BENCHMARKING EVALUATION OF AN OPEN SOURCE FUSED DEPOSITION MODELING ADDITIVE MANUFACTURING SYSTEM

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Abstract

The availability of more affordable open source Additive Manufacturing (AM) systems has lead to the increased awareness and use of AM technologies. However, further expansion will necessitate improved reliability and an increased understanding in the limitations of these systems. This paper will review previous benchmarking models, and present the development of a new benchmarking model and its application in the evaluation of an open source AM system based on fused deposition modeling (FDM). The proposed benchmarking model includes various geometric features to evaluate the AM system in terms of dimensional accuracy, thermal warpage, staircase effect, and geometric and dimensional tolerances.

1. Introduction

Additive manufacturing (AM) is a family of processes in which a numerical representation of an object is used to fabricate the object one layer at a time. The AM processes are distinguished by the build materials and means by which the layers are joined together. Kulkarni et al. [1] provides three general classifications based on how the layers are joined: chemical bonding, sintering, and gluing. Fused Deposition Modeling (FDM) is an example of an AM process based on the intra and interlayer chemical bonding resulting from the extrusion of molten acrylonitrile butadiene styrene (ABS) thermoplastic from a heated nozzle. Stratasys Inc. first commercialized FDM in 1992 and continues to provide various FDM based systems. However, their systems are proprietary (closed) with limited opportunities for use as a research platform in the enhancement of the FDM process.

Since the middle of the last decade, open source and relatively inexpensive AM systems based on FDM have become available. These systems include the Fab@Home 3D printer [2], the RepRap project [3], and most recently, the CupCake CNC and Thing-O-Matic 3D printers by MakerBot Inc [4]. The Fab@Home 3D printer was originally designed with a non-heated syringe based extrusion system with thermosetting polymer for the build material, but can now be configured to extrude melted ABS plastic like the RepRap and MakerBot systems. The objective of the RepRap project was to develop an open source 3D printer that could be used to fabricate its own components (“self-replicate”). The MakerBot AM systems are derived from the RepRap project, but are more so focused on the fabrication of generic objects and have received quite a bit of general media attention [5-8], but has received limited evaluation and application in the literature. Pei et al. [9] recently studied the three previously mentioned open source AM systems and evaluated the capacity of a RepRap based system (Rapman) to fabricate geometrically complex parts. Kesner and Howe [9] mentioned the potential for both the Fab@Home and MakerBot systems for fabricating application specific components for force sensors. Finally, Ludec-Mills and Eisenburg [11] noted both the Fab@Home and RepRap project, but they specifically utilized the CupCake CNC to fabricate parts based on 3D computer models created using their new spatial input device to introduce children to 3D modeling, design and fabrication. The CupCake CNC system, along with its other open source AM system counterparts are assembled by the end user. Thus, there is some inherent variability and uncertainty in the limitations and overall performance of each CupCake CNC device.

The objectives of this project are to review previous benchmarking models in the literature used to evaluate AM systems, and to develop a new benchmarking model to evaluate the MakerBot CupCake CNC AM system in terms of dimensional accuracy, thermal warpage, staircase effect, and geometric and dimensional tolerances (GD&T). The outcome will provide the AM community with, to the authors' knowledge, the first benchmarking evaluation of an open source FDM AM system. It will also help to expand the awareness and use of such systems as a research and development platform in the continued study of FDM AM process improvements and applications. It should be noted that this study is based solely on the configuration of our device and presents the corresponding findings of such.

In what follows, details of the CupCake CNC will be provided, followed with a discussion of benchmarking models used in previous AM studies and of a new benchmarking model developed specifically for open source AM systems such as the MakerBot CupCake CNC. The paper will close with evaluation results of the fabricated benchmarking model and conclusions and about the MakerBot CupCake CNC system performance.

2. Background

2.1. MakerBot CupCake CNC

The CupCake CNC MakerBot (see Figure 1) consists of a horizontally translating (x-y direction) heated build platform (HBP) with a useable build area of approximately 80mm x 100mm and a vertically translating (z direction) extruder nozzle with a maximum build height of 130 mm. Positioning for each axis is accomplished using a belt driven pulley system with stepper motors. The extrusion system is also driven using a stepper motor to feed 3mm diameter ABS (plastic) filament into a heated 0.4mm diameter nozzle. The configured CupCake CNC used in this study can fabricate parts with layer thicknesses at 0.25mm, 0.31mm, or 0.36mm and does not include the capacity to fabricate support structures. CupCake CNC has an indicated accuracy and minimum feature size of 0.08mm [12]. The device is controlled via USB connection to a PC running the ReplicatorG open source software which includes Skeinforge. Skeinforge is a fully configurable Python based tool chain used to slice and output tool path instructions in G-Code format readable by MakerBot and RepRap. Examples of configurable process parameters within Skeinforge are detailed in Table 1. The road width (width of extruded filament) can be determined by multiplying the layer thickness and road width over thickness ratio which results in a road width of 0.6mm using the values from Table 1.

