RESEARCH ARTICLE

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An Optimization Method for Improving the Accuracy of Multiple Parametric Printed Parts in FDM

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Abstract

Dimensional accuracy is one of the main key features for achieving the desired fit in fused deposition modeling (FDM). Printer tolerance and build orientation are the main challenges faced during the prototyping phase and hence there is a need for a method to calibrate the printer and the material being used that can serve as a guide to designing the clearances of mating parts. This paper presents the design and validation of a tolerance prototype and the study, which, with some analysis and data representation, gives the optimal solution. Hence, this can be used to compensate for the variations in dimensions while printing. A tolerance prototype model consisting of squares and circles of various dimensions is developed in Siemens NX 11.0 that tests the printer in three different orientations i.e., x-axis, y-axis and z-axis. FDM printers Accucraft i250 (heat bed type) and Flashforge (non-heat bed type) are used to print the prototype. The dimensions are measured with calipers to arrive at the dimensional correction templates that are further used to design and validate movable components.

Keywords: Printer tolerance, Build orientation, Calibrate, Clearances, Tolerance, Optimal solution.

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Introduction

Digital fabrication technology, also called 3D printing or additive manufacturing, creates physical objects from a geometrical representation by successive addition of materials.[1] It is gaining attention for manufacturing prototypes, tools and functional end products. Several existing technologies include selective laser sintering/melting (SLS/M), laser-photo resin curing (SLA), laser-cutting of sheet material (LOM), fusing of melted filament material (FDM), electron beam melting (EBM) and many others.[2] However, although these technologies have been available commercially, there are a wide range of qualities of the machine and the built part and so the price.[3] Recently, the price of the machine drops and even a small machine FDM based technology in the kit pack is underway to become a home appliance, just like the coffee maker.[4] Built part quality of 3D printer (FDM based technology) here is defined based on mechanical strength, surface finish, and dimension error or dimension accuracy.[5]

Research related to the mechanical strength of printed parts built by 3D printers can be found in many publications.[6] Accuracy of the printed part is predominant in this technology, where the designed part must be printed with accurate dimensions.[7] There are many possible ways of getting this inaccuracy based on the materials like PLA, ABS, Nylon, and TPU etc. and also based on printers there may be some variations in the printed part.[8] There are some techniques to resolve this issue. One of those is calibrating the printer using height gauges, where the measurement is taken through the displacement of the printer nozzle head in x, y, z directions, which is a complicated technique.[9] CAD software is used for the design and analysis of the parts and also Finite element analysis is done to get the properties of the designed part.[10]

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This research is focused on analyzing the tolerance of the FDM 3D printed part by using FDM printer equipment from T3D LABS PVT LTD of the printed part and comparing the tolerance change to find the error value and by the analysis there is a chance to take all the data to find the best optimal solution for the study which in turn can be used in the modification of the design part and print parameters setting to get the accurate print.[11] The tabulation of the design value and printed value is taken by the measurements using the measurement tools in the CAD software for the designed part and venire calipers are used for the printed part.[12] After the tabulation and conclusion, the resulting error percentage and by taking the references from the data achieved through FEA is can lead to finding the optimal solution used to design the movable part and observed for the validation of this process.[13]

Methodology

Materials

PLA is the material used in this study as this is the most ideal for the FDM printers. PLA melts more easily due to a lower melting point than any other renewable plastics. It requires less energy to transform so it's easy to work with PLA. 3D printing (45% market share) is completely dependent upon the PLA. It has a low melting point, is inexpensive, is easy to print, and has no fumes.

Printers

Accucraft i250+ divided by zero is low-noise operation, quick-load functionality, super-fast slicer and industrial-grade build quality to ensure fast and reliable print cycles. Latest data transfer mediums such as SD cards, USB, Ethernet and Wi-Fi allow seamless connectivity and the built-in camera facilitates remote monitoring of print batches with a low running cost and an easy-to-use interface.

Flash forge is a smart and light 3D printer; the nozzle can reach up to 200degree centigrade in just 50 seconds. This comes with the normal print bed but not the heat bed.

Slicing software

3D printing slicing software controls every aspect of your 3D print.It translates 3D models into instructions your printer understands. Better instructions mean better prints, so a simple software upgrade makes all the difference in the world. More than 90% of experts agree that 3D printing software has the greatest impact on print quality, even more so than the 3D printer itself. Simplify3D is the slicing software used in this study.

