Creating a CNC Machine from a Manual Drill Press

A Technical Report submitted to the Department of Engineering

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In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Completed Work:

This project was to consist of converting a manual Precision Matthews 727V milling machine to computer numeric control, or CNC. Our professor, Dr. Gavin Garner, had two identical PM-727V Milling Machines in the Mill, the room in which most of the machinery used on this project lived. Dr. Garner tasked us with converting one PM-727V to CNC and leaving the other as manual. This was for a number of reasons, the first being that a CNC machine can make certain cuts that are impossible using a manual machine. Secondly, the CNC machine takes the manual mill from its 0.001" table graduation accuracy using lead screws, to the ball screw and Servomotors' 0.00025" precision. Thirdly, the CNC PM-727V will be used to teach CNC machining to future UVA Engineering students. CNC will be taught alongside manual machining on the manual PM-727V mill. Being taught CNC and manual milling simultaneously would not only show students the basics and fundamentals of milling, but it would also give them appreciation for the comparative ease of CNC milling. While our project revolved around breaking one machine down and building it back up as a CNC machine, the team did rely heavily on the manual PM-727V to mill out various parts for our project.

To complete this project, many smaller goals had to be met along the way. These goals began with a near complete disassembly of one of the PM-727V machines. This was done in order to replace the already existing lead screws, screws used to translate rotational motion into the linear movements of the machine, with ball screws for better accuracy. Another goal was to attach motors to the X, Y, and Z axes which would drive the installed ball screws, moving the machine's base and spindle. Since the motors needed some sort of way to attach to the tables, motor mounts needed to be designed and milled out for each motor. Limit switches were to be added, so the machine would know its physical limits on each axis. Next, the motors would need to be attached to an ethernet-smoothstepper. The smoothstepper reads input code, converting it to step and direction signals, moving the motors. Finally, a touchscreen monitor was to be attached to the machine, running Mach 4, the software used to process inputs. All ordered parts, such as the previously mentioned ball screws and motors, were researched thoroughly to find the properly sized and best performing parts within reason. Other ordered parts were couplers, the aluminum blocks for mounts, and the limit switches.

In figure 1, the original Precision Matthews mill can be seen. In this state, there are knobs attached to each lead screw which can be manually rotated to move the platform in the X and Y directions. The Z axis has a handle on the back left side of the central tower that holds the spindle, that is rotated by hand to raise and lower the Z axis. A monitor can be seen resting on the milling platform in a grey plastic covering which displays the position coordinates of the platform in the X and Y directions and the tip of the drill bit in all the Z direction. Additionally, there is yellow grease covering the platform that was used to preserve and protect the material during transportation.

Figure 1. Initial PM-727V Prior to Any Work Done.

The first major task for our team to complete was to lead screw replacement. The original PM-727V was equipped with lead screws, which have a tendency to cause backlash within the system. In the case of the mill's lead screws, backlash would occur when the table does not react to the lead screw beginning to move due to a space between the threads of the screw and the corresponding nut. Having the error that backlash creates would decrease the accuracy of the machine's cuts, as the positioning of the X, Y and Z axes would be less accurate. The motion control device will not be able to detect this oversight, and thus all future movements will be affected. However, ball screws nearly eliminate backlash, as they use ball bearings in hemispherical threads, rather than a lead screw's threading system. Ball screws also provide a mechanical advantage over lead screws as they can transmit and deliver a significant amount of power while requiring much less torque input than traditional lead screws. Because ball screws have grooves similar to a bearing running through a helical semi-circle groove down the shaft, they have much lower friction and can run at cooler temperatures.

