Design Project - CNC Milling Machine
MIE 243

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1.0 Introduction

CNC (Computer Numerical Control) milling machines and routers are tools frequently used in industrial institutions and now, personal workshops. They use a cutting tool used to progressively remove material from a workpiece, creating an object that has previously been designed using specific computer software. This method of machining is called subtractive manufacturing. The principle difference between the milling machine and the router is that mills operate on torque, whilst routers operate on rotations per minute (RPM). Routers are generally used for cutting soft materials like wood, foam, and plastics, whereas mills can cut harder materials such as metals.

Milling machines can either be kit-based or non-kit based. A kit-based milling machine is received disassembled, and requires the user to assemble the parts together to create the machine. The aim of this project is to create a kit-based CNC milling machine that is best suited for beginners and hobbyists working within a home environment such as a garage or a personalized workspace.

A key feature of any milling machine is the number of axes used. The most common types of milling machines are either 3-axis or 5-axis. In a 3-axis milling machine, the cutting tool moves in the X,Y and Z directions, also known as the Cartesian coordinate system. In a 5-axis machine, the additional 2 axes are rotational, revolving around the X and Y axes. This enables the cutting tool to approach the workpiece in all directions. [1] There are fewer 4-axis machines available on the market and these involve one rotating axes that revolves around either the X- or Y-axis.

In order to obtain a general overview of the current state-of-the art technology present in the market at the moment, we have chosen to briefly analyze three milling machines that are in high demand. In doing so, we will be able to distinguish certain features and machine specifications that would be desirable for our design. Moreover, we are searching for features that may require improvement or modification in order to create a machine tailored for our target market; namely hobbyists and entry-level users.

2.0 Research

We conducted research on CNC milling machines that were applicable for use on projects of varying complexities. This helped us find trends in the general characteristics of the machines as well as more specific features such as the spindle speed and operation of the axes. The machines we chose to analyze all operated on a 3-axis Cartesian coordinate system with either the base/table moving the working piece around, the head of the spindle moving in the coordinate system, or a combination of both. Some of the mills were kit-based, made out of components that were easy to assemble and disassemble if replacement of a part is required. The heavier machines usually had advanced features while the lighter machines had the necessary features for an entry-level user or hobbyist. It was also noted that most of the CNC machines operated with leadscrew mechanisms while only a few used belt drives.

2.1 Current State-of-the-Art

Table 1: Summary of the current research on milling machines

Feature	**TW-32Qi Bed mill [2]**	**10" Sherline mill - CNC Ready [3]**	**Zen Toolworks 12x12 CNC [4]**
Machine Size	375mm x 298mm x 527mm	375mm x 324mm x 527mm	610mm x 610mm x 406mm
Table size	70mm x 330mm	70mm x 330mm	305mm x 305mm
Weight	1905kg	13.6kg	20.4kg
Cost	N/A	$930.00	$679.99 – $1,399.99
Functions	• Milling • Drilling • Boring	• Milling • Engraving • Carving • Cutting	• Milling • Engraving • Carving • Inlay Working • PCB Circuit working • 3D Printing
Travel	X-axis - 864mm Y-axis - 508mm	X-axis - 220mm Y-axis - 76mm	X-axis - 305mm Y-axis - 305mm

	Z-axis - 508mm	Z-axis - 159mm	Z-Axis - 51mm
Spindle Speed	60-6000 RPM	70-2800 RPM	Max: 11500 RPM
Additional Features	• Auto lubrication unit with metered check valves • Built-in coolant reservoir in machine base	• T-slots in the table for holding down the piece • Lubricating oils on all 3 axes • Headstock rotation (90° left/right) • Brass leadscrew cover for leadscrew maintenance • Partial Kit-based	• Kit-based • Anti-backlash brass nut design • Steel guide rods and precision linear bearings for maximum accuracy and rigidity • Enforced aluminum gantry

2.2 Specified Research

Feed Rate:

It is necessary to see what feed rate we require of our machine so that it can cut multiple materials. One of the hardest materials we want our machine to cut is aluminum, whilst one of the softest is soft wood. To gauge what type of spindle speed we want our machine to have, the feed rates for aluminum and soft wood were calculated (see Appendix A). The feed rate for soft wood was 200 inches per minute, whilst the feed rate for aluminum was 56.25 inches per minute.

Ball screw Driving Torque:

Ball screws have significant advantages compared to other motion conversion and transmission mechanisms. They operate, on average, at 90% efficiency which is significantly high when compared to other mechanisms. Moreover, they have the ability to translate significantly heavy loads at a fast speed, reducing the process time of any operation [5]. With such benefits, ball screws are increasingly used when designing CNC machines.

Ball screws are used to control certain axes found in a CNC machine and thus require a motor as a source of power. In order to translate the ball screw and any mass carried by it, the motor needs to possess a minimum driving force. When purchasing motors, the maximum driving torque is usually known. However, the driving force required by a ball screw required is based on its length, the mass it holds, and the frictional resistance it experiences with the guide surface. The calculations are shown in Appendix A.

3.0 Engineering Specifications

Our target market, as specified by the problem statement, are entry level users and hobbyists who would generally use the machine in a home environment. To produce a final machine design within this scope, our candidate designs needs to meet certain requirements, ensuring that all the features included are easy to understand and operate since our target market will not have vast amounts of experience with milling machines. The following requirements and goals have been identified in order to help us generate designs that comply with our scope.

3.1 - Engineering Functional Requirements:

These define the functions that our design must be able to complete in order to be considered as a viable solution for our specific problem.

- Should move in at least 3 different axes (X, Y, & Z) on the Cartesian Coordinate system
- Should be kit-based; assembly by the user must be possible
- Should be able to mill a range of materials including polycarbonate plastics, wood, and soft metals such as aluminum, which we assume will be the most common types of materials milled by a beginner user

3.2 - Engineering Design Requirements:

Design requirements are constraints imposed on the design of the milling machine in order to ensure our solutions are tailored towards hobbyists and entry-level users. The proposed final design must meet all the design requirements listed below:

- Must have a maximum weight of 52kg [6]
  - Target market is home users, hence the machine must be light enough for users to lift and move around without inducing injuries.

    - Average weight for two people to lift safely is 52kg [7]
- Must have a maximum of 100 parts that will be assembled (excluding screws and parts that can be attached directly on to the machine)
    - As the device is going to be assembled by the user, it is necessary to limit the number of parts to reduce the complexity of the assembly process
- Must have a maximum footprint area of 1219mm x 610mm [8]
    - This is an advisable size for lighter and smaller workbenches which would be relevant in a home environment such as a garage
- Must cost a maximum of $1500
    - Since our target market consists of beginners and hobbyists, the price of our design needs to be justified and affordable, as opposed to high-level users that would pay more attention to the number and complexity of features rather than price

3.3 - Engineering Design Goals:

These design goals will help us measure the success of our candidate designs as the design process progresses. Design goals can also be used as an idea generation tool; they spur various ideas whilst ensuring we adhere to the main concepts and features desired in our finalized design. Each candidate design had specific goals that it needed to achieve. Furthermore, each candidate design was tailored to achieve additional goals to encourage further divergence, and design considerations were made such that candidates would perform relatively well in their targeted goals.

Overall Design Goal:

- Positional resolution [9] of 0.254mm (0.01 inches) in the motion conversion and transmission mechanisms:
    - This is the suggested accuracy required for hobbyists to perform most milling tasks

Candidate 1 Design Goals:

- Cost Effectiveness:
    - Material and component selection intended to decrease cost
    - Design footprint area that minimises material used
- Simplicity of Design:
    - Minimal parts required for assembly

- Parts are straightforward to assemble

Candidate 2 Design Goals:

- Replaceability of components and maintenance:
    - Easy accessibility to parts that may need replacement
    - Material selection that increases maintainability
    - Choice of components that increase longevity of the machine
- Portability:
    - Minimizing weight of the machine
    - Customized Handling features included

Candidate 3 Design Goals:

- Positional Accuracy:
    - Reducing the backlash present in the motion transmission and conversion mechanisms
- Wider range of applicability:
    - Increased complexity of the designs that can be machined

4.0 Candidate Designs

4.1 - Candidate Design 1:

This design uses lead screws, a timing belt, a pulley and stepper motors to achieve motion in the different axes. To allow for cutting in the Z-axis, the spindle moves up and down by the action of the leadscrew. This movement is achieved by having a stepper motor connected to the lead screw that converts the rotational motion created by the motor into linear motion, lifting and lowering the head of the machine. A similar mechanism is used to enable the head to slide along the gantry bridge and translate along the X-axis.
To allow for cutting in the Y-axis, a stepper motor is connected to a timing pulley that rotates a timing belt. This belt translates the bridge of the machine (which is connected to the spindle) in the Y-axis. The design can also accommodate workpieces that are cylindrical in shape as there is a circular piece holder built into its bed, which is accessed by removing a cover that is located in the center of the bed.

Movement in Y-axes	Uses a timing belt and pulley system powered

	by a stepper motor
Movement in X- and Z-axis	Uses a lead screw connected to a stepper motor
Enhancement of Kit-Based	Minimal parts required to be assembled. Assembly parts are also simple to put together.

4.1.0 - Engineering Design Goals:

4.1.1 - Positional Resolution

This machine uses a timing belt in the Y-axis. To calculate the positional accuracy of the belt, we required the diameter of the timing belt pulley and the step angle of the motor. Knowing the diameter of the pulley enabled us to calculate the linear length travelled by the belt in one revolution of the motor. The choice of motor in this case was a NEMA 17 step motor and we used a timing belt pulley with an outer diameter of 16.129 mm and circumference of 50.67mm. The NEMA stepper motor was calculated to have 200 steps per rotation [10]. The positional resolution was calculated using the formula: circumference/steps per rotation. This gave a positional resolution of 0.253mm/revolution.

