3D Printer Buyer's Guide

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Compliments of NextFab Studio

NextFab Studio

Philadelphia's Premiere Maker Space

Design / Engineering / Fabrication Services

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Mission Statement

This analysis compares the performance of one industrial grade additive manufacturing system ("3D printer") with three low-cost additive manufacturing systems. The primary goal of this study is to help potential consumers understand some of the capabilities and tradeoffs as they consider purchasing one of these machines, and to assist users and manufacturers with evaluating, tracking, and improving the performance of their own systems. Comparisons include initial set-up / commissioning, finished part feature accuracy, precision, inherent technology tradeoffs between the machines, and cost.

Background

One of the biggest challenges in developing a mechanical part is that CAD software allows extreme flexibility in how a 3D solid part is constructed, allowing features to be specified that can be impossible to create in the real world once they are subjected to physical forces like gravity. Imagine a plastic kitchen table with a 0.010" thick surface. It can be specified in the CAD tool, and perhaps assembled, but will be very likely to crack and break when an object is placed on it. Changing the thickness or material may allow it to work as the designer intended.

This balance of structure, material choice, and manufacturing methods tend to make part development an iterative and often costly process. Depending on the material used, complexity of the design, and the number of parts that need to be made, different approaches, such as CNC machining of each part, or building injection mold tooling and molding parts, may be cost effective for manufacturing. Particularly in applications where hundreds or thousands of parts are needed, the complexity of the tooling to handle the job goes up, as does the time and cost to create them.

Additive manufacturing technology (colloquially known as "3D printing" and formerly as "rapid prototyping") first emerged commercially in the 1980's as a very expensive approach to refining designs prior to committing resources to machining of injection molding tooling (see 1 and 2 for excellent background on the technology). Additive manufacturing has matured over the last decade as a viable (though very expensive) low volume (< 100 parts) manufacturing process for parts with complex geometries. In the last five years, a number of open source, free and/or low-cost 3D printer systems [3,4,5,6,7,8] have become available which make the technology accessible to students and educators, hobbyists, and small businesses, and which generally encourage end-user experimentation and modification/enhancement of the technology. This end-user R&D is shared and documented in vibrant user groups such as reprap.org, thingiverse.com, and fabathome.org. The technology employed by the most popular of these low-cost systems is known as Fused Deposition Modeling (FDM), developed by Stratasys, Inc. For this reason we have chosen to focus our first study on FDM based systems.

Low-Cost / Kit Machines

MakerBot Industries CupCake CNC

Figure 1 - Assembled MakerBot Cupcake CNC from www.makerbot.com

http://www.makerbot.com/
$649 entry point, assembly required

Bits From Bytes BFB Rapman

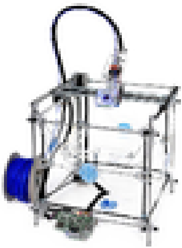

Figure 2 - Assembled RepRap from www.bitsfrombytes.com

http://www.bitsfrombytes.com
£795.00 (approx $1,200), assembly required

Bits From Bytes BFB3000

Figure 3 - BFB3000 from www.bitsfrombytes.com

http://www.bitsfrombytes.com
£1,995.00 (approx $3000)

Commercial Machines

Stratasys

Figure 4 - Stratasys Dimension 1200ES SST from www.dimensionprinting.com

http://www.dimensionprinting.com/3d-printers/3d-printing-sst.aspx
Approx $32,000

Experimental Design

The electro-mechanical systems that create these parts have distinct differences in capabilities and sources of variation. The basic approach we used to be able to compare these machines was to design a coupon that could be produced on all of the machines so we could take measurements of critical dimensions that give us insight into the capabilities of the process. High-resolution images are also taken of the parts to help us understand some of the more qualitative differences between the parts and capabilities.

As coupons were created in each of the open architecture machines, we also captured start and stop time. This not only allows us to capture the build time for each of the parts, but allowed us to correlate the ambient temperature and humidity conditions at the time of build, as recorded by a temperature/humidity data logger in the lab space, sampling at 5 minute intervals.

