Adaptive Benchmarking Design for Additive Manufacturing Processes

Abstract
Standards enabling the objective tolerancing and evaluation of dimensional and geometrical performances of additive manufacturing (AM) printers are still missing. The design, printing and measurements of geometrical benchmark test artefacts (GBTA) is the current solution proposed in literature. However, the current GBTA with fixed dimensions cannot cover most of the available printing area of printers with large building platform dimensions. This article proposes to solve this problem by developing an adaptive GBTA design whose main dimensions can be adapted to any common 3D printer. Moreover, an innovative design is implemented to decrease the risk of warping. The adaptive GBTA will then be used to characterise the performances of two different architecture material extrusion printers (Ultimaker 2+ and Pollen AM Series MC). Dimensional and geometrical accuracy, as well as top surface topography, were evaluated. The Ultimaker printer could reproduce features with maximum deviations below the tolerance interval (IT) 13 of the ISO 286-1, while the Pollen machine achieved a higher IT of 15 or 16. The highest geometrical deviations were observed for the coaxiality of cylinders oriented along the build direction (Ultimaker: 0.250 mm and Pollen: 0.497 mm). Top surface topography exhibited higher Ra values for Pollen (13.7 µm) than for Ultimaker 2+ (4.9 µm). The performances of the Pollen printer were lower than the Ultimaker machine in terms of surface topography, dimensional and geometrical accuracy. The proposed adaptive GBTA design covers most of the printing areas exhibited by Pollen and Ultimaker printers and offers flexibility to test other printers even with larger or smaller dimensions.

1 - Introduction

Additive Manufacturing (AM) is an expanding field, and has been since its introduction for commercial use in the 1980s with the first stereolithography machine [1]. Since then, several processes have been developed based on seven different working principles according to ISO/ASTM 52900:2015 [2]. They enable the generation of complex geometrical parts for a large panel of materials comprising polymers, ceramics and metals [3,4]. The variety of processes, and the need to use AM in the industry to produce accurate parts of a constant quality, justifies the need for tools and procedures to evaluate the dimensional and geometrical performances of AM printers [1].

AM processes are much more recent than conventional forming processes, such as machining [5,6]. They suffer from lack of standards, especially with regard to dimensional and geometrical performance assessment. As opposed to machining, there are currently no dimensional or geometrical tolerance values dedicated to AM processes [5,6].

Two approaches exist to assess the performances of a 3D printing machine: on-machine (direct) metrology and off-line (indirect) metrology [5–7]. On-machine metrology requires the observation of the part during manufacturing or the measurement of process-related variables [5–7]. Off-line metrology consists of taking measurements of a part, called transfer, test or benchmark artefacts, after manufacturing [1,5–7]. The latter is a less expensive method and is easier to implement within an industrial context [7].

Three families of benchmark artefacts exist following their purpose [8]. The mechanical artefacts objectively establish the mechanical performances (*e.g.* tensile strength) of printed parts [6] by using a design based on standards used in mechanical testing methods [1] such as ASTM D638-14 [9]. The process artefacts allow process optimisation [1,6]. The geometrical benchmark test artefacts (GBTA) enable the determination of the minimum dimensional and geometrical tolerances achievable by a printer, the assessment of its accuracy, spatial repeatability (ability to reproduce a given geometry at different locations of the build volume within a given tolerance [7]) and its surface topography [1,6]. The use of GBTA is, therefore, the best way to objectively assess the dimensional and geometrical performances of AM printers.
Since 2019, the GBTA design rules have been standardised with the first release of the ISO/ASTM 52902:2019 [10]. Before this standard, the authors based their GBTA design on the requirements found in literature [6] and used the same global methodology : selection of the GBTA global size followed by its features (geometry, dimensions, position and orientation) [1].