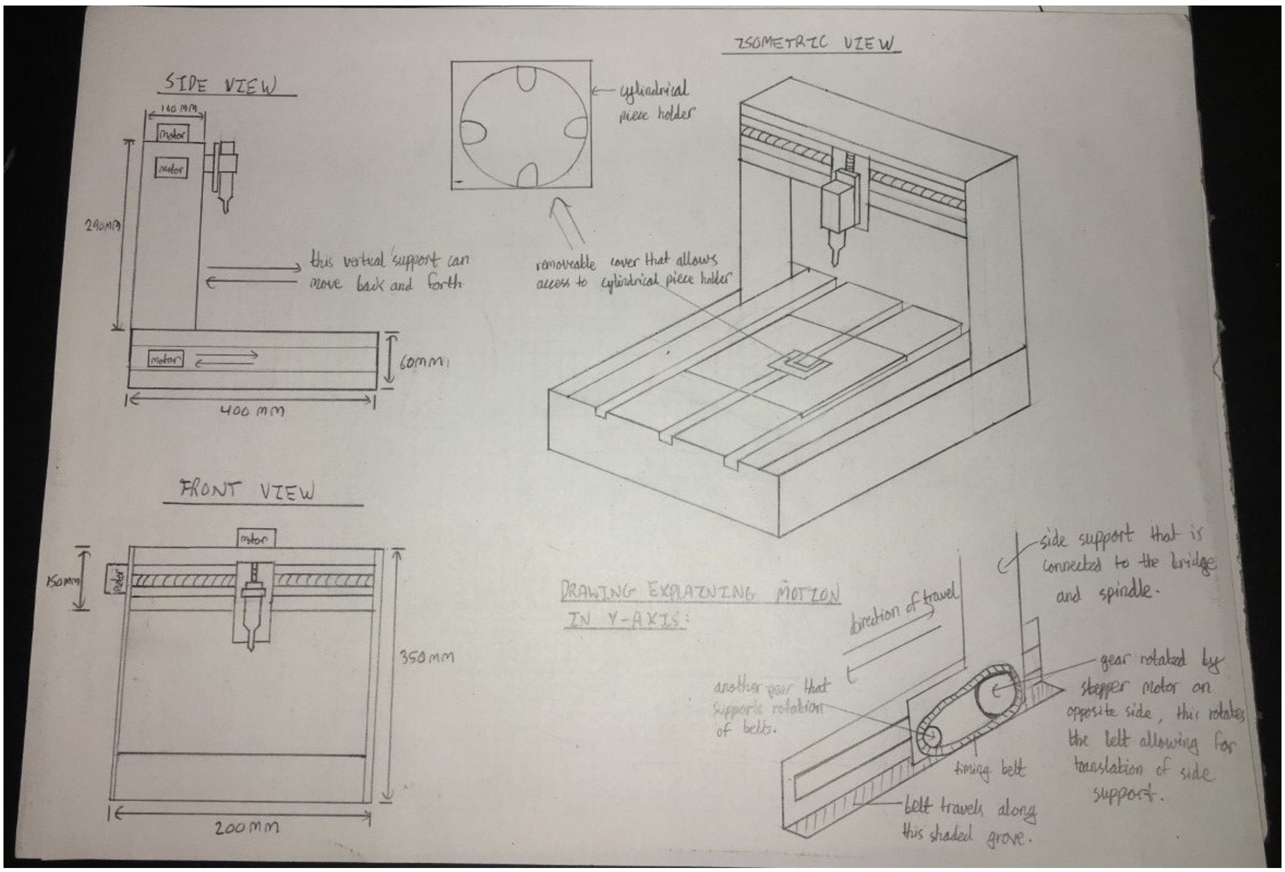
4.1.2 - Cost Effectiveness

To ensure that the design is cost friendly, the major components of the design were chosen to be made out of aluminum, a relatively cheap material. The size of the machine (including the workspace, table size, and maximum height and depth) was also kept to a minimum. Shorter dimensions were chosen to ensure functionality whilst reducing the amount of aluminum required, thereby lowering material expenses. Stepper motors, lead screws and a timing belt were chosen for motion transmission and conversion due to their competitive market prices in comparison to other potential components. Furthermore, due to the relatively small number of components involved in this design, manufacturing costs are further limited.

4.1.3 - Simplicity of Design

The kit-based design comprises of no more than ten assembly parts. These components are manufactured such that both their assembly and usage are made simple. Minimal work is required to put the machine together, adding to the kit-based nature of the design. The bridge, side supports, and bed are delivered pre-assembled [11], so the user only needs to attach the motors, timing belt and lead screws for the machine to be fully functional.

Figure 1: Candidate design 1 and its mechanisms



4.2 Candidate Design 2

This design is simple as it uses a single type of motion modification mechanism to allow travel in the X, Y & Z directions. This is done by converting rotational motion from the stepper motors to linear motion using ball screws and their corresponding screw nuts. These screws are mounted onto the frame by two support pieces on each end of the axes. The ballscrew for the movement of the X-axis will move the work surface in both the negative and positive directions. The Y-axis will move the spindle along the gantry and the Z-axis will be functional through the upward and downward motion of the spindle. Motion along each axis is supported by box-ways which reduce friction during motion, allowing for smoother travel along each of the axes. The work table will be held down by numerous screws and the MDF board for the vacuum table at the centre will be fitted into the manufactured table to keep it firm and in place. The vacuum table will allow for the machining of small objects that cannot be secured by the clamping system. Additionally, the vacuum table will facilitate the machining of thin sheets such as Aluminium as well as lighter materials such as MDF boards. The vacuum table has a dual purpose of stabilizing the workpiece and removing any debris off the table. Aluminium rails with screw holes will cover the work table vertically allowing for detachable clamps to be used to hold the milling material in place during the machining process. The functional specifications of the design are listed below:

Table: Candidate Design 2 specifications

Movement in X- & Y-axes	Usage of a NEMA 17 stepper motor connected to a ballscrew (double-nut) [12]
Movement in Z-axis	Usage of a NEMA 17 stepper motor connected to a ballscrew (double-nut) [13]
Enhancement of Kit-based	Majority of the components are externally mounted for ease of construction

4.2.0 - Candidate Design 2 Engineering Goals

4.2.1 - Positional Resolution

Positional Resolution is dependant on both the stepper motor and the ballscrew. This design incorporated a NEMA 17 stepper motor and a ⅝” Right hand threaded ballscrew (double-nut) respectively. The stepper motor was sourced from McMaster-carr [14], and it was stated that the step angle for the motor was 1.8 degrees with 200 steps per revolution [15]. The ballscrew was stated to have 5.08mm of linear travel along the ballscrew for a single turn. As such, the linear distance travelled by the ball screw per step of the motor is calculated to be 0.0254mm.

4.2.2 - Replaceability and Maintenance

As this design targets entry-level machinists and hobbyists, maintaining all the components must be user-friendly. The following components experience wear due to friction:

- Ball screws and their respective nuts and bearings
- Clamps
- Motors

Replaceability

- The ballscrews are placed in hollow sections of the frame so that they can be easily accessed when replacement is required
- All the motors present in the design are externally mounted to allow for easy access during maintenance or replacement
- The rectangular clamps are easily fixed into and removed from their positions using screws. This allows for a quick replacement process when necessary.
- The height of the gantry is 400 mm, allowing for adequate space to access all the important parts of the machine. The height from the base to the table is 200mm, enabling easy installation and maintenance of the X-axis ball screw and the pipes connected to the vacuum pump and table.

Maintainability

- The metallic frame is designed to be resistant to corrosion and can withstand the build up of internal stresses [16] as it is made from aluminium 6061.
- The choice of motors was narrowed down to stepper motors due to their open-loop [17] feature which eliminates the complexity of an encoder and resolver. Thus, a basic knowledge on maintenance is required in order to use them. Furthermore, the majority of the moving parts in a stepper motor are frictionless [18], undergoing minimal wear and thus reducing the maintenance they require.

4.2.3 - Portability

Considering the target market, the machine will probably be used in an environment like a garage. Therefore, portability is an important goal to consider as it allows for the user to easily set up the machine and locate it to their preference. This has been achieved by the following design considerations:

- The weight of the machine will be kept between 69-160 lbs as this is a safe weight that can be lifted between two adults [19]
- Two handles have been custom designed on either side of the machine frame to create an ergonomic grip allowing for easy re-positioning of the milling machine.

