

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 modelling (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 further carried out 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 the 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 callipers to arrive at the dimensional correction templates that are further used to design and validate a movable components.*

Index Terms— *Printer Tolerance, Build Orientation, calibrate, clearances, tolerance, optimal solution*

I. INTRODUCTION

Digital fabrication technology, also referred to as 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 and 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 and this 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].

This research is focused on analyzing 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 vernier 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 find the optimal solution which is used to design the movable part and observed for the validation of this process [13].

II. METHODOLOGY

2.1 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, easy to print, no fumes.

2.2 Printers:

- 2.2.1 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.
- 2.2.2 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.

2.3 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.

2.4 Specimen & preparation

First, the designing of the specimen was done 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 temperatures of 220 °C & 245°C, the printing of the specimen was done.

2.5 Analysis

- 2.5.1 Static Structural analysis
 - 2.5.1.1 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.
- 2.5.2 Steady-State analysis
 - 2.5.2.1 In the software Ansys, at the default temperature, through convection the rate of deformation is noted down and then the total heat flux is checked.
- 2.5.3 Transient Thermal analysis
 - 2.5.3.1 Using Ansys the temperature is given at the bottom

of the specimen and the temperature is varied at the top of the specimen and the change in the heat flux is noted.

III. DESIGNING PARAMETERS

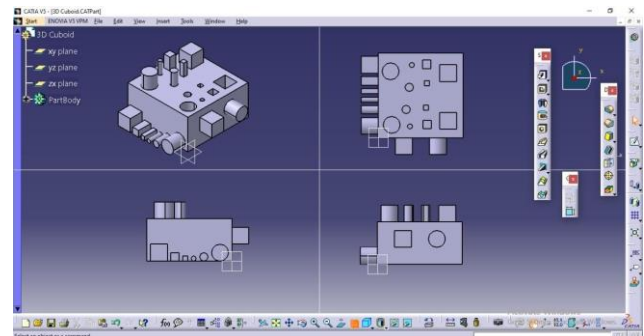


Fig.1 Test Specimen (Tolerance Gauge) 3D model in CATIA

3.1 DESIGNING

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

3.2 DRAFTING:

In Fig.2 the drafting is done in the CATIA software. Drafting, also spelled draughting, also called engineering drawing, 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.

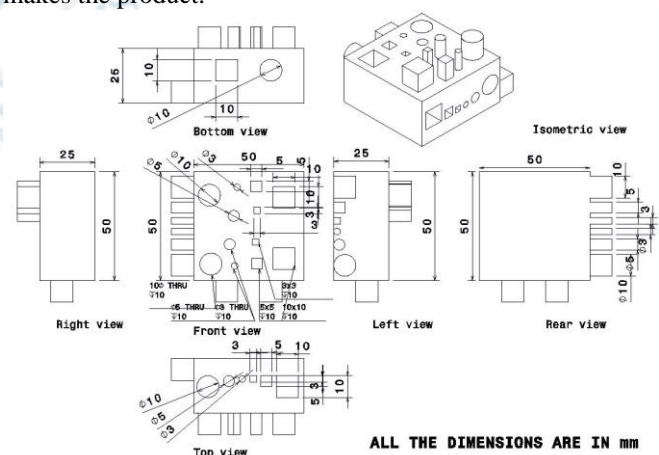


Fig.2 Drafted Test Specimen (Tolerance Gauge) 3D model in CATIA

IV. 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". Fig.3

shows the basic meshing of the part is as follows:

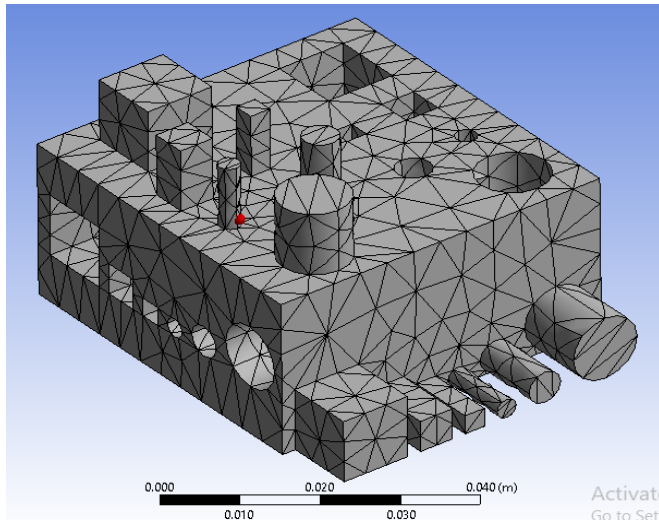


Fig.3 Tesselated Test Specimen (Tolerance Gauge) 3D model

After the process of tessellation the geometry is converted into the 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 printing temperature at the top, bed temperature at the bottom and ambient temperature in surrounding.

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

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

Properties of Outline Row 73: Poly(lactic 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

Fig.4 properties of PLA in ANSYS

4.1 TRANSIENT THERMAL ANALYSIS

4.1.1 HEAT BED CONVECTION:

For this study transient thermal analysis is used in which initial temperature of 22°C is considered as the room temperature and the part is assumed to be in still air whose convective heat transfer coefficient is assumed to be 20 W/m²°C. Hence convection boundary condition is specified on the outer surfaces of the body except at bottom of the part

as shown in Fig.5.

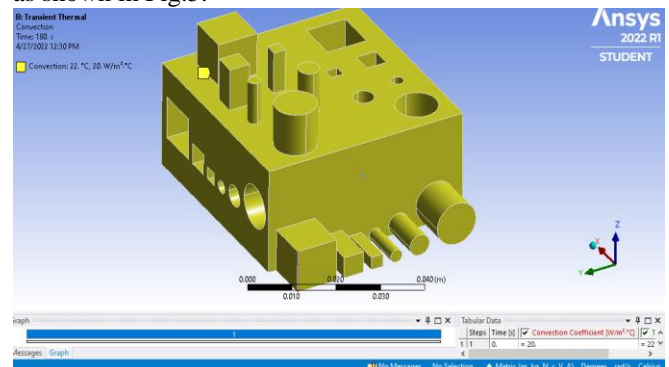


Fig.5 Convection of Test Specimen in ANSYS

4.1.2 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°C to 22°C. The graph and face selected is shown in the Fig.6.

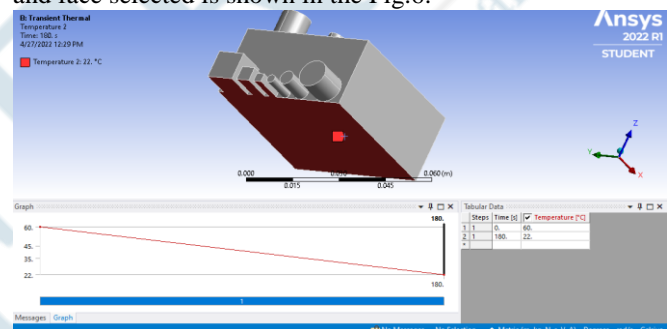


Fig.6 Gradual decrease in temperature from 60°C to 22°C

4.1.3 TEMPERATURE 2

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

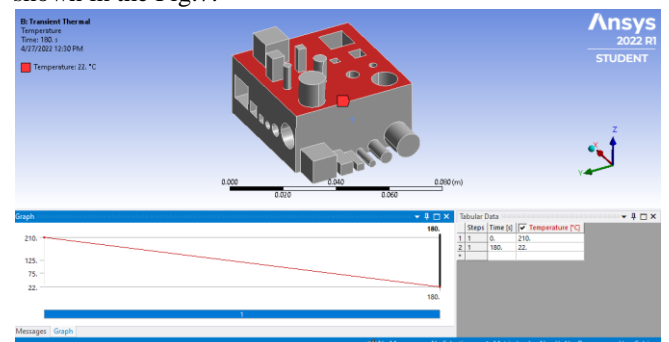


Fig.7 Gradual decrease in temperature from 210°C to 22°C

4.1.4 SOLUTION:

The final solution of the temperature distribution 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.

