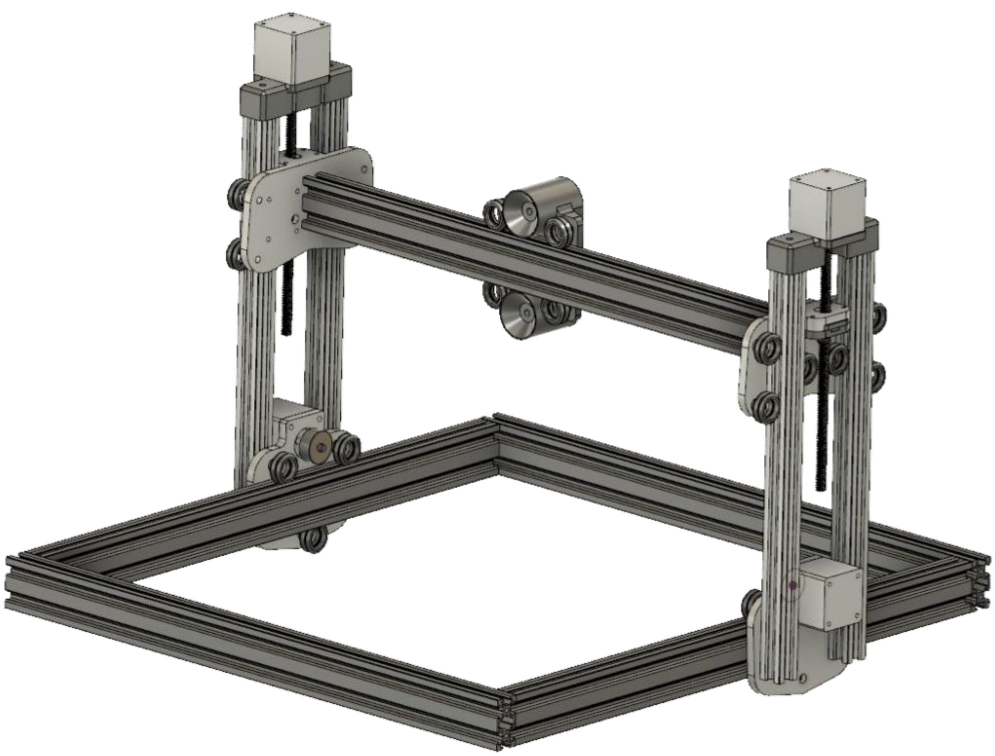
Union College

All-In-One CNC Machine



Jacob Rothschild

Senior Project

Advisor: Professor Rebecca Cortez

Mar 20, 2019

ABSTRACT:

The application of CNC (Computer Numerical Control) technologies in both industry and homes has exploded in recent years[1]. Today, thousands of individuals own 3D printers and many own CNC routers. There are very few, however, that own both. CNC routers, 3D printers, and other CNC machines like laser cutters, all function in essentially the same way. Each of these is designed to move a tool in 3D space, and it is the tool that really makes these machines different. Even so, in order to be capable of both 3D printing and CNC routing, individuals must purchase two separate machines, forcing most to choose one or the other due to the required investment of both money and space. For this project, I have designed and constructed a single machine configurable for 3D printing, routing, and many other light-duty CNC applications, in hopes of making more CNC functions accessible to hobbyists and makers. My design is very modular and can be easily scaled up or down to suit an individual's needs, it costs only $350, and is built from materials that are readily available online.

TABLE OF CONTENTS:

INTRODUCTION:

Rapid prototyping has become nearly ubiquitous in industry, and there are many machines designed for this purpose. Figure 1 depicts a standard 3D printer, its primary axes marked in red. Figure 2 depicts a CNC (Computer Numerical Control) router. These are both examples of CNC machines[2] and they share an important similarity. Both are designed to move a tool in three-dimensional space, and each does so using a 3-axis system. There are, however, some significant differences in how these tend to be designed. 3D printers are designed to be tall. In my experience, they are often compared with one another based on "maximum build volume," the maximum dimensions of an object it can print, of which the Z axis is a significant component. The printer seen in Figure 1, for example, has a maximum Z position of a bit less than 9 inches

---

[1] "Computer Numerical Control (CNC) Machine Market Size & Share Report By Type (Lathe, Milling, Laser, Grinding, Welding, Winding), By End Use (Industrial, Power & Energy, Automotive, Aerospace & Defense), And Segment Forecasts, 2018 – 2025." Grand View Research, Jan 2018.

[2] Rogers, Tony. "Everything You Need To Know About CNC Machines." *Everything You Need To Know About CNC Machines*, Creative Mechanisms, 20 May 2015, www.creativemechanisms.com/blog/everything-you-need-to-know-about-cnc-machines.

above the build plate[3], the platform on which an object is printed. The CNC router, on the other hand, is primarily used to carve sheets of wood (usually up to about 0.75" thick), so router designs trade off height for rigidity[4]. Finally, 3D printers typically decouple the Y axis from the X and Z axes in order to minimize the weight that the motor has to carry. On CNC routers, the tool is moved along all three axes and the routed part remains stationary to avoid issues with stability and accuracy.

Figure 1: An ANET A8 3D printer[3] modeled after the Prusa i3 MK2, which is often considered the standard.

Figure 2: A Laguna IQ CNC router[5].

There is also an important difference in their functionality. 3D printers are not designed to undergo any significant forces while they work. As it prints, the nozzle simply lays material down atop the previous layer[6]. It should not be pushing against anything, and nothing should be pushing against it. For a router, cutting forces can be rather significant. My research indicates forces up to approximately 20N (around 4.5 lbf) in the direction opposing that of the cut when machining woods like fir with a cutting depth 1.5mm and a feed rate of 5m/min[7].

Currently, despite their similarities, these machines remain separate, so each CNC machine purchased requires an additional investment of space and money. For many, this means that owning both a 3D printer and a CNC router, for example, is a prohibitively large investment of both space and money. With this project, I hope to change that.

For this project, I have designed and built a machine that can be configured for both purposes, or for any purpose that requires moving a tool around in 2D or 3D space for that matter. It has been designed to be inexpensive, with a total cost of approximately $350, relatively tall like a 3D

[3] "ANET 3D - A8 Reviews & Ratings." *3D Hubs*, www.3dhubs.com/3d-printers/anet-3d-a8.

[4] "Do It Yourself CNC Router: Design Considerations, the Gantry." *Do It Yourself CNC Router: Design Considerations, the Gantry, Router Source*, www.cncroutersource.com/do-it-yourself-CNC-router.html.

[5] "IQ Tabletop CNC Router | Industrial Desktop CNC Machine." *Laguna Tools | The Best Woodworking & CNC Machines*, lagunatools.com/cnc/iq-series/iq-24-36-cnc/.

[6] "What Is 3D Printing? The Definitive Guide." *What Is 3D Printing? The Definitive Guide | 3D Hubs*, 3D Hubs, www.3dhubs.com/guides/3d-printing/.

[7] Goli, Giacomo & Marchal, Rémy & Uzielli, Luca & Negri, Martino. (2018). "Measuring Cutting Forces in Routing Wood At Various Grain Angle Study and Comparison Between Up and Down Milling Techniques, Processing Douglas Fir and Oak." http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.498.8018&rep=rep1&type=pdf.

printer, but rigid enough to function as a CNC router, and its functionality can be changed quickly and easily by the user. My specific requirements and goals for this design are shown below, with indications of what I was able to achieve (a ✓for those that have been achieved, a ✗for those that have not, and -- for those that require more testing to confirm). Similar ideas have been attempted[8], but they do not provide the modularity and versatility that I hope to offer, in addition to demanding a much greater initial investment.