Figure 2: Candidate design 2 and its mechanisms

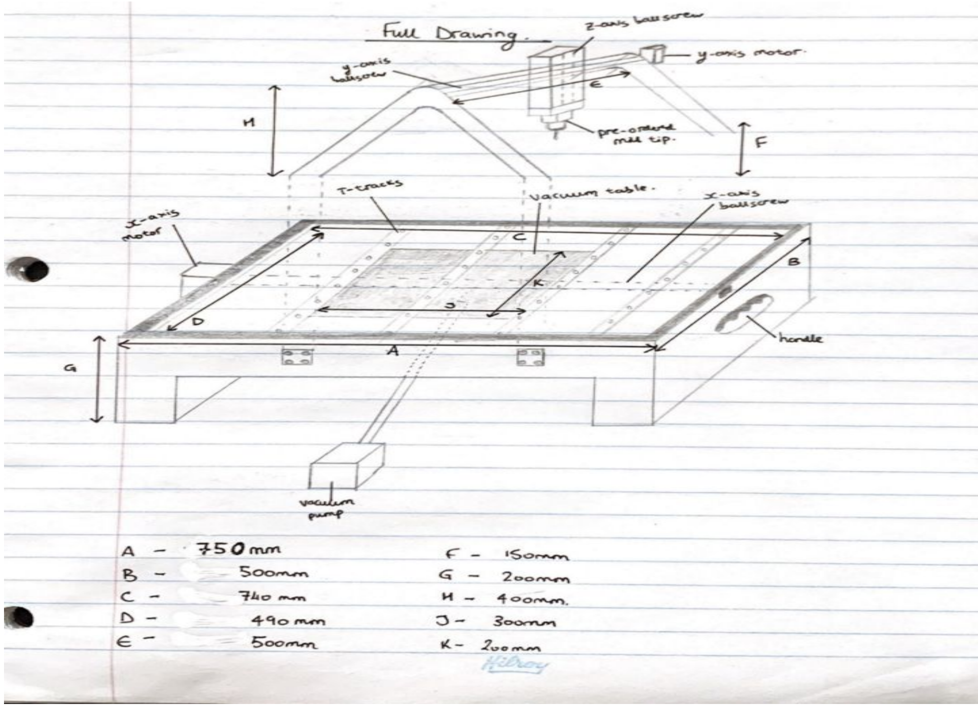
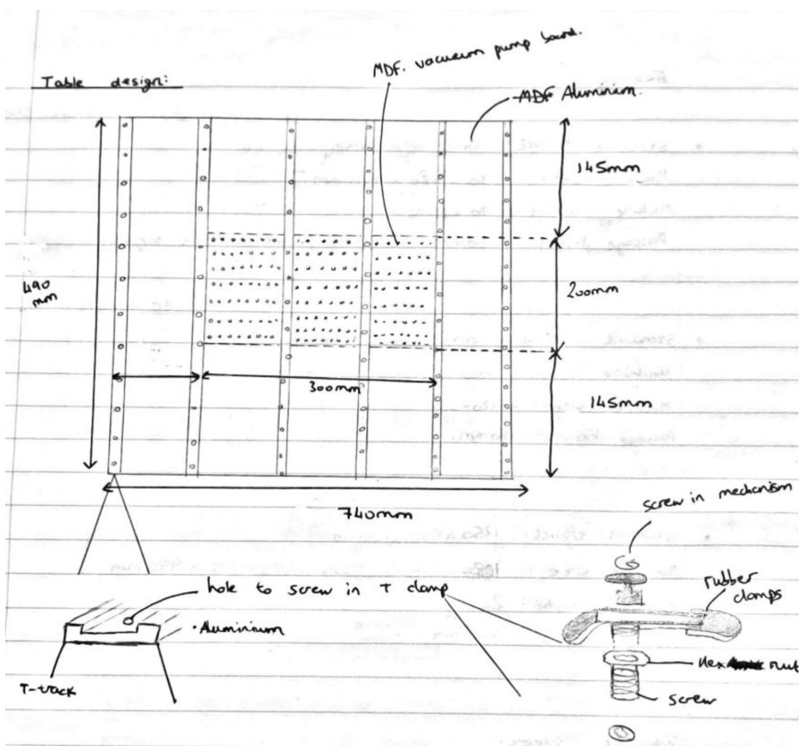


Figure 3: Candidate design proposed table



4.3 - Candidate Design 3

This milling machine operates on 4 different axes, each being controlled by stepper motors. No part of the system is controlled manually, other than the mounting of the workpiece. The machine is designed such that the table does not move, with a gantry bridge that towers over the table. The bridge has two arms that extend downwards outside of the table, where they are connected to the ball screws that convert the rotational motion from a motor into linear motion. This is how the Y-axis movement of the system is controlled. The ball screws are mounted onto support pieces that are found on the outside of two of the walls. Each ball screw has an anti-backlash nut system to reduce backlash, as well as bearings to support the motion. Attached onto the bridge is the head of the milling machine. There is a ball screw placed under the bridge to which the head is connected. Using guide rails, this ball screw enables the movement of the head along the bridge creating movement along the X-axis. Within the head of the machine, there is a shorter lead screw that controls the vertical movement of the spindle and thus the Z-axis. To allow the user to machine more complex designs, a fourth axis has been included. This mechanism is found directly on the table. It is comprised of one support piece that holds the workpiece above the table and a motor used to rotate the workpiece, that is found on the wall opposite to the support.

Movement in X- & Y-axes	Use of ball screws powered by stepper motors.
Movement in Z-axis	Use of a leadscrew to control the motion of the head of the machine.
Enhancement of kit based	The symmetry of the machine enhances the design for assembly[20]

4.3.0 Candidate 3 Design Goals

4.3.1 - Positional Resolution

For this candidate design, we chose to use the NEMA 17 stepper motors and ball screws supplied by McMaster Carr [21]. The positional resolution of our design was dependant on the linear distance travelled by the ball screw per revolution and the number of steps per revolution of the motor. In this case, the linear distance travelled by the shaft per rotation was 5.08 mm. The number of steps per revolution of the motor was found to be 200. Therefore, the distance travelled per step was 0.0254mm per revolution.

For the Z-axis, we chose a leadscrew with a linear distance travel per rotation of 2mm. Since we were using the NEMA 17 stepper motor with 200 steps per revolution, we calculated the positional resolution to be 2/200 = 0.01mm per revolution.

4.3.2 - Positional Accuracy

Backlash is present in ball screws and there is a need for it to be mitigated. This is done by preloading the ballscrew, specifically by applying tension between the two Belleville washers located at the centre of the screw. This method uses a spring to create the tension between the two mechanically coupled nuts [22]. The spring stiffness is high enough to help overcome the applied axial forces encountered when the machine is operating and reduce the gaps around the ball screws, ensuring there is no lag after any change in the direction of motion. Hence, there is effectively no backlash, allowing for greater accuracy of the mechanism. This anti-backlash mechanism is referred to as a double nut spring, which was implemented to the ball screws of the X, Y and Z axes.

4.3.3 - Wider Range of Applicability

The introduction of a fourth axis in this design presents users with an extra degree of freedom. The fourth axis, which enables rotation of the workpiece, brings about indexing which increases the accessibility [23] of the cutting tool to each part of the object that is being worked on. The additional fourth axis facilitates complex cuts such as arcs and grooves [24]. Thus, it also enables the user to increase the intricacy of the design being machined.

Figure 3: Candidate design 3 and its mechanisms

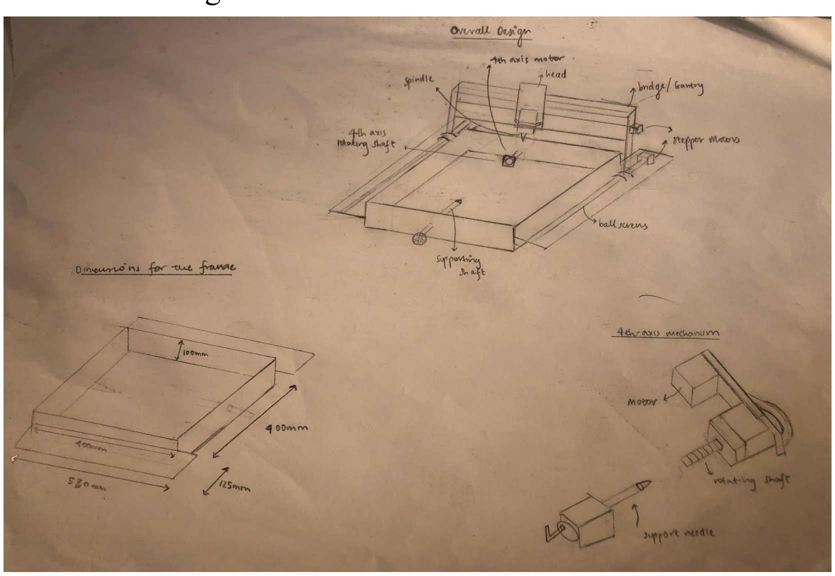
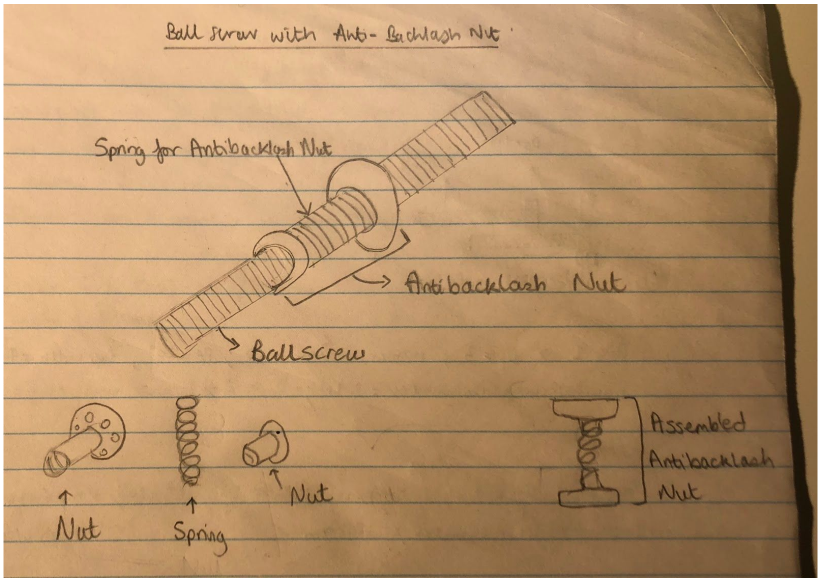


Figure 4: Anti-backlash mechanism for Candidate 3



5.0 Final Design

Within this section of the document, we will give an in-depth description of our final design. We will begin with focusing on the choices made in order to have our design achieve the key functional requirements stated at the beginning of the document. Then, we will proceed to explain the important features found within our final design, before concluding this section with a component and materials justification, as well as a cost analysis.

