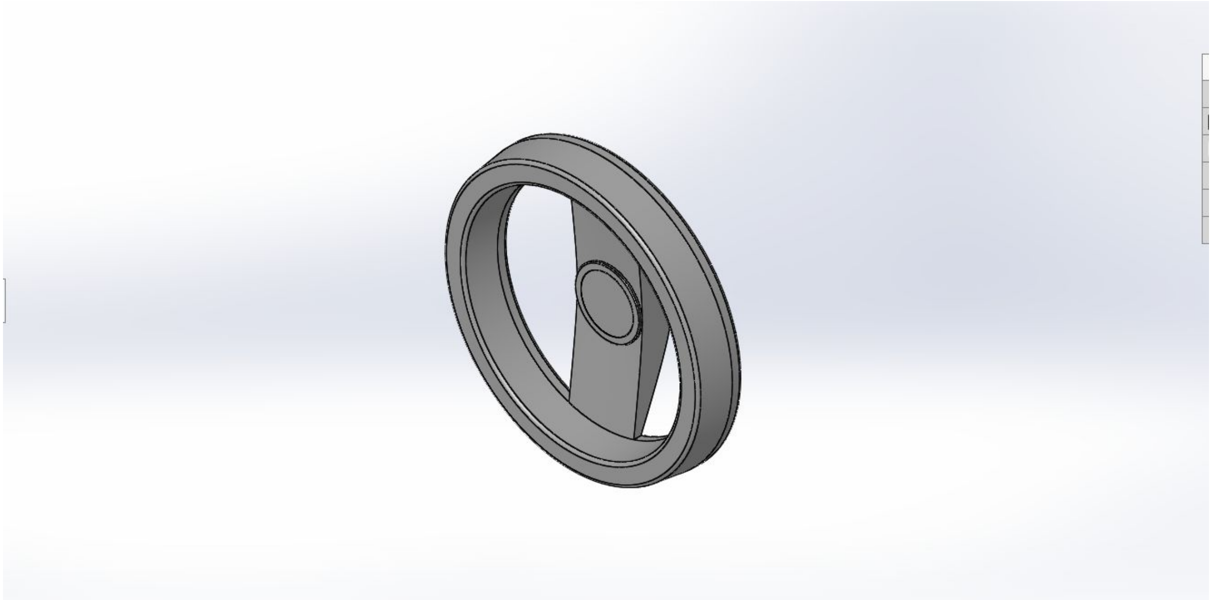
5912K600_OIL-EMBEDDED MOUNTED SLEEVE BEARING



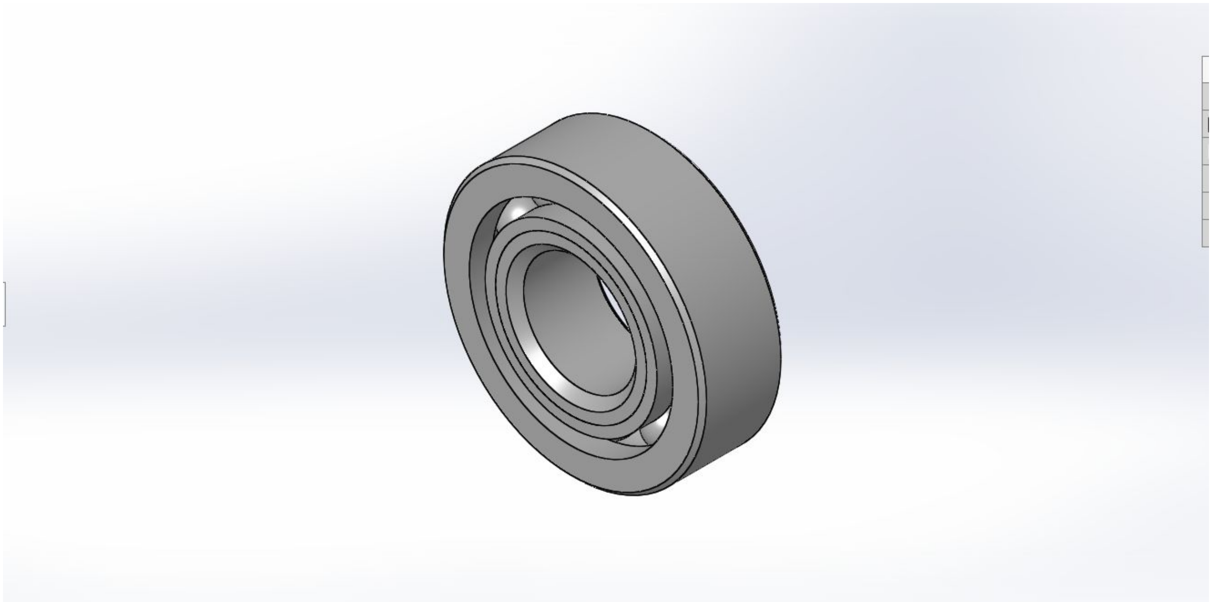
6295K140_MTL GEAR RACK--14-.5 DEG PRESSURE ANGLE



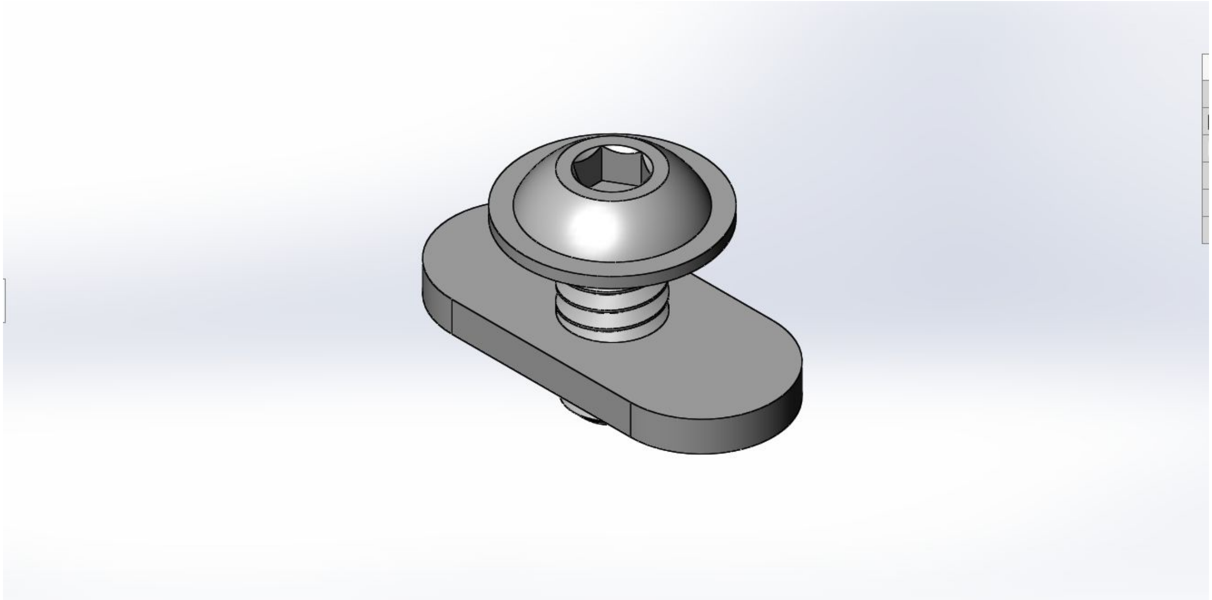
6325K130_MTL GEAR--14-.5 DEG PRESSURE ANGLE



6335K840_SPOKED THERMOPLASTIC DISHED HAND WHEEL (1)



6680K130_ANGULAR-CONTACT BALL BEARING



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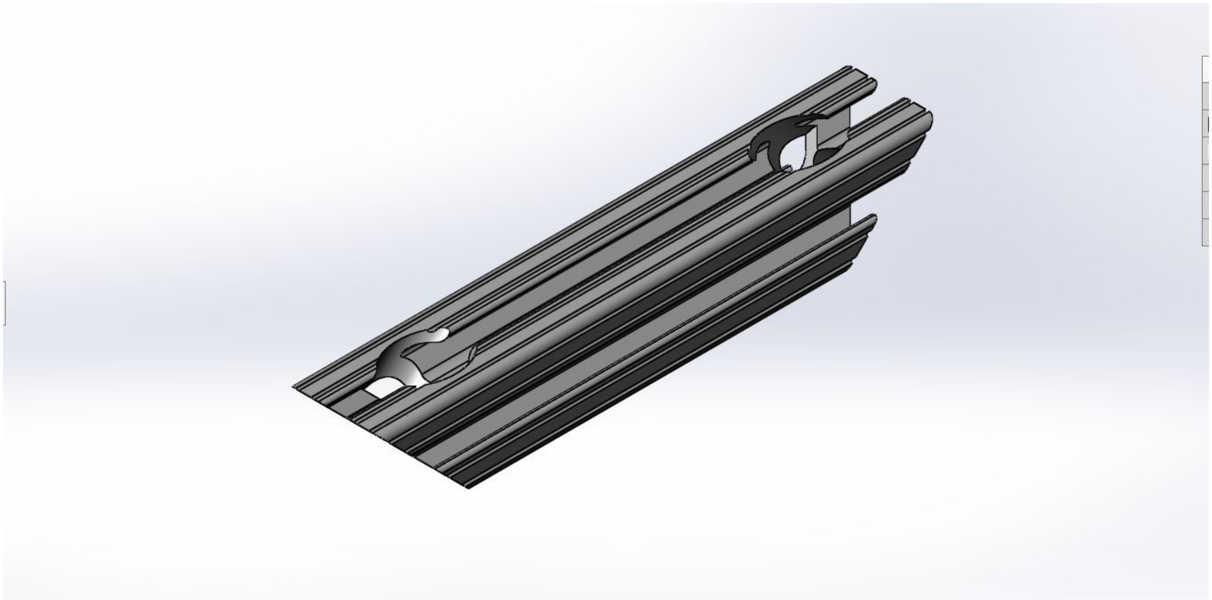