Requirements	**Goals**
✓No more than 2 screws required to mount tool.	✗Wiring need not be modified when changing tools.
✓At least 150mm (~6 inches) of Z axis travel.	-- Can cut hardwood.
✓At least 200mm x 200mm of X and Y travel.	✓Costs less than $500.
✓The machine is modular.	

DESIGN:

The overall design of the frame, seen in Figure 3, provides a total Z-travel distance of 160mm, and offers good stability by utilizing 2 vertical struts on each side. Each side is also driven by a separate motor, which adds the complication of having to calibrate the motors (via software) so that they run in sync, but also the benefit of added support and assurance that the X axis will rise and fall as desired. These motors are mounted atop each Z axis assembly and drive a leadscrew, which threads through a nut mounted on the Z-axis carriage (Figure 6). This is done via an assembly which mounts the nut in somewhat of a "sandwich" configuration. This configuration provides a degree of freedom for the threaded rod, allowing a small amount of movement in the X-axis direction, so that a slight bend in the rod or error in the way it has been coupled to the motor does not cause movement in the whole machine.

The X and Y axes provide ample travel – over 300mm on the X axis and nearly 400mm for the Y axis. The X axis is driven by another leadscrew, which provides great precision and minimizes the complexity of the X-axis carriage (Figure 4), as a belt-driven design would require much more complicated geometry. The Y axis, however, is belt-driven. As seen in Figure 5, each Y-axis motor is mounted to a carriage plate, with a pulley on its shaft. A timing belt runs under the V-wheels and over the pulley, engaging its teeth. The motor, then, can pull itself along the V-slot extrusion. This arrangement is used on both sides of the machine to maintain synchronicity on either side. A photograph of the completed assembly can be seen in Figure 7.

EVALUATION:

Overall, I am pleased with my achievements on this project. The tool mounting system, seen in Figure 3, is simple, modular, and effective, relying only on two screws for mounting any tool. It has two conical holes, into which a customized tool mount can register. The use of a cone

[8] "Z Store." *Zmorph*, store.zmorph3d.com/.

shape provides allowance for minor imperfections in both the X-axis carriage and the customized portions of the mounting system, and assures a snug fit and a properly located tool.

The overall design of the frame, seen in Figure 4, provides sufficient Z-axis motion and offers good stability by utilizing two vertical struts on each side. With each side driven by a separate motor, the user can rest assured that the X axis will rise and fall as desired. And the X and Y axes provide ample travel.

Finally, constructed primarily out of OpenBuilds V-Slot aluminum extrusions, this machine is extremely modular. It can be very easily scaled up or down without any modifications to any components other than the extrusions themselves and possibly to the leadscrews used for the Z and X axes. There are, however, some changes I would make on a future version.

Currently, when changing from one tool to another, some wiring must be reconfigured for each tool. It is my hope in the future to elaborate on my tool mount design such that any electrical connections occur through the mount. This would complicate the production of the customized portion, but could allow the user to make use of any tool with a properly configured mount simply by mounting the tool, and telling the computer which tool is connected.

In addition, I think further rigidity can be achieved by adding thickness to the Y-axis carriage plates, or machining them out of aluminum, and building in some additional support for the Z axis vertical struts, which are attached with only 2 t-nuts each. I would likely include support on 3 sides of each strut, provided by the Y-axis plates themselves.

Finally, I would consider redesigning the Y-axis motion system such that each motor drives the belt remotely (ie. the motor itself is mounted separate from the Y-axis plate). In lieu of this, I might modify the Y-axis plate so that the V-wheels themselves are not being used to help tension the belt, as these forces could pull the wheels out of the V-grooves of the extrusions and introduce inaccuracies in the machine's motion. Instead, I would provide space to mount two bearings under which the belt would run, keeping the belt off the wheels. This modification could also come with a reversal of the belt's path so that instead of running beneath the wheels and over the pulley, the belt would run over the bearings and under the pulley. An even better alternative would be to replace the belt entirely by using lead screws for all axes of motion, as they offer much greater precision and resistance to outside forces (under loads where a belt may stretch)

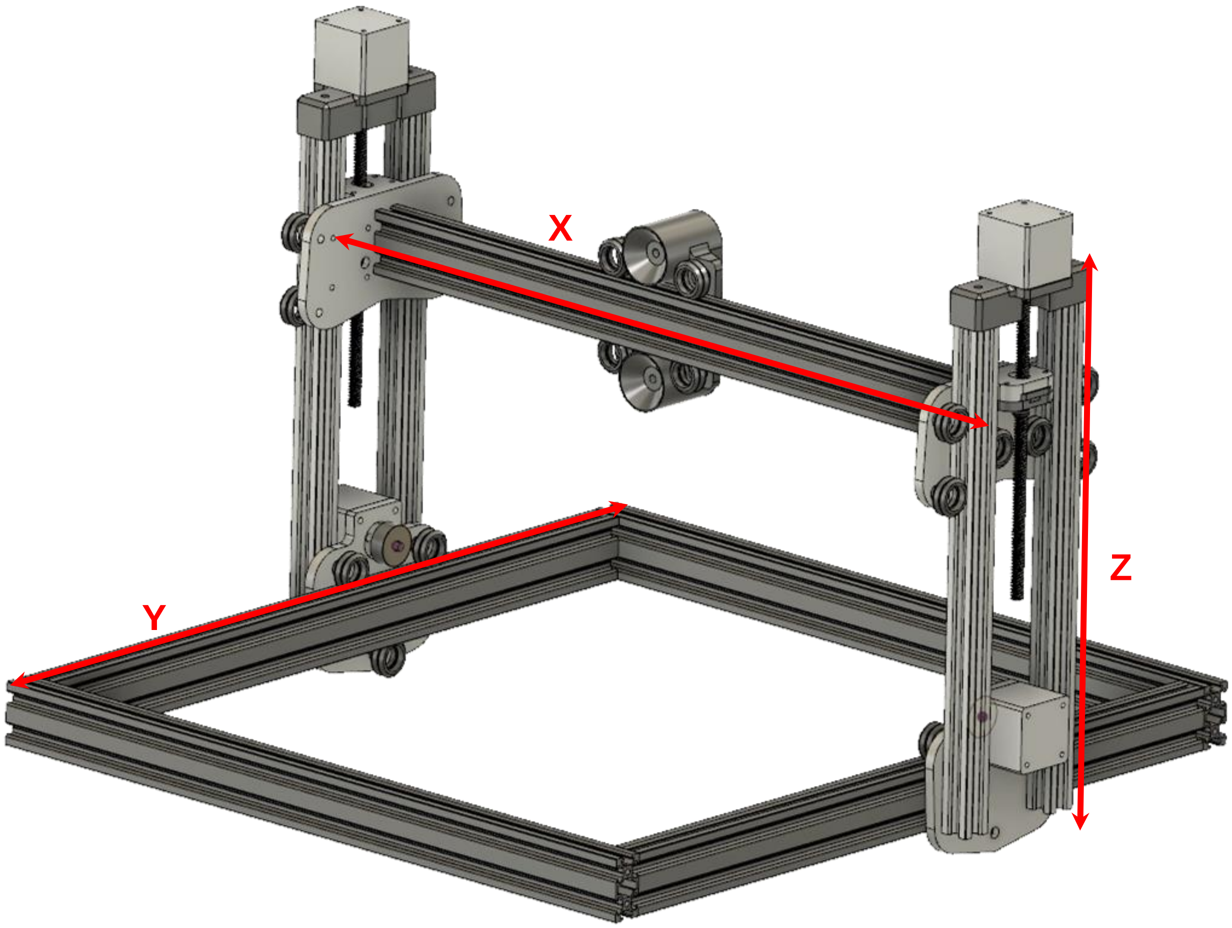


Figure 3: A design assembly depicting the structural framework of the CNC machine design, axes labeled. This is assembled primarily using OpenBuilds V-slot extrusions.