5.1 - Decision Making Process for Key Functional Requirements

The ways in which each candidate design fulfilled the functional requirements were tabulated for comparison as shown below:

	Candidate 1	Candidate 2	Candidate 3
Resolution [mm per revolution]	Timing Belt - 0.253 (Z-axis)	Ball screw - 0.0254	Ball screw for X and Y-axis - 0.0254

			Lead screw for Z-axis - 0.01
Enhancement of kit-based	Minimal number of components to assemble	Externally mounted components increases the ease of construction	Symmetry of parts makes assembly easier

5.1.1 - Motion in the X- and Y-axis - Ball Screw

For the motion in the X and Y axes, we chose the ball screw method that was implemented in candidate 2. From the table above, we deduced that the ball screw has a resolution ten times greater than the targeted goal. Moreover, the ball screw is significantly more efficient when compared to the lead screw. The efficiency of a ball screw is on average 90% whilst that of a leadscrew ranges between 20-80%. In addition, the sliding contact found in the leadscrew generates a greater amount of friction when compared to the rolling contact found in the ball screw. Therefore, the longevity of the ball screw is greater.

When comparing the belt drive to the ball screw, the resolution of the ball screw was also ten times that of the belt drive. The smaller linear distance per step of the motor enables a cut with a higher precision. Furthermore, to counteract the fact that the accuracy of the timing belts is higher than the ball screw, we implemented a nut and spring mechanism into each ball screw to eliminate the backlash. The spring creates a tensile force between the coupled nuts which can then prevent vibrations of the ball screw in the axial direction [25]. Therefore, considering the measures put in place to counteract the inaccuracies caused by backlash, and the higher positional resolution, we chose the use of ball screws for the respective axes.

5.1.2 - Motion in the Z-axis - Timing Belt Drive

For movement in the Z-axis, we chose to use the timing belt concept used in candidate 1. Initially, we chose to use a lead screw due to its smooth movement. This meant that the head could move without interruptions to its motion. However, lead screws have an inherent issue with backlash, meaning that the actual motion would lag and not be accurate. Hence, we decided to change the mechanism.

Accuracy is the difference between the theoretical distance travelled and the actual distance travelled [26]. We made an assumption that the designs of beginners and hobbyists would not be significantly complex and therefore the resolution required would not be the most important factor to consider. However, the accuracy required in the position of the spindle would be crucial. The specific timing belt chosen had a greater accuracy when compared to the lead screws and ball screws, making it the best option for us. The reason for the increased accuracy is as a result of the timing belt always being in tension [27], which negates the backlash.

The ball screw was not chosen for the replacement mechanism as it too suffers with backlash problems that inhibit accuracy. The anti-backlash mechanisms used for the X- and Y-axes were expensive, and in order to keep the cost of the overall machine down, we chose not to use ball screws and have to implement the anti-backlash system. Therefore, a belt drive was used, enabling cost efficiency whilst ensuring accuracy.

For a timing belt drive, both its initial cost and its maintenance are cheaper than that of the other two alternatives. This is because the only wearing component in the belt drive is the belt itself, which is cheap and easy to replace [28]. For a beginner CNC hobbyist, this is preferable, since their overall monetary investment in the machine would not be significantly high.

5.1.3 - Enhancement of Kit-based

Instead of comparing the features of each design and entirely eliminating those that were less suitable, this list focuses on gathering all the best aspects we chose to use from each candidate design that when combined, would enhance the kit-based nature of our final design. The list below highlights the features we chose to focus on in our design.

- Symmetry of the machine
- Weight
- Accessibility of components
- Reduced number of components
- Screw type

5.2 - Final Design Description

In coming up with the final design for our milling machine, we went through a number of iterations in terms of the overall shape of our machine, its components, and the positions of some of the major mechanisms. The features described in Iteration 2 were those eventually implemented in our final machine design.

Key Features of Iteration 1:

- X-axis - Ball screw parallel to gantry, with one guide rail on gantry and one guide rail through the gantry side pieces
- Y-axis - Ball screw and 2 guide rails mounted onto each of the side pieces. Gantry side pieces attached to each ballscrew
- Z-axis - Timing belt drive
- Fourth Axis - Motor and tailstock mounted onto two opposite walls
- Table - Aluminium sheet
- Frame - 4 walls enclosing the table, 2 side pieces attached to two of the walls
- Base - 6 Sorbothane© feet

Key features of Iteration 2:

- X-axis - Ballscrew parallel to gantry, with one guide rail on gantry and one guide rail through the gantry side pieces
- Y-axis - Two ball screws each with 2 guide rails mounted onto the aluminium base.
- Z-axis - Timing Belt drive
- Fourth Axis - External motor and tailstock that can be attached onto the T-slot table
- Table - T-slot aluminium table
- Frame - Supporting walls mounted onto two sides of the table
- Base - Aluminium block connected to the supporting walls

5.2.1 - Ball-Screw Motion Conversion and Transmission on the X- and - axes

Both the X- and Y-axes use ball-screws to convert the input rotational motion into linear motion. The Y-axis mechanism consists of two NEMA 23 Step motor, two ball screws, and 4 round guide rails. This entire mechanism is attached to the base of the machine. The ball screws are connected to a NEMA 23 motor via a flexible coupler and there is also an anti-backlash nut incorporated into the ball screw to counter any backlash. There are round guide rails on either side of the ball screw that have have been mounted on to the base. Each guide rail has a slider bearing that acts as a slider. There is a plate connecting the two guide rails, through which the ball screw passes. As the ball screw rotates, this plate moves accordingly, causing the slider bearings to translate along their respective guide rails. The side pieces of the gantry are attached to the respective connecting plates on either ball screw and thus, the operation of the ball screws enables the translation of the gantry in the Y-axis direction. We decided to use two ball screw mechanisms, both mounted onto the base, as this ensured the gantry was always perpendicular to the Y-axes; the use of one ball screw could lead to some lag between the positions of the gantry side pieces.

The motion along the X-axis consists of a NEMA 17 motor, a flexible coupler, a ballscrew with an attached anti-backlash nut (to counter any backlash), and two round guide rails. One of the guide rails will be mounted on top of the gantry and the other will be positioned in between the side walls of the gantry. The ballscrew will be placed in between the two guide rails and will run through circular passage-ways through the side of the gantry. The ballscrew will be fixed via a nut bracket with a bearing installed to allow for a smooth linear motion. The fixed support will be attached via a flexible coupling connected to an externally mounted NEMA 17 motor. Each guide rail has two slider bearings that allow for a sliding motion along the rails. L-shaped plates will attach to the work table and the base of the machine, leaving a hollow space between the two. In this hollow cavity, the ball screws and round guide rails will be mounted so as to facilitate the X-axis motion in both the positive and negative directions.

Figure 5: Design of X-Axis

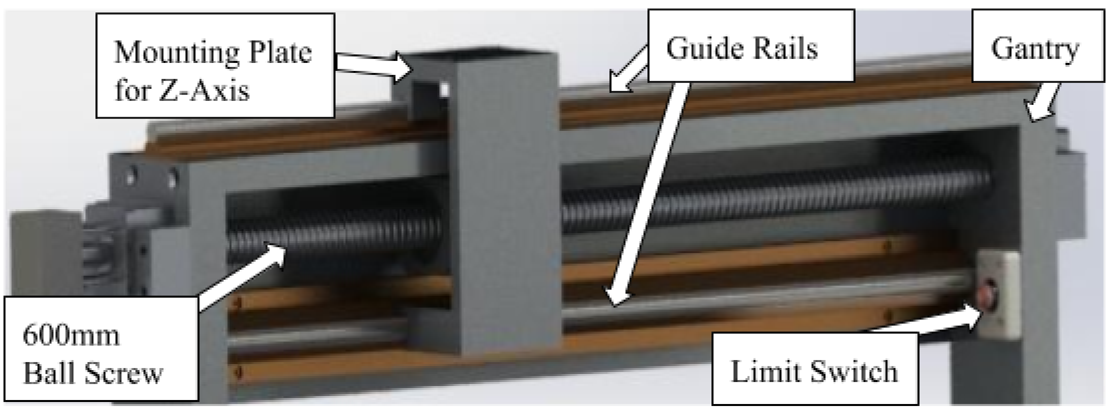
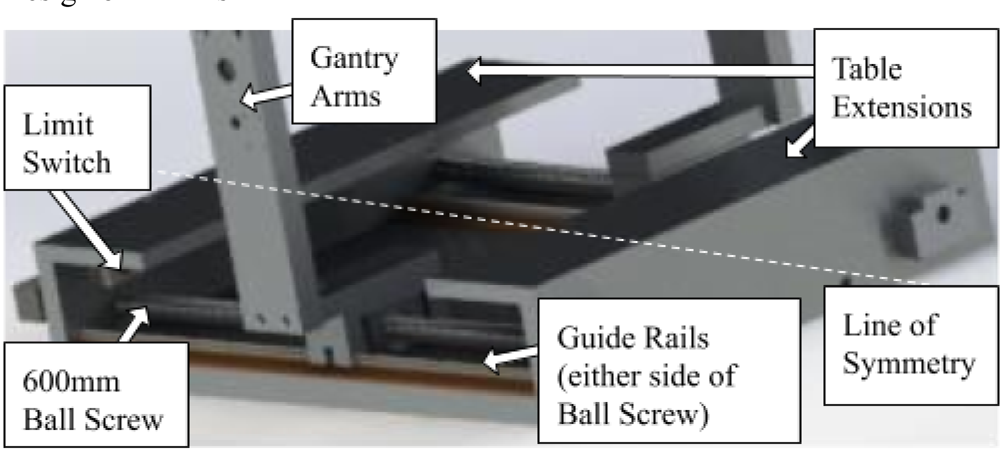


Figure 6: Design of Y-Axis



5.2.2 - Table

The first iteration for our final design used an aluminium sheet as our working table. For our final design, we changed this into an aluminium alloy (6061) sheet consisting of T-slots that were parallel to the Y-axis. We made this change to enable an external fourth axis mechanism to be easily mounted onto the table. Our first iteration had the table enclosed by four walls with the fourth axis mechanism mounted midway up these walls. The use of a T-slot table was one reason why we could eliminate the four walls, enabling for a greater efficiency in terms of the number of components in the design. Accordingly, it reduced the final cost of the machine, bettering the design in terms of the cost requirement. These T-slots also make it possible to utilize an external method of clamping the workpiece, to increase stability during operations. The applicability of an external fourth axis mechanism and clamping system due to the T-slots reduces the time required in the assembly process, further enhancing the kit-based requirement.

