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Design and Construction of a 3D Printer Platform

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Design and Construction of a 3D Printer Platform

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By

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This report represents work of WPI undergraduate students submitted to the faculty as evidence of a degree requirement. WPI routinely publishes these reports on its web site without editorial or peer review. For more information about the projects program at WPI, see http://www.wpi.edu/Academics/Projects
Abstract

The purpose of this MQP was to research, design, construct and test the platform components of a large scale 3D printer for use by the students and faculty of Worcester Polytechnic Institute. The MQP studied the current state of rapid prototyping on the WPI campus and designed a printer that addressed several limitations of the currently available printers at WPI.

Key goals of the project were to create a printer that was larger than any other on campus, with the ability to produce multiple parts simultaneously, and to produce parts with multiple colors without having to manually switch filament rolls. This team worked with two others to develop the necessary subsystems and assemble the printer. It satisfies all of the key goals and significantly expands the capabilities of WPI's rapid prototyping facilities.
Acknowledgments

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James Loiselle
Executive Summary

The WPI campus has several 3D printers, but the size of the available printers is limited to a maximum volume of 1200 in³, which is approximately the size of a basketball. Furthermore, no single dimension can exceed 12 inches, meaning any part larger than that must be designed and printed in multiple sections. Additionally, no printer on campus has the ability to print multiple copies of a part simultaneously, leading to longer lead times on printed parts.

The solution presented in this paper is a large format Fused Filament Fabrication (FFF) printer, with color mixing and simultaneous, multi-nozzle printing. This printer has a print volume of 36"L x 18"W x 9"H, over four times larger than any other printer on the WPI campus. It has a print bed large enough to print a full size baseball bat, or three basketballs side by side. This allows for larger parts to be printed as a single piece, rather than having to be assembled post printing. The printer can also be configured to use three nozzles simultaneously to create multiple copies of the same part. This modular head system subdivides the print bed into smaller, identical print volumes.

This project team successfully designed and constructed a printer with the above features, printing with three heads simultaneously or with a singular head over the entire print area. The printer is able to print in a variety of materials due to the heated bed and enclosure, which ensures that the ambient temperature and bed temperature stay consistent for proper bed and layer adhesion.

This project fulfilled all the design goals and task specifications. For future improvements, the team suggests replacing the glass on the print bed with borosilicate
glass, which has a lower coefficient of thermal expansion and thus is less prone to dimensional changes. Additionally, the team recommends replacing most of the 3D printed parts with machined aluminum parts, such as the Z axis brackets. This will strengthen the printer as a whole as well as provide a more consistent aesthetic. The basic platform developed in this MQP offers enormous potential for development, with potential future projects such as multi-material mixing or independent nozzle movement. Future MQPs could also consider the speed of rapid prototyping in an industrial environment, maximizing the potential of the printer’s multiple nozzles by upgrading them to high-flow nozzles such as the E3D Volcano hotend. Due to the open source nature of the project, it is very adaptable to custom firmware, hotend and extruder upgrades, and other structural improvements. CAD and written documentation will help future groups to utilize the printer developed in this project, with potential for development of a manual or collaborative online repository of the design iterations of the printer and its subsystems.

Figure 1: Photo of the Printer in the MQP Lab
This printer expands the current state of open source printers by developing a low cost solution relative to commercial printers of comparable size. The unique design brings together several features that are on the cusp of industry innovation, broadening the options for WPI students and faculty in need of rapid prototyping, and expanding the realm of possibility for additive manufacturing as a whole.
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Introduction

The world of manufacturing has been significantly changed since the invention of the 3D printer. This industry has rapidly changed over the past few years, seeing popularity with hobbyists and industrial applications alike. The capability of most commercial printers is essentially the same, printing parts and models layer by layer using a single color. What many of these printers lack is size and capabilities beyond printing singular, monochromatic parts. This project aims to construct a printer that exceeds the print size and capabilities of most commercial 3D printers.

