PCB MILLING MACHINE

MIE243 Group Design Project

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1. INTRODUCTION

1.1 OVERVIEW OF DESIGN PROCESS

The task at hand was to develop an advanced conceptual design for an entry-level professional PCB milling machine. The design was targeted towards small to medium sized professional businesses. Given these general conditions, a design process was ensued where objectives were ranked based on research.

Thorough market research was performed on existing PCB machines key characteristics such as weight, cost, and motor control were analyzed. From the market research, as well as other research into the general PCB milling process, safety standards surrounding machining, and the needs of small-medium sized business requirements; a design specification was drafted. The design specification was prioritized for durability, reliability, and user friendliness.

Three candidate designs were initially conceptualized. The different designs focused mainly on the motion mechanics on the x, y, and z axes, each meeting the objectives to various degrees. Since the PCB machine was designed for a small to medium sized business, it was assumed that the budget of these businesses were limited. Accordingly, the final design must be durable, such that the company should not have to worry about frequently replacing parts or machine failure. This is achieved by selecting mechanisms that reduce wear and materials that are appropriately durable for each use. In terms of user friendliness, it is assumed that the business will not have extensive funding for programs such as user-training, so the design should be relatively simple in terms of operation.

Based on these initial requirements, a final design was narrowed down to a minimalistic design involving 5 ball screws and a lead screw to allow for the spindle to traverse three axes freely and fluidly. These screws allow for very small linear movements, and paired with the spacious work bed and locking mechanism allows for a very convenient experience. Through these efficient mechanisms, a very accurate method of linear movement in achieved while maintaining the core values of the design.

After selecting the design for the main mechanisms of the x, y and z-axes, the rest of the design was conceptualized in greater detail according to engineering specifications. This involved aspects such as dimensions, material selection, additional features and a thorough cost analysis.

1.2 BACKGROUND: PCB BOARDS

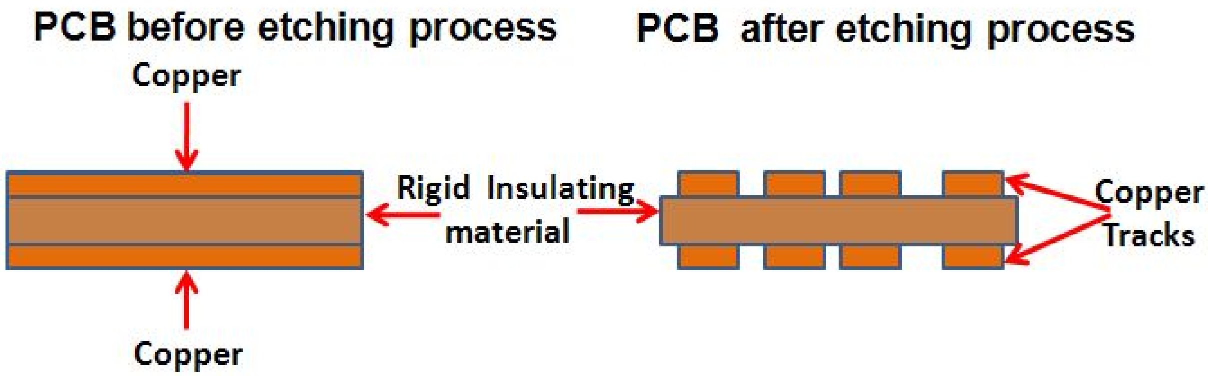


Figure 1: Multi layered PCB before and after milling [1]

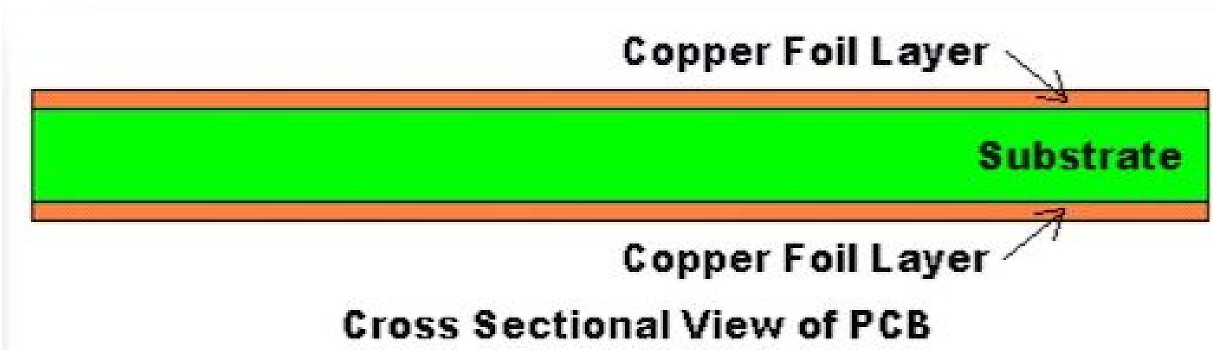
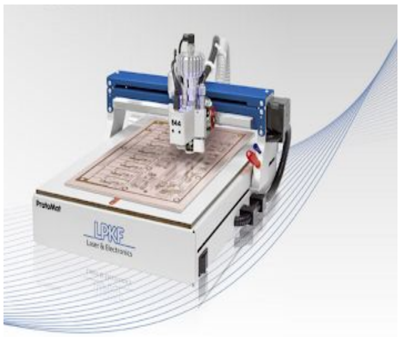


Figure 2: Four-layer PCB showing the various thicknesses of the layer structures [2]

A printed circuit board electrically connects the electronic components using conductive tracks made by etching. There are three types of PCBs: singles sided(one copper layer), double sided (two copper layers), or multiple sided (outer and inner copper). A typical PCB in the market today consists of four materials, which makes the four layers: laminates, copper-clad laminates, resin impregnated B-stage cloth, and copper foil.[3] Each layer has its own dimensions. Depending on the overall dimensions of the PCB, the type of etching facility is used.

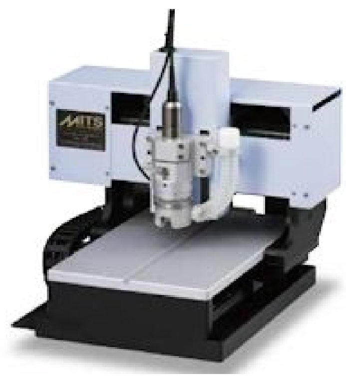
In manufacturing companies, the PCBs are designed using a milling machine only when the order is in small volume, or else chemicals and lasers are used. With the help of a drilling bit, which is usually made of tungsten due to its rigidity and hardness, the etching process is carried out. This allows for connections of electrical components, resulting in the current flow and operation of the machine. [3]

1.3 MARKET RESEARCH



PROTOMAT E34 [4]

Low cost entry to professional level in-house PCB prototyping.
Working Area: 230 x 305 x 5mm
Machine Dimensions: 370 x 300 x 450mm
Cost: $8,500
Weight: 15kg
Travel Speed: 100mm/s
Spindle Motor RPM: 30, 000

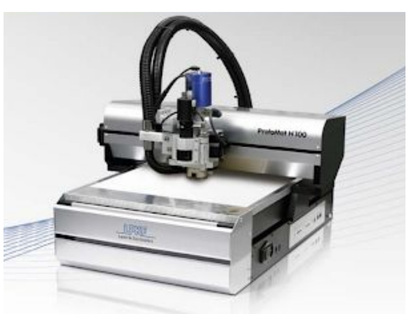


FP-21T PRECISION [5]

Working Area: 230 x 305 x 5mm
Machine Dimensions: 370 x 300 x 450mm
Cost:
Weight: 36kg
Travel Speed: 60mm/s
Spindle Motor RPM: 5,000 - 40,000

PROTOMAT S63 [4]

Working Area: 230 x 305 x 23mm
Machine Dimensions: 670 x 540 x 840mm
Cost: $21,00
Weight: 58kg
Travel Speed: 150mm/s
Spindle Motor RPM: 60, 000

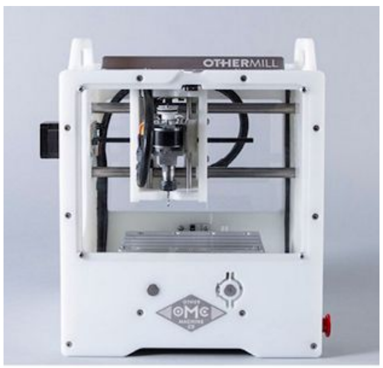


PROTOMAT H100[6]

Working Area: 380 x 365 x 14mm
Machine Dimensions: 650 x 430 x 750mm
Cost: $65,000
Weight: 50kg
Travel Speed: 150mm/s
Spindle Motor RPM: Max. 100,000 rpm, software controlled

ELEVEN LAB [7]

Working Area: 230 x 320 x 10mm
Machine Dimensions: 437 x 585 x 430mm
Cost:
Weight: 28kg
Travel Speed: 55mm/s
Spindle Motor RPM: 5000 - 41,000



OTHERMILL [8]

Working Area: 260 x 254 x 32mm
Machine Dimensions:
Cost: $2,199
Weight: 28kg
Travel Speed: 25mm/s
Spindle Motor RPM: 7000 - 16500

ACCURATE 421 (A421) [9]

Working Area: 255 x 305 x 30mm
Machine Dimensions: 508 x 432 x 305mm
Cost:
Weight: 32kg
Travel Speed: 150mm/s
Spindle Motor RPM: 5000-60000

ACCURATE 426 (A426) [10]

Working Area: 255 x 305 x 30mm
Machine Dimensions: 508 x 432 x 305mm
Cost: $2,199
Weight: 33kg
Travel Speed: 150mm/s
Spindle Motor RPM: 5000-60000

2. OBJECTIVES

Based on research surrounding the needs of small-medium sized businesses, the following high level objectives were determined:

1.) ***Maximize durability****:* Durability is measured by the amount of wear, pressure, and damage that can be done by components or a machine as a whole. This design targets a new small-medium sized business, so we can assume that the budget is fairly limited. Therefore, the company should not be concerned with frequent replacement or maintenance of the machine in order to remain within a reasonable monetary budget.

2.) ***Maximize ease of operation (number of parts)***: Easy operation is measured by the number of parts the operator needs to activate the machine. For our design, the company is new and seeking an entry-level machine. Therefore, the design should not require extensive training in order for user operation, as this may require an extended budget allocated to training users on the machine.

3.) ***Minimize cost*** - The cost of the machine is largely dependant on the durability of the machine (a very durable machine may be more expensive). While durability is major objective of the design, the cost should be minimized while maintaining this goal.

4.) ***Minimize noise*** - For our machine and context, noise is the measure of how much the operator will be bothered. As well, noise relates to the number of moving parts and friction. For our design, the working area is assumed to be small due to the nature of the business (new, small-medium sized). Therefore, the operation of the machine should not be disruptive to the rest of the work environment.

5.) ***Reliability*** - To measure reliability, moving and wearing parts are considered. More wear results in decreased precision, therefore less reliable. Our design focuses on an entry level design, so it is assumed this will be the only machine the owner will have. So, its need to be reliable such that it produces the expected outcomes for a long time.

3. ENGINEERING SPECIFICATIONS

The PCB milling machine is devised for businesses with low budget. Based on benchmarks of market research designs, specifications are established. The design prioritizes durability, user friendliness, reliability, minimize cost, and minimize noise.

Casing and Frame

- The design must have dimensions between 380 x 430 x 330 mm < L x W x H< 735 x 840 x 635 mm. This is based on the standard office spaces [Appendix A] and the market research [Appendix B].
- The design must weight less than 50 kg to help with durability [Appendix B].
- The design should have a covering to minimize the noise created by vibration, motors, and cutting.
    - The noise should be less than 60 db, maximum of 1m away from the machine with casing enclosed to correctly reduce noise [12].
    - The casing should be such that it allows the operator to see the operation.
- The design must use highly durable bearings to support the movement

Motion guidance system

Guides the motion of the XYZ axes

- Must allow 3 axes motion
- Should have a minimum milling speed capability of 12222 RPM [11]

Power and Control system

Controls the 3 axis and the spindle

- Must have a control torque between 4 - 10 kg-cm . [13]

Cutting system

- Must have a minimum working area of 178 x 280 mm< LxW < 356 x 559 mm. This value is based on the current designs in the market [Appendix C].
- Must allow for easy manual replacement of the cutting tool
- Must be capable of drilling and cutting at a speed of 80 mm/s in any direction relevant to the horizontal plane to remain competitive with the market
- Must employ a method of stabilizing the circuit board onto machine table

Safety

Must be safe for human operators to use

- Must adhere to implementation of ergonomic principles (ISO/TR 22100-3) [14]

- ➢ Must adhere to hygiene standards (ISO14159), the ability to free machine from product debris [15]

Accessories

- ➢ Should have a vacuum to remove the cut copper and debris to improve accuracy

Cost

Must be affordable for a small-medium sized business

- ➢ Maximum budget of $5,000
- ➢ Must minimize the operational cost
    - ○ $C_{operation} = C_{material} + C_{power} + C_{operator\_wage}$

4. CANDIDATE DESIGNS

Each of the candidate designs focuses on the main motion mechanism of the x, y and z axes. All designs were created with the intent to produce a set of diverse solutions according to the engineering specifications, which could then be compared against the engineering specifications to narrow down the ideal mechanism.

