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Preliminary Investigation of Dimensional Accuracy of 3D-Printed PLA—A Project-Based Learning Experience (WIP)

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1. Abstract

In the past decade, 3D printing has improved significantly and the use of 3D printed parts has extended to more precise industrial and scientific applications including space and medical applications. In subtractive Computer Numerical Control (CNC) machining, such as milling and Electro Discharge Machining (EDM), some tool offsets, applied through the G-code, are used during machining to compensate for the tool dimensions and to ensure the dimensions of the final machined product match the original designed CAD model. Similar techniques have been implemented in different 3D printers but they still experience dimensional inaccuracy. Some of these inaccuracies might be fixed by performing the proper calibration but others need further investigation. In this study, the authors investigate the dimensional inaccuracies in the 3D printing process and the printing parameters and configuration affecting them. These parameters include layer thickness, percentage infill, infill pattern, printing speed, printing temperature, and number of shells. The effect of some geometric aspects of the 3D printed products such as size, shape, orthogonality, curvature, and whether dimension is internal or external will be considered. A significant number of specimens will be prepared and analyzed with precision measurement tools to evaluate the dimensional inaccuracy. Offset parameters and/or dimensional compensations will be estimated based on the analysis of the results. These parameters are expected to guide users to scale or modify their model before printing to ensure they reach the desired accuracy in the printed product. The project is part of an initiative to supplement the knowledge and skills for engineering student through space grant and senior design class.

Keywords: NASA space grants, curriculum supplement, engineering technology

2. Introduction

2.1. Scope

As a form of curriculum supplement, this project is meant to involve some engineering technology students in hands-on experience, industrial codes and standards, as well as engineering research. The objective of the project is to investigate the dimensional accuracy of the 3D printed parts. This project is sponsored by Louisiana Space grant consortium (LaSPACE), which is a NASA affiliate, through their Senior Design (SD) grant program. In addition to the precision measurement and statistical analysis skills, this project allows participating student to gain high level knowledge in the process of 3D printing and associated industrial codes for designating and testing them. The project requires printing and testing of specimens with different lengths, diameters, curves, and drilled holes with different printing configurations. The printing configurations will include the infill density, infill pattern, the number of shells, and orientation of printing. The parts will be designed using SolidWorks with specified measurements. The SolidWorks models then will be uploaded into the MakerBot software where printing parameters can be customized. In the initial stage, we will be using the MakerBot Replicator+ model 3D printer with both Poly-Lactic Acid

(PLA). PRUSA 3D printer will be used to print the same specimens and test them. Once parts are printed, their dimensions will be measured with precise tools including micrometers and vernier caliper. The measurements will be compared to the original dimensions of the model and inaccuracy will be determined and linked to the type of the dimension as well as the printing configurations and material type. Also, parts will be printed with different settings and investigated whether or not that will affect the dimensional accuracy of the 3D printed parts. This paper will highlight the experimental results of the completed phase of the project (a senior design project spanning 2 semesters) as well as the achieved educational outcomes.