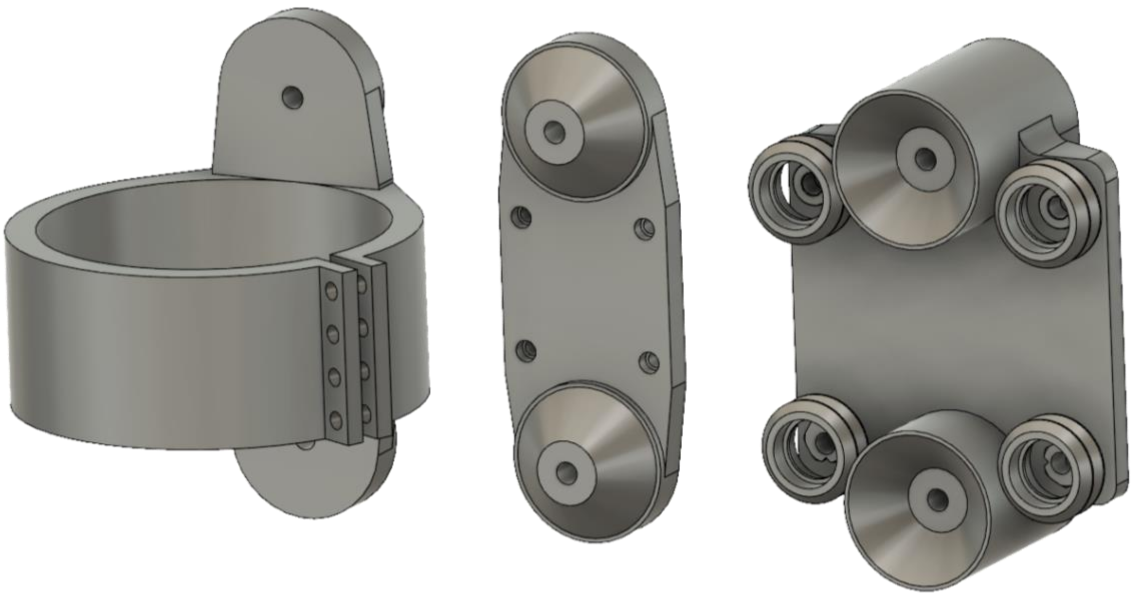


Figure 4: The overall tool-mount design, consisting of a 2-part system - the mount (right), referred to as the X-axis carriage, which receives the tool, and an attachment customized for each tool. The mounting plate (middle) can be used as a starting-off point for any other tool design, such as a mount for a router spindle (left).

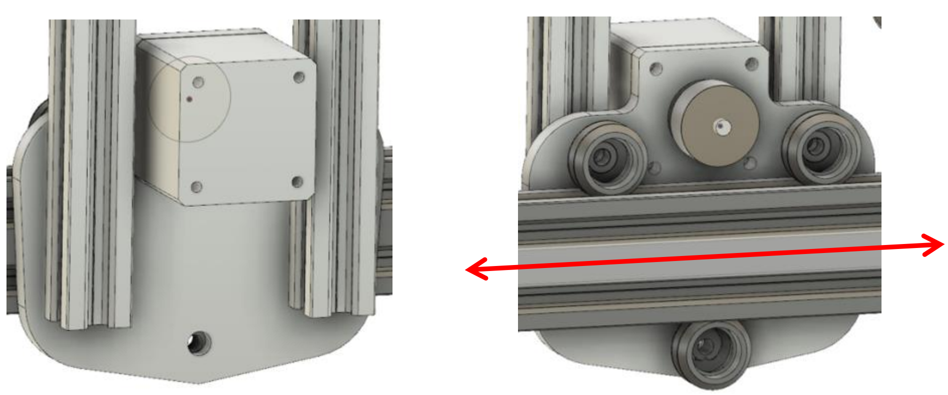


Figure 5: A closeup of the Y carriage assembly. Three V-slot wheels screwed to the plate rest in the V-groove of the extrusion. The Z shafts and the Y-axis motor are also mounted to the plate.

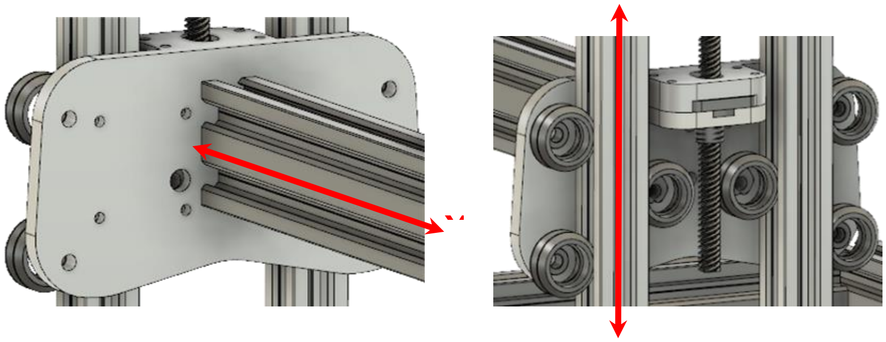


Figure 6: A closeup of the Z carriage assembly. This relies on two vertical shafts to maintain increased stability. The X axis shaft mounts to the plate, as do six V-slot wheels, and the leadscrew nut, encased in the assembly through which the threaded rod passes. The nut mounts on the darker plate, which is held on by the portion below it.