4.1. DESCRIPTION OF CANDIDATE DESIGNS

4.1.1 Candidate 1: Pulley-Belt System

Explanation of Device Operation

For operation of the x and y axis, there is a pulley-belt system (figure 3) for motion. In this design, the base moves in the x and y directions, while the spindle moves in the z direction. As seen in the diagram below, the axes are controlled by the following mechanisms:

Y-Direction: There are four pulleys and two belts which control movement in the y direction. The belts are located on the opposite side of the base. Perpendicular to the belts, on one side, there is a shaft connecting to the stepper motor which rotates the pulleys. On the opposite side, there is a shaft which simply acts as a support for the weight of the system.

X-Direction: On top of the belts moving in the y direction, there is a platform for each of the two pulleys controlling movement in the x direction. These pulleys are connected to one belt which moves in the x direction. On top of this belt is the base of the system, on which the platform for the circuit board would be placed. On either side of the belt, there are support shafts which assist in holding the weight of the base. One pulley is connected to the stepper motor which allows the belt to rotate.

Z-Direction: The motion of the z direction will be controlled using lead screws. The lead screws will be attached to the housing of the spindle and allow the spindle to move up and down. This mechanism requires one motor for the up and down movement, and another for the rotation of the spindle.

Design Process

This design mechanism was created with the intent to remove some the load from the top of the machine. In designs where the spindle moves in all directions, the system can be quite top-heavy, as the four motors are all located at the top of the machine. In this design, the two of the motors are located at the base, and two are located at the top in order to reduce the weight in the top of the machine.

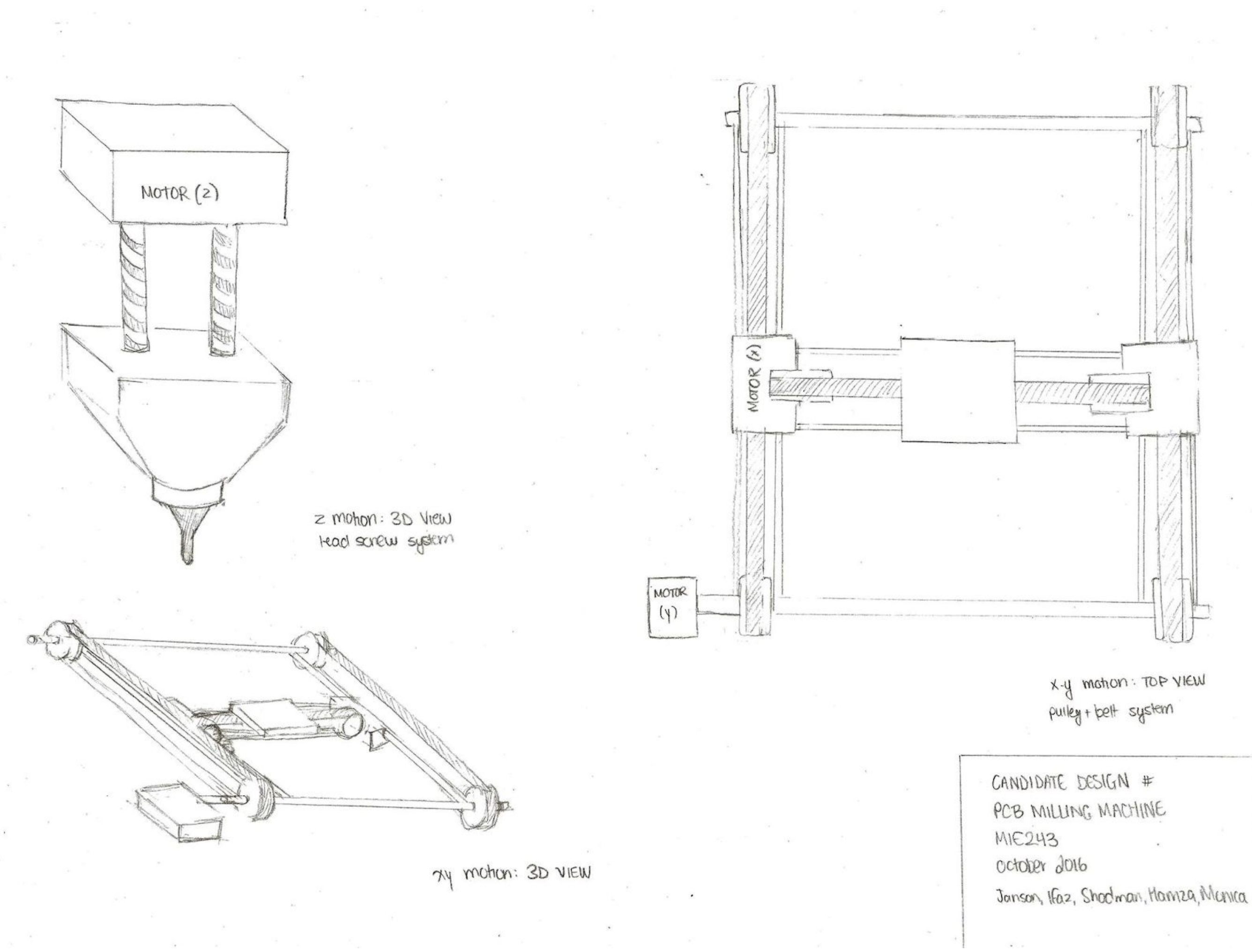


Figure 3: 2D hand sketch of candidate design 1: pulley-belt system

4.1.2 Candidate 2: Lead Screw System

Explanation of Device Operation

This design uses five lead screws (figures 4,5). The y axis moves on the two lead screws. The x and z axis movement is also allowed by the lead screw. A base board is placed on the x axis, that moves the z axis and the spindle motor. The axes are controlled by the following mechanisms:

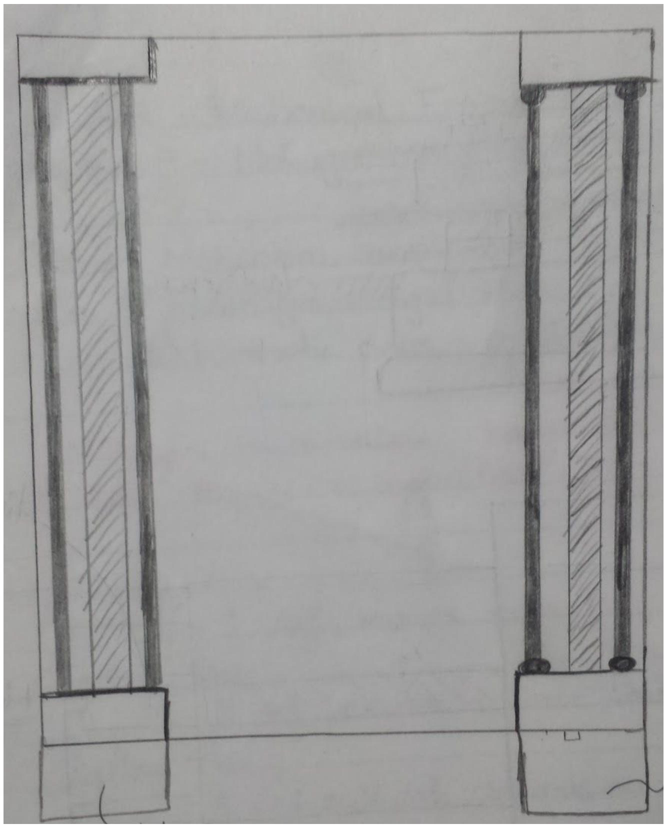
Y-Direction: There are two lead screws that are attached to two stepper motors. As the lead screws rotate, it allows the x-axis attached to move back and forth. Beside each lead screw, two metal supports are connected. This will help transmit smooth motion and improve the accuracy. At the end of each lead screw, ball bearing are press fitted into the machines support. This will help to reduce friction and support the motion. Lastly, the motors have a casing on top to protect against breakage.

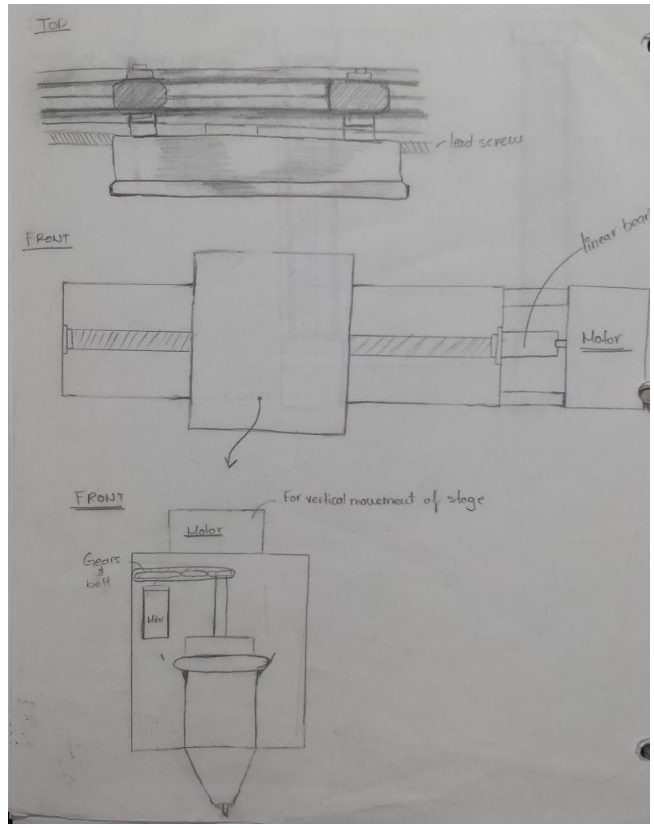
X-Direction: The movement of the x-axis is controlled by a lead screw and a stepper motor. The stepper motor has a hardened casing to protect against breakage. As the x-axis moves, the base board for the z-axis also moves. The base board is attached to gentry with wheels indulged into the gentry that allow the movement of the wheels and the z-axis as the x-axis lead screw is in motion. The lead screw is supported by a linear bearing and two ball bearings press fitted into gentry supports. This helps to reduce the radial force, resulting in improved movement.

Z-Direction: The vertical movement of the base plate is controlled by a lead screw and a stepper motor. The lead screw is supported by a linear bearing to reduce the radial force and improve the accuracy of cutting. The spindle is connected to the motor with a timing belt and a gear train mechanism that will allow for better accuracy.

Design Process

Currently, many in-market designs make use of the lead screws because of their low cost, durability, and strength. The milling machine requires cutting with good precision. According to engineering specifications, cutting with great precision and accuracy is important. Therefore, this led to the use of lead screws for all the axes.





Figures 4,5: 2D hand sketch of candidate design 2: lead screw system

4.1.3 Candidate 3: Ball Screws System

Explanation of Device Operation

The key hurdle involved with this design was to allow movement in both the x and y axis, where in this case this is driven by a ball screw laid upon another set of ball screws(figures 6,7).

Y- and X-direction: In the y-direction there consists of two parallel ball screws driven by stepper motors, to allow two ball nuts to move along the axis at the same rate and time. Allowing the two to move at the same time allows for the weight of the spindle, drilling motor, x-axis ball screw and stepper motor to be dispersed evenly to two motors, rather than a single offset motor. Attached to the ball nuts on the Y-axis ball screws are two couplings, which in turn are connected to one another as seen in the image. Between the two couplings there exists a third ball screw. For which the operation is to allow a third ball nut to move along the X – direction which would carry along the milling apparatus.