1.1 - GBTA Size
Firstly, the size of the GBTA is selected to fit into the building volume of the AM printer. Moreover, it should enable the measurement of a maximum area of the building platform (along the X and Y Cartesian axes of the machine) and allow the evaluation of spatial repeatability [1,6]. Indeed, testing the maximum area of the building platform is essential, since the accuracy of positioning devices can be very different at the centre compared to the corners [1]. An optimum between printing area coverage and part volume must be ensured since some AM processes are very expensive to operate and exhibit slow building rates [1,5,6,11]. Besides, if the GBTA is used to evaluate the process capability, it must be printed several times. Consequently, the time and material volume required to manufacture the GBTA have to be as limited as possible [1,7].

1.2 - GBTA Features
Since the GBTA are destined to characterise the dimensional and geometrical accuracy, they are fitted with a high number of features. These features also have to be from different sizes in order to cover the ISO286-1:1988 [12] dimensional ranges [1,6,7,13]. Simple geometries must be selected to simplify the measurement step of the analysis [6]. For example, solid cylinders can be used to determine the circularity, cylindricity and position tolerances [1]. Dedicated orientation and position must be given to the features to link the measured deviations directly with the machine Cartesian axes and ease the measurements using conventional measurement means, such as a CMM [1,6,7,14]. Specific features directly aligned with the end function of the parts that will be produced on the tested machine also have to be added to the GBTA (*e.g.* lattice in the case of biomedical implants used for osseous regeneration) [5–7]. The measurability of the GBTA with the chosen measurement device must be considered during the design process [1,6]. Indeed, complex 3D shapes can be obtained by AM but at the price of complicated or impossible measurements with conventional means [5]. The machine's minimum achievable feature size can be qualitatively evaluated using simple geometric features (*e.g.* circular or rectangular holes as well as solid cylinders and parallelepipeds) [1,7,14]. Overhang features also have to be added to determine their feasibility [14]. Features fitted with a tilted or spherical surface should also be added to the GBTA since they highlight the inherent staircase effect due to layer-by-layer processes, such as AM [14]. Indeed, the build inclination and layer thickness are the two process

parameters in Fused Deposition Modelling (FDM) which influence mostly the surface topography [15]. Methods aiming to reduce the surface roughness of FDM manufactured parts already exist, such as hot cutter machining (HCM) [16]. As far as the measurability of the designed GBTA has to be guaranteed by measurement means, ensuring the printability of features is essential [6]. General guidelines of Design for Additive Manufacturing are available in literature (*e.g.* the review of Thompson *et al.* [17] or the book of Yang *et al.* [18]) as well as simplified worksheets (Booth *et al.* for FDM printers [19] and Bracken *et al.* for powder bed fusion printers [20]). The risk of dimensional and geometrical accuracy degradation by post processes or physical phenomena must be minimised (*e.g.* the GBTA should be built without support structure to avoid post-processing operations before measuring the part) [7]. Indeed, applying post-processing before the measurements makes the source of errors ambiguous [7]. Finally, the base thickness of the part should be thick enough (higher than 5 mm [13]), so warping is less likely to occur during the fabrication or when removing the part from the building platform [13].

1.3 - Motivation and Objectives of the Study

Even though a standard has been released, it is still difficult to create a universal benchmark design. Indeed, even for a given AM process, such as FDM, there is a wide variety of printer configurations and available printing volumes. Among the existing benchmark artefacts found in literature, no one exhibits an adaptive design that can exploit the available printing area of each printer as much as possible. In the case of the Moylan *et al.* [7] or Minetola *et al.* [13] GBTA, for example, the authors reproduce the same design using different printers to test their performances. This article aims to answer this problem by proposing a modified version of an existing GBTA with an adaptive design. Modifications have been performed according to the maximum available printing area of each printer tested.

On the other hand, the printing of large polymer parts with AM processes, such as FDM, can be difficult due to the higher risk of warping. This can lead to the part separating from the building platform during the printing, and permanent deformations which can negatively affect the dimensional and geometrical printing performances [21]. No solution applied to FDM has been found in literature. Therefore, this article also proposes an innovative solution using self-supporting cavities to solve this problem for FDM printers.