Specimen & preparation

First, the specimen was designed in CatiaV5 according to our specified dimensions & geometry (circles and squares). Then the specified design was saved in (.stl) file format. It is then exported into a slicing software known as simplify 3D, using which we have taken default parameters like x, y and z. At a default temperature of 220 & 245℃, the specimen was printed.

Analysis

Static Structural analysis

In the software Ansys, fixed support was given to the specimen at one side of the part and then force is applied. The amount of deformation is checked and noted.

Steady-State analysis

In the software Ansys, at the default temperature, the deformation rate is noted down through convection and then the total heat flux is checked.

Transient Thermal analysis

Using Ansys, the temperature is given at the bottom of the specimen and the temperature is varied at the top, and the change in the heat flux is noted.

Designing Parameters

Designing

In Figure 1 we have shown that the part is designed in the CATIA software which is the best designing software consisting of many tools that make the designing easier.

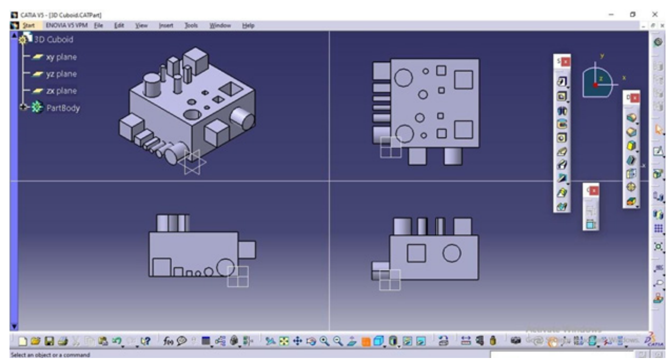


Figure 1: Test Specimen (Tolerance Gauge) 3D model in CATIA

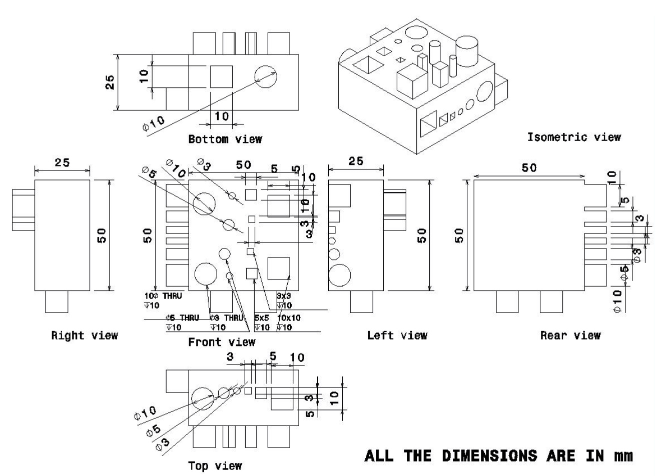


Figure 2: Drafted Test Specimen (Tolerance Gauge) 3D model in CATIA

Drafting

In Figure 2 the drafting is done in the CATIA software. Drafting, also spelled draughting, also called engineering drawing, is a graphical representation of structures, machines, and their component parts that communicates the engineering intent of a technical design to the craftsman or worker who makes the product.

Analysis

Finite element analysis (FEA) is the process of simulating the behavior of a part or assembly under given conditions so that it can be assessed using the finite element method (FEM). The analysis is done in the Ansys 2022 r1 student version. Meshing is the process of turning irregular shapes into more recognizable volumes called "elements". Figure3 shows the basic meshing of the part is as follows:

After the tessellation process, the geometry is converted into recognizable data which can be further used for the analysis part. The main need for the analysis is to find out the temperature gradients occurring in the 3d printed part due to the printing temperature at the top, bed temperature at the bottom and ambient temperature in the surroundings.

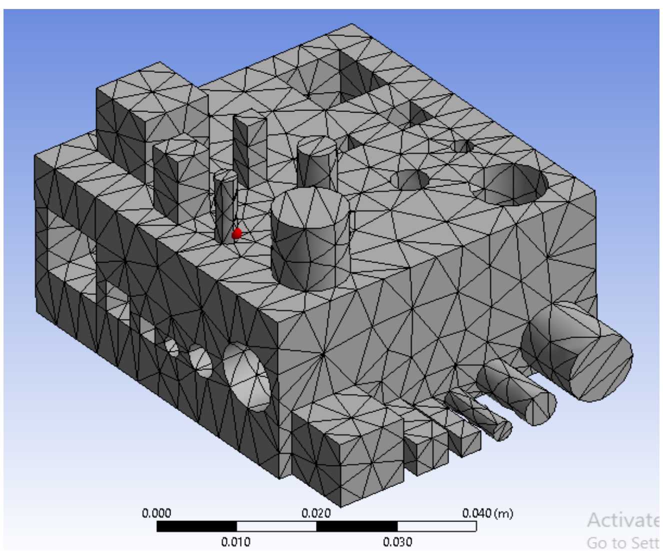


Figure 3: Tesselated Test Specimen (Tolerance Gauge) 3D model

Properties of Outline Row 73: Polylactic acid (PLA)