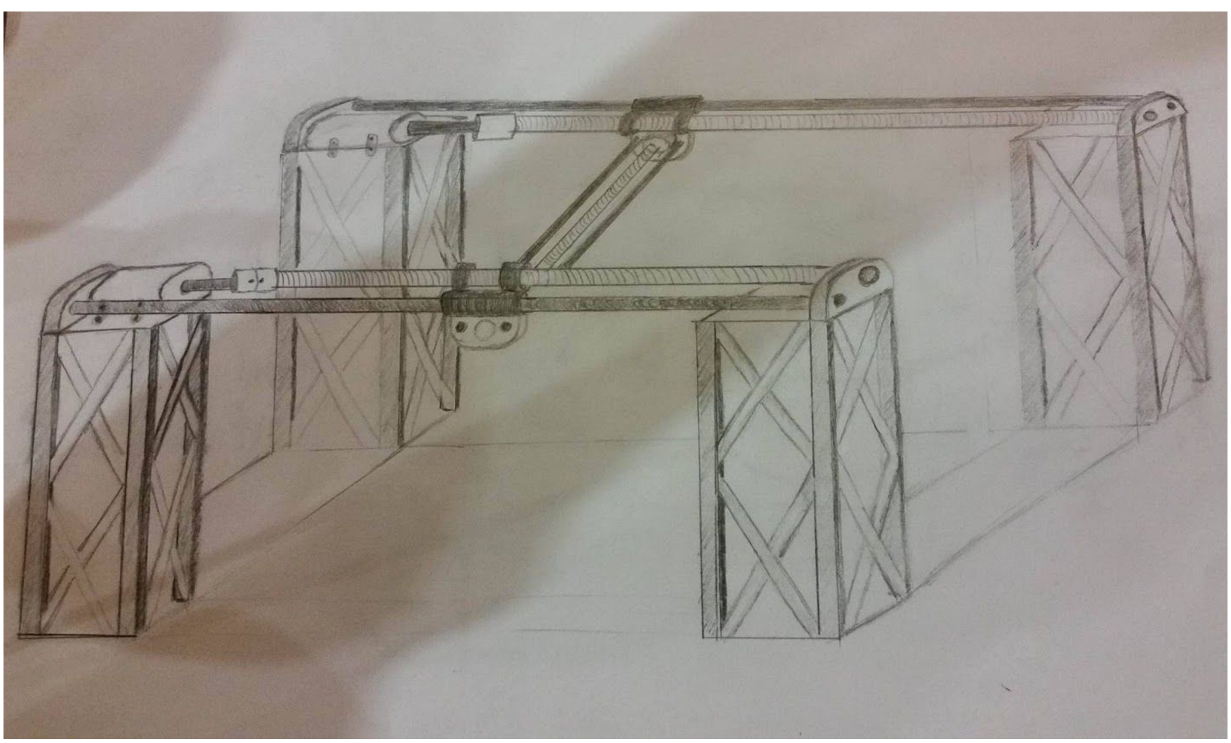
Z-direction: In the z-direction, a spindle and motor will be attached to a vertically placed lead screw as in the other candidates to allow for the movement of the drill head to dictate the depth of the cut.

Along these axes there exist numerous support rods, and the purpose of them is to ensure alignment of the ball nuts as the weight pressed upon them is typically not centered [16]. The support rods allow for a much straighter movement even with offset weights. As such reducing the wear upon the far more expensive ball screws and lead screws and allowing the wear to land more along the support rods, which again may be controlled using bushings to ease replacement cost.

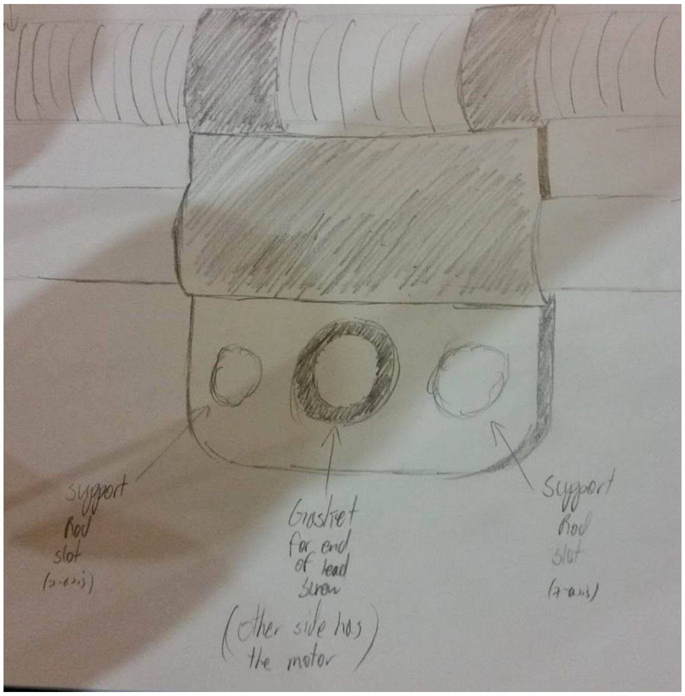
Design Process

There are numerous mechanisms for traversing two axes but a milling machine deals with quite precise cuts on typically a fairly small board. This leads to the assumption that a milling machine can make its cuts very close to one another and thus a mechanism of traversing the axes would be required to have a very small step size, and to be quite accurate. This led to the use of ball screws for the axes that require small step sizes.

A key issue with this design, is that there is a great deal of weight in the air, leaving the entire machine supported by 4 posts. This leads to very hefty posts that would need to be quite strong to overcome the top heavy nature of this apparatus. Apart from this issue the ball screw mechanism is very reliable, allows little to no play in the system, and allows for accurate movement along an axis.



Figures 6,7: 2D hand sketches of candidate design 3: ball screw system



4.2 COMPARISON OF CANDIDATE DESIGNS

Using the high level objectives outlined in section 2, the candidate designs were compared based on how well they fulfilled the requirements of the design.

Table 1: Pairwise comparison of Objectives [17]						
	Durability	**Easy Operation**	**Cost**	**Noise**	**Reliability**	**Rank**
Durability	---	1	1	1	1	**4**
Reliability	1	1	1	1	---	**4**
Easy Operation	0	---	1	1	1	**2**
Noise	0	0	1	---	0	**1**
Cost	0	0	---	1	0	**1**

From the comparison, durability and reliability are two main focuses of the design. Therefore, the design must utilize the a low number of possible components and use mechanisms that wear less and reduce friction.

Table 2: Advantages and Disadvantages of Candidate Design Mechanisms

Candidate Design	**Advantages**	**Disadvantages**
1: Pulley - Belt **(**Figure 3**)**	Flat belt: x-y axis ● Low cost ● Simple design (relative to gears) ● Belt may be elastic and absorb vibration and shock (more than gears) ● Best for low torque Lead Screw: z axis ● High precision (compared to gears) ● Long life span ● Durable	Flat belt: x-y axis ● Typically not used for precision applications - lead screws and gears are usually more precise ● Can slip if overloaded ● Will wear due to misalignment (can lead to failure due to belt breakage) Lead Screw: z axis ● A lot of friction ● Large amount of wear ● High cost
2: Lead Screw (Figure 4,5)	Lead screws ● High contact area ● Precise movement ● Durable Linear bearing ● Reduces vibration ● Precise movement	Lead screws ● High friction ● High wear due to a lot of contact ● Hard to lubricate ● High cost Linear bearing ● Can jam due to debris ● High wear
3: Ball Screw (Figure 6,7)	Ball screw ● High precision ● Low noise in reference to the gears but higher in references to the lead screws ● Little to no chance of slip ● Long lifespan ● Low friction due to rollers	Ball screw ● Requires a high torque input ● Expensive

After prioritizing the objectives that each design must focus on and finding the strengths and weakness of each design, a weighted decision matrix was used to compare the designs to the objectives(criteria). The weight of each criteria is based on the results from the pairwise comparison. According to the ranks, durability scored 4 out of the 12 possible points, therefore its weight is 4/12 = 0.33. The same calculations were carried out for the other criteria as well. By comparing the candidate designs to the objectives, it is possible to select a design that best meets the engineering specifications.

Table 3: Weighted Decision Matrix [18]

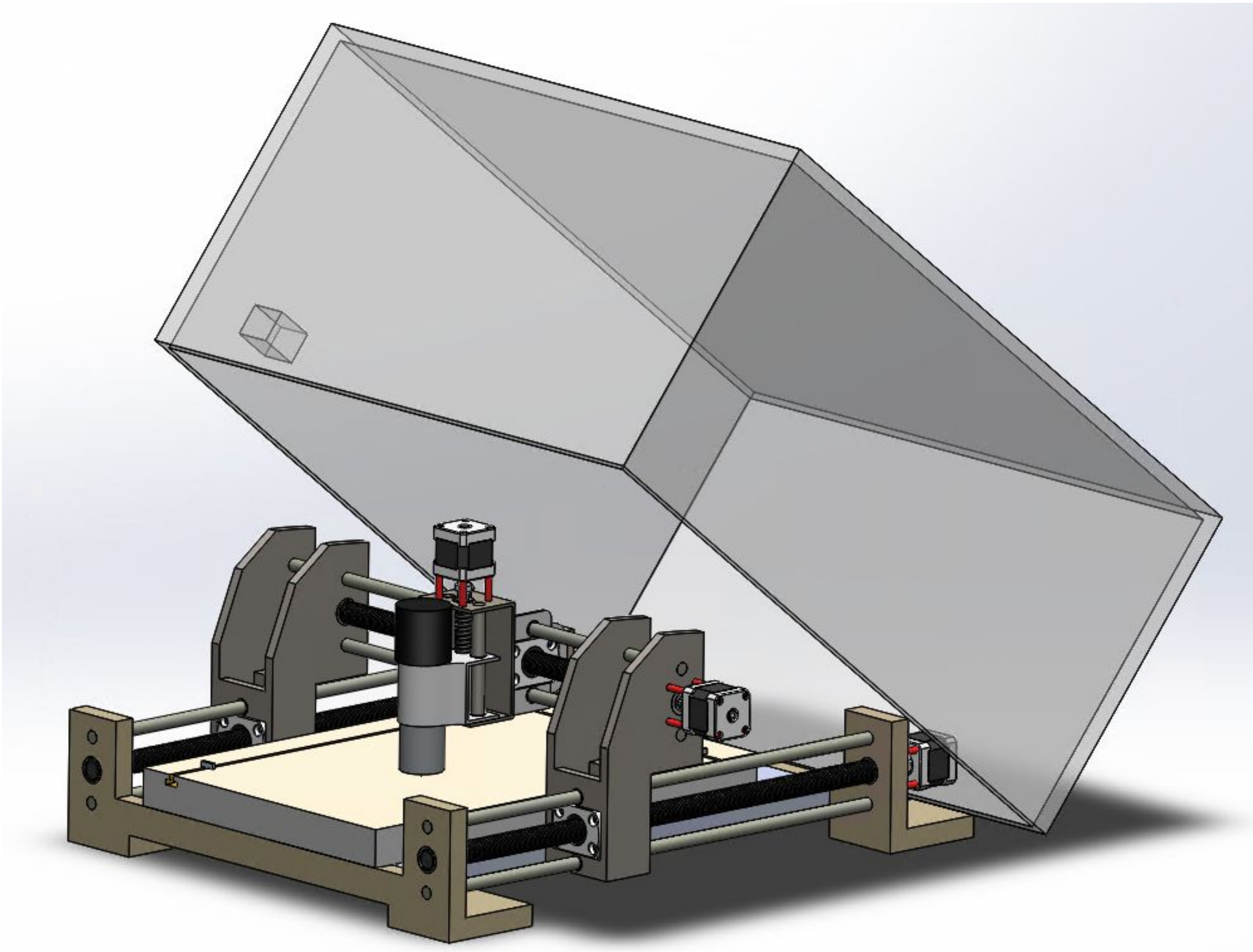
		Pulley and flat belt system		**Lead screw system**		**Ball screw system**	
Criteria	Weight	Rating (%)	**Score**	Rating (%)	**Score**	Rating (%)	**Score**
Durability	0.33	25	**8.25**	46	**15.18**	85	**28.05**
Reliability	0.33	47	**15.51**	80	**26.4**	80	**26.4**
Easy operation	0.16	15	**2.4**	30	**4.8**	45	**7.2**
Noise	0.09	55	**4.95**	48	**4.32**	40	**3.6**
Cost	0.09	62	**5.58**	50	**4.5**	30	**2.7**
Total	**1**		**36.7**		**55.2**		**67.95**

Table 4: Weighted Decision Matrix [19]

SCALE
0% - Does not meet objectives
20% - Meets objective very weakly
40% - Meets objective somewhat
60% - Mostly meets objectives
80% - Meets objective Strongly
100%-Outstanding with respect to the objective

Therefore, from the weighted decision matrix the ball screw system has the highest score as it meets with most of the engineering specifications criteria. This mechanism will be used with modifications and refinements in order to create a comprehensive final design.

5. FINAL DESIGN ANALYSIS



Figures 8: 3D view of our PCB milling machine

5.1 OVERVIEW OF FINAL DESIGN

The purpose of the design proposed is to create a device that is able to mill a pcb board to the greatest degree of proficiency as seen fit within the use case of a small to medium sized business. This led to a great expanse of decisions and options to be made, from the smallest of features to the main mechanisms at play, though what was consistent was the high degree of accuracy and precision involved with the final product. From designing with lifetime in mind, wear was reduced at every avenue available, and failure modes were controlled. The design proposed provides a good balance, for a very precise system, within reach of an average sized business.