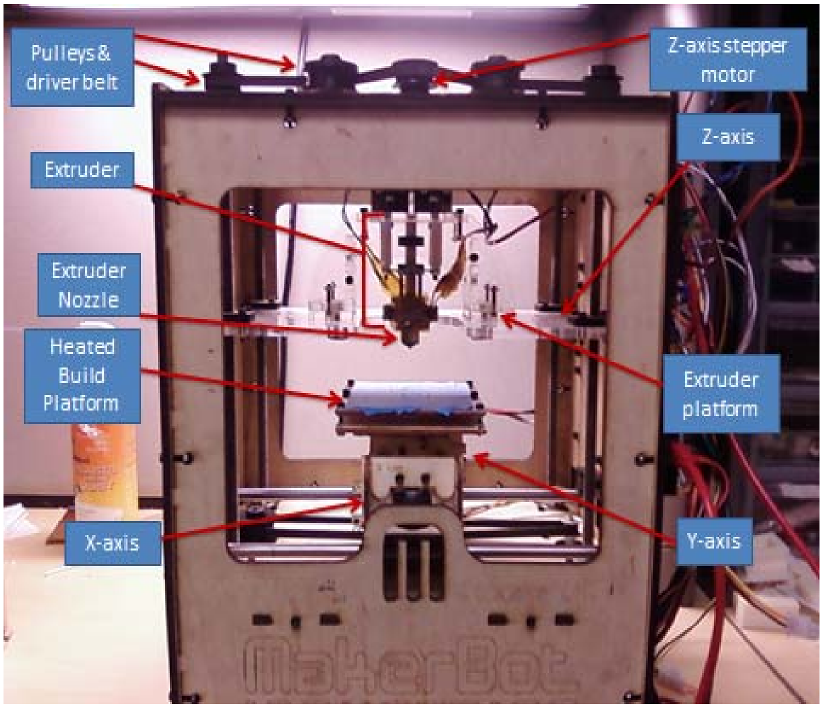


Figure 1. Assembled CupCake CNC MakerBot.

Table 1. Selected Skeinforge profile (fabrication) parameters.

Parameter Name	Setting	Description
Layer thickness (mm)	0.36	Layer thickness of object cross section
Road width over layer thickness ratio	1.67	Ratio of extruded filament width to layer thickness
Infill solidity ratio (%)	40	Percentage of filament deposited inside object cross section
Flow rate (rpm)	1.1	Filament extrusion rate
Feed rate (mm/s)	32	Speed of HBP
Extruder Nozzle Temperature (^oC)	220	Temperature of extruded filament
HBP Temperature (^oC)	135	Temperature of build platform

Skeinforge includes the option to fabricate objects using a raft structure, which serves as a platform upon which the object layers are placed. The raft helps to smooth any surface irregularities in the build platform and aids in the removal of the part from platform once fabrication is completed. As shown in Figure 2, the raft consists of evenly spaced parallel roads.

The road spacing is intended to facilitate the removal of the raft from the fabricated part during post-processing.

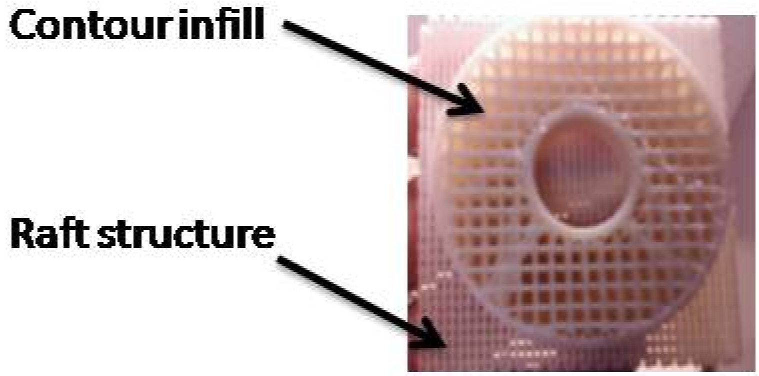


Figure 2. Example of the raft structure and a contour infill (infill solidity ratio of 0.40) of an object.

