Experimental assessment of Repeatability of Openware 3D Printer

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Abstract - As promising manufacturing process, additive manufacturing technique is looked upon. Apart from other additive techniques, the fused deposition modeling invented by Stratasys is widely practiced because of its simple design and fabrication. Apart from the prevalent advantages, it also has limitation such as dimensional accuracy, repeatability, and surface finish. This paper was aimed at evaluation of repeatability of an Openware desktop 3D printer in terms of standard deviation obtained from a set of samples. At first, an optimum set of parameters (layer height, speed of deposition and fill density) were evaluated using Taguchi method of DOE. Then with optimum parameters sample specimens were printed. On this sample set, statistical analysis was performed. From the statistical analysis of data about dimensional deviation, the repeatability of printer was interpreted.

Keywords: Additive manufacturing, Fused deposition modeling printer, Taguchi Analysis, Repeatability, Anderson-Darling Test

1. INTRODUCTION

Additive manufacturing (AM) is defined as "the process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies", as per ASTM F42. Continuously large amount of research has taken place in additive manufacturing. The application of AM is substantial in aerospace, automotive, biomedical and conventional prototyping. AM can be classified according to the type of material used (filament, sheets, liquid polymer), the technologies incorporated (FDM, SLA, VAT, and photo polymerization etc.). AM processes have an edge over the conventional subtractive manufacturing process in such way that it can make complex geometrical parts modeled in any CAD software. Fused deposition modeling (FDM) is one of the AM techniques [1]. In FDM, a thin filament of material is fed into a heated extruder machine, and the molten material is deposited on a heated bed layer by layer onto each other (Figure 1). With advancement in FDM process it has evolved over the period. Due to which it is showing its application in manufacturing sectors also, than just prototyping. FDM is prevalent among organization in various businesses, from automobile to consumer product fabrication [2]. Being simpler in design and construction it has process specific limitations such as availability of printable materials, existing CAD system, STL file size and its management, low-volume production, financial overheads, surface quality, dimensional accuracy and repeatability[3]. Its use further in manufacturing is limited due to such restrictions. For extensive use of 3D printer, knowledge of its capabilities should be more researched and these limitations needs to be minimized.

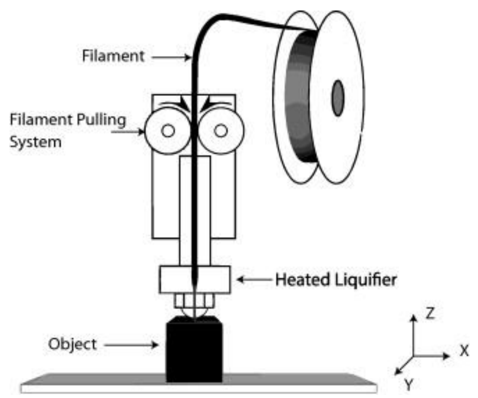

Fig - 1: Fused deposition modeling process

2. LITERATURE REVIEW

With number of printing parameters involving in the process, there has been need to find out the significant and optimum parameters for better surface roughness, accuracy, or other physical properties of printed parts. Concerning this, a noticeable amount of study has taken place to evaluate qualitative output of 3D printer. R. Anitha[4], found out the effect of parameters such as layer thickness, road width and speed of deposition on the printed parts using Taguchi technique. Further using ANOVA observed that layer thickness was significant factor among other two. This paper also asserted using Taguchi for design of experiment (DOE). C. K. Basavaraj[5], Che Chung Wang[6], Garrett W. Melenka[7] investigated on various physical properties such as dimensional accuracy, surface roughness or material properties using different techniques such as GRA analysis, TOPSIS, and CLT. Basavraj tried on achieving maximum tensile strength, optimum dimensional accuracy, and manufacturing time using Taguchi. For DOE, parameters such as layer thickness, part orientation angle and shell thickness were considered. This research found out the optimum parameters and also their significant level by ANOVA.