Coupon Development

To best compare the machines, we developed a test coupon with a number of features that would let us objectively compare some strengths and weaknesses of the test machines.
The coupon comprises two halves, referred to as 'A' and 'B', which are a mirror reflection of each other. This allows us to not only increase the count of features to compare, but it also changes certain orientations within the build envelope. Figure 5 depicts a plan view of the coupon with the face dimensions labeled, while Figure 6 presents an isometric view with the height dimensions labeled.

The features are relieved from a 25 x 25 x 10mm solid. 4mm solid cylinders are in the solid – one of which is in a 10mm cylindrical cavity, and the other within a 12mm cylindrical cavity. These are designed to test fairly close clearances of features. There are also 15 and 30-degree wedges at the corners of the parts. Fine points like these are a significant challenge for the machines to produce. Particularly with FDM technology, this requires the plastic extruder head to follow a very fine tool path. The CAD design specifies that each of the edges with the angled wedge has a 25mm length. The finer a feature that each of the machines can create, the closer they will come to making a point and having an overall dimension of 25mm.

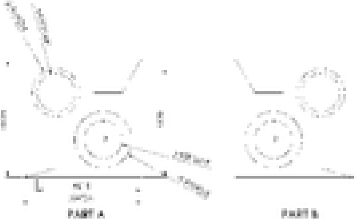

Figure 5: Test Coupon Top Dimensions

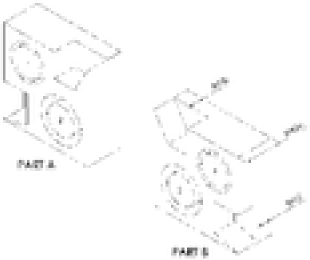

Figure 6: Test Coupon Elevation Dimensions

Critical Dimension Discussion

Table 1 shows all of the measurements defined and measured across the samples made on each of the machines.

Measurement Name	Design Dimension [mm]	Description
ALOA	25	Part A - Length Overall
AWOA	25	Part A - Width Overall
AHOA	10	Part A - Height Overall
AL15	25	Part A - Length of edge with 15 degree wedge
AL30	25	Part A - Length of edge with 30 degree edge
A1PILLAR	6	Part A - Diameter of 1st pillar
A1HOLE	10	Part A - Diameter of 1st hole
A2PILLAR	6	Part A - Diameter of 2nd pillar
A2HOLE	12	Part A - Diameter of 2nd hole
AH15	4	Part A - Height of shelf adjacent to 15 degree wedge
AH30	4	Part A - Height of shelf adjacent to 30 degree wedge
BLOA	25	Part B - Length Overall
BWOA	25	Part B - Width Overall
BHOA	10	Part B - Height Overall
BL15	25	Part B - Length of edge with 15 degree wedge
BL30	25	Part B - Length of edge with 30 degree edge
B1PILLAR	6	Part B - Diameter of 1st pillar
B1HOLE	10	Part B - Diameter of 1st hole
B2PILLAR	6	Part B - Diameter of 2nd pillar
B2HOLE	12	Part B - Diameter of 2nd hole
BH15	4	Part B - Height of shelf adjacent to 15 degree wedge
BH30	4	Part B - Height of shelf adjacent to 30 degree wedge

Table 1 - Coupon Measurement Name and Descriptions

Performance Analytics

The following sections evaluate performance of each of the low-cost machines relative to each other. At the onset of the analysis, there were several significant differences that seem noteworthy to mention ahead of the discussion below.

First, although the build time was fairly consistent between iterations of the same job on a given machine, the CupCake CNC was significantly faster than the BfB machines. The CupCake CNC averaged 0h 31m per coupon, where the BfB Rapman took 1h 22m, and the BFB3000 averaged just a little longer at 1h 24m. Observing the machine build parameters, this appears to be driven by the different layer thicknesses and head speed.