2.2. Literature review

3D printing started about 50 years ago and has made a significant impact in the field of engineering. 3D printers are capable of printing and creating parts with a variety of materials. Some of these materials include but are not limited to: ceramic particles, high performance composite powder called Z150 with clear binder solution zb63, photopolymer material, Poly-Lactic Acid (PLA) a thermoplastic polymer or PLA Tough, 15-5PH steel, and polymers. Researchers have been investigating different aspects of 3D printing accuracy including the effect of layer thickness and printing orientation on dimensional accuracy. Farzadi et al. discussed this dimensional accuracy for porous samples for bone tissue engineering [1]. Islam et al. investigated the dimensional accuracy for 3D printed parts using a Z450 3D printer [2]. They a simple U-shaped object with a hole in a test to investigate the dimensional accuracy and a Model D-8 coordinate measuring machine was used. As a result, they concluded that findings in the XY plane were consistently undersized, while the Z plane was always oversized. The printed holes were always undersized and had a bell mouth shape to them. Chand et al. investigated the dimensional accuracy for 3D printed parts using a multi-jet printer [3]. The study was on the precision and repeatability of said printer. The parts are designed with a combination of a rectangle, cylinder, and filets, along with the various orientations. As a result, one orientation provided less dimensional deviation than other part orientations on the base plate. This suggests that more area of the part on the base plate will give better results in dimensional accuracy. Hanon et al. examined the use of PLA material in cylindrical as well as “dog bone” 3D printed [4]. The dimensional accuracy of diameter and length within the cylindrical specimens was tested as well as within the width and thickness that correlated with the Dog-bone specimens. They showed that the worst dimensional accuracy for the cylindrical specimens is when it is printed at 45 degrees angle, due to gravity increasing distortion. Alafaghani et al. tested a PLA dog bone specimens and with a Taguchi’s L9 array and various parameters [6]. The results showed that a lower extrusion temperature, smaller layer thickness, lower infill percentage, and hexagonal infill pattern were best for dimensional accuracy. The study found that increasing the strength of FDM parts, a higher extrusion temperature, an optimized layer thickness, a triangular infill pattern, and a higher infill percentage gave the best results. They also studied the aging of the accuracy of 3D printed dental models and found a significant decrease in dimensional stability after 3 weeks of aging under constant conditions [7]. Matthisson et al. investigated the dimensional integrity of thin-walled parts [8]. They chose 3 basic shapes where 27 specimens were printed. They used PLA and Zaxe Z1 + industrial 3D printer with 100% infill. Most of these studies focused on specific printers or parameters and did not make a full analysis of all factors. In addition, they did not investigate all possible causes of all inaccuracies they discovered. In this project, a deeper investigation and analysis will be conducted to have a better understanding of dimensional inaccuracies.

3. Methodology

3.1 U-Shaped specimen

In this project, a study on the accuracy of 3D printed parts and consider different dimensions such as length, width, height, and diameter, was performed. The experimental part of the project includes preparing a part that covers all those dimensions in 3D modeling programs with specified dimensions. The participating student went through training to use the MakerBot software and PRUSA slicer and was introduces to different printing parameters that are considered in the study. Time was spent in printing simple parts and observing visual defects that lead to visual dimensional inaccuracy and techniques to eliminate them. Visual defects observed included stringing, elephant foot, layer shifting, and warping. Different printing parameters were adjusted to ensure none of these defects exist in the final test specimens as the goal of this project is to determine the dimensional inaccuracy for parts that are free of defects. The part that was decided to be used was a U-shape part with 4 circular holes, 3 square holes, and 2 extruded cylinders, Figure 1. This part was chosen and designed, after multiple iterations, to consider different shapes in the part, and to cover printing direction in all 3 axes. ASTM F2971, [9], standard was followed to link all linear dimensions to the 3 axes. ASTM library was accessed through the school subscription and all relevant standards were studied.

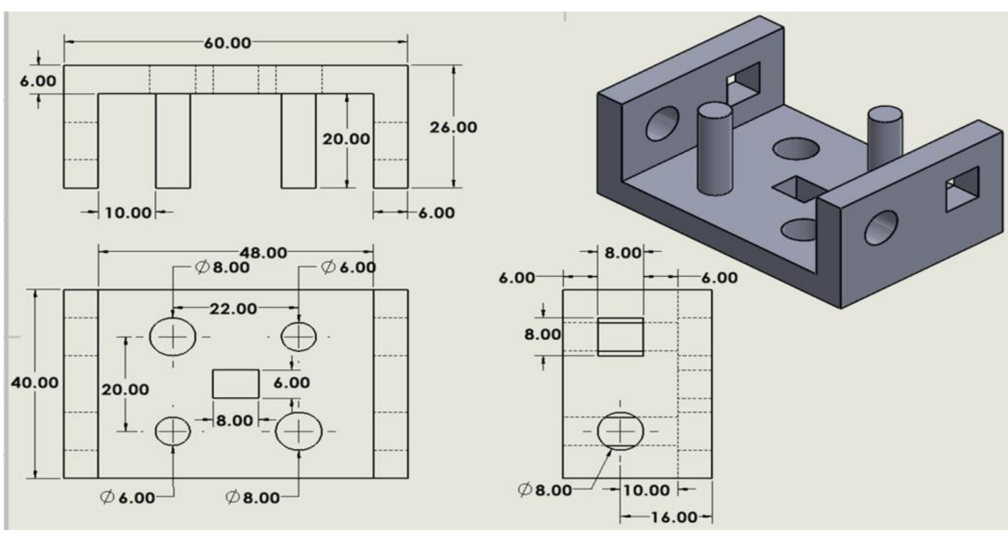

Figure 1. U-shape part and Dimensions

The parameters to be changed include the printer being used, the layer height, the infill percentage, the infill pattern, and the number of shells. The specified settings are applied through the slicer software for both MakerBot Replicator+ and PRUSA i3 MK3S+ printers. An array of specimen batches similar to Figure 2 were printed.