Wang integrated Taguchi method with Gray relational analysis and verified using TOPSIS. Optimum levels of parameters such as layer height, deposition style, support style, deposition orientation in X and Z direction, and build location were evaluated by Taguchi. At first, Malenka

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investigated effects of printing parameters such as layer height, infill percentage and part orientation on material properties. Then, compared results from DOE with theoretically predicted elastic moduli using Classical laminate plate theory (CLPT).

Further, by applying desirability function approach Stephen O. Akande[8] stated optimum levels for better dimensional accuracy and surface finish and also tested the parameters by samples printing for illustration. For DOE, to evaluate optimum level following parameters were considered layer height, speed of deposition and fill density (infill percentage). Tobias Lieneke[9], formed a methodological approach to identify tolerance values under common conditions, and also stated need of further work for different geometrical shapes. The paper emphasized on requirement of knowledge of process capabilities for manufacturing purposes. In manufacturing point of view, the 3D printers are assessed previously for dimensional accuracy of printed parts; but the consistency of acquiring specified dimension i.e. repeatability needs to be discussed. This research aims to evaluate optimum parameters for higher dimensional accuracy and then employing the parameters for assessing repeatability of dimensions in standard deviation of dimensional deviations of printed parts.

3. METHODOLOGY

The experimentation was consisted of mainly two parts. Evaluation of optimized parameters was followed by assessing the repeatability of printer. For improvisation of the performance of manufacturing process, experimental design is a critically important tool. It provides a powerful and efficient method for designing products that operate consistently and optimally over a variety of conditions. So the Taguchi method was used for design of experiment [11] [16]. Using three factors and three levels, an L9 orthogonal array was formed [15]. In past various parameters were taken into consideration such as layer thickness, build orientation, road width, number of contours, speed of deposition etc. From former experience of working of the printer in which speed of deposition, layer height and fill density parameters showed substantial contribution in the quality of printed parts[8], [3], [7], [4], and [6]. Further, to perform the experiments, three basic geometrical shapes were determined [9] such as cuboid, hemisphere and cone. Then to obtain original dimensions, these printed parts were measured on CMM. The responses were calculated as deviation in designed dimensions of printed parts. For these multi-responses relative weighing method [12] for Taguchi analysis; wherein signal-noise ratios were compared for evaluation of optimum parameters levels for each geometrical shape. A cuboid was preferred for comprehensive understanding of three axes of printer. Further, with the optimized parameters 35 cuboid were printed. The dimensional deviation observed from the designed dimension gave flexibility to assess the individual axes of printer for repeatability. From these data, a descriptive statistics were evaluated along with graphical representations. In addition, these data tested for Normality using Anderson-Darling test to define goodness of fit [13].

4. EXPERIMENTAL PROCEDURE

The Openware desktop 3D printer used for experimentation fabricated in College of Engineering Pune (Figure 2). With three basic shapes, cuboid, cone and hemisphere, the experiment was initiated. The designs of specimens used for evaluating optimum parameters are shown in Figure 4. These parts were modeled in CATIA and the converted .stl file. loaded into CURA, slicing software, for generation of tool path after setting of the various parameters. The layer height values in CURA are ranging from 0.08mm-0.35mm; hence the values such as 0.15, 0.25mm and 0.35mm were taken for experimentation. Further, the fill density value varies between 10%-100%. From the pilot experimentation performed, it was observed that the less than 50% fill density the printing quality was unacceptable. Hence, the levels of fill density were takes as 50%, 75% and 100%. Lastly, the levels of speed of deposition were selected as 15mm/s, 30mm/s and 45mm/s (Table 1).