Second, the build envelope of the three machines was also highly varied. Although the BfB Rapman and BFB3000 have significantly larger build envelopes, these do not allow significantly larger objects to be built. As the size of the object increases, the lack of a controlled (heated) environment results in excessive thermal contraction and warping of parts, and detachment of parts from the build surface. Note that heated build platforms are now available for the MakerBot, and we hope to study the effect of these on maximum part size in the near future.

Figure 7 shows an image of each of the coupon sets from the machines. The non-uniformities can all be seen, and remains of some of the plastic can be seen as the toolpath transitioned from one section to another.

Figure 8 shows some of these details more clearly. Sample 7 of all the open architecture machines are being used for both sets of pictures, so the details can be better compared. Note the small clearances around the cylinders present a significant challenge for all of the machines except the Dimension 1200es.

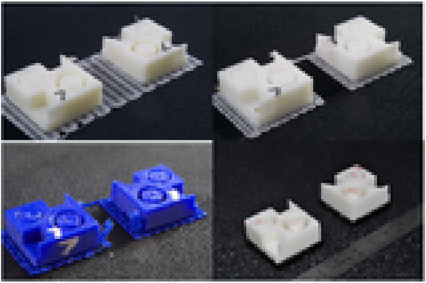

Figure 7 - Isometric view of coupons printed by all test machines – Top Left - MakerBot Cupcake, Top Right – BFB Rapman, Bottom Left - BFB3000, Bottom Right - Stratasys (UPRINT)

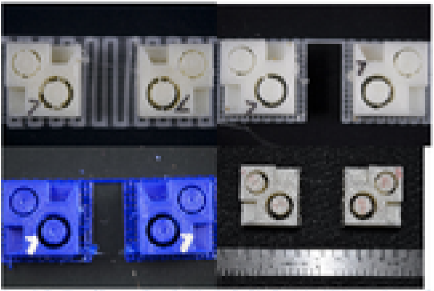

Figure 8 - Top View of Coupons - Top Left - MakerBot Cupcake, Top Right – BFB Rapman, Bottom Left - BFB3000, Bottom Right - Stratasys (UPRINT)

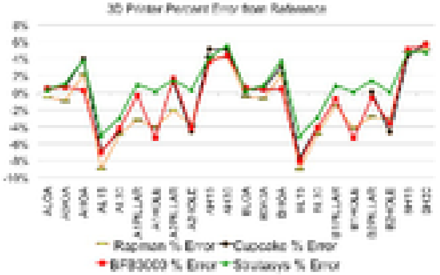

Figure 9 - Average Percent Error

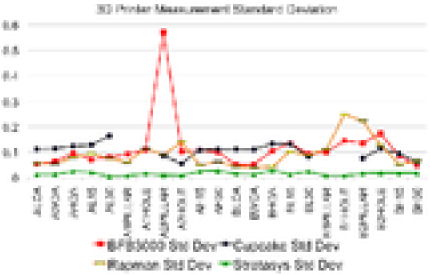

Figure 10 - Measurement Standard Deviation

Figure 9 represents all of the quantitative analysis performed in this study. 10 samples were produced on each of the machines (15 on the BFB Rapman), and the defined measurements were taken with a set of calipers. Those measurements were then averaged and compared to the reference design dimension, as noted in Table 1, and the percentages are plotted against each other.

Figure 10 shows the standard deviations of the data that make up the datapoints of Figure 9. The standard deviation gives us insight into how consistently the machines have been able to hold certain dimensions in each sample. The smaller the standard deviation, the more reliable the process tends to be. We see that the Stratasys has very low standard deviations, but the open architecture machines still are still producing a good result, albeit more varied.

There are a few points of interest to note in Figure 10. First, the A2PILLAR dimension's standard deviation was significantly higher than everything else. This was driven by a single outlier, as seen in Figure 11.