	A	B	C
1	Property	Value	Unit
2	Density	1250	kg m^-3
3	Isotropic Secant Coefficient of Thermal Expansion		
4	Coefficient of Thermal Expansion	0.000135	C^-1
5	Isotropic Elasticity		
6	Derive from	Young's Modulus an...	
7	Young's Modulus	3.45E+09	Pa
8	Poisson's Ratio	0.39	
9	Bulk Modulus	5.2273E+09	Pa
10	Shear Modulus	1.241E+09	Pa
11	Tensile Yield Strength	5.41E+07	Pa
12	Tensile Ultimate Strength	5.92E+07	Pa
13	Isotropic Thermal Conductivity	0.144	J m^-1 s^-1 C^-1
14	Specific Heat, C_p	1190	J kg^-1 C^-1
15	Isotropic Resistivity	4.31E+09	ohm m

Figure 4: properties of PLA in ANSYS

Now, the analysis is done according to the printer's features. The default temperature at room is provided with 22°C and the time for the analysis is set for 180 seconds.

The properties of the PLA (Polylactic Acid) in ansys are shown in Figure 4.

Transient Thermal Analysis

Heat Bed Convection

For this study, transient thermal analysis is used in which the initial temperature of 22°C is considered the room temperature and the part is assumed to be in still air whose convective heat transfer coefficient is assumed to be 20 W/m^2°C. Hence, the convection boundary condition is specified on the body's outer surfaces except at the bottom of the part as shown in Figure 5.

Temperature 1

The temperature of the heat bed with 60°C is provided in the printer while printing the part. The temperature is gradually set to be decreased from 60 to 22°C. The graph and face selected is shown in Figure 6.

Temperature 2

As the part is printed at 210°C, the op face of the part is considered to be initially at 210°C and is gradually set to decrease from 210 to 22°C. The graph and face selected is shown in the Figure 7.