5.2.3 - Base

The initial design iteration comprised of a support mechanism that utilised 'Sorbothane©' supporting feet which were screwed into the base of the machine using 1/4-20 Hex Socket Head Cap Screws. Each stand would cost $20 USD and could only support 12.07 kg each [29]. This design was deemed unsuitable due to the weight restrictions placed on the machine as well as the cost of each stand.

This design was improved upon by substituting it with an L-shaped Aluminium 6061 block attached to either end of the work table, which in turn was connected to a rectangular base made of the same material. The L-shaped supports are 75 mm longer on each side of the work table to eliminate wastage of the workspace. For instance, when the gantry is positioned to the complete end of its axis, the Z-axis is 148 mm in front of this position. Thus, the user will still be able to utilize the entirety of the workspace. This L-shaped frame will connect to a supporting base at the bottom of the machine that will rest upon the work bench. Such a design is easy to assemble and reduces the cost of the machine itself.

The solid aluminium 6061 base is a suitable substitute as the contact area with the supporting workbench will be maximised. The large base evenly distributes the machine's load, as well as the forces generated during operation across the table. Accompanying this, the machine is less prone to vibrations during operation, thus improving the quality of machined parts.

The base is 25 mm thick to ensure that the material will not have non-uniform mechanical properties [30]. The thickness is also sufficient enough to reduce the stress range via the 'thickness effect' [31], since the thickness of the base is greater than 20mm.

5.2.4 - Frame

The external frame of the milling machine constitutes entirely of aluminium 6061 as this material resists the build-up of internal stresses, which reduces the chances of failure [32]. The initial design constituted of the work table being surrounded by four walls which had additional support sheets that housed the ball screws and the round guide rails. The walls also facilitated the attachment of the fourth axis and the supporting tailstock. This led to unnecessary cost incursions and a design that would have a longer assembly process.

This design was replaced with a simpler one in which the Y-axis motion components are housed between the work table and supporting base. The work table is connected to the supporting base via two L-shaped aluminium blocks which provides a stable method to hold the work table.The walls surrounding the work table and supporting sheets were eliminated due to the improved design. Moreover, the fourth axis is now directly mounted to the work table via double ended studs and clamps which can be attached and detached as necessary.

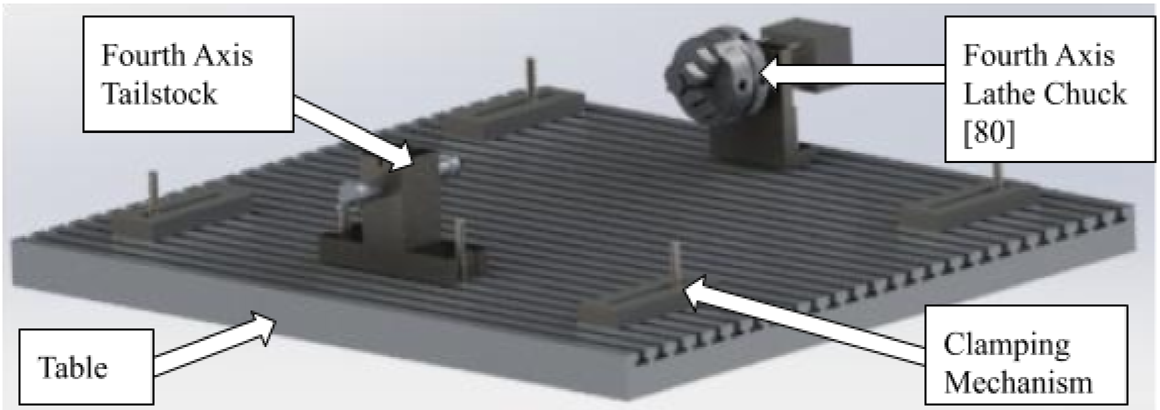
5.2.5 - External Fourth Axis

The fourth axis was initially attached onto the original walls of the table that were directly parallel to the head of the machine. However, this was changed and iterated on, since the fourth axis was found to be too heavy to be supported on the walls. Moreover, the motor and tailstock (support) of this mechanism were mounted onto walls across each other. The initial fourth axis also had to be assembled by the user, and consisted of multiple parts such as a lathe chuck, support pieces, and a motor.

To make the assembly of the machine easier for the user, we decided to purchase a premade fourth axis system that must be fixed onto the table when the user desires to use it. Due to the table now having “T-slots”, the fourth axis system that was chosen was one that could be screwed into the table both perpendicular and parallel to the head of the machine, giving the user more flexibility. Furthermore, the distance between the motor and tailstock is flexible and hence the fourth axis can be operated on workpieces of a greater range.

The actual system comprises of two main parts: the lathe chuck, and the tailstock. Both are fixed on elevated platforms so that the larger workpieces can be machined. The tailstock’s lathe centre can be extended to different lengths, meaning that the user can use workpieces of different diameters or widths. The head of the system has a lathe chuck that is used to fix the workpiece in the three main Cartesian axes whilst it is being spun.

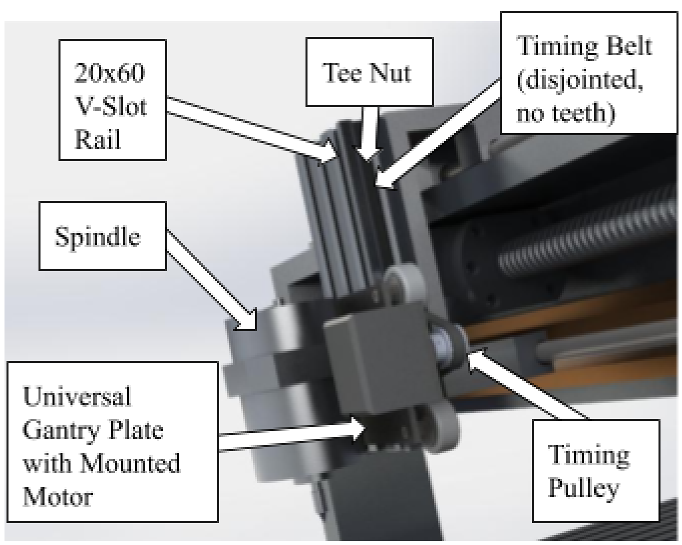
Figure 7: Fourth Axis Mechanism



5.2.6 - Z-axis Timing Belt Drive

Our final design incorporated a timing belt drive to control the vertical motion of the head of the machine. The Z-axis mechanism was mounted onto a metal sheet that forms part of the head of the machine. We attached a 20mm x 60mm v-slot rail to this metal sheet. A universal gantry plate that had 4 solid V wheel kits, attached into each corner, was placed onto the v-slot rails. A NEMA 17 motor was attached to the universal gantry plate, rotating a timing pulley which controlled the movement of a GT2 timing belt. This timing belt was placed on the v-slot rail and its movement caused the motion of the wheels. The translation of the wheels along the V-slot rail enables the vertical movement of the spindle.

Figure 8: Design of Z-Axis



5.2.7 - Spindle and Spindle Support mechanism

The spindle will be used to cut through and shape materials by producing relative motion between the workpiece and the cutting tool. The operating speed of the spindle can be set in a range from 3000-12000 RPM [33]. The spindle device consists of a 500W power supply [34] that will be used to turn a motor, which in turn spins the shaft connected to the bit (that is used to cut the material).

The spindle chosen comes with thirteen ER11 collets, which serve as sleeve bushings that offer varying degrees of support to the bit used for machining. A mounting bracket also comes with the spindle, and is used to fix and support the spindle onto the universal gantry plate on the Z-axis.

The spindle used was chosen as it was relatively cheap compared to other ones on the market, whilst coming with other useful components, such as the collets, which improve the usability of our overall design. The fact that the spindle is premade is also beneficial to our design, as it reduces the complexity of the assembly process, which for our target audience of beginner users, is important. Spindles need to be cooled in order to prevent them from overheating, which would be a safety risk. The spindle chosen is air-cooled, meaning that no external cooling system is needed, one again reducing the complexity of assembly of our overall design and reducing the incurred costs.

Feed Rate

The actual feed rate for our chosen spindle for the milling of aluminum was 33.75 inches per minute, whilst for the milling of softwood it was 120 inches per minute (see Appendix A). Although these values are lower than those calculated whilst we were completing our research, the overall impact on the design is not that large. This can be said as the time taken to cut straight through an average-sized workpiece does not differ significantly between the feed rate based on our research and the feed rate based on our actual design (see Appendix A).