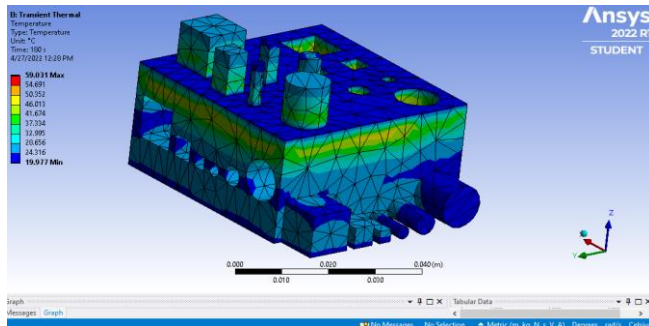


Fig.8 Temperature distribution in the internal body of the specimen (heat bed)

4.1.5 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 bottom of the part is given as shown in Fig.9.

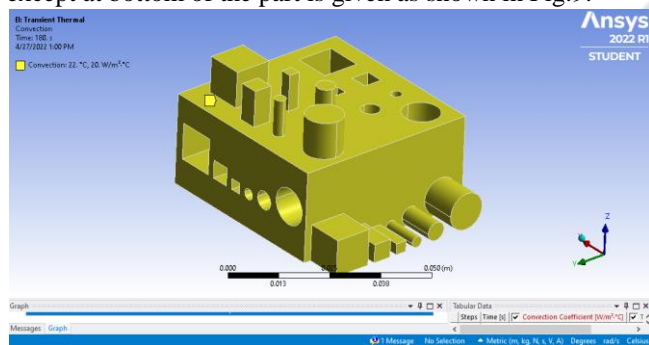


Fig.9 Convection of Test Specimen in ANSYS

4.1.6 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°C to 22°C. The graph and face selected is shown in the figure.

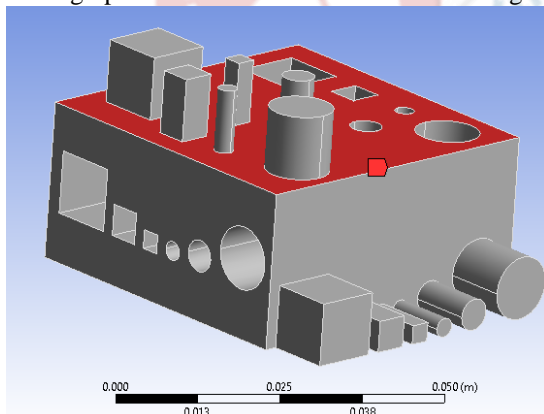


Fig.10 Gradual decrease in temperature from 210°C to 22°C

4.1.7 SOLUTION:

The final solution of the temperature distribution obtained. The temperature provided at the top of the part according to the printer type (Non-heat bed). The maximum 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 and results in the less quality printed part with low tolerance.

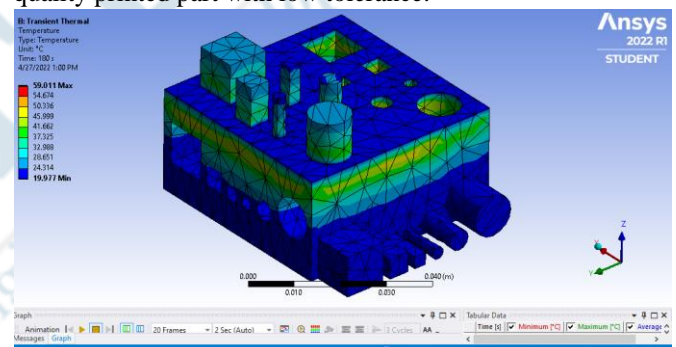


Fig.11 Temperature distribution in the internal body of the specimen (Non-heat bed)

4.2 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 is about 0.00026m and the minimum deformation is 0m as shown in Fig.12.