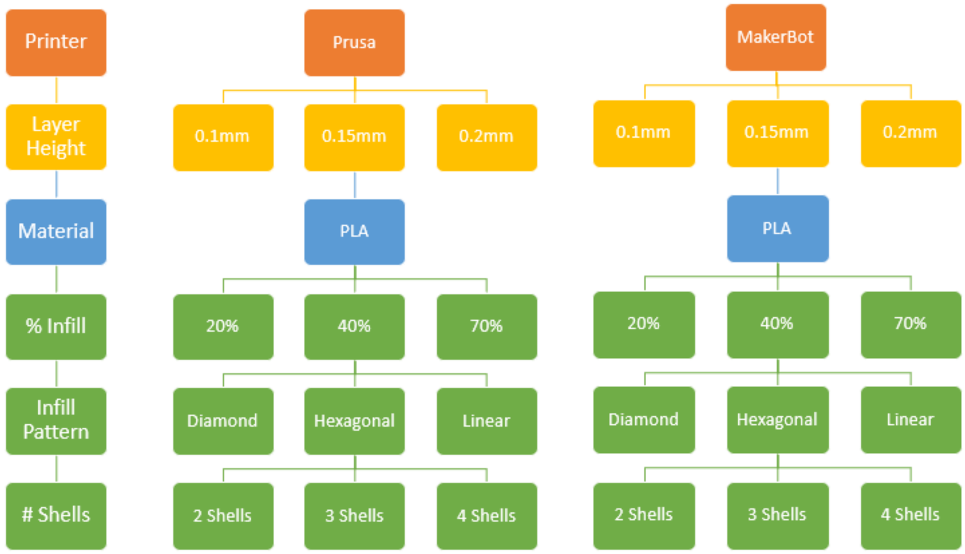

Figure 2 specimen printing and coding configuration

The U-shaped part was generated in SolidWorks with set dimensions. Along Z direction, the height of both vertical walls is measured in four different spots and the height of both extruded cylinders are measured multiple times, and average is taken (H1, H2, H3, H4, H5, and H6). Along Y direction, the width is measured in 5 different spots (W1, W2, W3, W4, and W5). Along X direction, the length is measured in in 3 different spots (L1, L2, and L3). The thickness of walls is measured in 4 different spots (T1, T2, T3, and T4). The diameter of the circular column is measured at 4 different spots (d1, D2, D3, and D4). Similarly, internal dimensions for the circular and rectangular cuts were measured including the diameter of the base circular hole (db), the diameter of the side circular hole (ds), length and width of the base rectangular hole (lb and wb), length and height of the rectangular hole in the side walls (ls and hs). Figures 3-7 show the locations of these measurements.