Before our team could begin disassembly work, the yellow protective grease needed to be removed from the platform. Various chemicals were used to remove this grease without causing harm to the mill's platform. Next, the team got to work on disassembling the mill. Initially the team worked to remove the metal housing surrounding the Z axis so that the Z lead screw could be removed. Next, the hardware and metal parts containing the X and Y lead screws were removed, as well as anything connecting them to the platform. This proved to be a very time consuming process, but ultimately the team was able to safely remove the lead screws without any other setbacks. Figure 2 is a representation of what the PM-727V looked like after removal of the yellow grease, the Z axis covering, and the X and Y lead screws.

Figure 2. PM-727V after partial disassembly.

Next, the Z lead screw was removed. There were a lot of parts both attached and blocking the Z lead screw which were all removed in order for the new ball screw to be installed. This required virtually the entire machine to be disassembled in order to remove all three of the lead screws. Figure 3 shows the mill after removal of the Z lead screw and all of the hardware in the machine except for the bolts that hold in the base plate.

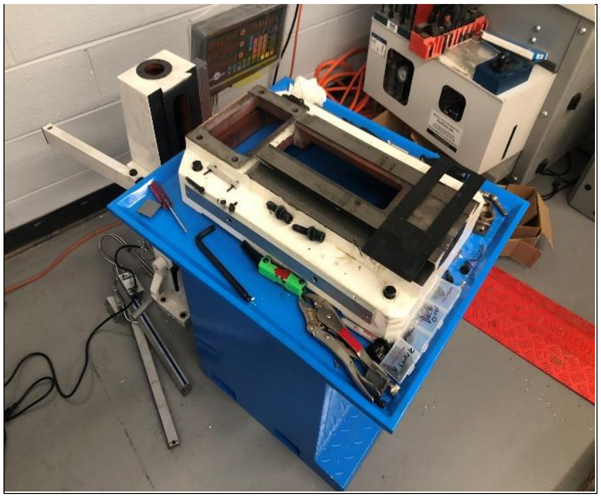

Figure 3. Completely Disassembled PM-727V.

Because the disassembly took so long, and due to a lack of foresight in sourcing and ordering parts, the team realized there would only be time to perfect a single axis, the PM-727V. After disassembly was completed, we attempted to place the Y axis ball screw inside the base, but it was discovered there was not enough room for it. The team considered two options in order to make more room for the ball screw: cut the end of the ball screw (which was deemed to be unnecessarily risky and difficult), or file down the base to create additional space for the Y ball screw to fit. Roughly ⅛ - ¼ of an inch was taken off of the base from filing before the ball screw started to fit. The team then installed the ball screw into the PM-727V, securing it with the front plate and the ball nut housing.

After this was completed, it was time for motor installation. Our team decided to go with the ClearPath-SDSK motors for four main reasons: the first being that this model allows the user to precisely servo-control position using "step & direction" command signals which can be easily manipulated using Mach 3 software and that can be sent in both the clockwise and counterclockwise directions, allowing the platform to move back and forth. The second benefit is that these motors supply sufficient torque to the ball screws, proving themselves powerful enough to move the mill's platform. The third benefit is that these ClearPath motors are relatively cheap compared to other similar motors that give out more torque that would be unnecessary for the team's purposes. The fourth reason is that ClearPath motors remember their position which gives them a smaller chance of triggering the limit switches, serving as a secondary safety precaution. The motors also have enhanced resolution and constant torque output which aids the team in their chase to gain additional microns of accuracy, which ultimately allow the mill to create better products.

After the motor was picked, a mount was required. Using SolidWorks, a computer aided design program, the team composed a 3D model to be milled out of a single aluminum block. Even though the team was only going to finish the PM-727V, the parts required for the rest of the axes were all acquired, including aluminum blocks of appropriate sizes for the X and Y axes. The Z axis would not need a mount as it could directly attach to the top of the frame.