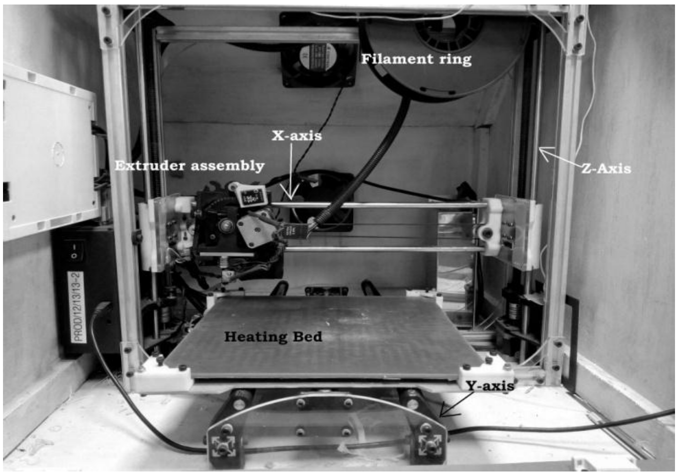

Fig - 2: Openware Desktop 3D Printer

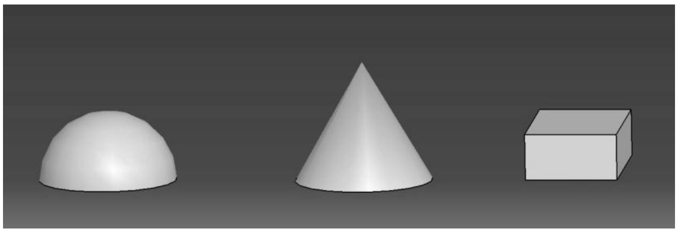

Fig - 3: Geometrical Specimens- Hemisphere, Cone, Cuboid

Table - 1: Factors and their levels for Taguchi Design

Factors	Level		
	1	2	3
Layer height (mm)	0.15	0.25	0.35
Fill density (%)	50	75	100
Speed of deposition (mm/s)	15	30	45

5. DESIGN OF EXPERIMENT-TAGUCHI TECHNIQUE

While performing experiment other printing parameters are kept constant. The selected parameters are arranged in L9 orthogonal array (Table 2). For each geometrical shaped specimen, nine experiments were performed.

Table - 2: L9 orthogonal array for given factor and levels

Expt. No.	Speed of Deposition (mm/s)	Layer Height (mm)	Fill Density (%)
1	15	0.15	50
2	15	0.25	75
3	15	0.35	100
4	30	0.15	75
5	30	0.25	100
6	30	0.35	50
7	45	0.15	100
8	45	0.25	50
9	45	0.35	75

The cuboid was placed in printing space in such a way that the length was placed parallel to X-axis, width was parallel to Y-axis and height was parallel to Z-axis. Then the cone was placed on its circular base so the hemisphere. That made responses obtained different along three axes. These printed parts were measured using Coordinate measuring machine. For each specimen the responses were calculated as the dimensional deviations.

6. EXPERIMENTAL OBSERVATIONS & ANALYSIS

6.1 Multi response Taguchi Analysis

As it was multi-response Taguchi analysis, relative weighing method was used. For each response, normalized quality loss is computed. An equal weighing factor was assigned to each normalized quality loss value. Further, for each specimen their respective total normalized quality loss function was calculated by adding multiple normalized quality loss values. Responses for cuboid were about length, width and height; for cone were about height and diameter of base; and for hemisphere, were along circular base diameter and vertical radius. The signal-noise ratios obtained for cuboids are arranged in Table 3, also the main effect plot of normalized response with the factors is shown in Figure 4.

Table - 3: Response Table for Signal to Noise Ratios of cuboid

Smaller is better			
Level	**Speed of deposition**	**Layer height**	**Fill density**
1	-5.5340	-6.4690	-5.8810
2	-5.0940	-6.1720	-5.3850
3	-6.5590	-4.5450	-5.9200
Delta	1.4650	1.9230	0.5350
Rank	**2**	**1**	**3**