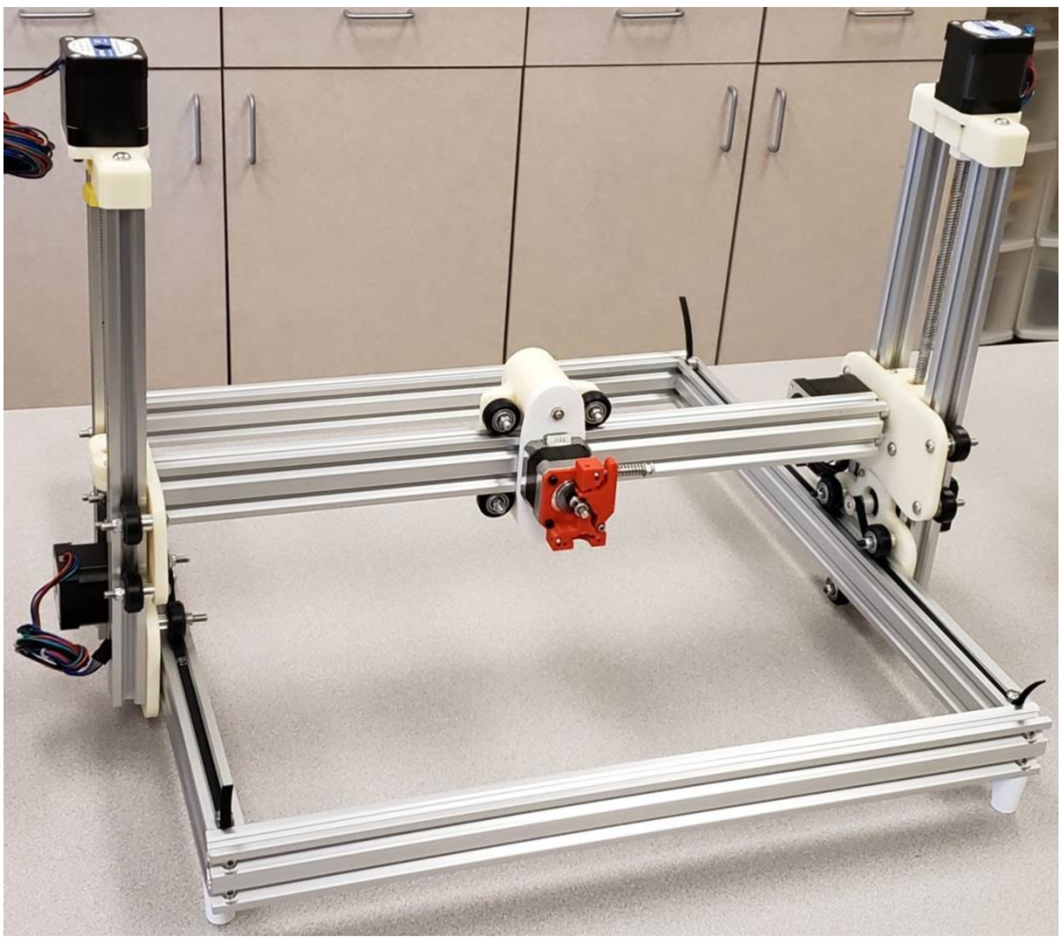


Figure 7: The CNC machine, assembly completed, configured for 3D printing

DESIGN PROCESS:

This project has been long and involved, providing many opportunities to utilize my experiences in several courses, particularly those that involved physical projects like Dynamics and Kinematics and Design of Mechanical Systems.

During this process I began by working on a general frame design. I came up with two options, the design I've ended up using, and an alternative seen below. This alternative was very unique, in that the X and Z axes were rigidly connected, and were raised and lowered as a unit. This would mean that the overall height of the machine could vary, and when lowered (as it would likely be when being used as a router), this reduced effective height would aid in reducing moments on the vertical struts and improve the overall rigidity of the Z assembly. However, in spite of these improvements, it also meant that the machine would have to be positioned on a table no wider than its base to provide clearance so the that Z-axis struts could lower below the table's surface, resulting in less versatility and ease of use.

Having settled on a frame design and a building material (OpenBuilds V-slot Aluminum extrusions), I directed my attention, before going any further, toward determining whether this idea was even feasible. In my design, the extrusion used for the X-axis is approximately 500mm (about 20in) in length, and will be expected to support a router spindle which, based on online searches, I estimated to weigh approximately 10lbf. I estimated the torque the router may cause when mounted and performed a simple finite-element analysis to estimate the displacement due to torsion on a beam of equal length. Unfortunately, the actual extrusion had too complex a profile for the FEA software to build a sufficient mesh, so a simple rectangular cross-section was used. The results of the simulation can be seen in Figure 9. This estimates that, at worst (at the corners), this torque produces a displacement of under 1mm. I also ran a simulation to estimate the displacement of the beam due to the weight alone, which, at 500mm from the fixed end of the beam, produced a maximum estimated displacement of only 0.25mm (shown in Figure 10). With this confirmation, I was able to continue as I had planned. Other analyses were attempted, but due to the dynamic nature of the machine's use cases, and the difficult-to-predict nature of 3D printed parts, these could not be trusted to provide accurate information.

By the end of MER497, I had completed the design of the frame and all motion components aside from the X axis, and I had submitted a Student Research Grant proposal to purchase all components required for the frame so far.

My MER498 term began with work designing a modular tool mounting system, while I awaited delivery of the parts I purchased with my SRG funding. This was definitely one of the more difficult components to design. In total, I had six design ideas, two of which made it to the CAD design stage of development -- the mount I selected for the final design, and the one depicted in Figure 11. This mount is nearly identical to my final design, but features square pyramids where the tools attach instead of cones. This offers the same benefits of the cones, but could not be machined, only 3D printed, due to the sharp inside edges. I wanted this part to be able to be machined out of aluminum, so I elected to adjust the design to rely on cones instead, which are relatively easy to machine if needed.

My other major goal for MER497 was to select and purchase all necessary electrical components for the machine, including a power supply, motor drivers, and a controller board. Much research went into this step to source compatible components. I had to ensure the power supply could provide enough power, that the control board had the correct number of each type of connection, and that the motor drivers were compatible with both the board and the motors. I was able to submit an SRG proposal for these components and with their purchase, all parts for this project that could be sourced from third parties were obtained. Finally, the components that remained were 3D printed and the machine was ready for assembly.

Currently, all mechanical components have been assembled. The machine has been built and mechanically functions as intended, but the work is not done. I am now assembling all electronic components with the expectation of having a fully functional CNC machine ready for demonstration at Steinmetz Symposium, 2019.

Figure 8: An early alternative design for the machine frame. This design featured a single, rigidly connected, X/Z assembly, which would rise and fall as a single unit.