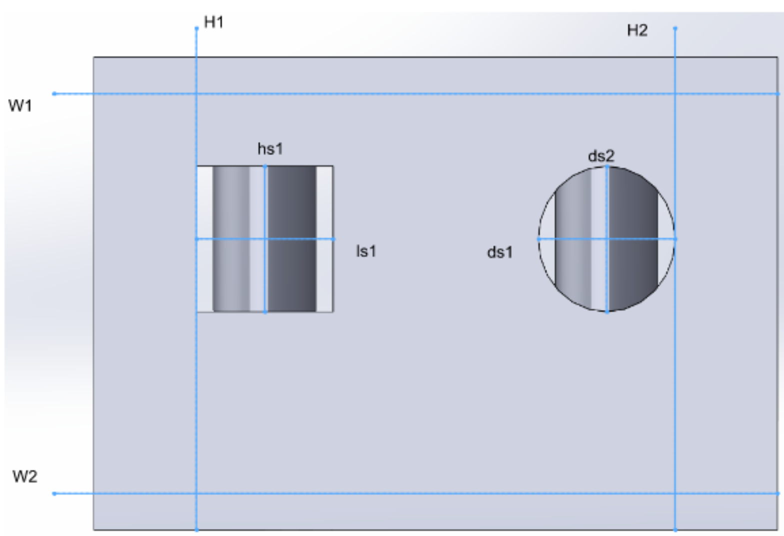

Figure 3. Left Side view of measurement placement

A total of 110 specimens with different printing settings were printed and measured. Additional 14 flat specimens with 2 internal circular holes were printed and measured to further investigate the major findings after measuring all u-shaped specimens.

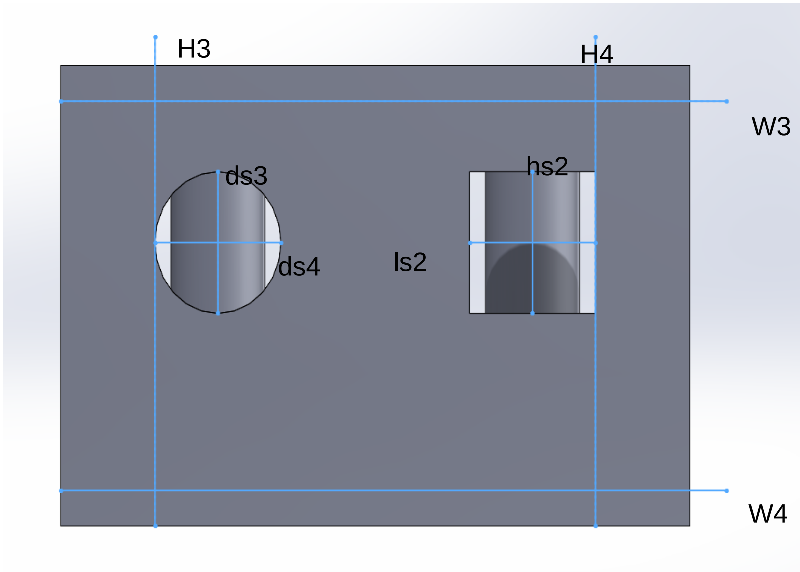

Figure 4. Right Side view of measurement placement

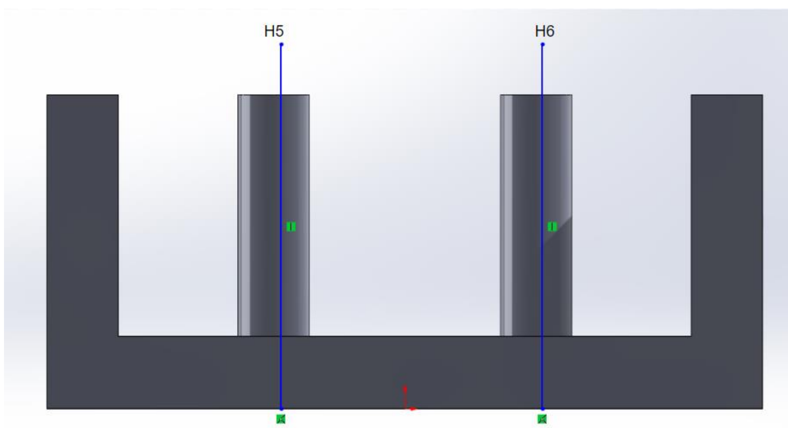

Figure 5. front view of measure placement

All specimens were coded with a 9-digit alphanumeric code indicating the configuration of the printing in addition to an extra digit indicating the serial number of each specimen in each configuration batch. The code included letters and/or numeric for the used printer (M for MakerBot or S for PRUSA), layer height (100, 150, or 200 μm), material (P for PLA), percentage infill (20%, 40%, or 70%), infill pattern (D for Diamond, L for Linear, or H for Honeycomb), and number of shells (2, 3, or 4). The layer height and number of shells were fixed after to 200 μm and 2 early on as they were both discovered to have no significant effect on the dimensions. An example of coded specimen is M200P70H2-2 which is the second specimens of a batch that was printed with MakerBot printer with 200 μm layer height, PLA, 70% infill, Honeycomb pattern, and 2 shells.