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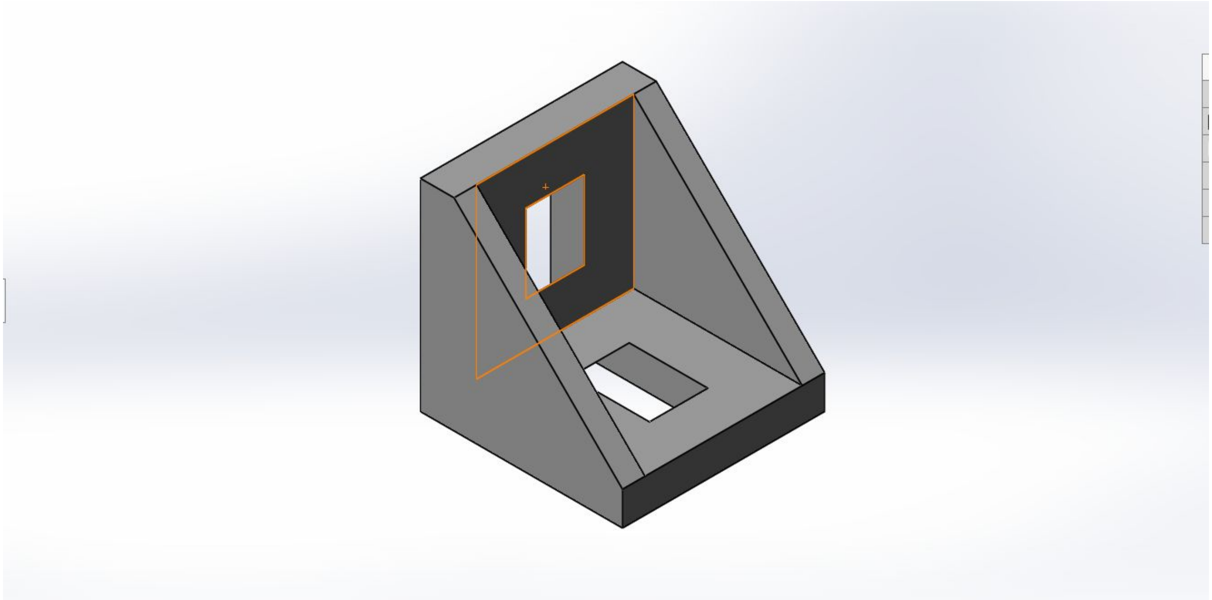

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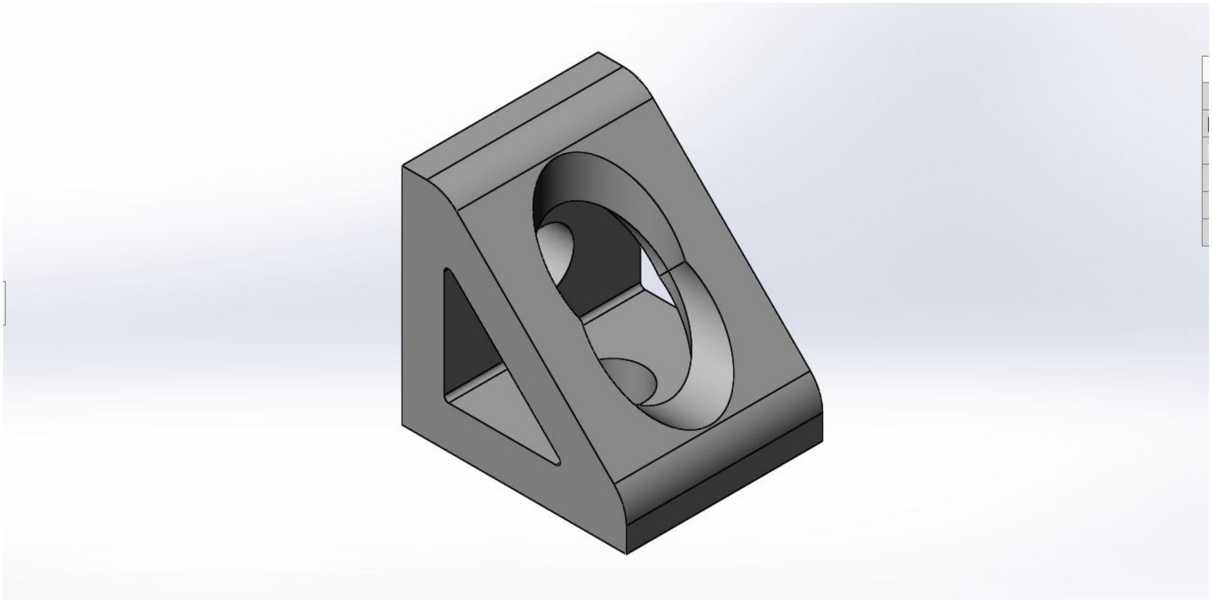

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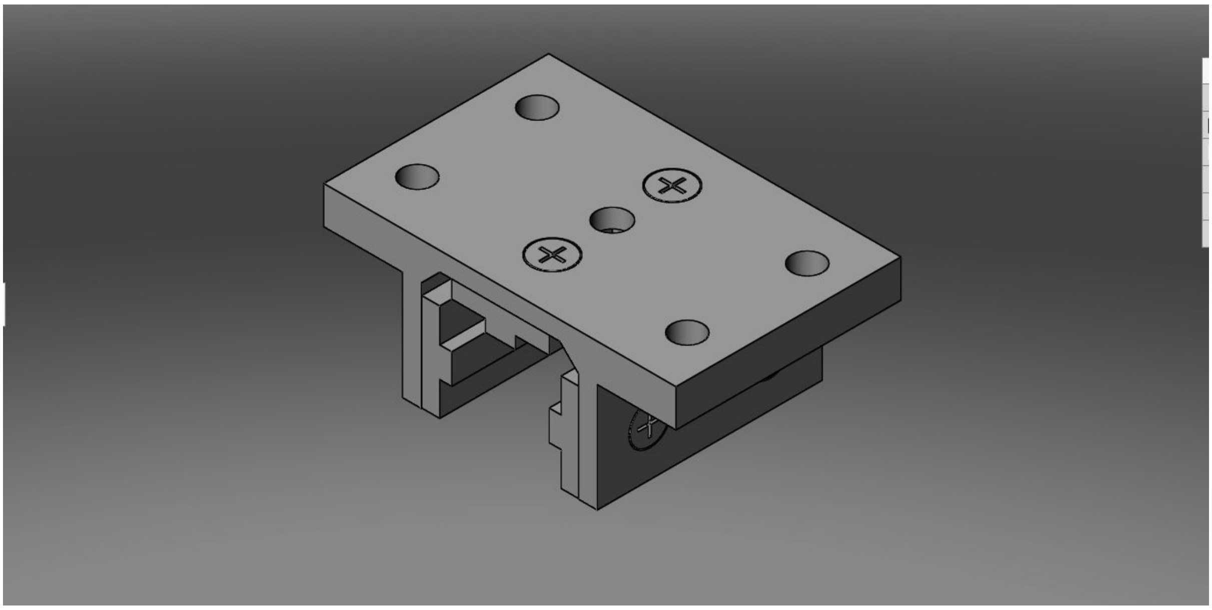