Types of 3D Printing

Fused Filament Fabrication (FFF)

FFF uses a heated printer nozzle to extrude a filament onto a print bed in a thin layer. The printer constructs the 3D part by extruding layers on top of previously deposited material, building up a solid object from a series of cross sections. Material layers in parts printed by FFF are usually between 0.10mm and 0.30mm (0.004” to 0.013”) thick. [1]
Selective Laser Sintering (SLS)

Selective Laser Sintering uses a laser to form 3D parts from a reservoir of powder, either metal or plastic, mixed with a binder material. The laser melts the powder into the shape of a layer, then the part is lowered and a fresh layer of powder is rolled over the part, allowing another layer to be formed. The fine powder used as the part material acts as a support structure and eliminates the need for additional support material when printing complex geometries such as overhangs. Typical layer thickness for SLS ranges from 0.060mm to 0.150mm (0.002” to 0.006”). [2]
Stereolithography (SLA)

Stereolithography uses a vat of ultraviolet (UV) curable resin as the part material and a UV laser as the print head. The laser traces out one layer on the surface of the resin, curing it into a solid layer. The print surface is then lowered and a fresh layer of resin can move over the top of the previous, allowing a new layer to be formed by the same process. Features such as overhangs and bridges are supported using breakaway supports or a water soluble support material. Typical layer thickness for SLA ranges from 0.05mm to 0.15mm (0.0006" to 0.005"). [3]
Digital Light Processing (DLP)

Digital light processing uses a projector to cure a photopolymer, similar to stereolithography. However instead of using a UV light, DLP cures resin using a more conventional light source such as an arc lamp from a projector. A projector projects an image onto the bottom of a resin tank with a clear bottom, curing the resin into a layer in the shape of the image. The part is then raised out of the bed by one layer thickness allowing the projector to cure another layer. This method can also be used to print 3D models in wax. These wax models can then be used to cast metal parts using the lost wax casting method. [4]
Multijet Printer

A multijet printer sprays a thin layer of liquid polymer into the shape of a layer, which is then cured by a UV light fixed to the print head. This method allows for multiple nozzles to be used, which enables printed parts to use several materials. The nozzles can also print removable support structure while printing the main part, allowing for more complex geometries.[5]

Figure 6: Multijet Diagram [1]
Electron Beam Melting (EBM)

This process is similar to laser sintering, using a beam of electrons to fuse metal powder into a full strength and uniformly dense part. To achieve an electron beam this process must be carried out in a vacuum, unlike traditional laser sintering. EBM produces parts with uniform material properties and high strength compared to other methods. [6]
Printers Available at WPI

Makerbot Replicator

![Figure 8: Makerbot Replicator 2X](image)

The Makerbot Replicator is a FDM 3D printer geared toward the hobbyist market, optimized for printing parts in ABS and PLA plastic. It uses dual extruders to print in ABS with water soluble support, and features a fully enclosed design with a heated aluminum build plate. The full enclosure prevents thermally sensitive plastics such as ABS from warping due to air currents or rapid environmental temperature changes. The Replicator has a minimum print layer resolution of 100 microns (0.0039”), positioning accuracy of 0.0004” in X and Y and 0.0001” in Z, with a build volume of 11.2” x 6.0” x 6.1” (410 in³). It accepts standard 1.75mm filament and prints using a 0.4mm nozzle. [7]
The Dimension SST uses Fused Deposition Modeling (FDM) to deposit ABS plastic in 0.010” or 0.013” layers, building models from the base upwards. The Dimension also uses a dissolvable support material to support features such as overhangs or bridges during the print. This material can be dissolved in a water based solution after the print has been completed. The printer can also add breakaway supports to a model, which are simply broken off once the print has been finished. The machine prints using a special blend of ABS sold as ABSplus by Stratasys, with a maximum build volume of 10 x 10 x 12 in (1200 in³). Minimum recommended wall thickness is 0.060”, with a minimum feature size of 0.045”. The dimensional accuracy of the Dimension SST is +/-0.006”. [8]
The Mark 2 is a 3D printer designed to produce high strength parts for engineering applications. It uses FFF technology to print in nylon plastic, with the ability to blend and reinforce parts with high strength materials such as Kevlar, carbon fiber, and fiberglass. To add fiber reinforcing, the Mark 2 utilizes two print heads, one which extrudes the base nylon, and a second which can be used to reinforce with one of the available fiber materials. The Mark 2 uses proprietary filament and a custom 3D printing software with a touchscreen interface to help users achieve desired material properties. Minimum layer resolution is 100 microns (0.0039”), with a print volume of 12.6” x 5.2” x 6.1” (400 in³). [9]
The Wanhao Duplicator is based on the Prusa i3 printer design, developed by Josef Průša of Prusa research. The design is open source, and a variety of low cost kits and prebuilt variations of the design are available on the market today. The Duplicator i3 is a prebuilt clone of the Prusa i3 with a steel frame and heated bed, as well as fully enclosed and cooled electronics and a custom filament spool holder. The printer uses a PTFE lined hotend with a maximum temperature of 240° C, capable of printing common plastics such as ABS, PLA, and PETG. It has a maximum print volume of 8” x 8” x 7” (448 in³) and a minimum layer height of 100 microns (0.0039”). It uses standard G-Code to control the printing motion, and therefore can be used with any open source software that generates this style of build code. [11]
Objet 260 Connex