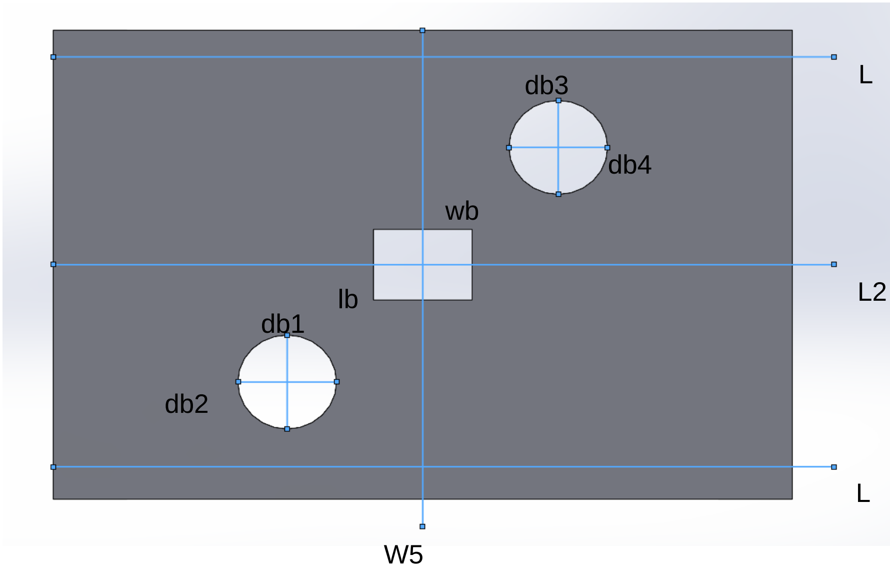

Figure 6. bottom view of measurement placement

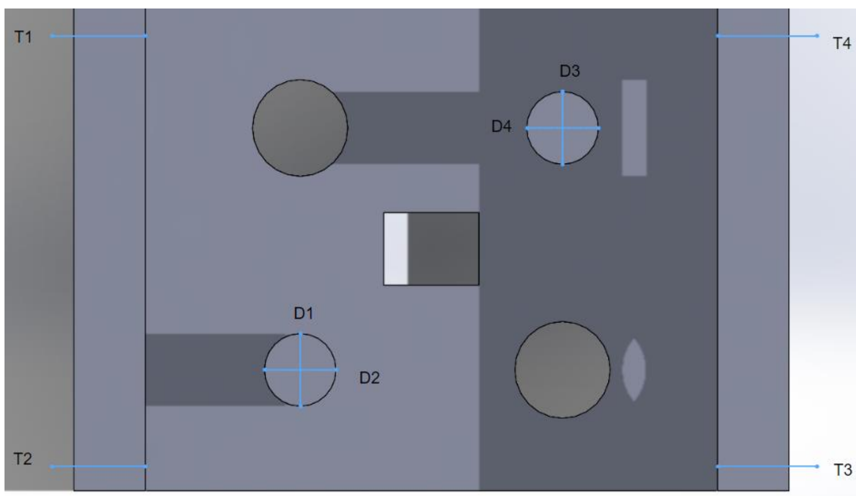

Figure 7. top view of Measurement Placement

3.2. Extra specimen development

As the measurements of the specimens progressed, it was discovered that the dimensions with significant inaccuracy were the internal dimensions and new flat specimens with 2 circular holes were printed. These extra specimens were added to further investigate and verify the internal holes accuracies. The specimen was printed with three different internal hole diameter to investigate whether the discovered inaccuracy proportional to the length or of fixed value. Figures 8-10 shows the details of these specimens.

