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# Comparative Study for the Metrological Characterization of Additive Manufacturing artefacts

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**Abstract** Additive Manufacturing (AM), also known as 3D printing, has been introduced since mid 90' but it begins to have a broader use along last ten years. The first uses of AM process were for rapid prototyping or for 3D sample illustration due to the weak performances of mechanical characteristics of the materials available. However, even if this technology can provide answers for mechanical requirements, it will be largely used only if geometrical and dimensional characteristics of generated parts are also at the required level. In this context, it is necessary to investigate and identify any common dimensional and/or geometrical specifications of the parts generated by AM process. Highlighting singularity of AM systems should be based on the fabrication and measurement of standardized artefacts. Even if those test parts allow assessing some important characteristics of AM systems, there are still some challenges to characterize the capacity of generating freeform surfaces and features. In the literature, none of existing test parts are proposing those kind of features even if the generation of free-form surfaces is a significant benefit of AM systems. In this context, the aim of this paper is to provide a metrological comparative study on the capacity of an AM system to generate freeform parts based on an artefact.

**Keywords:** Additive manufacturing; measurement artefact; free form characterization; dimensional metrology

## 1 Introduction

Additive Manufacturing (AM) is the process used to build a physical part layer by layer directly from a 3D model [1]. The first uses of AM process were for rapid

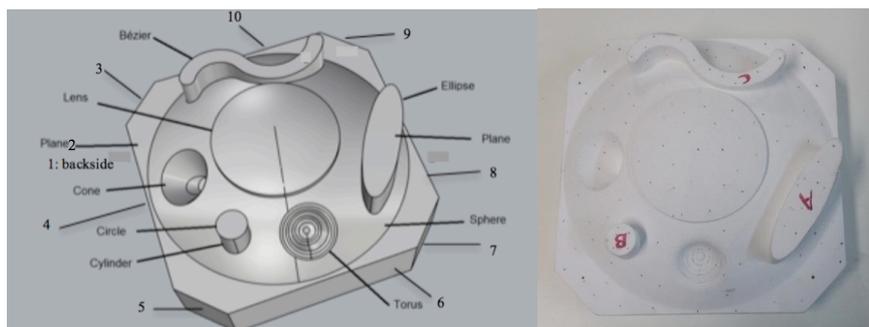
prototyping and 3D sample [2] illustration due to the weak performances of mechanical characteristics of the materials available. Recent development and more particularity with the use of metal and ceramics powder, broadens considerably the field of use of AM. It is now reasonable to considerate the use of parts fabricated by this process in such industries as aerospace or automotive. This technology will be largely used only if geometrical and dimensional characteristics of generated parts were also at the required level [3]. In this context, we believe that an investigation is necessary to identify the common dimensional and geometrical specifications of the parts generated by AM process. The knowledge of the capacity of AM process generating parts with dimensional and/or geometrical requirements could allow to take into the account a correction factor at the design step. By this way printed parts specifications will increase. This study can be based on the design of an artefact. The artefact should be representative of the complex forms and geometry that can be built by an AM system but they must also, reflect metrology characterizations.

In the literature, only few studies focus on these topics. Moylan & all from NIST, start their work by noting that even if different test parts have been introduced by the past, there are no any current standard parts for AM systems [4]. They summarized the existing parts by studying the important features and characteristics found on those parts and propose a new artefact intended for standardization. The part is composed by various canonical geometries: staircases, holes, pins, fine pins and holes, negative and positive cubes, vertical surfaces, ramp and cylinders. Yang & all, proposed an assessment of the design efficiency of the test artefact introduced by NIST team and based on their analysis they provided a re-designed artefact [5]. They analysed in more details seven characteristics: straightness, parallelism, perpendicularity, roundness, concentricity, true position for z plane and true position for pin. They concluded that some geometrical characteristics are redundant and some dimensions have relevant effects on the parts build. Based on their conclusion, they introduced a new part using the same kind of geometrical forms but they provided different orientation and features dimensions in order to analyse the capacity of the AM system to generate the same features in different sizes and directions. Islam & all, [6] provide an experimental investigation to quantify the dimensional error of powder-blinder 3D printer. They use a test part defined by superposition of concentric cylinders with descendant radii from down to top and a central cylindrical hole.