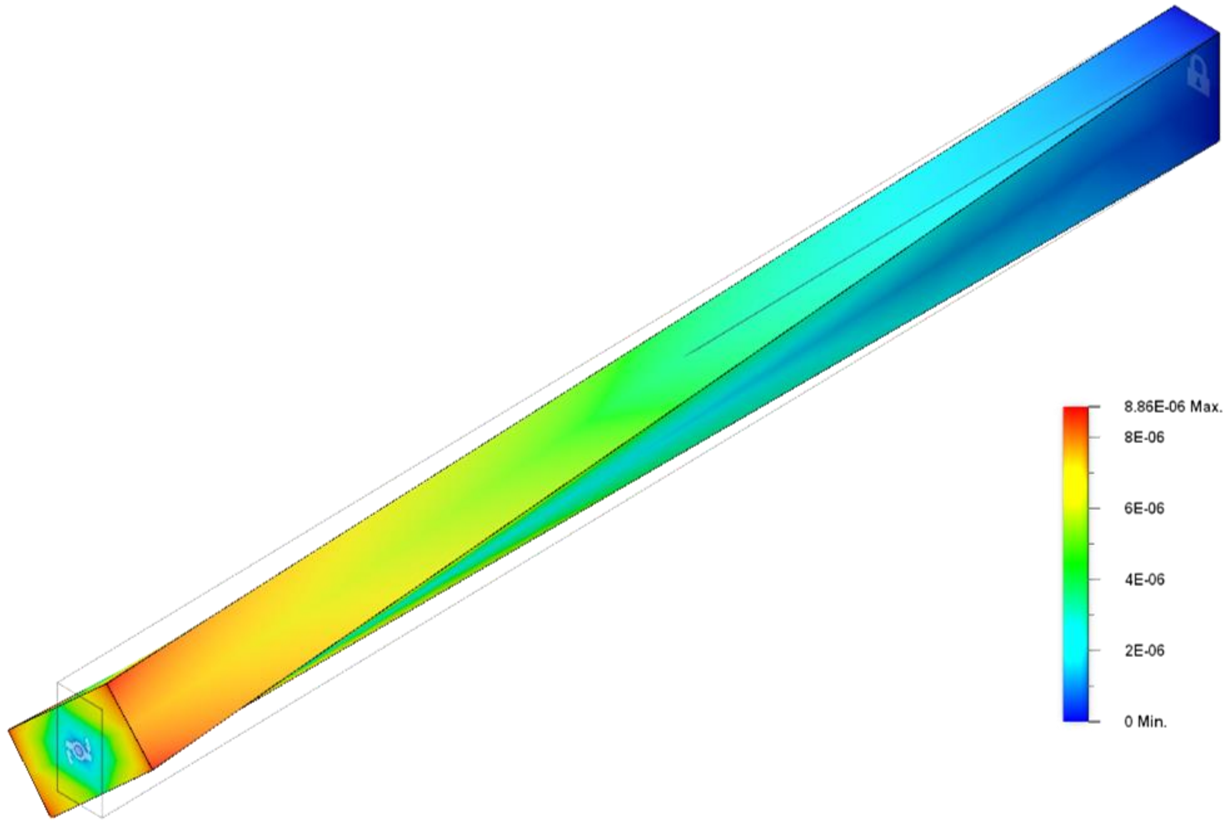


Figure 9: The results of an FEA analysis, using Autodesk Fusion 360, of a single beam under torsion to estimate possible displacement due to the weight of the tool being used. This analysis estimates, at worst, far less than 1mm of torsional displacement.

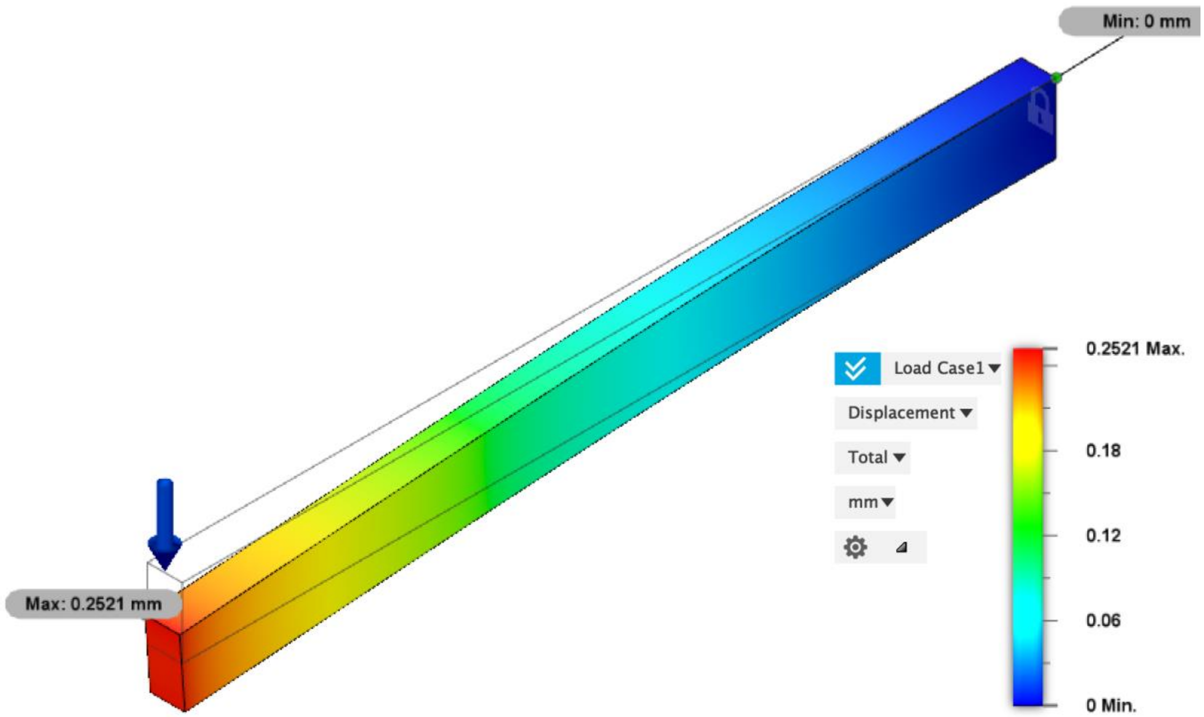


Figure 10: The results of an FEA analysis, using Autodesk Fusion 360, of a 500mm beam under a 10lbf load.

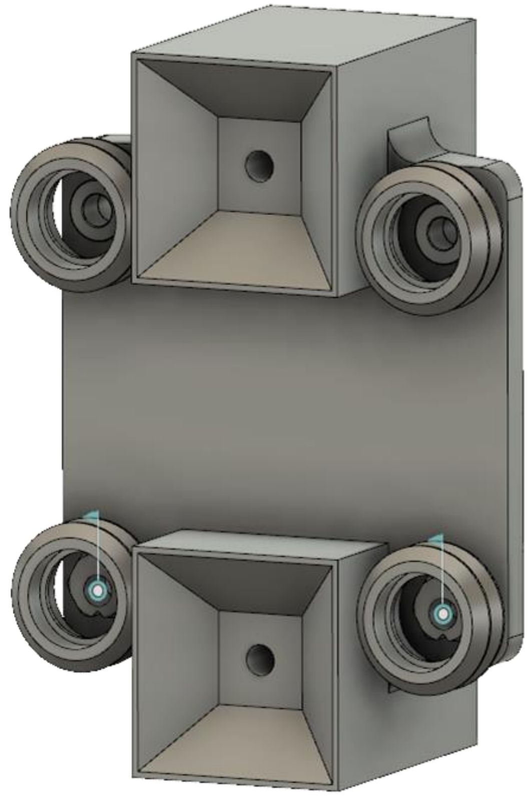
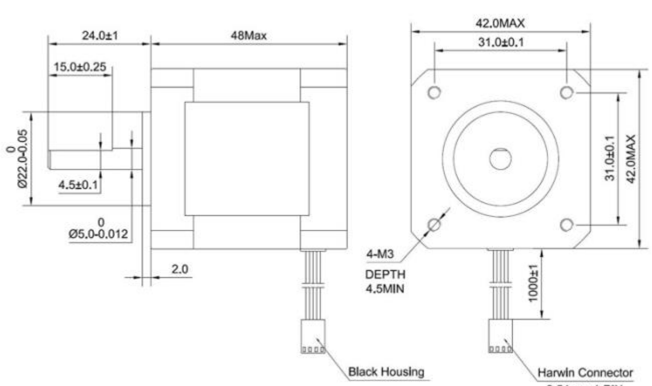


Figure 11: An alternative tool mounting (X-axis carriage) design. This design features pyramidal openings, as opposed to the conical holes I chose for my final design.

