# Effective 3D-Printing Project

By: Abhishal Kochhal

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## Introduction

An FDM 3D-printer, otherwise known as a “Fused Deposition Machine”, is a distinct form of 3D-Printing in which a CNC machine extrudes molten filament in a pre-programmed path to produce a part. The first FDM 3D-Printer to enter the market was produced by Stratasys in the early 1990s. Stratasys had exclusively owned the intellectual property to the 3D printer until the early 2000s, when Dr. Adrian Bowyer produced the first open-source, “Rep-Rap” 3D printer, which could be assembled with components that could be easily sourced as well as parts that were produced on another 3D printer, creating a process in which 3D printers could self-replicate. The release of the first open-source 3D printers made the technology more accessible to the average consumer who could not access Stratasys machines exclusively. Since then, consumer-grade 3D printers have tried to outpace each other in reliability, productivity, and overall quality. As of April, 8, 2026, consumer-grade 3D-printer manufacturers have started making machines with more closed-source parts, with a distinct parallel to other machines that try to fit within the “Rep-Rap” tradition with added innovation. Since “Rep-Rap” opened the opportunity for all sorts of innovation in DIY 3D printing, it is possible to use well-known engineering principles and techniques used in industry in the past to make better 3D printers. In this paper, a printer called “Boaz” will be built according to these principles to test their validity. If the machine is successful and reaches certain performance standards, then key “dogmas” will be identified for the construction of an effective DIY 3D printer.

## Theoretical Background

Aluminum extrusions are the main profiles used when building DIY “Rep-Rap” 3D-Printers because they are readily available online and provide a proper interface for mounting other components using T-Nuts.

Early draft, begun April 2026. Superseded by the book and the IEEE SoutheastCon 2027 paper;
some claims in it were later corrected. Not peer reviewed. Abhishal Kochhal, amkochhal@gmail.com

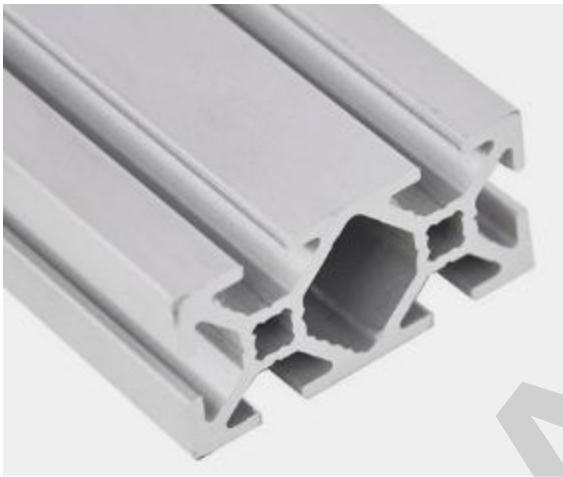


*Fig 1: Aluminum extrusions can have slots for T-Nuts that can be used to mount components*

For an effective 3D-Printer design, the frame has to be both square and very rigid to absorb vibrations and preserve dimensional accuracy when printing. Most machines, both open source and DIY, use simple 20x20mm aluminum extrusion profiles for their frames. These profiles are too thin and simply cannot handle the various resonances of high-speed 3D printing.



*Fig 2: VFA artifact on "Voron Trident" 3D printer due to it using thin, 2020 Aluminum profiles*

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An obvious solution to this problem is to use 20x40mm extrusion profiles or even 40x40mm profiles to make a more rigid frame. A DIY machine called the “monolith” mitigated this effect with very little software input using a stronger frame with 20x40mm extrusion profiles.



*Fig 3: “Monolith” Machine can reduce VFA effects by virtue of its using 20x40 profiles*

Sometimes, if using larger extrusions is not enough, it might be useful to also fill the cavities of the extrusions with some sort of media such as sand, gravel, or concrete to weigh the printer down and dampen the frame to stop resonances



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*Fig 4: Developer of "ServoBelt XY" 3D-printer filling 40x40 and 40x60 extrusions with lead and resin to dampen frame.*

Another manufacturing principle that is very important for 3D-printers is the "squareness" of the frame. A frame that does not have extrusions that are properly squared together will directly translate that imperfection into its prints.

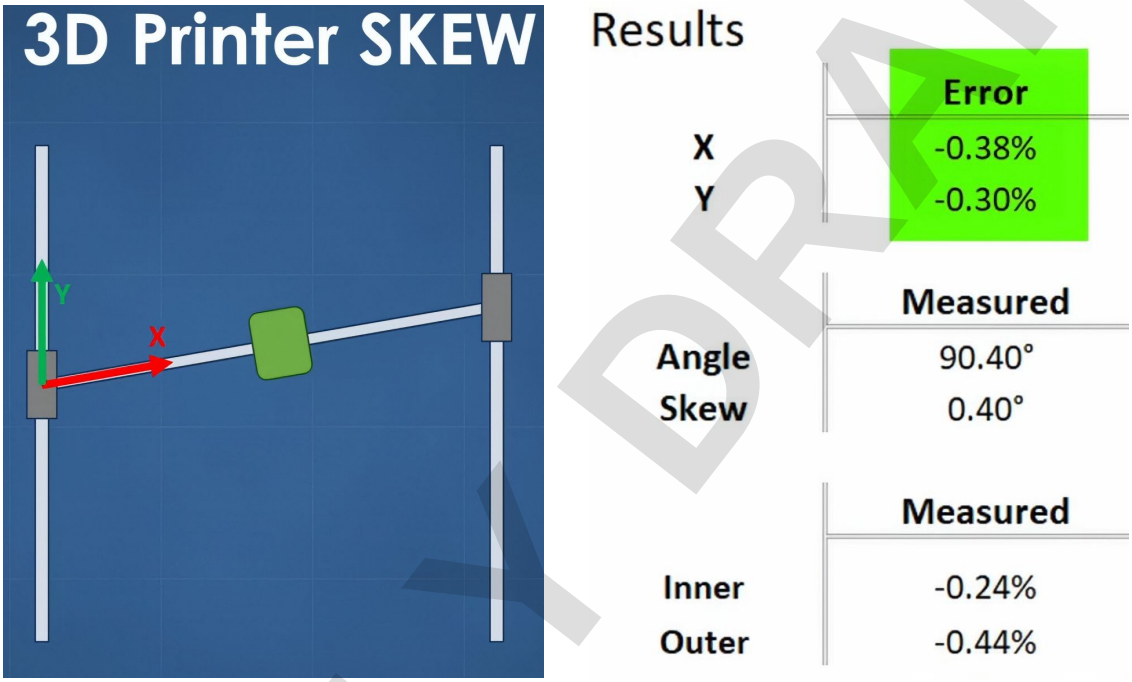



*Fig 4: The skew created by an unsquare frame translates dimensional errors in prints*

Another important component in the frame is the joining method of the extrusions. Some of the common methods of joining are corner brackets, blind joints, and gusset plates. Many of the corner brackets on the market, even from reputable sellers, are not perfectly square. This usually means that they have to be post-processed in a way that is not ideal for a fabricator. The other option is the blind joint, which uses bolts and threaded holes in the extrusions to connect them. Also, it technically is the strongest method of joining two extrusions together. Still, it suffers from the problem of squareness, as most extrusions that come from China are cut using chop

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saws or miter saws, which often give non-flat surfaces that make any form of trimming nearly impossible, as a bolted surface often gives little play. Another issue with blind joints is the connection of three profiles at one point, such as at the corner of a frame, since screws can't intersect each other.

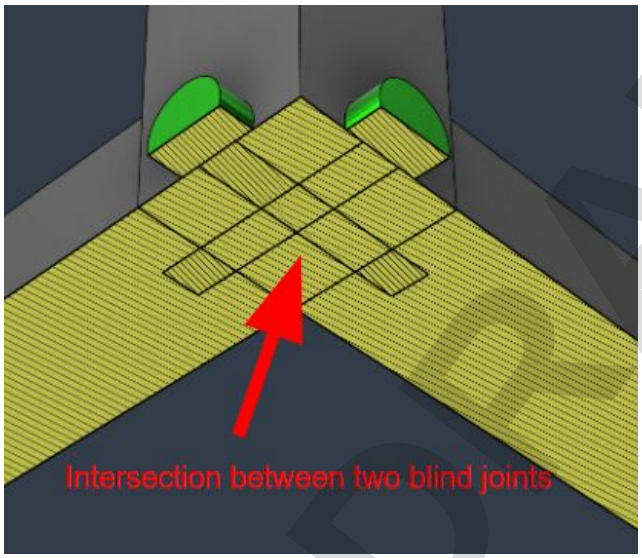
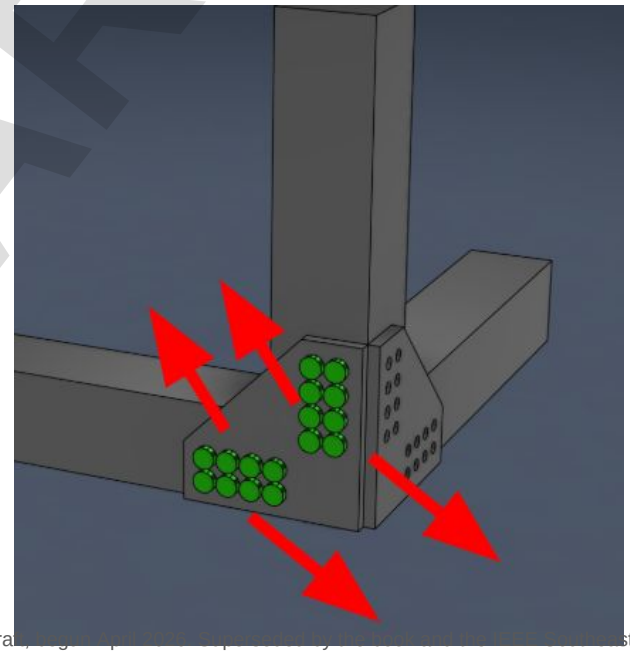



*Fig 5a: Blind Joints at the corner of a frame will have screws that intersect each other*

The final option is a gusset plate, which is a piece of sheet metal that serves as a medium for extrusions to connect, and the holes in the plates are larger than the M5 screws that clamp the plates with the extrusions. This means that there can be tramming in the square joint between both extrusions whilst also being able to join three different extrusions at one corner of a frame.



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Early draft, [illegible] stCon 2027 paper;
some claims in it were later corrected. Not peer reviewed. Abhishal Kochhal, amkochhal@gmail.com

*Fig 6: Gusset Plates allow for corner joints as well as tramming*

The frame of a 3D-printer also has to consider the existence of other subsystems and how they interact with each other. For example, a frame must usually be larger than the expected print area to fit the XY motion system, the Z axis, and leave room for electronics storage. The printer mentioned in this paper incorporated this design in its "two-tier" frame, which contains a level for the motion system, side profiles for the Z-axis, and a plate on the bottom for electronics mounting. The frame was also constructed using a granite surfacing plate and a machinist square with a reasonable percent error for squareness to mitigate potential dimensional issues in the prints listed above.

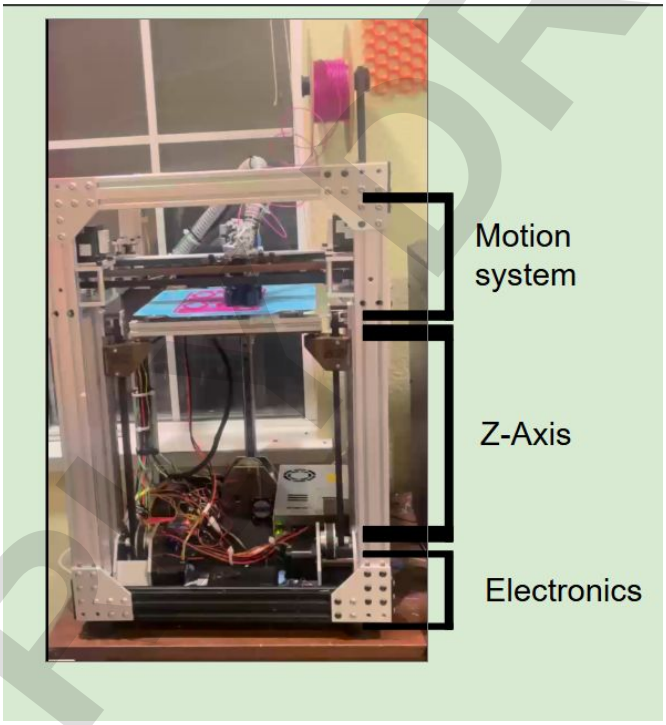



*Fig 7: Frame harmonizes all of the sub-systems.*

Another approach to electronics mounting that is used in industrial applications on real CNC machines is via a separate electronics container. One good example of this in "Rep-Rap" machines is called a "side pack," which creates another area adjacent to the print area where the electronics are situated. This could add extra space for machines that require more or larger

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electronics and could also prevent the spread of fire since it would be easier for a fire-suppression system to work in an area where the electronics are consolidated.



*Fig 8: A sidepack on an enclosed 3D printer*

A side-pack often requires more extrusions, which is not optimal for cost and complexity, and for the sake of simplicity, the machine built in accordance with this study will not use it in its design. Another thing to consider with any frame overall is whether it's enclosed. Many materials like PETG, ABS, or any kind of engineering material will require an enclosed chamber to stop cool air from warping parts. Additionally, these enclosures might have heaters inside of them to raise the ambient temperature to aid layer adhesion.

In 3D printing, there needs to be some sort of motion system to move the nozzle around the X and Y axes. One of the most common approaches to this problem is with assigning one motor to each axis in three distinct configurations. One of these configurations is called a “bed-slinger,” where the X axis is paired to the Z axis, and the bed in which the print is laid serves as the Y axis.

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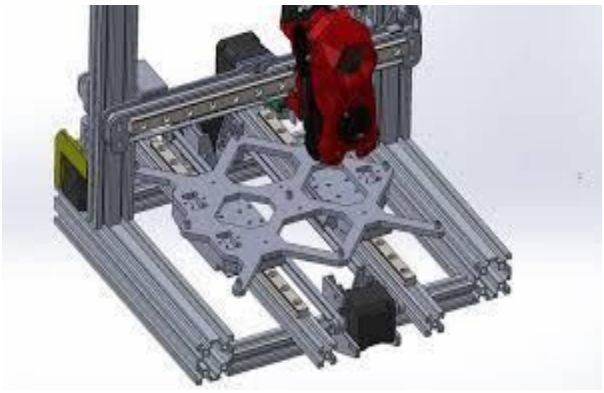


Fig 9: An example of a “Bed Slinger” 3D-printer

The main issue with a “Bed-Slinger” design is that the movements of the bed can often fan air straight into the bottom of the print, causing warpage. Another issue is that the bed itself has to be made of some sort of thick aluminum to be flat (especially under long-term strain from heating), which means it would be harder to get higher printing speeds due to the extra mass. Another example of a system that uses individual motors to move each axis is a “Top-Down” machine, which utilizes a box frame as discussed in the framing section, in which the x and y axes move independently of the bed.

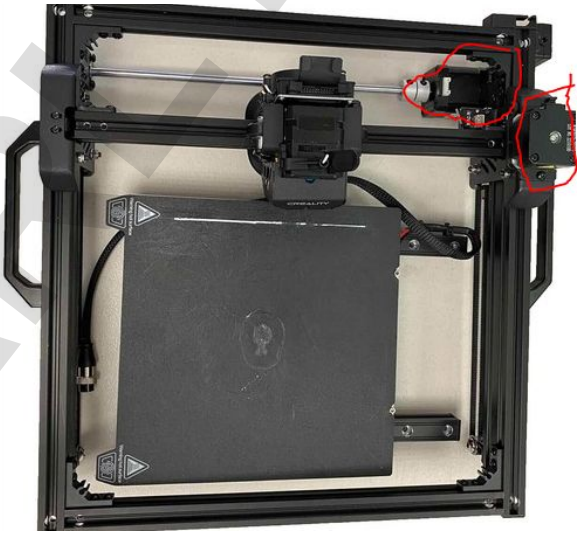


*Fig 10: Top-Down configuration where x axis is controlled by a motor on the gantry and the y axis is controlled by a separate motor*

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The “Top-Down” motion system solves the problem of warpage as the bed is not moving back and forth but rather the toolhead. The issue with this system, however, is that the motor for the x-axis has to be mounted on the gantry and the motor for the y-axis elsewhere. Stepper motors and any form of CNC drive motors are extremely heavy when accounting for the total weight of the gantry; this added mass also makes high-speed movements harder. Another way of incorporating a box-shaped frame whilst not having to deal with the issues of the “top-down” system is through a system called “Core-XY”. In essence, there are no motors mounted to the gantry of the machine, nor are there specific motors for any axis; instead, the two motors work in tandem to produce X and Y movements and can be mounted anywhere on the plane.

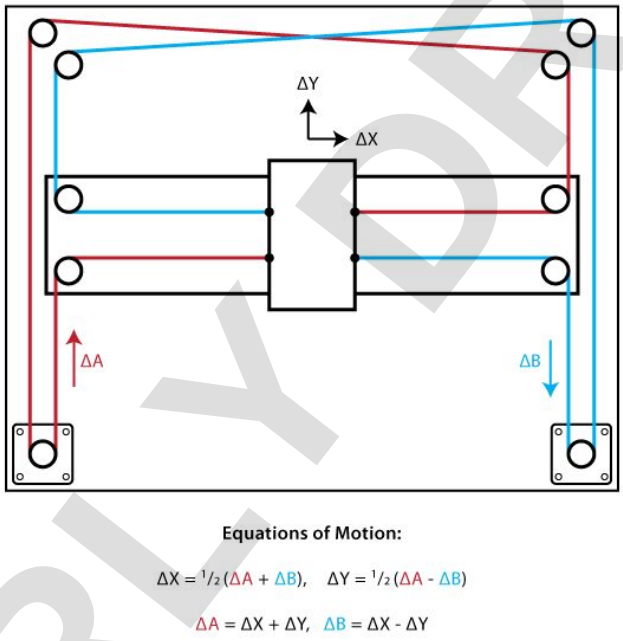



Fig 11: “core-xy” Motion System and its equations of motion

The major benefit of the system is that there is no need for motors on the gantry of the machine, which significantly reduces the mass on the gantry. Since Newton's second law states that F=m*a, the lesser mass allows for higher accelerations, thus increasing print speed.

Once the motion system is resolved, CAD software needs to be used to map the alignment of each component on a 2D plane to make the design easier.

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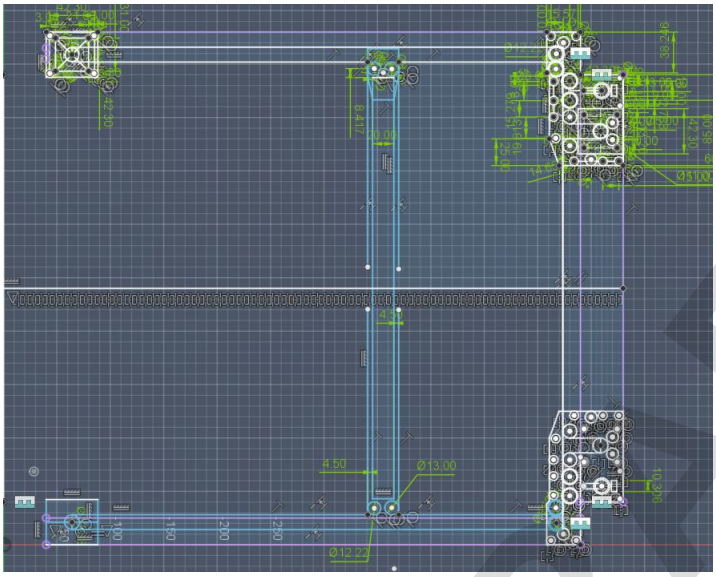
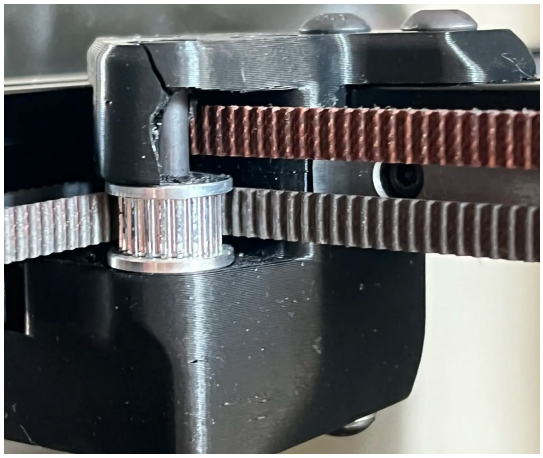



Fig 12: 2D drawing of motion system

This 2D drawing needs to factor in the shape of the sheet-metal parts on which other components are mounted, the components on the gantry, and the belts that link the motion system together. This 2D drawing serves as the foundation for how all other motion components will be designed later and will represent the system's precise dimensions.

The components on any CAD design for a 3D printer need to be meticulously chosen for performance and rigidity. For example, it is structurally superior to use sheet metal parts stacked in an “ice cream” format with spacers rather than using plastic parts. Plastic parts also generally tend to expand and lose tolerance in applications where ambient temperature is high, such as in an enclosed 3D printer.

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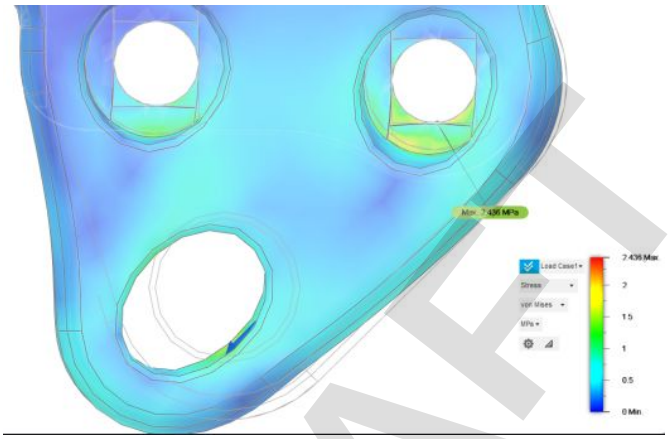


Fig. 13 & 14: Plastic 3D-printer parts fail under forces of tension, heat, and clamping force of hardware.