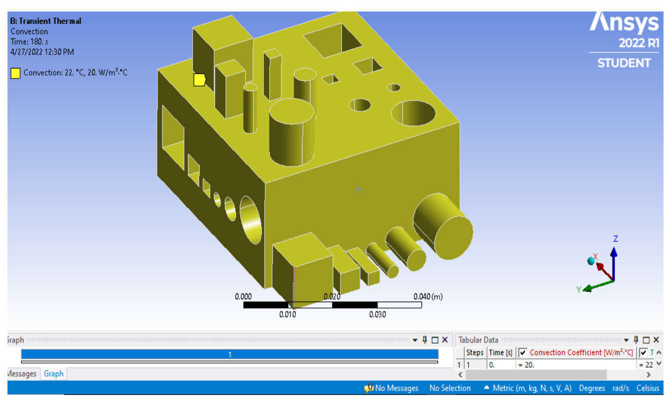


Figure 5: Convection of Test Specimen in ANSYS

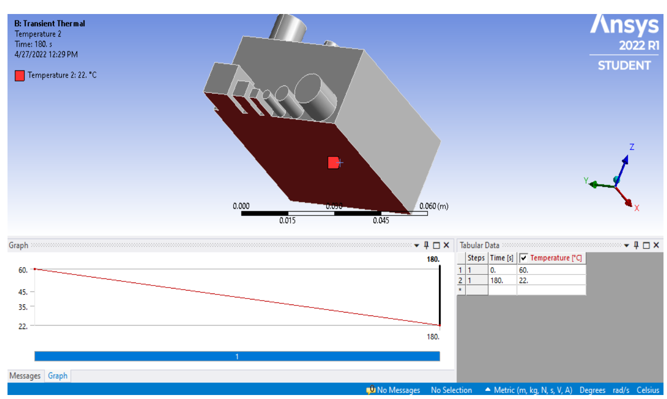


Figure 6: Gradual decrease in temperature from 60 to 22

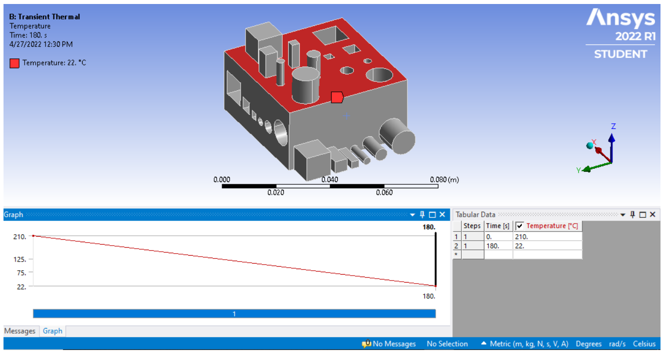


Figure 7: Gradual decrease in temperature from 210 to 22

Solution

The final solution of the temperature distribution was obtained. The temperatures are provided at the top and bottom of the part according to the printer type (heat bed). The maximum temperature of 59.03°C is found below the layers of newly printed areas and the rest of the temperatures are distributed accordingly. This analysis shows the problem of uneven distribution of the temperatures after each layer is resolved using the heat bed which provides the temperature from the bottom and results in the best-printed part with better tolerance.

Non-Heat Bed Convection:

For this study, transient thermal analysis is used in which the convection of 22°C on the outer surfaces of the body except at the bottom of the part is given as shown in Figure 9.

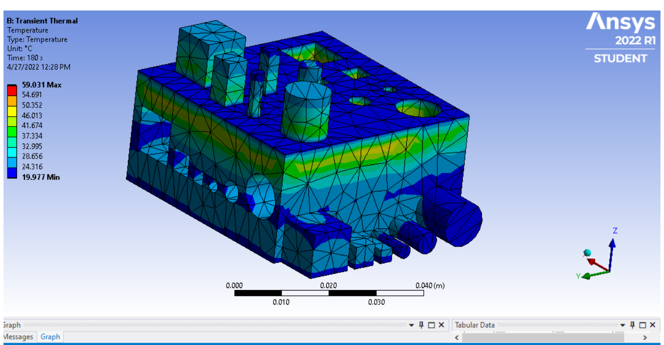


Figure 8: Temperature distribution in the internal body of the specimen (heat bed)

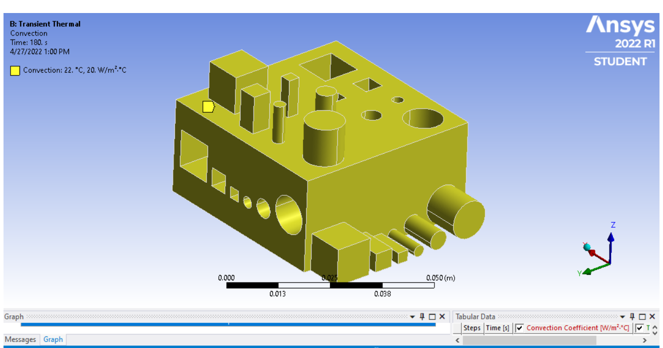


Figure 9: Convection of Test Specimen in ANSYS

Temperature

The temperature of the printer nozzle with 210°C is provided in the printer while printing the part. The temperature is gradually set to be decreased from 210 to 22°C. The graph and face selected are shown in the figure.

Solution

The final solution of the temperature distribution was obtained. The temperature provided at the top of the part according to the printer type (Non-heat bed). The maximum

