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Dimensional and geometrical performance assessment of two FDM printers using a benchmark artifact

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Abstract
Additive Manufacturing (AM) is a promising process allowing the generation of complex geometries in near net shape. Standards are under development in a joint effort between ASTM and ISO to facilitate the use of AM processes in the industry. However, some areas of interest, for assessing dimensional and geometrical performances of AM printers, are still not covered.
In this article, dimensional and geometrical performances of two Fused Deposition Modelling (FDM) printers with Cartesian architecture (Ultimaker S3 and Intamsys FUNMAT HT) are compared using an original benchmark artifact design. Five parts were printed on each printer in ABS. Five other parts were also produced with the Ultimaker S3 in PLA to show the influence of material choice on the printer's dimensional and geometrical performances. Intervals of tolerances (IT) were determined using the ISO 286-1 method.
Both machines can lead to an IT between 10 and 15 depending on the size of the measured features. In terms of geometrical deviations, coaxiality was the highest deviation observed on both printers with average values between 0.376 mm and 0.679 mm for the Ultimaker S3 in PLA and ABS, while the FUNMAT HT can reach values of 0.759 mm in ABS.
The FUNMAT HT exhibits a better homogeneity of computed IT according to its X and Y axes, while lower performances according to the Z axis were observed compared to the Ultimaker S3. In terms of geometrical performances, the FUNMAT HT has a lower ability than the Ultimaker S3 to reproduce features according to the Z axis. Except for this category, other geometrical features were more accurately reproduced with the Intamsys printer on a global level. The material choice also has a slight influence both on the dimensional and geometrical performances of the Ultimaker S3.

Additive manufacturing, benchmarking, dimensional accuracy, FDM, geometrical accuracy, IT grades, performance evaluation.

1. Introduction

Additive Manufacturing processes pave the way to new methods in the design and fabrication of parts [1]. A wide variety of machines already exists and the ISO 52900 classified their processes into seven categories [2]. However, AM printers still do not meet the surface topography, dimensional and geometrical accuracy of conventional processes, such as machining [3]. This limitation hampers the wide use of AM processes in very demanding sectors, such as the aeronautical or medical industry [3–5]. Indeed, mastering the dimensional and geometrical tolerances of parts is required to use them (e.g. in assembly). The relative youth of the AM processes deprives them also of well established standards, especially to assess the achievable performances and tolerances of AM printers [4,6]. The measurement and testing of parts called Geometrical Benchmark Test Artifact (GBTA) is well adapted in an industrial context (limited measuring means) [4]. Guidelines for the design of these parts were established recently by the ISO 52902 standard [7]. Nevertheless, no standardised method currently exists to assess the performances and tolerances of AM printers. Moreover, recommendations given by the ISO 52902 standard result in long printing time and do not cover the method to directly link the observed deviations to the printer's dimensional and geometrical performances [8].

This article assesses the performances of two commercial AM printers exhibiting Cartesian architectures: the Ultimaker S3 from Ultimaker and FUNMAT HT from Intamsys. Dimensional and geometrical performances were evaluated using an adapted version of a previously developed benchmark artifact [8].

2. Methodology

2.1 Comparing printers

The printers Ultimaker S3 from Ultimaker and FUNMAT HT from Intamsys were compared in this study. Their AM working principle according to ISO 52900 [2] is material extrusion (Fused Deposition Modelling, FDM) and they both exhibit a Cartesian architecture. Ultimaker S3 was fed with a 2.85 mm diameter filament, while the FUNMAT HT used a 1.75 mm filament. Both were fitted with a 0.4 mm diameter nozzle and exhibit a closed chamber, a glass build platform and a parallelepipedic building volume. The dimensions of the latter reached 230 mm x 190 mm x 200 mm (X, Y and Z axes) in the case of the Ultimaker S3 and 243 mm x 243 mm x 260 mm (X, Y and Z axes) for the FUNMAT HT. The X and Y axes positioning resolution both reach 6.9 µm according to the Ultimaker and 25 µm for the FUNMAT HT. The Z axis positioning resolution reaches 2.5 µm for both printers. The slicing of the CAD file is ensured by Cura for the Ultimaker and by IntamSuite for the FUNMAT HT.