2.2. Benchmarking Models in AM Evaluation

It is observed in the literature that benchmarking models are often used to characterize and evaluate the performance of both subtractive and additive manufacturing systems. Mahesh [13] identifies three types of benchmarking models as it pertains to AM: Geometric, Mechanical, and Process. Geometric benchmarking models provide a means for system evaluation in terms of geometric accuracy, capacity to fabricate specific geometry, repeatability, and surface roughness. Mechanical benchmarking models can be used to determine and evaluate various material and mechanical properties of parts produced by AM systems, such as tensile strength and impact toughness [14-16]. Process benchmarking models can be used as a means to evaluate and/or optimize the AM fabrication process itself. Evaluation metrics for process benchmarking models might include those used in geometric [17-19] or mechanical benchmarking models, and also fabrication time and cost [20]. Considering the potential for overlap across these three model types, a hybrid benchmarking model could be considered for a fourth type of classification in which the model incorporates various aspects of the geometric, mechanical, and/or process benchmarking models and associated evaluation metrics [21], [22].

Benchmarking models have been used extensively in the performance evaluation and optimization of AM systems. As early as 1991, Kruth [23] evaluated the performance and possible applications of four AM processes (Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM) and FDM using a geometric benchmarking model consisting of overhangs, an inclined cylinder, and various peg structures. Juster and Childs [24] devised a more complex geometric benchmarking model to assess the performance of SLA, SLS, LOM, and FDM AM systems in terms of dimensional accuracy, geometric tolerances, repeatability, and fabrication limitations. The model included features such as square bosses, overhangs, freeform geometry, and vertical and horizontal holes.

In 2000, Xu et al. [22] presented a benchmarking model to evaluate the horizontal (x-y plane) dimensional accuracy of the same set of AM systems examined by Juster and Childs. Given the primary intent of Xu's study, the model consisted of various sized thin walls, notches, cylindrical bosses and an overhang structure. Mahesh et al. [25] used a benchmarking model previously developed by his co-author to evaluate four AM systems and processes. The model incorporated more features than any other previous study and examined the AM systems' performance based on dimensional accuracy, geometric and dimensioning tolerances and thermal warpage. Scaravetti et al. [17] and Campanelli et al. [18] both sought to improve the SLA process using process benchmarking models. Scaravetti et al. achieved limited success in their attempts to decouple observed dimensional and geometric (form and orientation) tolerances from the fabrication material versus the SLA device itself. Campanelli et al. determined the optimal SLA process parameters (layer thickness, hatch overcure, and border overcure) to minimize the measured dimensional, positional and form deviations of the part relative to the CAD model.

Overall, most benchmarking models and studies have been limited by small sample sizes, and mostly of the geometric benchmarking model classification to evaluate multiple AM processes in terms of geometric accuracy, surface roughness, repeatability, geometrical tolerances. The models have typically consisted of a rectangular base with various features to achieve the desired performance and evaluation metrics. These features included square and cylindrical bosses, vertical and horizontal through holes, inclines, thin walls, notches, overhangs, freeform geometry, fillets, and chamfers. The models were evaluated using coordinate measurement machines (CMM). Based upon these previous works, a new geometric benchmarking model for the evaluation of the CupCake CNC AM system is presented. To the authors' knowledge, this is the first benchmarking model to be specifically designed and presented in the literature for the evaluation of an open source AM system**.**

3. Benchmarking Model Development

Based on the benchmarking models discussed in the previous section, a new benchmarking model was designed to assess dimensional accuracy, feature size and geometry limitations (e.g., unsupported overhangs, and double curved geometry), geometric and dimensional tolerances, and repeatability all within the relatively smaller build envelope of the CupCake CNC. Table 2 and Figure 3 provide a brief description and visual representation (CAD model) of the specific features of the new benchmarking model.

Table 2. Benchmarking model feature descriptions

Feature	ID	Description	Evaluation
Square Boss	A1-A3	6x6x6mm (Qty 3)	flatness, X-Y linear accuracy, and repeatability
Rectangular Boss	B1-B2	10x10x6 mm (B1) 15x15x7 mm (B2)	flatness and X-Y linear accuracy
Concentric cylindrical boss	C7 & C23	20mm Dia., 7mm tall (C7), 10mm Dia., 5mm tall (C23)	cylindricity and concentricity
Cylindrical Boss	C4, C20, C24	6mm Dia., 7mm tall (Qty 3)	cylindricity, roundness, and repeatability
Inclines	A11-A14	15 , 25, 35, 80 degrees	angularity, sloping smoothness and linear accuracy
Hemisphere	SP26	15mm Dia.	profile, slope changes, and symmetry
Thin walls	XW1,1.5,2 & YW1,1.5,2	1, 1.5, & 2mm thicknesses. 3x10mm, 3mm deep cavity	linear accuracy, parallelism, and wall thickness
Circular holes	C21, C6, C5	5mm Dia, 3mm deep, 15mm Dia, 20mm Dia.(in base feat).	roundness, relative position, and repeatability
Circular holes	C28 & C27	5mm & 10mm Dia.3mm deep. (in tower feature)	roundness, relative position, and repeatability
Overhangs		40, 45, 50 degrees	angular accuracy and sloping limit
Square notches	XN1.5-4 & YN1.5-4	1.5, 2, 2.5, 3, 3.5, & 4mm, spaced 5mm apart. (Qty 2)	linear accuracy and consistency