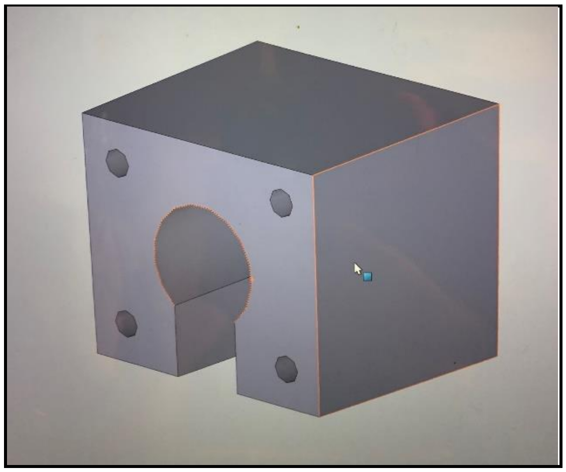

Figure 4. 3D Model of the Motor Mount for the PM-727V.

It was determined that in order to complete the manual mill's transformation, multiple parts would need to be manually milled with the replica PM-727V in the MILL. In order to expedite this process, a power feed motor was installed onto the X axis of the second mill so that there was no need to slowly rotate the attached knob by hand. This proved to speed up the milling speed significantly, but the Y and Z axes were both required to be manually manipulated which proved to be a bottleneck to this overall process. However, with multiple iterations due to inaccuracies caused by the human aspect in manual milling, the team was able to create the necessary aluminum parts, namely the spacer blocks and modifications to the motor mounts so that they could be utilized within the team's design.

Further emphasizing the importance of our project, we were unable to mill out the round edges of the aluminum mounts using the manual PM-727V located in the mill due to the difficulty in moving both the X and Y axes synchronously, so the team decided to go to Lacy Hall where a waterjet cutter could be used to manufacture the mounts. The waterjet milled three aluminum mounts with round holes and slots. Said slots and holes were intended to have sufficient clearance for couplers and ball screws, while still allowing access to tighten the couplers. The three mounts were of sufficient width and length after being faced on the manual mill. However, the Y-axis' spacer block (similar to Figure 3) impinged upon the ball screw's pillow block in the center and required further milling to allow the pillow block to fit snugly in the center of the block. This adjustment will likely need to be repeated on the X and Z axes' spacer blocks. Additionally, the 4 screw holes on the large spacer blocks were slightly too small and required extra milling to fit the M6 x 95mm screws.

Figure 5. Waterjet Blasting into an Aluminum Block.

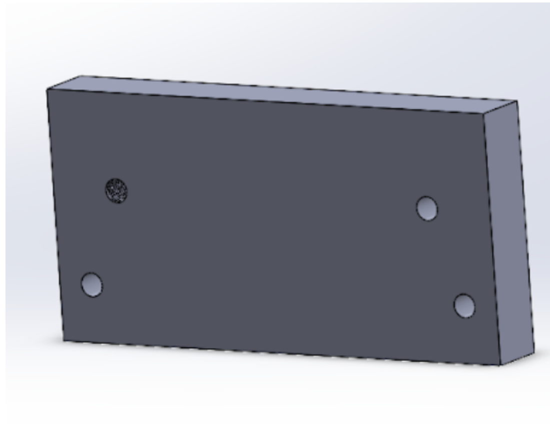

Figure 6. 3D Model of the Spacer Block for the PM-727V.

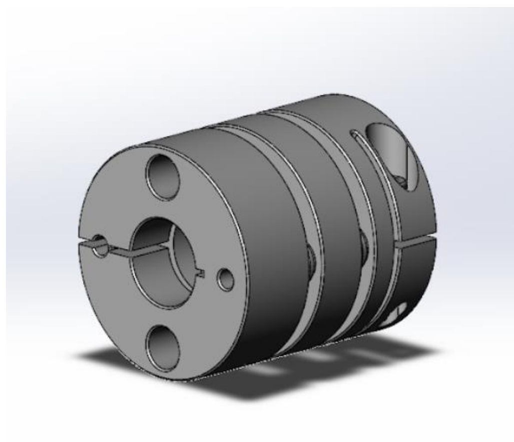

Figure 7. 3D Model of the ½" x 10mm Coupler for the PM-727V.