Additionally, the type of hardware used in assemblies is a major factor to consider while designing. Most additive manufacturing machines utilize metric fasteners in their assemblies. The Metric fastening system is coded by “M” followed by a specific number to match its diameter. For example, an M5 fastener is 5mm in diameter. Assemblies should prioritize using the highest diameter fastener that is realistically possible, as larger fasteners can withstand stronger forces and increase design simplicity, which is important for real-world assembly.

Another design element to prioritize in assemblies is idlers and pinions. These are toothed and smooth gears that allow belts to be wrapped around to create a core-xy motion system. It is important to use both toothed and smooth idlers,s as belt traction is important for proper Cartesian movement;s for example, using the toothed side of a belt on a smooth idler will cause friction that will damage the belt. The usage of toothed and smooth idlers is often followed by the usage of dowel pins, as using standard M5 screws will cause the idler to move eccentrically,y as M5 screws are usually sized down 0.2mm due to their threads. The eccentric movement of idlers under standard M5 screws can cause bad print quality, as based on their eccentric position, the belt layout can be slightly larger or smaller. If the most basic Core-XY setup needs at least 8 idlers, this small eccentric change can be amplified if M5 screws are used.

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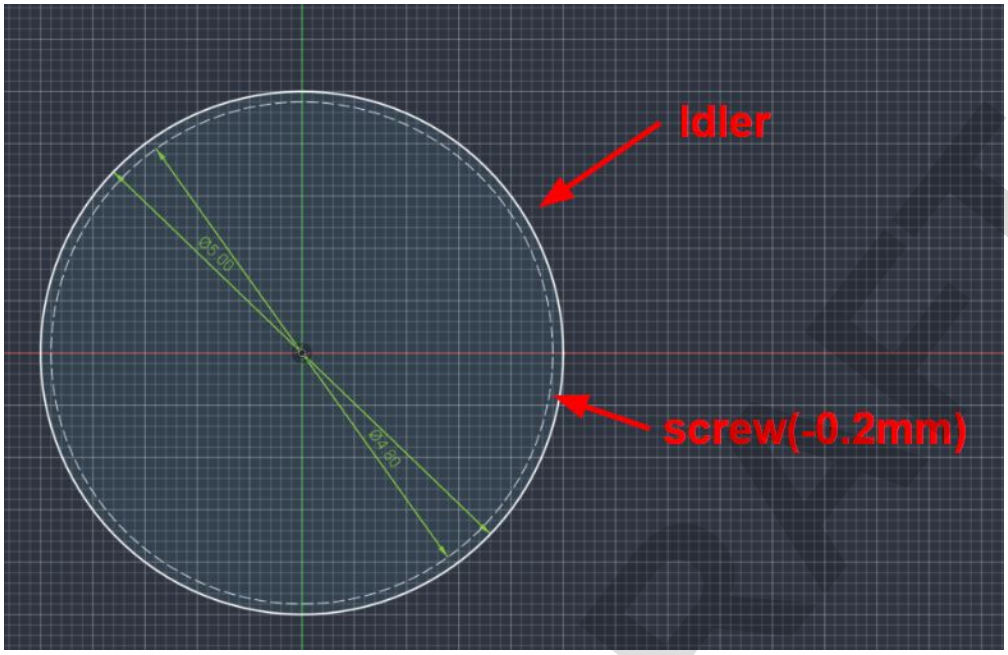



Fig 15: Eccentric idler mounting via M5 screws

Due to the fact that most layer stacking anomalies that show up on colloquially “bad quality” prints are usually deviations of a couple dozen microns, a runout of up to 0.2mm on every idler can make this issue worse, thus creating the need for such precision for idlers.

The belts in a 3D-Printer system also require some form of tensioning. The tension of the belts is important for print quality; too much slack, and the printer will struggle with accuracy and precision, and too tight, and the whole system will struggle to move. Tensioning needs to be done via some mechanism in the XY assembly. There are many ways to approach a belt tensioning system, but to save space, it is important to integrate them into the CAD assembly as well wherever other idler pins are located and mounted. To make tensioning absolutely precise, a tensioning screw is used to push the tensioning idler back and forth.

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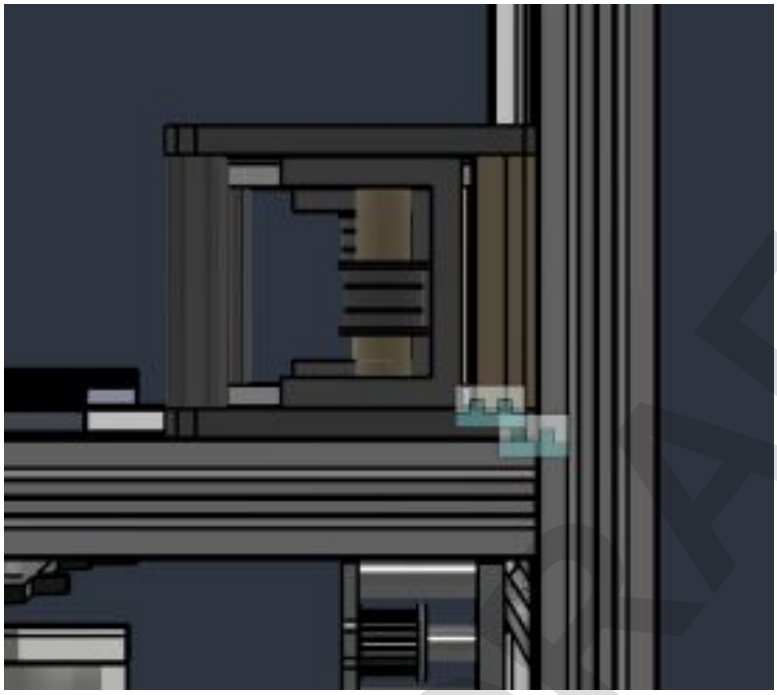


Fig 16: Tensioning assembly example

Belt width is important for how CORE-XY assembles. Many 3D printers on the market today use 6mm GT2 or 2GT belts. There are many issues with using smaller 6mm belts, namely the fact that tensioning becomes harder as the tensioning force enforced by tensioner blocks stretches the belt rather than reducing its footprint. This necessitates the use of 9mm belts or even larger 12mm belts to avoid stretch. The quality of these belts is also reflective of their manufacturers, as authentic belts from manufacturers like Gates or Runice have materials like Kevlar and glass infused to reduce stretching in comparison to counterfeit or cheap belts. Idlers need to factor the widths of these belts. The pitch of the belt also matters a lot for print quality. Resonances that show up on 3D-prints are often spaced out relative to the pitch of their belts. For example, a 2mm pitch belt(GT2 or 2GT) will leave resonances that are 2mm apart from each other.

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Fig 17: Different Belt Pitches yield different results on 3D-prints

The movement of components in the XY axis as well as the Z axis also requires some sort of guiding rail. In the past, many machines would try to use cheap bearing rollers or linear rails for the movement of components like the toolhead and gantry. While these options did work to some extent, it is superior to use CNC-grade linear rails such as those from HIWIN. These rails use two rows of balls on either end of the block to precisely guide it on the rail while minimizing friction. It is also important to understand the preload of the balls inside the block, as a high preload will increase friction while also allowing for a slight increase in precision. Preload itself, as a concept, is based on small increments in ball size inside linear rail systems to manipulate the variables described. In normal 3D-printing applications, high preload blocks are not necessarily needed, and it is suggested to use low-preload blocks to ensure smooth and fast movement. Linear rails also come in a wide variety of different sizes. In the HIWIN MGN series, for example, each linear rail code starts with an MGN and is followed by a number that represents the width of its respective rail, such as “MGN-15” or “MGN-9”. In smaller printers, where the load on bearing blocks is relatively low, MGN-9 rails are typically used. However, in larger

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printers, such as the one being built in this study, MGN-12 or even MGN-15 rails will have to be used to account for the different loads of 3D printing applications.

MGN-15 rails will have to be used to account for the different loads of 3D printing applications. For example, the rail on the gantry(x-axis) of a 3D printer is often subject to torsional force applied from the nozzle during a collision with a part or the bed during the first layer, which implies that a larger MGN rail should be used to handle it. Similarly, on the Y-axis, the rail could be subject to a static load from the gantry, especially on larger 3D-printers, which also necessitates a larger rail. Another factor to consider while using linear rails is lubrication. Without lubrication, especially in high-speed 3D-printing applications, the balls in the block can often develop flat spots that will create major issues in the movement of components; thus, it is suggested to use whatever type of lubricant is specified by the manufacturer of the linear rails.

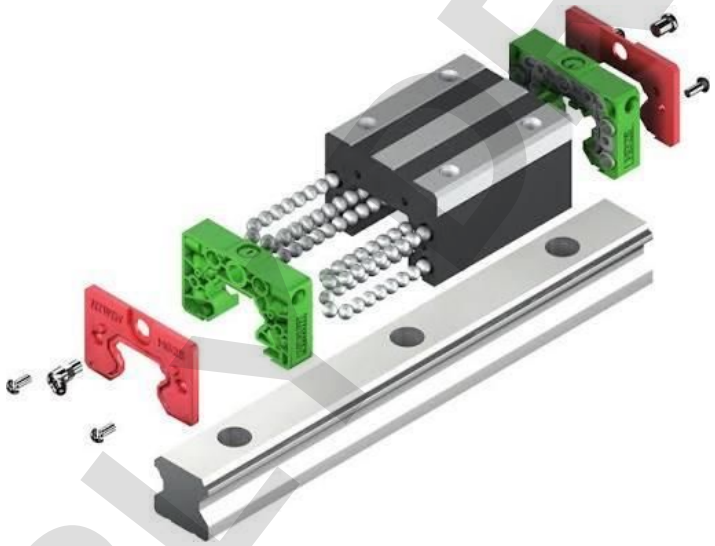


Fig 18: Exploded view of a HIWIN linear rail

The X-axis on a 3D-printer is usually the gantry, where the toolhead is attached to a rail, and it moves from left to right. The gantry itself is an important element in the design of any 3D printer, as it has to be light enough to achieve higher speeds. Still, it should also be able to handle the torsional forces from nozzle collisions, as discussed earlier. In the past, many 3D printers used aluminum extrusion for their gantry; however, aluminum extrusions are not very good at handling torsional forces, as their shape does not help stop rotational force.

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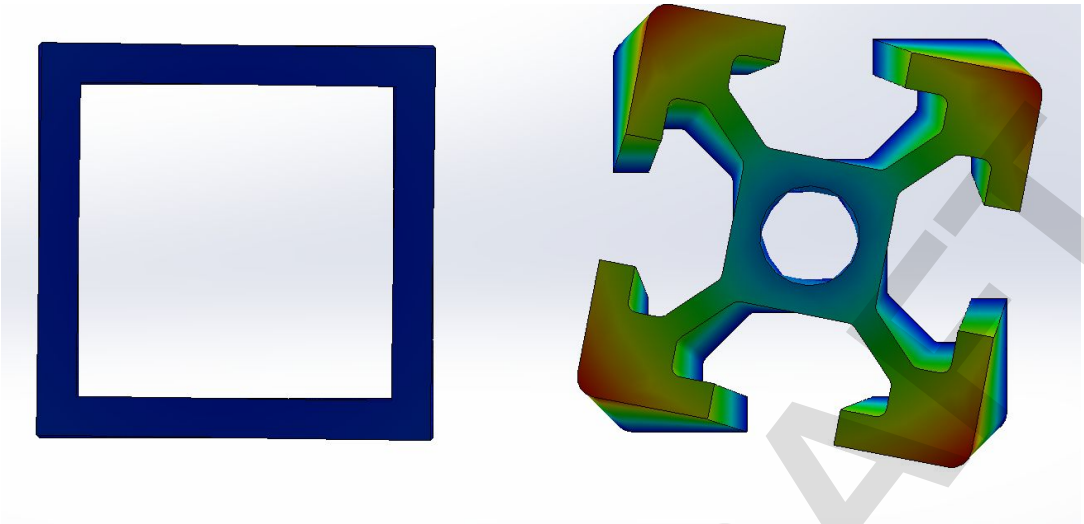


Fig 19: Torsional forces create higher deformation in aluminum extrusions than in aluminum tubing

Aluminum tubing, on the other hand, has a square shape that creates stiff resistance to any torsional force, as it would have to combat 4 right corners to create any form of deformation. In essence, this makes tubing a superior option but also creates fabrication complexity because holes need to be drilled for mounting components. Additionally, the gantry itself can also be subject to an " ice cream sandwich " design where metal plates can be installed on either end to mount idlers for a CORE-XY system.

The toolhead is another major component in any 3D printer, and its design will have a major effect on high-speed 3D-printing. The first requirement is high flow, which is needed for high-speed 3D-printing. This is usually achieved with a strong extruder. This component uses a motor, often with a geared configuration, to push filament, as well as a hotend with a large heating zone to amplify flow. The second major consideration is the overall weight of the toolhead. According to Newton's second law, to achieve the highest level of acceleration with a constant force, the mass of the object needs to be lowered (F = MA; A = F/M). In addition to weight, the components of the toolhead must align properly to have a center of mass that is directly in the line of motion. If the center of mass is deviated in any way, then the resonances from the constant acceleration and deceleration of the toolhead will translate directly into the print due to inertia. By virtue of this, it is easier to mount the linear rail facing forwards on the

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gantry(X-axis) rather than on the top or the bottom, as it would push the center of mass in either direction.

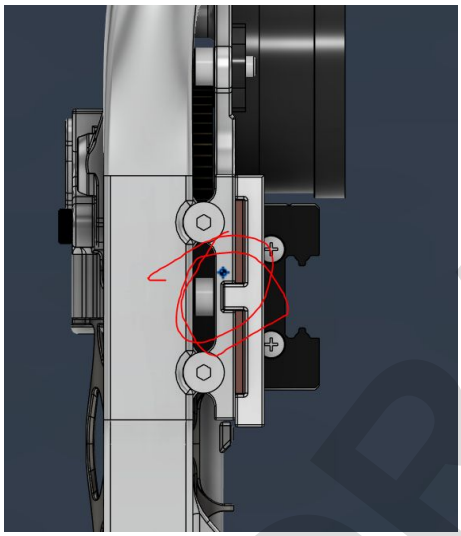


Fig 20: A 3D-printer toolhead with a proper center of mass

The best way to effectively account for center of mass in a 3D-printer is to take precise account of the material type that each component has, for a precise analysis. The toolhead also needs a way to cool the filament as it comes outside of the hotend. Some materials need less cooling and others more, but for high-speed applications, high volumes of air are needed. There are two ways to approach this issue: either mounting the cooling fans directly on the toolhead, or using a CPAP tube to direct air with an external fan. The only added benefit of mounting cooling fans directly onto the toolhead is a slight loss in complexity, as mounting the fans would cause a major change in center of mass, it would add more mass to the toolhead, and the fans have to be small to preserve its footprint, meaning that they will not produce a high volume of air for cooling. In this regard, CPAP is far superior, as CPAP fan systems can deliver a high amount of air mass, especially when paired with a filter that can utilize the venturi effect to increase airspeed.

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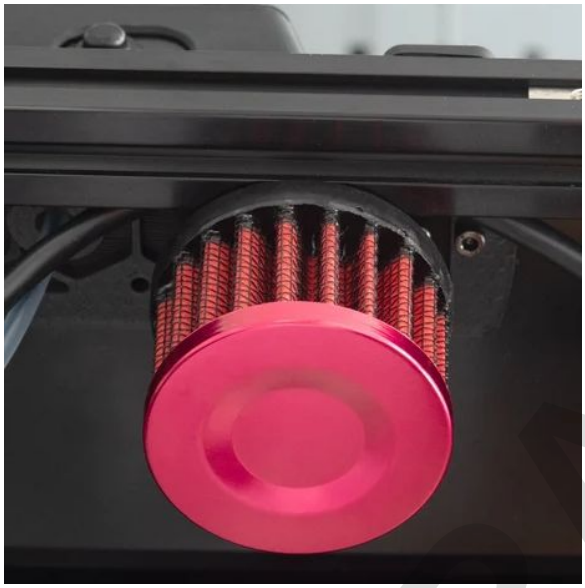


Fig 21: A CPAP system that uses an air filter to increase air speed via the venturi effect

The ducts that fan systems use to transfer air to the hotend are also very important to consider. There are two different routes to approach this problem. In some 3D-printing applications, such as for large parts, ducts should be optimized to spread air out to cool large areas around the hotend. In other 3D-printing applications, such as for parts that need a high degree of detail, it might be necessary to have a duct that directs air straight towards the nozzle, where the filament could be cooled immediately. Whichever way a duct could be designed to address both of these scenarios, it is also important to create a path of least resistance for the air inside the duct, which means that the air should not make any dramatic turns and should not have to go through areas of smaller or larger volumes(where the airspeed and volume of air can change correspondingly)

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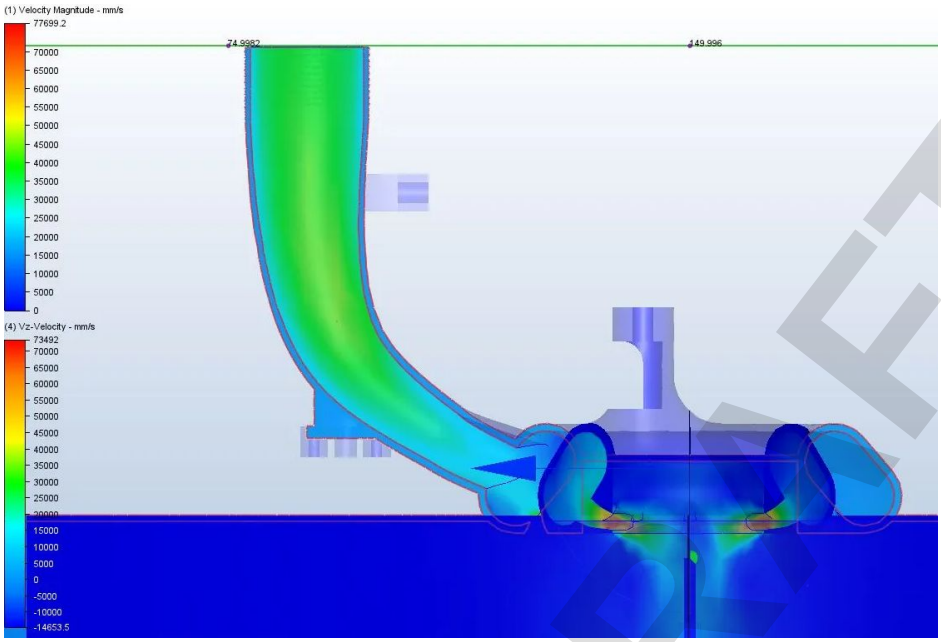



Fig 22: Software can be used to assess airflow through a CPAP duct, to find regions of resistance

The Z-axis of a 3D-printer needs to consider the mode of movement. In the X and Y axes, it is common to use belts, but in the Z-axis, it is common to use a leadscrew, ballscrew, or a belted system. Leadscrews are commonly used in applications where extreme precision is not needed, and where budget is a high consideration. This means they often cannot handle high loads and are not as precise, as they are very thin and can be bent easily. Ballscrews are far superior, as they are used in high-precision CNC applications. They are the simplest form of z-axis movement, as they simply need to be turned by a motor. They can handle extremely large loads, but they are very costly when it comes to precision, as there are almost 6 different grades of ballscrews, and the highest precision grade is usually priced in the hundreds of dollars. Since ballscrews are usually made of very thick metal, they also exert a high axial force in their rotation based on how imprecise they are. These axial forces can bend the frame around them, which can cause problems with further use. Another issue is that these ballscrews have a high footprint for coupling, and a fully coupled system with a motor and screw can take almost 70mm of movement from the axis. Lastly, ballscrews require a high amount of maintenance with

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lubrication, and it is almost impossible to rebuild a ballscrew block should there be a need to do so.

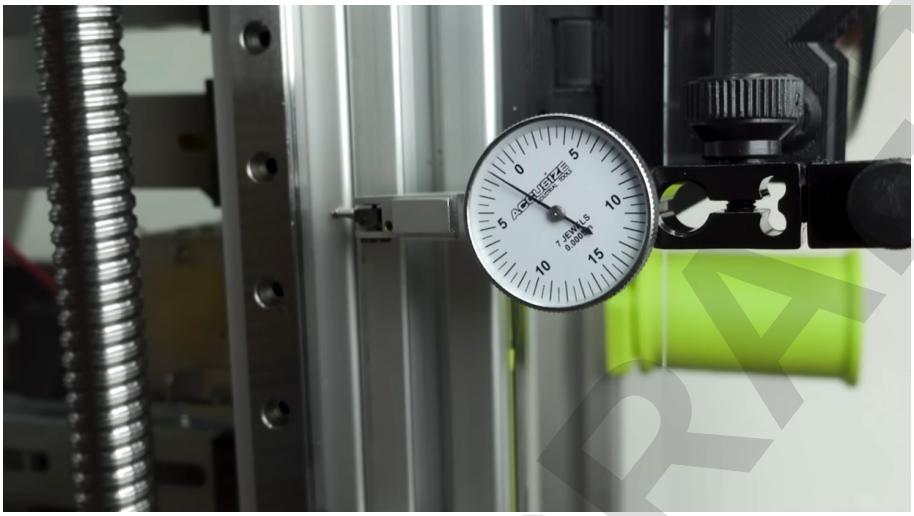


Figure 23: Ballscrews used in a 3D-Printer project called the “Hev-Ort” cause bending in the frame as they move up

The last option is using a belted system. As shown in the X and Y axes, belts are extremely cheap and precise by virtue of their simplicity. Good quality belts are usually made of a mix of rubber and Kevlar, and since they can bend and are fluid, they can’t cause any mechanical bending of anything around them. A belted system is also very fast; ballscrews inherit some sort of mechanical advantage due to their pitch and threads, but belts can be moved quite quickly, which can be important in 3D-printing applications. A major issue with a belted system is that belts can not tolerate high loads. In fact, when a motor loses its holding torque after a machine is turned off, for example, nothing is stopping the belts from slipping and causing the bed to fall. This generally means that a belted system needs to have a gearbox to create enough mechanical advantage to stop the force of gravity from the bed.