The main component of a pcb milling machine, or of any such device is the task of allowing the spindle(4) and drill to traverse the x, y and z axes. This can be done through numerous different aspects, where trade-offs between accuracy, noise, cost and performance are made. In the case of this design, upon pondering through pulley systems and gear trains, a method of using ball screws(5) and lead screws(8) suited the situation and the values best. As from the candidate designs there is a set of ball screws(8) to allow ball nuts and therefore couplings(9) to traverse the y-direction. Attached to such couplings(9) is another ball screw(5) that allowed for the movement along the x axis, and so forth for the z–axis, with the exception of there being a lead screw along the z – axis.

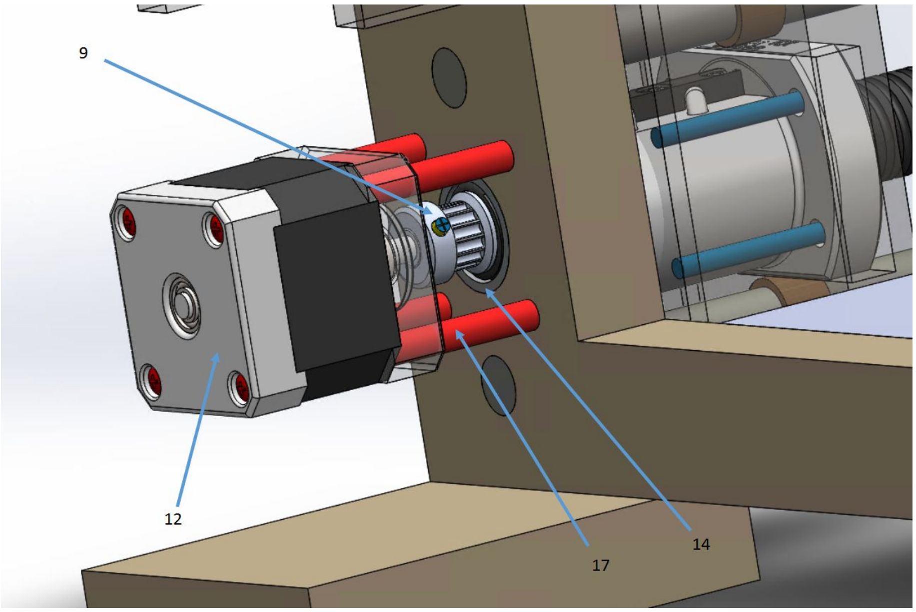


Figure 9: Motor and motor attachments

From the useful candidate designs it was clearly evident that the third design, the one resembling closest to our values, had a fatal issue of being extremely top heavy. This conflicted with the goals of having a reliable system for a small to average sized business. As to support all the weight that is lifted into the air, the supports, along with the base must be quite bulky and be weighted appropriately to counteract the effects of a top heavy design. So through the re-working of the supports, it was possible to move one axis to the lower portion of the design, by attaching vertical supports along the y – axis couplings(9), which then attach to the x – axis ball screw(5). This allowed for a more even weight distribution and a much sturdier design.

In order to support the systems movement there are numerous measures put in place to ensure rigidity, while extending the lifetime as far as possible. This is done by providing support rods(6) alongside each ball and lead screw. This allows for the weight being pulled by the couplings(9) on the screws to move linearly and without being slanted due to the offset weight. The support rods(6) on either side allow for the load to not change the direction of movement, and to allow the coupling to maintain its alignment with the screw. The secondary benefit of such a supporting rod(6) is it allows for the weight that is being pushed and pulled by the nut and screw mechanism to be divided, allowing for the much cheaper to replace, support rods to take some of the wear that would otherwise lie solely on the ball screws(5). Although in order to optimize the lifetime of the product, especially considering that along the support rods is the one point along the x and y axes where a sliding friction occurs, in order to control this mode of failure bushings(11) were decided to be placed between the coupling(9) and the support rods(6). This allows for the wear due to the sliding friction to lie largely on the bushing that is much easier to replace, and much cheaper, again increasing the overall lifetime of the product.

With the movement along the axes and the supports in place, the mill has all the necessary precautions to move about the working area, that is large enough for most medium applications at a surface bed reaching 12 x 18 inches. Although with the mill able to be moved, the board itself still dictated any design decisions as the method of keeping it in place was key and vital to a well functioning device. In order to maximize the working area versus the footprint of the machine ratio, the mechanism used to lock the board in place(10) is done so using a single corner of the bed having a raised edge in order to provide support for the board. Although

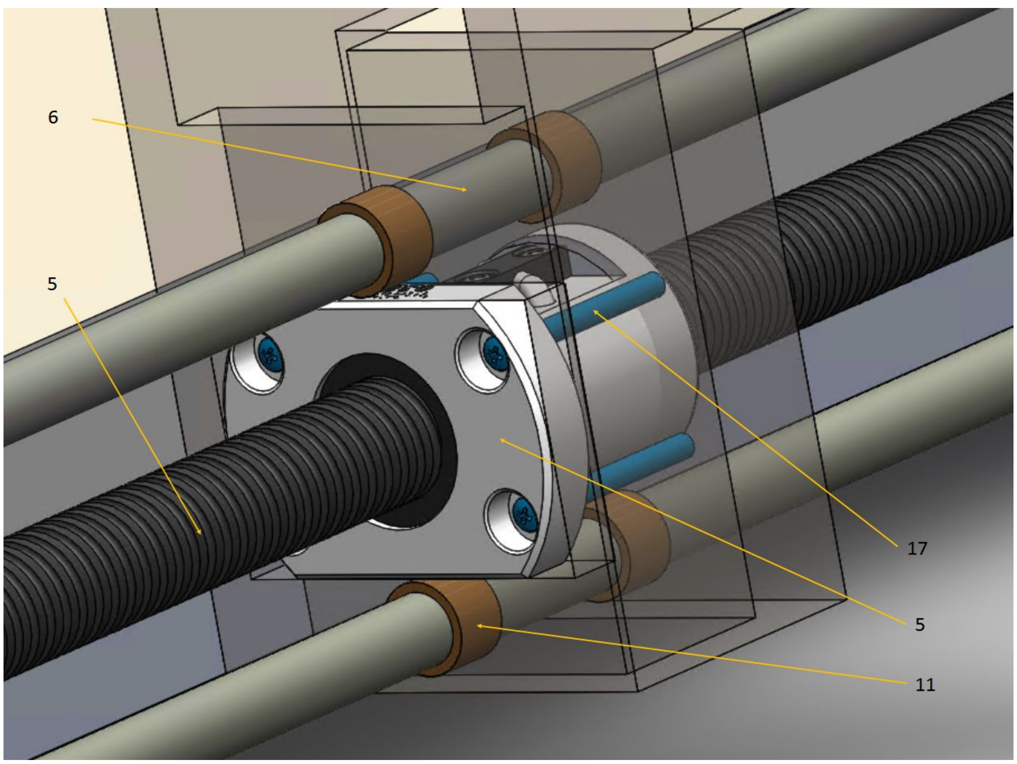
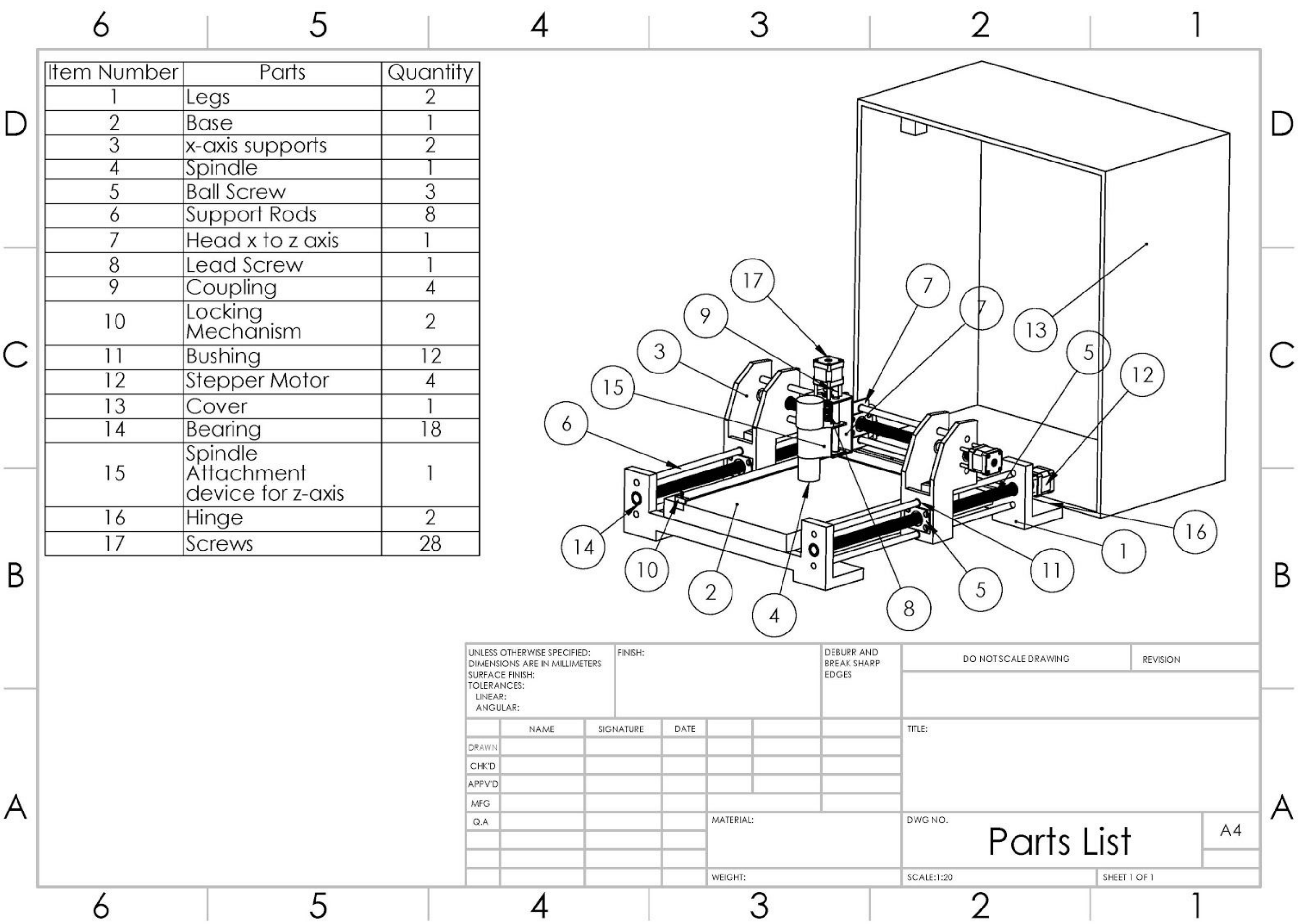


Figure 10: Y-axes moving mechanism

support along one corner would not be enough to affix a board while being milled, the mechanism of slots and clamps was utilized. By allowing two slots to be made in the bed, one in the y direction and the other in the x, it was possible to place two sliding clamps(10) within these slots to allow for a board to be placed against the raised edge and then the clamps being pulled up to the other two sides of the board. This allows for the board to be secured from one corner and the two opposing sides, resulting in a completely secured board, capable of withstanding the force that is exerted by the mill on the board.

Thus from the method of movement along the x and y directions, to the type of locking mechanism for the board itself, the design involves well thought out and justified decisions as detailed in the coming tables. Allowing for a clearer rationale behind each decision made and how it lines up neatly with the values and ideals behind this design.



Item Number	Parts	Quantity
1	Legs	2
2	Base	1
3	x-axis supports	2
4	Spindle	1
5	Ball Screw	3
6	Support Rods	8
7	Head x to z axis	1
8	Lead Screw	1
9	Coupling	4
10	Locking Mechanism	2
11	Bushing	12
12	Stepper Motor	4
13	Cover	1
14	Bearing	18
15	Spindle Attachment device for z-axis	1
16	Hinge	2
17	Screws	28

Figure 11: Drawing and parts list of the PCB milling machine

5.2 DETAILED DESCRIPTION OF FINAL DESIGN

5.2.1 X-Axis

Component	Qty.	Function	Justification
Closed Ball Bearings 	2	Motion support for the ball screw	The closed ball bearings are supporting the ball screw responsible for the movement of the z-axis. The ball screw is fixed at ends, so a minimal axial force is present but with moderate to high radial forces produced by the vibration and friction of the x-z axis supports and the ball screw. The bearing will be press fit into the outmost vertical supports to compensate for durability. Lastly, the operating environment at such height is expected to have dust, so a closed ball bearing is better suited.
Oil-embedded bushing 	4	Support linear motion and control wear	The bushings are press fitted into the z-axis platform. The movement of the platform in the x-axis requires the transmission of rotational motion of the ball screw into a linear motion. While in motion, the bushings will support the low speed movement by reducing friction and allowing surface to surface slip of the supporting rods and the platform in contact. This will reduce wear and allow for easy lubrication.