2.2 Manufacturing of parts

A previously published benchmark design [8] was adapted to cover the available build platform area of the Ultimaker S3 and the FUNMAT HT as much as possible. Figure 1 gives the final part design for the Ultimaker S3 and the FUNMAT HT. Consequently, the Ultimaker S3 part exhibits global dimensions of 174 mm x 174 mm x 25 mm (X, Y and Z axes), while the FUNMAT HT has global dimensions of 227 mm x 227 mm x 25 mm (X, Y and Z axes). Ten parts were produced on the Ultimaker S3 with standard filaments from Ultimaker: five in PLA and five in ABS. Five other parts were produced on the FUNMAT HT in ABS using a filament from Verbatim. The layer thickness was set at 0.1 mm for each printer, while the density of infill stood at 20% in the cubic pattern strategy.

The PLA parts were printed using a 215°C printing temperature and 60°C build platform temperature. The ABS parts produced on the Ultimaker S3 were manufactured with a printing temperature of 240°C and a build platform temperature of 85°C. The printing temperature of the FUNMAT HT parts stood at 255°C, while the build platform temperature was also set at 85°C. The Ultimaker S3 PLA part took about 24 hours to be printed, while the ABS part required 29 hours. The printing time of the FUNMAT HT part took about 54 hours. Finally, the parts were separated from the build platform before their measurement. No post treatment was performed.

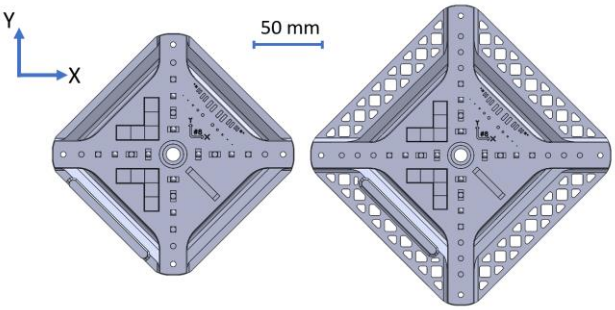

Figure 1. Ultimaker S3 (left) and FUNMAT HT (right) artifact design.

2.3 Dimensional and geometrical evaluation of the parts

The dimensional and geometrical evaluation of the parts was performed using an LH54 Coordinate Measuring Machine (CMM) from Wenzel with the 2021 version of the Metrosoft QUARTIS Measurement Software to acquire and process data. This configuration is completed by a PH10M head and a 1.5 mm diameter spherical probe from Renishaw. The probe diameter was selected to avoid the influence of the staircase effect on the measurements. All cylinders were measured by taking eight points distributed over two circles, while hemispheres were measured using nine points distributed over three circles. Six points were used to probe the planes in general except for the top surface which required 40 points in the case of the Ultimaker S3 parts and 47 for the FUNMAT HT parts. Small features heights were characterized using one point. 683 and 771 points were probed, respectively on each Ultimaker S3 and FUNMAT HT part. The number of probed points allows to give sufficient precision to the measurements while ensuring a fast measuring: about 30 minutes for each Ultimaker S3 part and 45 minutes for the FUNMAT, as required in an industrial context with limited time and measurement means.

The dimensional evaluation was conducted using the ISO 286-1 [9] method to determine the tolerance intervals (IT) achievable by each printer. Although this standard is dedicated to subtractive processes, other authors successfully applied it to AM printers [10]. 395 dimensional measurements were performed on each Ultimaker S3 part, 476 for the FUNMAT HT.

The geometrical evaluation was performed by computing the angularity, coaxiality, cylindricity, position, flatness, parallelism, perpendicularity, profile and straightness deviations. The total geometrical measurement number stands at 483 (Ultimaker S3) and 564 (FUNMAT) on each printed part.

3. Results and discussion

3.1 Dimensional analysis

Table 1 gives the average achievable IT for each dimensional size range of the ISO 286-1 [9]. The results were classified over the different printers cartesian axes (X, Y and Z). A dedicated category called “Other” takes into account the measurements according to more than one axis (e.g. diameter dimension of a Z axis cylinder relies on axes X and Y together). The smaller the IT, the more accurate the printer. The best results (IT 10 and 11) are coloured in blue.