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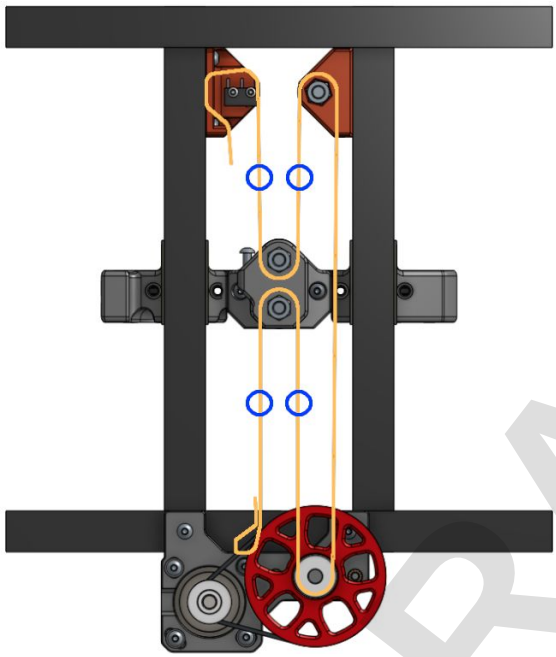


Figure 24: Belted systems use a gearbox to counteract the force of gravity from the bed

The next thing to consider is the actual mounting of the bed itself. The common way is with two drive motors, moving the bed up while the bed is firmly mounted to its movement system.



Figure 25: Classical Z-axis movement system

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One major issue of a classical Z-axis system is racking. For the sake of explanation, suppose that one of the blocks on the movement to the right is higher than the left. There is no way for this system to compensate if the difference between them is high. Another issue is the coupling of the bed to the movement itself; even a small difference(from left to right) of just 0.2 mm could require lots of software and probing compensation. Overall, a classical system creates too many constraints, which makes any form of tramming to precision impossible. A possible solution to this problem is by using a Maxwell kinematic joint.

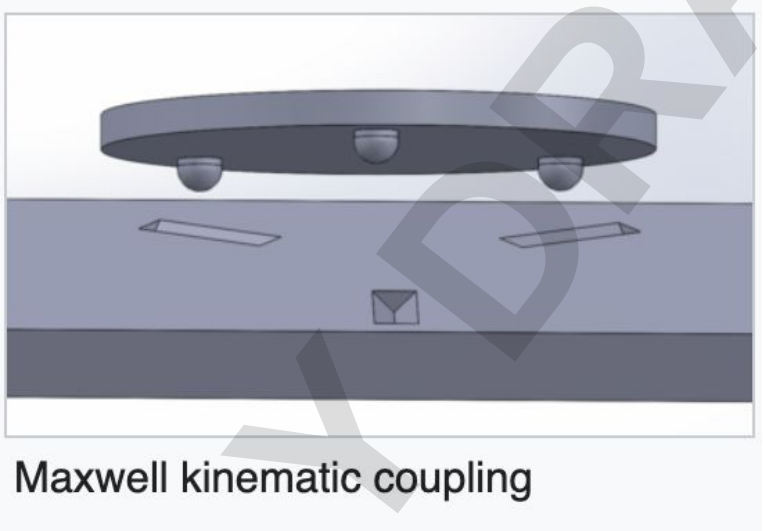



Figure 26: Maxwell kinematic Joint

Most Maxwell kinematic systems use 3 points of movement or 3 joints, whilst others can use up to 4 joints based on configuration. Each joint is usually a ball joint, as its movement needs to allow the bed to tilt in multiple directions, and the grooves that each ball joint rides on allow the bed to tilt by compensating for the change in distance. In addition, each joint has its own actuator (usually a motor and a belt) which moves on its own. The benefits of such a system are that it properly constrains the bed during printing and it does not require precise alignment to avoid tilt, as each joint on the kinematic system can be adjusted as each actuator moves it up or down. This means that with a probe, 3D-printing software can identify areas of tilt and compensate for them. In more niche applications, a bed mounted on a Maxwell kinematic system can also be used for non-planar 3D-printing where the layers are more fluid.

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The design process then moved onto the motion system in the x and y axes. The first step was a full 2D design, then all the parts in the 2D design were extruded into sheet metal plates in CAD software. The spacing of these plates is used to cater to the width of these belts, which are 9 mm belts for high-speed movement and proper tensioning.

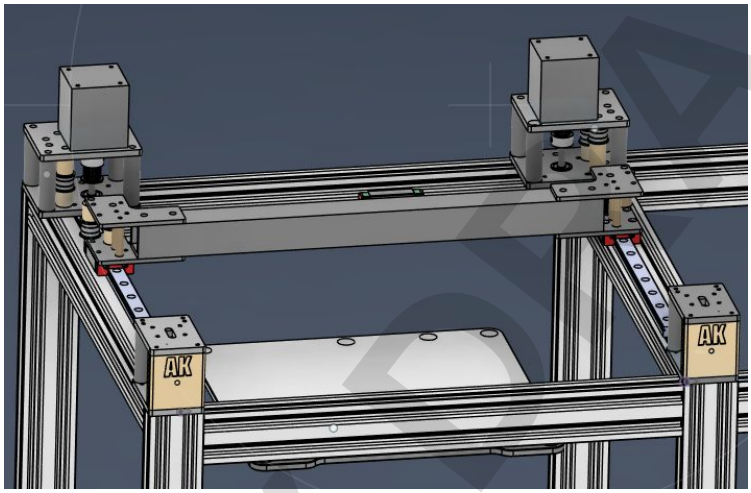
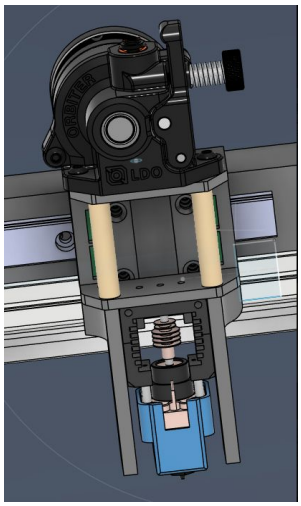



Fig 27: Barebones motion system

The toolhead was the next challenging part. It needs to be designed around a proper center of mass (COM) but also be space-efficient. The common theme of the first design and among all other designs is the usage of metal 3D-printed parts. The whole body of the first design and all designs after use an SLM metal 3D-printed part

.



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Fig 28: First toolhead design.

The space in between the small hotend and the extruder was neither necessary nor effective for a proper center of mass. So the extruder was changed to a lighter “VZ-hextrudort,” and the hotend was changed to a larger “VZ Goliath” hotend. To maintain a proper center of mass, the extruder was rotated to distribute the mass evenly. The larger hotend also pushed the center of mass down, as the concentration was largely upwards at that point. It also has the added benefit of having a large melting zone(one of the largest of any hotend on the market today)

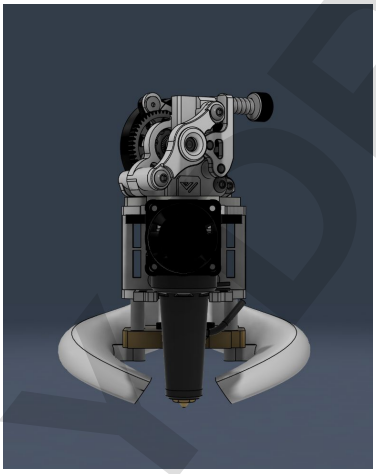


Fig 29: Toolhead with revised components

The next step was to design the cooling ducts. Proper analysis of airflow was not done, but the design process followed the typical intuition that all ducts need to gradually flow the air rather than making any dramatic change in air direction. To design a duct with such an organic flow, a 3D spline needs to be used in Fusion 360, and a profile extruded alongside it. The profile of the duct itself was relatively thick to push the COM down and create rigidity if there was a collision during the print. At this point, the COM is still not aligned in the proper direction, so the mounting plate for the probe was replaced with a thick brass plate that successfully pushed the COM down to the right position.

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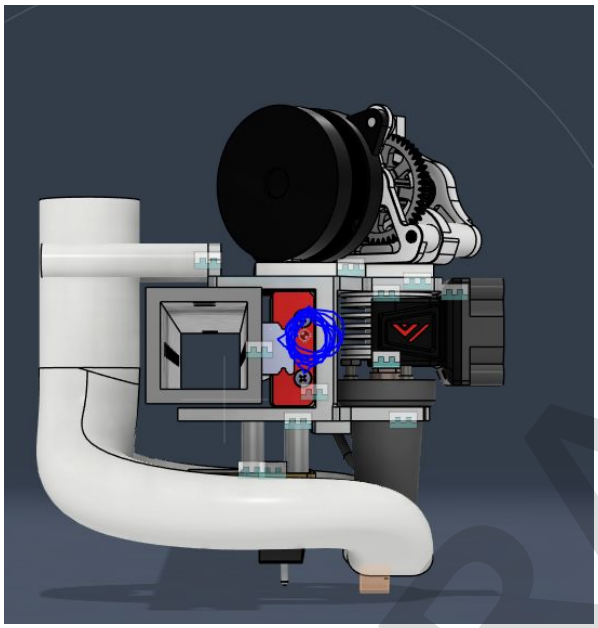
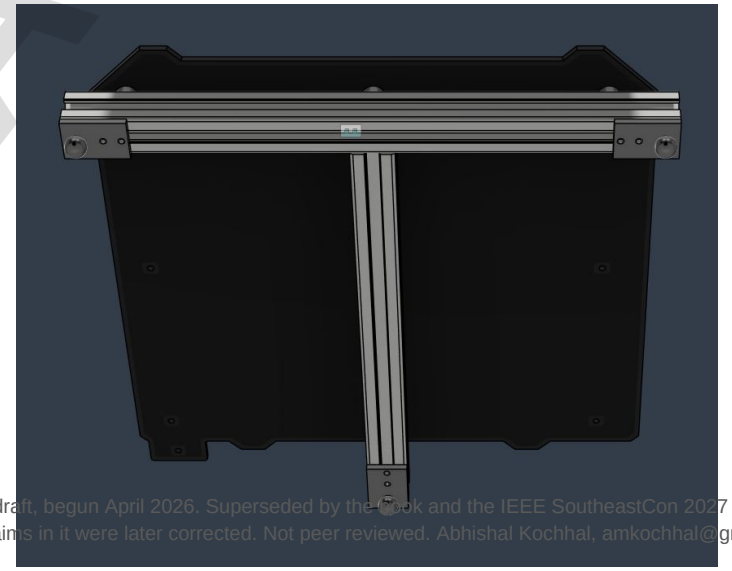


Fig 30: The center of mass(the black and white circle) encircled by the visual blue circle is properly in front of the direction of motion, which is in front of the x carriage.

After the toolhead was finished, the next step was to design the z-axis. The expected bed size was drawn in a 2D sketch, and the exact positions of the joints were estimated. To create a Maxwell kinematic system, the joints have to be positioned in an isosceles-like triangle. The bed itself was a major issue in the design process. The cost-effective way was to use a cheap PCB bed from Prusa, but for later testing and others', PCB beds are far inferior to thick MIC-6 aluminum plates that are far flatter and more resistant to warping from heat over time. The usage of a PCB bed necessitates some sort of rack to position it relative to the joints, which follows the same isosceles configuration.

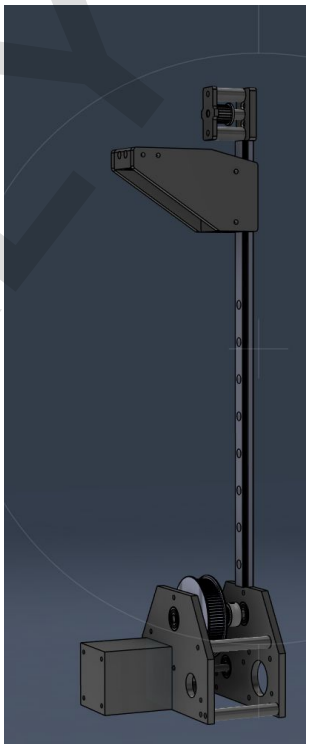


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Early draft, begun April 2026. Superseded by the book and the IEEE SoutheastCon 2027 paper;
some claims in it were later corrected. Not peer reviewed. Abhishal Kochhal, amkochhal@gmail.com

Fig 31: Bed rack that allows isosceles joint configuration

The actuators that are used to move each joint were designed around the belt configuration. Not only because a ball-screw configuration would take up additional space, but also because a ball-screw configuration does not have to rely on extremely expensive and precise ballscrews. The gearbox, which is needed to create mechanical advantage to stop the bed from falling, was designed in a similar “Ice-Cream Sandwich" configuration with sheet metal and uses belts instead of actual gears to limit backlash in a 1:5 ratio. The main belt would run through the carriage where a set of teeth would latch onto it for movement and would wrap around an idler at the end.



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Fig 32: Belted Z-axis configuration with all 3 major components, the gearbox(that uses belts), the carriage, and the idler at the end

## Construction and Design Implementation

To thoroughly understand every relevant system in the construction, it is important to map everything out via a graph.

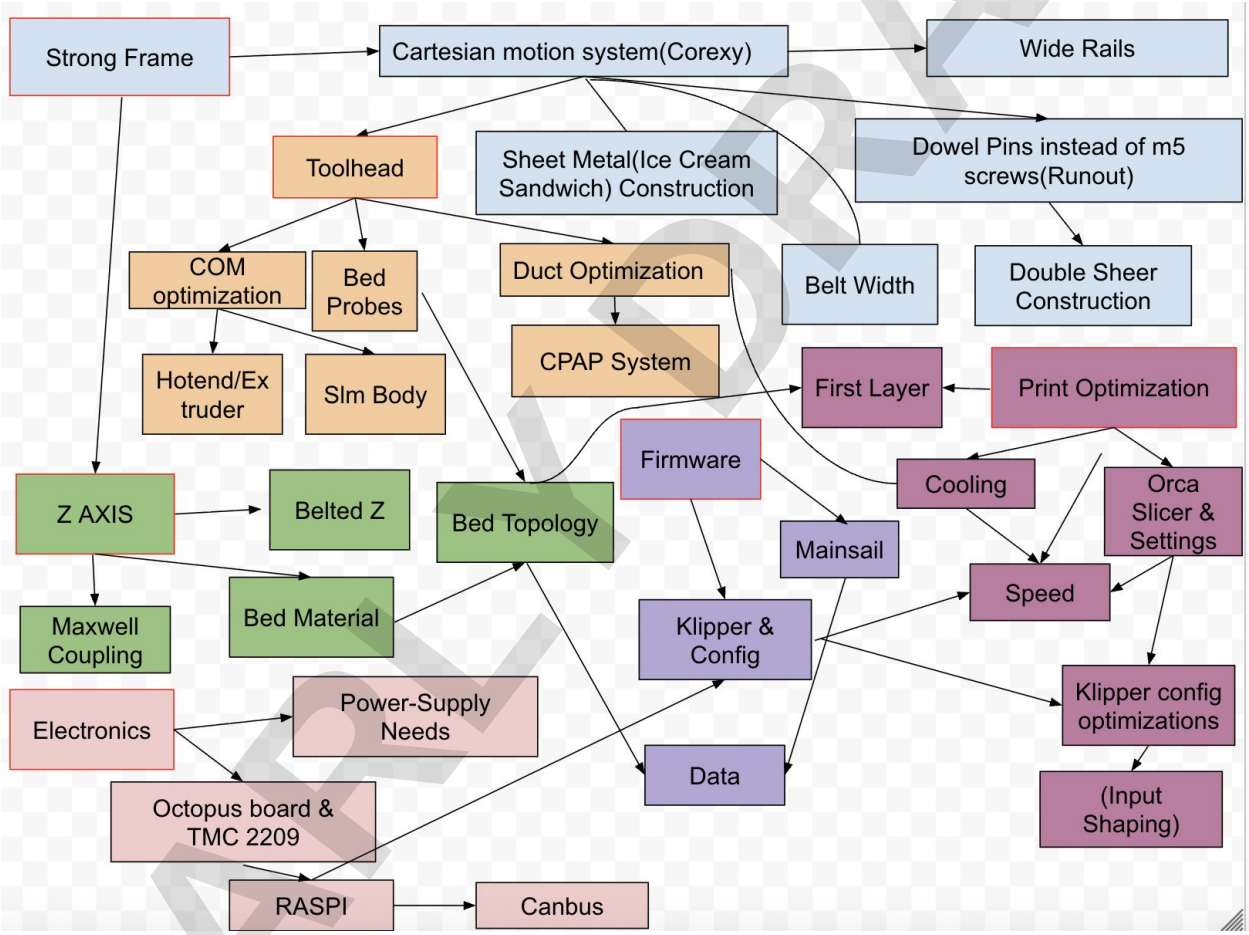
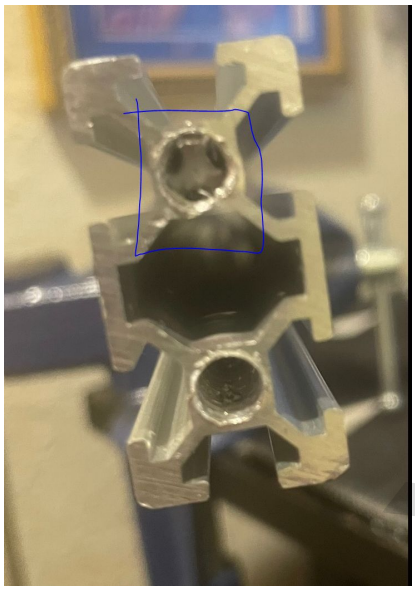



Fig 33: Total design and build graph

In the beginning, the build started with a sturdy frame of 2040 extrusion sourced from AliExpress in China. One major goal at the start of the build was to use blind joints. Blind joints were used to construct both the left and the right sub-assemblies(or the left and right profiles of

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the frame itself). As the frame construction progressed, many analyses were done where the frame was compared with a machinist square to gauge the squareness of the blind joints. What was found was that some blind joints were square, but others were not. This is primarily because the tapping process for the blind joints often needs to be done by hand, which can be subject to human error, as well as the fact that most hand taps cannot tap deep enough to make blind joints the best possible solution. In addition, the worst part about using this process is that it is impossible to trim blind joints if they do produce an unsquare connection.



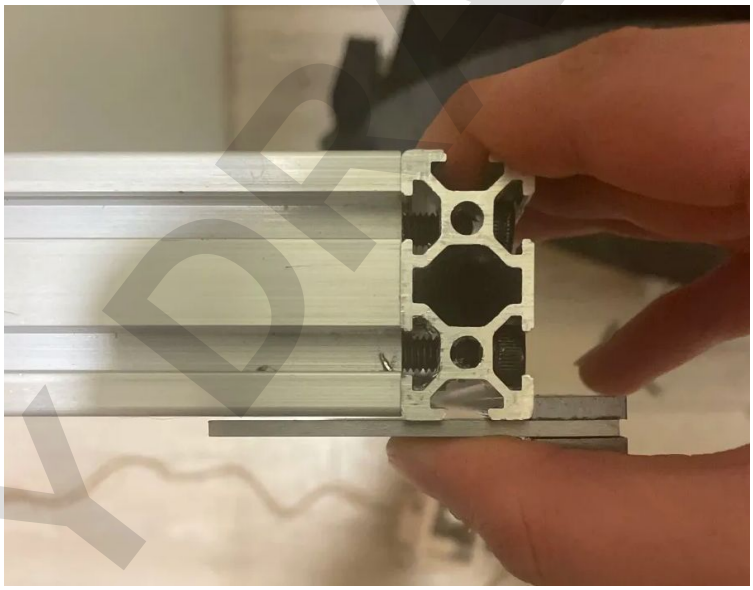
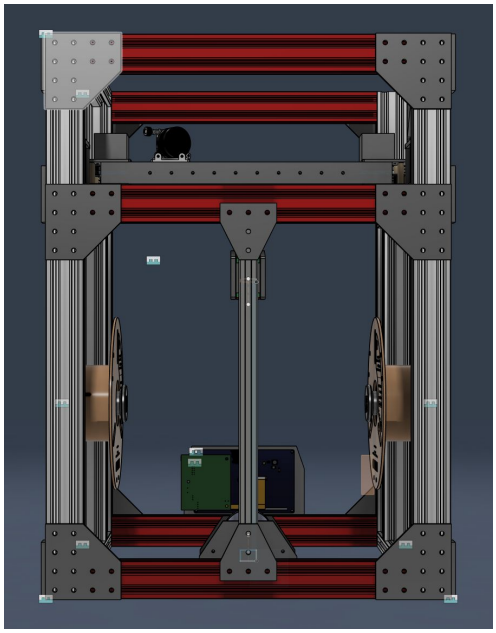


Fig 34: Blind joints created a major shift in extrusions that could not be adjusted for

Fig 35: Hand-Tapping tool gets stuck inside extrusion in attempt to have deep threads(for a strong joint) even when oil is used

This issue with blind joints led the construction to start using gusset plates instead, as they can provide high-strength connections that can also be trammed properly. Since blind joints can not connect 3 extrusions in 3 ways, both a blind joint construction and a gusset-joint construction have to use gussets to connect the left-right sub-assemblies.

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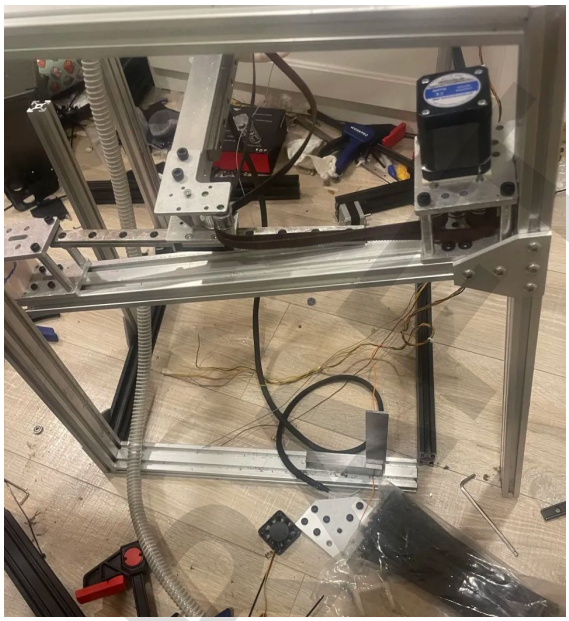


Fig 36: Middle Extrusions(Highlighted in Red) connect left and right sub-assemblies

Fig 37: Frame being reconstructed without blind joints on left and right sub-assemblies and being reconstructed with gusset plates

Once the basic shape of the frame was done, work on the XY-axis had commenced. The first step was to construct all of the sheet-metal parts in plastic to ensure reliable assembly. The parts were printed in beige PLA filament and did not provide any real insight into the design that could not be replicated in CAD software. In fact, it created even more uncertainty, as the tolerances for 3D-printing are far different than those of sheet metal cutting, which made it harder to gauge the proper sizing for the dowel pin and bearing fitting.