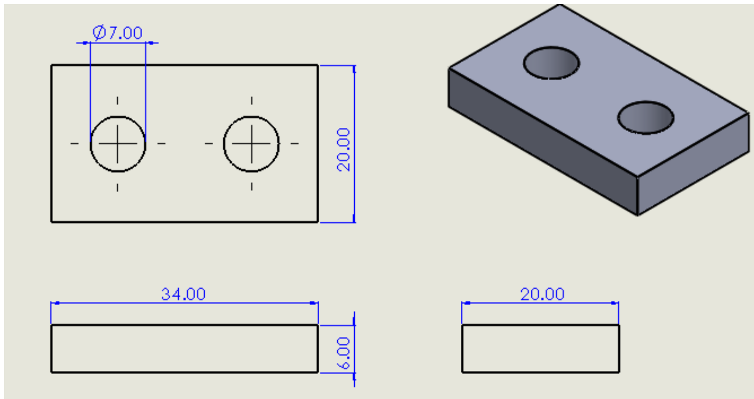

Figure 8. Flat specimen with 7mm 2-hole

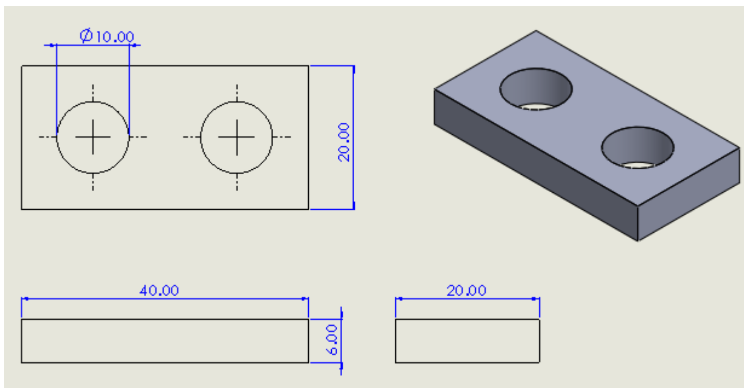

Figure 9. Flat specimen with 10mm 2-hole

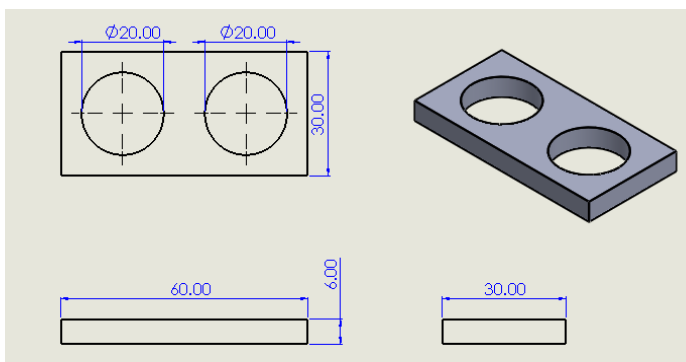

Figure 10. Flat specimen with 20mm 2-hole

3.3. Specimen with correction factor

More flat specimens were printed with 6.1 mm, 9.1 mm, and 19.1 mm to test the possibility of a correction factor of 0.9 mm for internal dimensions.

3.4. Measurement tools

To record accurate measurements of the printed specimen 3 precise micrometers and a vernier caliper were used. Figure 11 shows the internal micrometer for dimensions from 5mm to 30mm while Figure 12 shows the micrometer for external dimensions from 1-2 inch and Figure 13 shows the micrometer for external dimensions from 0-1 inch. Figure 14 shows the vernier caliper. All tools except for the vernier caliper give 3 decimal places.

Figure 11. Digital Caliper-Jaw Inside Micrometer:5 mm to 30 mm, .001mm accuracy

Figure 12. Mitutoyo Micrometer 1-2 inch with 0.001 mm accuracy

Figure 13. Starrett Micrometer with 0.001 mm accuracy (0-1 in)

Figure 14. vernier caliper .01mm accuracy

4. Results

4.1. U-Shaped specimen results

Measurements of all u-shaped specimens were performed and statistical analysis for all batches was completed. Samples of measurements are presented in Table 1 – Table 10. Sample measurements of height of the specimen batch M200P20H2 is presented in Table 1. It shows that the deviation from the model height (26 mm) is ranging from 0 to 0.1 mm. Sample measurements of width of the specimen batch M200P20L2 is presented in Table 2. It shows that the deviation from the model width (40 mm) is ranging from 0.02 to 0.1 mm. Sample measurements of thickness of the specimen batch M200P40D2 is presented in Table 3. It shows that the deviation from the model height (26 mm) is ranging from 0 to 0.02 mm. The trend with the same with all other external dimensions, with the deviation in both directions, regardless of the printing settings.