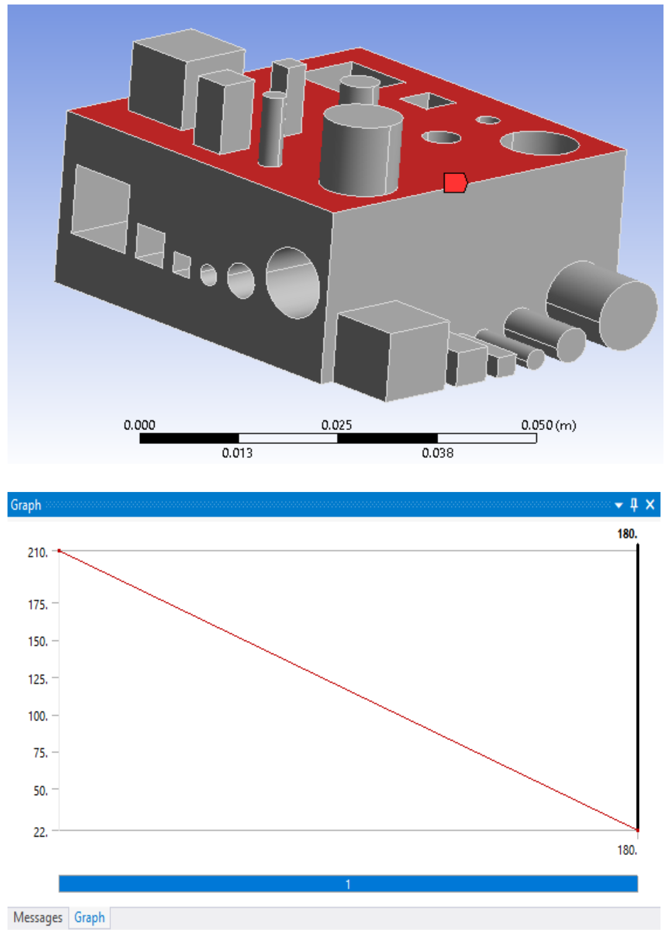


Figure 10: Gradual decrease in temperature from 210 to 22°C

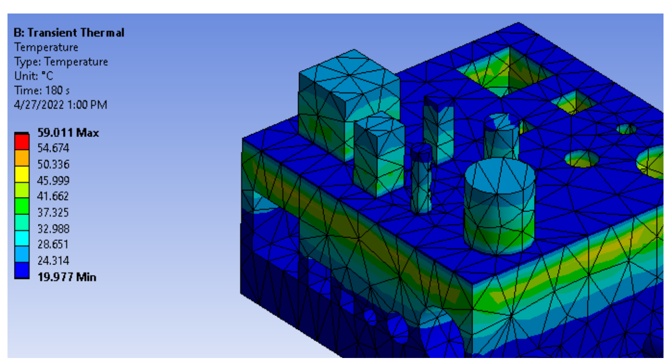


Figure 11: Temperature distribution in the internal body of the specimen (Non-heat bed)

temperature of 59.11°C is found below the layers of newly printed areas and the rest of the temperatures are distributed accordingly. This analysis shows the problem of uneven distribution of the temperatures after each layer is printed, resulting in the less quality printed part with low tolerance.

Static Structural Analysis

This analysis is done to show the direction in which the expansion takes place while one end is kept fixed. The max deformation is obtained at about 0.00026 m and the minimum deformation at 0 m, as shown in Figure 12.

Printers And Printer Parameters

Accucraft i250+

Print parameters of Accucraft i250+ are shown in Table 1.

Flash Forge

Print parameters of flash forge are shown in Table 2.

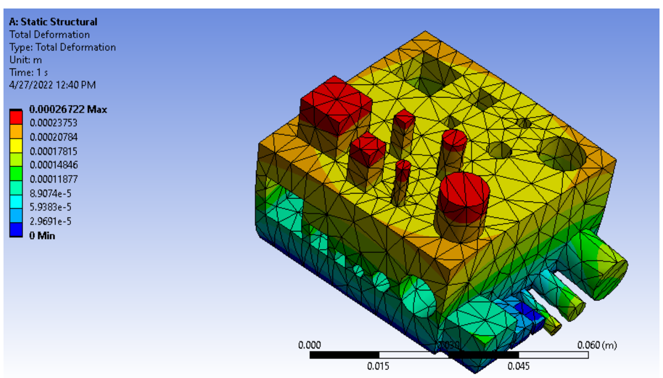


Figure 12: Direction of expansion takes place while one face is fixed

Table 1: Print parameters of Accucraft i250+

Default Values	*Optimised Values*
Layer height: 0.25 mm	Layer height: 0.18 mm
Temperature: 245°C	Temperature: 220°C
Print speed: 60 mm/s	Print speed: 60 mm/s
Travel speed: 80 mm/s	Travel speed: 80 mm/s
Fill Density: 45%	Fill Density: 50%
Fill Pattern: Line	Fill Pattern: Line
Heat bed: 90°C	Heat bed: 90°

Table 2: Print parameters of flash forge

Default Values	*Optimised Values*
Layer height: 0.18 mm	Layer height: 0.15 mm
First layer height: 0.27 mm	First layer height: 0.25 mm
Temperature: 220°C	Temperature: 210°C
Print speed: 60 mm/s	Print speed: 60 mm/s
Travel speed: 80 mm/s	Travel speed: 80 mm/s
Fill Density: 45%	Fill Density: 80%
Fill Pattern: Line	Fill Pattern: Triangular
Combine Infill: Every 2 layers	Combine Infill: Every 2 layers

Printed Data

For the study, there is a need to print two similar parts in two different printers as it is necessary to differentiate the printed pats according to their print quality. The dimensional changes are taken into consideration and the data is taken to check whether there is any trend that is followed by the printer like the print accuracy having some particular similarities in a particular orientation so that that there can be a chance of getting the optimized solution in terms of the print orientation and hence there might be chance to find the optimal resolution for the particular trend and that can result in the accurate printing part. Those two printed parts are numbered with cube 1 and cube 2 for identity purposes, as shown in Figures 13 and 14.