Figure 11 - [illegible] BFB3000 Coupon showing large standard deviation

At a high level, we can see that the Stratasys Dimension 1200ES tends to have less error than the other machines, but it is interesting to see that in this type of sample, the less expensive machines are all performing with less than 10% error to the design.

We can note that overall x and y dimensions (ALOA, AWOA, BLOA, and BWOA) all performed very well, in the 1-3% error range. Relatively speaking, the heights are more of a challenge for the CupCake.

As expected, the length of the sides with the angles (AL30, AL15, BL30, and BL15) all run lower than the design specified, since the toolpath of the extruder head cannot reach the edge of the part. The Stratasys clearly gets the closest to these dimensions, with the CupCake and BFB3000 getting the next closest.

Error Compensation Techniques

In this section, we discuss some techniques to compensate for the types of errors that we observed in the coupons in the previous section.

CAD Model Transformations

Observing the largest errors in Figure 9 - Average Percent Error, we observe that all of the machines have difficulty creating the full dimension of the angled wedge, specifically the AL15 and BL15 dimensions. By extending the x dimension of the edge of the solid, we can get closer to the desired overall dimension of 15mm. Note that this will distort the angle of the wedge. To compensate for this, we could proportionally extend both the x and y dimensions to preserve the angle, though that may distort other features of the solid.

There may also be situations where a dimension can't be allowed to go beyond a certain specification. This is where we can use the standard deviation to help us plan for model transformation. For example, the AH08 and BH08 dimensions on the BFB3000 were very close to the specified value (very low percent error), but looking at the corresponding standard deviation, this suggests that about half of the parts would be over the height specification. If an application of a part couldn't tolerate the dimension being over the specified height, we could make the height 2 or 3 standard deviations lower than the original specification, and we would expect the vast majority of the parts to fall below that dimension of interest.

Post Processing

Once a part has been created, there are also certain post processing steps we can perform to correct dimensions slightly above or below the intended specifications. Using traditional material removal processes (sanding, cutting, routing, drilling, etc.), we can purposely design a part to be slightly larger than intended and use some of these processes to fine tune dimensions, finishes of the plastic, or create contours that would be difficult or impossible for some of these machines to print by themselves.

Similarly, we can use additive techniques to both give desired visual and tactile finishes as well as grow dimensions that may have been printed smaller than desired. This is generally a more challenging process than removing material, but can be effective to add sub-millimeter thicknesses.

Conclusions

As we hope this study has shown the reader, all of the machines tested can produce useful parts from CAD files. Generally speaking, the more expensive machines did have less part to part variability than the least expensive, but the least expensive (CupCake) had very respectable results, and did so much faster than the BFB products.

There are certainly limitations in the type of part that is possible to build in these machines. For example, the open architecture machines do not have support material, so any contour that doesn't build on a firm base (overhangs, large bridges across material gaps, etc) will not be able to be produced very well. While it is possible on some of the platforms to add additional heads to make this possible, the Dimension printer has developed this capability as part of its core architecture, albeit at a much higher expense.

Environmental conditions should also be considered in the space that the parts are to be built. Observing the commercial machines, great care is taken to control the ambient environment and humidity of the material. Further, as the diary showed, better behavior was seen just getting the room temperature above 65F.

All of these machines have performed well. As we've discussed, there are a lot of influencing factors that could steer a developer to one machine or another. The assembly process on the CupCake and Rapman were lengthy, where the BFB3000 came pre-assembled. The build time was the best on the CupCake, though further experiments could be run to attempt to speed up the BFB machines from their defaults. For consistency, the Dimension was clearly the best.

Regardless of the open architecture machine you choose, the good news is that the developer community is active, and help is often available to help. Even when holding tolerances forces the use of one of the commercial machines, the open architecture machines can be invaluable to help develop the features of the part, and then transition to something like the Dimension once you have a mature design and are ready to scale up.