In this context, we provide an experimental comparative study on the capacity of an AM system to generate freeform parts. A complex geometry artefact was designed and produced and in order to provide an independent study, three different measuring instruments were used to characterize the dimensions and geometry of the test part. Conclusions of this study and future works are also highlighted.

## 2 Artefact design and experimental context

In the literature, many artefacts have been used to study AM systems, but they are only designed with regular surfaces [4,5,6]. In this context we introduce a new artefact designed with freeform and regular surfaces. The *NPL* (National Physical Laboratory-UK) provide a freeform artefact called "FreeForm Reference Standard". But it has been designed to aid the assessment of contactless coordinate measurement system such as laser scanner [7,8] and not to assess the dimensional and geometrical characteristics of parts manufactured by AM systems. The *NPL* artefact is defined by a single part built by blending several geometrical forms. The analysis of this part let us conclude that it is not enough appropriated to characterize an AM system. However, some of its forms can be used. Based on this conclusion, a new artefact is designed with the following regular geometries: plane; cylinder; sphere; extruded ellipse; cone and torus; and an axisymmetric aspherical shape (lens) and a Bézier surface for freeform geometries. A Computer-Aided Design (CAD) model was generated using CATIA V5 software, with basis dimensions of 240 x 240 mm. Figure 1 presents the designed artefact with respective geometries.

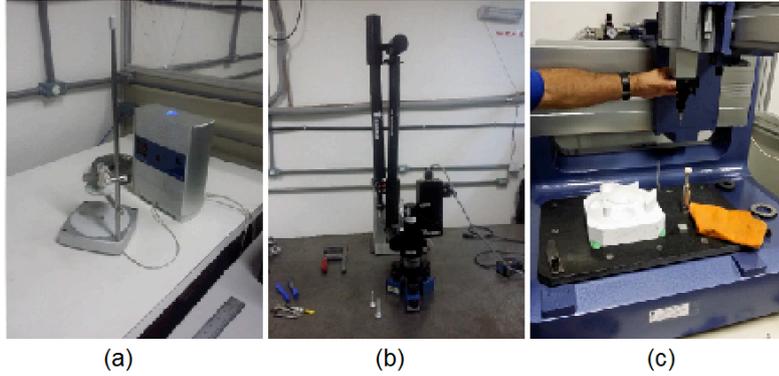


**Fig. 1.** Free-form artefact designed to evaluate the AM system.

The part has been manufactured with a ZPrinter 450 from Zcorporation, a powder-binder process machine [9] with part tolerances of  $\pm 1\%$  or  $\pm 130 \mu\text{m}$  according to the manufacturer [10]. The CAD model was implemented in this machine and the artefact was produced with zp150 (gypsum) material.

The artefact was measured with three different instruments, a Cantilever type Coordinate Measuring Machine (CMM), an Articulated Arm CMM (AACMM) and a laser scanner. The Cantilever CMM is a Mitutoyo and has a work volume of 300 x 400 x 500 mm, with a standard combined uncertainty of 0.003 mm. The AACMM is a Romer arm and has a spherical work volume of 2.5 m in diameter, with standard combined uncertainty of 0.03 mm. The laser scanner is a NextEngine system and has an accuracy of 0.26 mm. Figure 2 presents the measuring instruments. As a part of the study process, the measurement system can introduce variations and

influences the study's conclusion. This is why we used three different systems to take into account this potential variation source that is not related to AM system.



**Fig. 2.** Measuring instruments: a) Laser scanner ; b) Articulated Arm CMM ; c) Cantilver type CMM.

Each characteristic has been measured five times in order to compute the average, standard deviation, and other statistical characteristics. Two-dimensional characteristics have been measured for the regular surfaces: diameters and height (distance between two nominal surfaces), as well as flatness, parallelism and perpendicularity between situation features. For the freeform surfaces, the deviation of the geometries in respect to the theoretical CAD model has been measured. A graphical analysis with the means and the error bar, determined with t-Student distribution and 95% probability, complete the study.