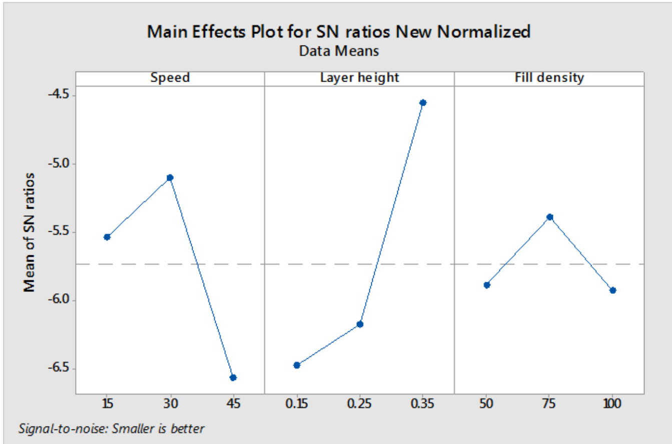

Fig - 4: Main Effect Plot of Cuboid

Similarly, for printed hemispheres and cones the SN ratio tables of normalized values are listed, along with the main effect plot against the factors (Table 4-5, Figure 5-6).

6.2 Statistical Analysis for Repeatability

For evaluation of repeatability, a cuboid was preferred as its simpler structure along XYZ axes of printer. Thirty-five cuboids were printed with the optimum parameters obtained earlier. The cuboid was positioned as shown in Figure 8 on printer bed using the slicing software. These printed cuboids were measured on CMM three times to minimize the random error in measuring. The deviations observed along three sides in printed parts were recorded. From these readings, descriptive statistics were estimated (Table 6). In these descriptive statistics shows measure of central tendency and measure of dispersion [14]. Here, the emphasis was given to measure of dispersion to evaluate the distribution type of dimensional deviation. Further, the data were tested for goodness of fit of normal distribution using Anderson-Darling Test.

Table - 4: Response table for Signal to Noise Ratios of Hemisphere

Smaller the better			
Level	**Speed of deposition**	**Layer height**	**Fill density**
1	9.1540	4.1530	4.8210
2	7.9170	6.4520	10.4870
3	1.7590	8.2250	3.5220
Delta	7.3940	4.0710	6.9650
Rank	**1**	**3**	**2**

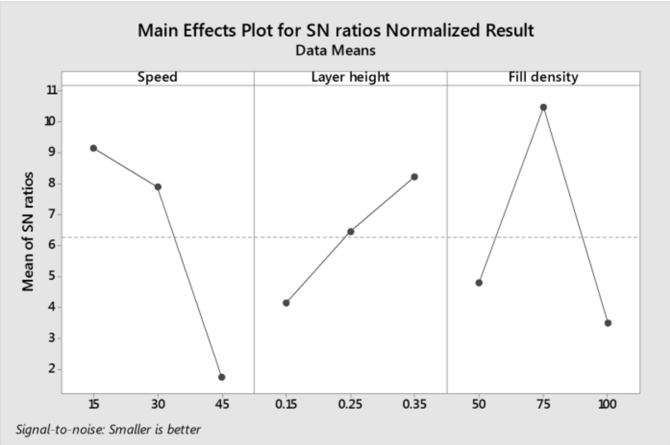

Fig - 5: Main Effect Plot of Hemisphere

Table - 5: Response table for Signal to Noise Ratios of Cone

Smaller the better			
Level	**Speed of deposition**	**Layer height**	**Fill density**
1	15.0467	7.3401	6.0390
2	10.2417	3.8855	6.2636
3	-0.5223	13.5405	12.4635
Delta	15.5690	9.6550	6.4245
Rank	**1**	**2**	**3**