The data of both the cubes are provided as follows

CUBE 1(Non-Heat Bed) is shown in Table 3.

Cube 1

By taking face 1 as a reference, X-axis is considered as length, Y-axis is considered as height and

-ve z-axis is considered as width. These default dimensions follow each face.

The cube dimension was obtained better in Z orientation by default printing.

Face 1

- Width of the part in -ve Y orientation, its accuracy is less as the print value (9.35 mm) is compared to the actual value (10 mm) for squares.
- It has better accuracy with 0.01 mm least difference for the circles for face 1 which are extruded in Y orientation.

Face 2

- Face 2 consists of a square and cylinder which are printed at some height with support material.
- Accuracy for the square is moderate up to 0.1 mm difference and less compared to the cylinder which obtained with better accuracy of 0.01 mm difference.

Face 3

Extrudes

- Squares (S1, S2) obtained better accuracy than S3, which has low accuracy and the height difference is almost similar with 0.11mm difference for all the squares.

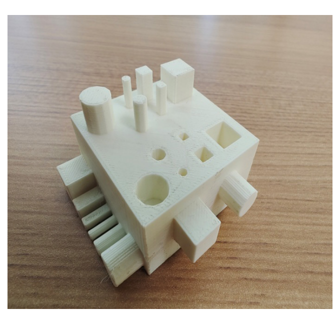


Figure 13: Isometric view of the 3D printed part

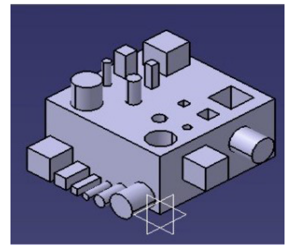
Figure 14: Parts printed in Accucraft and Flash forge printers

Table 3: CUBE 1 (Non-Heat Bed)

	Data From Flash Forge	*Faces*

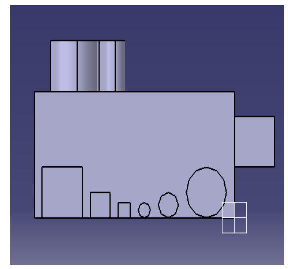
A.

Box Extrnal	Corner 1	Corner 2	Corner 3	Corner 4	Avg	Orignal	Difference
Length	50.16	50.2	50.14	50.16	50.165	50	0.165
Width	50.19	50.14	50.15	50.21	50.172	50	0.175
Height	25.25	25.21	25.15	24.78	25.097	25	0.097



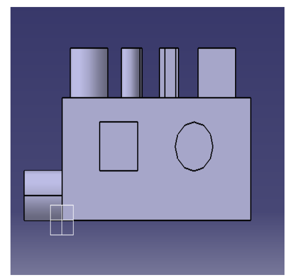
B.

Face-1											
Squares	S1	Original	Diffrence		S2	Original	Diffrence		S3	Original	Diffrence
Length	10.21	10	0.21		5.22	5	0.22		3.18	3	0.18
Height	9.73	10	-0.27		5.07	5	0.7		3.11	3	0.11
Width	9.35	10	-0.65		9.99	10	-0.01		9.98	10	-0.02
Circles	C1	Original	Diffrence		C2	Original	Diffrence		C3	Original	Diffrence
Diameter	10.35	10	0.35		5.09	5	0.09		3.1	3	0.1
Width	10.01	10	0.01		10.04	10	0.04		10.03	10	0.03



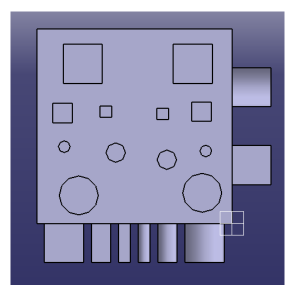
C.

Face-2			
	Square	Original	Diffrence
Width	10.16	10	0.16
Height	10.24	10	0.24
Length	9.98	10	-0.02
	circle	Original	Diffrence
Diameter	10.05	10	0.05
Length	9.93	10	-0.07



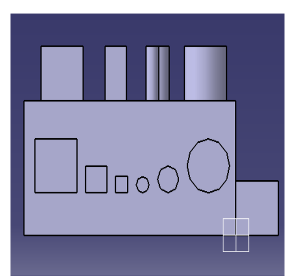
D.