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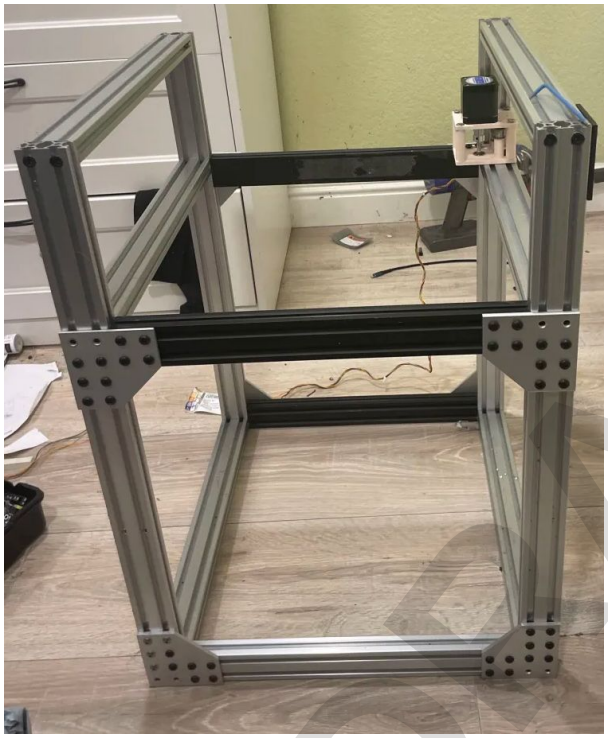


Fig 38: Finished frame with plastic-constructed motor mounts

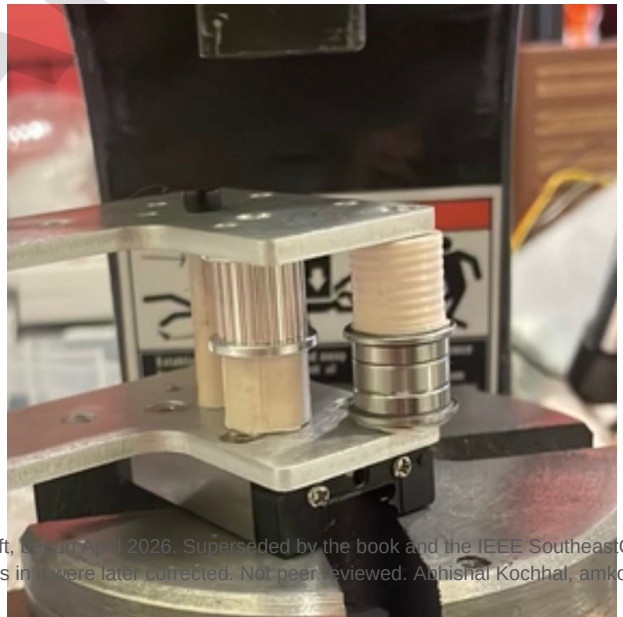
After this, the sheet metal parts were ordered, and fitment began. The uncertainty of how the dowel pins would be fitted remained. On the motor mounts, a 5mm reaming tool was used. The issue was that the part was reamed using a drill press, and the 0.05 mm runout on the spindle caused the hole to be larger than the dowel pin that was supposed to be fitted. The only two possible solutions to allow any press-fit could be to use some sort of shims or to use retaining compound. Retaining compound is often a liquid glue that is used to fill small tolerance gaps in industrial parts. Unfortunately, in this situation, the retaining compound was unable to provide any support to the larger hole, and it also did not help that the dowel pins themselves were sourced cheaply from China and were undersized by about 0.04 mm. The decision was made to use a part from a plastic bag which is about 50 micrometers thick, as a shim for the dowel pin. This system worked, and the dowel pin was successfully press-fit into the motor mount.

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Fig 39: Dowel Pin fitted with plastic shims

The uncertainty behind a proper press-fit still remained, as any angularity in the dowel pins will cause runout and a loss of positional accuracy when printing. It is obvious that to do a press fit, there needs to be an interference fit, but how much was still a problem. Other press-fits were done at a -0.2 mm tolerance,e which created angularity, as it requires an incredible amount of force even with an arbor press. Out of all the press-fits that were done, none of them were a reliable press fit and were only one of the two extremes. Another factor to consider during the press fitting process was the top plates in an “Ice-Cream Sandwich” configuration. These top plates are not only press-fitted onto the dowels but also bolted down, so either extreme, too large or too small, would make the build process extremely tedious and uncertain.



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Early draft, circa April 2026. Superseded by the book and the IEEE SoutheastCon 2027 paper;
some claims in it were later corrected. Not peer reviewed. Abhishal Kochhal, amkochhal@gmail.com

Fig 40: Assembly of X-Axis bearing mounts via an arbor press

Another issue with tolerances was with the tensioning blocks. Since the dowel pins had to move back and forth with the tensioner, the design included a slot for the dowel pin to slide through. The design intentionally oversized the slot to stop the dowel from seizing if it was too small, which could be another potential source of a loss of positional accuracy.

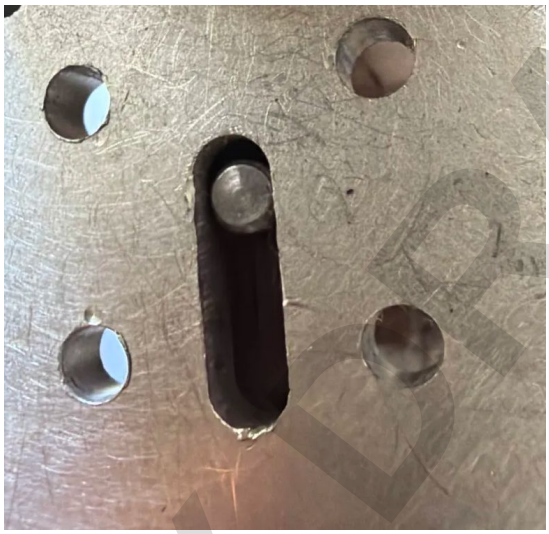


Fig 41: 0.1mm tolerance on tensioning block

After the motor and bearing mounts were finished, the focus moved onto thex-axiss. As mentioned, a tube needs to be used, so the choice was made to use a 1x1 inch steel tube. A drill press was used to drill holes into the tube using the x-axis linear rail as a jig for the drill bit. Proper jigs were also used to align the linear rail on the centerline of the tube. One major issue with using steel tubing is that it is extremely heavy, which is not optimal for high-speed 3D printing as less mass is needed. Another thing that was not done was internal standoffs. The clamping force from the screws of the linear rail can bend the tub,e which necessitates internal standoffs to counteract the force.

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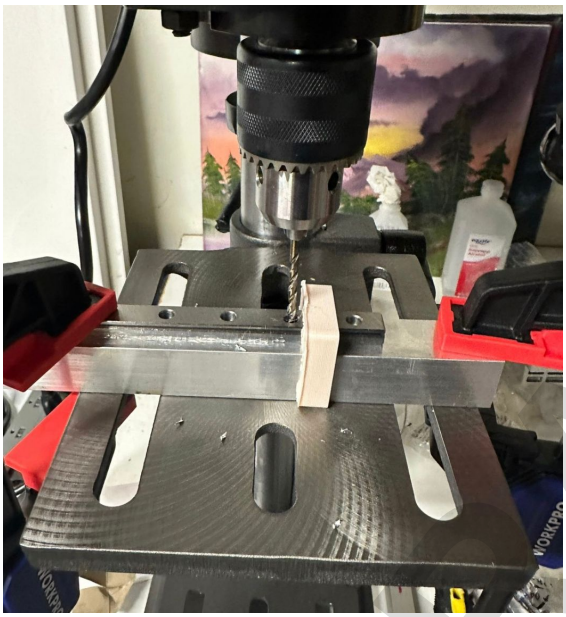
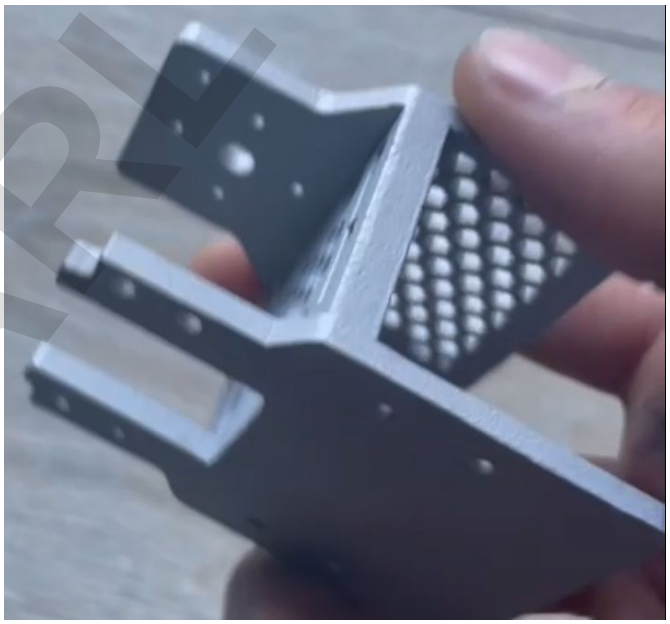


Fig 42: Drilling holes into steel tubing for X-axis on drill press

The next step in the process was to finish the toolhead. The SLM part came with proper tolerances and the design required various post-processes such as countersinking and tapping which went without difficulty.



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Fig 43: The Metal SLM toolhead part(printed in aluminum) being inspected

The duct for the toolhead was printed sideways to optimize strength; if it were printed vertically, shear between layers would be likely.

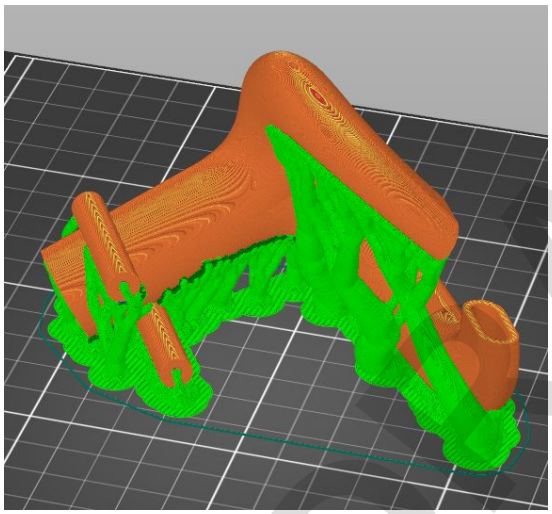


Fig 44: The first iteration of the duct being printed

To mount to the extruder, a doubler plate was required to space the hotend from the other mounting fixtures on the SLM toolhead body. This doubler plate was originally printed in PLA but later replaced with an ABS part. The issue with a 3D-printed doubler plate is that it's prone to warping from the heat transferred from other components on the toolhead.

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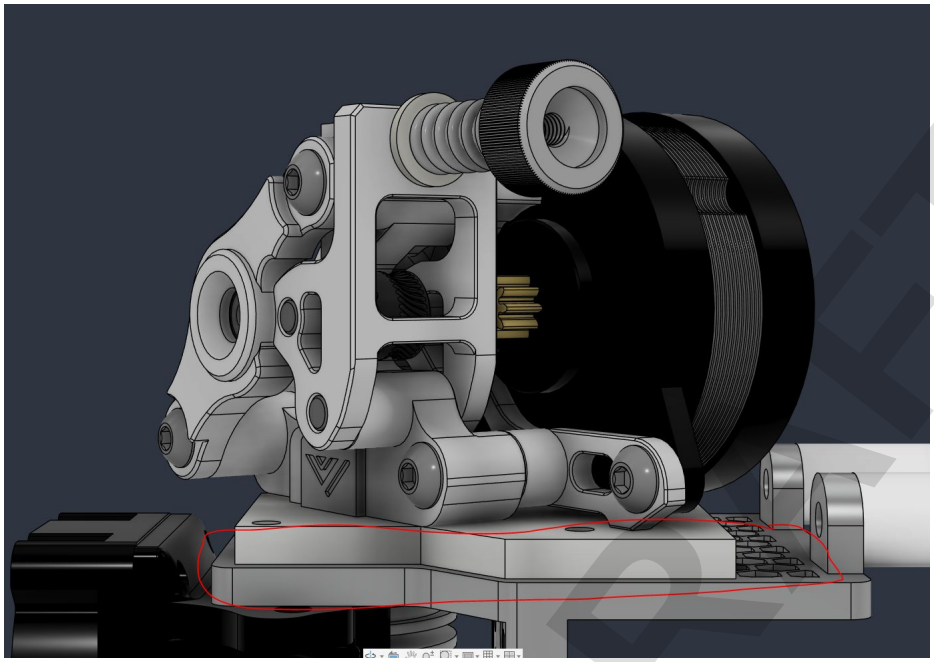


Fig 45: The doubler plate for extruder mounting

With the rail and toolhead mounted onto the X-axis assembly, the final step for the XY sub-assembly was to mount both to the Y-axis rails. The primary issue in the physical assembly in this design is ensuring parallelism between both rails. If both rails are not parallel, then the rigid X-axis will have to compress or depress(which is hard due to it being made of steel), or the forces could translate to the actual frame itself. The issue of preload also manifested itself in the physical assembly process. The linear rail systems used in most DIY machines often have too little of a preload in order to ensure smooth and fast movement, but in this design, the x-beam itself is 300mm, and any form of torsional force would have disastrous effects on the life of the balls inside the block.

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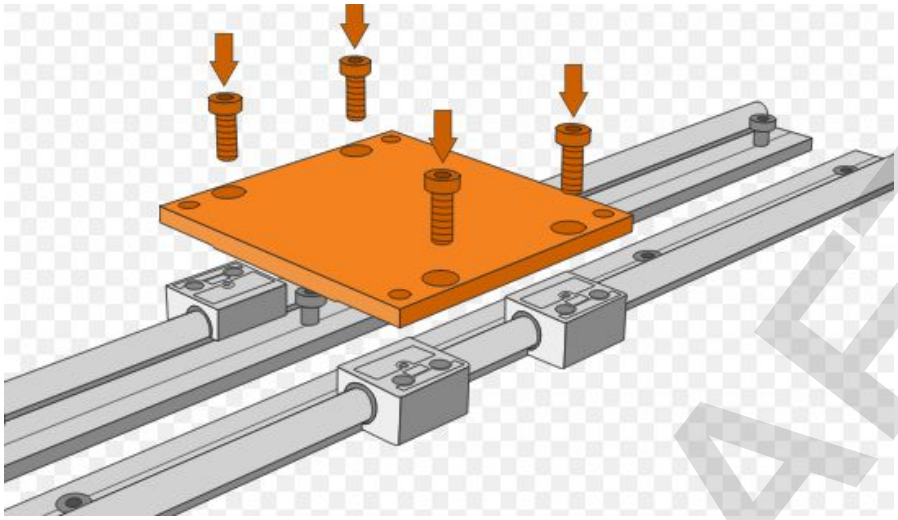


Fig 46: The necessity of parallel rails in linear applications

After the mounting was done, the next step to ensure proper movement was to lubricate every rail. According to HIWIN, the best lubricant to use on MGN series rails is “Mobil Mobilux EP1” grease,e which is a standard lubricant used in industrial applications. The grease was injected via the port inside the linear blocks, but the movement of the rails slowed down increasingly with the grease; it seemed like the viscosity was too high for high-speed applications. Additionally, when the gantry was moved on the Y-axis, a significant amount of bending in the frame occurred from left to right. This issue thus required a thorough process of reseating the rails, but absolute perfection was not accomplished. This could be because the 0.2mm tolerances in the Jigs were simply not enough to ensure proper parallelism.



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Fig 47: Bending of the frame inwardly and outwardly based on the Y position of the x-gantry due to unparallel rails.

After solving these problems with a heuristic solution, the next aim was to do the Z-axis. The actuators were first printed with PLA to ensure that the entire assembly could be properly assembled, and the system was used for the first few prints. Still, plans were made to use their respective aluminum sheet metal parts, as the PLA assemblies bent under tension. The rails used a similar jig-mounting technique, finalized with a square relative to the bottom of the frame to prevent misalignment.



Fig. 48: A 3D-printed Z-actuator and its usage on the machine, where the force of tension of the main belt was bending it.

Another critical issue discovered was tensioning the belts in the Z-axis. Each actuator has two belts. One belt, for the gear reduction, and another belt for the main belt to move the carriage up and down, connected to the reduction gear via a dowel pin. Both belts still had significant slop in

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their movement. The hardest of which was the gear reduction, so the decision was made to add a plastic hump in place of the normal standoffs, which would push the belt to give it proper tension. The main belt had issues as well; it was attached to the carriage via a set of 3D-printed teeth, but there was no tensioning mechanism, so the only form of tensioning would be through manually stretching the belt with a tool before squeezing it into the teeth.

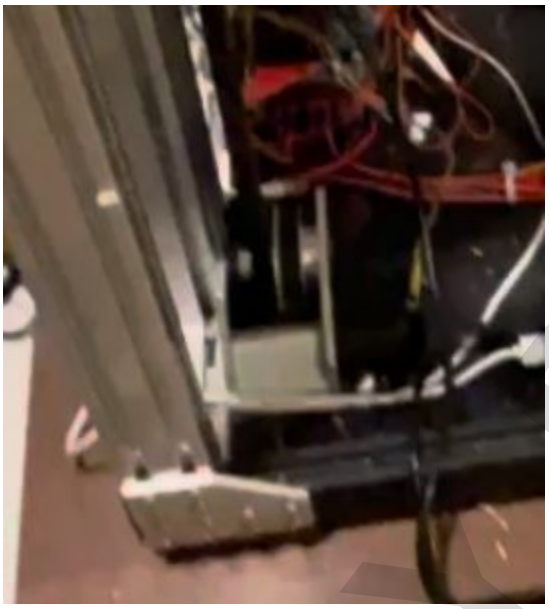




Fig 49&50: The gear reduction tensioner and the teeth part used to mount the belts.

The bed, which was mounted onto the Z-axis itself, was a PRUSA Mk 67752 bed. It is known for being relatively cheap and being a PCB bed with multiple mounting holes. The bed itself was mounted to a rack using standoffs and T-nuts, but the rack did not encompass all possible holes, only the three in the center and the two on the sides. The rack itself had balls mounted on an aluminum plate to form the Maxwell kinematic joint presented in the formal design.

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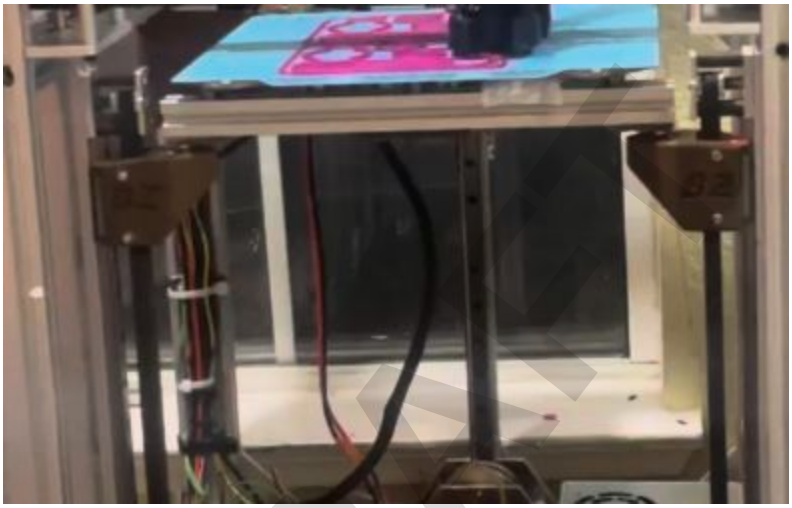
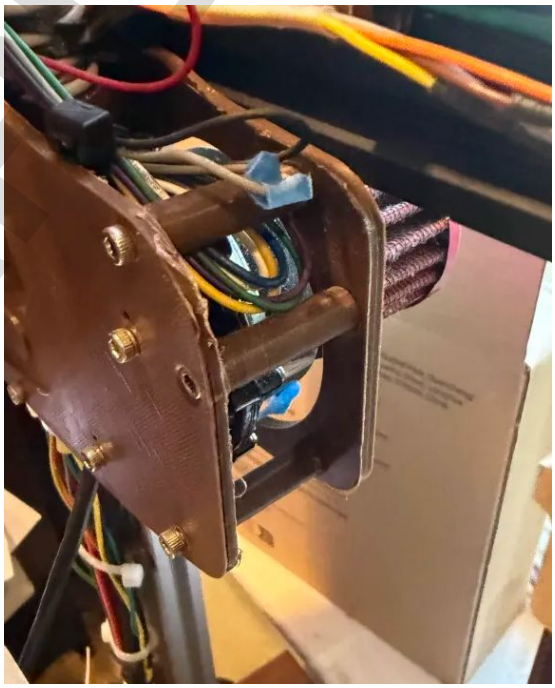


Fig 51&52: The Rack used to make the Maxwell kinematic joint and the mounting of the bed itself to the rack

The last step was to mount the CPAP cooling fan. The fan was mounted using a plastic enclosure of plates separated by standoffs, to house both the fan and its respective electronics close to it for redundancy. An opening was also designed for the filter.



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Fig 53: CPAP mounting assembly

After all the mechanical components were installed, the focus then moved to the electronics. A solid ABS sheet was mounted on the bottom of the frame for the electronics to be mounted. The first consideration of electronic components was power usage. The Mk 52 Bed requires about 220 watts at 24 volts, and the fact that the bed is 24 volts also meant that the power supply should only output 24 volts on all components for redundancy(as using different power supplies at different output voltages would make the system more complicated). The XY motors(assuming they could run at a peak of 1.5 amps) both require around 72 watts (1.5*2*24), and the Z motors would also require an additional 108 watts at the same 1.5-amp peak. The hotend, which had a large melt zone, also required a correspondingly large heater,r which was an additional 100 watts, as well as 48 watts for the extruder motor. The CPAP system would add 50 watts. All of these energy requirements combined gave a total of 550 watts. Still, there should always be some leeway for motherboard operation and the entire system itself, as it's not healthy to run a power supply at peak output for a long time. This meant that the best power-supply option could be the Meanwell LRS-600-24, which outputs a total of 600 watts at 24 volts.