Although the time taken for our machine is higher, it is a compromise we were willing to make. Since our spindle was significantly cheaper than those with higher RPM ranges, the costs incurred were lower. This was important to us, since it meant that our machine could garner greater attention from our target audience of beginner hobbyists, who we assumed would not be comfortable spending large amounts of money on a hobby they had just taken up.

5.2.8 - Additional features

As this machine is suited for a house or garage environment, we designed it in a manner such that it is as compact as possible. From our first iteration, we had support pieces mounted onto two of the walls of the frame of the machine. These support pieces had widths of 125mm, used to hold the Y-axis mechanism, which would cause the final footprint to be significantly large. However, in our second and final iteration, we changed the entire frame of the machine which enabled the Y-axis mechanism to fit in the space between the work table and the base. Therefore, the side pieces became redundant and were taken out of the final design, enabling a smaller footprint. Having a more compact design allows the targeted user more freedom in the location of this machine. Moreover, this change reduced the number of parts required for the user to assemble, aiding the kit-based requirement.

The design also incorporates limit switches [35]. These switches are placed at either end of the ball screws used in the x and y axes, and they prevent axial motion past the switch. They do this by communicating the physical limits of the axes to the software being used to control the machine. When the object being moved by the ball screw comes into contact with the switch, an electrical signal is sent to the computer signalling for it to stop the motor, stopping the axial motion. By adding these, we are increasing the time taken for the ball screws to wear as there is a reduction in the cyclic stresses that are imposed on to the components of the axes. The switches also reduce abrasive wear of the supports of the axes by preventing the components being moved on the ball screw from colliding with the supports.

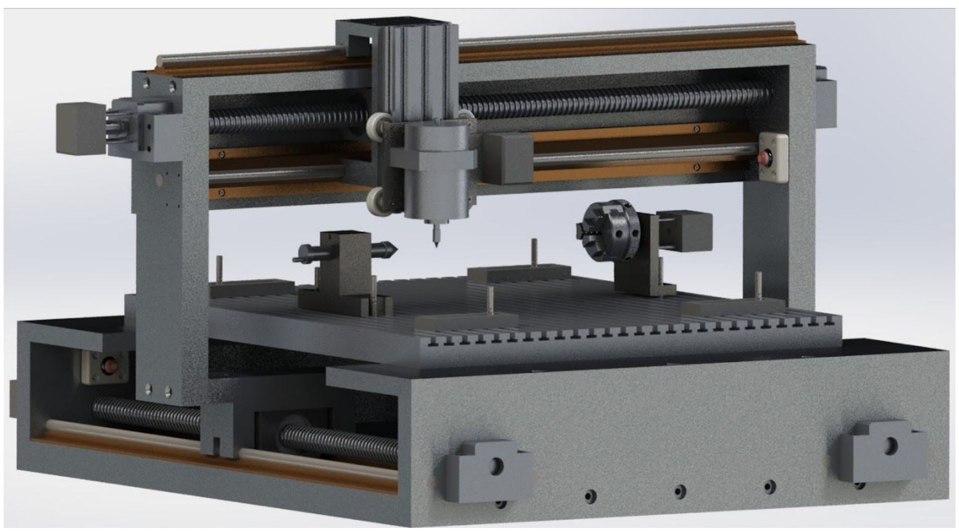
For additional support, we implemented sealed straight roller bearings into the walls of the frame through which each ball screw passed. These helped support the radial forces exerted on the individual ballscrews due to the weight of the frame of the machine. These straight roller bearings are easily assembled into the frame using a press-fit method.

5.3 - Final Machine Specifications

Feature	**Specification**
Machine Size	710mm x 720mm x 380mm
Table size	450mm x 400mm
Working area	450mm x 400mm
Weight	31.69kg
Travel	X- axis - 600mm Y-axis - 600 Z-axis - 150mm

Spindle Speed	3000-1200 RPM
Spindle Power	500W
Feed Rate	33.75 inches/min
Additional Features	• Air-Cooled Spindle • Kit Based • Anti-Backlash Nut Installed into Ball Screws • External 4th Axis included

Figure 9: Final Render of Design



6 Design of Kit-Based Nature

6.1 Breakdown of Machine into Separate Components that Form the Kit.

Adhering to the kit based requirement stated in the problem statement, most of the components would be provided to the user unassembled. However, there are some exceptions as some components purchased from online markets are pre-assembled. The following list shows the components that the user would receive pre-assembled:

- Delrin V wheels
- 4th Axis Tailstock

- Slider Bearings mounted onto their respective guide rails
- Ball screw nuts and their respective housing pre-mounted onto the individual ball screws.

Taking these into account and disregarding screws, the total number of parts which required assembling was 99 parts, which was below the constraint of 100 parts set earlier. This ensured that our design would be easy to assemble for our target audience of beginner hobbyists.

6.2 Features that enhance the kit-based nature of the machine

The CNC machine was designed to be kit based. This required the user to assemble the separate components into the complete machine. With our target market consisting of hobbyists and entry level CNC machinists, it was assumed that their experience in building and maintaining such machines was low. Hence, to reduce the complexities of this process, we included features in our design that targeted the ease of assembly and maintenance. These features are explained in the table below.

Feature	Justification
Light components	• The machine had a weight of 31.69kg. Therefore, no component itself had a weight of 31kg which is the maximum weight limit one person should carry [36]. This ensured the safety of the user during the assembly process whilst reducing the time required to handle and position each component.
No small components	• This design ensured that there were no significantly small parts. This allowed for easy handling of the components during assembly and/or disassembly, increasing the rate of assembly and/or disassembly.
Accessibility to all parts of the machine	• The design ensured all components could be accessed without having to change the orientation of the machine. This features reduces any time wasted on re-orientating the machine in order to access certain parts. Thus,

	assembling or disassembling is a quicker and more convenient process.
Externally mounted components	● Externally mounted components are easily accessible and can thus be assembled or disassembled faster. This allows for easy maintenance in the case where components need replacement.
Externally attached components	● Components such as the 4th axis and the workpiece clamps could be externally attached onto the table whenever required. Thus they did not need to be permanently mounted into the frame of the machine. This allows the design to minimize the number of features that require permanent assembly, reducing the time and complexity of this process.
Symmetry in machine	● Symmetry increases the amount of 'mistake-proofing' [82], ensuring the orientation of the individual parts in the assembly process is easy to recognize. This reduces the complexity and time taken for assembly. ● Symmetry also results in faster positioning of components and thus, reduced assembly time.
Screws	● Flat head hex screws were chosen for this design. These screws have their heads above the surface of the components making it easier for the user to fasten any two components together[37] ● This design incorporated three different sizes of flat head screws. With minimal variations in screw types and sizes, the user required a minimal amount of screw heads to

	assemble the machine. ● All screws of a certain size were designed to be the same length to enable easier identification by the user during the assembly process.
Standardization of Dynamic Parts	● The design incorporated both custom and standardized parts. However, the standardized parts are the dynamic components in this design. These parts will experience wear at a higher rate and will require higher levels of maintenance or more frequent replacement. Therefore, having these parts standardized ensures they are readily available on the market and can easily be replaced by the user.
Additional features	● Flexible couplers allow for some tolerance in the positioning between the ball screw and the motor shaft [38]. This further increased the 'mistake-proofing' of the design, making it easier for the user (a beginner) to assemble the machine. ● The straight roller bearings implemented were sealed. This meant that debris from any milling process was unable to enter the bearing and propagate any wear. This increases the longevity of the bearing and reduces the number of replacements required.

7.0 Justification of Final Design Components

7.1 - For movement in X and Y axes

a. Ball Screws:

Ball screws are well suited for the linear actuation applications of our CNC milling machine. That is, ball screws allow for highly efficient conversion of rotational motion to linear motion as they operate at efficiencies of 90% on average. The use of ball bearings alongside nuts reduce friction and provide a smooth surface for the screw to translate on. The ball screw selected for use in our final machine design is fitted with an anti-backlash nut. Additionally, ball screws are useful for the precision they offer with the positional resolution of the chosen ball screw being 0.0254 mm. This resolution allows for intricate details to be machined. Furthermore, ball screws are able to carry large loads while performing at high speeds, safeguarding the effective functionality of our proposed milling machine.

b. Specialized anti-backlash nut including holes for guide rails

These anti-backlash nuts connect the guide rails to the ball screws serving as a guide support for the motion of the ball screw. The specialized nuts are moulded to have threads which compliment those on the ball screws. Considerations were made in selecting a nut design which would minimize backlash, such that delays in motion transmission are limited and frictional forces are regulated. In this case, our anti-backlash system involved pre-loading using nut and spring system.

c. Round Guide Rails

These round guide rails are linear and permit the transmission of motion in the X and Y directions. They are located parallel to the X- and Y-axes in the housing assemblies. We chose to use round guide rails because they allow for slight misalignment in the assembly of the entire mechanism. Moreover, they incur a 0.254 mm deviation in the straightness of travel for every 305 mm [39] and thus, provide excellent parallel motion [40]. The guide rails further act as supports for loading generated in the radial directions as the ball screws rotate.

d. Slide Bearings for Guide Rails

These act as a contact point for the guide rail and the component being translated. Such bearing types are suitable because they are simple, reduce the amount of friction generated in the process and can support the speeds and precision requirements expected with our kit-based milling machine design. These components, together with the guide rails, adequately complete the ‘sliding contact linear motion bearing’ guide setup implemented in the machine design.

e. Flexible Coupling

Coupling components are used in the design to connect the X-axis and Y-axis motor shafts to the ball screws, such that torque can be transmitted. Specifically, flexible couplers have been implemented as they correct parallel, axial and angular misalignment[41] which is likely to occur due to the fact that the machine is kit-based and is user assembled. As such, couplings can absorb vibrations, withstand impacts, prevent wear, and improve overall performance of the machine with respect to motion transmission [42], thus deeming it a suitable choice as a coupling mechanism.

f. <u>Ball Bearing</u>

A ball bearing support will be mounted onto each ballscrew to act as an interface with the nut. The ball bearings operate through rolling ball forms, with each ball serving to absorb a load. The support offered by ball bearings reduces rotational friction and tolerates both radial and axial loads. Ball bearings also offer allowances for misalignment in the assembly process [43], which is likely to occur as the machine will be assembled by the users. Linear ball bearings were selected because they increase the level of precision which can be achieved [44], are widely available, and are relatively cheap compared to other support counterparts.

g. <u>Straight Roller Bearing</u>

The ball screws are subjected to high radial loads due to the weight of the gantry (for the Y-axis ball screws) and the weight of the Z-axis (for the X-axis ball screw) being imposed onto them. In comparison to radial loads, we expect that the ball screws will not be exposed to significant axial loads, and hence, we will focus on trying to reduce the radial loads only. Straight roller bearings provide excellent support for radial loads [45], and hence they are necessary for our ball screws.