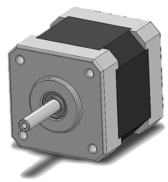
5.2.2 Y Axis

Component	Qty.	Function	Justification
Close Ball Bearing 	4 (2 on each ball screw ends)	Ball screw rotational support	The closed ball bearings are supporting the ball screws. Due to the supports above and below the ball screw, some of the radial force created is reduced when the gantry is in motion. The bearing shall will be press fitted into the machines's support to account for making it durable. While in operation, the milling will produce waste so a closed ball bearing is best suited for such environment.
Oil-embedded bushing	4	Supports linear motion, control	The fours bushings are press fitted into the gantry. During the linear movement of the gantry on the supporting rods, friction will be reduced and a surface to surface slip will be present. This will prevent the

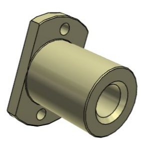
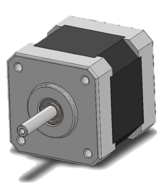
		wear	surface from wearing. In result, the movement will be precise and the cutting accuracy will be improved.

5.2.3 X and Y Axes

Component	Qty.	Function	Justification
Ball screw 	1 - X-Axis 2- Y-Axis	Motion transmission from rotational to linear	The ball screw is used rather than other mechanisms that do the same job, such as the aforementioned pulley system or any other gear train type system for the main reason of accuracy [40]. Where pulley systems allow for slack and slippage, and gear trains would rely on much more complicated systems to transform a typical motor into a smooth but very accurate linear movement. The ball screw not only is far more accurate and allows smooth linear movement along a constant path, it also reduces the main mode of failure of a lead screw by transferring the normal sliding friction into a much more efficient rolling friction. Increasing lifetime and accuracy, while maintaining simplicity is the main reason for the ball screw decision.
Support rods 	2 - X-Axis 4- Y-Axis	Motion Support and alignment	The purpose of the support rods are to ensure alignment of the ball nuts as the weight pressed upon them is typically not centered [45]. The support rods allow for a much straighter movement even when an offset weight is present. The rods also relieve some of the weight left on the screws and as such reduce the wear upon the far more expensive ball screws and lead screws. Allowing more wear to occur along the support rods, which again may be controlled using bushings between the coupling and the support rod to ease replacement cost and control the location of excess wear.
Stepper motors	1 - X-Axis 2- Y-Axis	Motion transmission by giving power	Stepping motors are brushless motors so have longer lifetimes, bearings are the only wear-out mechanism. Being digital motors they can be positioned accurately without hunting or overshoot. The drive modules are

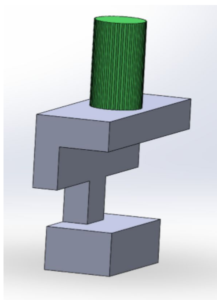
			not linear amplifiers which means less heat sinks, higher efficiency, greater reliability. They have excellent low speed torque and can drive many loads without gearing. So transmissions are shorter which means higher reliability, greater efficiency and less backlash.

5.2.4 Z Axis

Component	Qty.	Function	Justification
Lead Screw  	1	Motion transmission from rotational to linear	The lead screw is used to adjust the height of the cut in the board and to allow the spindle to be clear of the working area when not in use. The lead screw was chosen for this aspect, as it allows for smooth vertical movement with enough accuracy to dictate the depth of a cut, without the need for micron level precision as once the depth is set, the spindle's height will not to be adjusted as often. It is also more convenient to use a lead screw for this axis, as the vertical nature of it, proves to be a greater issue for a ball screw.
Stepper motor 	1	Motion transmission by giving power	The justification is almost the same as the x and y axis stepper motors, the difference being the holding torque (kg.cm). For the z-axis, 5.8 holding torque is being used because it does not require a large force to move the ball screw as the force of gravity will help with motion.

5.2.5 Overall Design

Item	Qty	Function	Justification
Machine Hood	1	Casing/covering	A machine hood is necessary for many reasons, such as protecting the user from harm due to the machining process and keeping stray/flying dust and other particles formed during the machining process contained. A hood will also prevent debris from

			entering the machine during and after the machining process. It will contain the noise level during the machining process as well as protecting the machine when out of use.
PCB board locking mechanism 	2	To secure the pcb board during milling	The locking system consists of a sliding clamp mechanism and a compression spring. The compression spring offers resistance to a compressive force applied axially.[23] Once the pcb board is on the base, the board can be secured to the base. This will support by reducing vibration and improved cutting.

5.2.6 Dimensions

Item	Dimensions	Justification
Working area	305 x 460mm	See Appendix C On average, maximum PCB panel size is 406 x 559 mm. It was determined through market research that the dimensions should be within the range of 180x286mm<WxL<350x560mm. For an entry level machine, the working area need not be as large as the upper bound, but should still fall within the range.
Overall Machine	450 x 400 x 400mm	The height of the machine was approximated based on market research averages, and using the ratios of W:L:H, and working area:overall machine dimensions found in Appendix C,

5.3 MATERIAL SELECTION

Primary Material

Aluminum alloys are one of the most used alloys in the industry [32]. They are lightweight, making the PCB milling machine easier to move around if needed, thus increasing user-friendliness. Furthermore, they have good corrosion resistance and have good relative strength-to-weight ratios, enhancing durability and reliability as they are more wear resistant and thus require less maintenance or any replacements [33]. For these reasons, we chose aluminum alloy for the main body parts of the PCB machine.

From table 5, we decided that aluminum alloy 6061 would be used. Alloy 6061 is lighter than the others alloys listed in Table 5, yet durable because of its good strength and corrosion resistance [34]. It's also the second-cheapest alloy from the table, at $5.40/ft^2. Furthermore, it can be furnace brazed, leaving it a sleek finish.

Table 5: Aluminum Alloys

Aluminum Alloy	**Overview**	**Common Applications**	**Cost**
Alloy 3003	Most commonly used aluminum alloy in industry. Consists of added manganese which increases the strength. Excellent corrosion resistance [34].	Cooking utensils, kitchen equipment, decorative trim, awnings, siding, storage tanks, chemical equipment.	$3.07/ft^2 for .032" thick 3003 Aluminum Sheet [35]
Alloy 5052	One of the highest strength alloys available, it has a higher fatigue strength than most other alloys [34].	Aircraft components, home appliances, marine and transportation industry parts, equipment for bulk processing food.	$6.10/ft^2 for .032" thick 6061-T6 Aluminum Sheet [35]
Alloy 6061	Great range of mechanical properties. Good corrosion resistance. Used widely for purposes where appearance, good corrosion resistance, and good strength is needed [34].	Screw machine parts, truck bodies and frames, floors, platforms, cover plates, almost any structural component.	$5.40/ft^2 for .063" thick 5052 Aluminum Sheet [35]
Alloy 7075	Alloy 7075 has one of	Used mostly in aircraft	$9.13/ft^2 for .04"

	the highest strength grades, and is ideal for highly stressed parts. It's high cost makes this metal more suited for higher cost projects [34]	and transportation industry where strength is critical.	thick 7075 Aluminum Sheet [35]

Base

Aluminium alloy 6061 is the most suitable material for our design due to its high strength, high resistance to corrosion, and good workability.[46]. During milling, the vibration can negatively effect the cutting accuracy. Therefore, aluminum will allow the vibration to uniformly spread through the board to reduce the overall vibration in a short span of time.

	Impact Resistance	**Carbon content**	**Applications**
#E5614 - Copper Kettle Engineering Hardwood [36]	Medium	High	House flooring
High-density polyethylene plastic[36]	Low - It bounces off	Medium	Pipes Cutting boards
Aluminium Alloy 6061[46]	Medium	Low - Medium	Screw machine parts, truck bodies and frames, Floors, Platforms, Cover plates, almost any structural component.

Machine Hood

Possible plastic materials for transparent machine hoods include polycarbonate, glass, polyphenylene ether plastic [37]. The most suitable option for a design which is intended to be durable is polycarbonate (common for transparent machine hoods).

	Features	**Applications**

Polycarbonate Plastic [40]	• Lightweight: polycarbonate has a high stiffness to weight ratio [39] • Low cost: the cost is ½ - ⅔ the price of insulated glass [39] • High impact resistance: the impact resistance is 200 times stronger than glass [39] • Easily manufactured [39]	• Machine hoods [40] • Greenhouse walls [38] • Packaging [40] • Electronic housing [40]

Machine Parts
Motors

	Axis	Specifications
4 Wire NEMA 23 Stepping Motor	x, y	• Step angle: 1.8° • Voltage: 8.6V • Current: 2.0A • Holding Torque: 24kgcm • Cost: $23.89
6 Wire NEMA 23 Stepping Motor	z	• Step angle: 1.8° • Voltage: 2.0V • Current: 2.0A • Holding Torque: 5.8kgcm • Cost: $12.95

Spindle

The spindle and its motor can be purchased as one comprehensive unit. Spindles are available from a variety of sources, some of which are listed below.

	Specifications	Cost

CNC On a Budget - Spindle and motor [42]	● 3Speed Spindle for PCB milling	$102
Wolfgang Engineering - WW650 Spindle [41]	● Housing of spindle: 6061 T-6 Aluminum ● Stainless steel head (adds support for collet and cutter, can take heavier side cutting loads, acts as a shield for 2 bearings in head) ● 1.27mmx1.9mm stainless steel bearings ● Spindle diameter: 30mm, length: 11mm ● Milling speed: 25,000rpm ● Capable of cutting brass, aluminum, wood, plastic, more	$189
Westwind Air Bearings - PCB Spindles (http://www.westwind-airbearings.com/pcb/index.html)	● Milling Speed: 20,000 - 200,000 rpm ● Hole diameter range: 6.35mm-0.05mm ● Weight: 3.9kg	$240
CNC High Speed Spindle - High speed, Low Static PCB Drilling Spindle [44]	● Milling Speed: 80,000 - 370,000 rpm ● Hole diameter range: 6.35mm-0.05mm	-

Based on market research, it was concluded that the Wolfgang Engineering - WW650 Spindle, or a similar model is suitable for the design. It is a medium cost spindle, and the specifications are suitable for the required application. As it is one comprehensive component and the materials are selected for extended lifespan and protection, the part is in accordance with the objectives of durability, reliability and user friendliness.

Ball Screws (X and Y axes)

- Shaft Diameter: 15mm

- Preloaded
  - A preloaded system allows for there to be little to no backlash and axial play
- Lead: 5 mm
  - Smaller pitch allows for a smaller increments of linear movement per step of the stepper motor
- Total Screw length (y axis): 500mm
- Total Travel length (y axis): 460 mm
- Total Screw length (x axis): 350mm
- Total Travel length (x axis): 310mm
- Accuracy Grade: C3 (max. 30 microns of error per metre)
  - The accuracy grade is based off a standardized specification [43]

Lead Screw (Z - axis)

- Shaft Diameter: 22 mm
- Accuracy: 150 microns of error per
  - Smaller value is better, but this axis need not as much precision as the others
- Pitch: 5 mm
  - Smaller pitch allows for a smaller increments of linear movement per step of the stepper motor
- Total Screw length (z axis): 150 mm
- Total Travel length (z axis): 100 mm

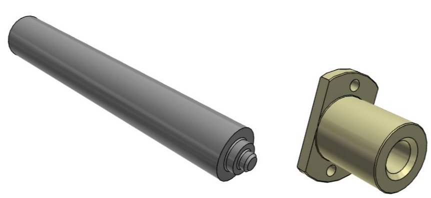
Sealed ball bearing

- Inside Diameter: 3/16"
- Outside Diameter: 1/2"
- Wd: 0.196

Oil-embedded sleeve bearing

- Temperature range: 10° to 220° F
- Length 2’’
- Pre Lubricated with oil
- Outside diameter 1 1/4"