Selection Matrix

	MakerBot CupCake	[illegible]	BFB3000	Stratasys Dimension [illegible]
Approx. Cost	$950	$1,[illegible]	$[illegible]	$[illegible]
Ease of Assembly	OOO	OO	N/A - Preassembled	N/A - Preassembled
Ease of Calibration	OO	OOOO	OO	OOOOO
Ease of Operation	OO	OOOO	OO	OOOOO
Repeatability (Std Deviation)	O	OOO	OOO	OOOOO
Accuracy	OOO	OOO	OOOO	OOOOO
Maintenance	OOOO	OOO	OO	OOO
General Strength	Construction is [illegible] and simple	[illegible]	High quality prints.	[illegible]
General Weakness	[illegible]	Construction is [illegible]	[illegible]	[illegible]

References

1. 3D Printing article on Wikipedia.org [illegible]
2. Additive3D.com, additive manufacturing news and reference website [illegible]
3. Bits from Bytes, low-cost additive manufacturing systems [illegible]
4. CandyFab, Evil Mad Scientist Laboratories [illegible]
5. Dimension Printing (Stratasys, Inc.), commercial additive manufacturing systems [illegible]
6. Fab@Home Project [illegible]
7. MakerBot Industries, low-cost additive manufacturing systems [illegible]
8. RepRap Organization, open source additive manufacturing project [illegible]

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Appendix A

Machine Set-Up and Calibration

As all of the low cost / kit machines were tested, they all shared the fact that they had an involved set up and calibration process. The bulletized lists below are the observations and notes that were made during the system commissioning process.

MakerBot CupCake

- Construction time = 4 work days
- Strengths
    - Simple design → easy and fast construction
    - Large knowledge base and community
    - Informative instructions
    - Available upgrades (heated build platform, most notably)
    - Short build times
    - Easy access to electronics
    - Bridging small gaps in material
    - Easily installed electronics and wires
    - Construction allows easy access to repair or replace parts
- Weaknesses
    - Low precision
    - Small build platform
    - Unintuitive calibration (Skeinforge settings vary from one machine to another too greatly for precise presets)
    - Quite loud
    - Extruder problems (Plastruder mk4)
    - Not automated (one must adjust start height before build, and then must continuously adjust the height throughout the construction of the raft)
    - DC extruder motor prevents "suck back" ooze control.

- Extruder construction can be messy and difficult.
- Messy wires.
- Filling small areas (e.g. circles of radius < 4mm)

- Modifications:
  - Plastruder MK5 drive gear.
  - Thicker acrylic insulator retainer

- Comments:
  - Warping seems more prevalent at environmental temperatures under 68°
  - Heated build platform and end stops might make the machine more automated.

BFB Experience

- Construction time ≈ 10 work days
- Strengths
    - High precision
    - Large community
    - Informative instructions (3D pdf)
    - Quiet
    - "Suck back" ooze control
    - Well automated (after initial calibration, a build only requires two button presses)
    - Preset Skeinforge settings are effective
    - Adjustable-level build platform
    - Clean wires
    - Comes with a filament spindle
    - Comes with a pre-organized hardware bin
    - Does not need to be connected to a computer to run
- Weaknesses
    - Z-stage rises unevenly, and can sometimes skip.
        - This leads to consistent oscillating vertical edges.
    - Bridging gaps in material
    - Difficult and time consuming construction (one notable cause is the corner-clamp design)
    - Difficult access to PCB
    - Warped build platform
    - Difficult and time-consuming wiring and electronics
- Modifications
    - Placed a wooden block under a motor; the weight of the motor caused large

deflection in the acrylic motor mount

- Replaced z-mount switch (old inconsistently triggered before the "click")
- Placed washers under the build platform to bend the warped acrylic into a straighter shape

- Comments
  - Netfabb software results in higher quality surfaces and small area fills, but does not have any z-size control.
  - Default settings in RPP were used.