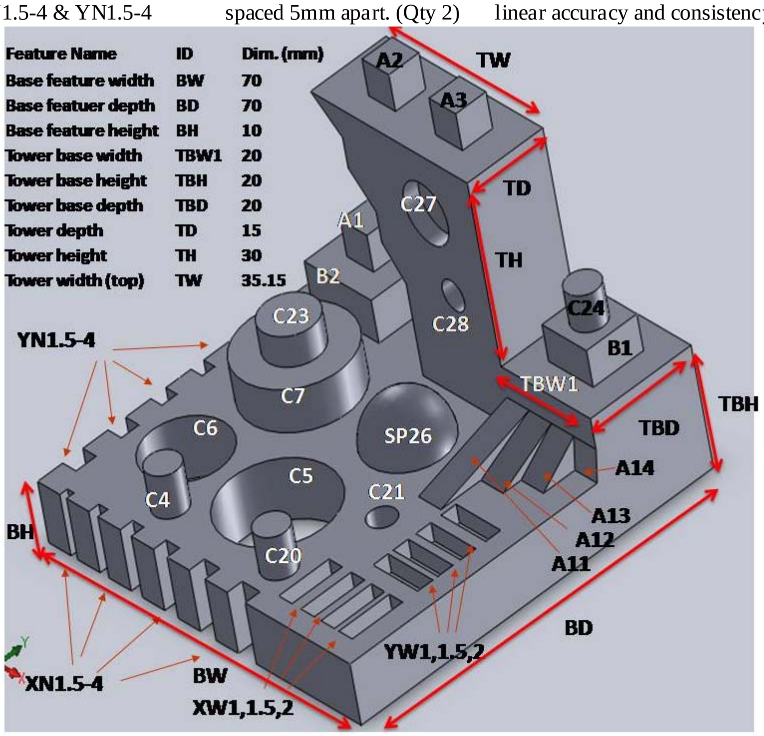


Figure 3. CAD version of benchmarking model with referenced feature identification (IDs)

4. Benchmarking Fabrication and Evaluation Results

The benchmarking model was fabricated with the parameters discussed in Table 1. The model took 2.5 hours to fabricate and used 36.4 cm^3 of ABS filament. Figure 4 (a-c) presents the original CAD model along with angled front and back, and top views of the fabricated benchmarking model. The following observations were based on a visual inspection of the part:

1. Notches were fabricated, but did not have uniform gap spacing especially towards the bottom of the base feature.

2. Holes in base appeared circular, but showed nonuniform interior surfaces.
3. Horizontal holes on the tower feature and tower base appeared uniform.
4. Warping of 45^o and especially the 50^o overhangs was present (Figure 4c).
5. Warping was also visible along the edges of the bottom of the base feature.
6. All vertical sides of the base feature tapered outward from the bottom surface.
7. All thin walls were fabricated, but the 1.5 and 2mm walls had core voids. Core voids were also present at two other locations on the top surface of the base feature. (See circled areas in Figure 4d)
8. The staircase effect was inversely related to the inclines angles. The staircase effect was present to a lesser degree in the hemisphere.