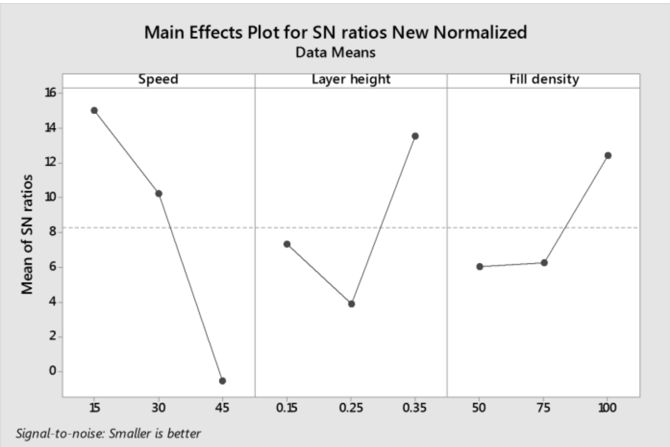

Fig - 6: Response table for Signal to Noise Ratios of Cone

Here, the critical value c and adjusted AD statistics fro given sample size; then AD statistics and p-value for each data set were calculated for inference. The graphical representation of the data is shown (Figure 8-10).

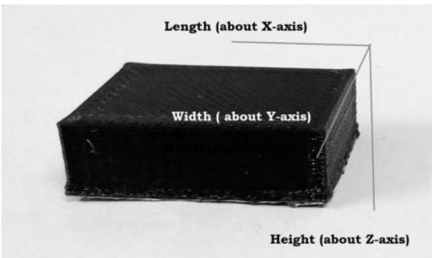

Fig - 7: Cuboid Positioned in 3D Printer

Table - 6: Descriptive statistics

	X-axis (Length)	Y-axis (Width)	Z-axis (Height)
Mean	-0.0730	-0.1257	-0.4815
Standard Error	0.0066	0.0104	0.0110
Median	0.0691	0.1278	0.4835
Mode	NA	NA	NA
Standard Deviation	0.0388	0.0613	0.0653
Sample Variance	0.0015	0.0038	0.0043
Range	0.1641	0.2270	0.2748

7. RESULTS

Assessing the data under Normal distribution was performed using Anderson-Darling Test. The expected critical value c for 35 number of sample size is 0.7337 with confidence level of 95% which is greater than adjusted AD statistic for data set of each axis (Table 7). Also the p-value for the given each axis is found to be greater than the AD statistic; the both conditions implies the data of three axes is normally distributed. The p-value and AD value calculated are listed (Table 8).