The proposed design is analysed in terms of possible dimensional and geometrical measurements. The dimensional and geometrical performances of two printers are then compared using the proposed benchmark design. The surface topography, minimum achievable feature size and generation of overhang features are also investigated.

2 - Comparison of AM Printers

Two different FDM printers are compared in this study: the Ultimaker 2+ and Pollen AM Series MC. Table 1 gives their main characteristics. The first machine is an entry level printer with a Cartesian architecture [22] using a standard 2.85 mm diameter filament. The second is a mid-range printer with a parallel architecture (vertical linear Delta) [22] using pellets and an extrusion screw to generate the deposited material. Each printer can be fitted with a 0.4 mm nozzle, and both use a heated glass building platform. The slicing is ensured by the Cura software on both printers. The Ultimaker 2+ provides a building volume of 223 mm x 223 mm x 205 mm along its X, Y and Z axes while the Pollen printer exhibits a cylindrical printing volume with an announced 300 mm diameter and a height of 300 mm (only a disk of 270 mm diameter is effectively available for printing). Both printers have a closed chamber, reducing temperature variation during printing. The technical specifications indicate an axis positioning resolution of 12.5 µm for the X and Y axes and 5 µm for the Z axis of the Ultimaker, while the Pollen printer is said to exhibit 5 µm for the X and Y axes and 40 µm for the Z axis. The Ultimaker 2+ is designed to print parts in different polymeric materials, such as PLA, ABS or TPU 95A, and composites, such as PETG reinforced with short carbon fibres or stainless steel-polymer composites. On the other hand, the Pollen printer is fitted with four nozzles and screws which can extrude different types of pellets of pure material or charged with particles, such as ceramic and stainless steel. Both printers are used with PLA for this study thanks to the ease of printing and relatively low cost it offers compared to other available materials.

Table 1 Main characteristics of the Ultimaker 2+ and Pollen AM Series MC printers.

Characteristics	Ultimaker 2+	Pollen AM Series MC
AM working principle	Material extrusion (ME)	Material extrusion (ME)
Architecture	Cartesian	Parallel (vertical linear Delta)
Feedstock	2.85 mm diameter filament	2 mm to 4 mm pellets
Nozzle diameter	0.4 mm	0.4 mm
Effective building volume	Parallelepiped of 223 mm x 223 mm x 205 mm (X, Y and Z)	Cylinder of Ø 270 mm x H 300 mm
Axis-positioning resolution	12.5 µm (X and Y axes) and 5 µm (Z axis)	5 µm (X and Y axes) and 40 µm (Z axis)

3 - Method

3.1 - Generation of an Adaptive Benchmark Artefact Based on an Existing Artefact

The literature review showed the great variety of the existing GBTA. However, only few benchmark parts were very well documented and satisfied the majority of the listed requirements. The GBTA of Moylan *et al.* [7] was selected since all its dimensions were available and because its design fulfilled most of the gathered design requirements. Nevertheless, this design does not exploit the whole available printing area of all printers since its dimensions are fixed (a square of 100 mm x 100 mm along the X and Y axes) and it does not allow the profile deviation to be evaluated. Modifications were made to adapt the selected part to the listed requirements. Other modifications were also performed to ensure a reliable printing of the part by decreasing the risk of warping and permanent deformation after the removal of the part from the building platform.

Figure 1 (a) shows the initial Moylan *et al.* benchmark part [7]. The design generated for the Ultimaker 2+ is depicted in Figure 1 (b) while Figure 1 (c) gives the benchmark part generated for the Pollen printer. The Ultimaker 2+ and Pollen designs exhibit a diamond shape with rounded corners and dimensions along the X and Y axes reaching 207 mm x 207 mm for the Ultimaker 2+ and 254 mm x 254 mm for the Pollen. Specific features showing the orientations of the machine axes have been added on the part, as advised by the ISO 52902 [10]. The Ultimaker 2+ and Pollen printer dedicated benchmark parts' CAD files (in .STL) are available in the supplementary files of this article.