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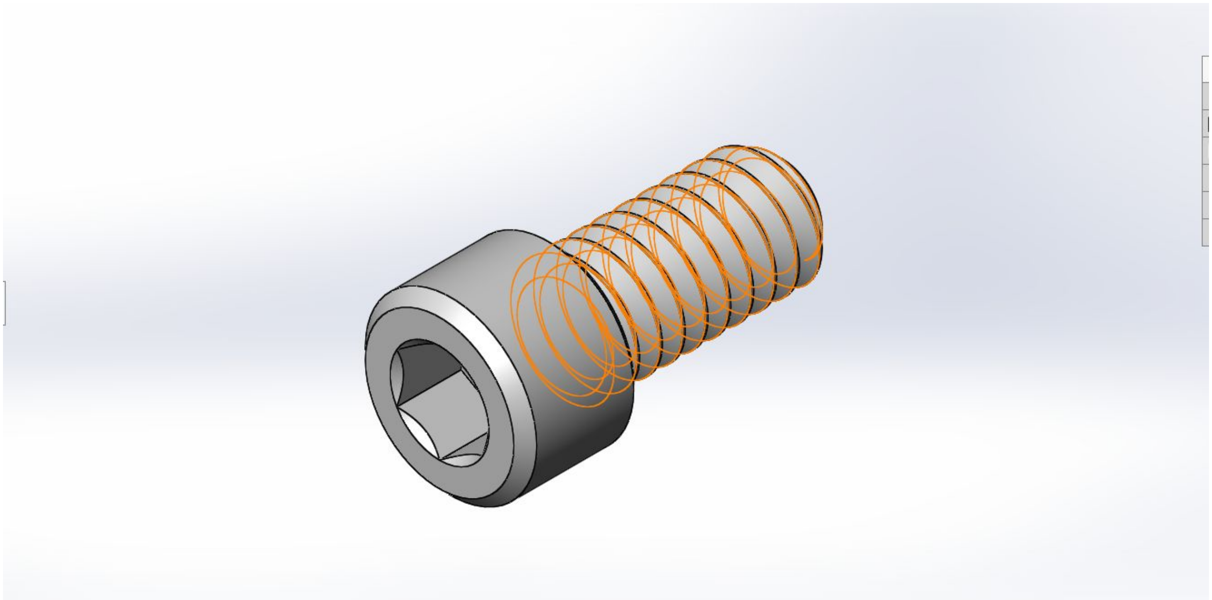
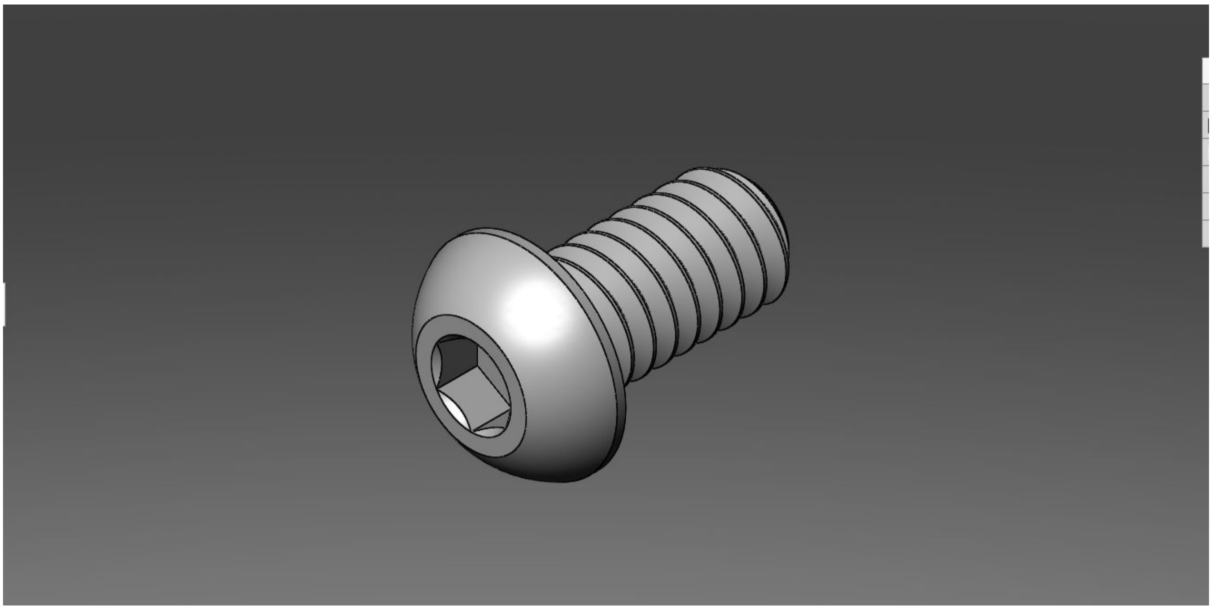
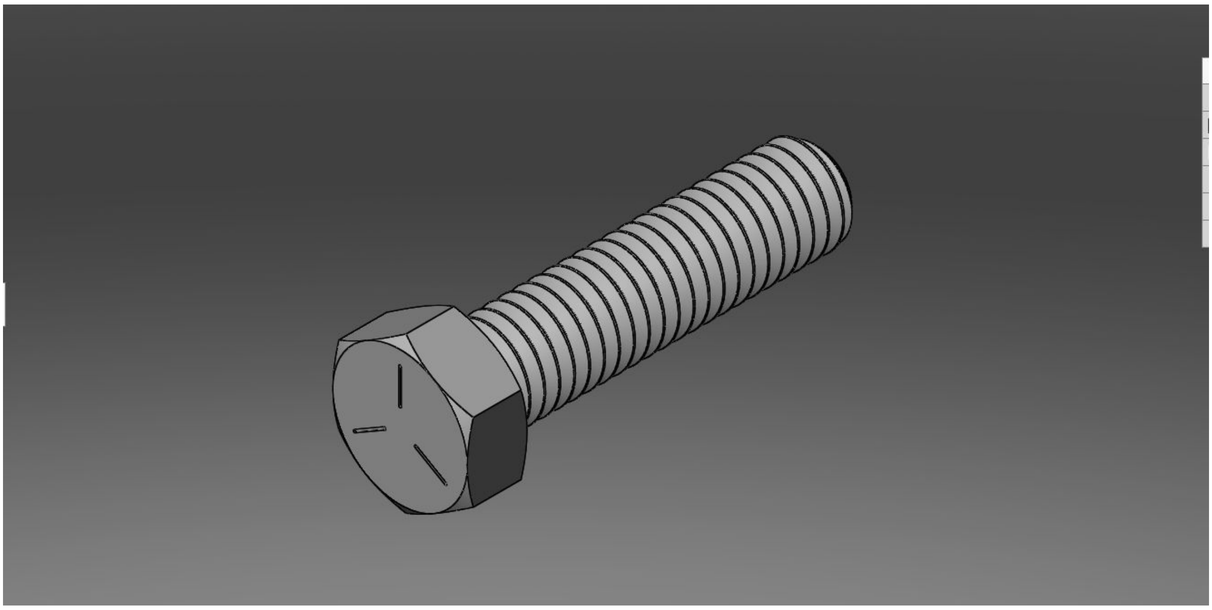


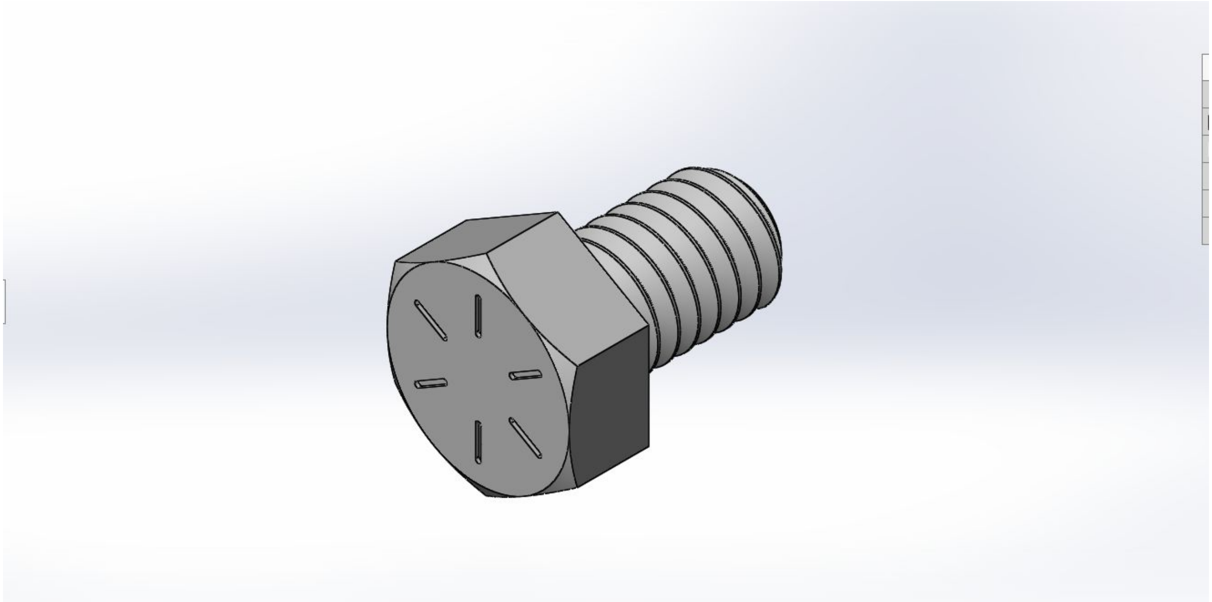
91251A537_BLACK-OXIDE ALLOY STEEL SOCKET HEAD CAP SCREW



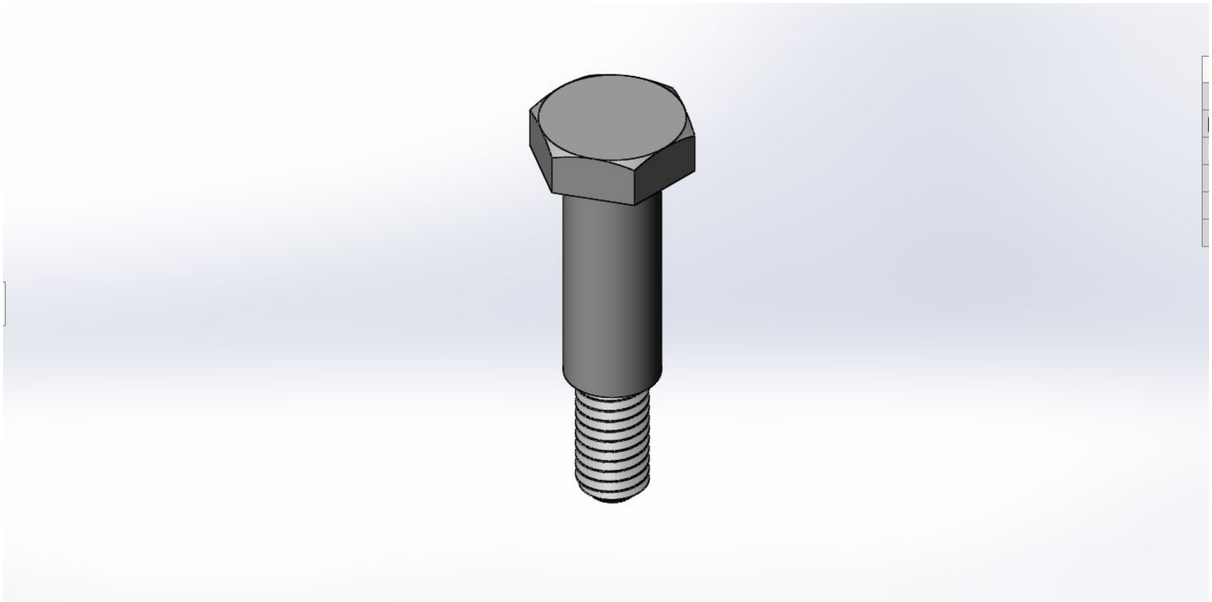
91255A537_ALLOY STEEL BUTTON-HEAD SOCKET CAP SCREW