The Objet 260, made by Stratasys, uses PolyJet 3D printing to create a part within the print volume. The printer deposits a UV-curable resin in a fine layer, then solidifies the resin using a UV light. Where there are overhangs or similar features on the model, the printer jets a water soluble support material which can be removed in post processing using a waterjet. This also allows the Objet to mix materials during the print, creating up to 14 different material properties within a single part. By blending various resins, the printer can simulate the material properties of a wide range of commonly used plastics, as well as
create color blended and smooth prototypes. The Objet has a print volume of 10.0” x 9.9” x 7.9”, with a layer thickness ranging from 0.0006” to 0.001”. The accuracy for features smaller than 50mm is +/− 0.0008”-0.0033”, with a total model accuracy of up to +/− 0.0078”. The minimum feature size is approximately 0.015”, but features of that size may experience damage in post processing. The Objet can create parts with either a glossy or matte surface finish, as well as printed with one material and coated with another.

However, printing using the PolyJet technology is approximately 4-5 times the cost of the Dimension's FDM technology. [10]

Campus Printer Summary

<table>
<thead>
<tr>
<th>Printer</th>
<th>Dimensions</th>
<th>Min. Layer Height</th>
<th>PLA</th>
<th>ABS</th>
<th>PETG</th>
<th>Nylon</th>
<th>Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makerbot Replicator</td>
<td>11.2” x 6.0” x 6.1”</td>
<td>100 Microns</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Dimension SST 1200ES</td>
<td>10” x 10” x 12”</td>
<td>330 Microns</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>MarkForged Mark 2</td>
<td>12.6” x 5.2” x 6.1”</td>
<td>100 Microns</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Objet 260 Connex</td>
<td>10” x 9.9” x 7.9”</td>
<td>15.2 Microns</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Wanhao Duplicator i3</td>
<td>8.0” x 8.0” x 7.0”</td>
<td>100 Microns</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

*Table 1: Detail Summary of On-Campus Printers*
Design Considerations

Size
While WPI boasts a number of 3D printers, none of the printers exceed 1200in$^3$ in print volume. This was the first specification that this project intended to address. Starting with a print area goal of 24” x 36”, the print area was dropped to 18” x 36” early on in the design process. This was done after it was determined that the PCBs and glass were only readily available in these reduced dimensions, and the 24” wide surface would have made the printer too large to fit on most standard table surfaces.

Simultaneous Printing
The majority of printers on the market use a single print nozzle and print one part at a time. Some printers, such as the MarkForged Mark 2, employ a dual nozzle system, allowing the printer to print in two different materials at once. Typically, this configuration is used when a large amount of support structure is necessary, so that one nozzle can print these supports in an easily removable/dissolvable material, and the other can print in the desired plastic. Our synchronous print system is designed to be modular, allowing either one, two, or three identical parts to be printed simultaneously. Each hotend extruder is mounted within a carriage, which can be coupled to the other hotend carriages using rigid aluminum straps. This allows the carriages to move synchronously even though only one carriage is being driven by the XY motion system.
Subsystems of the Printer

Numerous mechanical and electronic subsystems were incorporated within this printer that were essential to its operation. In order to complete all of the required tasks within the time constraints of this project, these subsystems were addressed by three independent teams, which interfaced with one another frequently across the span of the project. This project team was focused on six fundamental components: the structure, the bed leveling, the Z-axis motion, the enclosure, the heated bed, and the rail system.

Structure

The structure of the 3D printer is a critical component, as all of the hardware was designed around and constructed on the frame. The critical specification of the frame was the rigidity and strength, as the printer cannot function properly if the entire printer deforms or changes dimensions during the print.

To this end, the team decided to construct the frame out of 80/20 aluminum extrusion. The extrusions geometry and material allow it to remain rigid over the distances necessary for a printer of this size. The extrusions were ordered directly from the manufacturer cut to length, and assembled by the team. Minimal manufacturing was performed on the extrusions by the team with the exceptions of tapping and drilling access holes to utilize end fasteners. End fasteners are secured using an end tap in the profile of the 80/20, and a tab that is held in place using a button head cap screw. Once in place, the fastener is tightened through a pre drilled access hole in the mating strut section. The end
fastener assembly process is shown in Fig. 13. The top and bottom frames are identical in size and made from 25mm x 50mm profile.