Appendix A: BILL OF MATERIALS – purchased

Purchased components, used in build

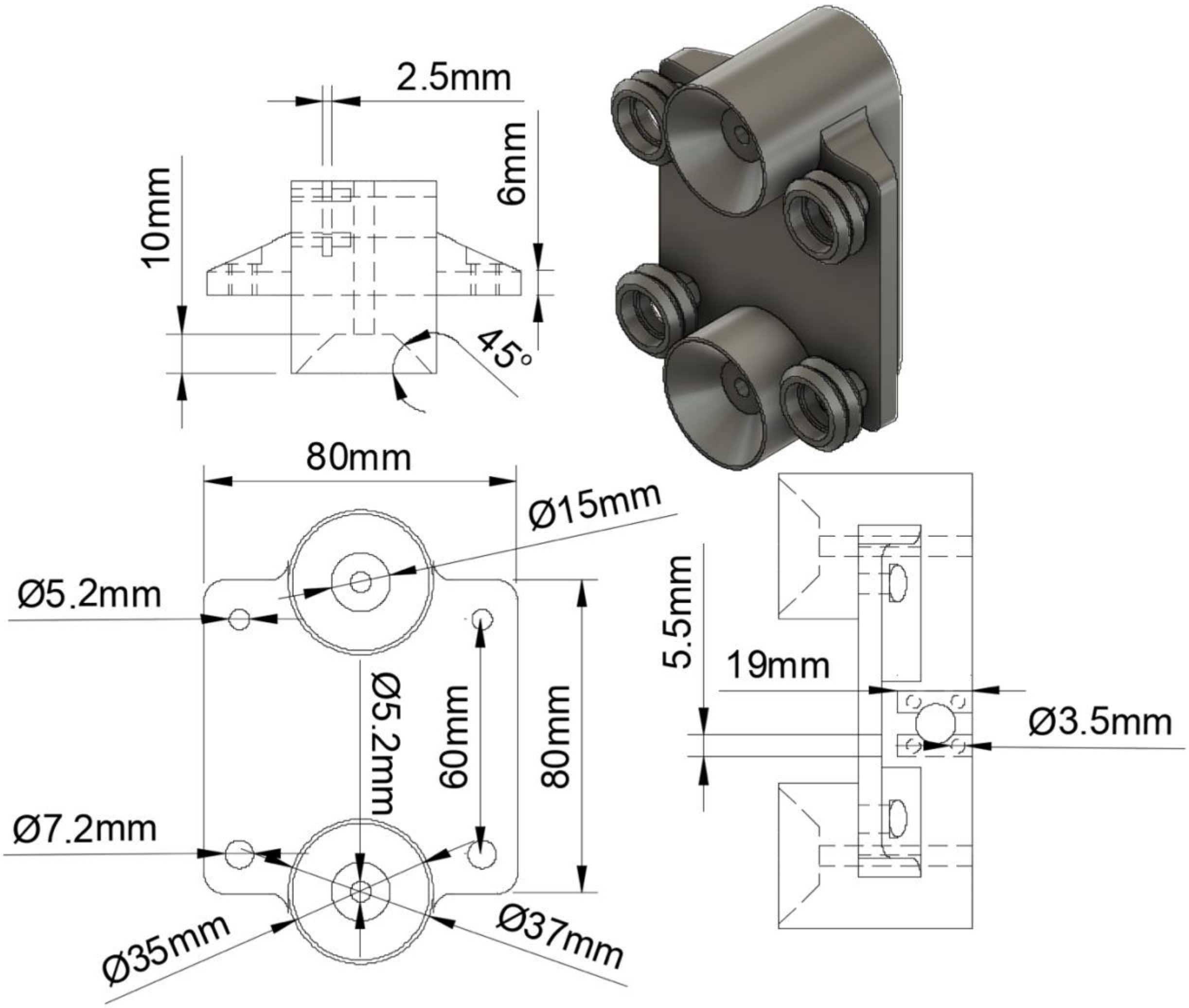
Part	Manufacturer	Model Number	Quantity	Unit
2040 V-slot Extrusion	OpenBuilds	285-LP	2	1500 mm
2020 V-slot Extrusion	OpenBuilds	280-LP	1	1500 mm
V-slot wheels (6 pack)	CCTREE	CC-V-Wheel-6	24	Wheel
M8 ACME Thread Lead Screw	Drillpro	DRILLPROTSZYmall1592	3	400 mm
NEMA 17 Stepper Motors	STEPPERONLINE	17HS19-2004S1	5	Motors
GT2 timing belt	Mercurry	L16011611	1	5 m
Aluminum GT2 Timing Belt Pulley (5PCS)	DROK	300362	5	Pulley
T Nut for 2020 Extrusion (160PCS)	IZTOSS	JG979	1	160-piece variety
RepRap RUMBA Controller Board	BIQU	Tango V1.0	1	Board
DRV8825 Stepper Motor Drivers	Witbot	DRV8825	5	Driver
Limit Switch Endstops	URBESTAC	CL20	5	Endstop
Power supply (12V, 360W)	eTopxizu	S-360-12	1	PSU
Electrical connectors	DiER	B07G2Q7HGV	1	280-piece variety
JST-XH Connectors (460 pack)	GeeBat	GB0011	1	460-piece variety
JST-XH Crimping tool	GeeBat	GB0030	1	Crimping Tool



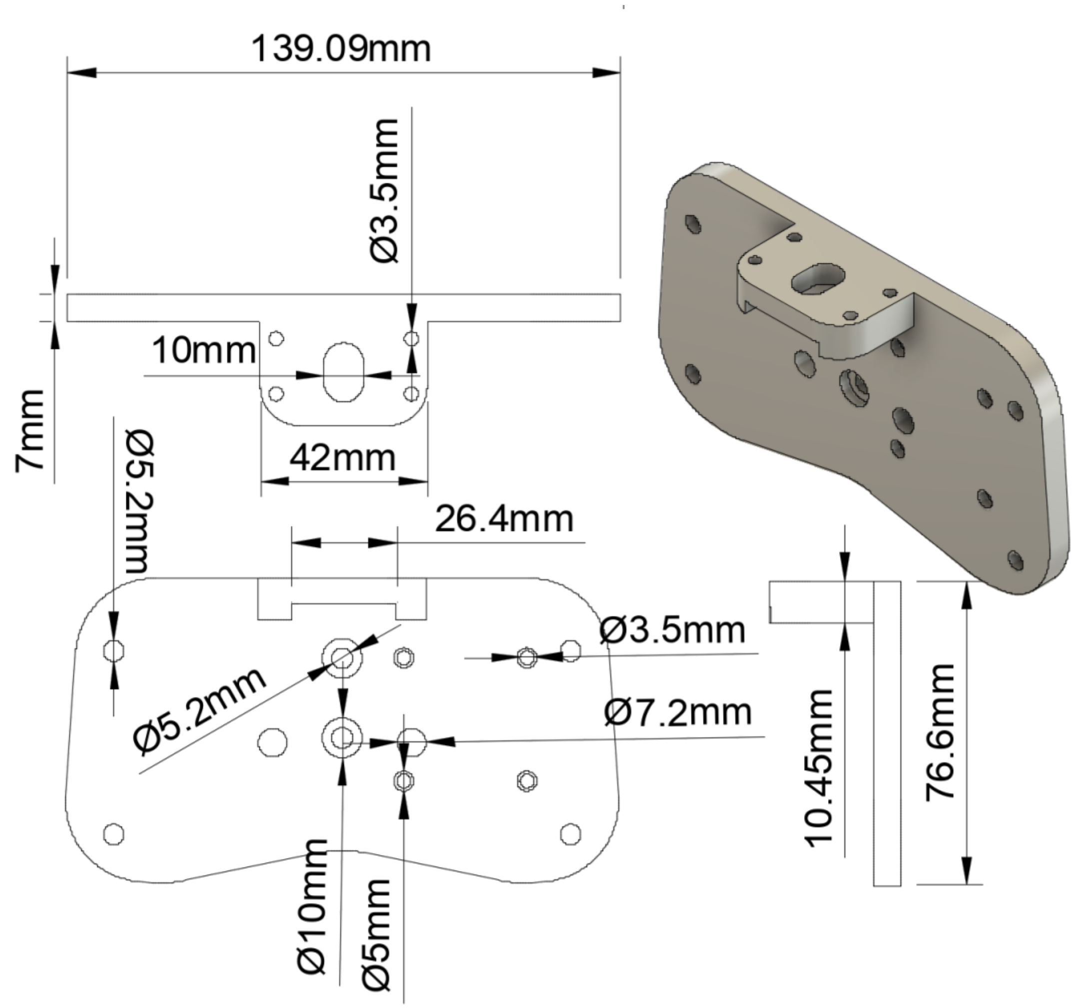
NEMA 17 Stepper Motor
Holding torque: 59Ncm(83.6oz.in)
Step Angle: 1.8 deg