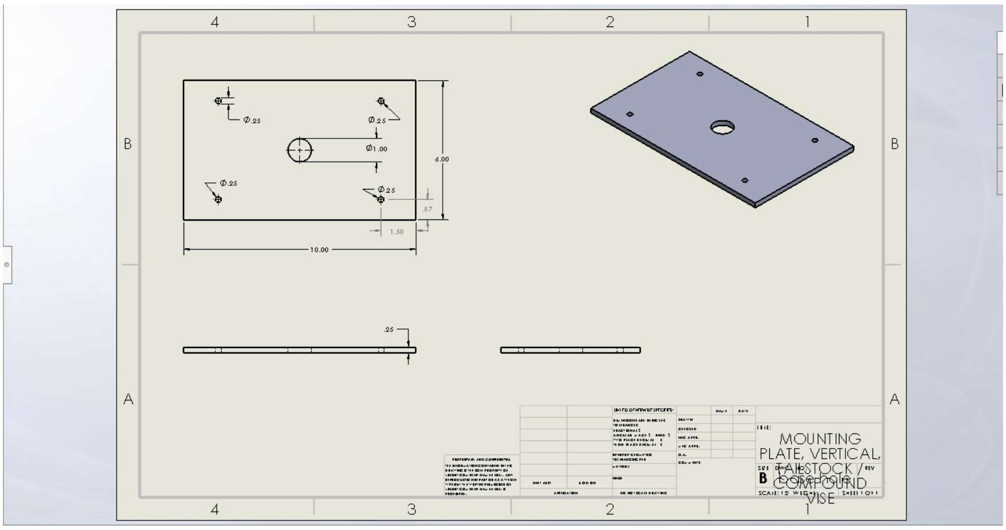
92190A111_GRADE 5 STEEL LEFT-HAND CAP SCREW



92620A578_HIGH-STRENGTH GRADE 8 STEEL CAP SCREW



94496A210_ZINC-PLATED STEEL HEX HEAD SHOULDER SCREW



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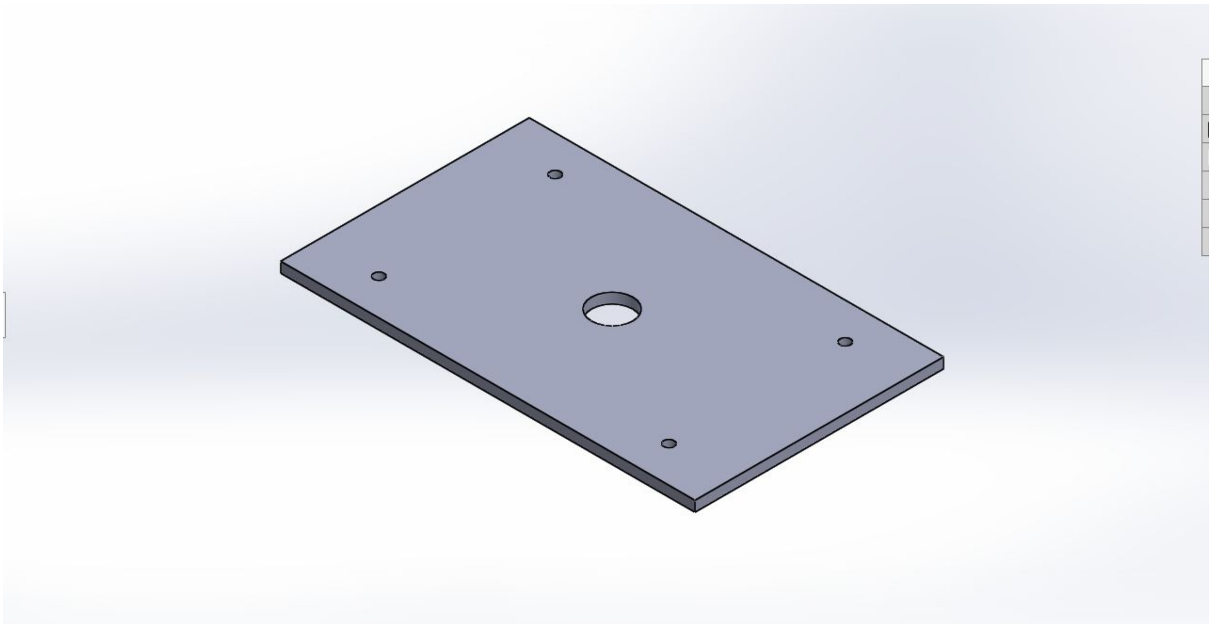

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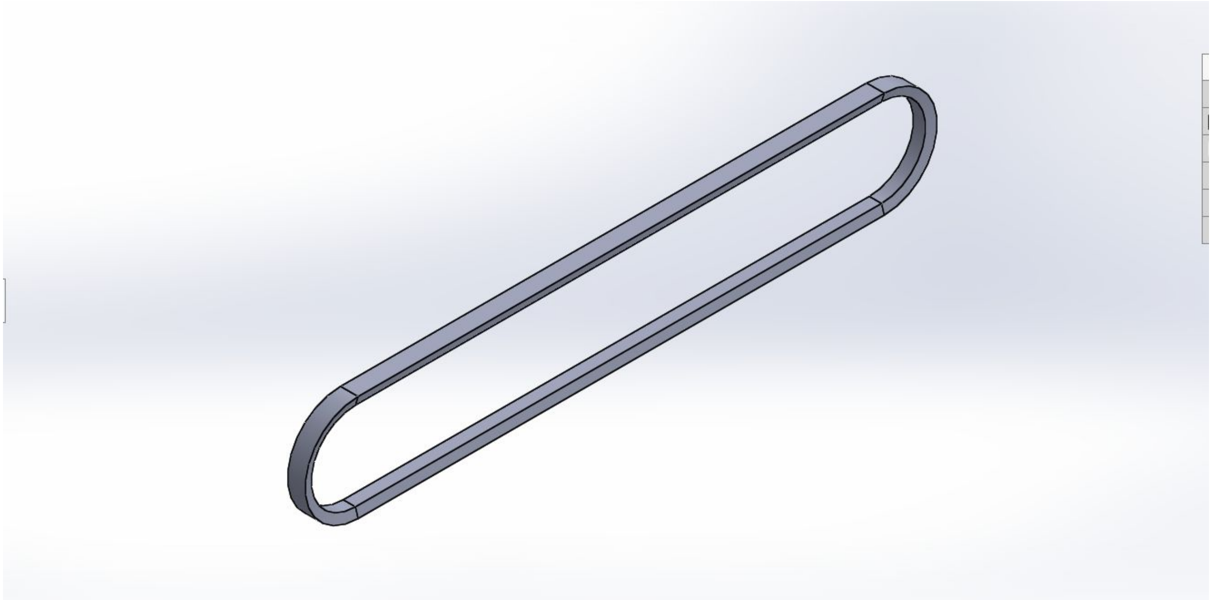

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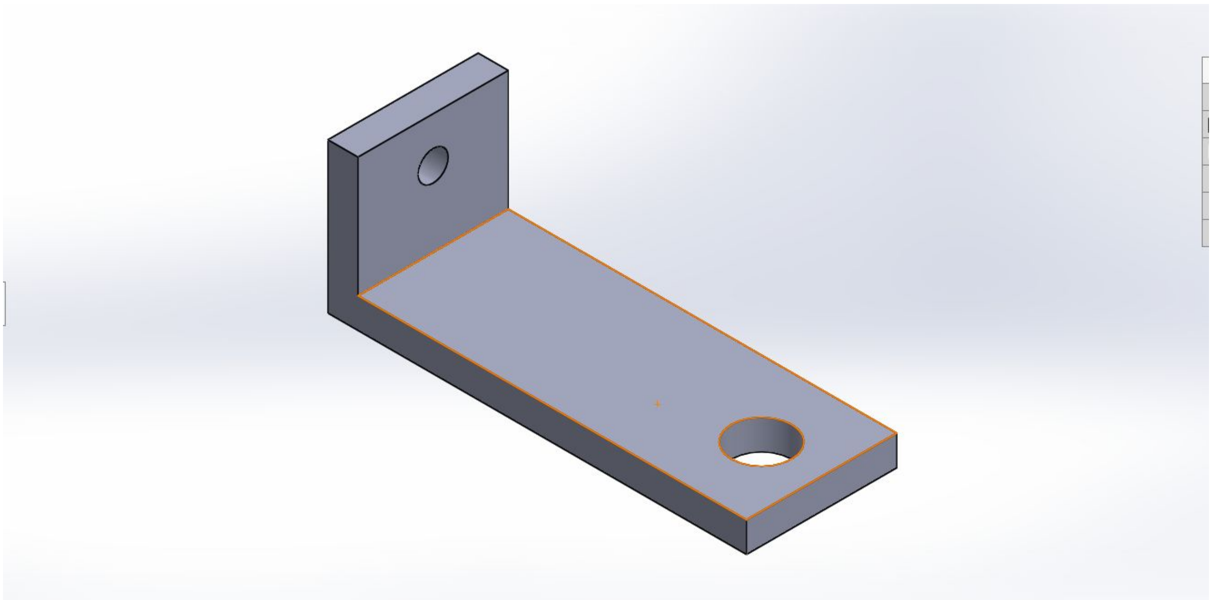

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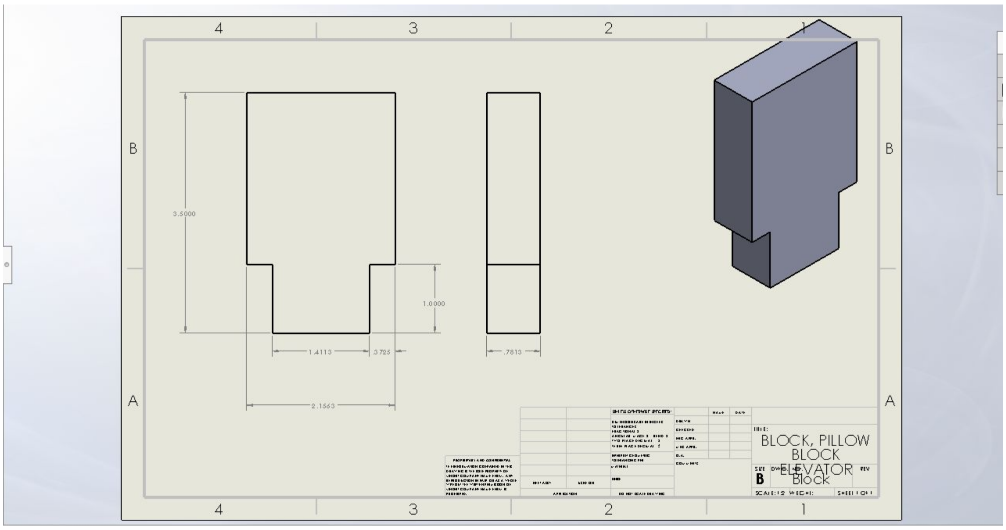