Upon further investigation, it was noticed that the baseplate of the mill did not have the required space needed to install the ball nut housing onto the top of it. It was decided that the easiest course of action was to carve out a rectangular space in the baseplate until the ball nut housing could be centered for the ball screw to be inserted into the middle of the machine. Once this was successful, screws were installed into the threads created for the previous lead screw housing to mount it to the platform and levels were used to ensure that the ball screw's motion did not become offset.

It was now time to attach our manufactured and purchased parts onto the mill. The team carefully inserted the ball screw beneath the Y axis on the disassembled PM-727V. The servomotor shaft coupler was then attached to the end of the ball screw, allowing the torque to be transmitted from the SmoothStepper motor to the lead screw. Figure 7 represents this stage of the assembly process. After installing the coupler, the ball nut housing was fastened to the ball screw to transfer motion from the ball screw to the platform. Next, the spacer block, motor mount and SmoothStepper motor were fastened into the center of the machine so that the rotor of the motor could be secured into the housing of the coupler so that the motor could be structurally supported as well as look pleasing to the eye.

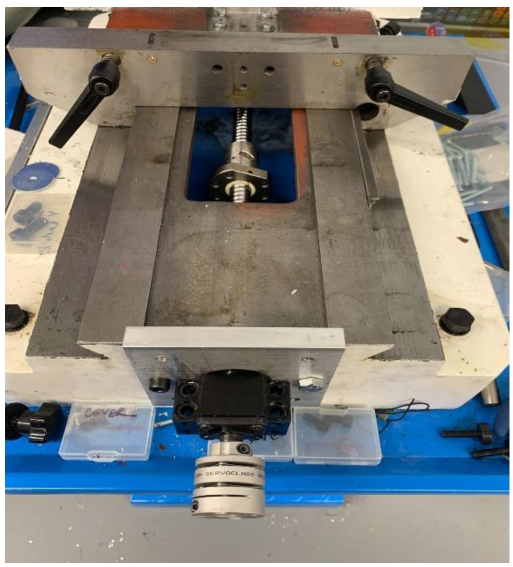

Figure 8. Coupler and Pillow Block attached to the PM-727V

Once all of this assembly work was completed, it was time to test the PM-727V. A propeller chip running simple spin code was connected to the motor, sending pulses to make the motor go back and forth at different speeds in both directions. The test turned out to be a success, as the ball screw was able to move smoothly and accurately at both high and low speeds. The test revealed that 4,064 step pulses sent to the motor were required to move the base plate 1 inch in the Y direction.

Future Work Required:

In undertaking this project, it was made apparent to us the sheer amount of time that would be required to complete the CNC conversion in a way that would create a precise, reliable, and lasting machine. Because of a failure on our part to source and order the necessary parts as quickly as possible, as well as the difficulty of working through a shortened semester and navigating around many other pandemic-related restrictions, it became evident that the entire conversion couldn’t be completed at an acceptable quality in the given time frame. Instead of hastily completing all three axes, and potentially making alterations to the machine that would prevent it from later being completed in an acceptable way, we decided to concentrate our efforts on finishing the Y-axis and laying out a plan for the rest of the machine that Prof. Garner and the department’s machinist can later complete.

Assembling the X Axis

An abbreviated list of the steps required to complete the X axis is given below. Details related to each step will be given after:

1. Connect the X axis ballscrew (the longest one) to the base plate (fig. 9), ensuring that it’s level and completely parallel to the machine

2. Modify the aluminum motor mount plate (fig. 10) so that it fits on the end of the machine, and so that the center of the stepper motor aligns with the center of the ballscrew.