The parts manufactured in PLA and ABS on the Ultimaker S3 allowed to see the influence of the material chosen on the printer dimensional performances. The parts in ABS and PLA exhibited the same general tendency: higher IT were achieved for dimensions according to the Z axis or according to a combination of axes (Other). This is quite logical since a combination of axes’ positions will result in the combination of their own positional errors. However, below the 18 mm to 30 mm category, the performances of the ABS parts were lower than the PLA parts. Between 18 mm and 30 mm and between 80 mm and 120 mm, the results were quite the same for the ABS and PLA parts of the Ultimaker S3. After 120 mm, the difference between the PLA and ABS parts was slightly stronger with lower performances according to the X axis for each material.

The same global tendency was observed for the FUNMAT HT, with the worse results coming from the machine’s Z axis. However, compared to the Ultimaker S3 parts manufactured in ABS, the FUNMAT HT showed better homogeneity between the X and Y axes. Nevertheless, higher IT were reached for dimensions between 10 mm and 30 mm according to the Z axis. This can be explained by the locations of the measured features. Indeed, they are placed on the top of the part surface which exhibits a higher area than the Ultimaker S3. This can lead to a higher risk of permanent deformations of the part and, consequently, lower performances.

Table 2 gives the ratios (in %) between the standard deviation and the mean of the number of tolerance units for each couple of printer-material. This number of tolerance units is defined in ISO 286-1 and allows to compute the IT. Each IT corresponds to a given number of tolerance unit thresholds [9–11]. The results were distributed over the different printer axes. Again, these ratios confirm that the FUNMAT HT printer exhibits more homogeneous performances for its X and Y axes compared to the Ultimaker S3. Indeed, with respect to its X axis, the Ultimaker S3 showed lower disparities of measurements (9%) than the FUNMAT HT (13%). However, the Y axis results of the Ultimaker S3 reached 18% in PLA and 27% in ABS, while the FUNMAT HT printer only exhibited 12%. Repeatability of positioning for the Ultimaker S3 Y axis was then lower compared to the X axis. The Z axis of both printers using ABS showed higher disparities of measurements (ratios of 19% and 31% respectively).

No direct conclusion can be drawn on the quality of the printers axes. Indeed, linking a deviation to its cause(s) can be difficult, almost impossible, using benchmark artifact [3,12]. However, reasonable assumptions can be made to explain the observed difference of performances. Both printers exhibit a Cartesian architecture: their X and Y axes are serial, while their Z axis is independent. The latter is actuated by a ball screw, while the X and Y axes are actuated using belts. These differences of design can explain the lower performances reached by the Z axis on both printers and the possible interaction between their X and Y axes since they are linked.

Table 1. Average achievable IT for the Ultimaker S3 in PLA, ABS and the FUNMAT HT in ABS (best results highlighted in blue).

	Ultimaker S3 PLA				Ultimaker S3 ABS				FUNMAT HT ABS			
ISO 286-1 size ranges/mm	X	Y	Z	Other	X	Y	Z	Other	X	Y	Z	Other
1-3	11	11	12	10	11	11	12	11	12	13	13	12
3-6	12	13	13	13	13	14	13	13	12	12	14	13
6-10	12	12	13	15	13	13	13	15	11	11	13	14
10-18	10	10	12	10	10	11	12	11	11	11	15	12
18-30	12	12	14	10	12	12	14	11	11	11	15	12
30-50	12	12	/	/	12	12	/	/	12	12	/	/
50-80	12	13	/	/	13	12	/	/	12	12	/	/
80-120	13	13	/	13	13	13	/	12	13	13	/	14
120-180	12	11	/	/	13	11	/	/	13	13	/	/
180-250	15	14	/	/	14	13	/	/	14	14	/	/

Table 2. Ratios of the standard deviations and the average number of tolerance units according to ISO 286-1 [9].