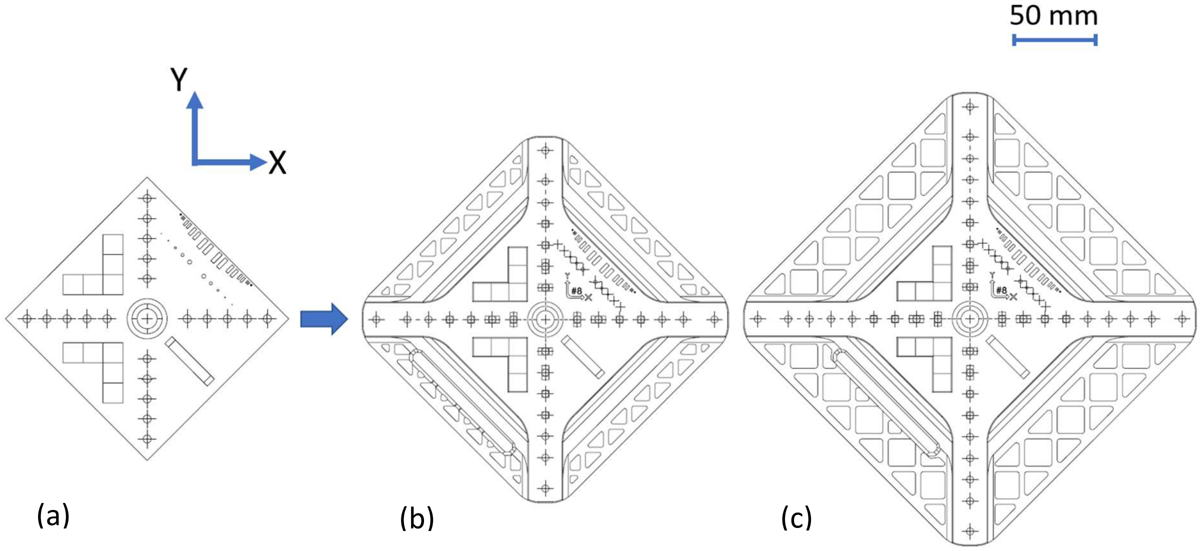


Figure 1 Geometrical Benchmark Test Artefact of Moylan *et al.* [7] (a), generated design adapted to the Ultimaker 2+ (b) and to the Pollen printer (c).

3.1.1 - Design Description

The final design generated for an Ultimaker 2+ FDM printer is shown in Figure 2 with dedicated colours showing the modifications which were performed.

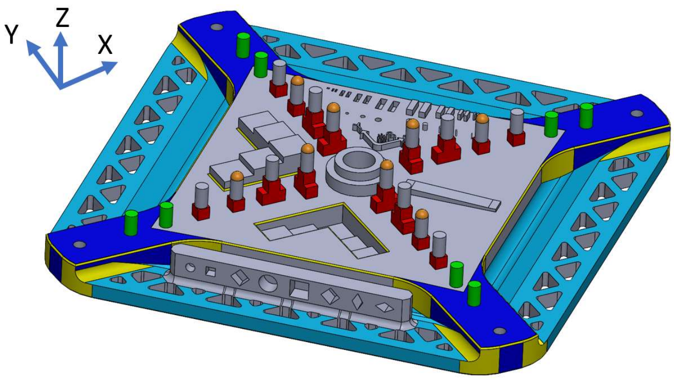


Figure 2 The GBTA adapted to the Ultimaker 2+ printer.

To adapt the design to the printer, four arms were added (as shown in dark blue in Figure 2). The length of the arms is chosen according to the available printing area of the printer building platform and the building platform adhesion type. For example, the FDM Ultimaker 2+ printer exhibits a building volume of 223 mm x 223 mm x 205 mm according to the X, Y and Z axes. Moreover, the adhesion type selected to print the part is a brim of 8 mm. So, the total length of the part can be 207 mm x 207 mm according to the X and Y axes. The Moylan *et al.* GBTA exhibits a diamond shape of 100 mm x 100 mm with cylinders aligned on its diagonals (each measuring 141.421 mm). When printing this part, the diagonals will be aligned with the X and Y axes. So, the total length of each part arms according to the X and Y axes reaches 32.790 mm. In the case of the Ultimaker 2+, the proposed GBTA design with the addition of arms allows to cover 92% of the available length along the X and Y axes instead of 63% with the Moylan *et al.* GBTA design. For the Pollen printer, the proposed design covers 94% of the available length along the X and Y axes instead of 52% with Moylan *et al.* GBTA design.