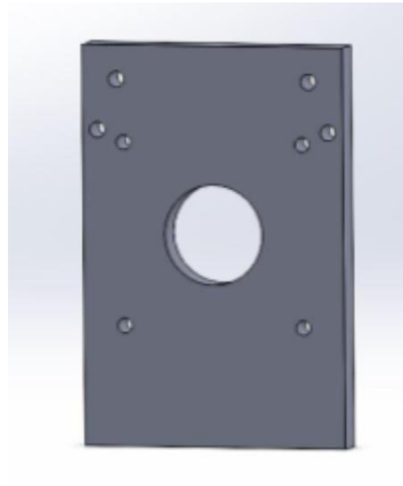

Figure 10 - X Axis Motor Mount Plate

3. Machine a new support block to go on the opposite end of the motor. This block will attach to both the mill body and the BF12 pillow block (fig. 11) to support the floating end of the ball screw.
4. Attach the BK12 pillow block (fig. 12) to the motor end of the ballscrew, attach the coupler to the ball screw shaft and motor shaft, and secure the 100 mm M6 bolts through the motor, the spacer block (fig. 13), and into the motor mount plate.

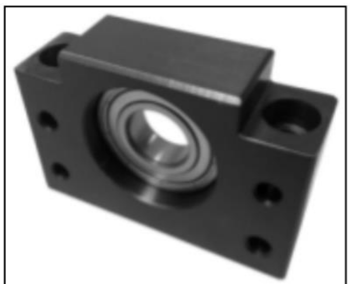

Figure 11- BF 12 Pillow Block (floating end)

Figure 12 - BK12 Pillow Block (fixed end)

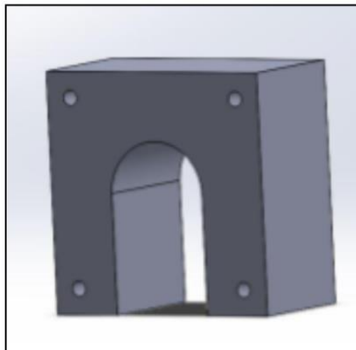

Figure 13 - X Axis Spacer Block

<u>Step 1: Attaching Ball screw to the Base Block</u>

At least 6 mm will need to be milled out of the base block so that the HD16 ball nut housing (fig. 14) can fit. More may need to be milled out so that the ball screw is aligned vertically with the large hole on the motor mount plate. The HD16 housing attaches to the ball nut using 6x 18 mm M5 bolts. The HD16 housing will then be attached to the base block using 4x M5 bolts of appropriate length.

Figure 14 - HD16 Ball Nut Housing

Step 2: Adjusting the Motor Mount Plate

Once the ball nut and HD16 housing are attached to the machine body, and are ensured to be parallel and level, the motor mount plate can either be adjusted or redone entirely to fit the new height of the ballscrew. The upper four holes, which connect to the machine body, can be turned into slots so that the motor mount plate can be raised to match the height of the ballscrew.

Step 3: Support Piece for BF12 Pillow Block

The floating end pillow block can be attached to the machine on the opposite end from the motor using a vertical plate similar to the motor mount plate, which uses the 4 existing holes on the end of the machine where the hand cranks used to be. The ballscrew is slightly longer than the milling table itself, so a spacer may be needed to align the pillow block with the end of the ball screw. Alternatively, a horizontal piece coming out from the underside of the machine may be easier, depending on how far the ballscrew extends past the end of the table. The BF12 pillow block has both vertical and horizontal holes for mounting it to the machine.

Step 4: Assembling the Motor End

Once the ball screw is level and the motor mount plate adjusted so that the center of the ballscrew aligns with the center of the large hole, the motor shaft can be connected. First, the BK12 fixed end pillow block will need to be pressed onto the end-machined part of the ballscrew, and pressed flush using a mallet. Then, notice the threaded portion on the end-machined part of the ballscrew. The BK12 pillow block comes with a small square piece that screws onto this threaded portion and presses against the pillow block to lock it in place. Then, the motor coupler, which is in the box with the motors, can be tightened on both the ball screw and motor shaft. Finally, 100 mm M6 bolts can be inserted through the motor, through the spacer block, and into the motor mount plate. The spacer block (fig. 13) may need to be milled out on the side that contacts the BK12 pillow block so that it sits flush on the pillow block and doesn't contact the protrusion. The holes on the spacer block will also need to be widened to fit the M6 bolts, as will the holes on the motor itself. After the motor is securely fastened to the machine and the set screws on the coupler are sufficiently tightened, the motor can be connected to the IPC-5 power supply and the Ethernet Smoothstepper breakout board to begin receiving pulses.