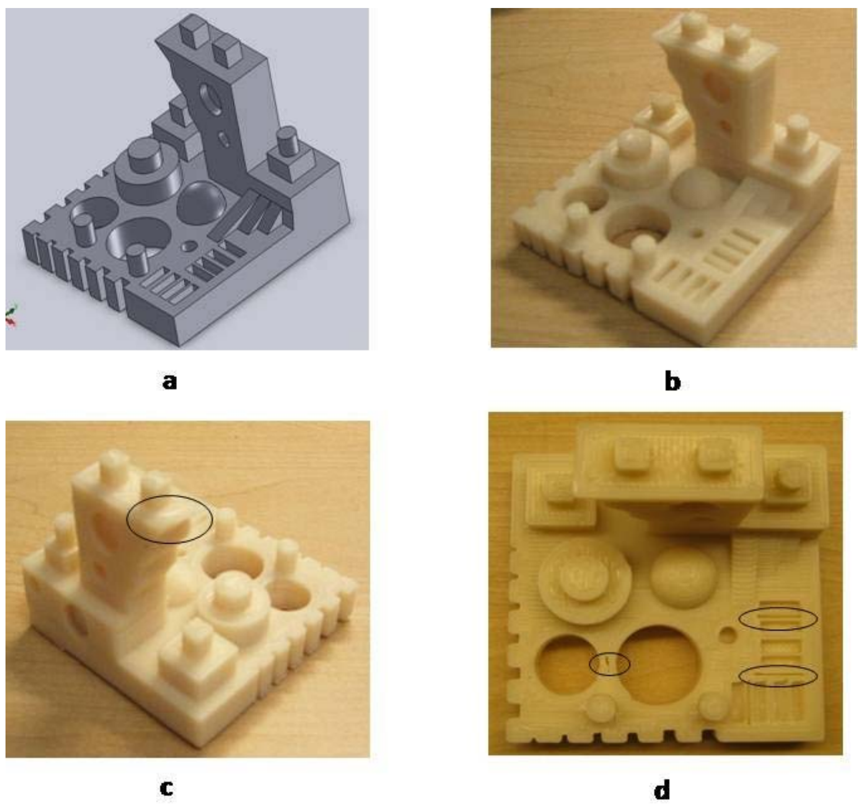


Figure 4 (a-d). CAD (a) and fabricated (b, c and d) versions of benchmarking model

4.1. 3D Laser Scanning Results and Discussion

The benchmarking model was scanned by a service provider using a 3D laser scanning system. A laser scanning approach is uniquely suited for the inspection of parts fabricated using AM considering the possibility of layer-wise deviations. However, 3D laser scanning systems are relatively less accurate than coordinate measurement machines (CMM) traditionally used for inspection. The 3D laser scanning system used had an accuracy of 0.0089mm and was suitable for our inspection given the stated 0.08mm minimum feature size limitation of the CupCake CNC. Furthermore, our benchmarking model contains features no smaller than 1.0mm.

Based on the scan of the fabricated model, a total of 2,999,732 data points were used to determine the deviation from the nominal CAD model dimensions after aligning the scan data with CAD model using a best fit approach. Deviations are defined based on the shortest distance between a scanned data point and any point on the CAD model. Figure 5 (a-d) provide the subsequent error (deviation) maps for various orientations of the model. The areas of the model in green are within +/- 0.1 mm of the CAD model, red areas are outside the CAD model (oversized) by 1mm or greater, and areas in blue are inside the CAD model (undersized) by -1mm or less. The standard deviation for the data is 0.3101mm, with 98.46% of the points within +/- 2 standard deviations, 79.2% of the points within +/- 0.2mm, and 97.7% of the points within +/- 0.5mm of the nominal CAD dimensions.

Most of the observations from the visual inspection were readily confirmed in the error maps of Figure 5(a-d). For example, Figure 5c shows warping along the edges of the bottom surface. The rest of the bottom surface has mostly a positive deviation likely due to the incomplete removal of the raft structure. Observations 7 and 8 were not as apparent in the error maps due to the use of color averaging (color averaging does not influence the numerical results). The positive (red) deviation of the 25^{o} incline (A12) was not obvious from the visual inspection. However, this deviation was a result of the inadvertent use of a benchmarking CAD model version with an A12 incline angle of 30^{o} instead of 25^{o} for the deviation study. All other incline features on the CAD model were verified and consistent with the value reported in Table 2 and Figure 3.

In addition to the error map plots, the 3D scan data was also used to obtain the dimensions of various features on the fabricated benchmarking model. A listing of additional dimensional values for the model features is provided in Appendix 1. Deviation values were computed using the CAD model dimensions as the reference. Unless otherwise noted, the average of three cross sections of the scan data were used to determine the mean dimensions of each feature. All dimensions and deviations are in millimeters. Table 3 shows the overall dimensions of the fabricated model. The tower width had the largest deviation of the group which was expected given the warping of the 50^{o} overhang evident in Figure 4b and c.

As shown in Table 4, the cylindrical boss diameter deviations were all positive (oversized). The 6mm diameter cylinders had a range of 0.11mm. Based on Table 5A, the heights of the cylindrical bosses are defined along the z-axis and thus subject to an inherent deviation due to the fixed layer thickness (0.36mm). For example the 7 mm tall, 6mm diameter cylindrical boss would require 19.44 layers, which rounded down to 19 layers results in an expected negative deviation in the boss height. All boss height deviation values are consistent with being over or undersized based on the expected deviation due to layer thickness.