Face-3											
EXTRUDES											
Squares	S1	Original	Diffrence		S2	Original	Diffrence		S3	Original	Diffrence
Length	10.16	10	0.16		5.1	5	0.1		3.26	3	0.26
Width	10.14	10	0.14		5.15	5	0.15		3.35	3	0.35
Height	10.11	10	0.11		10.11	10	0.11		10.11	10	0.11
Circles	C1	Original	Diffrence		C2	Original	Diffrence		C3	Original	Diffrence
Diameter	9.86	10	-0.14		4.84	5	-0.16		3.09	3	0.09
Height	10.14	10	0.14		10.13	10	0.13		10.07	10	0.07
HOLES											
Squares	S1	Original	Diffrence		S2	Original	Diffrence		S3		Diffrence
Length	9.88	10	-0.12		4.99	5	0.01		3.05	3	0.05
Width	10.44	10	0.44		5.04	5	0.04		3.12	3	0.12
Height	10.17	10	0.17		10.15	10	0.15		10.17	10	0.17
Circles	C1	Original	Diffrence		C2	Original	Diffrence		C3	Original	Diffrence
Diameter	9.66	10	-0.24		4.61	5	-0.39		2.65	3	-0.35
Height	10.11	10	0.11		10.16	10	0.16		10.15	10	0.15



E.

Face-4											
Squares	S1	Original	Diffrence		S2	Original	Diffrence		S3	Original	Diffrence
Width	9.84	10	-0.16		4.85	5	-0.15		2.89	3	-0.11
Height	9.5	10	-0.5		4.66	5	-0.34		2.79	3	-0.21
Length	9.94	10	-0.06		9.98	10	-0.02		9.96	10	-0.04
Circles	C1	Original	Diffrence		C2	Original	Diffrence		C3	Original	Diffrence
Diameter	9.63	10	-0.27		4.67	5	-0.33		2.83	3	-0.17
Length	10.01	10	0.01		9.95	10	-0.05		9.93	10	-0.07



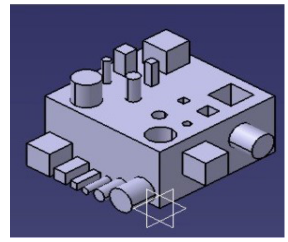
Increased values (yellow)
decreased values (green)

Table 4:

Data From Accucraft | *Faces*

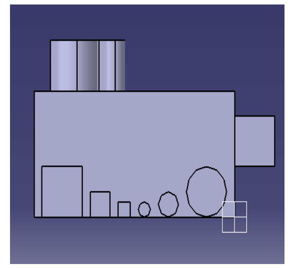
A.

Box Extrnal	Corner 1	Corner 2	Corner 3	Corner 4	Avg	Orignal	Difference
Length	50.15	50.15	49.94	50.07	50.077	50	0.077
Width	50.11	50.18	50.2	50.02	50.127	50	0.127
Height	24.22	25.02	25.08	24.96	24.82	25	0.18



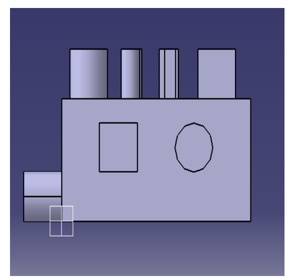
B.

Face-1									
Squares	S1	Original	Diffrence	S2	Original	Diffrence	S3	Original	Diffrence
Length	10.17	10	0.17	5.2	5	0.2	3.12	3	0.12
Height	9.86	10	-0.14	5.06	5	0.06	3.07	3	0.07
Width	10.1	10	0.1	9.94	10	-0.06	10.05	10	0.05
Circles	C1	Original	Diffrence	C2	Original	Diffrence	C3	Original	Diffrence
Diameter	9.73	10	-0.27	5.11	5	0.11	3.14	3	0.14
Width	10.01	10	0.1	10.12	10	0.12	10.03	10	0.03



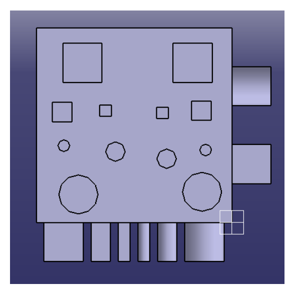
C.

Face-2			
	Square	Original	Diffrence
Width	10.18	10	0.18
Height	10.13	10	0.13
Length	10.07	10	0.07
	circle	Original	Diffrence
Diameter	9.97	10	-0.03
Length	10	10	0



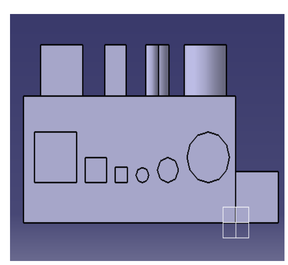
D.