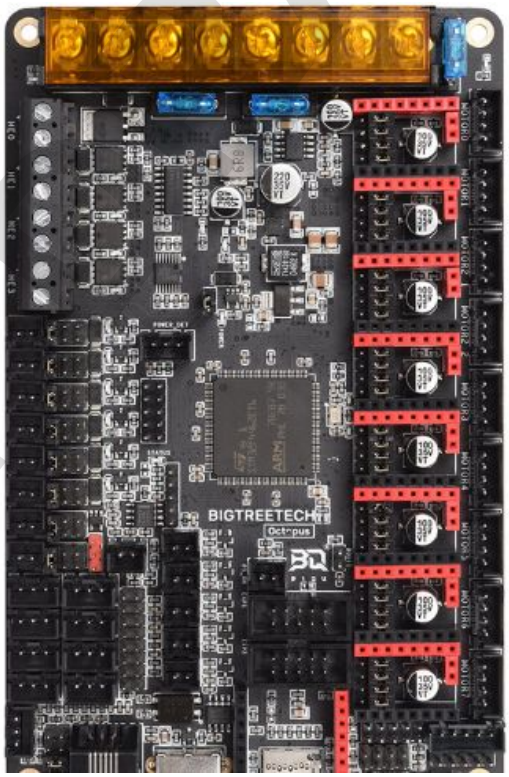
The motherboard was the next component to choose. The motherboard itself was highly contingent on the type of firmware chosen. Most DUET boards run on “RepRap” firmware, which allows for a high degree of customizability. Still, the learning curve is correspondingly high for programming the board, and DUET boards are extremely expensive (almost 3x the cost of any other board on the market). The other kind of firmware is called “Klipper,r” which is more DIY-friendly as it allows for easy programming whilst also providing relevant variables on performance and function. “Klipper” usually runs on “BigTreeTech” or “Mellow” boards, which are open source boards that are cost-effective and also have the added benefit of “hot-swap” drivers, which allow motor drivers such as TMC 2209 or TMC 5160 to be easily swapped without soldering by hand. It is also important to note that both “RepRap” firmware and “Klipper” firmware require an external computer, such as a “Raspberry Pi,” to aid in computing movements and to access the internet, through which the user can control the machine or program it via SSH. The decision was thus made to use the Klipper board from “BigTreeTech” called the “Octopus Pro 1.1”,  which offered 8 “hot-swappable” driver ports at a competitive

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price of $80, which was almost ¼ the cost of a similar Duet board. Klipper itself was also the best option in this case, as this machine had a relatively simple Cartesian motion system which did not need the detail provided by DUET boards. The drivers used were TMC 2209 drivers, as they were also relatively cheap and easy to configure. TMC 2209 drivers also had the added benefit of "load-based" homing, which meant that homing sensors would not be needed to home each axis(its position in the firmware), but rather, it would be calculated based on some load expectation. Finally, the "Raspberry Pi computer" used was a flagship "Raspberry Pi 5," which had an advanced computer with lots of memory to aid the motherboard.

Fig






54&55: Duet "RepRap boards" vs Klipper "BigTreeTech boards"

The electronics were mounted onto the ABS sheet using normal screws and plastic standoffs. Proper plastic components were also used to create a proper enclosure for the power-plug terminal that connected the AC from the wall to the power supply itself.

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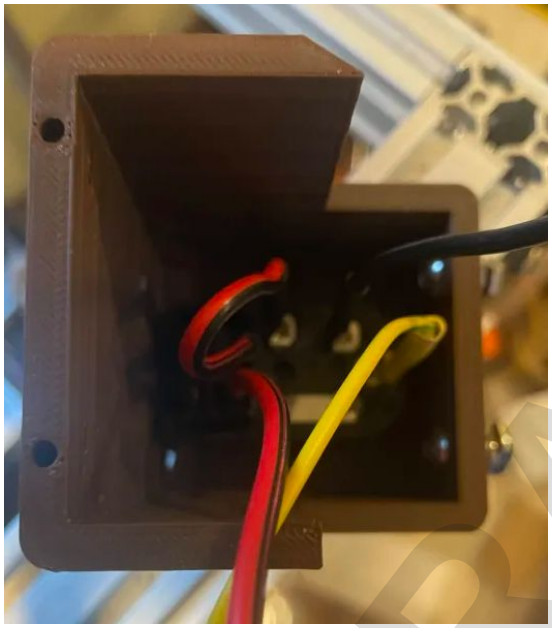


Fig 56: AC connector enclosure

The process of installing the firmware was not easy. The first roadblock was actually accessing the “Raspberry Pi” via an internet connection facilitated by a “Google Home” router. This router specifically stopped devices from interacting with each other on the network, which meant a new router was needed to allow this to happen. After that, the installation was relatively easy, as it was done according to the Klipper tutorial on the website itself. The next process was to program the board itself. To overcome the learning curve, each sub-assembly was programmed incrementally. A graph is used to show the main considerations in the incremental programming process.

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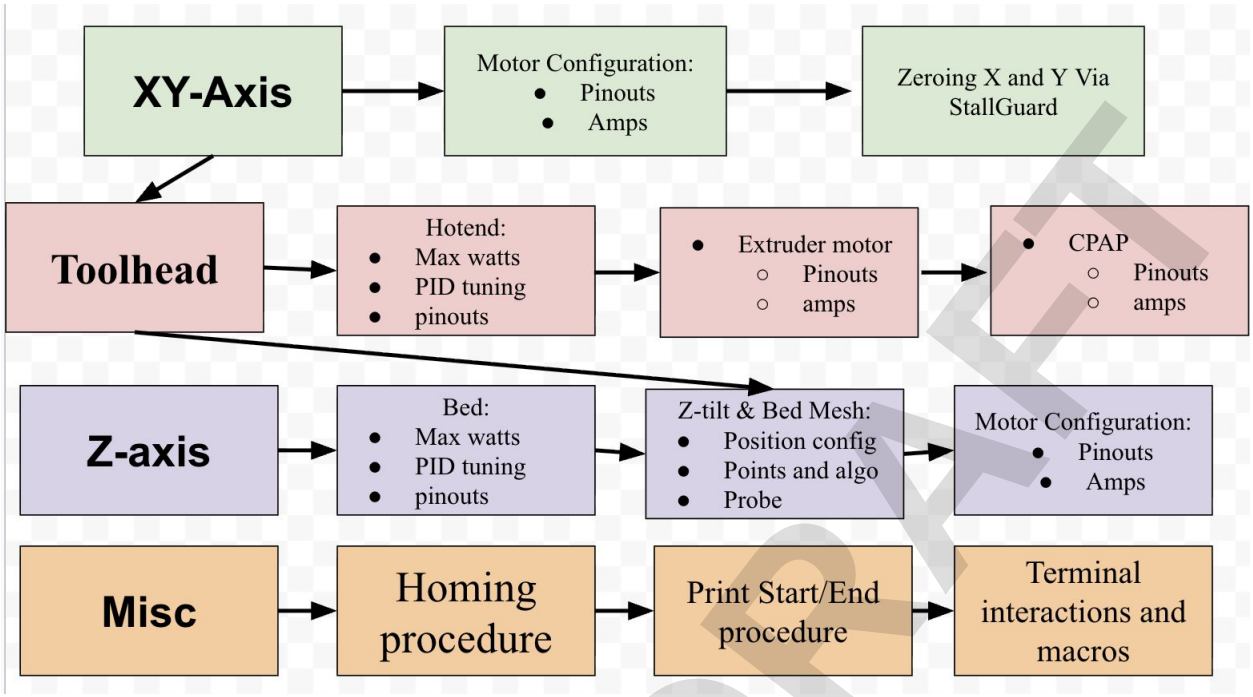
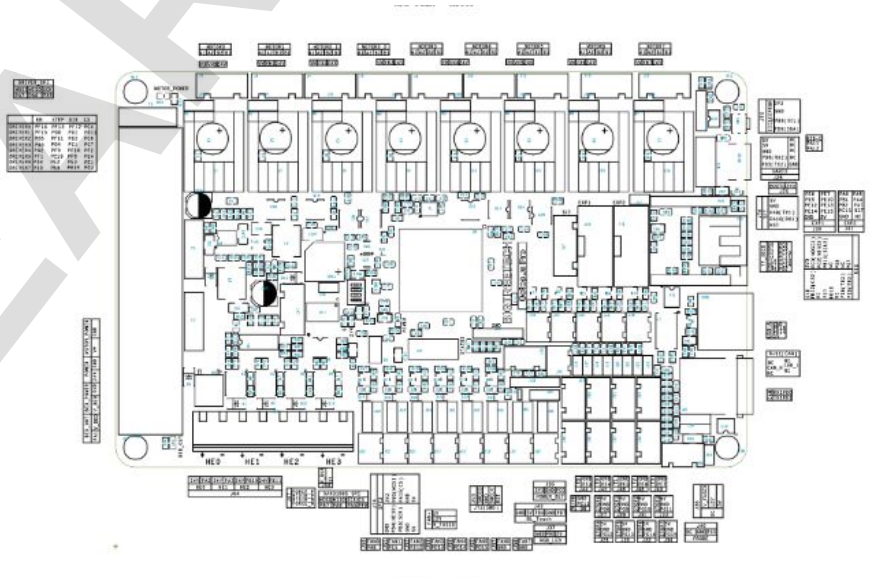



Fig 57: Incremental programming process divided by sub-assembly and relevant categories for each

The first section was the XY axis. It started by importing the program configuration of a similar machine that used similar motors and drivers as the design, and the Klipper WIKI was referenced to understand the meaning of each variable and configure them for my machine. Another part of programming each sub-assembly was matching each electrical component's connection to the motherboard, and mapping it into the program via a pinout map of the board itself.



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Fig 58: Pinout map for the “Octopus Pro 1.1” where each pin would be mapped to its respective component in the firmware

The mapping of the motors was relatively easy, and the “Stall Guard” Threshold was meticulously set via trial and error to find the value that allowed for effective homing. The next step was configuring everything related to the toolhead. Each pin for the thermistor, heater, extruder, cCPAP system, hotend fan, and probe was mapped using the diagram into the program. Max power usage was also assigned for each component as before. The probe already had its own programming from the manufacturer, so all I had to do was assign its pinout, and I was done.

The next part of the process was the Z-axis. The first thing I did was assign each motor its pins and amps, just like before. Then I had to configure the Z-Tilt feature, which is specific to the Maxwell kinematic joint. The three positions of each ball joint in the kinematic system were plugged into the program, and each point corresponded with the motors themselves. The procedure was then set to create a macro for Z-tilt before the bed mesh itself for every print. Unlike the XY axes,s however, the Z axis is not homed via “Stall Guard; rather, the bed is fully homed when it comes in contact with the probe. The bed mesh, which is also a result of the probe, also has two important aspects: mesh points and mesh algorithm. Since my probe was a slow “BL-Touch probe”, which requires the probe to touch every single point physically, it would take a long time to probe along many points on the bed, so there had to be an optimization to take the least amount of time. The other important factor is the mesh algorithm: the normal Lagrange algorithm can only take a maximum of 6 points and draws specific polygons between the points to interpret them, while the other algorithm is called “Bicubic”, where there could be an infinite amount of probed points on either axis. Each point is interpolated via a curve that can be adjusted with the “Bicubic tension”. According to many Klipper users, Bicubic seems to be the most superior algorithm as it allows for the most optimization.

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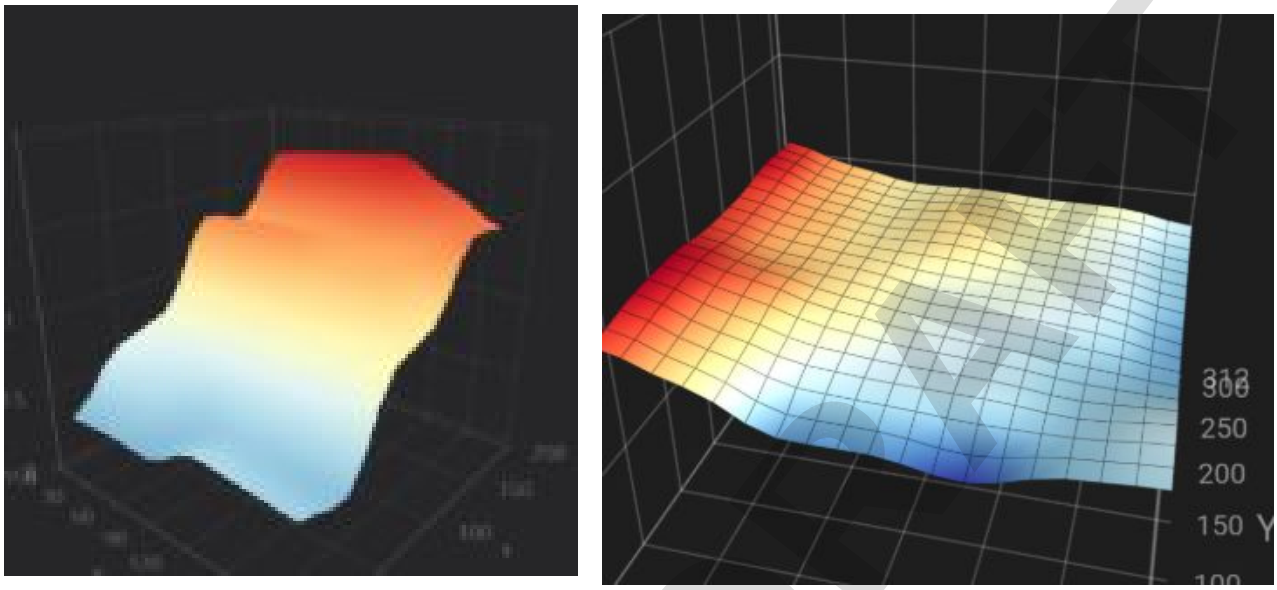



Fig 59: Lagrange vs Bicubic interpolation

There is a near-infinite amount of detail that can be done for programming the firmware of a machine. Still, a simple methodology outlined above can be characterized in a simple list:

1. Copy and paste the Config program from another printer that is similar to the design
2. Map the pins from each design and, through trial and error, solve whatever issues are highlighted by the compiler
3. Work through adjusting the variables for each component and test in respective sub-assemblies
4. If any issues persist, look into the Klipper Wiki for specific information about the code module or consult the wiki
5. Even after the sub-assembly works, continue to optimize the program

## Intermediate Reflection

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After all the firmware and building issues had been resolved, it was finally time to conduct the first print. After fiddling around with some of the slicer settings, the first print was done. The print was not bad overall, but the first thing that had to be done to improve it was to adjust the extrusion multiplier until it was suitable for printing via a ruler test.

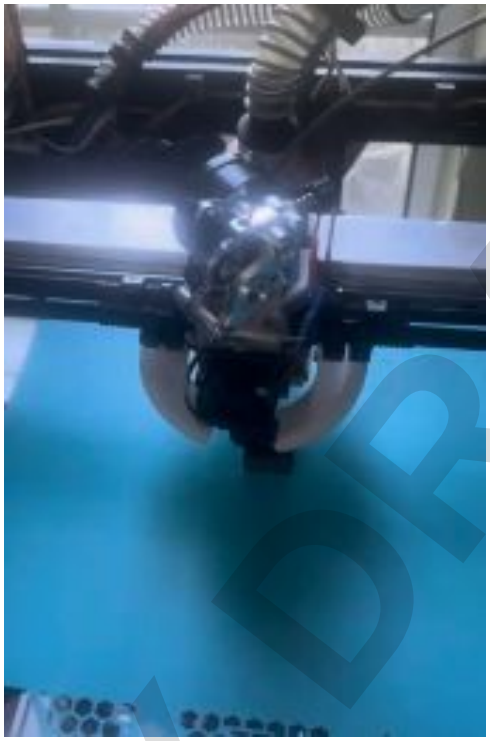


Fig 60: The first print ever on this machine

The ultimate challenge that I could devise for this machine would be to print as many toys as possible in about two months for the “IC3D toys for tots” 3D printing challenge. In printing the first few toy dolphins for the challenge, the main issue was the first layer. As mentioned earlier, the Prusa MK52 bed was only mounted in a T-shape with the rack, but the assumed stiffness of the MK52 bed was not enough, as there were large areas of sagging(more than -0.2 mm from 0) in the bed mesh where the bed was not bolted.

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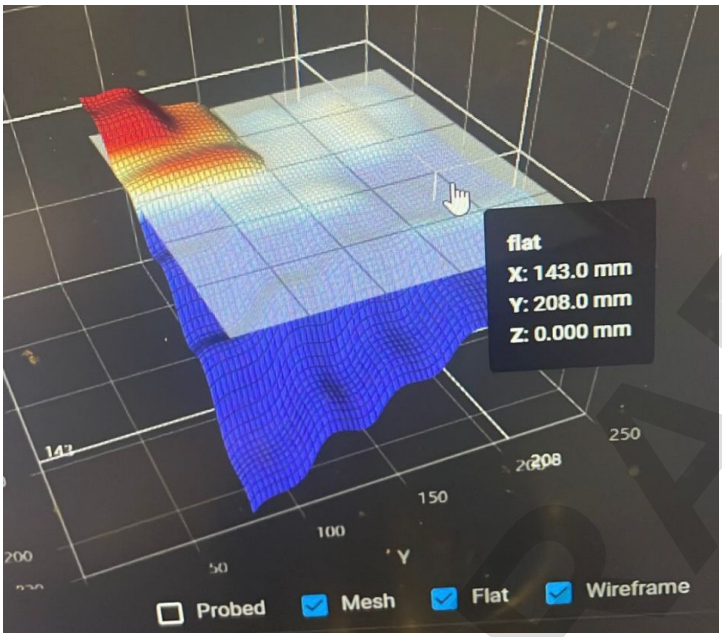



Fig 61: Bed mesh map of the Prusa Bed before the print(+0.4 to -1.2 mm deviation)

Since there was not enough time to rework the whole bed system, every first layer had to be manually jogged to account for areas that were sagging or above 0, which was extremely tedious. One method that was tried to mitigate this was to set the algorithm to bicubic and increase the mesh points, as a more detailed bed mesh would allow for more compensation in specific local areas of deviance. The main issue with this method is that the normal BL touch probe had to individually come in contact at each point and then also retest two times in order to get the most accurate reading. This was extremely time-consuming, and while it did make some minor improvements in the first layer, it did not get rid of the tedious process of jogging the first layer offset entirely. The next method to try to make this process easier was to change the bicubic tension, which would help interpolate the curve of the bed mesh better. The highest number for bicubic tension was 2, which represents the maximum amount of compensation, while lower numbers reduce compensation. Even when the bicubic tension was set to 2, the printer was still not able to fully compensate for local areas of deviance.

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Fig 62: Toy dolphins being printed on the Prusa Mk 52 bed

Other niche issues with the Prusa Mk52 bed include the lack of reliable heating, as even when the heating program was PID tuned, there would still be a large amount of deviance from the target. This could be due to the outside temperatures at the time, which also created another issue: the PCB bed took a long time to heat up.

The Cartesian Motion system of the printer also did not hold up well. The first issue arose from a lack of understanding of the role belt tension had on racking and skew of the XY axes. To tighten the belts, each belt was individually tightened, rather than once, which caused a high degree of skew in the x-axis. This problem was eventually overcome, and the issues of belt tension and belt slippage went away, as they had caused layer shifting in earlier toy batches.



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Fig 63: Failed toy print that had shifted layers due to belt issues

Another problem was the overall quality of the printed toys. The layer lines themselves were quite grainy due to the overall imprecision of the system. This was primarily due to a major misunderstanding of dowel pin installation. The pins were installed with a minor clearance fit, where they could almost easily be pressed in by hand. The press-fitting process presupposed that the hole should be reamed to an identical size to the pin itself, as it was thought that trying to expand the metal via an interference fit would be impossible. This lack of understanding of press–fitting, which is often done via an interference fit of a hole -0.05 mm in size, caused a major amount of runout, even when retaining compound was used to fill the gaps. It also did not help that the dowel pins themselves came from 3rd party vendors and were often undersized relative to the expected 5mm reamed hole.

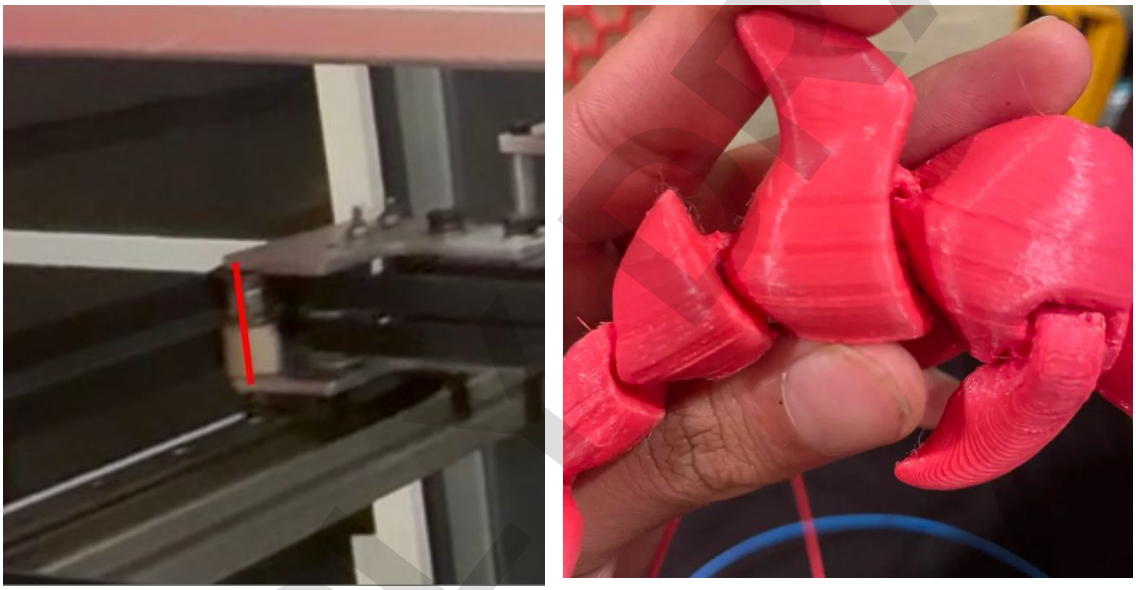


Fig 64&65: skew in an idler after a couple hundred hours of printing as well as an ugly toy printed by the system

To stop this inconsistency with layers, the decision was made to reduce the overall acceleration and speed of the printer while printing. The speed and accelerations of the machine itself were strained by the steel tube, which was extremely heavy relative to other aluminum options. It also did not help that the duct was often very bulky, and while it did aid in the center of mass, it failed to provide a wide area of cooling for the part, which was necessary for PLA. The CPAP tube itself also had a lot of slop, as it was not supported towards the top of the toolhead, so it flopped around while printing, causing it to get itself loose from the duct gradually.