Appendix B: BILL OF MATERIALS – 3D printed or Machined

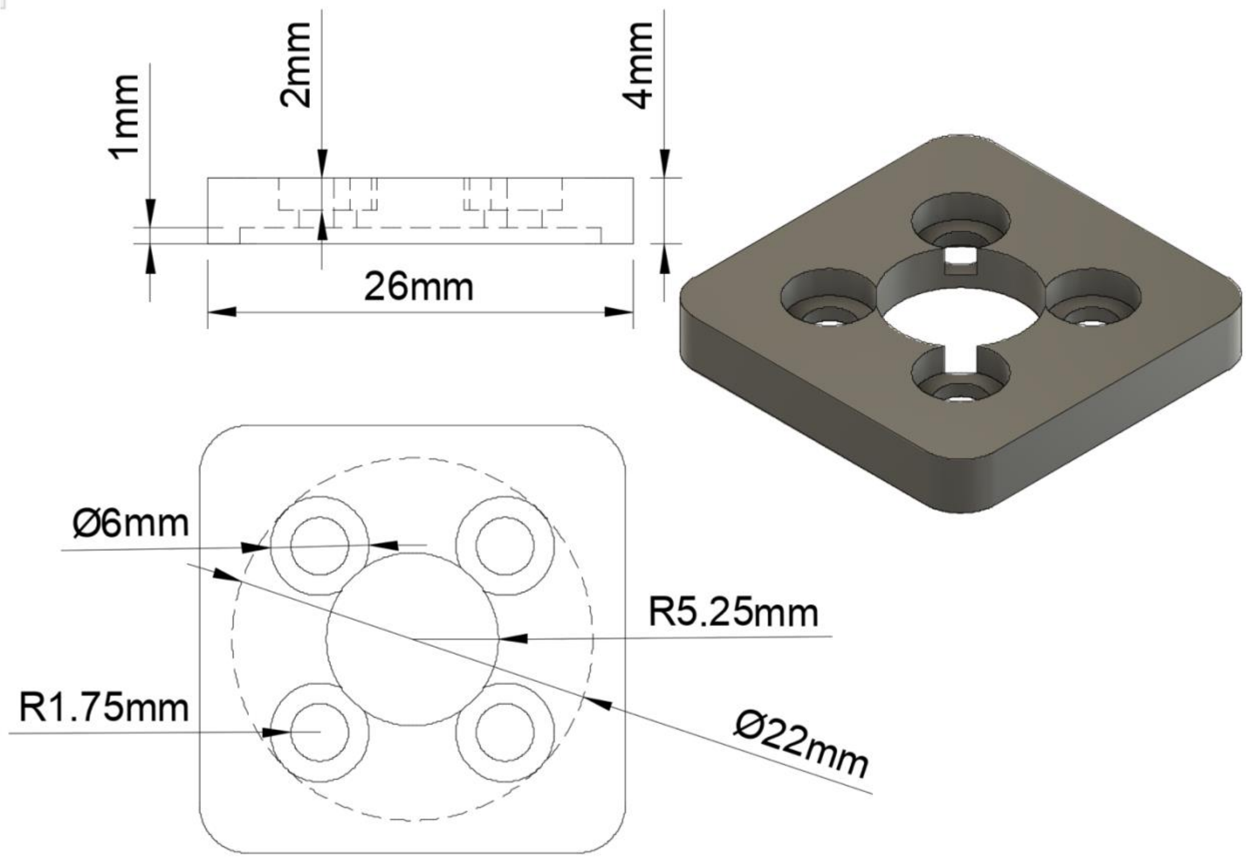
3D printed or Machined components



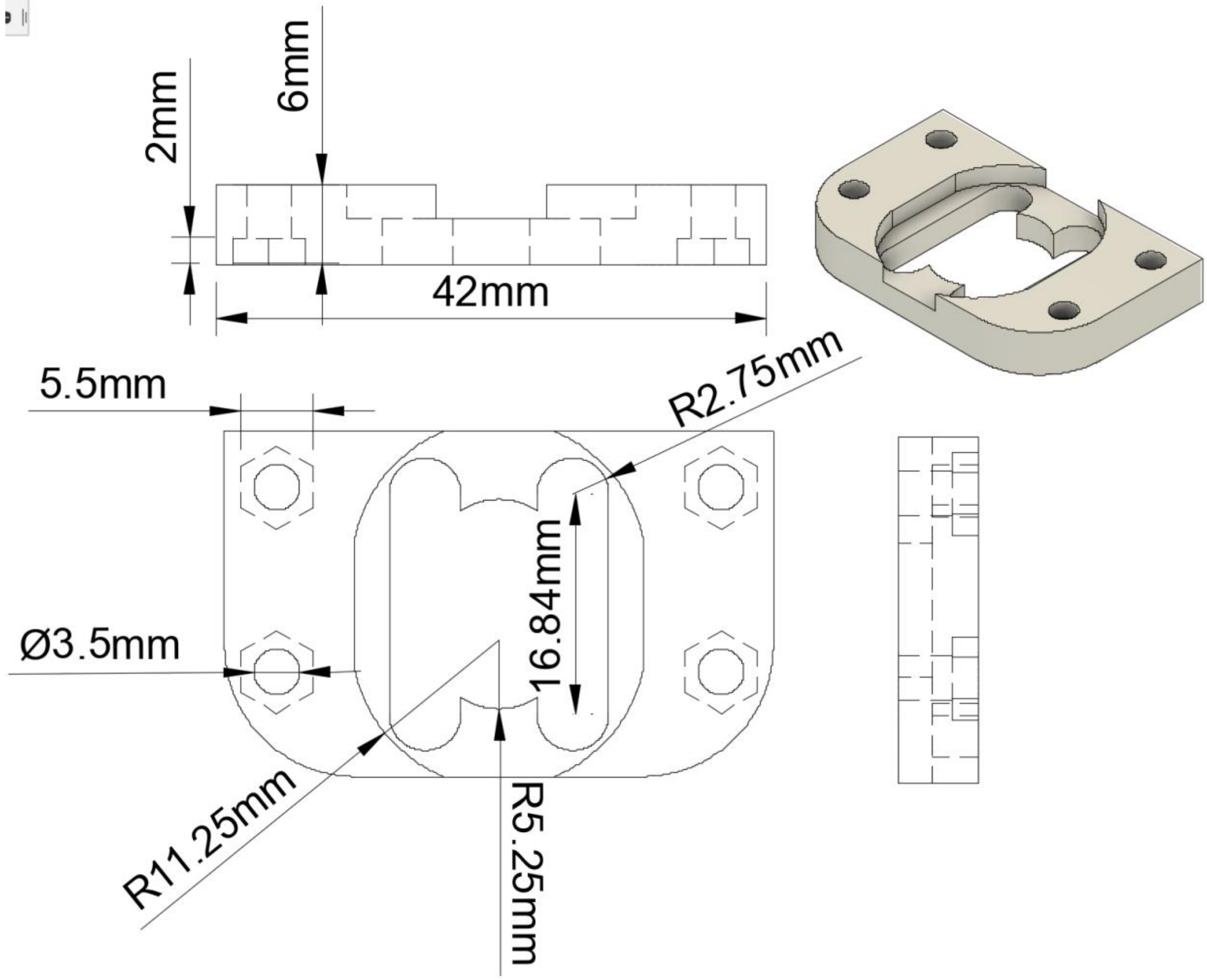
X-axis Carriage and Tool Mount