Table 1. Measurements of the height of the specimen batch M200P20H2

Specimen #	H1	H2	H3	H4	H5	H6
M200P20H2-1	26.001	26.092	26.068	26.068	26.138	26.134
M200P20H2-2	25.995	26.008	25.974	26.021	26.04	26.046
M200P20H2-3	25.997	26.008	25.967	26.007	26.069	26.06
M200P20H2-4	26.025	26.024	25.997	26.036	26.053	26.04
mean, mm	26	26.03	26	26.03	26.08	26.07
stdev, mm	0.0139	0.04	0.0461	0.0262	0.0436	0.0435
u, mm	0.007	0.02	0.023	0.013	0.022	0.022
measurement	26±0.007	26.03±0.02	26±0.023	26.03±0.013	26.08±0.022	26.07±0.022

Table 2. Measurements of the width of the specimen batch M200P20L2

Specimen #	W1	W2	W3	W4	W5
M200P20L2-1	40.013	39.899	40.011	39.915	39.937
M200P20L2-2	40.036	39.867	40.021	39.878	39.948
M200P20L2-3	40.055	39.956	40.023	39.9	39.979
M200P20L2-4	40.052	39.945	40.007	39.917	39.925
mean, mm	40.04	39.92	40.02	39.9	39.95
stdev, mm	0.0192	0.0413	0.0077	0.018	0.0232
u, mm	0.01	0.021	0.004	0.009	0.012
measurement	40.04±0.01	39.92±0.021	40.02±0.004	39.9±0.009	39.95±0.012

Table 3. Measurements of the thickness of the specimen batch M200P40D2

Specimen #	T1	T2	T3	T4
M200P40D2-1	5.999	6.025	6.016	6.02
M200P40D2-2	6.024	6.025	6.024	6.016
M200P40D2-3	6.001	6.015	6.032	6.03
M200P40D2-4	6.021	6.022	6.016	6.031
mean, mm	6.01	6.02	6.02	6.02
stdev, mm	0.0131	0.0047	0.0077	0.0074
u, mm	0.007	0.002	0.004	0.004
measurement	6.01±0.007	6.02±0.002	6.02±0.004	6.02±0.004

The measurements of the internal holes revealed the most significant inaccuracy for all specimens. This can be seen in the sample measurements of the internal diameter of the circular hole in the base of the u-shaped specimen for batch M200P40L2, Table 4. It shows that the deviation from the model diameter (8 mm) is ranging from 0.66 to 0.8 mm. Similar trends were observed for all printing settings with errors ranging from 0.5 to 0.9 mm. In all cases, the printed internal diameters were larger than the model value by the aforementioned deviations.

Table 4. Measurements of the base circular hole diameter of the specimen batch M200P40L2

Specimen #	db1	db2	db3	db4
M200P40L2-1	8.637	8.751	8.651	8.786
M200P40L2-2	8.699	8.742	8.679	8.795
M200P40L2-3	8.675	8.751	8.733	8.807
M200P40L2-4	8.624	8.82	8.695	8.797
mean, mm	8.66	8.77	8.69	8.8
stdev, mm	0.0345	0.0362	0.0342	0.0086
u, mm	0.017	0.018	0.017	0.004
measurement	**8.66±0.017**	**8.77±0.018**	**8.69±0.017**	**8.8±0.004**

These deviations from the original dimensions were in the same range and not correlated to any of the printing settings.

4.2. Flat specimen results

The internal diameters of the flat specimens were measured and it was observed that for the specimens with model diameter of 7 mm, the deviation from the original dimension is ranging from 0.85 to 0.97 mm, Table 5 and Table 6. For the specimens with model diameter of 20 mm, the deviation from the original dimension is ranging from 0.93 to 1.03 mm, Table 7. In all cases, the printed internal diameters were larger than the model value by the aforementioned deviations.