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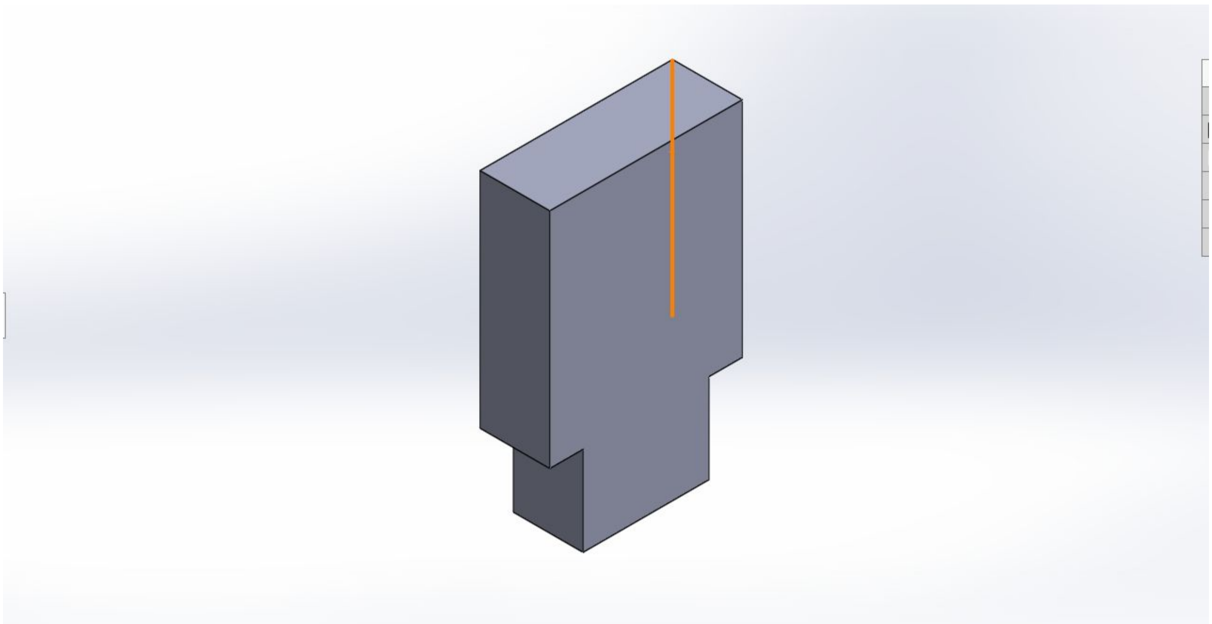

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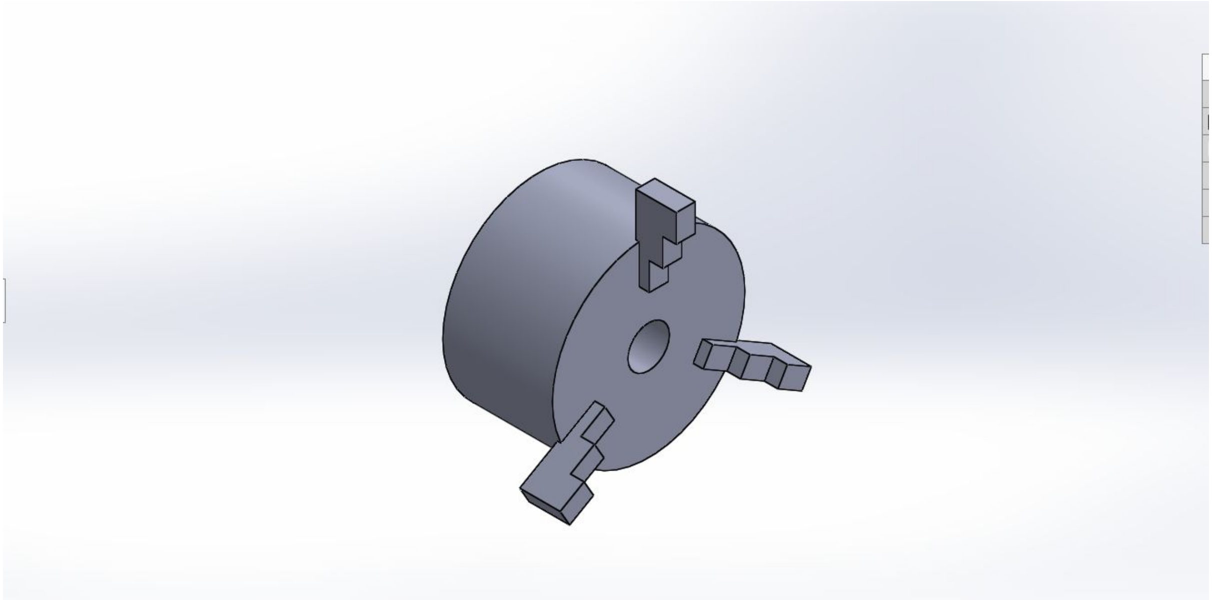

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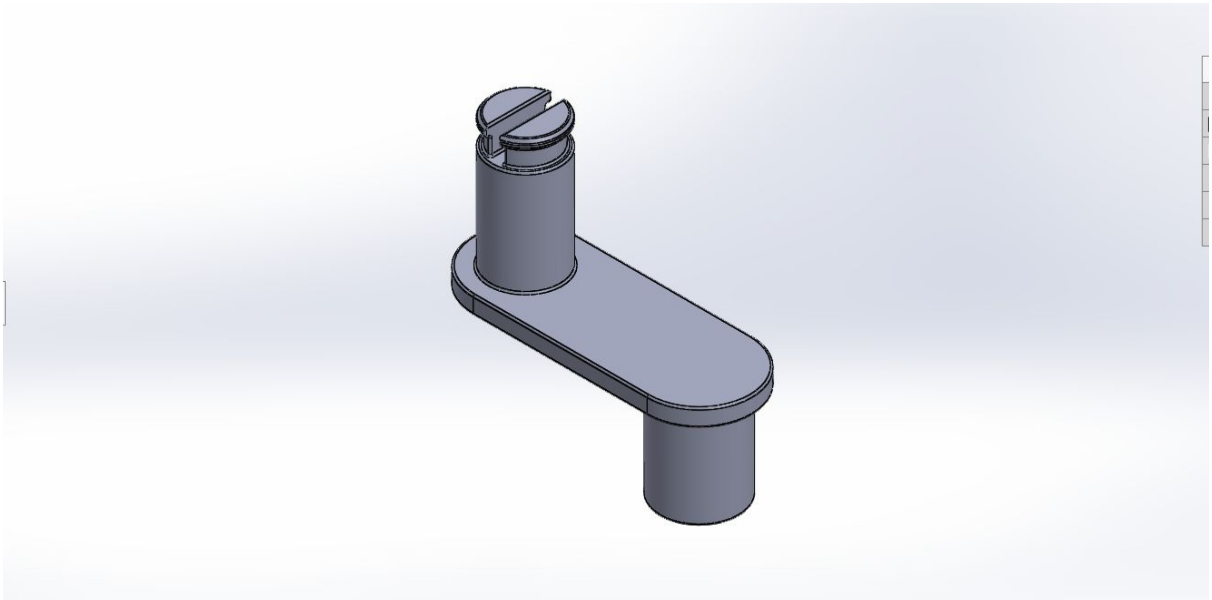

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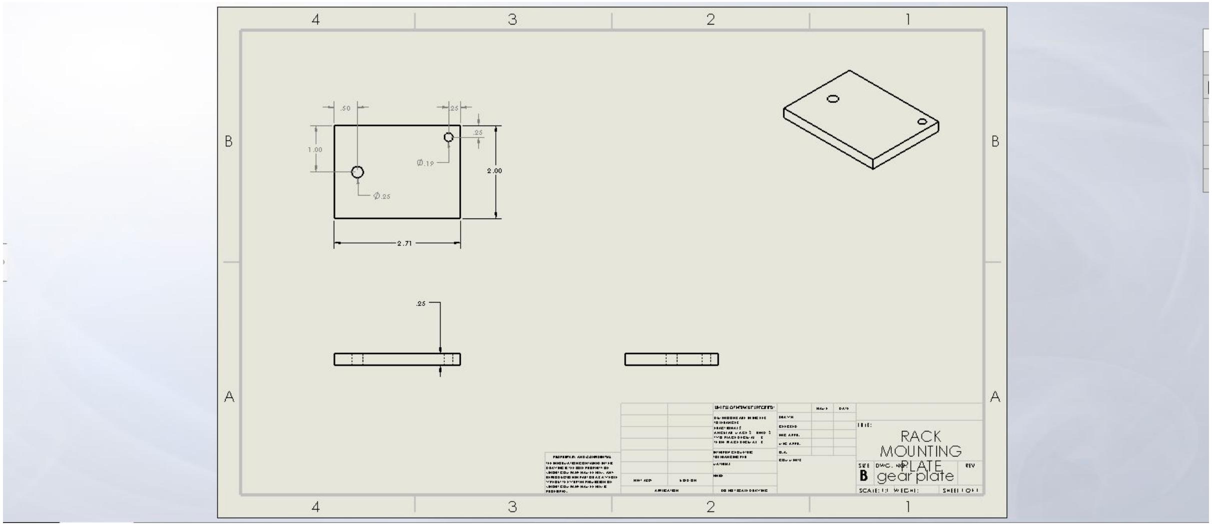