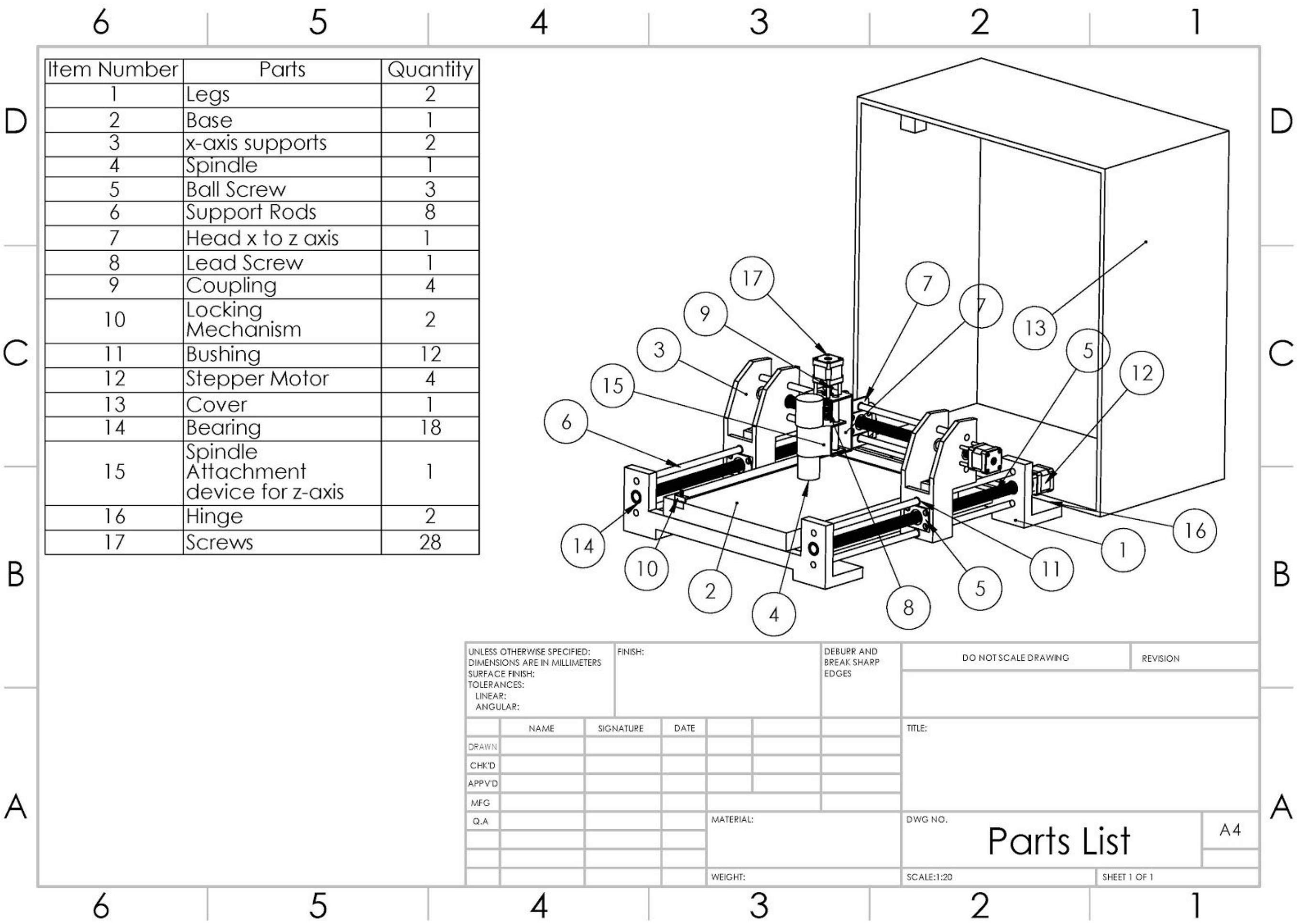
5.4 BILL OF MATERIALS

Component	Picture and Description	Quantity	Unit cost ($CAD)	Overall cost ($CAD)
Y - axis Ball Screw [29]	 Y - axis Ball Screw - 460mm X- axis Ball Screw - 350 mm Both screws are of the same type, simply of different length. Both of accuracy standard C3 or less than 15 microns of error in the travel distance With a 5 mm lead, and 15 mm diameter	Y - axis 2	$770	$1540
X- axis Ball Screw [29]		X- axis Ball 1	$665	$665
Z - axis Lead Screw [30]	 Z - axis Lead Screw -150 mm. A lead screw with a 5 mm pitch and an accuracy of 150 microns. The 22 mm diameter screw allows for a stronger bar holding the delicate spindle in rigid place.	1	$145	$145
Spindle Wolfgang Engineering - WW650		1	$189.99	$189.99

Spindle [41]	 A spindle with aluminum housing, stainless steel heads, and stainless steel bearings. The milling speed is 25,000rpm. Can drill through brass, plastic, wood, and more. Spindle and motor is included.			
Polycarbonate Hood [31]	914x1829mm sheet	2	$107	$214
Closed ball bearing [21]	 Inside Diameter: 3/16" Outside Diameter: 1/2" Wd: 0.196	6	$15.40	$92.4
Oil-embedded sleeve bearing [24]	 Temperature range: 10° to 220° F Length 2’’ Pre Lubricated with oil Outside diameter 1 1/4"	8	$10.50	$84

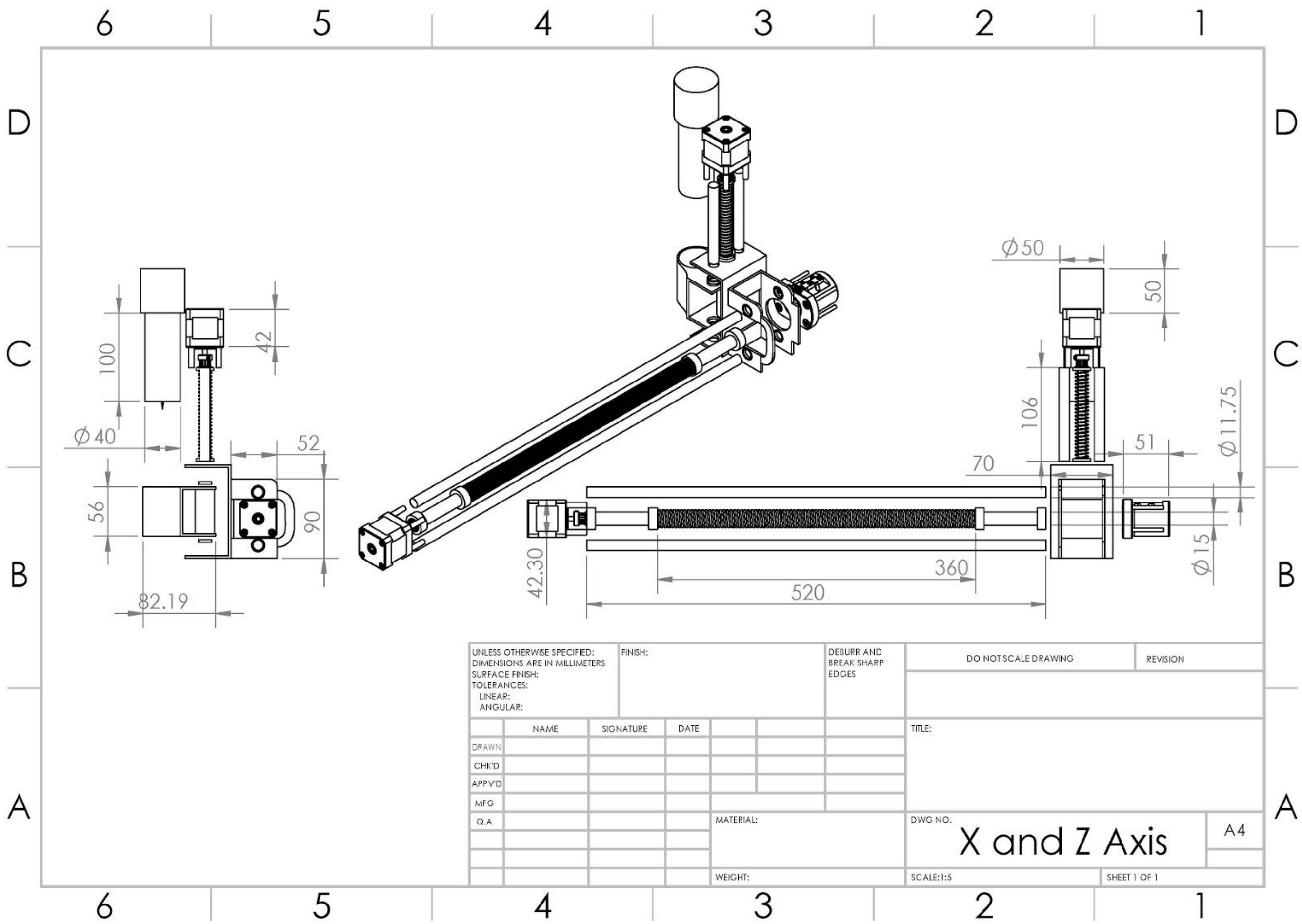
Aluminum [Density and cost based on CES software, as seen in Appendix E]	Component	Volume (mm^3)	Mass (kg)			
	Legs	844 000	2.4476	2	$9.01	$18.02
	X-axis support	465 600	1.3502	2	$4.97	$9.94
	Head x to z axis	35 646	0.1034	1	$0.38	$0.38
	Coupling	42 840	0.1242	1	$0.46	$0.26
	Spindle Attachment Device	57 400	0.1665	1	$0.61	$0.61
	Base	4 862 480	14.1012	1	$51.89	$51.89
	Bottom surface (the area in which the Base lies on)	3 094 720	8.9747	1	$33.03	$33.03
Steel [Density and cost based on CES software, as seen in Appendix E]	Component	Volume (mm^3)	Mass (kg)			
	Y - Support rods	59 529	0.4703	4	$0.40	$1.60
	X - Support rods	56 385	0.4454	2	$0.38	$0.76
	Z - Support rods	11 494	0.0908	2	$0.08	$0.16
Total						**$3047.04**

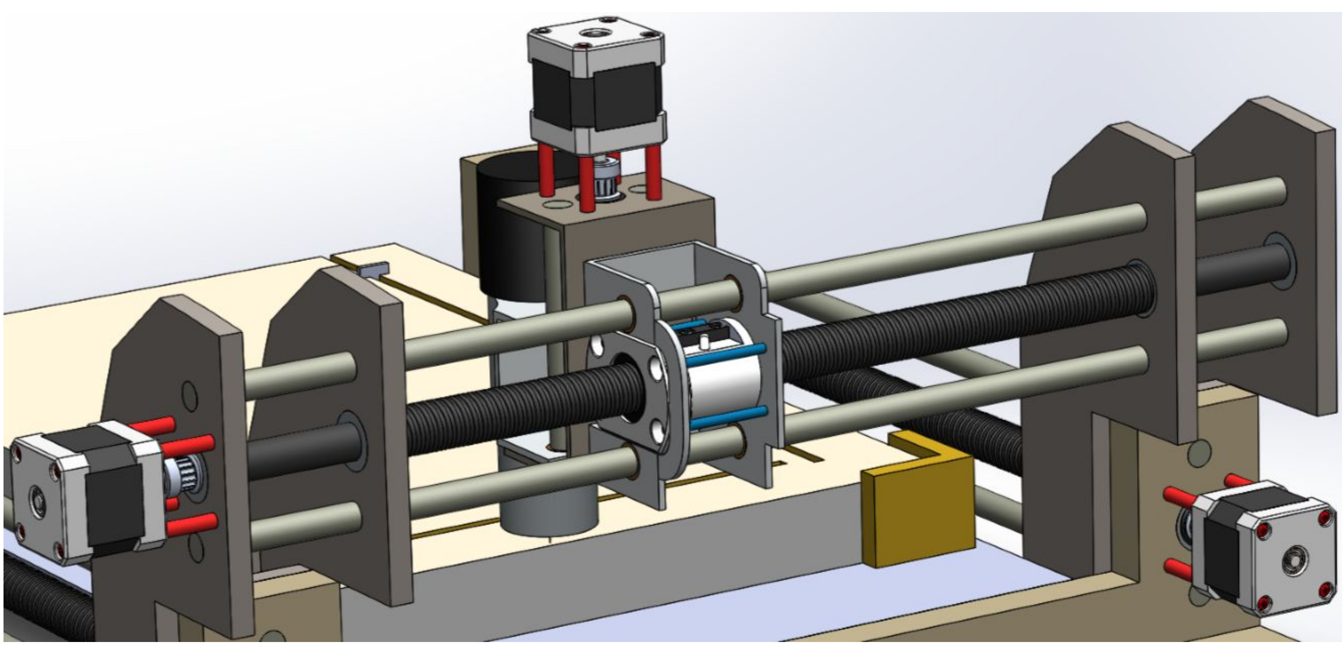
6. DRAWINGS



Item Number	Parts	Quantity
1	Legs	2
2	Base	1
3	x-axis supports	2
4	Spindle	1
5	Ball Screw	3
6	Support Rods	8
7	Head x to z axis	1
8	Lead Screw	1
9	Coupling	4
10	Locking Mechanism	2
11	Bushing	12
12	Stepper Motor	4
13	Cover	1
14	Bearing	18
15	Spindle Attachment device for z-axis	1
16	Hinge	2
17	Screws	28