### 3 Results and discussion

#### 3.1 Dimension characteristics of regular surfaces

For the measurement of regular surfaces, CMM and AACMM with two different contact probes have been used: a point contact stylus probe with 0mm ball diameter (AACMM<sub>0</sub>) and a 6mm ball diameter stylus (AACMM<sub>6</sub>). Table 1 presents the data analyses resulting from the measurements: deviation (d), standard deviation (s) and the standard deviation of the mean (sm<sub>95</sub>).

$$sm_{95} = (t.s)/\sqrt{n} \quad (1)$$

with  $t = 2,776$  : the t Student parameter for 95% and  $n = 5$ : the sample size

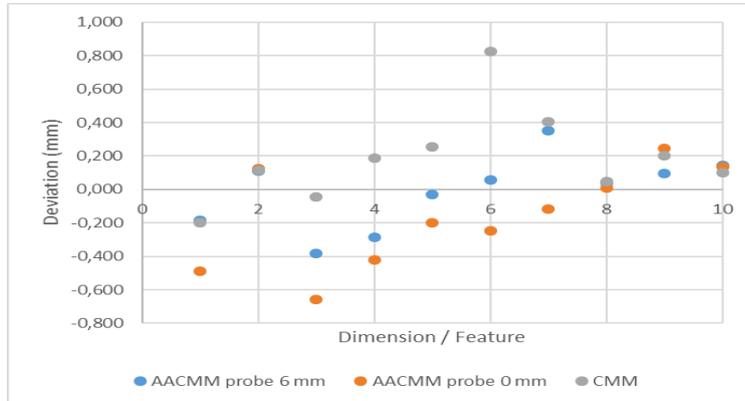
$sm_{95}$  is used to present the standard deviation of the mean associating 95% probability to the result.

In table 1, " $D$ " means diameter; " $H$ " means the height of the given feature and " $L$ " means the distance between two given plane surfaces.

**Table 1.** Data analyse for regular surfaces measurements in mm.

	AACMM =6mm			AACMM d=0			CM		
	d	s	$SM_{95}$	d	s	$SM_{95}$	d	s	$SM_{95}$
1 D cylinder	-0.186	0.048	0.060	-0.490	0.029	0.036	-0.198	0.030	0.038
2 H cylinder	0.112	0.015	0.018	0.124	0.053	0.065	0.114	0.006	0.007
3 D sphere	-0.382	0.398	0.494	-0.656	0.081	0.101	-0.044	0.097	0.121
4 L plane 5-9	-0.284	0.015	0.019	-0.422	0.019	0.024	0.188	0.356	0.441
5 L plane 3-7	-0.028	0.013	0.016	-0.198	0.020	0.025	0.254	0.465	0.578
6 L plane 6-10	0.058	0.011	0.014	-0.246	0.019	0.023	0.828	0.285	0.354
7 L plane 4-8	0.352	0.086	0.107	-0.118	0.151	0.188	0.407	0.104	0.129
8 L plane 1-2	0.040	0.012	0.015	0.010	0.010	0.012	0.048	0.012	0.015
9 H Bézier	0.098	0.048	0.059	0.244	0.048	0.060	0.203	0.019	0.024
10 H ellipse	0.146	0.050	0.062	0.136	0.059	0.073	0.100	0.096	0.119

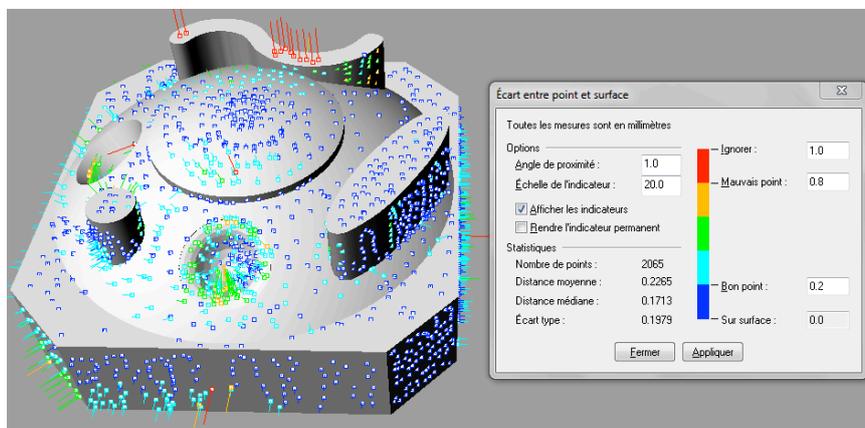
Figure 3 presents a graphical analyse of the deviation value summarized in table 1. For instance, the fourth column of x-axis of figure 3 represents the fourth line of table 1, namely the deviation " $d$ " computed on the data for each measurement system. This graphical analyse shows that for half of the features the deviation values are similar regardless of the measurement system (1, 2 8, 9 and 10). For the second half the values depend on the measurement system used, but we can notice a constant variation for all the systems: the CMM gives a positive deviation, the AACMM0 a negative deviation and the AACMM6 has an approximately constant gap. The values summarized in table 1 do not allow concluding on a general trend of oversizing or undersized. A complementary study should be provided to explain this variation.