Figure 13: 80/20 Connectors

Figure 14: Basic Frame
Between these two frames, four polished linear shafts compose the vertical supports of the printer and double as axes to allow the bed to translate smoothly. These rods were attached using 12mm shaft supports at each end, fastened to the frames using T-nuts designed to slot into the extrusion profile. With the four shafts assembled on the printer frame, the main structure was complete.

Additionally, 80/20 extrusion was used to create a frame for the bed. Due to the rigidity of the material and the standards of manufacturing from the supplier, the extrusion was ideal for creating a level surface upon which to set the bed. This would provide a reference for the bed leveling system, as the bed frame could be leveled from the corners rather than needing to address leveling within the boundaries of the print area.

*Figure 15: Print Bed Frame*
Bed Leveling

The bed leveling system is the interaction point between the bed frame and the printer structure, as well as a connection for the Z axis motors. It is imperative that the bed remains level during printing, as the process of FFF printing cannot print in non-level layers. The bed was chosen as the component to move in the Z-axis to simplify the upper frame which holds the CoreXY motion system. Traditional i3 style 3D printers often use small springs over bolts at the corner of the bed assembly. However, the larger bed used on our printer would require much heavier springs to support.

The initial bed leveling system used a plastic plate to connect two lead screws to the bed frame. The bed was attached at each corner to the four 12mm smooth rods via 3D printed blocks and linear bearings. However, to level the bed it must be able to move independently of the attachment to the linear motion framework. Since the 80/20 frame the bed sits on was designed to be used as a rigid framework for the PCB heated beds and print surface, we determined that the bed assembly must sit on top of a frame or structure of some kind.

Figure 16: Original Bed Levelling System
The second bed leveling design used two sections of aluminum L channel as the primary supports for the bed. These support bars were machined to fit ABS corner blocks that hold 12mm linear bearing to guide the vertical motion of the Z axis. Although each support assembly moves independently, the Z axis stepper motors receive the same signal, ensuring the two support assemblies remain aligned relative to one another. Bolts in the corner blocks are trapped in 3D printed ABS cones at each corner, providing a method for leveling the bed. The taper within the cones locks the bed into position under its own weight, keeping it secure during printing. This iteration was the final design used, and has provided a very sturdy platform for the relatively heavy bed.

Figure 17: Final Levelling Blocks
Z Axis Motion

Several design iterations were required for precise Z axis (the vertical direction), control. We were constrained to only using two stepper motors to drive the Z axis due to the limited amperage output of the control board used.

The first design iteration used two 2mm pitch four start lead screws at the center of the support assembly on either side of the bed. Lead screws are measured using their lead, which is the distance the nut travels in one turn, and by the pitch of the threads. The original lead screws had a 2mm pitch with 4 thread paths, giving them an 8mm lead. Comparisons of different start lead screws is shown in Fig. 18.

These screws, which are designed for linear motion, would provide rapid motion as well as accurate positioning of the bed. However, the weight of the bed caused the stepper drivers controlling the Z axis motors to overheat. The bed assembly also experienced significant vibrations across the Y axis, which required a structural improvement to correct. Our redesign of the Z axis motion system was designed to address the excess vibrations and the overheating drivers.
To resolve the issues with the first iteration of the Z axis motion we focused on increasing both the mechanical advantage and stability of the bed. The first change was the lead screws. They were upgraded from two 2mm pitch four start (8mm of linear travel per revolution) to four 2mm pitch single start (2mm travel per revolution). Doubling the number of lead screws greatly improved the stability of the bed, as it was driven from four points instead of two. New holes were machined in the support bars to accept the upgraded leadscrew drive assembly.

In addition to reducing the pitch of the leadscrews, a tensioned belt drive system was developed to drive two lead screws simultaneously using a single stepper motor. This belt drive used a 20 tooth drive pulley on the stepper motor to drive two 60 tooth pulleys on the leadscrews in tandem. The system is tensioned using several idler pulleys to ensure...
the belt does not skip teeth when driving the bed. This improved belt drive system provides the necessary stability for the bed assembly during a print, as well as reducing the direct load on the stepper motors via the mechanical advantage provided by the drive pulleys.