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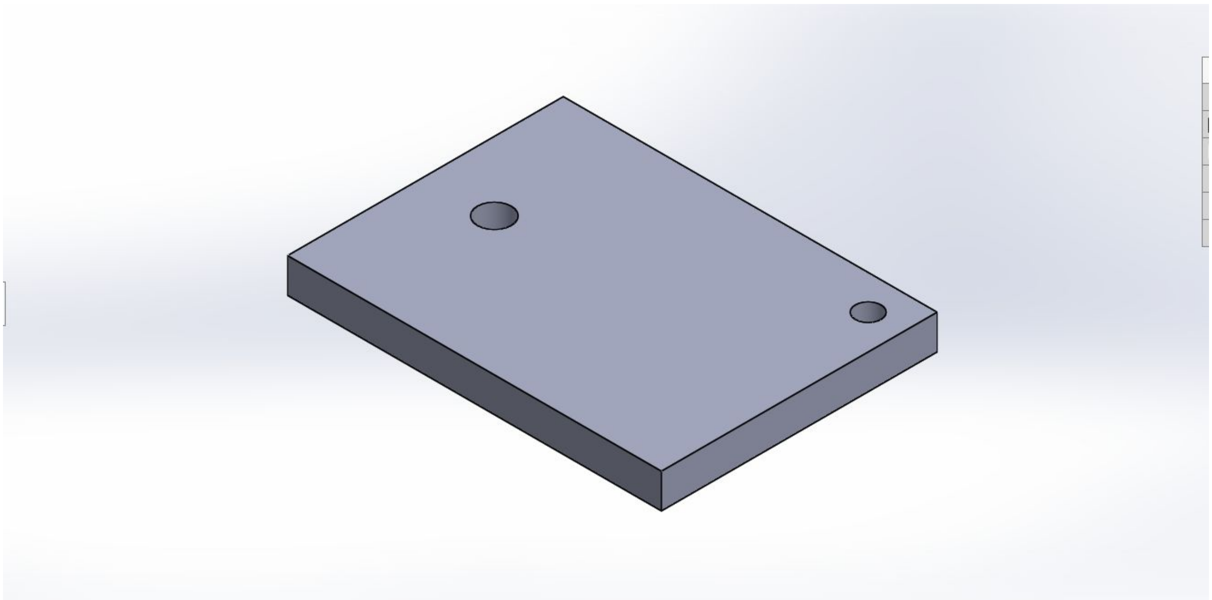

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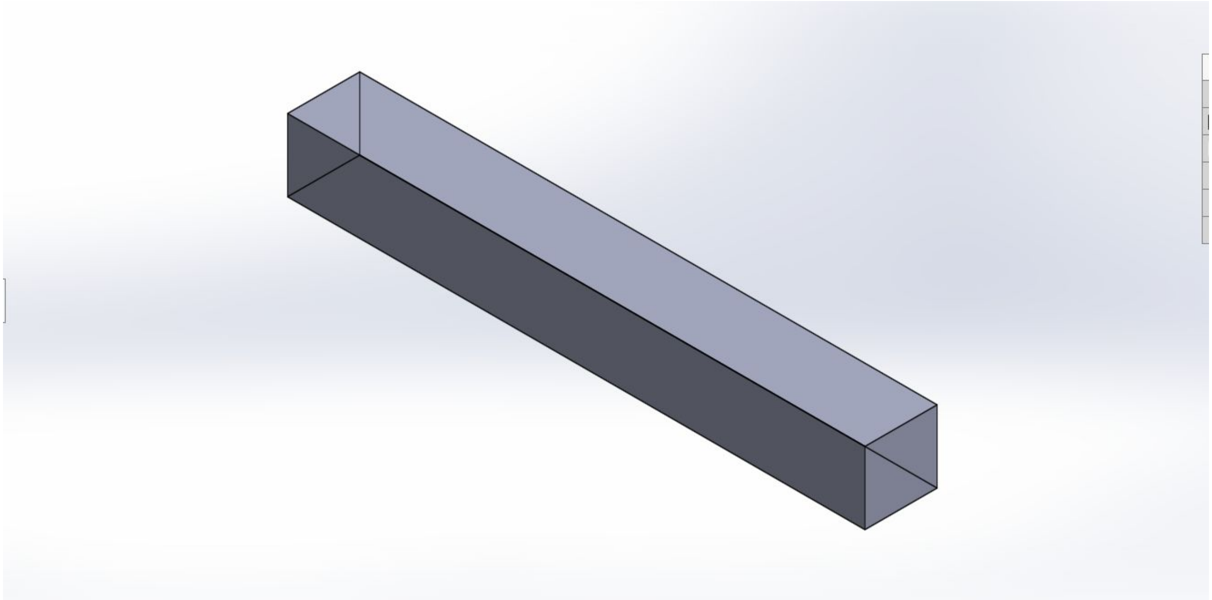

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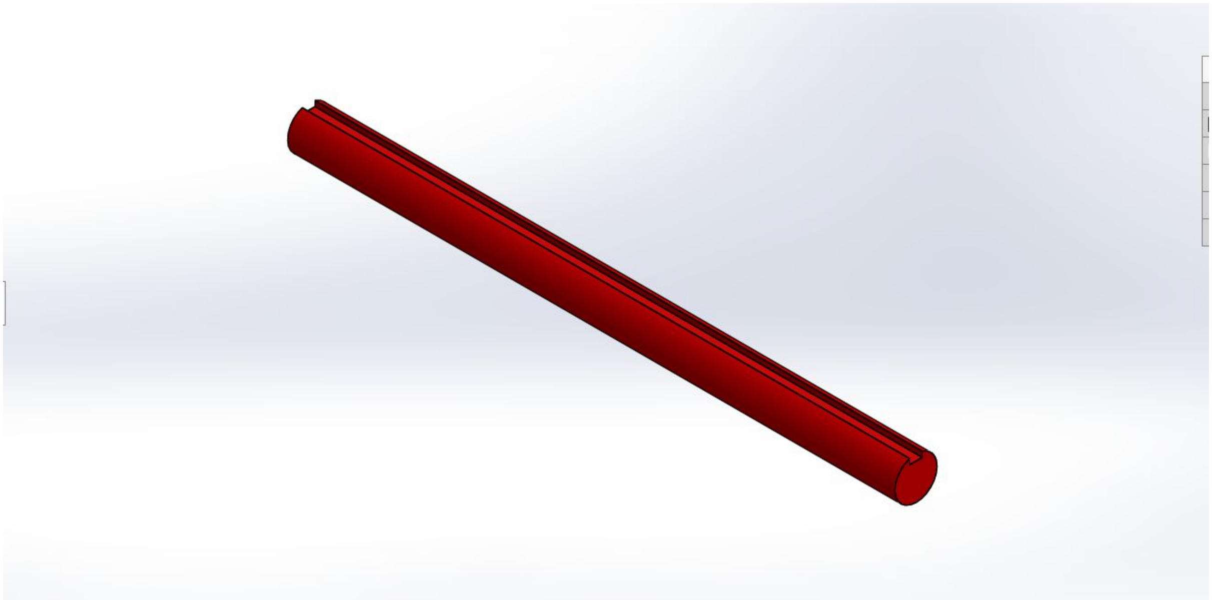

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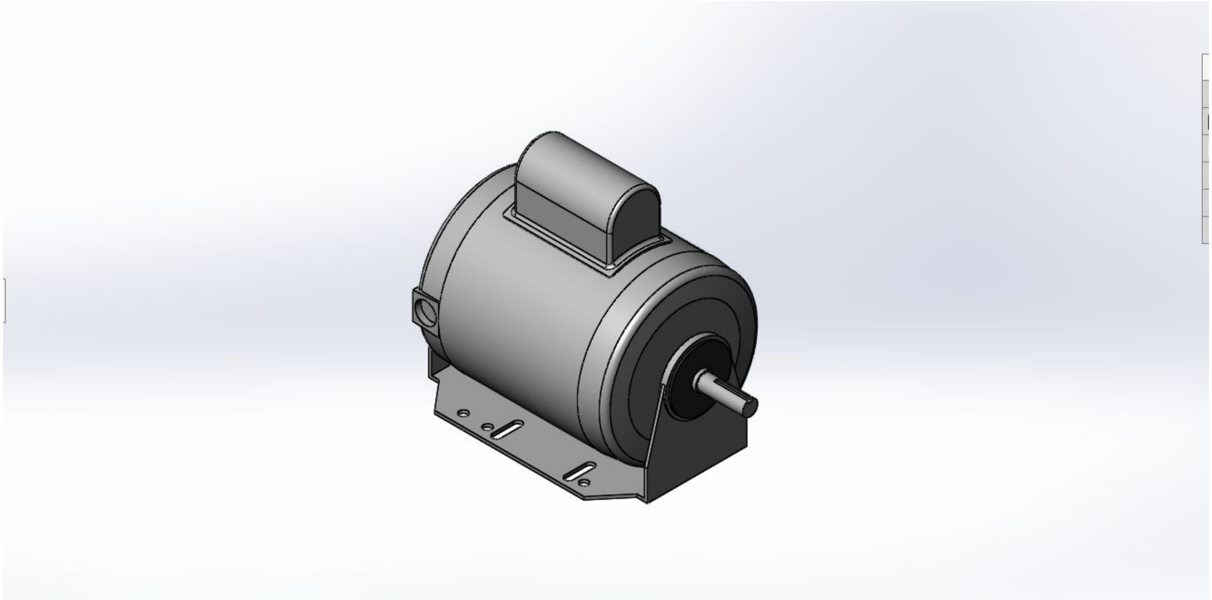
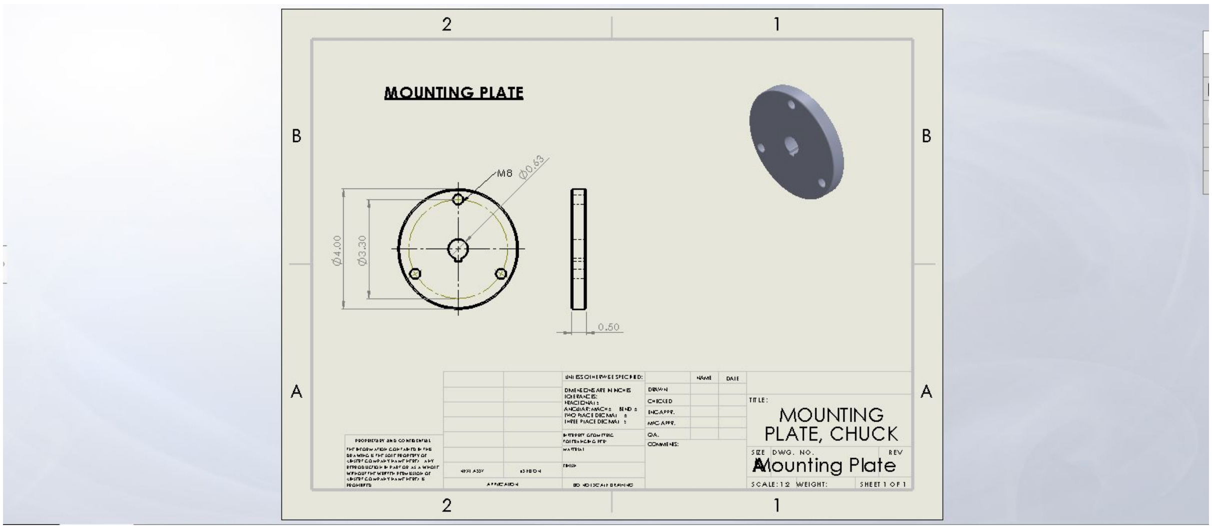