	X/%	Y/%	Z/%	Other/%
Ultimaker S3 PLA	9	18	24	18
Ultimaker S3 ABS	8	27	19	29
FUNMAT HT ABS	13	12	31	20

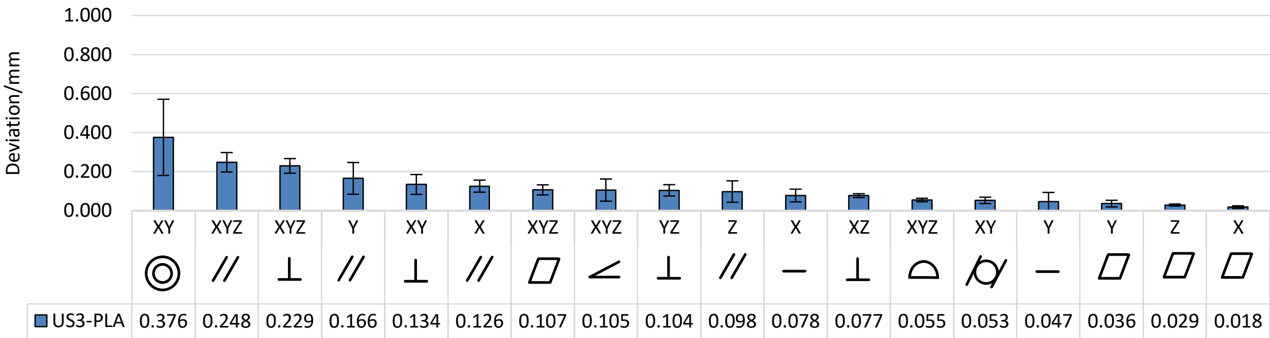

Figure 2. Ultimaker S3 PLA geometrical performances.

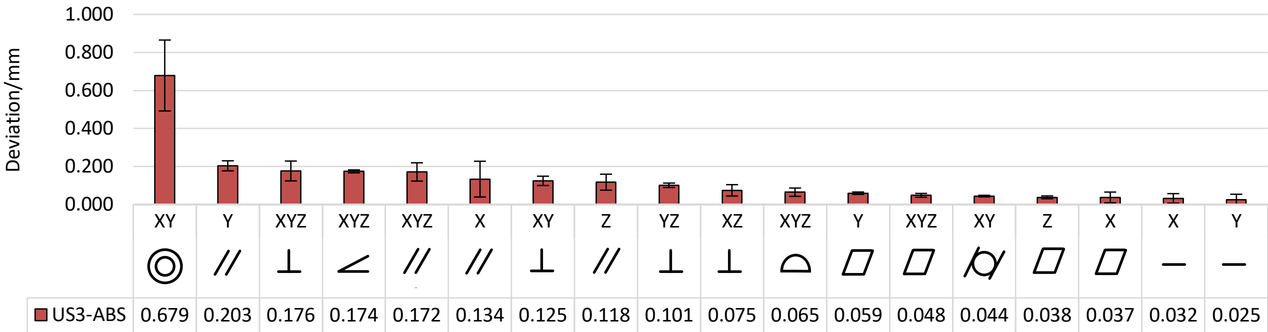

Figure 3. Ultimaker S3 ABS geometrical performances.

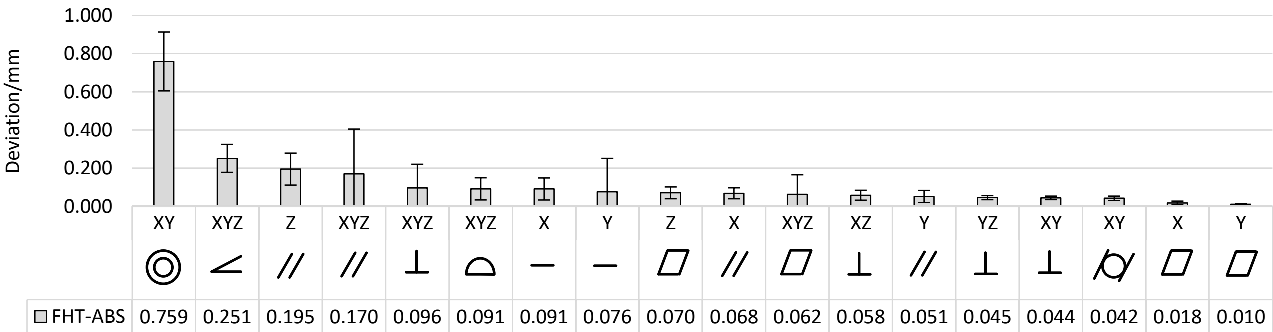

Figure 4. FUNMAT HT ABS geometrical performances.