Figure 20: Photo of the Z-Axis Drive System

Enclosure

The enclosure of the printer was designed as two separate assemblies. The main enclosure houses the entire range of bed positions and allows access to the print bed via a set of doors. The top enclosure sits on top of the frame and encloses the rail system, wiring, and Bowden tubes, and is easily removable to allow access to the printer heads.
Main Enclosure

The purpose of the enclosure is to protect the operation of the printer as well as allow a clear view of the part being printed. It was constructed from glass panels and supported by aluminum brackets and frames. Glass was chosen as the transparent material because of its hardness and clarity. Acrylic panels were considered, but it is much easier to scratch or mar acrylic than glass, and for the expected life of the printer, the glass surface would remain unscratched.

The main enclosure houses the entire print volume and consists of glass panels on three sides and the electrical mounting board on the fourth. The glass panels are mounted on the right and rear sides of the printer via a set of machined corner blocks that attach directly to the 80/20 frames.

Top Enclosure

The top enclosure consists of acrylic panels connected by custom angled brackets that were 3D printed. The top enclosure protects the wires and rail system while also giving a clear view of the print operation. It needed to be removable to allow for maintenance or configuration changes. As such, glass panels were determined to be too heavy and fragile to be moved on and off of the printer assembly. Acrylic was chosen because any potential damage would not compromise the integrity of the enclosure.
Heated Bed

The heated bed was constructed from two layers. The bottom layer is two side-by-side 18” x 18” heated printed circuit boards (PCBs). Each PCB requires its own dedicated 600W power supply and is able to reach 90° C. The top layer is a sheet of 18” x 36” window glass. Glass was selected for the print surface because it is rigid, flat, and very smooth, allowing for a clean and consistent surface finish on printed parts. While borosilicate glass is the industry standard for print beds due to its extremely low thermal expansion coefficient, a sheet of the size required for this printer exceeded the budget limitations. Replacing the window glass with borosilicate would make an excellent future upgrade for this printer.

A previous iteration of the bed included a middle layer, which was an 18” x 36” sheet of 3003 aluminum selected for its good workability and low price point. This layer was intended to more evenly conduct the heat from the heated PCBs, evenly dispersing the heat to prevent hot or cold spots from forming before it reached the glass.

Unfortunately, the aluminum was too thin and warped after just a few prints due to the rapid heating and cooling. This warpage caused the glass to become unleveled during printing. To eliminate this issue, the aluminum sheet was removed from the bed assembly. This allowed the PCBs and glass to use the 80/20 frame for flatness.

To test the PCBs, we ran them for forty minutes at 60° C, and recorded the temperatures using a Seek Thermal Compact camera, which let us use a cell phone to take infrared photos like the ones featured below. As Fig. 21 shows, the heat distribution in the PCB was fairly uniform as the bed warmed. The heat was concentrated primarily in the
corners, but the cold spot in the middle of the bed was small enough and warm enough that it was not deemed to be an issue.

![Figure 21: Seek Thermal Photo of the Heated Bed](image)

However, once the bed was fully assembled, we saw cold spots begin to form. Where the aluminum 80/20 bed support contacted the underside of the PCBs (around the edges and in the center), it acted as a heat sink, slowing the rate at which those areas gained heat.
To remove the cold spots, cork insulation was added underneath the contact areas. This prevented the heat from dissipating through the frame and allowed for more uniform bed surface temperature. The final heated bed assembly is shown below in Fig. 22.

Figure 22: Exploded Bed Assembly
Rail System and X-Y Axes of Motion

Rail Shafting and Blocks

Contained within the top frame of the structure is the XY rail system. This consists of four linear shafts and four 3D printed blocks to orient the shafts perpendicular to one another. The block supports house bearings that move along the Y direction, with the linear shafts in the X direction moving with the blocks. The hotend carriages travel along the linear shafts in the Y direction, and contain the endpoints for the CoreXY system discussed below.

Initially the linear shafts in the X direction had a diameter of 8mm, but after assembly the block supports were seen to be rotating around the shafts in the Y direction. This meant that the X direction shafts were deflecting under the weight of the hot end
carriages. Calculated beam deflection of a single 8mm shaft supporting half the working load is shown below in Equation 1. Full deflections calculations are shown in Appendix C.

\[
\text{Deflection at } x=d \text{ (Center of Bar)}
\]

Shaft Diameter:

\[
D := 8\text{mm} \quad I := \frac{\pi \cdot D^4}{64} = 201.062\text{mm}^4 \quad E := 200\text{GPa}
\]

\[
y_d := \frac{1}{6 \cdot E \cdot I} \left[ R_A \cdot d^3 - 3 \cdot M_A \cdot d^2 - \frac{w}{4} \cdot (d - a)^4 \right]
\]

\[
y_d = -0.178\text{mm}
\]

The calculated deflection of 0.178mm is almost double a standard 100 micron layer thickness, which indicates that a part would experience a Z height difference of this value over the full bed travel. This was determined unacceptable and a full redesign was required.