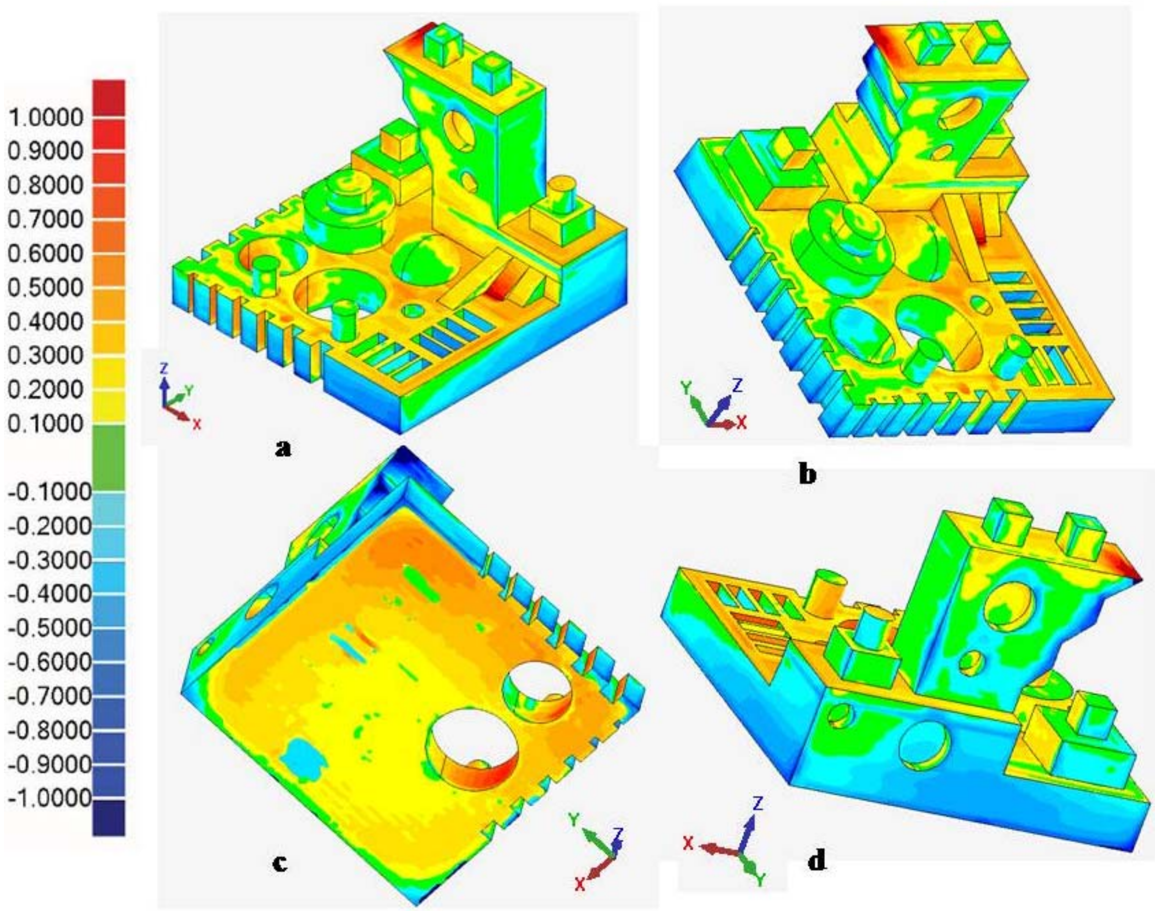


Figure 5(a-d). 3D Comparisons (error maps) of benchmarking model based on nominal CAD dimensions.

Table 3. Overall dimension and deviations of benchmarking model.

Feature Description	Feature ID	CAD Dim.	Mean Dim.	Deviation	
Base Width	BW	70	69.35	-0.65	
Base Depth	BD	70	69.08	-0.92	
Base height	BH	10	10.45	0.45	
Tower Base Height	TBH	20	20.53	0.53	
Tower Height	TH	30	29.89	-0.11	
Tower Base Width	TBW1	20	19.79	-0.21	
Tower Width	TW	35.15	32.86	-2.30	
Tower Base Depth	TBD	20	20.20	0.20	
Tower Depth	TD	15	15.132	0.132	
Note: Each tower dimension based on a single cross sectional sample					

Table 4. Cylindrical boss diameters and deviations.

Feature Description	ID	CAD Dim.	Mean Dim.	Deviation
6mm Dia Boss,7mm tall	C4	6	6.26	0.26
6mm Dia Boss,7mm tall	C20	6	6.15	0.15
6mm Dia Boss,7mm tall	C24	6	6.21	0.21
10mm Dia Boss, 5mm tall	C23	10	10.19	0.19
20mm Dia Boss, 7mm tall	C7	20	20.17	0.17

The hole diameter and deviations in the base feature (C5, C6, and C21) are presented in Table 5B. There was insufficient data to determine the C5 diameter, but the other two diameters were undersized (negative deviations). These results are at least in some aspects due to our Skeinforge settings which did not compensate for road (filament) width when traveling in circular tool paths (in the x-y plane). The "stretch" Skeinforge plugin can be used to account for this issue by essentially widening the hole diameter. Although the diameters for C27 and C28 were also undersized, they are instead (at least) affected by the tool path in the x-direction and the layer thickness.