Assembling the Z Axis

Because the design of the Z axis is less completed, and the physical components that we do have already (spacer block, pillow blocks, ball nut housing, etc.) are assembled very similarly to the X axis components, only an abbreviated list of tasks will be given for the Z axis assembly.

1. Attach the HD16 ball nut housing to the spindle head block (the part of the Z axis that travels up and down. The HD16 housing will attach to the ball nut exactly as on the X axis. Some kind of spacer will need to be fabricated to go in between the HD16 housing and the spindle head block, so the bolts can be inserted through the spindle head block and attached to the HD16 housing.

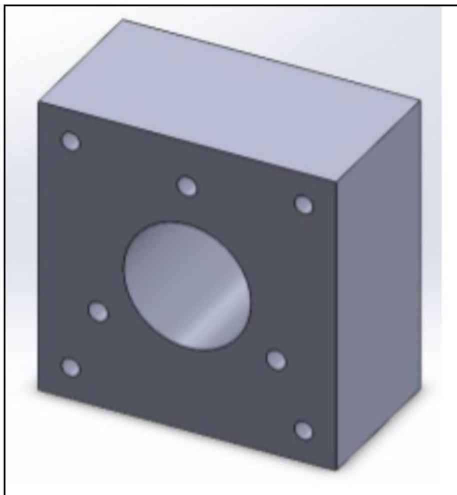

Figure 15 - Z Axis Spacer Block

2. Widen or add holes on the Z axis spacer block (fig. 15). The 3 circular pattern inner holes on the spacer block don't align with the 3 existing holes on top of the Z axis, due to mismeasurement. These can either be widened or redone on the waterjet to fit the existing holes.
3. Tap the 4 outer holes on the spacer block. The bolts that secure the motor will then be tightened into the tapped spacer block. The holes should be tapped for M6 bolts, and the 4 holes on the motor will need to be drilled out slightly to fit the M6 bolts, just as on the X axis motor.
4. Assemble the motor end. Because the weight of the Z axis is distributed vertically, a pillow block on the floating end may not be needed, but can be added if deemed necessary. Otherwise, attach the coupler to the motor shaft and ball screw, and add the long M6 bolts through the motor and into the tapped spacer block holes. Then, insert bolts through the 3 inner holes that align with the already tapped holes on the top of the Z

axis. Once all the bolts and the coupler have been tightened, the motor can be connected to the power supply and ESS.

What Did We Learn?:

There are many things that could have been improved during this project. Most importantly, many of the issues we encountered when converting the PM-727V mill could have been avoided by modeling the entire machine in SolidWorks, a CAD software, prior to beginning milling or disassembly. Less vitally, but very instructionally, we made mistakes with regards to the orientation of parts and picking parts. This section will outline in further detail what our group learned by erring during the conversion of the PM-727V, and the mistakes we will not make in the future.

First, our group made the mistake of not modelling the entire PM-727V in SolidWorks, instead modelling only the parts that we planned to create ourselves. Specifically, we modelled around a portion of the Y-axis base plate and the ball screws intended to drive the base plate. Our group inserted the SolidWorks models found online for ordered parts (coupler, Clearpath motors, screws) into the overall assembly in order to check clearances, alignments, etc. We then used SolidWorks sketch tools, along with measurements taken from the partly disassembled PM-727V to create shapes for aluminum mounts that we believed would provide adequate support for the NEMA34 ServoMotors.