MOTOR



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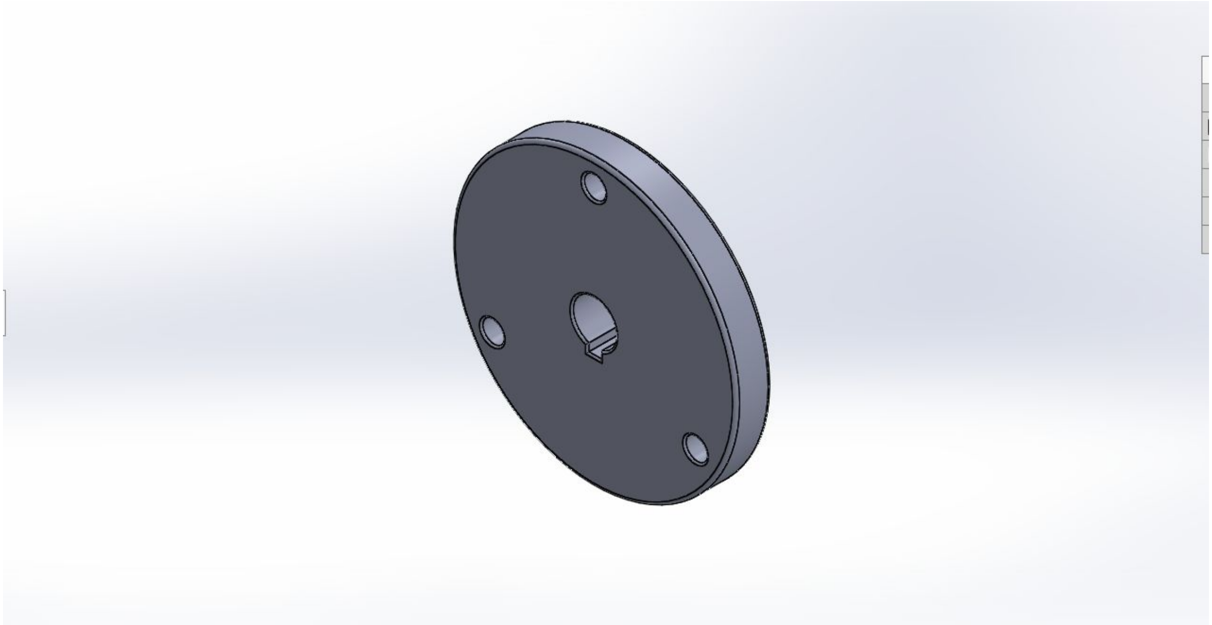

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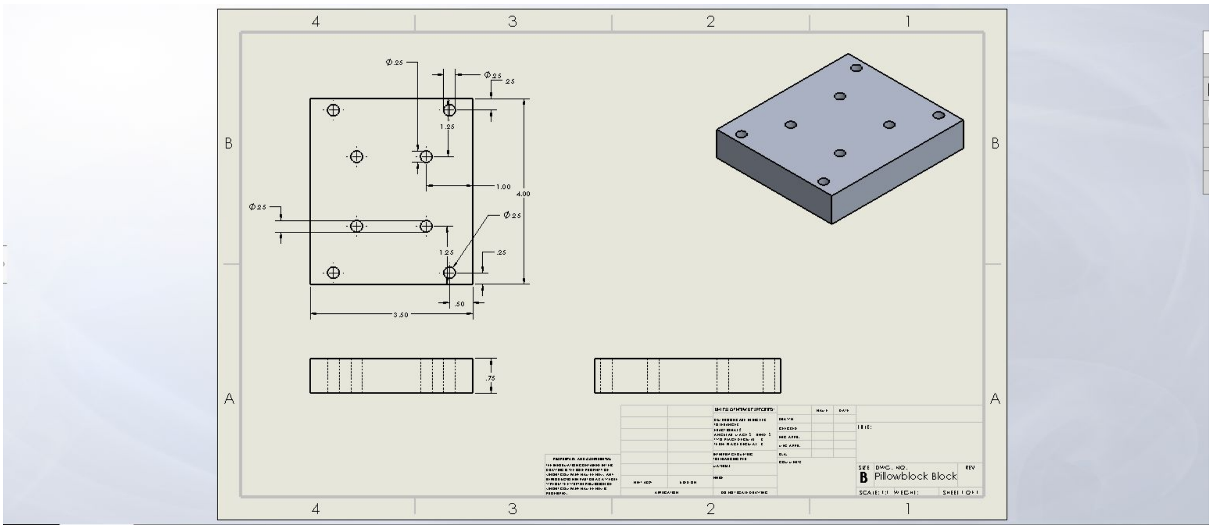

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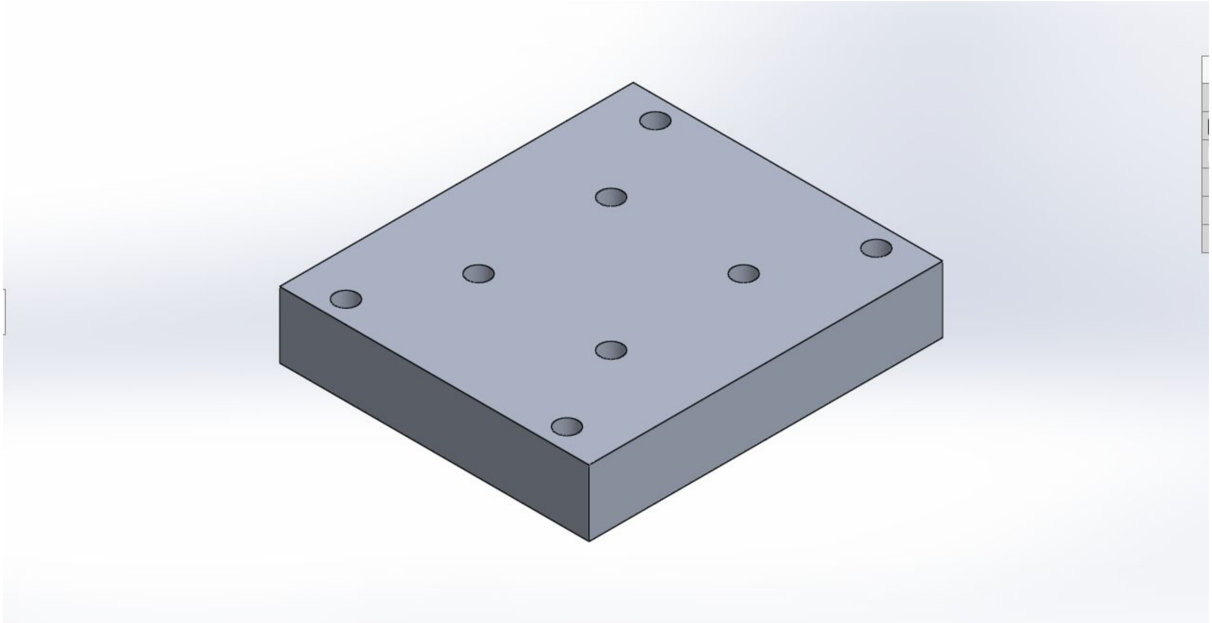