BFB 3000

- Construction time = None (2-3 hours of calibration)
- Strengths
    - Very precise
    - Quiet
    - Pre-built
    - Multiple extruder design
    - "Suck back" ooze control
    - Three built-in filament spindles
    - Large build platform*
    - Scrap filament bin
    - Does not need to be connected to a computer to run
    - Single acme threaded rod allows straight vertical edges
- Weaknesses
    - *Warped build platform renders the usable build area smaller
    - Hall effect limit switches (particularly on the z stage) results in inconsistent home heights, preventing confident automation
    - The extruder becomes easily jammed, and must be disassembled to repair
        - PTFE tubing is too thin
    - Nozzles may be unlevel, leading to difficult z-height calibration, and can cause one nozzle to come into contact with the build
        - This issue is made worse by the warped build platform
    - Bridging gaps in material
    - Extruders are extremely difficult to access, and even more difficult to take apart.
    - Not much slack in extruder cables; the 'extruder 2' cables become disconnected very easily, to the point where the machine sometimes removes it.

- Modifications
    - Replaced PTFE tubing (6mm OD, 3mm ID) with new PTFE tubing (6mm OD, 4mm ID)
    - Ziptied the extruder 2 cable in place
    - Placed washers under the build platform to bend the warped acrylic into a straighter shape
    - Lowered z-stage hall sensor
- Comments
    - Had to modify the default settings in Axon.
    - There is very little support for this machine since it was just released. However, because it is derivative of RapMan 3.1, the problems and solutions to both machines may be similar.
    - The hall sensors weren't always consistent. The problem started occurring after one week of printing.
    - The reason it is more difficult for the BFB machines to bridge gaps is likely to due to the lower viscosity (from higher extruder temperatures) and slower head speed.

Appendix B

Machine Commissioning Diary

The next sections are notes that were taken during the machine setup and calibrations. Although user communities have been helpful, it's our hope that these notes may help see some of these issues coming as you set up your new 3D printer.

MakerBot Cupcake

- Kapton tape is a mess
- Acrylic insulator retainer snapped on installation
- Z-motor was initially reversed in the firmware. The extruder plunged and slightly dented the build platform.
  - After this happens, the x-stage nuts become unaligned, and must be realigned as the extruder is not needed.
- If the firmware reversal setting is on, the extruder sometimes does not extrude. I changed the "time to advance" and "time to reverse" parameters to 0.
- Plastruder jammed
  - Flossed teeth, and forced filament in. Now works
- Edited start.txt to raise raft temp to 220C
- Thermistor keeps shorting or opening. It often will just read "255". Adjusting the wire position fixes the problem.
- Changed infill pattern to "rectangular"
- Tried Z-curve parameter from 1.46-1.47 with poor results.
  - 1.47-1.51 with poor results. I'm leaving it at 1.46 for now
- You **must** print with the SD card. After doing two prints of a pillar, one via SD and one via USB, it is clear that the SD card prints the fine and small areas better.
  - Printing from SD is tricky since there is no "Continue" prompt on the computer after the start.txt has heated up the extruder. You need to sit and watch the extruder with pliers ready to remove the excess filament.
- New calibration using new Skeinforge knowledge.
  - PWM: 110

- Extrusion diameter = .594mm -> ratio = 1.4151
- Extrusion width = .5962mm -> ratio = 1.6227737

- Raft keeps curling. I will wait until the room is warmer (greater than 69 degrees F).
- Testing the xy head speed-dependent small area quality
  - If you increase feedspeed by x times, the cross-sectional area (per unit time) of each position on the path is divided by x.
    - The resulting diameter is [illegible]
    - You want to keep all of your same ratios, so you need to multiply the layer height by [illegible] keep the same print quality.
    - You can also use this and solve for the settings you would need for a particular layer height, theoretically.
  - I tried one 1.5 times faster, one 1.5 times slower, and one with normal settings on a small pillar test. No pillar printed any better than it ever does.
- Warping doesn't seem to occur (as much) at 71 degrees F.
- Sometimes while printing from the SD card, ReplicatorG will give you read errors. While the makerbot is on and ReplicatorG is running, press the "Reset" button on the motherboard and try again.