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Overall, the machine was able to print about 200 toys, which was exceptional compared to an older Prusa I3, which only printed around 150 toys. This could likely be due to the immense attention this machine got in terms of maintenance and overall interest, and other considerations, like printing at night, also discouraged even more output, as there was no formal enclosure for stopping any debris from falling into the electronics below.

After the challenge, other materials were also used, namely PETG, as it was needed to print medicine boxes for a specific organization. Multiple failed PETG prints due to over-cooling demonstrated that the precision cooling provided by the first duct design was not needed for most materials, and the warpage of the PETG print during the process was also because the printer was still open-air, even though the frame design was specifically done to have an enclosure.

The Z-axis, which was still made of primarily 3D-printed parts, still did not have its aluminum replacements up until the end of the challenge, as well as the PETG tests. The bending of the PETG components caused an immense amount of runout in the Z-axis,s which might have also contributed to the issues in print quality.

## Upgrades

The main issues that were highlighted before and after the challenge, as well as the tests, could be put in a simple list:

- Reliability
    - Lack of a flat surface for printing and a hassle-free first layer
    - Lack of a probe that could allow for better bed meshes
    - Lack of enclosure to stop warpage
- Print Quality
    - Imprecision caused by improper installation of dowel pins
    - Skewness in the Z-axis caused by plastic parts that have to be aluminum
    - Poor duct design that did not account for wider areas
    - Unoptimized slicer settings
    - Lack of firmware improvements
- Speed
    - Heavy toolhead with brass weight and bulky duct
    - Heavy x-axis beam that was made of steel

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    - Underperformance of motors
- Safety
    - Lack of a proper electronics enclosure to stop debris
    - Lack of overall enclosure to stop fumes from propagating in the workspace

The most necessary first step in the upgrade process was to change the bed of the machine. The first approach was to make a new rack that would allow the MK52 bed to be mounted on all 9 points, and then trammed with shims on the standoffs to eliminate areas of deviance. This would essentially make the entire topology of the bed contingent on the rack, so special extrusions from MISUMI were ordered and assembled with gussets and corner brackets.

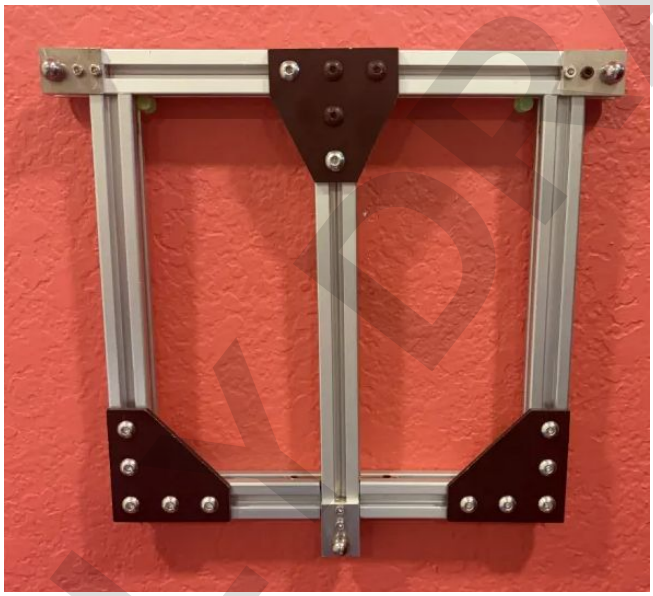


Fig 66: New rack that allowed for all points to be mounted

The main issue with this new design was that the stiffness of the PCB bed often fought the stiffness of the rack itself, and the PCB bed would usually win, as the joints (corner brackets) that connected the components of the rack would fail easily. This would make any form of tramming impossible or useless, as the rack would just bend to conform to the already deviated bed when shimmed. Even when shimming could be done, areas of deviance would simply form in the spots in between the mounting holes. Due to this issue, the decision was made to abandon the MK52 bed and the rack itself.

In many CNC applications, the mounting plate or surface is usually a thick piece of precisely flat aluminum. This aluminum alloy is usually referred to as ATP-5 or MIC-6,6, as it can maintain a

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high degree of flatness even when subjected to many heat and cooling cycles compared to a normal piece of 6061 aluminum, which often warps during heat and cooling cycles. The thicker the piece of Aluminum alloy, the more resistant it is to another common force called deflection. The force of gravity usually causes deflection on an object that is suspended on either corner, just like in a Maxwell kinematic joint.

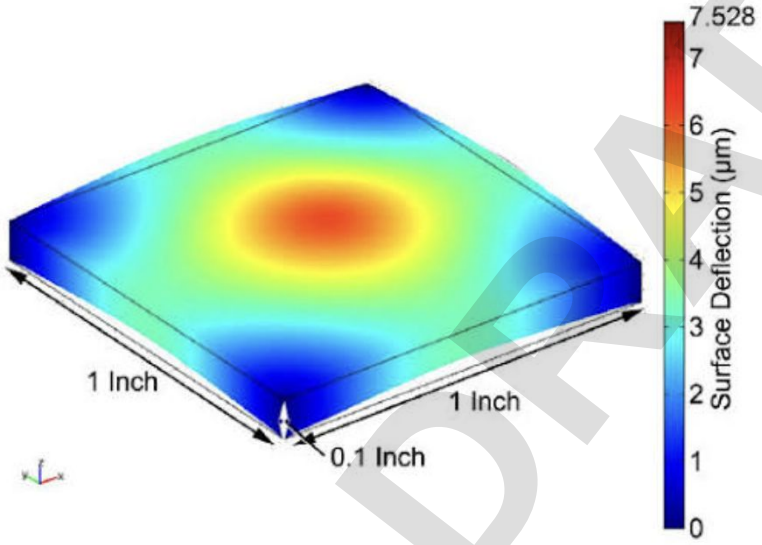



Fig 67: CAD simulation of the deflection of an aluminum plate

Due to this, the decision was made to get a 5/16” thick ATP-5 aluminum plate. The only option to heat aluminum plates like this is through a silicone heating mat. There are two approaches to a silicone heating system; however, the first is AC heating, which converts AC wall power into DC with an SSR (Solid-State Relay) but often requires a high degree of electrical safety. The other option was using a plain DC mat, which was decided because the electrical room for such a system was already made with the 600-watt power supply. To properly mount the printing plate itself to the bed, a magnetic sheet was also ordered that would go on top of the aluminum plate. The construction of the bed itself was quite simple, as it did not need to have a rack; all that needed to be done was drill the holes for the balls(Maxwell kinematic joint) and stick the mat and magnetic plate on.

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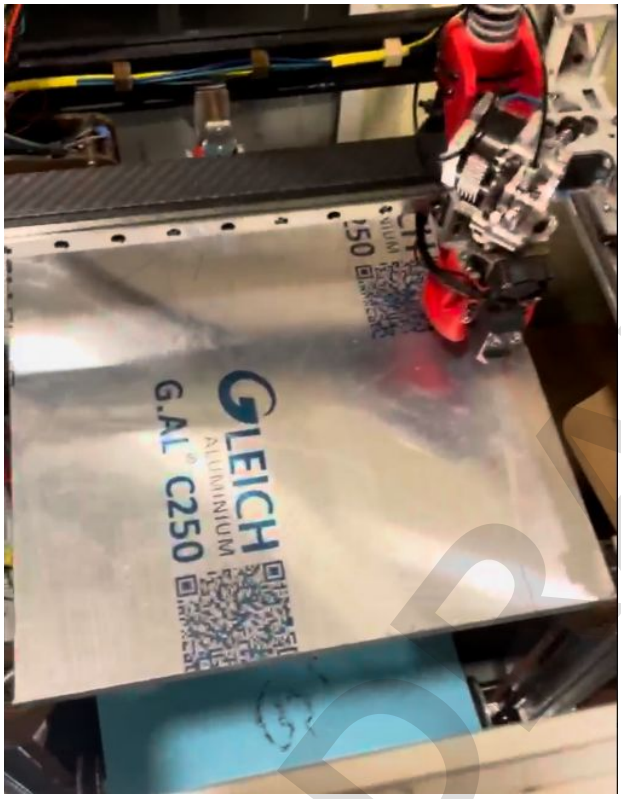



Fig 68: Construction of new bed system

After the new bed was installed, the first layer was considerably better, and for small batch prints, jogging the Z offset was not needed. But for larger prints, there needed to be a large number of probe points to avoid jogging, but the probing process would be extremely long with the normal touch probes. At this point, a new class of probing sensors called “eddy-current probes” started to come out. These probes could take hundreds of probe points by simply hovering over the plate (even whilst moving) and blasting eddy current waves onto it (it can only be done on metal beds and not PCB beds, which is another downside to using them). Eddy current probes also had the added benefit of being able to calculate the best possible Z-offset by virtue of their firmware. The Eddy current probe chosen was called the “BigTreeTech Eddy”. The mounting of the eddy current probe would be on the new duct that will be discussed later.

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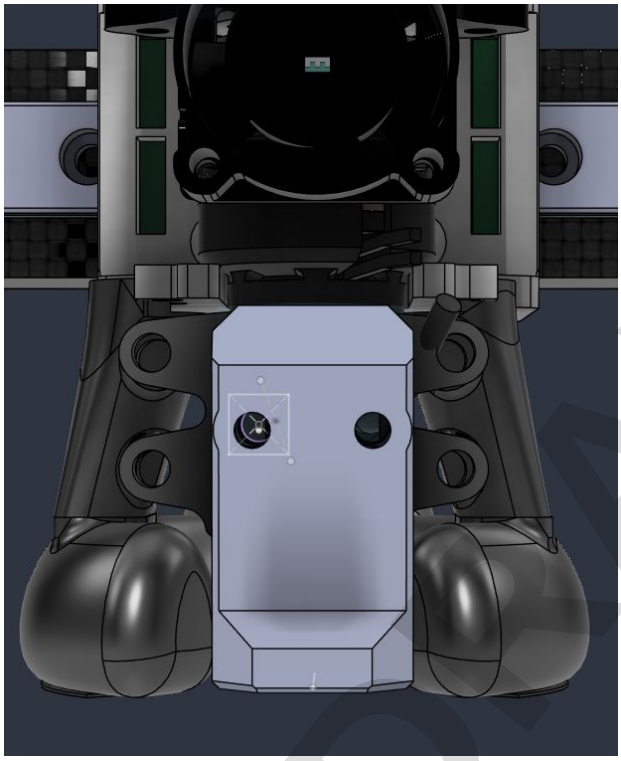


Fig 69: CAD of eddy probe mounted on its own rack on the duct

The firmware installation of the Eddy probe was quite difficult. First, the Eddy probe has its own MCU chip that needs to be confirmed by the Klipper firmware. Then various calibrations need to be done to compensate for changes in eddy currents as the bed temperature increases. After that, more tuning has to be done to find the precise offset of the probe to account for all possible deviations. It is also important to note that a properly squared gantry and a precise XY motion system are essential for Eddy probes, as they need accurate position readings for each point mapped on the mesh. But after all, the Eddy Probe was able to give 100x100 point bed meshes in a matter of seconds, which would have taken an eternity with any standard mechanical probes. The high amount of mesh points also made the whole first-layer process completely hands-off, as there was no need for jogging the Z-offset whatsoever.

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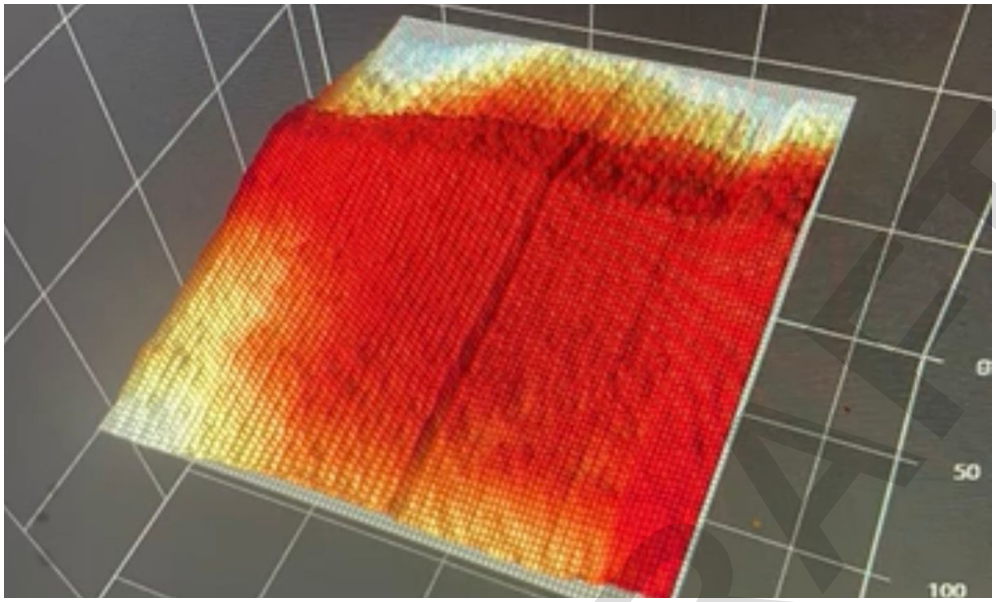



Fig 70: 100x100 bed mesh of new ATP-5 bed with eddy probe(+0.2 to 0 mm deviation)

One issue that arose during testing of the eddy probe on large prints was that the printer started to overcompensate for small areas of deviation rather than undercompensate as before. As a result, the bicubic tension also had to be lowered, which allowed for a less dramatic curve to interpolate between the layers, refuting the prior supposition that a higher bicubic tension was best for handling any deviation in the bed.

The next issue to deal with was the duct and the toolhead itself. Two main problems needed to be addressed with the new design. The first was to have a less bulky duct that prioritizes a larger cooling area, and the second was to secure the CPAP tube on top of the toolhead. To prioritize a greater area of air displacement, a new type of duct design called the “UFO Duct” was used, which centers the air into a massive disk near the printer area with small outlet holes that direct the air in all directions. The main challenges in the UFO design process were optimizing the entrance of air into the disk as well as the size of the disk itself. A larger disk would allow for a larger area, but it also needs a small displacement as mentioned before. After the ducts were designed, a small 3D-printed fixture was also bolted to the top of the toolhead from the two mounting holes on the back of the SLM body to secure and direct the CPAP tube. To stop the warpage of the doubler plate, which was also mentioned earlier, a laser-cut aluminum version was also added.

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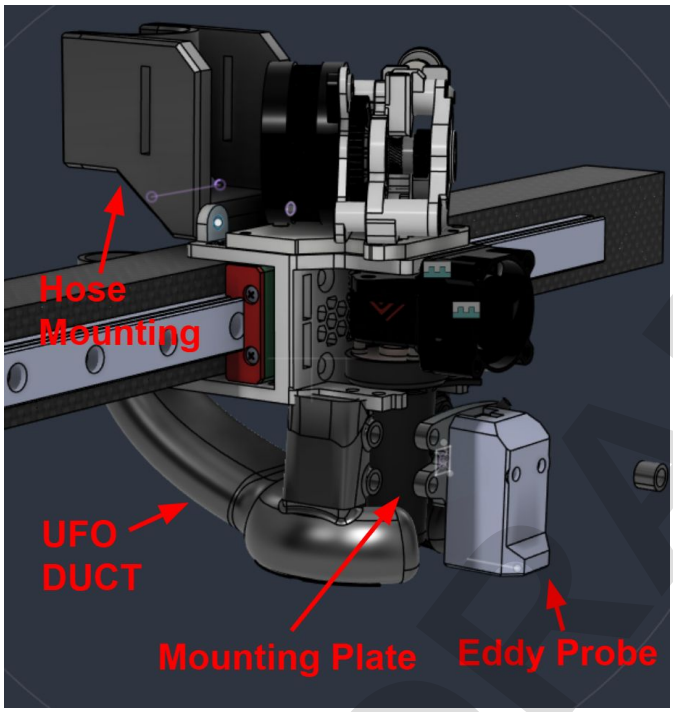



Fig 71: New Duct with “UFO” duct design, fixture, and doubler plate

The first upgrade needed to improve speed was to replace the steel tube with another material. The best possible material in this case would be carbon fiber, as its stiffness would lead to less deflection. Most carbon fiber tubes, however, have very small shell thicknesses, so internal standoffs also had to be printed to ensure there was no internal bending. The tube ordered was about 20mm longer than needed, so masking tape and a Dremel were used to cut the additional material without damaging the individual fibers. Masking Tape was also used on both ends to protect the fibers when drilling holes for the linear rails.

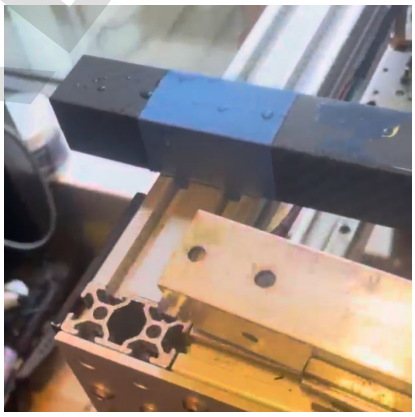


Fig 72: The Steel tube and Carbon fiber tube replacement side by side

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At that point, the only main problem with the whole machine was the motion system and its imperfections. Due to this, the decision was made to completely redesign the motion system, as new motor mounts and tensioners could be designed to increase the total area of movement in the y-axis, and the belts could be routed through the back so that they don'tinterferew with the view in the front. A new motion system would also have the added benefit of being able to start from scratch and not make any mistakes. As normal, the new motion system was designed using a 2D sketch with all components accounted for. The motors were mounted diagonally to reduce the size of the motor mounts, and everything was optimized to be smaller. Another electronic feature of this new design is that it used larger “long-shaft” motors than the ones prior,r with their own separate TMC 5160 drivers, which are used for higher speeds,s as well as a separate 48-volt power supply to power them(higher voltages equate to faster accelerations and speeds)

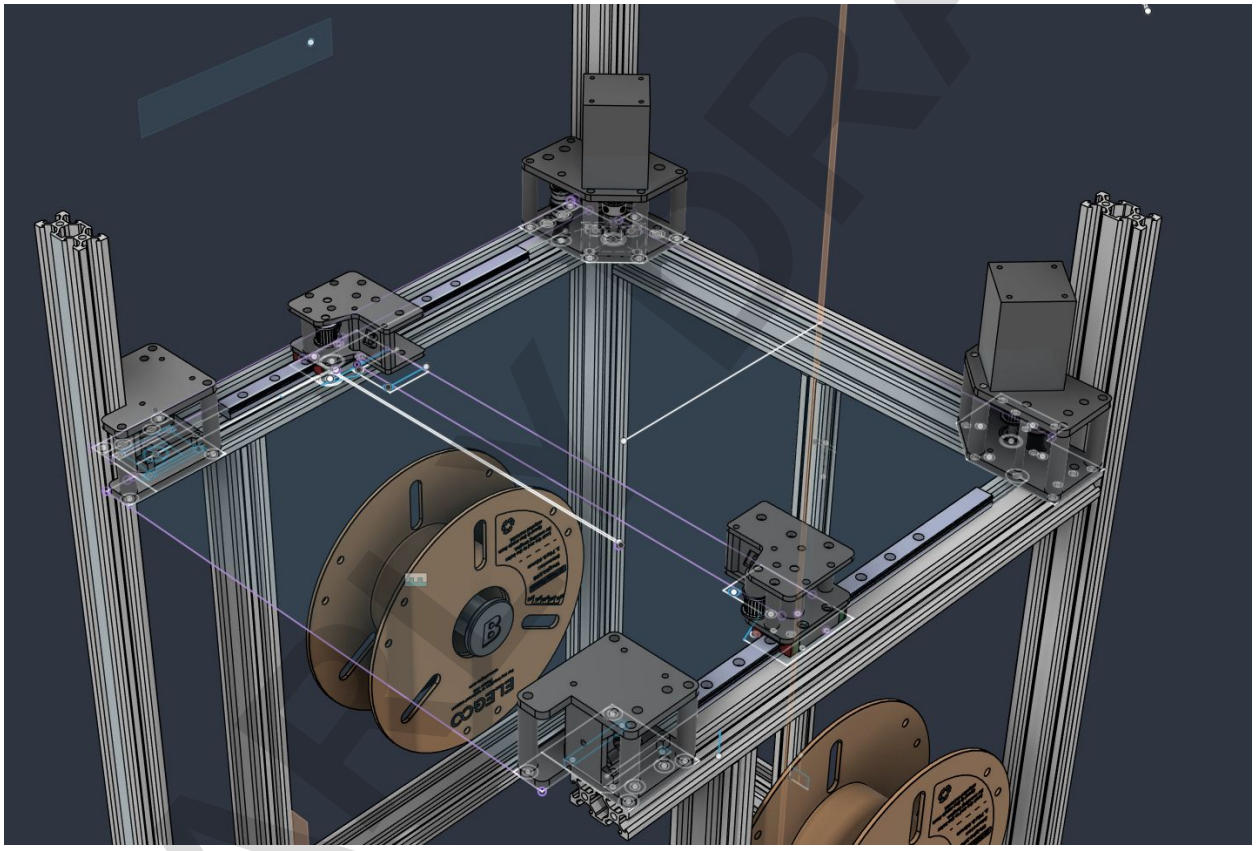


Fig 73: 2D Sketch of the new motion system with the sheet metal components extruded

The Tensioner also had a major change: it used a real aluminum SLM part but rode on a set of plastic channels rather than the dowel being in a very loose channel, causing runout. The new idler mounts on the X beam also used an aluminum SLM facade and two spacers to preserve the alignment of the dowel pins, as the former design lacked spacers to keep both the top and bottom plates in line.