To address the issues of deflections, the block supports were redesigned and 12mm shafts were used for the X direction. As shown in Equation 2, this gave only 0.035mm of deflection at the center of the rod, an acceptable value for Z axis error over the entire length of the bed.
This increase in shaft diameter represented an 80% reduction in beam deflection across the travel of the bed. Additionally, in the new design two aluminum bars were added between the block supports to prevent any rotation about the Y linear shafts. These were placed as to not interfere with movement of the X direction shafts or the hotend carriages. These 0.125" x 1.25" aluminum sections helped to further reduce deflection and add extra stiffness to the head assembly.

The shaft blocks were iterated once again as a failsafe in the event that the hotend nozzle collided with the print bed during calibration or printing. The original shaft blocks held the ends of the X axis shaft captive by clamping around it using two bolts. This provided a very secure hold, but introduced problems in other areas. One of the key specifications for this printer is the relative ease of removal for additional heads, allowing the printer to produce one large part or many smaller parts. Captive shaft ends made removing nozzles difficult and time consuming. Additionally, the captive design constrained both the nozzles and the print bed rigidly. In the event of a collision, damage
would occur to some component of the printer. Since the printer is designed to be used by a wide range of people, including potentially unskilled operators, fail safes should be in place to avoid permanent damage to the printer. The original clamping shaft blocks are shown in Fig. 24.

![Figure 24: Second Iteration of Rail Support Blocks](image)

The final iteration included a V shaped channel so that if the hotend and print bed collided, the X shafts would lift out of the support blocks, preventing stresses at the nozzle tip from breaking the glass print bed or damaging the nozzles or motion assemblies. Since there is no vertical force exerted upwards during printing, the blocks can simply be set in place and the V groove will center them. The updated blocks installed on the printer are shown in Fig. 25 and Fig. 26.
During operation, the liftout blocks worked as designed, preventing damage to both the print bed and the nozzles. This lift-out feature also makes it much easier to switch the printer between the full size single nozzle configuration and the triple nozzle simultaneous print configuration. Once the rails are lifted, the carriages can easily be slid free.
CoreXY System

CoreXY is a type of Cartesian motion systems that uses two stationary motors to drive the head assembly in both the X and Y directions. Two crossed belts, each attached to the end effector at two locations, allows the head to move in the XY plane. The system was developed in 2012 by Ilan Moyer of MIT, with the goal of creating a scalable motion systems with a lightweight end effector driven by only two motors. The basic function is shown in this image, along with the equations of motion that model the movement of a CoreXY system. [13]

Equations of Motion:

\[ \Delta x = \frac{1}{2} (\Delta A + \Delta B), \quad \Delta y = \frac{1}{2} (\Delta A - \Delta B) \]

\[ \Delta A = \Delta x + \Delta y, \quad \Delta B = \Delta x - \Delta y \]

*Figure 27: CoreXY Illustration*
Traditional Prusa i3 style printers use a bed that moves in the Y direction, and a head that moves in the X direction. Due to the large printer bed desired in this project, moving the bed was not feasible as it would have required a space twice as wide to receive full bed travel. I3 style machines also have a head that is mobile in both X and Z, allowing it to raise and lower as well as move side to side. While this style is effective for smaller spans, over the large distances considered in our project, the rods experience significant deflection under loading, as the stepper motor that drives the X motion must be carried along the Y axis. By implementing the CoreXY system, the motors that drive X and Y can be stationary, and the bed can move in the Z axis. This allows for higher accelerations at the head and rapid travel, essential for such a large print area.

Results

After several design iterations, the large format printer platform met all the initial task specifications and was integrated with the hotends, extruders, motors, and controls from the other two project teams. The total print volume exceeds the available printers by over four times, with a maximum dimension of 36”, three times larger than any of the WPI printers. The frame provides a rigid and easily expandable platform, utilizing the slotted profile to attach components such as motors and linear rods. The CoreXY motion system provides accurate X and Y motion using only two frame mounted stepper motors. The printer has a heated bed and is fully enclosed to allow printing of thermally sensitive plastics such as ABS and nylon without warping. The lift out shaft blocks eliminate
breakage of the bed glass due to nozzles crashing, as well as provide an easy and quick systems for adding or removing auxiliary hotend carriages.