Rolling-element bearings give warnings such a noise [46] when they are coming to the end of their life. This is beneficial for our design since it means that the user will know when they have to replace the bearings, making maintenance of the machine easier. Straight roller bearings are also easily positioned, and use a press fit method to be positioned into the frame of the machine. This makes it easier for the user to assemble, since no further tools are required for assembly. Straight roller bearings are also relatively cheaper [47] than other types of bearings in small quantities. Since our design only requires six bearings, this is an advantage.

7.2 - For movement in the Z axis

a. Timing Belt (for motion in the Z direction)

In aiming to reduce the slip that occurred in the Z-axis belt drive mechanism, we opted to use a timing belt. With a timing pulley, high positive engagement is created which enables accurately timed motion [48]. The timing belt performs well under the kit base goal as there is minimal wear that occurs in a timing belt relative to other belt types and parts are easily replaced. Moreover, a timing belt has a high mechanical efficiency between 91-98% [49] and is relatively cheap compared to other motion transmission/conversion mechanisms.

b. V-slot rail

The V-slot rail to be used in our design is manufactured to have bevelled edges [50], such that the timing belt for movement along the Z-axis will fit inside its profile. Moreover, the cross-sectional area of the V-slot enables the wheels to fit into its profile and helps reduce the number of extra components required for motion support.

c. V-slot wheels

Four of these are attached to both the gantry plate and the V-slot rail, allowing for the gantry plate to move without slip. The 'V' shape of the wheels allows them to fit into the profile of the slots and translate smoothly along the rail, enabling precise movement of the universal gantry plate in the Z direction.

d. Ball bearing

These offer support for the rotational movement of the wheels rolling along the V-slot rails. Similar to their uses for motion in the X and Y directions, the ball bearings reduce rotational friction as the wheels move whilst absorbing loads produced as a result of misalignments [51] .

7.3 - Input Motion

a. NEMA Stepper Motors (for motion in the X and Y directions and Fourth Axis)

The NEMA Stepper motor was selected due to the open loop feature which eliminates the complexity of an encoder and resolver, meaning only basic knowledge is required for maintenance. Furthermore, the majority of the moving parts in a stepper motor are frictionless, undergoing minimal wear [52] and thus reducing the maintenance they require. The quality of the finished product is maintained at a high standard as these motors provide precise positioning and repeatability of movement with an accuracy of 3-5 percent [53].

- For the X-axis we used a NEMA 17 Stepper Motor. The ball screw on the X-axis held the weight of the Z-axis which was approximately 1.6kg. With an assumed coefficient of friction and efficiency of 0.2 and 0.9 respectively, this ball screw of length 600mm would require a driving torque of 0.33 N.m. A NEMA 17 motor provides a driving torque of 0.54 N.m which is sufficient for this axis [62].

- For the Y - axis we used NEMA 23 Stepper Motors. As we had two ball screws for this axis, the load of the gantry and Z-axis was assumed to be carried evenly by both these ball screws. The mass carried by each ball screw was then calculated and found to be approximately 3.5kg. With an assumed coefficient of friction and efficiency of 0.2 and 0.9 respectively, these ball screws of length 600mm would require a driving torque of 0.729 N.m. A NEMA 23 Stepper Motor provides a driving torque of 1.24 N.m which is sufficient for this axis [81].

7.4 - Structural Support

a. <u>Gantry Plates</u>

A gantry plate is one of the most important features in our design as it facilitated the operation of the X and Z axes. The gantry plate has the components of the X and Z motion mechanisms mounted onto it. The use of the gantry ensured that both the X and Z axis mechanisms and their relative motions were thoroughly supported.

The gantry is mounted onto the Y-axis ball screws on either side of the table via extending arms. This allows for the movement of the gantry along the Y-axis, thus removing the need for any table movement. By doing this, the space required for our machine decreased. As our target audience is beginner hobbyists, who are most likely using the machine at home or in a small garage, this was important as it means our machine will not impose itself in their environment.

b. <u>Eccentric Spacers for V-Wheels and V-Rail</u>

These components are used to adjust the spacing between the v-wheels and the v-rails. They are a necessary component because if the wheels are too close to the rails, they will not be able to turn properly, impeding movement. If the wheels are too far from the rails, they will be unable to properly translate motion. Therefore, there are two eccentric spacers needed for the v-rail.

c. <u>Universal Gantry Plate for V-Rail</u>

This plate is what the v-wheels are mounted on to, and what moves up and down the v-rail. Hence, when the wheels move along the belt, the plate also moves. The wheels are attached onto the four corners of the plate. Two of the top wheels near the motor mounting plate are attached using the eccentric spacers described above. The other two wheels are connected using regular hex bolts and nuts. It is on this plate that the head of the machine is attached, allowing it to move up and down in the Z-axis.

d. <u>Motor Mounting Plate</u>

The motor mounting plate is a simple plate that is rectangular in shape. It has a circular cutout for the motor to be inserted into, along with screw holes at each corner, enabling the motor to be screwed into place onto the plate. The plate also has another hole that needs to be aligned with the universal gantry plate. This allows the motor mounting plate to be screwed into a fixed position on the universal gantry plate, and allows for the continuous motion of the wheels along the belt.

e. <u>Screws</u>

Screws are found in multiple locations throughout the design. They are used to secure components into place and prevent any type of unwanted motion in the system. The screws are also used to join two components together. For example, screws are used to join the table to the walls. The size of the screws varies depending on where they are placed; the screws used on the slide bearings are of a smaller size than those used to fix the walls to the table. Where possible, the same standard screw type has been used, in order to make the assembly process easier for the user.

It was decided that flat socket screws would be utilised instead of sharp screws. This eliminates the physical hazard posed during the maintenance process. They provide an adequate contact surface between the hex key and the screw [54], which makes it easier to use. The main reason this screw type has been chosen is they extend above the surface, and as such the user can easily access the screws. Finally, hex screws use hex keys or hex screw attachments to screw them in. These are widely available and long lasting.

f. Workpiece Support Mechanism:

The function of this support is to hold the workpiece in place so that it does not shift while being cut. These supports consist of metal plates with engraved slots, M5 screws, nuts, and washers. The head of the screw is positioned inside a T-slot along the machine's table and the screw's position is locked through the use of a nut and washer. Depending on the thickness of the material to be cut, the screw can be positioned at any point along the slot to adequately provide support and prevent movement. This is done by aligning the shafts around the workpiece and securing them in place with the M5 screws, nuts, and washers.

This method of supporting the workpiece was the simplest to implement and required the least materials reducing the incurred costs. Furthermore, it involves a minimum number of custom parts, since M5 screws and washers are readily available.

8. Justification of Material Components

This section highlights the justification for the materials chosen in the CNC milling machine for its various applications. These components have been tailored with reference to material composition in order to legitimize the design goals and requirements.

A. Base, Frame and Table:

These sections are made from aluminium 6061 alloy. This specific alloy has magnesium and silicon as its major alloying elements. As a result, this alloy has a high corrosion resistance [55], making it long lasting and durable. Most importantly, the density of the material is 2.70 g/cm^3 which allows for the components to be lighter and thus more portable.

When considering the material to be implemented , an important factor to consider is the machinability of a sample. aluminium has a machinability rating (MR) of 0.6 [83] which was established using the Brinell Hardness Number (BHN). [83] This highlights that the components required for the milling machine can be easily manufactured which will reduce the costs of production.

Lastly, aluminium has a commendable damping coefficient of 0.007-0.01 η which allows for the efficient conversion of vibrations to internal heat.

B. Wheels along the V rail:

The wheels are primarily made of Acetal-Delrin®. This plastic offers good wear and abrasion properties [56] which ensures a long machining life for the user. The plastic is naturally lubricated, which enables for smooth motion along the V-rail during motion transmission of the Z-axis.

C. Timing Belt:

The timing belt facilitates the Z-axis motion and is composed of fiberglass. Fiberglass has a low elongation under an applied load, specifically less than 3% [57]. This helps maintain the belt in a state of constant tension without any slack. This is vital as it prevents the loss of motion during the machining process, leading to a higher quality finish. The belt is inert; it is unaffected by sunlight or bacteria. Due to its low cost, it facilitates an economical method of providing motion along the Z-axis.