The notch feature (XN and YN) gap dimension deviations are plotted as a group in Figure 6. Four of the six notch gap (absolute) deviations where greater in the x-direction than in the y-direction, with the 2mm notch gap in the x-direction having the largest absolute deviation (0.35mm) of the group. All but one of the gaps in each direction was oversized (positive deviation). Mostly positive feature deviations were also noted for the larger single axis (x or y-direction) tool paths associated with the width and depth dimensions of the rectangular bosses, A1-3 and B1 and B2 (See Appendix A). The ranges for the width and depth dimension of the square bosses were respectively, 0.13mm and 0.19mm. Notwithstanding the relatively small sample size, the consideration of the range values of the square and cylindrical bosses suggests some level of repeatability in the fabrication of these features.

Figure 7 shows a cross sectional view of the scanned inclines for the 15^o, 25^o, and 35^o inclines, with the red lines showing the CAD model incline. A screenshot of the 80^o incline is not shown, but measured 77.4^o. The staircase effect is reduced as the incline angle increases. This relationship was noted by Pandey et al. [26].

Table 5. Height/depth values and associated deviations for A) Circular bosses and B) Holes.

Table A.

Feature Description	ID	CAD Dim.	Mean Dim.	Deviation
10mm Dia Boss, 5mm tall	C23	5	5.021	0.021
6mm Dia Boss,7mm tall	C24	7	6.197	-0.803
6mm Dia Boss,7mm tall	C4	7	6.295	-0.705
20mm Dia Boss, 7mm tall	C7	7	6.705	-0.295
6mm Dia Boss,7mm tall	C20	7	6.82	-0.18

Table B.

Feature Description	ID	CAD Dim.	Mean Dim.	Deviation
5mm Dia., 5mm deep Hole	C21	5	N/A	N/A
20mm Dia. Hole	C5	15	14.62	-0.38
15mm Dia. Hole	C6	20	19.49	-0.51

Note: All height dimensions based on a single cross sectional sample

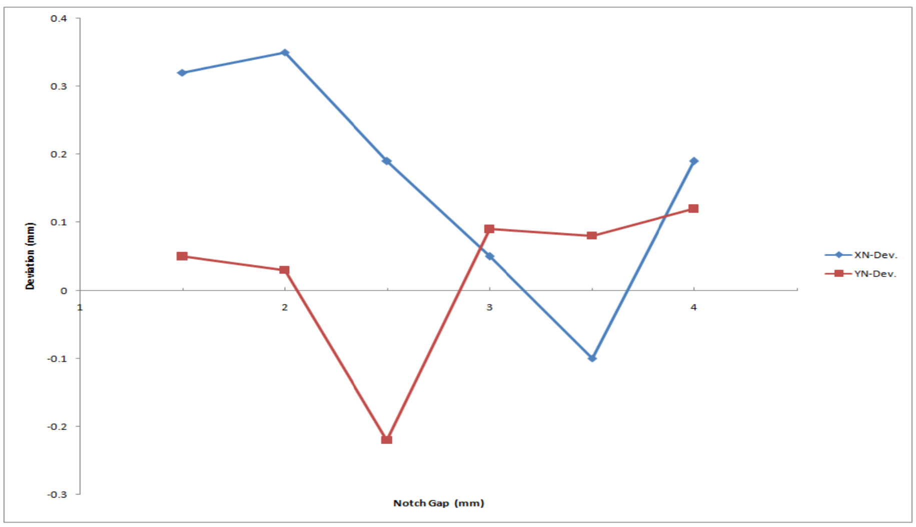
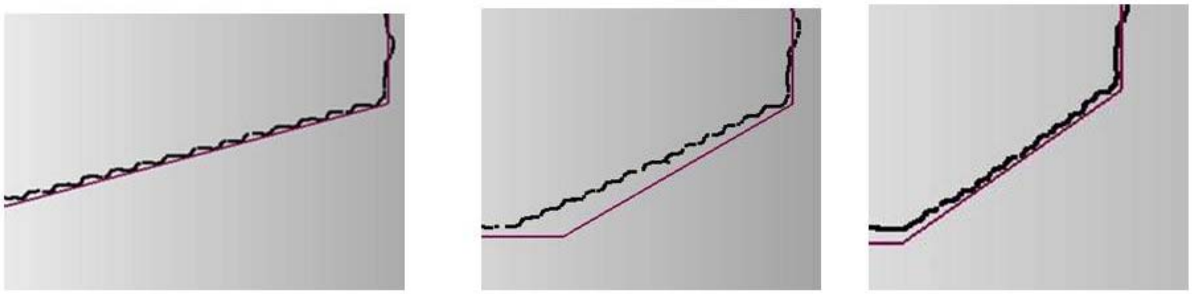


Figure 6. Notch gap deviation in x and y-directions.