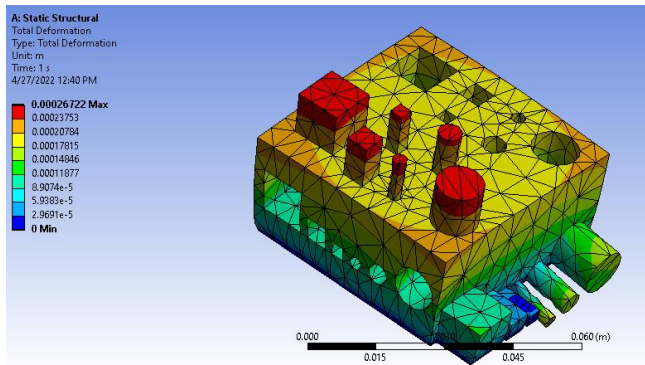


Fig.12 Direction of expansion takes place while one face is fixed

V. PRINTERS AND PRINTER PARAMETERS

5.1 Accucraft i250+

Table 1

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

Print parameters of *Accucraft i250+* are shown in Table1.

5.2 Flash Forge

Table 2

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

Print parameters of flash forge are shown in Table2.

Printed Data:

For the study, there is a need to print two similar parts in two different printers as there is a need for differentiating the printed parts according to their print quality the dimensional changes are taken into the 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 orientations 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 the identity purpose as

shown in Fig.15 and Fig.16.

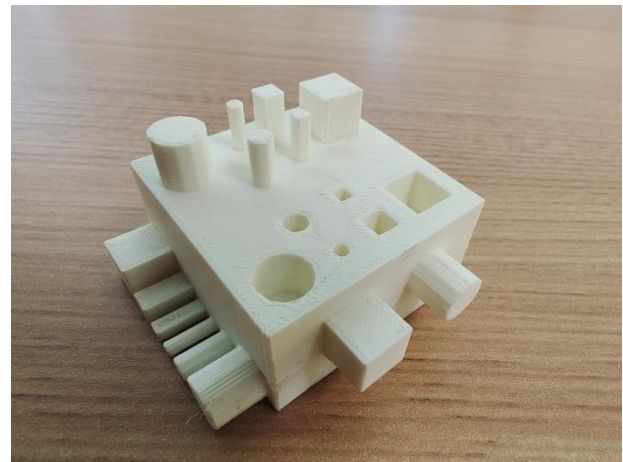


Fig.15 Isometric view of the 3D printed part

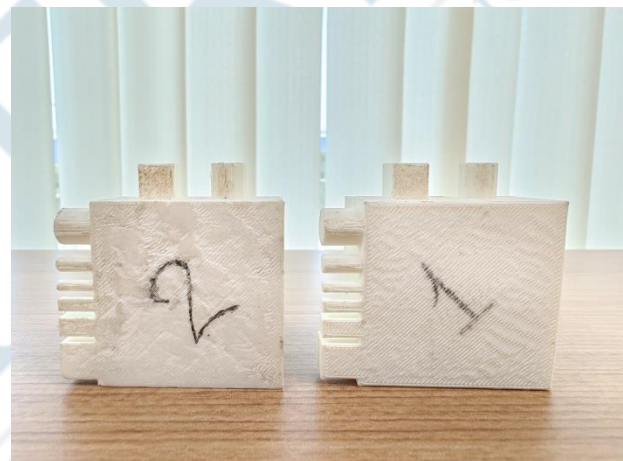
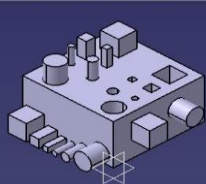
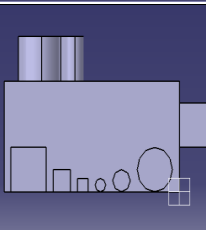
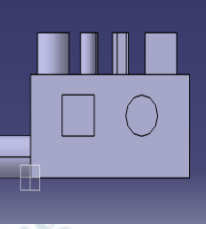
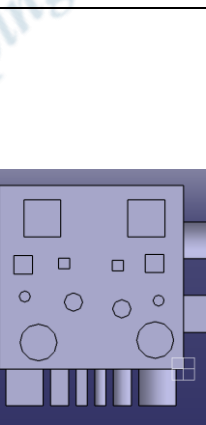
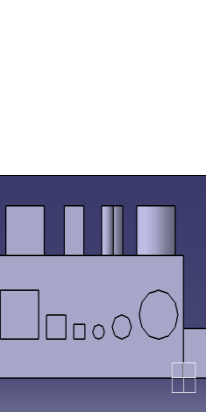