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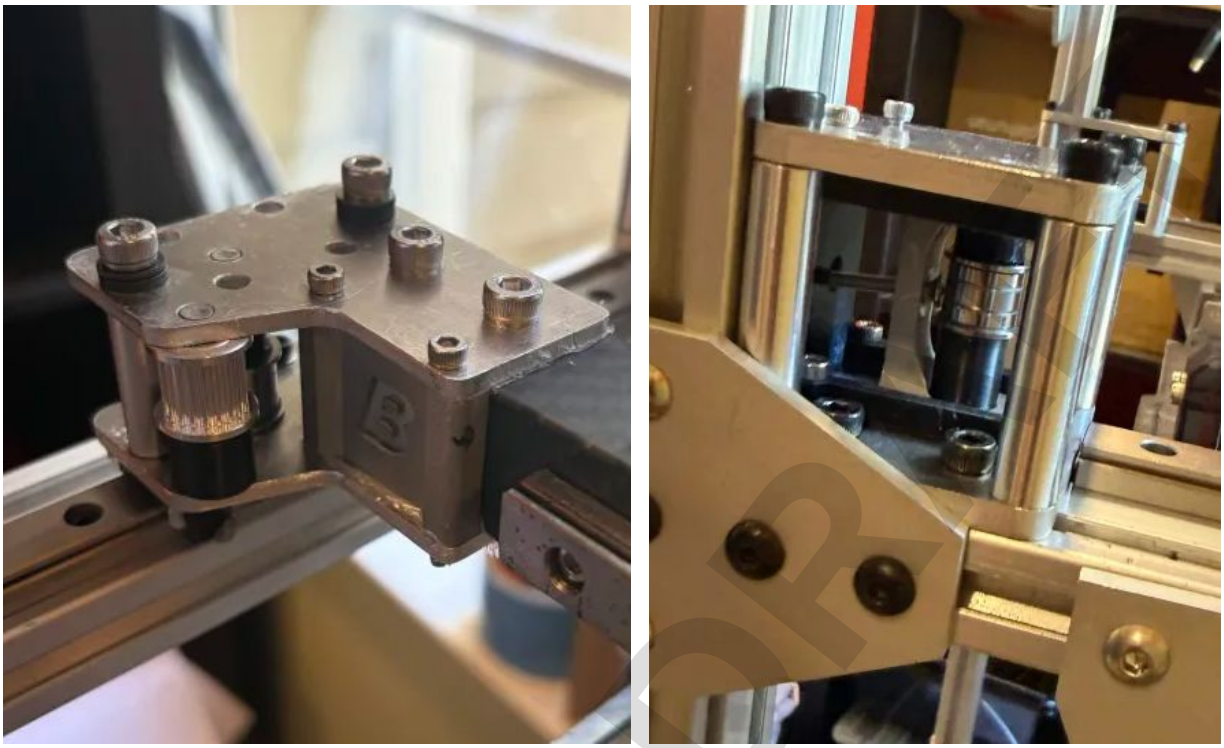


Fig 74&75: The new Idler mounts and Tensioner. The tensioner runs on a set of plastic channels that can be trammed, instead of having the whole dowel run on a loose channel with extra tolerance.

Every dowel pin hole in CAD was designed -0.2 mm from the actual 5mm dowel pin diameter. The dowel pins themselves were ordered from a reputable vendor with rigorous tolerances (McMaster-Carr).




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Fig 76: The Dowel pins are measured with a micrometer to ensure that they are not undersized

The plates were then laser cut, and to mount every single dowel pin, a 4.95mm reamer was used on a drill press and reamed by hand (turning by hand) to get a precise 4.95mm hole for an interference fit. It is very easy for dowel pins to be press-fit unsquare from their plates, so plastic jigs were used to position the dowel pins correctly, and they were press-fit with an arbor press.

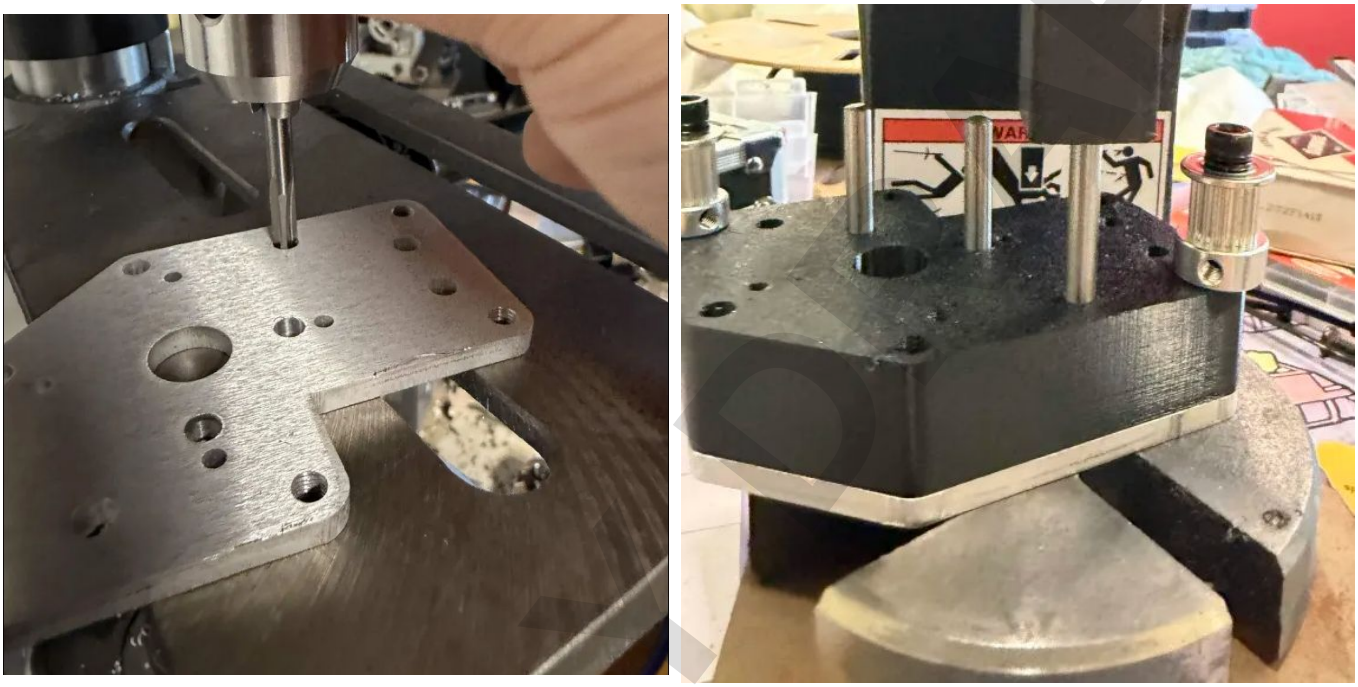


Fig 77&78: Holes are reamed, and dowel pins are press-fit via plastic jigs

On the most crucial components in the motion system that utilized dowel pins, they were first squared by clamping them in between two granite blocks, then put in a setup with a dial gauge to measure runout. If their runout were too high, then the plates would be realigned until the runout was less than a thousandth of an inch. The runout analysis would be done at multiple points of the idler or toothed idler to ensure that the runout is equal at each point, which ensures that the dowel pin is properly parallel. If there were issues in this process, then the spacers for the plates would be sanded to precision,n as they could be the only other potential cause for imprecision.

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Fig 79: Dial-Gauge testing setup

The new motor mounts and tensioners also allowed for almost 50mm more space for rails. This meant that the older 250mm rails could be replaced with 300mm rails, which added more build area in both directions.

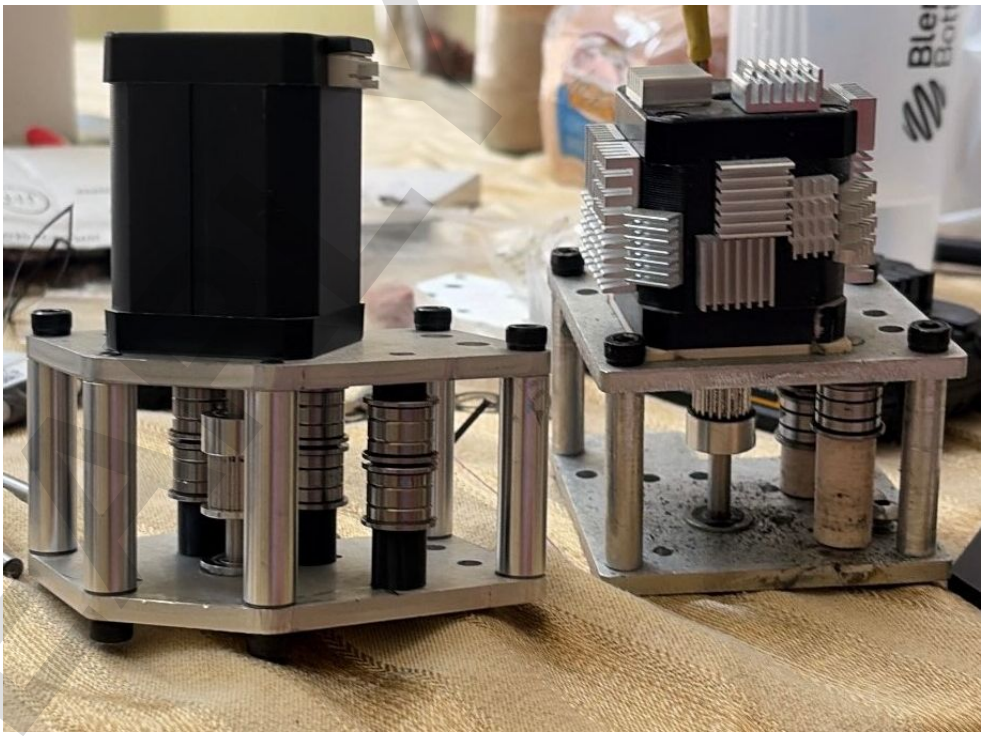


Fig 80: New Vs Old Motor Mounts

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The rails were honeybadger rails, a variant of the HIWIN MGN-12H rails with a more reliable preload specific for 3D-printing. The lubricant used was also changed to “Two Step Process” from a company called “Lukes Laboratory". This new lubricant was a lithium-based lubricant that was less viscous than Epilux EP1, making it far better for 3D-printing. Earlier, the parallelism of these rails was crucial for preventing skew, so a new method was devised to ensure parallelism. As before, a set of plastic jigs was used to center the rails, but then a dial gauge was mounted onto each carriage and referenced onto a granite block clamped to the side of the machine(referencing the dial gauge to the extrusions would not work because most extrusions are not precisely flat). Then, the rails were trammed slightly until there was no measurement skewed from the Dial gauge, which would move left or right as it moved down the rail.



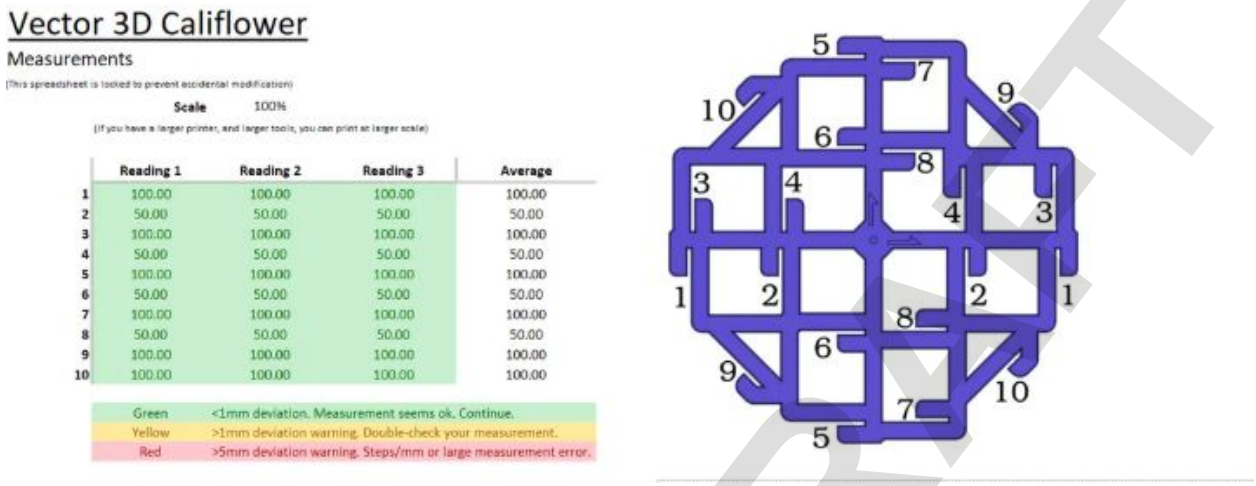
Fig 81: Dial gauge parallelism setup with a granite block as the reference

These new methods allowed the whole system to come together to move smoothly without any binding or frame bending. A rule of thumb that was discovered with the plastic standoffs for the bearings was to use small shims between the plastic spacers and the bearings or idlers, because if the arbor press pressed them too hard, then the friction between them would increase,e making them hard to move. So small shims would prevent that error.

Something that was discovered when trying to print precision parts with the new motion system was minor racking that would cause certain parts not to fit together properly, as they would lack very precise parallelism. One new method that was used to fix this was called the “Cauliflower Calibration Tool”. This tool would not only measure normal tolerances in both the X and the Y

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axis, but also diagonally, and use a mathematical model to figure out the total skew of the printer and provide the necessary firmware changes to stop it.



Vector 3D Califlower

Measurements

(This spreadsheet is locked to prevent accidental modification)

Scale 100%

(If you have a larger printer, and larger tools, you can print at larger scale)

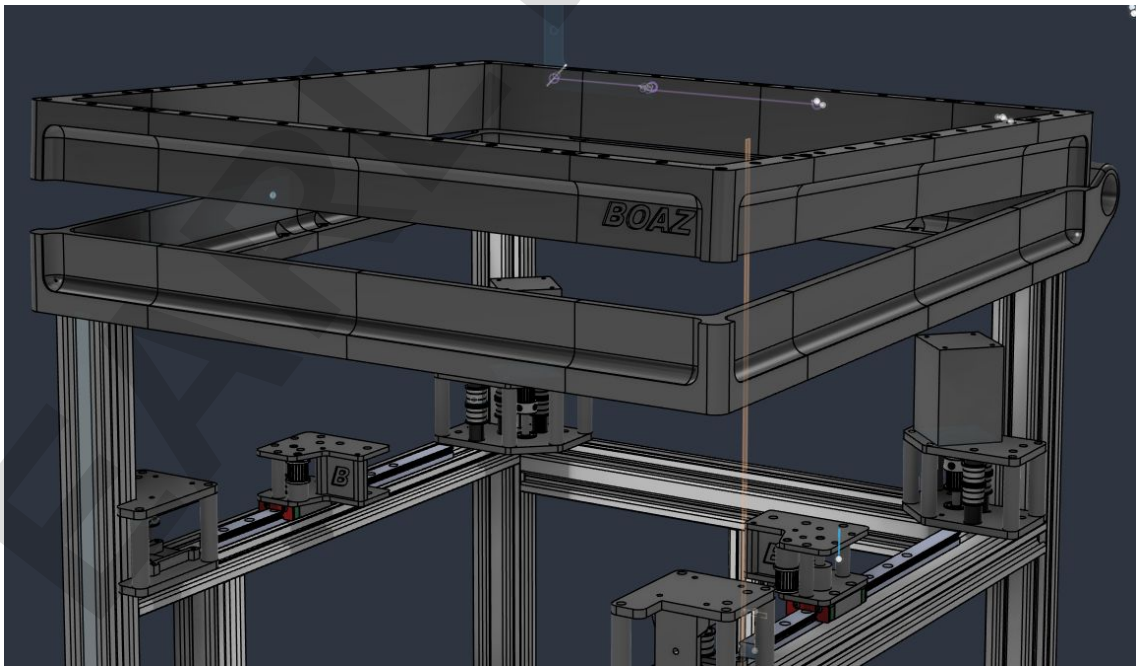
| | Reading 1 | Reading 2 | Reading 3 | Average |
|---|---|---|---|---|
| 1 | 100.00 | 100.00 | 100.00 | 100.00 |
| 2 | 50.00 | 50.00 | 50.00 | 50.00 |
| 3 | 100.00 | 100.00 | 100.00 | 100.00 |
| 4 | 50.00 | 50.00 | 50.00 | 50.00 |
| 5 | 100.00 | 100.00 | 100.00 | 100.00 |
| 6 | 50.00 | 50.00 | 50.00 | 50.00 |
| 7 | 100.00 | 100.00 | 100.00 | 100.00 |
| 8 | 50.00 | 50.00 | 50.00 | 50.00 |
| 9 | 100.00 | 100.00 | 100.00 | 100.00 |
| 10 | 100.00 | 100.00 | 100.00 | 100.00 |

| | |
|---|---|
| Green | <1mm deviation. Measurement seems ok. Continue. |
| Yellow | >1mm deviation warning. Double-check your measurement. |
| Red | >5mm deviation warning. Steps/mm or large measurement error. |



Fig 82: “Cauliflower” Calibration tool

After the mechanical improvements, the enclosure was the next main goal. A “Top Hat” was designed with a bottom and a top that would fold with bearings. Every part was printed in segments, and the bottom was bolted onto the top extrusions, whereas the Top was connected via long dowel pins. The benefit of such a folding “Top Hat” design is that it allows the machine to be accessed from the top for maintenance.




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Fig 83: Top Hat

The rest of the panels were cut from polycarbonate and bolted onto the frame, with their overlap as a primary consideration(thus requiring spacers). The front of the enclosure panels also had a door, which also used dowel pins and bearings as its joints.



Fig 84: Printer with enclosure

The last physical thing needed to be done was the electronics enclosure. The best way to do this was to order a large electronics enclosure box online and put all the electronic components on DIN rails, with a plastic organizer in the middle to help direct the wires to their respective components. This new box is also weatherproof and clear, which allows for proper visibility whilst also protecting the electronics from debris.



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Fig 85: Electronics Enclosure

In addition to the mechanical improvements, research done on the slicer gained multiple important insights. First, in OrcaSlicer, the first layer pattern can always be changed in order to manage the internal stresses that cause warpage.

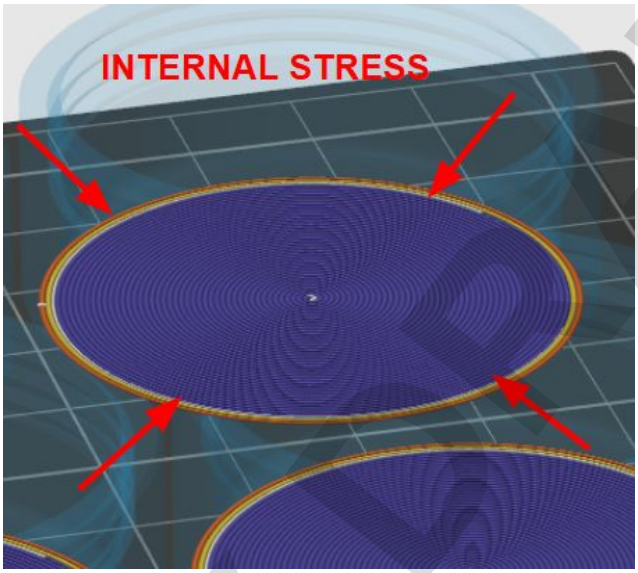



Fig 86: Unique first layer pattern that allows circular parts to be printed without warpage

Additionally, other settings in Orca-Slicer such as layer order, the layer height, and specific speed-related settings like Jerk and feature-specific accelerations allowed for superior print quality. Most of the presets, however, were sufficient in gaining good print quality, and complex settings did not need to be changed.

The only major change to the firmware on top of the eddy-current probe was the addition of settings specific to the TMC 5160 driver such an “SPI Bus” which allows the board to communicate with the driver and make adjustments in real time as well as the addition of a form of tuning called “Input Shaping” which uses an accelerometer to optimize printer movements to stop resonances and vibrations that directly translate onto the print. The input-shaping algorithm, in pair with the accelerometer, can usually show a graph that gives other important insights like the maximum recommended acceleration, and the shape can reveal certain mechanical issues like axis binding or loose parts.

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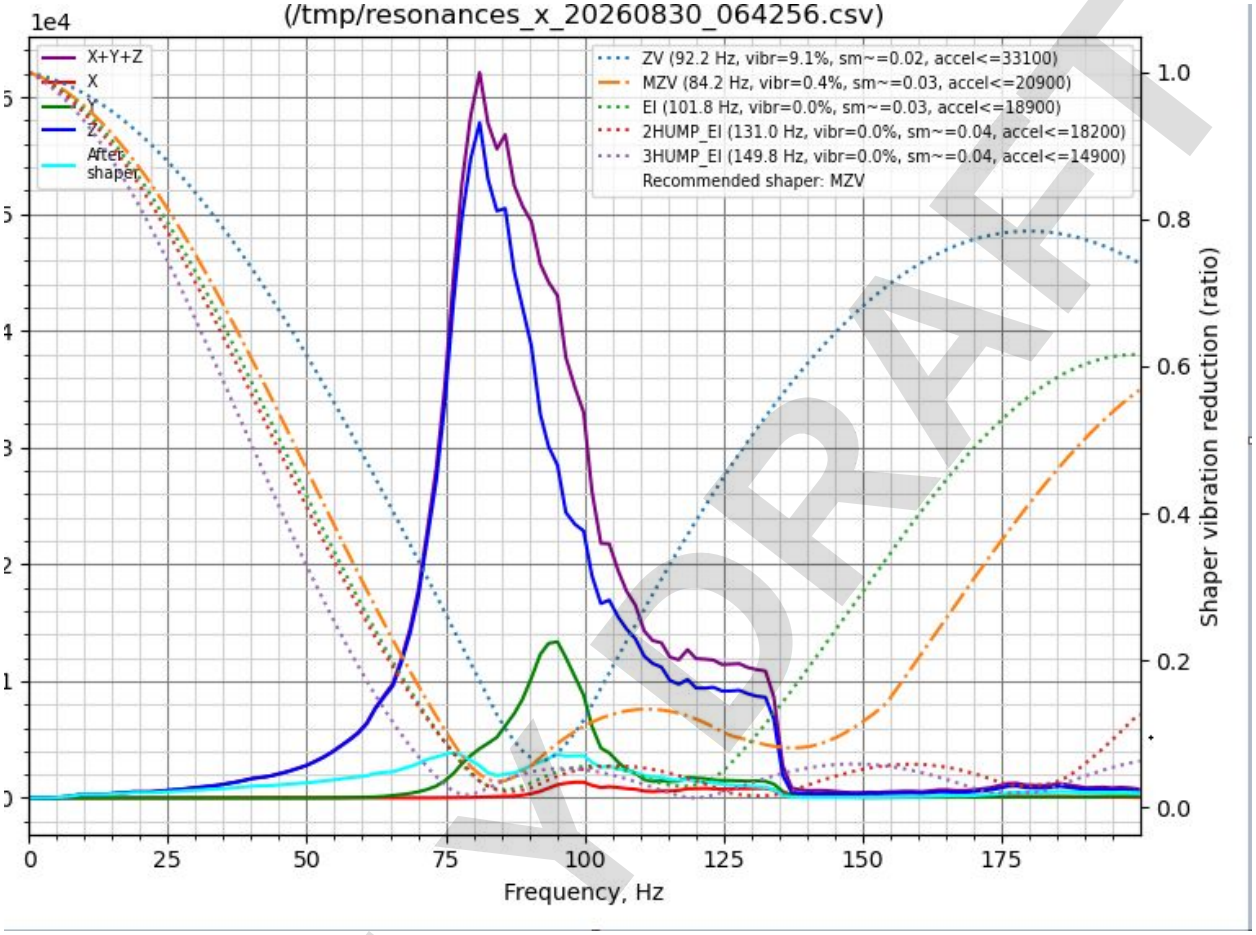



Fig 87: Input-Shaping acceleration graph

This input shaping graph reveals that all of the precise work that went into building the machine successfully paid off. The best input shaping graphs will reveal a singular(blue or purple) line that has one peak and progressively goes down which is what the machine achieved. Multiple peaks at different frequencies indicates that there is some mechanical issue and it will be harder for the algorithm to compensate for multiple frequencies. An algorithm that has to do compensate for a rugged graph, with lots of peaks, will translate major feature-changes into its parts, such as rounding on sharp corners or minimal smoothing.