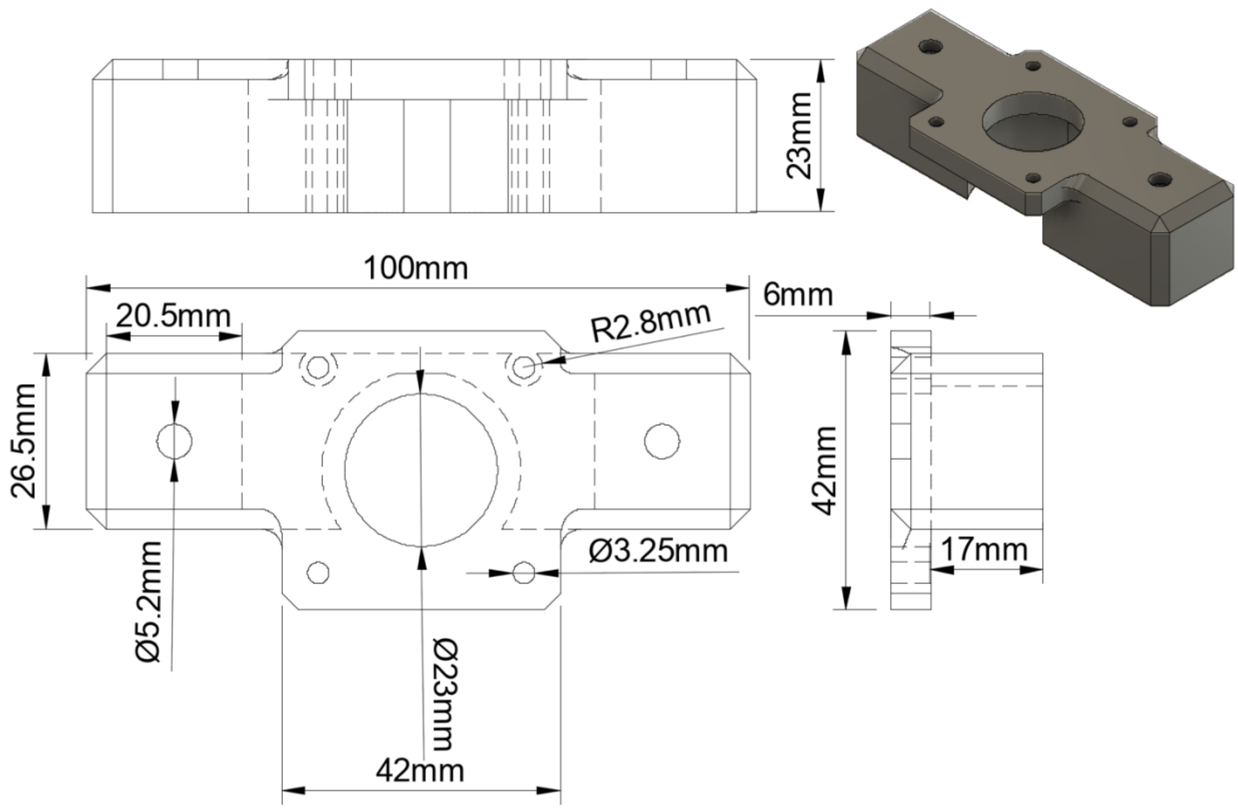
Z-axis carriage plate



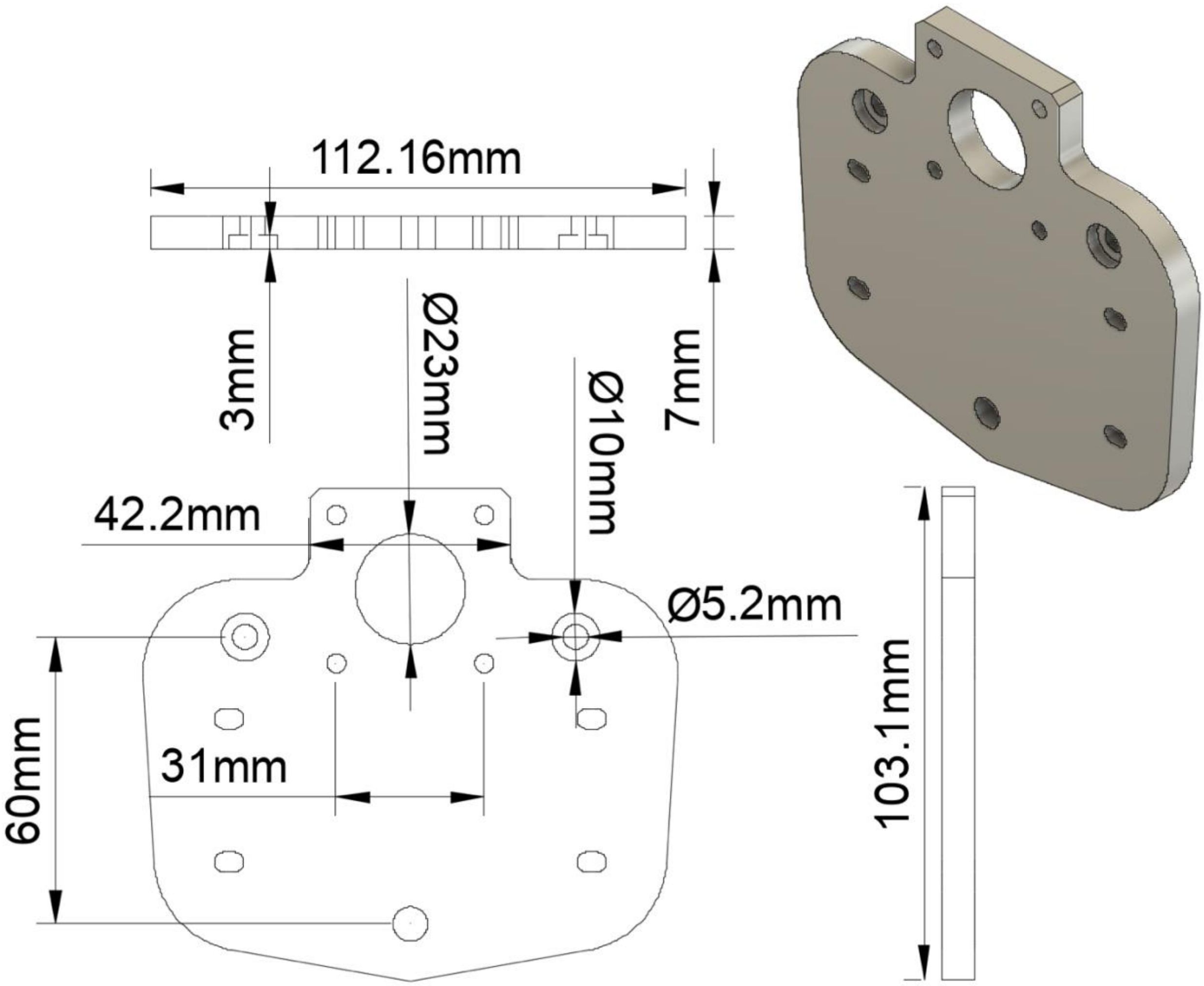
Z Nut Mount - part A



Z Nut Mount - part B



Z Axis Top Cap



Y Axis Carriage Plate