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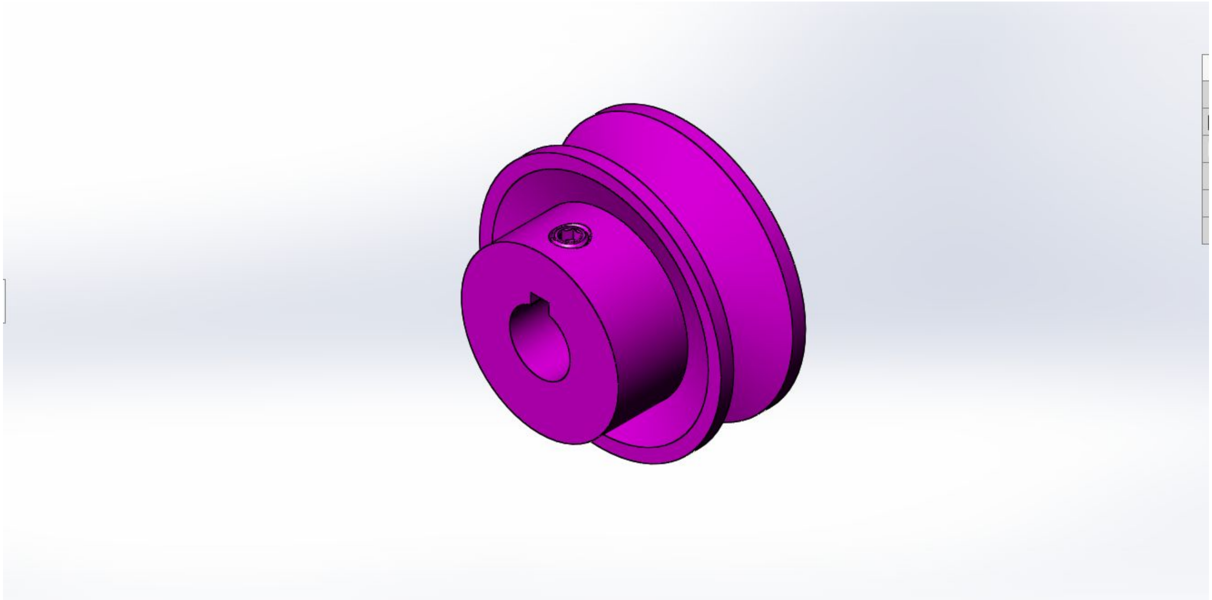
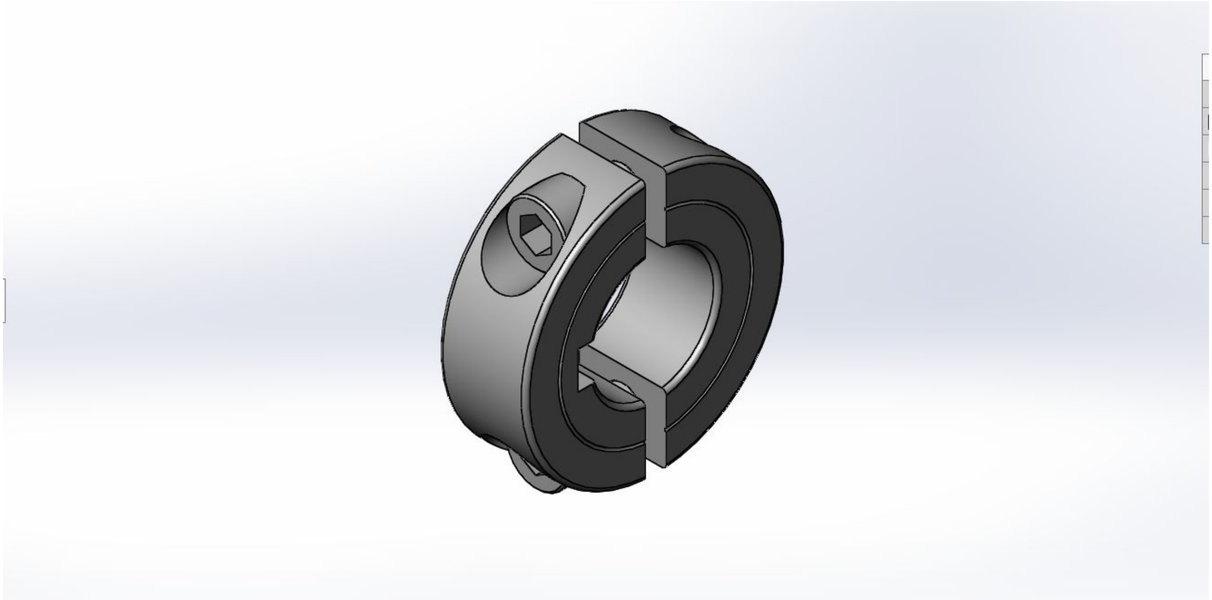


PULLEY WHEEL



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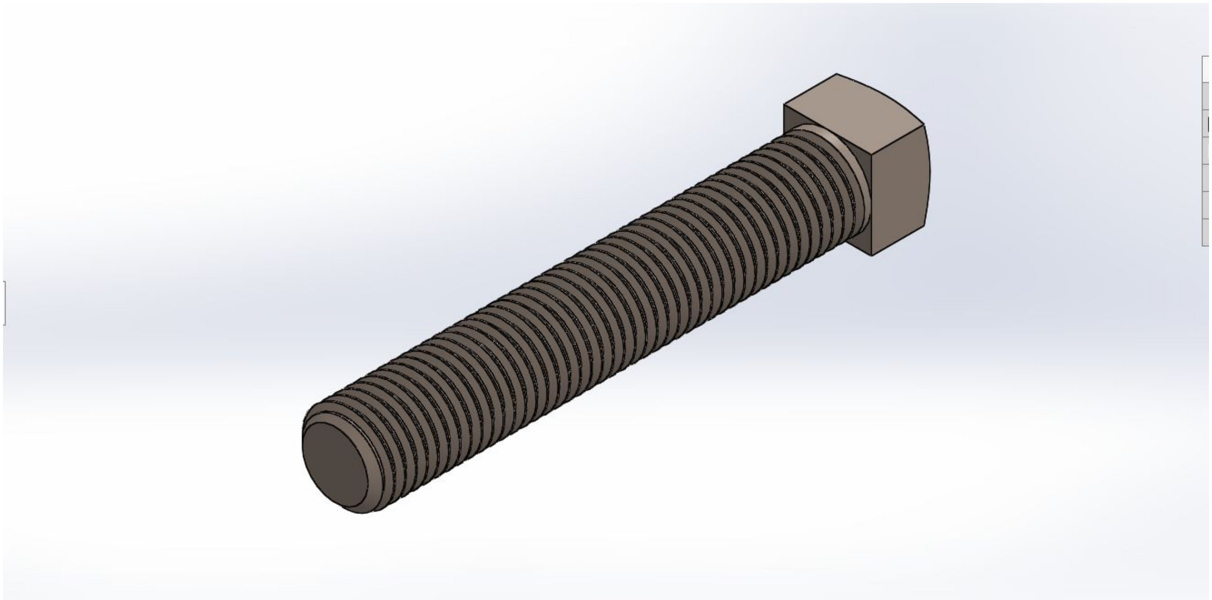
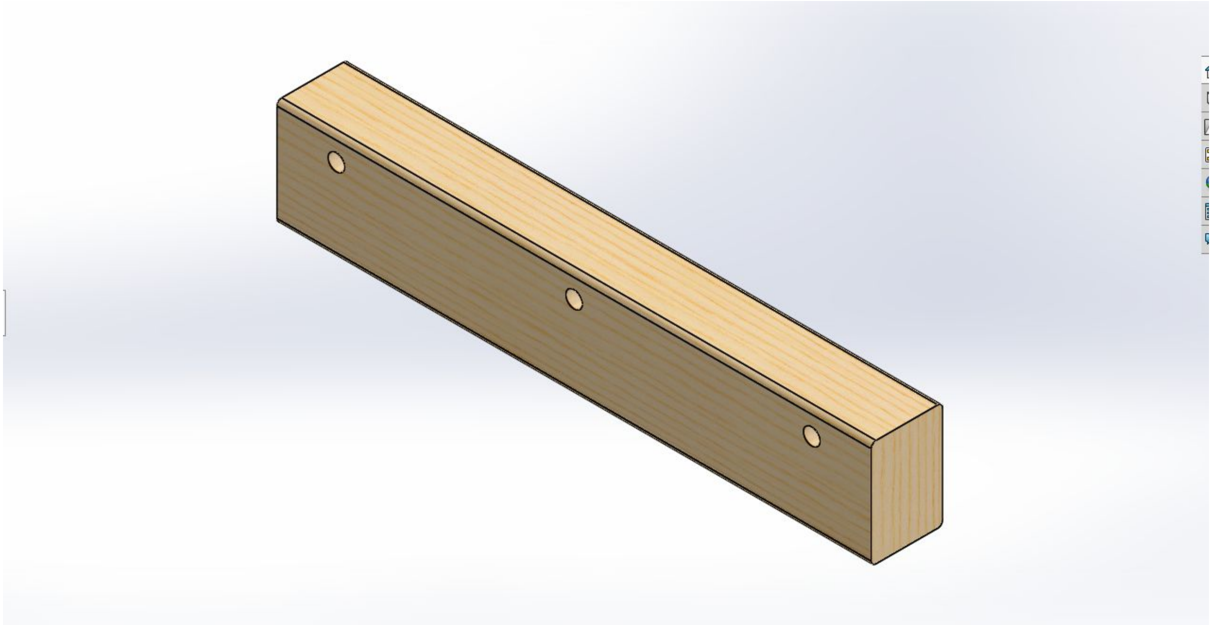
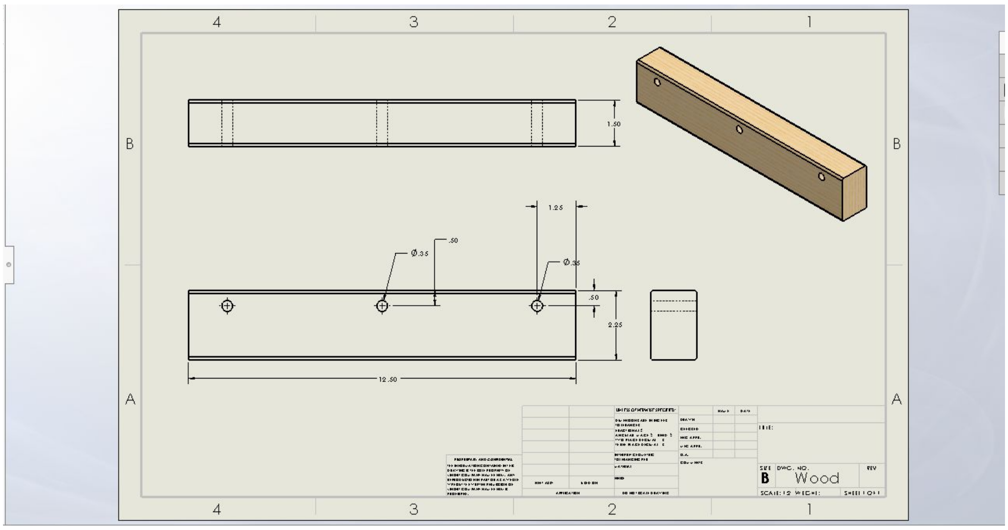


TOOL POST NUT



WOOD



WOOD DRAWING

12 Annotated Bibliography