Table 5. Measurements of the circular hole diameter of the specimen batch S100P20D2

7mm 2-hole	D1	D2	D3	D4
S100P20D2-1	7.934	7.906	7.939	7.898
S100P20D2-2	7.967	7.931	7.878	7.936
S100P20D2-3	7.989	7.932	7.983	7.939
S100P20D2-4	7.974	7.931	7.972	7.915
mean, mm	7.97	7.93	7.94	7.92
stdev, mm	0.0232	0.0127	0.0472	0.0192
u, mm	0.012	0.006	0.024	0.01
measurement	7.97±0.012	7.93±0.006	7.94±0.024	7.92±0.01

Table 6. Measurements of the circular hole diameter of the specimen batch M200P20D2

7mm 2-hole	D1	D2	D3	D4
M200P20D2-1	7.839	7.902	7.845	7.93
M200P20D2-2	7.856	7.889	7.86	7.95
M200P20D2-3	7.864	7.931	7.886	7.945
M200P20D2-4	7.841	7.912	7.85	7.916
mean, mm	7.85	7.91	7.86	7.94
stdev, mm	0.012	0.0177	0.0183	0.0154
u, mm	0.006	0.009	0.009	0.008
measurement	7.85±0.006	7.91±0.009	7.86±0.009	7.94±0.008

Table 7. Measurements of the circular hole diameter of the specimen batch S100P20D2

20mm 2-hole	D1	D2	D3	D4
S100P20D2-1	20.96	20.928	21.032	20.961
S100P20D2-2	21.04	20.983	21.025	20.97
S100P20D2-3	21.034	21.012	21.063	20.973
S100P20D2-4	21.051	20.798	21.013	20.971
mean, mm	21.02	20.93	21.03	20.97
stdev, mm	0.0414	0.0948	0.0213	0.0053
u, mm	0.021	0.047	0.011	0.003
measurement	21.02±0.021	20.93±0.047	21.03±0.011	20.97±0.003

4.3. Flat specimens with correction factor

It was determined that the deviation in the internal dimensions (or the major part of it) is mainly fixed value. After some analysis and trials and error, it was decided to use internal diameters that are less than the desired diameter by 0.9 mm for both printers and the resulting diameters were more precise with deviations from the desired dimensions ranging from 0.007 mm to 0.03 mm in case of the MakerBot printer and from 0.061 mm to 0.128 mm in case of PRUSA printer, Table 8, Table 9, and Tabe 10.

Table 8. Measurements of the circular hole diameter with 6.1 mm model diameter

6.1mm 2-hole	D1	D2	D3	D4	**AVERAGE**
M200P20D2	6.889	6.993	6.983	7.015	**6.970**
6.1mm 2-hole	D1	D2	D3	D4	**AVERAGE**
S200P20D2	7.066	7.055	7.081	7.043	**7.061**

Table 9. Measurements of the circular hole diameter with 9.1 mm model diameter

9.1mm 2-hole	D1	D2	D3	D4	**AVERAGE**
M200P20D2	9.902	10.024	9.989	10.018	**9.983**
9.1mm 2-hole	D1	D2	D3	D4	**AVERAGE**
S200P20D2	10.099	10.054	10.099	10.06	**10.078**

Table 10. Measurements of the circular hole diameter with 19.1 mm model diameter

19.1mm 2-hole	D1	D2	D3	D4	**AVERAGE**
M200P20D2	19.896	20.083	19.945	20.046	**19.993**
19.1mm 2-hole	D1	D2	D3	D4	**AVERAGE**
S200P20D2	20.181	20.104	20.157	20.072	**20.128**

5. Conclusion

Both educational and experimental objectives of this project were achieved. The participating student gained practical knowledge and skills in the field of 3D printing which he would not normally get through regular classes. This knowledge and experience allowed him to smoothly use and configure two different 3D printers while avoiding most of the common printing deficiencies. He was also able to follow the guidelines set by the ASTM standards for specimens prepared by additive manufacturing, design, as well as analyze test specimens. He mastered the use of multiple precise measurement tools, used statistical analysis, interpreted the results, and utilized them to suggest corrective action. This experience meets the goals of the initiative set by the author [10], [11], [12], to use senior design classes and space grants to supplement the engineering technology curriculum. On the technical side, the project reached a preliminary conclusion that the major dimensional inaccuracy in the 3D printed PLA was in the internal dimensions and it was mainly systematic. A trial was made to correct this error using a correction factor and it was relatively successful. This error is believed to be related to the mechanical structure of the 3D printers or the G-code generated by the slicer software. Further investigation will be performed to determine the exact source of error and possible means to eliminate it. Another future goal is to further investigate the errors in external dimensions and their possible causes.

6. Acknowledgement

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