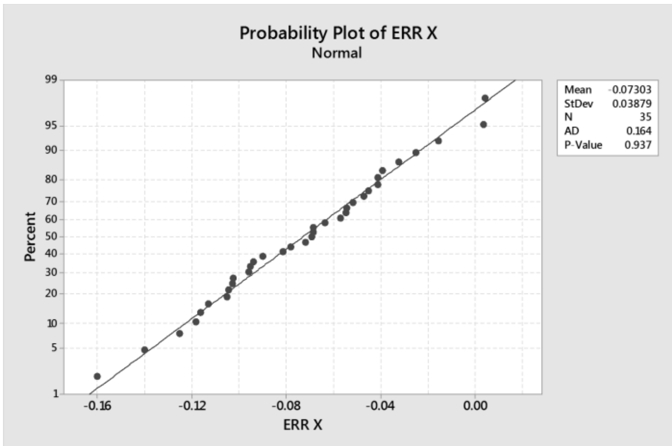

Fig - 8: Probability plot of the deviation about x-axis

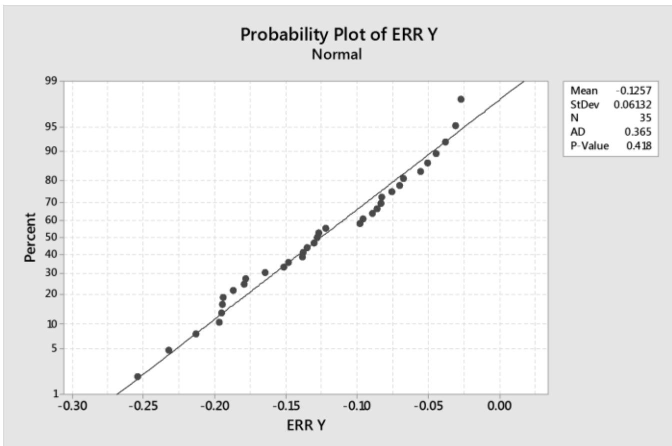

Fig - 9: Probability plot of the deviation about y-axis

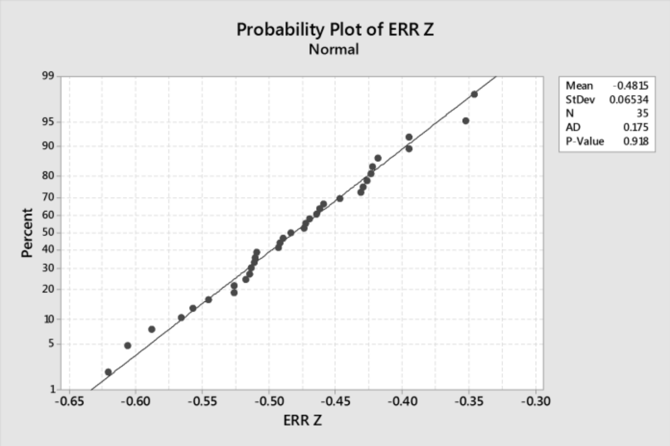

Fig - 10: Probability plot of the deviation about z-axis

The p-value represents the probability of the data showing normal distribution with a confidence level of 95% and the adjusted AD-statistics calculated value that passes critical AD test value. The descriptive statistical values of data are shown in Table 6 for printed cuboids with optimum parameters. The mean of the sample gives the average of change in dimension of printed parts. The standard deviation illustrates its spread. This obtained standard deviation reckoned as the repeatability of the Openware desktop 3D printer under normal distribution about the mean's value.

Table - 7: Adjusted AD Statistics

X-axis	Y-axis	Z-axis
0.168	0.3734	0.1790

Table - 8: AD Statistics & p-value

Normality of	p-value	AD statistics
X-axis	**0.937**	**0.164**
Y-axis	**0.418**	**0.365**
Z-axis	**0.918**	**0.175**

8. CONCLUSION AND DISCUSSION

i. The optimized parameters obtained from Taguchi analysis of three specimens- cuboid, hemisphere and cone are listed (Table 9).

Table - 9: Optimized Parameters of specimens

	SPECIMENS		
PARAMETERS	Cuboid	Hemisphere	Cone
Layer Height, *mm*	0.35	0.15	0.25
Speed of deposition, *mm/sec*	30	45	45
Fill Density, *%*	75	100	50

ii. The descriptive statistical values of data are shown in table 4.26 for 35 printed cuboids with optimum parameters. The mean of the sample gives the average of deviation found in printed parts. The standard deviation gives the spread of dimensional deviation as per the statistical inferences that are shown (Table 10).

Table - 10: Mean & SD of printed part about XYZ-axes

	X-axis	Y-axis	Z-axis
Mean	-0.0730	-0.1257	-0.4815
Standard deviation	0.0388	0.0613	0.0653

With the calculated SD, we have observed repeatability in printed parts along three axes. The obtained set of data in table 10 shows standard deviation. Thus, the repeatability of the FDM printer is estimated as **0.0388mm in X-axis, 0.0613mm in Y-axis, and 0.0653mm in Z-axis** around respective means.

Any machine is manufactured with a certain acceptable repeatability. This repeatability is affected over period due to wear and tear. The Openware FDM printer showed standard deviation in table 10 about the mean of dimensional deviation, which assumed to be reflecting the machine limitation and its depreciation over period of use. The lesser repeatability leads to lesser accuracy of printed part. For better quality of printed part, in terms of dimensional accuracy and the repeatability of printer needs studied extensively. This experimentation was also limited by the specimen size and the elementary of geometrical shapes. Thus for extensive comprehension about repeatability of printer different geometrical shapes can be studied. Moreover, the accuracy of the printer in terms of quality of printed parts needs to be discussed.

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