3.2 Geometrical analysis

Figures 2, 3 and 4 give the geometrical performances of the Ultimaker S3 in PLA, in ABS and of the FUNMAT HT in ABS. Error bars of 2σ are displayed to show the disparity of measurements, while the same vertical axis scale was chosen to ease the comparisons. These graphs emphasise the highest observed geometrical deviations. Indeed, coaxiality is the common highest deviation for both printers and materials. However, the FUNMAT HT exhibited higher results with mean values of deviation reaching 0.759 mm, while the Ultimaker S3 reached 0.376 mm and 0.679 mm, in PLA and ABS respectively. Parallelism and perpendicularity of planes according to more than one axes came second and third in the case of the Ultimaker S3 in PLA, with average values reaching 0.248 mm and 0.229 mm respectively. Since these characteristics involve several axes of the machine, they suffered from a combination of their errors. In the case of the Ultimaker S3 in ABS, the second highest geometrical deviation was the parallelism of planes normal to the Y axis. The associated deviation reached 0.203 mm. Perpendicularity of planes according to more than one of the machine axes came in third with values of 0.176 mm. The FUNMAT HT printer had a different behaviour compared to the Ultimaker S3. Angularity of planes involving different machine axes and parallelism of planes with a normal parallel to the Z axis were the second and third highest deviations with values of 0.251 mm and 0.195 mm respectively.

As shown in the dimensional analysis, the FUNMAT HT had more difficulty in reproducing features according to the Z axis. Indeed, while the FUNMAT HT reached values of 0.195 mm for the parallelism of horizontal planes (normal to the machine's Z-axis), the Ultimaker S3 exhibited values of 0.098 mm and 0.118 mm in PLA and ABS respectively. The average flatness of planes with a normal parallel to the Z axis was also higher for the FUNMAT HT with values of 0.070 mm, while the Ultimaker S3 exhibited values of 0.029 mm (PLA) and 0.038 mm (ABS). However, except for the features involving the Z axis or more than one of the machine's axes, the FUNMAT HT exhibited better geometrical performances than the Ultimaker S3 while ensuring the flatness, parallelism and perpendicularity of planes. Cylindricity is in the same order of magnitude for both printers. Nevertheless, the FUNMAT HT was less efficient to reproduce the hemispheres, slope and alignment of cylinders along the X and Y axes compared to the Ultimaker S3.

General conclusions can be drawn for the Ultimaker S3. Indeed, almost all geometrical deviations were in the same order of magnitude for parts in PLA and ABS except for the angularity, flatness and straightness of features along the X axis. Features involving several axes of the printer also exhibited different results depending on the material chosen to build the part. The material in which the part is manufactured has then a slight influence on some of the geometrical deviations observed.

4. Summary

The dimensional and geometrical performances of two AM printers (Ultimaker S3 and FUNMAT HT) were assessed using an adapted version of a previously developed benchmark artifact [8]. The influence of the material choice on the dimensional and geometrical performances was also investigated. Both machines achieved an IT between 10 and 15. Better homogeneity of IT was observed for the FUNMAT HT in ABS according to its X and Y axes, while lower performances were achieved according to its Z axis. Coaxiality was the highest geometrical deviation observed, with average values between 0.376 mm and 0.679 mm for the Ultimaker S3 in PLA and ABS, while the FUNMAT HT reached values of 0.759 mm in ABS.

5. Conclusions

The following are the main results of this study:

- Depending on the size range of the measured features, both printers achieved IT between 10 and 15.
- Along the X and Y axes, the dimensional performances of the FUNMAT HT exhibited higher homogeneity, while its features aligned with the Z axis were less accurately reproduced than with the Ultimaker S3.
- The higher area of contact of the FUNMAT HT artifact with the build platform, the higher the influence on the dimensional performances of the printer along its Z axis due to a higher risk of permanent deformations.
- Repeatability of positioning of the Ultimaker S3 Y axis is lower than for the X axis.
- The FUNMAT HT geometrical performances were lower for features according to Z axis or a combination of axes. Except for this category, other geometrical features were more accurately reproduced on a global scale than with the Ultimaker S3.
- The material choice may have a slight influence both on the dimensional and geometrical performances of the Ultimaker S3 printer.

6. Future work

A deeper analysis of the influence of the material choice on the dimensional and geometrical performances could be studied for this work.

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