Positioning Accuracy

The positioning accuracy of the printer was used a metric to gauge the stiffness and stability of the frame and the linear motion system. Positioning accuracy was validated using a standard machinist’s dial indicator with magnetic base. The axis to be tested was homed to 0, then moved to a given location. The indicator was then moved into position and locked into place, with the dial reading zero at the indicated location, as shown in Fig. 28.

![Figure 28: Testing Position Accuracy](image)
The axis was then moved 40mm away from the point, then returned to that same point. To ensure backlash within the belts would be considered, the point of interest was approached from both sides during the testing. The results of the positioning accuracy are shown in the following table:

<table>
<thead>
<tr>
<th>Displacement From 0 After 40mm Travel (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Axis</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>-0.001</td>
</tr>
<tr>
<td>-0.001</td>
</tr>
<tr>
<td>0.002</td>
</tr>
<tr>
<td>-0.001</td>
</tr>
<tr>
<td>0.002</td>
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<td>0.0025</td>
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<td>-0.002</td>
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<tr>
<td>-0.001</td>
</tr>
<tr>
<td>-0.002</td>
</tr>
</tbody>
</table>

*Table 2: Position Accuracy Test Results*

These displacement results show a positioning accuracy of less than 0.001 in both X and Y, as well as only 0.0024 in Z. This Z positioning error is approximately half of a standard layer height (0.0039”), which we determined was accurate for the positioning of a FFF head. Since FFF technology is inherently limited by components such as the hotend nozzle,
extrusion multipliers, nozzle size, and accuracy of the flow rate of plastic, the accuracy and precision of the part will not be limited by the X, Y, and Z positioning of the platform.

Sample Prints and Print Quality

![Figure 29: Benchmark Boats](image)

These boats are a common benchmark print, used to test dimensional accuracy. These were printed at every major iteration and design change to test the capabilities of the printer. The first few generations of these prints were rough and imprecise, and many didn’t survive at all. These three are from the final round of testing, when the printer was completed. The dimensions of these boats are accurate to within 0.01mm. They were printed at the same time, utilizing the simultaneous printing feature.
This was an overhang test, which was printed to test the maximum unsupported angle the printer could operate at before failure. The numbers etched into the front of the part indicate the angle at which that section is positioned at, with respect to vertical. This picture clearly shows that the part is accurate up to 80°, where the print quality begins to deteriorate.
This photo shows the range of pigments the diamond hotend is capable of printing. All of these colors were made using only magenta, cyan, and yellow colored filaments. At the time of writing this document, only the center nozzle carriage is equipped with a diamond hotend, and so these spectrum prints can only be produced by the center nozzle.
Conclusions and Recommendations

The printer design is highly functional and produces high quality prints. It allows multiple copies to be made simultaneously. It allows for multiple colors from a single extruder. It maintains its precision across the large build space. However, our team still has several recommendations to further improve the print quality as well as the longevity of the printer. The window glass covering the print surface could be replaced with an equivalent sized piece of borosilicate glass. Borosilicate glass is the industry standard for print beds due to its low thermal expansion coefficient, but unfortunately our allocated budget did not allow for this expense. Over time, the window glass used might crack due to the cyclic stress of being heated and cooled. We also recommend the replacement of 3D printed parts with aluminium equivalents as time and budget allows. While 3D printed ABS parts are adequate for the prototyping and testing phase, aluminum parts would add rigidity as well as improve the longevity of the various printer systems.
References


http://www.nookindustries.com/LinearLibraryItem/Acme_Screw_Thread_Form_Terms

[13] CoreXY, n.d., “CoreXY| Cartesian Motion Platform”, from
http://corexy.com/theory.html

http://www.engineersedge.com/beam_bending/beam_bending19.htm
Appendix A

Pictures of Printed Parts

Figure 32: Printed Functional Screw and Nut

Figure 33: Three Hairy Lions, Printed Simultaneously
Figure 34: Letter Cubes. The red cube was an early print. The blue cube was printed once construction was finished. The difference in quality is significant.