BFB Experience

- 3D pdf assembly guide is interesting and useful
- Comes with a hardware kit that is quite useful
- Sanded the build platform with 220 grit paper to create a better surface on which the filament will stick
- End of page 28 is confusing
- The threaded rods are all dirty. I cleaned them, although not to the best of my abilities. The process already seemed too time-consuming and they didn't seem much of an importance for cleaning the threaded rods.
- Top frame large shafts are too large for 25mm screws.
    - Quite annoying
- I forgot to peel away the protective film from the backside BFB logo.
- I broke the back right top rod cap. The air pocket it creates makes it difficult to place them on.
- Page 46 has mis-numbered and confusing instructions.
    - Same with page 47
- The z-stage "jumps". This may be problematic.
    - (It only results in oscillating vertical edges)
- The wire conduits are extremely difficult. It is hard to keep the wires from either getting jammed or the guide tape coming undone.
    - These conduits make me sad.
        - I used the blue duct tape-esque tape for the second conduit I wove.
- The electronics board doesn't mount well. It hangs and is partially free to rotate around the shaft and can move radially outwards.
- Grommets on the extruder sometimes grab the bolt.
- Thermistor and nichrome parts seem to be built into the heater. I like this.
- 16mm bolts are too short for the extruder fan; I'm using 20mm instead.
- They didn't pack m3x20 bolts for the extruder pressure bearings. We'll have to wait on those.

- I broke one of the orange caps while placing it on the screw.
- I only left barely enough slack for the yellow wires. It works though.
- I had to re-level the table.
- The raft sizes keep coming out too inconsistently.
- Z-axis switch activates before it "clicks".
    - This has been replaced and fixed
- There was a lot of curling on the fine angle test piece.
- When there is a 20C difference (in either direction) between the raft and the object, it is easier to separate the raft.
- BFB Axon is more useful than Netfabb for toolpath generating. While circles, surfaces, and small areas aren't as good, it has great color control. The parts I'm making are almost string-less.
- Axon's default ABS setting works well.
- The Z-motor keeps wobbling. This was always a problem, but with firmware 4.0, it now makes the z-motor stall while jogging.
- Extruder casing was loose, possibly inhibiting build consistency.
    - Fixed

[illegible]

- The nozzles aren't level
- The adjustable screws and the triangular support frame make the build platform bend a lot.
    - Partially fixed with washers
- Printed great PLA prints using Axon's default PLA setting.
- The extruder jammed while printing ABS.
- The machine is ridiculous to take apart.
- The screw in the aluminum escaping might dig into PTFE too much.
    - This is untrue.
- The filament broke off in the PTFE tube and expanded, thus jamming the extruder.
- Surfaces come out extremely poorly.
    - Changed extrusion diameter to value on spreadsheet. Surfaces look good now.
- The PTFE tube seemed to be too thin. It had an ID of 3mm for filament that was 3mm.
- We ordered new PTFE tubing that had the same length, but a 4mm ID.
    - This worked well.
- Accidentally reversed the prongs on extruder 1 temp-wires. The tab for the connector should now face away from the aluminum escaping. The connector for extruder 2 should still be tab-inward.
- Homing is extremely sensitive to the placement of the magnet. Also, for some reason the voltage was still too low, even at maximum magnet height.
    - The magnet has been flipped and we lowered the hall sensor. It's fine now*
- You have to keep resetting and hitting "run file" until you observe that it homes to the right height, since the z-home is so inconsistent.
    - If it is consistently far off, adjust the magnet height.
- The filament stopped extruding again.
    - The filament was easily removed from the PTFE. This didn't seem to be the problem.

- There seems to be a problem with the extruder pulling in filament too…
    - It's fine if you keep creating slack by spinning the spindle many times every once in a while.
- It's difficult to measure the test part height because the raft sticks too well to the ..., has to be removed in one piece by a razor.
- It's difficult to measure [illegible] and [illegible] because of the ooze strings.