Face-3									
EXTRUDES									
Squares	S1	Original	Diffrence	S2	Original	Diffrence	S3	Original	Diffrence
Length	10.1	10	0.1	5.05	5	0.05	3.27	3	0.27
Width	10.08	10	0.08	5.1	5	0.1	3.32	3	0.32
Height	10.18	10	0.18	10.08	10	0.08	10.08	10	0.08
Circles	C1	Original	Diffrence	C2	Original	Diffrence	C3	Original	Diffrence
Diameter	9.81	10	-0.19	4.9	5	-0.1	3.09	3	0.09
Height	10.1	10	0.1	10.08	10	0.08	10.08	10	0.08
HOLES									
Squares	S1	Original	Diffrence	S2	Original	Diffrence	S3	Original	Diffrence
Length	9.87	10	-0.13	5.07	5	0.07	3.02	3	0.02
Width	10.2	10	0.2	5.2	5	0.2	3.11	3	0.11
Height	9.99	10	-0.01	10.09	10	0.09	10.08	10	0.08
Circles	C1	Original	Diffrence	C2	Original	Diffrence	C3	Original	Diffrence
Diameter	9.55	10	-0.45	4.68	5	-0.32	2.74	3	-0.26
Height	9.86	10	-0.14	10.1	10	0.1	10.1	10	0.1



E.

Face-4									
Squares	S1	Original	Diffrence	S2	Original	Diffrence	S3	Original	Diffrence
Width	9.08	10	-0.92	4.82	5	-0.18	2.82	3	-0.18
Height	9.29	10	-0.81	4.5	5	0.5	2.68	3	-0.32
Length	9.93	10	-0.07	10.12	10	0.12	10.1	10	0.1
Circles	C1	Original	Diffrence	C2	Original	Diffrence	C3	Original	Diffrence
Diameter	9.09	10	-0.91	4.52	5	-0.48	2.39	3	-0.61
Length	10.46	10	0.46	10.02	10	0.02	10.1	10	0.1



Increased values (yellow)
decreased values (green)

- Circle (C3) obtained with better accuracy of 0.07 mm difference compared to C1 and C2.

Holes

- Squares (S2, S3) obtained better accuracy than S1, which has low accuracy of 0.44 mm difference and the height difference is almost similar for all the squares around 0.17 mm difference.
- In circles the obtained diameter is reduced and the height is almost all are similar, around 0.15 mm difference.

Face 4

- The entire square obtained lower accuracy with negative values and S3 obtained better accuracy compared to S1 and S2 with a 0.01 mm difference.
- The length of the circle is accurate, around 0.01 mm difference compared to the diameters.

CUBE 2(Heat Bed)

Cube-2

By taking face 1 as a reference, X-axis is considered as length, Y-axis is considered as height and
-ve z-axis is considered as width. Each face is followed by these default dimensions.

The cube dimension obtained best in Z orientation by default printing.

Face 1

- The print dimensions are good for the S3 with 0.05 mm difference.
- The circles almost got similar dimensions with 0.1 mm difference.

Face 2

- The width in the square got better accuracy with around 0.01 mm difference.
- The perfect length is obtained with 0.01 mm difference in a circle and the diameter about 0.01 mm difference is a bit less but accurate.

Face 3

Extrudes

- Squares (S1, S2) obtained better accuracy with 0.02 mm difference compared to S3 with 0.35 mm difference, which has low accuracy and the height difference is almost similar for all the squares with 0.08mm difference.
- Circles (C2&C3) were obtained with better accuracy, about 0.01 mm difference than C1 with 0.1 mm difference.

Holes

- Squares (S2, S3) with an average of 0.05 mm difference obtained better accuracy compared to S1 with 0.2 mm difference.
- Circles (C2, C3) with 0.1 mm difference are observed to have similar and better accuracy obtained than C1.

Face 4

- Square (S1) obtained with decreased vales but nearest values in length about 0.07 mm difference 1.
- Circle diameters with 0.4 mm difference are obtained less.

Conclusion

- Dimensions increase within 3 to 10 mm.
- Perfectly circular objects cannot be printed either due to STL file resolution or layer height.
- Any particular trend in X, Y or Z directions that results in size deviation and that could not be identified.
- Some features had positive deviations and others had negative deviations.
- Thermal expansion behavior and the deviation of the printed part are of similar order <0.26 mm.
- Internal thermal gradients developed when the part is in the cooling phase are analyzed, possibly contributing to dimensional inaccuracy.

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