Fig.16 Parts printed in Accucraft and Flash forge printers

The data of both the cubes are provided as follows:
CUBE 1(Non-Heat Bed) shown in table 3.

Table 3

DATA FROM FLASH FORGE										FACES	
A.	Box Extnal	Corner 1	Corner 2	Corner 3	Corner 4	Avg	Original	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	Difference	S2	Original	Difference	S3	Original		Difference
	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	Difference	C2	Original	Difference	C3	Original		Difference
	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	Difference								
	Width	10.16	10	0.16							
	Height	10.24	10	0.24							
	Length	9.98	10	-0.02							
	circle	Original	Difference								
	Diameter	10.05	10	0.05							
	Length	9.93	10	-0.07							
D.	Face-3										
	EXTRUDES										
	Squares	S1	Original	Difference	S2	Original	Difference	S3	Original		Difference
	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	Difference	C2	Original	Difference	C3	Original		Difference
	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	Difference	S2	Original	Difference	S3	Original		Difference
	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	Difference	C2	Original	Difference	C3	Original		Difference
	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	Difference	S2	Original	Difference	S3	Original		Difference
	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	Difference	C2	Original	Difference	C3	Original		Difference
	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
decreased values

Cube 1:

By taking face 1 as reference, x- axis is considered as length, y- axis is considered as height and

-ve z-axis is considered as width. Each face followed by these default dimensions.

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

Face 1

- Width of the part that is in -ve Y orientation, its accuracy is less as the print value (9.35mm) is as compared to actual value (10mm) for squares.
- It has better accuracy with 0.01mm 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 0.1mm difference and less compared to cylinder which obtained with better accuracy of 0.01mm difference.

Face 3

Extrudes

- Squares (S1, S2) obtained better accuracy compared to S3 which has low accuracy and the height difference is almost similar with 0.11mm difference for all the squares.
- Circle (C3) obtained with better accuracy of 0.07mm difference compared to C1 and C2.

Holes:

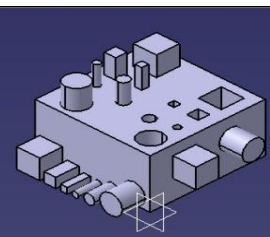
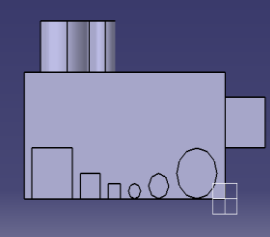
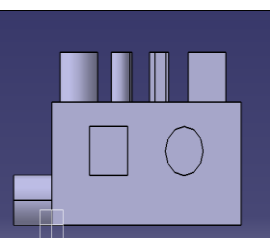
- Squares (S2, S3) obtained better accuracy compared to S1 which has low accuracy of 0.44mm difference and the height difference is almost similar for all the squares around 0.17mm difference.
- In circles the obtained Diameter is reduced and the height is almost all are similar around 0.15mm difference.