**Fig. 3.** Graphical analyse of the deviation presented in Table 1.

### 3.2 Free-form surfaces and features

For the measurement of freeform surfaces, CMM, scanner and AACMM<sub>0</sub> (The AACMM<sub>6</sub> does not allow free-form measurement) have been used. All the features in this paragraph have been measured as cloud of points without any geometry association process or criteria. In a second step, the set of points have been processed in Rhinoceros software [11] as illustrated in figure 4.



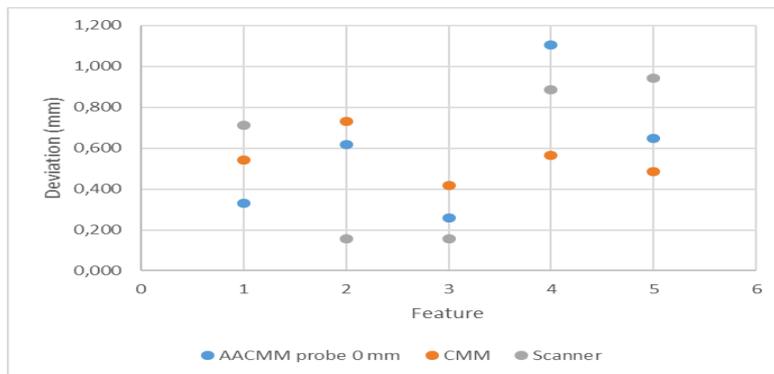
**Fig. 4.** Analyses of deviations between data points and CAD model in Rhinoceros.

Table 2 presents the deviations of points to the CAD model in the same terms than table 1:  $d$ ,  $s$  and  $sm_{95}$ .

**Table 2.** Data analyse of freeform geometries measurement in mm.

		AACMMd=0			CMM			Scanner		
		d	s	sm <sub>95</sub>	d	s	sm <sub>95</sub>	d	s	sm <sub>95</sub>
1	Bézier	0.331	0.224	0.278	0.541	0.427	0.530	0.714	0.619	0.768
2	Torus	0.617	0.434	0.539	0.731	0.500	0.621	0.155	0.102	0.127
3	Lens	0.258	0.135	0.168	0.416	0.363	0.451	0.158	0.115	0.143
4	Ellipse	1.107	0.492	0.611	0.563	0.380	0.472	0.885	0.638	0.792
5	Cone	0.649	0.459	0.570	0.487	0.360	0.447	0.944	0.519	0.644

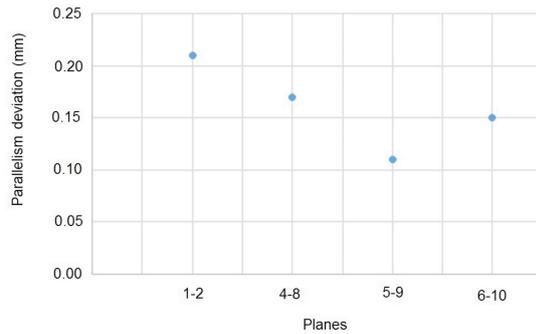
Figure 5 presents a graphical analyse of the deviation for each line of table 2. As shown in figure 5, for freeform features, the values are more scattered but the analysis shows that all the deviations are positive. In other terms, for those freeform features a volumetric expansion has been identified. This expansion is coherent regarding the literature. Especially if we take into account the material used [12]. This conclusion may be related to some previous work [6] although in that case it was on dimensional errors on regular forms. Even if this seems to be in opposition with previous section, as the computation methods used in both sections are different it is not possible to conclude.