Figure 12: Drawing and parts list of the PCB milling machine





Figures 13, 14: X-axis and Z-Axis

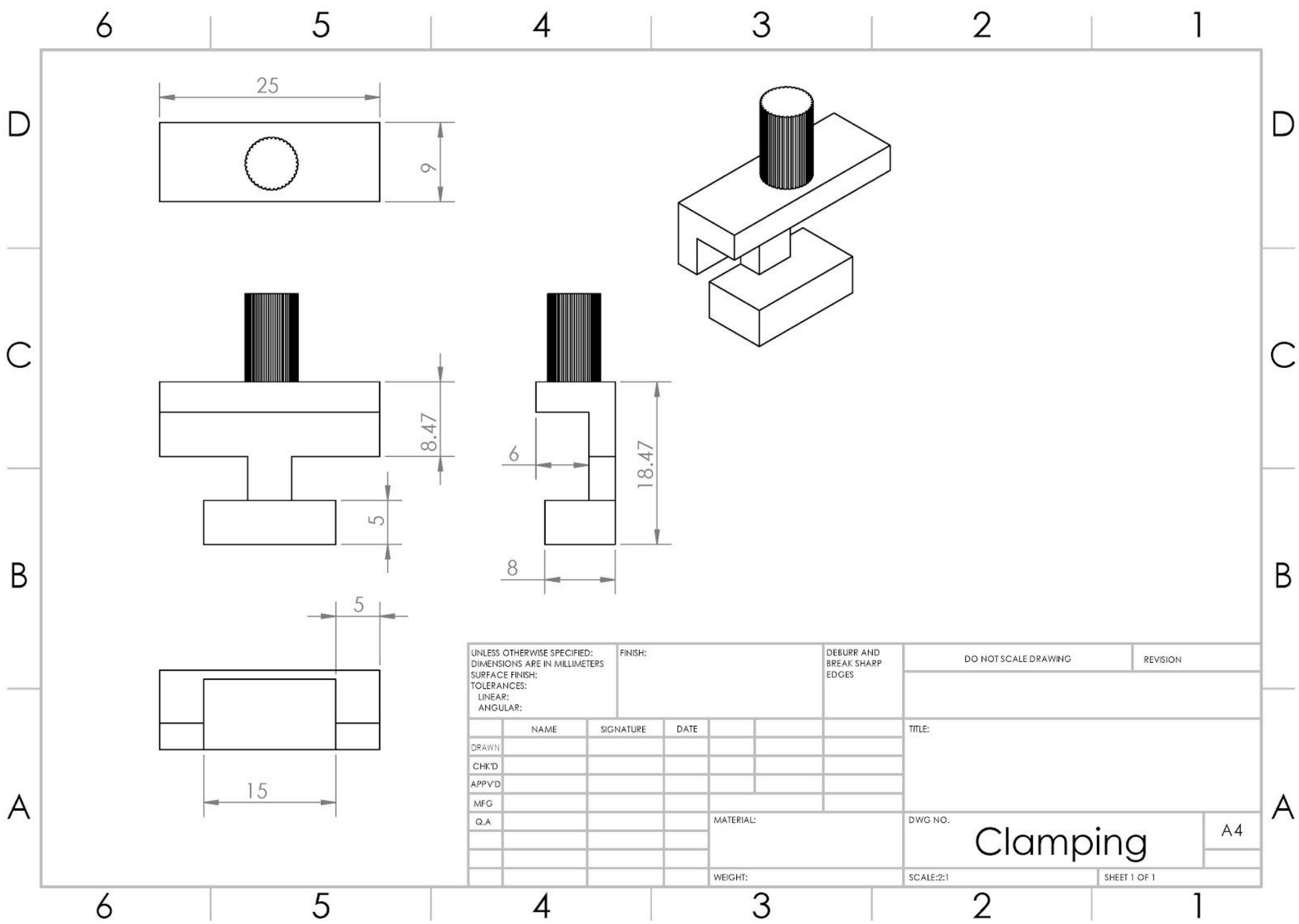


Figure 15: Locking mechanism

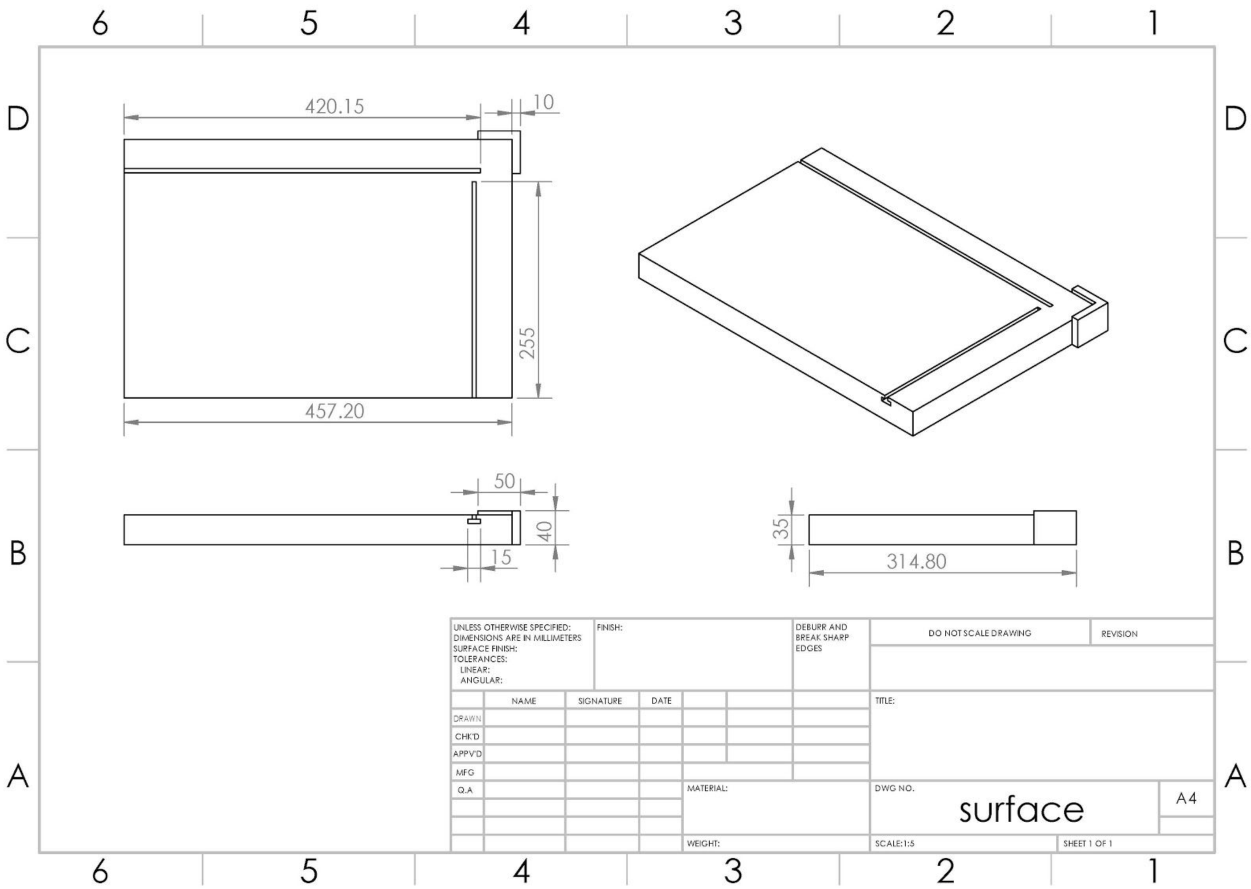
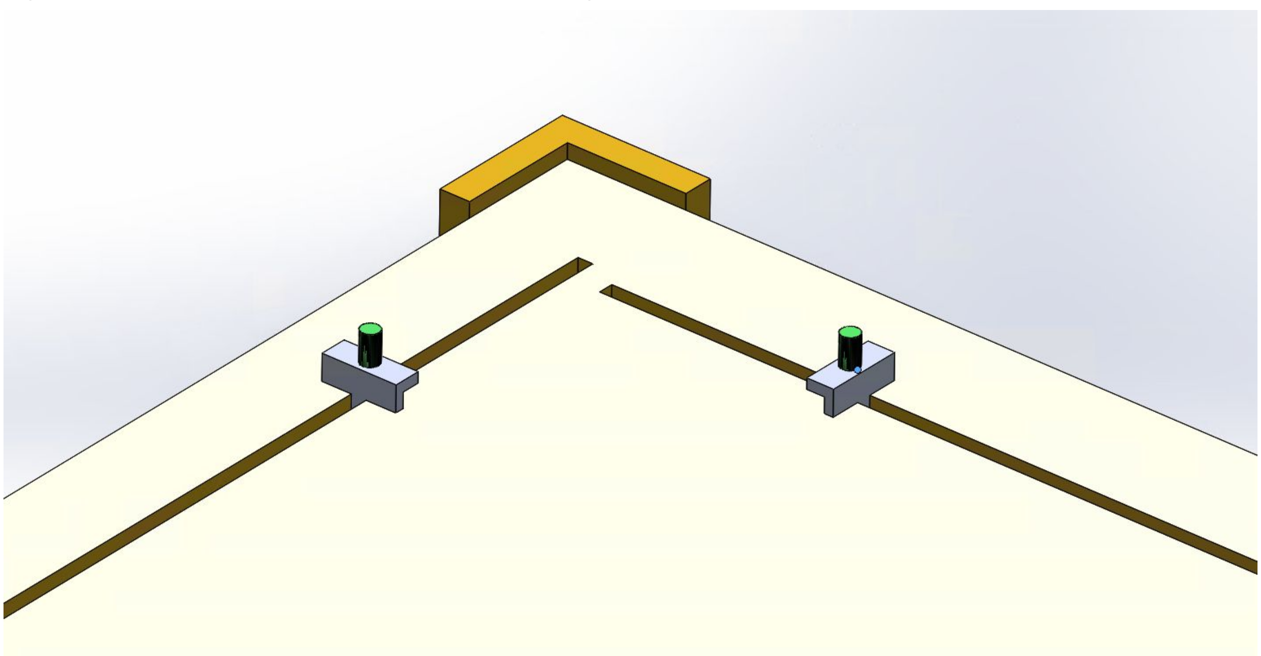
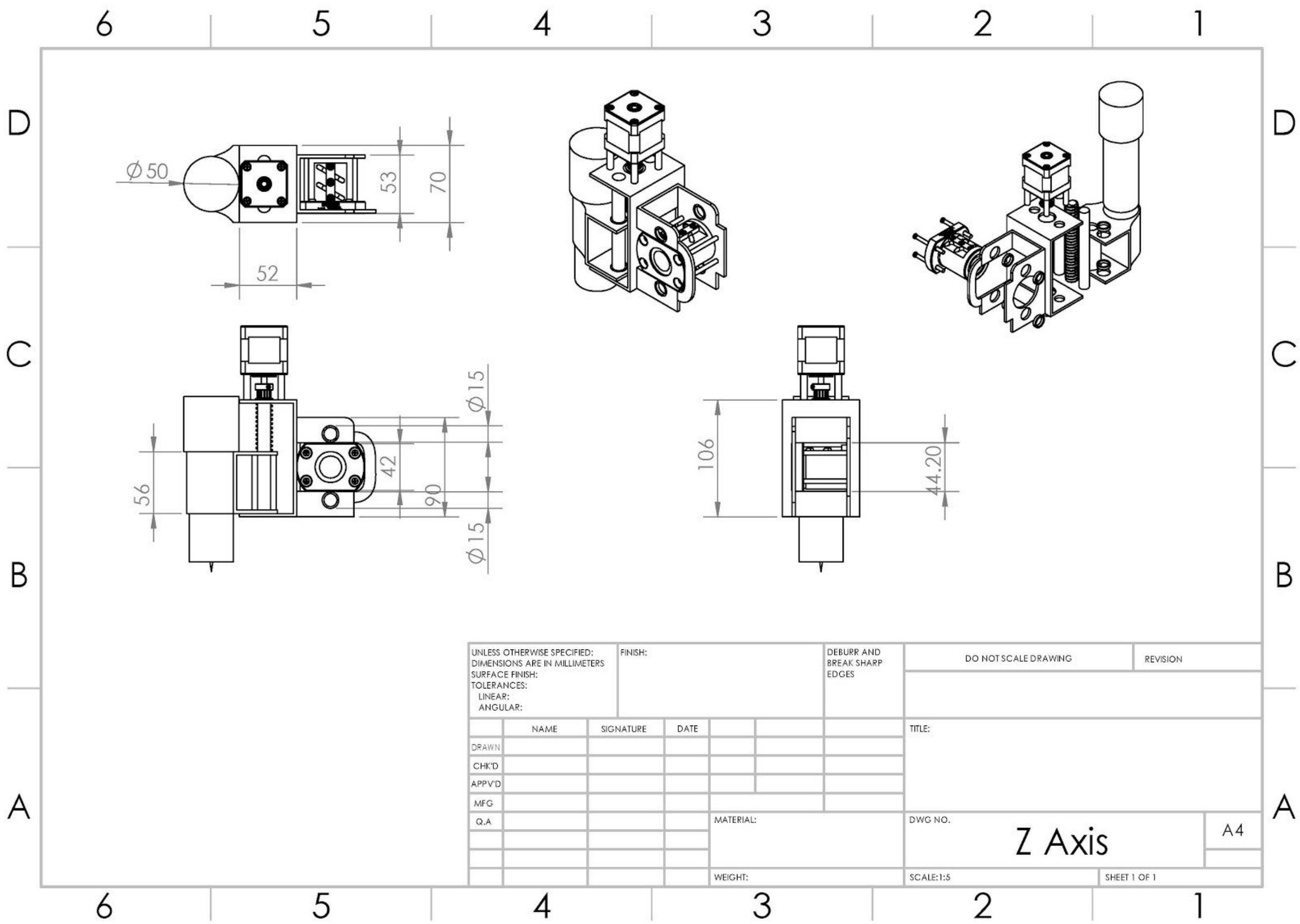