Face 4

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

CUBE 2(Heat Bed)

Table 6.2

	DATA FROM ACCUCRAFT								FACES		
A.	Box Extrnal	Corner 1	Corner 2	Corner 3	Corner 4	Avg	Original	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	Difference	S2	Original	Difference	S3	Original	Difference	
	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	Difference	C2	Original	Difference	C3	Original	Difference	
	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	
	Face-2										
	Square	Original	Difference								
	Width	10.18	10	0.18							
	Height	10.13	10	0.13							
	Length	10.07	10	0.07							
C.	circle	Original	Difference								
	Diameter	9.97	10	-0.03							
	Length	10	10	0							

D.

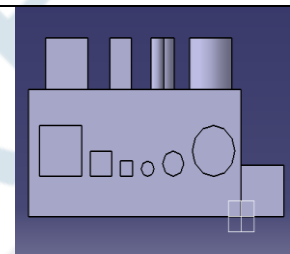
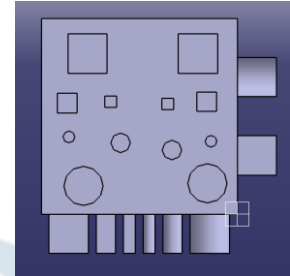
Face-3									
EXTRUDES									
Squares	S1	Original	Difference	S2	Original	Difference	S3	Original	Difference
Length	10.1	10	0.1	5.05	5	0.05	3.27	3	0.27
Width	10.08	10	0.08	5.1	5	0.1	3.32	3	0.32
Height	10.18	10	0.18	10.08	10	0.08	10.08	10	0.08
Circles	C1	Original	Difference	C2	Original	Difference	C3	Original	Difference
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	Difference	S2	Original	Difference	S3	Original	Difference
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	Difference	C2	Original	Difference	C3	Original	Difference
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

Technical drawing of the top face of a mechanical part. It shows a rectangular plate with several square and circular features. Dimensions are indicated: a central square is 10.1 by 10.18; a smaller square is 5.05 by 5.1; a circular feature has a diameter of 9.81 and a height of 10.1. Other features include a 3.27 by 3 square, a 3.32 by 3 square, and a 10.08 by 10 square. The drawing is a top-down view with a blue background.

E.

Face-4									
Squares	S1	Original	Difference	S2	Original	Difference	S3	Original	Difference
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	Difference	C2	Original	Difference	C3	Original	Difference
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

Technical drawing of the bottom face of a mechanical part. It shows a rectangular plate with several square and circular features. Dimensions are indicated: a central square is 10.1 by 10.18; a smaller square is 5.05 by 5.1; a circular feature has a diameter of 9.81 and a height of 10.1. Other features include a 3.27 by 3 square, a 3.32 by 3 square, and a 10.08 by 10 square. The drawing is a bottom-up view with a blue background.



Increased values
decreased values

Cube-2:

By taking face 1 as reference, x- axis is considered as length, y- axis is considered as height and -ve z-axis is considered as width. Each face 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 0.05mm difference.
- The circles almost got the similar dimensions with 0.1 mm difference.

Face 2

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

Face 3

Extrudes

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

Holes:

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

Face 4

- Square (S1) obtained with decreased vales but nearest values in length about 0.07mm difference1.
- Circle diameters with 0.4mm difference are obtained less.

VI. CONCLUSION

1. Dimensions increases within 3mm-10mm.
2. Perfectly circular object cannot be printed either due to STL file resolution or layer height.
3. Any particular trend in x, y or z directions that results in size deviation and that could not be identified.
4. Some features had positive deviation and other had negative deviation.
5. Thermal expansion behavior and the deviation of the printed part are of similar order <0.26mm
6. Internal thermal gradients developed when the part is in cooling phase are analyzed which is a possible contributing factor for dimensional inaccuracy.

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