**Fig. 5.** Graphical analyse of the deviation summarized in Table 2.

Using the same method of computation and study the influence of size variation on the deviation for a given feature could bring an answer. However, it seems reasonable to conclude that in this case a correction parameter could be used in the CAD model to generate a manufactured part in concordance with the nominal dimensional requirements.

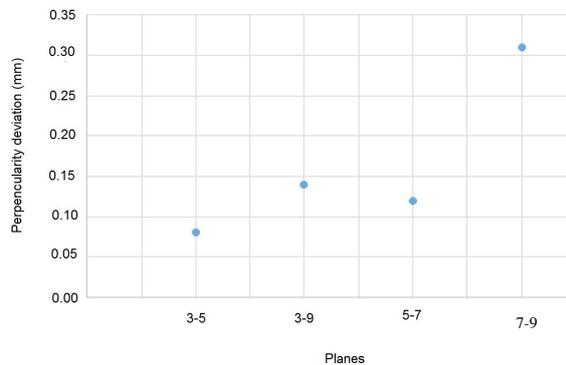
### 3.3 Geometric deviations

Figure 6 shows the parallelism deviation, in mm, between planes 1 and 2, planes 4 and 8, planes 6 and 10 (Please refer to figure 1 for surface numeration).



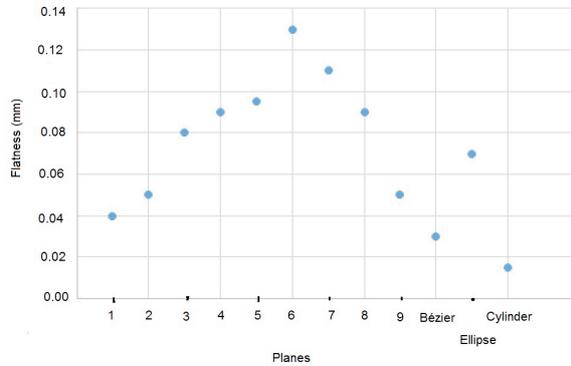
**Fig. 6.** Parallelism deviation.

Figure 7 shows the perpendicularity deviation, in mm, between planes 3 and 5, planes 3 and 9, planes 5 and 7, planes 5 and 9. (Please refer to figure 1 for surface numeration).



**Fig. 7.** Perpendicularity deviation.

Figure 8 shows the flatness of the plane surfaces of the artefact. Note that "*Bézier, Ellipse and Cylinder*", are referred to the planes at the top of the mentioned features: the top plane of the Bézier feature; the top plane of the ellipse feature; the top plane of the cylinder.



**Fig. 8.** Features Flatness.

According to figure 6, parallelism deviations in all major directions are similar even if the maximum deviation (between planes 1 and 2: 0,21 mm) is twice the minimum deviation (between planes 5 and 9: 0,11 mm). At this stage no explanation can be given.

For perpendicularity, we can also observe (figure 7) a similar deviation in all major directions except between plane 5 and 9, where the deviation is almost 3 times higher than in other cases.

For the flatness, according to figure 8, we can conclude that in the major cases, when the planes have the same orientation, the flatness is similar: planes 1 and 2; planes 3 and 7; planes 4 and 8. When the planes have different orientations, the flatness is also different for instance in between planes 6 and 9. We can assume that orientation of the generated surface in the AM manufacturing space has an influence on the flatness of the generated parts.

## 4 Conclusions

There is only few works on the dimensional accuracy assessment of AM systems to manufacture freeform shapes while the generation of those surfaces is one of the major advantages of AM process. To address this weakness, we developed a new geometric artefact designed to characterize dimensional and geometrical capabilities of an AM system to generate freeform parts. The artefact has been built using a powder-binder AM system and a comparative measurement study has been performed. Based on the measurements, we can conclude that the volumetric expansion on free-form features has a considerable impact on the geometrical characteristics. As a perspective of this work, it will be interesting to study the possibility to introduce a correction factor here. A second conclusion can be drawn regarding the variation of the orientation and its influence on the flatness

while the parallelism and perpendicularity seems independent of orientation. Future research efforts will concentrate on establishing more knowledge about correction parameters when considering features of size and the relative positioning of the surfaces regarding the build direction. Another issue is the measurement of internal features using CT scanner.

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