The accelerometer, that was used to measure the input shaping graph, was mounted at the top of the toolhead, close to where the duct outputs to the CPAP tube. Ideally, the accelerometer must be mounted close to the nozzle itself for slightly more accurate results, which I believe would make the peak thinner.

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The teal line, called “After Shaper” shows all the vibration reductions after the input shaping algorithm is installed, which is less than 0.1 on the shaper vibration reduction, demonstrating extreme vibration reduction. The box on the right, shows all the algorithms, and the accelerations that they are rated for. The chosen input-shaping algorithm, MZV, allows the machine to safely print below 20900 mm/.s^2 in acceleration and the ZV algorithm can bump it up to 33100 mm./s^2 in acceleration. The ability of this machine to have such a high degree of vibration reduction at high accelerations also attests to its superior precision, and speed capabilities.

## Reflection

In the beginning, one way that was tested to check the reliability of all sub-assemblies in sync was to print high-detail parts that were also very tall. This is because highly detailed parts stress the X and Y axes, and proper layer stacking can only be ensured with a reliable Z-axis. One such part that was tested was a large Buddha statue.

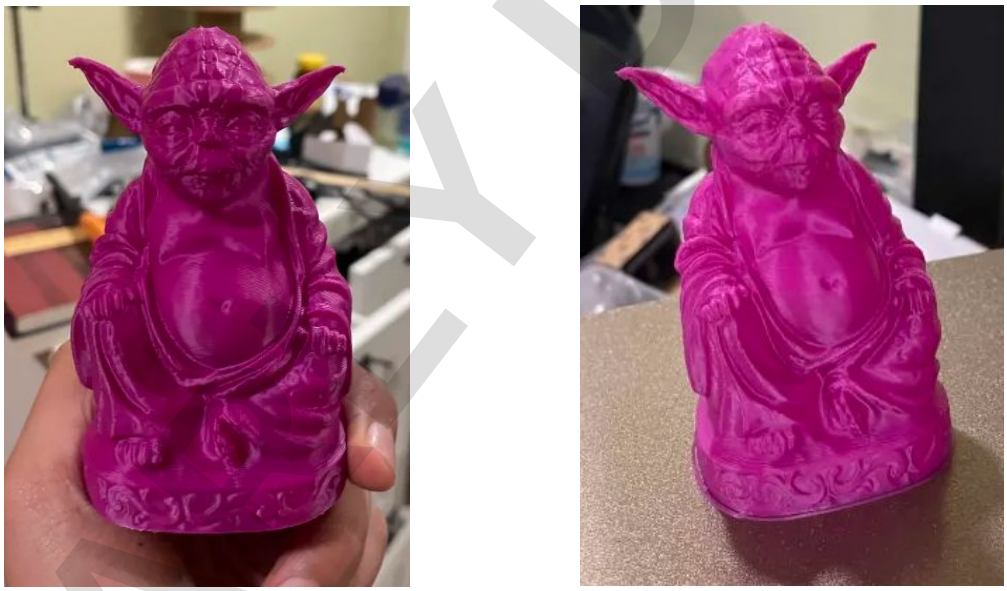


Fig 88: Machine prints Buddha statue with good quality

The ultimate challenge to test the new and upgraded printer was through a printing contract for a medical organization in Iraq. This organization wanted around 1000 pet medicine boxes that could survive the hot sun in Iraq. Two machines were used to print these 1000 boxes, one being the “Elegoo Centauri Carbon”, which was a new budget Core-XY printer on the market, and the other was the machine being designed. Over the course of 10 days, the machine was able to print around 50 boxes a day, compared to about 60 that the Elegoo Centauri Carbon could make.

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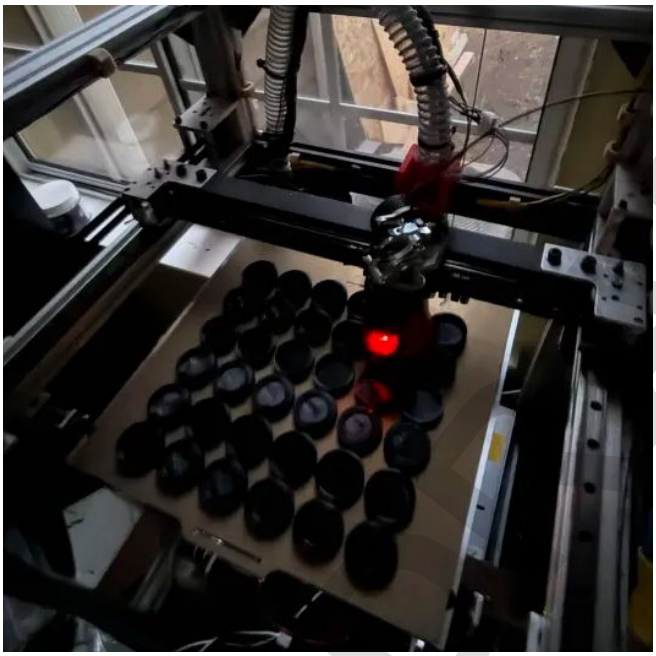


Fig 89: Machine prints full plates of PETG boxes and precise tolerances

One major benefit of the upgrades that allowed the machine to print such a high volume of parts is the new bed and eddy current sensor. The great-detail bed meshes allow for hands-free printing when the parts from the previous batch are removed. This solves one of the main struggles for 3D-printing up until this point, which is the constant “babysitting” of the first layer(which often has to be printed slowly to stop warpage) and the jogging of the Z-offset whilst watching the first layer be printed.

The enclosure also aided in the process of printing other engineering-grade materials like Carbon-Fiber PETG, as it allowed for the chamber temperature to be high enough where the layer-bonding issues of PETG were not detrimental. On larger PLA prints, such as large vases or mock-ups, the “UFO” duct served a very important purpose in cooling the vast areas that each layer in the part had.

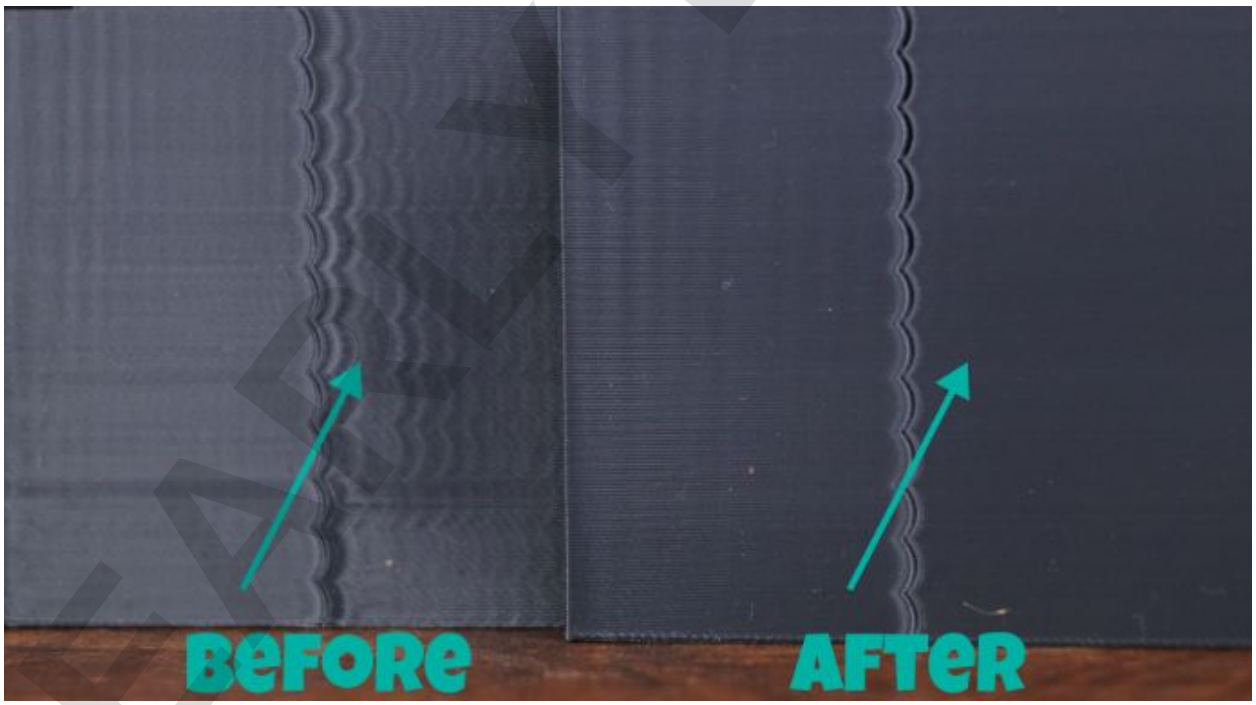


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Fig 90: Large layer areas of a PLA part being cooled with “UFO” duct

One of the main benefits of the new motion system was positional accuracy both in printing and in the bed mesh process. As mentioned earlier, for eddy-current probes to take in a high volume of probing positions, there also needs to be a high degree of positional accuracy; if there is some form of skew or racking, then each horizontal pass for probing will be slightly diagonal. The new motion system also helped with positional accuracy, as the boxes that needed to be printed during the contract required less than a 0.2mm tolerance for the threads to engage and move smoothly, which was not able to be done when similar boxes were printed earlier on the old motion system.

Input shaping also gave a higher degree of print quality in comparison to prints on the machine before input shaping. One of the main struggles of 3D printing, as mentioned before, is managing vibrations throughout the printer whilst it prints, as they can affect the print quality. Before the addition of the Input Shaper, some minor solutions such as rubber feet were added, which were important because the surface that a printer sits on can greatly affect the movement of vibrations through the frame, but the input shaper did the best at managing the vibrations.




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Fig 91: A print with Input shaper and a print without input shaper in harsh lighting(not on this machine but similar results were found)

The last relevant test for testing the performance of the printer is called the “Speedboat Challenge”. The challenge is to essentially print a small plastic boat with the best possible quality in the lowest amount of time. This challenge encompasses one of the other two major challenges in 3D-printing: the trade-off between speed and quality. To have more quality, the speed and accelerations have to be low, but to have faster prints, the speeds have to be high(which compromises quality), and a performance printer can do both without any trade-offs. The machine was able to print a bench  in a span of 16 minutes on its first try, with quality that is comparable to other enthusiast-grade DIY printers that are available that do not use the design methods encompassed by this study(after lots of testing and tuning).The machine can also possibly exceed this by going into the 6 minute category as this was just the first try. The overall quality of the prints was also superior, as the “UFO” ducts combined with a high-power CPAP system allowed smaller features like the smoke stack and bow to be printed with minimal sagging.

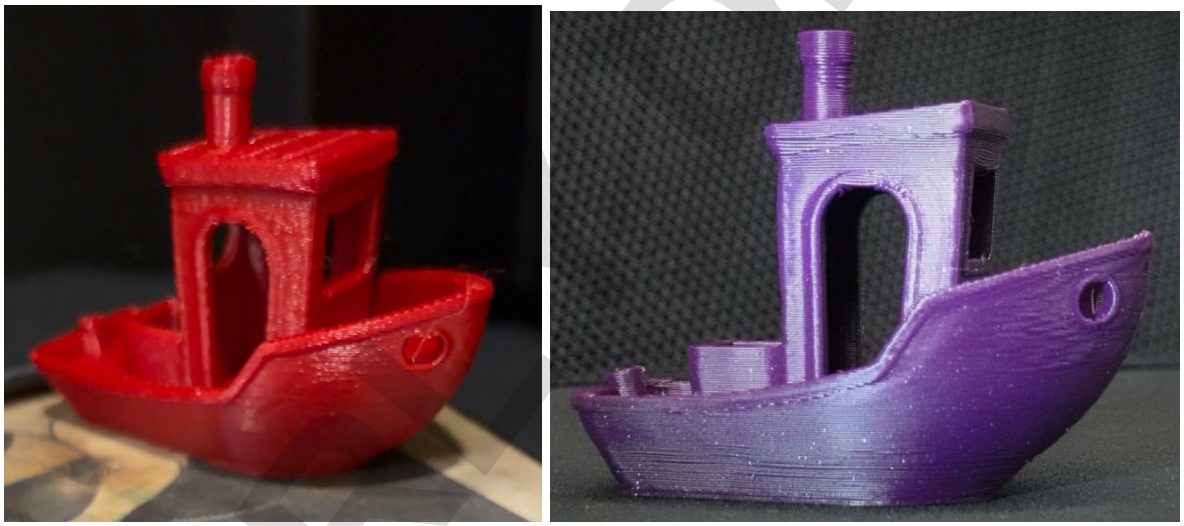


Fig 92 & 93: Speed Benchy comparison between the machine(left) and the “Hev-ort” 3D printer(right), which is a common enthusiast printer. Both of these were printed in 16 minutes, and the left shows a better smokestack, with less artifacts on the bow and back.

## Personal Reflection

This project began in October of 2023. It came out of a need for designing a printer that could be made cheaper than other DIY designs, but also have a degree of customizability that other retail printers could not offer. The idea of building a 3D printer came during mid-2022, when there

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were not really any reliable 3D printers on the market that were not exclusively marketed to big corporations or that had slow print speeds. The first design inspirations for this project were other open source projects that heavily utilized plastic parts. It took a while to understand how to design these plastic parts, as many of these printers prioritized aesthetics rather than actual functionality or strength. Still, when a small plastic mockup was made, the issues with plastic parts glared.

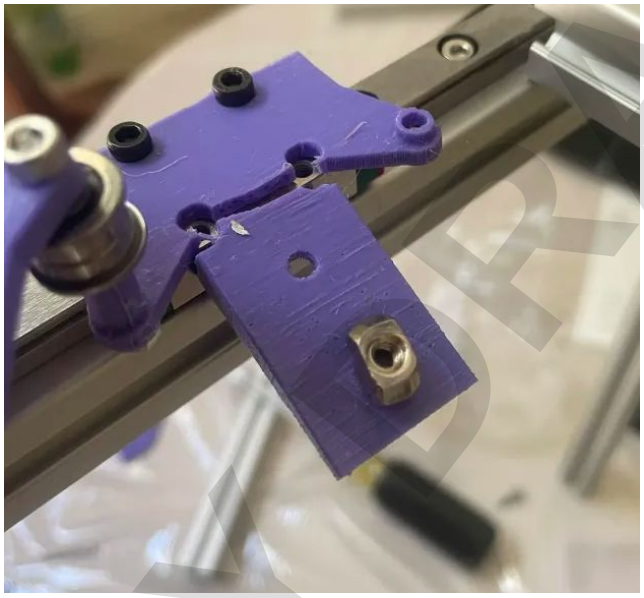


Fig 94: Broken plastic parts in Core-XY mockup

It was only when I joined an online community of people who had a different approach to building 3D printers that I realized that everyone had been doing it all wrong. These people specifically used sheet metal parts that were separated by aluminum standoffs, which they coined “Ice Cream Sandwich Design”, and they heavily stressed the lack of strength in plastic parts, especially in demanding applications like 3D printing. They had an entire knowledge base for understanding other important concepts such as the need for tubing instead of extrusions for the gantry to manage torsion, as well as the need for stiff and rigid frames rather than floppy 2020 extrusions used on other builds.

What struck me the most, however, was the way they upheld precision. When looking into the original DIY machines that used plastic parts, I never took the time to understand many of the aspects of precision that they overlooked, such as using more than one jig to check parallelism, the runout in their screw joints for idlers, granite blocks for seeing if important components were actually flat, or the proper usage of machinist squares to ensure that everything was actually

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square. I knew that these methods existed, but I only thought that they were necessary for extremely precise machines like CNC mills and lathes. But it made sense to me: all the major inconsistencies in 3D-print quality were due to the lack of these very principles, and that's when I realized that this was the right way to go.

My research did not end with the community knowledge base itself, however, as I talked to specific people who were also in the community,y such as former CNC technicians and toolsmiths, who also gave me an insight into how to achieve precision whilst building. I also asked them questions about my designs as I moved throughout the design process, and they gave me valuable information about how to improve my designs. For example, when I was designing the tensioner, a member of the community gave me an important piece of advice about centering the screw in the middle of the tensioner block, because it would stop it from tilting under load, in addition to other recommendations that they gave me.

I think that the fact that I was not able to perfectly do everything that I theorized on the very prototypes and had to do upgrades shows that I was oriented towards perfection rather than settling for a heuristic solution.

Financial issues also held back the whole build process because my parents would only give me 100 dollars a month to buy parts. This meant that everything had to be done in small increments, which has the benefit of perfection but also shortens the time available for testing and doing upgrades after the fact. My parents also put a lot of pressure on me to finish this project before I fully knew everything was ready, which also compromised the quality of the parts the first time around. It is also important to note that the people whom I talked to also were not the kindest; sometimes they were intentionally vague or did not think that my questions were worth my time.

## Conclusion

In the age of high-performance, reliable, and cheap 3D printers from China that are readily available to enthusiasts and the average consumer, it almost seems as if there is no real purpose for personal DIY machines that are far more expensive, take an incredible amount of time to build, and still might not match the quality of these machines. But this is simply not the case; for example, in many parts of the United States, new legislation is being passed, where consumer-grade machines are being forced to put “spyware” in which the government can track what people print in order to stop the printing of “contraband,” despite the fact that it violates the rights of consumers and can not practically attain its alleged goal. DIY 3D printers can solve that, as they rely on open-source firmware and other components that can be bought off the shelf to construct.

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Another practical case for the use of DIY 3D printers is in military and defense applications. It would not be uncommon for machines coming out of China to have already been compromised with spyware that can compromise designs used in military applications. This is why the U.S. military often has 3D-printer contracts that specifically require the use of domestic parts (which are readily available to the DIY enthusiast) and open-source firmware that can be changed for privacy.

. Despite this, there is a main point of question in this study that needs more mathematical and empirical testing: whether Core-XY is actually the most superior motion system. It is already known that superior motion systems require axes to be light without motors moving alongside the gantry. But Core-XY is not the only motion system that works in this way; in fact, there has recently been a major push toward an alternative motion system called Cross-XY, where the X and Y axes form a cross in which the toolhead sits at the center of the two. This way, the motors are not moving with the axes, but integration for 4+ motors is possible. These printers are built in a similar way to the machine referenced in this study, with strong sheet metal parts, and precision achieved through various means whilst also achieving exceptional performance.

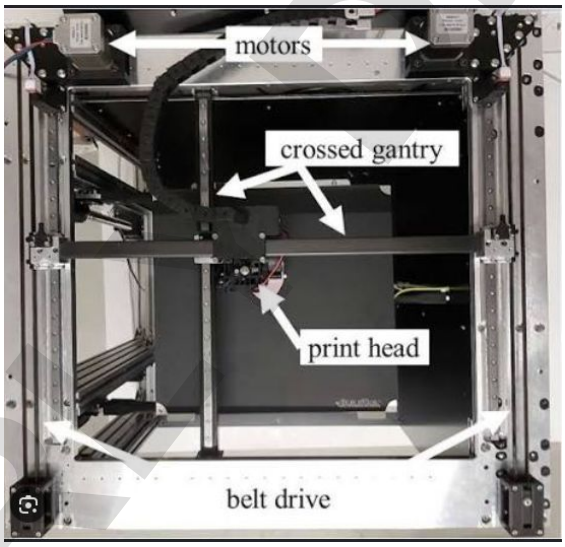


Fig 95: Cross-Gantry printer

However, regardless of this point, the main theme remains. These printers require the same levels of construction and precision to attain proper performance and reliability. Therefore, the best way to conclude is to note the 11 dogmas of 3D-printer design outlined by this study to produce a 3D-printer which is:

1. A strong and rigid frame, with large and thick extrusions, connected by gusset plates with many joints
2. Enclose the machine to stop fumes and retain heat

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3. Enclose the electronics to stop debris
4. Design every toolhead for maximum cooling, plastic flow, and Center of Mass
5. Design every motion assembly(all axes) with sheet metal and metal spacers
6. Use pressed dowel pins(into a reamed hole) and retaining compound instead of screws to mount idlers to stop runout.
7. Achieve proper precision in the squareness of the frame using proper machinist squares.
8. Use dial gauges and granite blocks to properly align rails in all axes, measure runout, and align sheet metal assemblies
9. Limit weight on motion parts (e.g., SLM parts for toolhead, carbon fiber tubes, CPAP)
10. Use the latest technology(like Eddy Probes and Accelerometers) to increase reliability
11. Print calibration prints to dial in settings in slicer and firmware

## References

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