Geometric and dimensioning tolerance results are shown in Table 6. The scanned data associated with each feature was compared with the corresponding CAD feature. The cylindrical bosses (except C24) and through holes (C6 and C5) had reduced tolerance zones with increased diameters. The staircase effect was a contributor to the cylindricity tolerance zones of the holes with horizontal axes (C27 and C28). The flatness of the top surfaces of the base, tower base, and A2 features were comparable, with the top surface of the tower having a much larger tolerance zone due to the thermal warpage of the 50^{o} overhang. The perpendicularity tolerance zones were also comparable with the exception of the front tower surface (with the top surface of the base feature as the datum).



15° (meas. 15.6°) 25° (meas. 24.5°) 35° (meas. 34.5°)

Figure 7. Cross sectional views of the 15^0, 25^0, and 35^0 inclines. CAD inclines in red and scanned data in black.

Table 6. Geometric and dimensioning tolerance results for selected features.

Feature Description	ID	GD&T Feat.	Meas. Tol. Zone	Feature Description	ID	GD&T Feat.	Meas. Tol. Zone
6mm Dia Boss, 7mm tall	C4	Cylindricity	1.92	Base Feat. (top)	1	Flatness	1.89
6mm Dia Boss, 7mm tall	C20	Cylindricity	1.41	Tower Base (top)	3	Flatness	1.24
6mm Dia Boss, 7mm tall	C24	Cylindricity	3.68	Tower (top)	18	Flatness	5.15
10mm Dia Boss, 5mm tall	C23	Cylindricity	1.23	A2 (top)	19	Flatness	1.42
20mm Dia Boss, 7mm tall	C7	Cylindricity	0.96				
5mm Dia., 5mm deep-Vert.	C21	Cylindricity	5.28	Base (top). Front Base-Datum	16	Perpendicularity	0.94
15mm Dia. Hole	C6	Cylindricity	2.51	Tower (front). Base (top)-Datum	15	Perpendicularity	2
20mm Dia. Hole	C5	Cylindricity	1.42	B2 (front). Base (top)-Datum	22	Perpendicularity	0.81
5mm Dia.,3mm deep-Horiz.	C28	Cylindricity	2.2	B1 (right side). Tower Base (top)-Datum	17	Perpendicularity	0.45
10mm Dia, 3mm deep-Horiz	C27	Cylindricity	2.83				

5. Conclusion

A benchmarking model was developed to evaluate the performance of the MakerBot CupCake CNC AM system. The evaluation metrics included dimensional accuracy, staircase effect, and thermal warpage, and geometric and dimensional tolerances. The benchmarking model had a square base (70x70x10mm) and included features such as thin walls, rectangular and cylindrical bosses, through and blind holes, inclines, notches, and a hemisphere. The overall height was 56mm. The part was successfully fabricated with noticeable warping along the bottom edges of the base feature and for the 45^0 and 50^0 overhanging inclines (unsupported during fabrication). Based on 3D laser scanning of the part, most of the measured data points had positive deviations, and overall 97.7% of the points were within +/- 0.5mm of the nominal CAD dimensions. These results are based on a single sample produced with a configuration specific to our device. Notwithstanding these limitations, the results suggest that the MakerBot CupCake CNC is a viable alternative to more expensive propriety FDM AM systems. Future work will evaluate the fabrication of the benchmarking model using a commercial FDM system and comparison of the results from the model fabricated with the CupCake CNC system.

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Appendix A.

Table A.1. Square Boss Width Deviations

Feature Description	Feature ID	CAD Dim.	Mean Dim.	Deviation (X-Dir)
Square Boss (6x6x6)	A1	6	6.02	0.02
Square Boss (6x6x6)	A2	6	6.07	0.07
Square Boss (6x6x6)	A3	6	6.15	0.15
Square Boss (10x10x6)	B1	10	10.23	0.23
Square Boss (15x15x7)	B2	15	14.99	-0.01

Table A.2. Square Boss Depth Deviations

Feature Description	Feature ID	CAD Dim.	Mean Dim.	Deviation (Y-Dir)
Square Boss (6x6x6)	A1	6	6.17	0.17
Square Boss (6x6x6)	A2	6	6.05	0.05
Square Boss (6x6x6)	A3	6	5.98	-0.02
Square Boss (10x10x6)	B1	10	10.25	0.25
Square Boss (15x15x7)	B2	15	15.25	0.25

Table A.3. Square Boss Height Deviations

Feature Description	Feature ID	CAD Dim.	Mean Dim.	Deviation (Z-Dir)
Square Boss (6x6x6)	A1	6	6.12	0.12
Square Boss (6x6x6)	A2	6	5.77	-0.23
Square Boss (6x6x6)	A3	6	5.82	-0.18
Square Boss (10x10x6)	B1	6	5.76	-0.24
Square Boss (15x15x7)	B2	7	6.75	-0.25