Our team believed the mounts we had created for the motors would be adequate support for the Clearpath motors; however, our team ran into problems nearly immediately. During a group discussion involving the project supervisor, Dr. Garner, we were informed that the motor mounts we had modeled possessed curves that would not be feasible for us to mill by hand using the manual PM-727V mill. To remedy this, we had to outsource the aluminum milling to a waterjet located in Lacy Hall, adding time to the overall process of conversion. Additionally, we had not modelled a complete SolidWorks Assembly of the mount and machine, so could not perform F.E.A (Finite Element Analysis) to test the strength of the mount-motor system, ensuring that it could withstand the axial and torsional stresses/moments present during milling. Essentially, our group was flying blind.

Due to our unpreparedness, when our aluminum bars arrived from McMasterr-Carr and the individual spacers and base plates were created using the waterjet, the motor mount assembly did not fit together entirely snugly. We had failed to include the ball screws' pillow blocks, the bearings that keep the ball screws' ends aligned and spinning freely, in our CAD models, so further manual milling was required to allow the pillow block to sit snugly inside the spacer blocks. Additionally, the M6 x 95mm bolts used to attach the motors, mount and mill together, were too large for the screw holes on the mounts created during the waterjet process, as well as the stock screw holes in the NEMA 34 motors. Lastly, at least with regards to the Y-axis that we completed, a third aluminum spacer was needed to allow the motor to be flush against the largest, center spacer block. This smaller spacer was milled by hand in two separate instances using the manual PM-727V in the Mill, as the initial milling did not allow enough space for the coupler to fit in the block's center.

Luckily, the mounts created had sufficient strength to support both the axial and torsional requirements of moving the mill along the Y-axis, but it is unknown if the same will be true for the other two axes. Many of the hours spent assembling the motor mounts and the machine itself could have been avoided using prior CAD modelling. Pre-emptive modelling of the entire apparatus allows an engineer to determine required clearances, appropriate dimensions for any parts that will be created by the engineer, and to test the strength of an assembly using Finite

Element Analysis or Fluid Analysis. In the future, the engineers in our group will model any mechanical assemblies in CAD so as to avoid wasting our employers' time, money and resources.

Along with lackluster planning, our team also faced the challenges of inexperience. For instance, the parts ordered were sometimes of inadequate size or quality. The M6 x 95mm screws mentioned previously that attach the motors to the mill were the right size for the mill, but too big for the motors and mounts. The screws ordered to attach the Y-axis' base plate to the Y-axis' ball nut were also too short to complete this once a spacer was added to perfect the alignment of the ball screw (another shortcoming of inadequate CAD modeling). To remedy this problem, the top of the base plate was milled down roughly 5mm, and a set of four M5 x 35mm bolts were cut down to roughly 18mm in length, and used to attach the baseplate to the ball nut. With more experience and computer modelling, correctly sized bolts would have been ordered/stocked. Additionally, these zinc-plated steel screws are "corrosion" resistant, but will rust quickly. This kind of small mistake is one that more experienced engineers would have avoided, and one that will have to be fixed by the engineer that completes this conversion. In the future, we will aim to create sustainable designs, not messes that will need to be cleaned up after us.

Overall, this conversion has been a tremendous learning experience for us, Team Joe. We learned that, in the words of Dr. Garner, if you drive blind, you are bound to crash. CAD Modelling allows engineers to predict the future: the exact sizes for parts to be modelled, the correct parts that need to be ordered and when those parts/assemblies will break. We also learned that some mistakes will only be remedied through experience and failure. With our many failures in the realms of the part selection and assembly of this machine, we have learned valuable materials lessons, such as with the rusting tendency of zinc screws, and how to select the correct size of screws and other materials. We now know that with the proper implementation of modern engineering technology, projects such as the conversion of a manual mill to CNC can be done swiftly and efficiently.