9. Final Parts List and Bill of Materials

Part	Supplier	Unit Price (USD)	Quantity	Total Price (USD)
Machine Frame				
Aluminium 6061 Alloy T-Slot Table	Custom-Made	149.41	1	149.41
Aluminium 6061 Base	Custom-Made	210.93	1	210.93
Aluminium 6061 Frame Sheets	Custom-Made	43.29	2	86.58
Extensions of T-slot Table (Aluminium 6061)	Custom-Made	33.50	2	67.00

Workpiece Clamp (Plastic)	Custom-Made	3.64	4	14.56
Aluminium 6061 Gantry Plate	Custom-Made	30.09	1	30.09
Aluminium 6061 Gantry Walls	Custom-Made	9.09	2	18.18
Motors				
NEMA 17 Stepper Motor [62]	OpenBuilds Part Store	17.99	2	35.98
NEMA 23 Stepper Motor [81]	OpenBuilds Part Store	27.99	2	55.98
X-Axis Motion				
Anti backlash ball screw 2005 350mm+ end support BK15BF15 + ballscrew nut housing + coupling [63]	AliExpress	67.78	1	67.78
SBR16 width 16mm linear rail any length support round guide rail - 350mm (2pcs)[64]	AliExpress	42.92	1	34.92
Mounting Plate	Custom-Made	35.10	1	35.10
Y- Axis Motion				
Anti backlash ball screw 2005 600mm + end support BK15BF15 + ballscrew nut housing + coupling[65]	AliExpress	78.99	2	157.98
SBR20-600mm 20mm Fully	Bearings Canada	27.36	2	54.72

Supported Linear Rail Shaft[66]				
20mm Aluminium Linear Slide Bearing (4 Pack)[67]	Wal front	24.32	1	24.32
Z-Axis Motion				
GT2-2M Timing Belt (By the Foot)[68]	OpenBuilds Part Store	2.49	1	2.49
GT2-2M Timing Pulley - 20 Tooth[69]	OpenBuilds Part Store	5.99	1	5.99
V-Slot 20mm x 60mm Linear Rail (100mm Length)[70]	AliExpress	5.20*	1	5.20
V-Slot Gantry Kit - Universal (Includes 127mm x 88mm Plate with Pre-Drilled Holes, Eccentric Spacers, 4 Solid V-Wheels, Low Profile Screws, Aluminum Spacers)[71]	OpenBuilds Part Store	37.99	1	37.99
Motor Mount Plate - NEMA 17 Stepper Motor[72]	OpenBuilds Part Store	6.99	1	6.99
4th Axis Motion				
Fourth Axis with Tailstock and 3 Jaw 50mm Chuck.[73]	AliExpress	55.97	1	55.97
Spindle				

Spindle with Power Supply, 13 Collets, Mounting Bracket [74]	AliExpress	80.88	1	80.88
Mounting Plate	Custom-made 75x65x20 (mm)	2.66	1	2.66
Screws and Bearings**				
M2 x 0.5 x 3 (50 pack)	AliExpress[75]	0.52	1	0.52
M2 x 0.4 x 16 (50 pack)	AliExpress	1.43	1	1.43
M3 x 0.5 x 20 (50 pack)	AliExpress	2.55	1	2.55
M5 x 0.8 x 30 (10 pack) 71	AliExpress	2.15	8	17.20
40mm M5 Double End Stud (10 pack)	AliExpress[76]	2.21	1	2.21
Straight Roller Bearing	AliBaba[77]	0.75***	6	4.50
Emergency Stop System				
Emergency Push Button Switch[78]	AliExpress	1.44	1	1.44
Limit Switches				
Limit Switch (5 Pack) [79]	AliExpress	0.96	1	0.96

The price of Custom-Made parts was found using the “Costing” feature in SolidWorks

*Estimate based on AliExpress manufacturer that can make pieces of the required dimensions (average of minimum price of $2.20 and maximum price of $8.20)

**All screws used were flat head hex screws. Although the suppliers used for the costing of the screws provide more screws than necessary, when making the kit, we will only put the required amount of each screw.

***Estimate based on AliExpress manufacturer that can make pieces of the required dimensions (average of minimum price of $0.50 and maximum price of $1.00)

10. Conclusion

This project was aimed at designing an entry-level, kit-type CNC milling machine. It was mandated that the design be suited for home-usage, with beginners and hobbyists as the target audience. Supplementary research was conducted into existing state-of-the-art machines prior to the design team developing an engineering specification and defining our functional and design requirements. The team then proceeded to brainstorm three candidate designs, each of which was centered around unique design goals. The final design for our CNC milling machine was conceptualized through iterations of combining desirable characteristics from each candidate design, while ensuring that the functional and design requirements previously outlined were met. Through the engineering process, a machine design which is expected to be reliable in producing consistent results, sufficiently accurate and precise, simple to assemble and cost-effective was developed. To further cater to the anticipated needs of the target audience, considerations were made regarding the workspace area and weight of the machine, such that it would be optimum for use at home or in small offices/garages. As our targeted users are not professionals in the operation of CNC machines, we tailored a limit switch mechanism to avoid collisions of the dynamic parts within the machine. In addition to the three standard Cartesian axes, we added a fourth axis as to diversify the operations which the machine could perform. Materials and components were chosen to create a precise machine with increased stability and in turn, producing a high quality product. The overall design included features that enhanced the kit-type requirement of this machine, with the use of standardized parts where necessary to allow for easy replacement of the components.

11. Appendix A

Feed Rate Calculations:

To calculate the feed rate, an online calculator [58] was used. It required three values in order to compute the feed rate: speed (of the spindle) in RPM, number of flutes on the cutting bit being used to mill the workpiece, and the chip load per tooth. The website of the calculator used provided a table for the chip loads for different materials and different cutting diameters.

Feed Rate Calculations for Research:

The most common spindle speed range for CNC machines is 7000-18000 RPM. This yielded an average spindle speed of 12500 RPM. To find the number of flutes on the cutting bit, flutes were chosen from McMaster-Carr [59] for both soft wood and aluminum. The bit chosen for soft wood had a cutting diameter of 3/16" and two flutes. The bit chosen for aluminum had a cutting diameter of ⅛" and one flute. Using the table provided on the online calculator, ranges for the chip loads for both materials were acquired. The chip load per tooth had a range of 0.001" to 0.015" per tooth for wood, giving an average chip load per tooth of 0.008". For aluminum, the range was 0.001" to 0.008" per tooth, giving and average chip load per tooth of 0.0045".

Using the online calculator, these values for spindle speed, number of flutes, and chip load per tooth were substituted in. This gave the feed rate for soft wood as 200 inches per minute, and the feed rate for aluminum 56.25 inches per minute.

Feed Rate Calculations for Final Design:

The calculations for the approximate feed rate of the machine were based on milling of soft wood and aluminium workpieces, which covered a spectrum of materials that we wanted our machine to mill, from soft wood being the softest, to aluminum being the hardest. An average value of the speed of our chosen spindle was calculated and used; the maximum speed of the spindle is 12000 RPM, whilst the minimum is 3000 RPM. Hence, the average spindle speed was 7500 RPM.

The bit used and the chip load per tooth stayed the same as those used for the calculations for the research. Hence, only the spindle speed value needed to be updated in the calculator. After changing this value, the feed rate for soft wood for our machine was found to be 120 inches per minute, whilst the feed rate for aluminum was 33.75 inches per minute. It is important to reiterate that this value is an approximation, since every value that was inputted into the calculator was an estimate that based on several factors.

Time Taken to Mill straight through Workpiece:

For our final design, our working area meant that we assumed the largest size of a workpiece that a user would want to mill to be 300mm x 300mm, with a thickness of 30mm. The thickness of 30mm is equivalent to a thickness of 1.18".

Using this thickness and the feed rate, the time taken for the machine to mill straight through the workpiece can be found using the formula:

$Time\ [seconds] = \frac{Distance}{Speed} \times 60$, where distance is the thickness, and speed is the feed rate.

	Time using Research Feed Rate [seconds]	Time using Actual Design Feed Rate [seconds]
Soft Wood	0.354	0.588
Aluminum	1.26	1.8

Hence, the differences in the time taken to mill through wood soft wood and aluminum between the research feed rate and the actual design feed rate are both less than one second (0.234 seconds and 0.54 seconds, respectively). In practical terms, this difference is negligible.

<u>Ball Screw Driving Torque Calculations:</u>

In order to calculate the driving torque required, the following formula was used:

$Torque = \frac{Frictional\ Resistance\ from\ Guide\ Rails\ (N)\ x\ Length\ of\ Ball\ Screw\ (m)}{2\ x\ \pi\ x\ Ball\ Screw\ Efficiency}$ [60] where,

$Frictional\ Resistance\ (N) = Mass\ Carried\ by\ Ball\ Screw(kg)\ x\ Coefficient\ of\ Friction(\mu)\ x\ 9.81(g)$ [61]

The following is an example of a sample calculation.
Assumptions:

- $\mu = 0.2$
- M = 5kg
- Length of Ball screw = 0.5m
- Ball Screw Efficiency = 0.9

The Driving torque required for this ball screw would be 0.867N.m.

Positional Resolution Calculations:

The calculation for the positional resolution of our motion transmission mechanisms was dependant on the component itself as well as the motor used to control it. The following is a sample calculation for the positional resolution achieved in candidate design 3.
This design used a NEMA 17 step motor that had a step angle of 1.8 degrees. This meant that there were a total of 200 (360/1.8)steps per revolution. According to the ball screw used, one rotation of the screw translated the screw linearly by 5.08mm. Therefore the positional resolution or distance travelled per step was found by calculating 5.08/200 giving us a value of 0.0254 mm per revolution of the motor.

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