Figure 16, 17: The base board and the locking mechanism slots




6
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90
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
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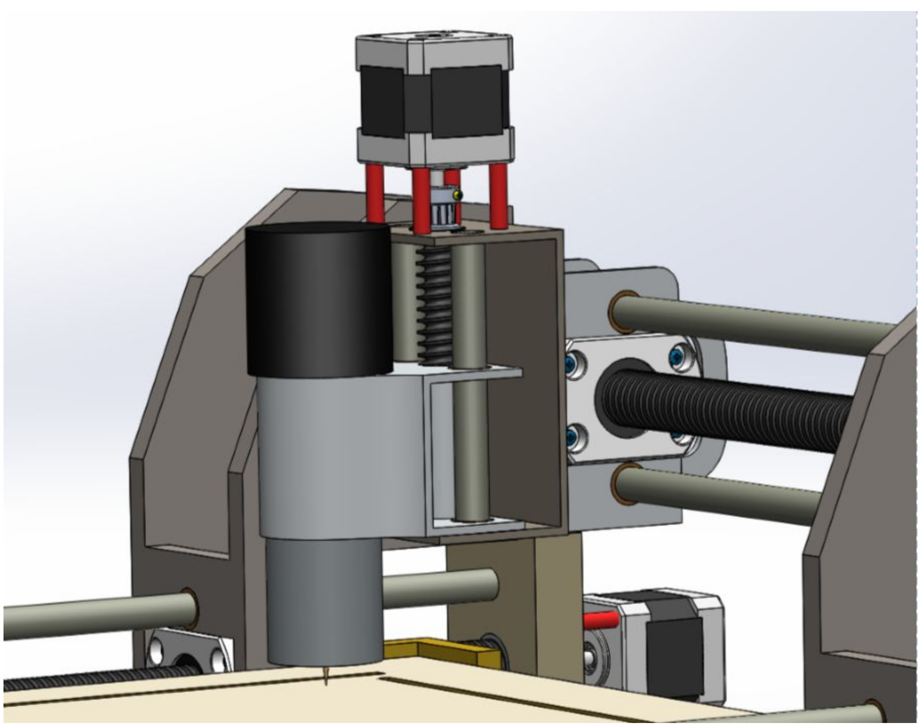
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
Z Axis
A4
WEIGHT:
SCALE:1:5
SHEET 1 OF 1



7. CONCLUSION

The objective of this project was to design an entry level PCB milling machine for small to medium sized businesses. The PCB milling machine was expected to be entry-level, and suitable for the specified work environment. These general requirements were the basis for the final generated design.

The project was initiated by thoroughly understanding the problem at hand and making general assumptions. It was assumed that these new and smaller types of businesses had limited resources and time. Therefore, the design had to be user friendly due to the lack of budget directed towards training machine users. Furthermore, the limited resources meant that the design had to be durable, ultimately limiting the need to frequently replace and maintain the machine or its individual parts, which can be a costly process. For similar reasons, the design was intended to be reliable for the business. To achieve reliability, mechanisms and parts that are wear resistant were selected as a focal point of the design. Next, a list of detailed engineering specifications was created, based on market research and general understanding of mechanical engineering design. The engineering specification included detailed objectives regarding the size, cost, operation specifications, and other aspects of the final design. Then, the process of generating candidate designs began. Candidate designs focused on the major motion mechanism of the spindle across the x,y,z axes. Each candidate design that was generated was compared to the high level objectives of the project. After narrowing the designs down, the details of the design were refined.

The final conceptualized design is a system of 5 ball screws and a lead screw to allow motion of spindle along all three axes (x,y,z). The screws allow for small and precise linear movements along the work bed. The machine housing is manufactured with an aluminum alloy, and the base and milling surface are also made of aluminum. Additional features include a locking mechanism with which the PCB board can be easily stabilized onto the surface, and a transparent machine hood made from polycarbonate plastic for user safety, cleanliness, and noise control. In combination, these features produce a system that is easy for the user to operate and will be suitable for use over a long period of time. In addition, the size and cost of the machine make it ideal for a small to medium sized business with limited budget and resources.

The final result of the team’s work is a PCB milling machine that is durable, user friendly, and reliable, which can effectively be implemented in small to medium sized businesses.

9. APPENDICES

9.1 APPENDIX A

The PCB machine should fit in the average workspace. The average workstation has a primary desk and a secondary surface (such as a credenza) [25]. The average area of this workspace is generally 152-183 cm x 152-213 cm [25]. For the purposes of designing for specifications, the larger measurements will be taken into account, giving a total area of 183 x 213 = 32376 cm^2. The average size of an office chair is 40 x 48.26 ≈ 1930 cm^2. The average size of an office desk is 152.4 x 76.2 ≈ 11613 cm^2 [26]. Therefore, the absolute maximum working area of the PCB machine is 32376 cm^2 - 11613 cm^2 - 1930 cm^2 = 18,833 cm^2.[26]

9.2 APPENDIX B

The optimal milling speed for PCB boards is dependant on the diameter of the milling drill bit, and the type of material being used. The equation to find the optimal RPM of the tool is given by RPM = SPM*12/π/D, where SPM is surface feet per min and D is the diameter of the tool [27]. The materials that require the highest SPM to operate optimally are magnesium and aluminum [aa][bb], assuming plastic and wood materials will not be used. The optimal SPM for aluminum and magnesium are both about 300. The minimum milling speed for aluminum and magnesium, with a drill bit size of 1/16 of an inch, is 12222 RPM. [28]

9.3 APPENDIX C

Average working area

L=(9+6+9+15+9+12+12)/7

= 10”

W=(12+6+12+14.4+12.6+10+9)/7

= 11”

H=(0.2+1+0.9+0.55+0.4+1.3+1.3)/7

=0.8”

LxWxH=(10, 11, 0.8) >>> converted to mm >>> LxWxH=(254, 280, 20)

Average overall dimensions:

L=(15+16+26+26+17+10+20+20)/8

=18.75”

W=(18+20+33+30+23+11+17+17)/8

=21.13”

H=(11+15+21+17+17+2+12+12)/8

=13.38

LxWxH=(18.75, 21.13, 13.38) >>> converted to mm >>> LxWxH=(475, 535, 340)

Average ratios:

W/L: 1.2+ 1.25+1.26+1.15+1.35+1.1+0.85+0.85 = 1.15

W/H: 1.64+1.33+1.57+1.75+1.35+1.41+1.41 = 1.3

For upper bound: choose largest W=33 → H=25, L= 29

approx. 735x840x635 mm (LxWxH)

For lower bound: choose smallest W=17 → H=13, L=15

approx. 380x430x330 mm

Average weight:

=(15+36+58+50+28+8+32+33)/8

=33kg

Standard power consumption:

Min= 100V

Max= 240V

Average travel speed

=(100+60+150+150+55+25+150+150)/8

=105 mm/s

Working Area

Range of thickness for PCB boards: 0.008" to 0.250"

Max PCB panel size: 10”x12” or 16”x22”

Based on Market Research:

Average ratio of length of machine to length of working area: 2.1:1

Average ratio of width of machine to width of working area: 1.5:1

Based on upper bound for machine dimensions, upper bound for working area should be: 350x560 (14”x22”)
Based on lower bound for machine dimensions, lower bound for working area should be: 180x286 (7”x11”)

9.4 APPENDIX D

Motor Comparison Table

Motor	https://www.circuitspecialists.com/nema_23_stepping_motor_57bygh006.html	https://www.circuitspecialists.com/nema_23_stepping_motor_57byg320.html	https://www.circuitspecialists.com/nema_23_stepping_motor_57bygh317.html	https://www.circuitspecialists.com/nema_23_stepping_motor_57bygh310-d.html	http://www.robotshop.com/ca/en/3v-17a-68oz-in-stepper-motor.html	http://www.robotshop.com/ca/en/soyo-reprap-stepper-motor.html	http://www.robotshop.com/ca/en/rbsoy02-soyo-unipolar-stepper-motor.html	https://www.circuitspecialists.com/nema_23_stepping_motor_57byg210.html
Control Torque	4.4 c	10 kg-cm	18 kg-cm	24 kg-cm	4.8 kg-cm	4.4 kg-cm	2.6 kg-cm	5.8 kg-cm
Resolution	1.8	1.8	1.8	1.8	0.9	1.8	1.8	1.8
Ratio (torque / resolution)	2.44	5.55	10	13.33	5.33	2.44	1.44	3.22
Price ($)	10.95	24.49	23.89	23.89	21.73	33.22	19.67	12.95

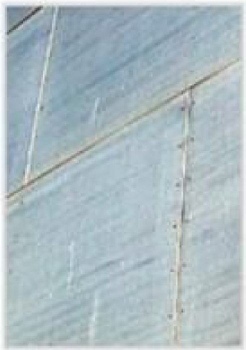
9.5 APPENDIX E

CES 2016 EDUPACK

Aluminum alloys

Description

Image



Caption

Aluminum can be formed both by casting and by deformation.

The material

Aluminum was once so rare and precious that the Emperor Napoleon III of France had a set of cutlery made from it that cost him more than silver. But that was 1860; today, nearly 150 years later, aluminum spoons are things you throw away - a testament to our ability to be both technically creative and wasteful. Aluminum, the first of the 'light alloys' (with magnesium and titanium), is the third most abundant metal in the earth's crust (after iron and silicon) but extracting it costs much energy. It has grown to be the second most important metal in the economy (steel comes first), and the mainstay of the aerospace industry.

Compositional summary

Al + alloying elements, e.g. Mg, Mn, Cr, Cu, Zn, Zr,

General properties

Density	2.5e3	-	2.9e3	kg/m^3
Price	* 3.21	-	3.68	CAD/kg

Mechanical properties

Young's modulus	6.8e10	-	8.2e10	Pa
Yield strength (elastic limit)	3e7	-	5e8	Pa
Tensile strength	5.8e7	-	5.5e8	Pa
Elongation	0.01	-	0.44	strain
Hardness - Vickers	1.18e8	-	1.48e9	Pa
Fatigue strength at 10^7 cycles	2.16e7	-	1.57e8	Pa
Fracture toughness	2.2e7	-	3.5e7	Pa.m^0.5

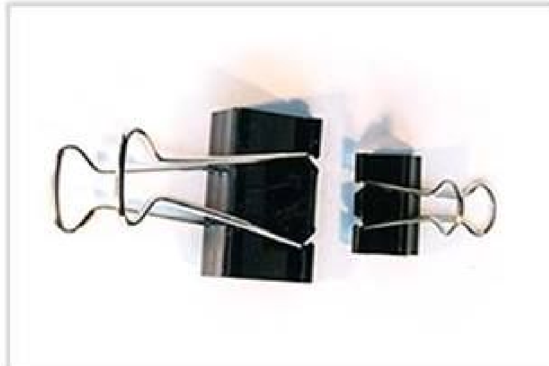
Thermal properties

Melting point	475	-	677	°C
Maximum service temperature	120	-	210	°C

High carbon steel

Description

Image



Caption

1. Bearing made of high carbon steel. © Granta Design 2. Drawing board clips made of high carbon steel. © Granta Design

The material

High carbon steels (0.5-1.7% carbon) harden when quenched - a quality that gives great control over properties. High carbon steels achieve hardness sufficient for them to be used as cutting tools, chisels and cables, and "piano wire" - the metal strings of pianos and violins.

Compositional summary

Fe/0.7 - 1.7%C

General properties

Density	7.8e3	-	7.9e3	kg/m^3
Price	* 0.843	-	0.858	CAD/kg

Mechanical properties

Young's modulus	2e11	-	2.15e11	Pa
Yield strength (elastic limit)	4e8	-	1.16e9	Pa
Tensile strength	5.5e8	-	1.64e9	Pa
Elongation	0.07	-	0.3	strain
Hardness - Vickers	1.57e9	-	6.37e9	Pa
Fatigue strength at 10^7 cycles	* 2.81e8	-	6.06e8	Pa
Fracture toughness	2.7e7	-	9.2e7	Pa.m^0.5

Thermal properties

Melting point	1.29e3	-	1.48e3	°C
Maximum service temperature	* 350	-	400	°C
Thermal conductor or insulator?	Good conductor			

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