Figure 35: Collection of Test Parts
Appendix B

Complete CAD Rendering

Figure 36: Complete CAD Rendering, including the top enclosure
Printer Photos

Figure 37: Printer in Action
Figure 38: Control Box and Panel, showing how the panel can slide in and out of its box
Figure 39: Print Heads at Work
Figure 40: Z-Axis Drive System
Figure 41: Levelling Blocks
Appendix C

Linear Rod Deflection Calculations

Main Printer Rod Beam Deflection:
Modeled as a rigidly constrained beam with distributed load at center

\[ L_{\text{rod}} = 930 \text{mm} \quad d := \frac{L_{\text{rod}}}{2} = 465 \text{mm} \quad c := 57.6 \text{mm} \]

\[ m_{\text{total}} := 0.175 \text{kg} \quad w_{\text{total}} := m_{\text{total}} g \]

\[ b := d + \frac{c}{2} = 493.8 \text{mm} \quad a := b \]

\[ w := \frac{w_{\text{total}}}{c} = 29.795 \text{ N/m} \]

Reaction Forces at End Blocks:

\[ R_A := \frac{w_{\text{total}}}{4L_{\text{rod}}} \left( 12d^2 - 8d^3 - \frac{2b^2c^2}{L_{\text{rod}}} - \frac{c^3}{L_{\text{rod}} - c^2} \right) \]

\[ R_A = 0.858 \text{ N} \]

\[ R_B := w_{\text{total}} - R_A = 0.858 \text{ N} \]

Moment

\[ M_A := \frac{w_{\text{total}}}{24L_{\text{rod}}} \left( 24d^3 \frac{L_{\text{rod}}}{L_{\text{rod}} - c^2} + 3c^3 - 4c^2 - 24d^2 \right) = 0.199 \text{ N-m} \]

\[ M_B := \frac{w_{\text{total}}}{24L_{\text{rod}}} \left( 24d^3 \frac{L_{\text{rod}}}{L_{\text{rod}} - c^2} + 3c^3 - 2c^2 - 48d^2 + 24dL_{\text{rod}} \right) = 0.199 \text{ N-m} \]

Deflection at \( x = d \) (Center of Bar)

Shaft Diameter

\[ D := 12 \text{mm} \quad I := \frac{\pi D^4}{64} = 1.018 \times 10^3 \text{ mm}^4 \quad E := 200 \text{ GPa} \]

\[ y_d := \frac{1}{6EI} \left[ R_A d^3 - 3M_A d^2 - \frac{w}{4}(d-a)^4 \right] \]

\[ y_d = -0.035 \text{ mm} \]

Equation 3: Linear Rod Deflection Calculations
80/20 Beam Deflection

80/20 Deflection Calculations

Assumptions:
- Beam can be modeled as fixed at both ends with a point load applied to the center
- This calculation models the effect of a person leaning on the printer frame during a print, which represents the maximum force that would ever be applied to a section.
- The 80/20 section used is standard 25mm x 50mm strut, with properties from the 80/20 catalog.

Assuming a person leans on the center of the unsupported top rail with a force of 30lbf exerted directly at the center (point load)

\[ W_{\text{load}} = 30\text{lbf} = 133.447\text{N} \]

Beam Length: \[ L_{\text{beam}} = 1150\text{mm} \]

At center, \( a = b = x \)
\[ a = 575\text{mm} \quad b = 575\text{mm} \quad x = 575\text{mm} \]

Moments at Ends:
\[ M_{\text{end}} = \frac{W_{\text{load}} \cdot a \cdot b^2}{2} = 19.183\text{N\cdotm} \]

Reaction Forces at Ends:
\[ W_{\text{end}} = \frac{W_{\text{load}} \cdot b^2}{3} \left( \frac{L_{\text{beam}}}{L_{\text{beam}}} + 2 \cdot a \right) = 66.723\text{N} \]

From 80/20 Catalog:
\[ I_x = 12.1715\text{cm}^4 \quad I_y = 3.1967\text{cm}^4 \quad E = 70326.5 \frac{\text{N}}{\text{mm}^2} \]

Deflection at Center:
\[ y = \frac{W_{\text{load}} \cdot x^2 \cdot b^2}{6 \cdot E \cdot I_x \cdot L_{\text{beam}}} \left[ 2\cdot a \left( L_{\text{beam}} - x \right) + L_{\text{beam}} \left( a - x \right) \right] \]

\[ y = 4.862 \times 10^{-3} \text{in} \]

Equation 4: 80/20 Beam Deflection. Sketch from [14]