The maximum altitude of the Moylan *et al.* part reaches 17 mm according to the Z axis with respect to the part's base. This limits the dimensional size ranges according to the Z axis to the 10 mm to 18 mm class of the ISO 286-1:1988 [12] standard as described in [21]. Furthermore, the initial Moylan *et al.* part does not allow dimensional measurements along the X and Y axes belonging to the dimensional size ranges of 1 mm to 3 mm and 3 mm to 6 mm of ISO 286-1 [12] to be evaluated. However, along the Z axis, there are 22 and 13 measurements, respectively, according to these size ranges. Consequently, one or two parallelepipedal bases of 4 mm x 4 mm or 4 mm x 8 mm were added to 16 cylinders (as shown in red in Figure 2). These allow measurements along the X and Y axes for the dimensional size ranges of 1 mm to 3 mm and 3 mm to 6 mm. Moreover, since the cylinder heights were not changed, these bases also provide different heights for the cylinders and allow them to reach the size range of 18 mm to 30 mm from ISO 286-1 [12].

The profile deviation cannot be evaluated for the GBTA of Moylan *et al.* Consequently, eight hemispheres (as shown in orange in Figure 2) with a 4 mm diameter were added on top of the eight cylinders belonging to the centre of the part.

Each of the added arms is fitted with extra little cylinders of the same diameter, such as those proposed by Moylan *et al.* (4 mm). The number of the added cylinders is determined by the available space on the arms and the interspace between each cylinder. This interspace is fixed at 10 mm in the original Moylan *et al.* part. With the addition of parallelepipedal bases on some cylinders, the space between the cylinders had to be increased in order to ease measurements using a CMM probe. Consequently, the interspace was set at 12 mm for all cylinders. Moreover, at the end of each arm, there was a 4 mm diameter bore located 8 mm from the edge of the surface. For the Ultimaker 2+ benchmark, for example, this means that the total number of 4 mm diameter cylinders increased to 24, instead of 16 as proposed by Moylan *et al.* The extra cylinders for this printer are shown in green in Figure 2.

To decrease the risk of permanent deformations, such as those faced in [21], different fillets were added to the part (depicted in yellow in Figure 2). Indeed, sharp edges increase the risk of stress concentration and permanent deformations.

Warping is likely to happen with flat parts exhibiting large dimensions as the proposed benchmark artefact. As shown by Scaravetti *et al.* [23], minimising the contact surface between the part and the building platform can help reduce the risk of warping. According to the literature review and ISO 52902 [10], the GBTA must be printed without support structure. As a result, self-supporting cavities (as shown in red in Figure 3) have been added to the bottom of the part to allow printing without support, while reducing the part's bottom surface in contact with the building platform. Triangles were chosen to separate the bottom of the part into four beams of 8 mm wide as depicted in green in Figure 3. Three other beams of 4 mm were also arranged (as shown in blue in Figure 3) while a bigger concentric triangle pattern was used to produce cavities below the negative staircase.

The parts were separated from the building platform before their measurements, as this could be performed before being assembled with other parts. There is no standardised method to ensure the repeatability of this separation or to avoid the deformation of the part. Consequently, all the arms were linked two by two, by an extra volume as depicted in light blue in Figure 2. To also limit the contact surface between these volumes and the building platform, triangular pockets were added to them. These pockets were designed to create a lattice structure with 3 mm wide beams. Finally, in the case of the Ultimaker printer, cavities and pockets also allow 21.8% of material volume to be saved compared to a part without them.

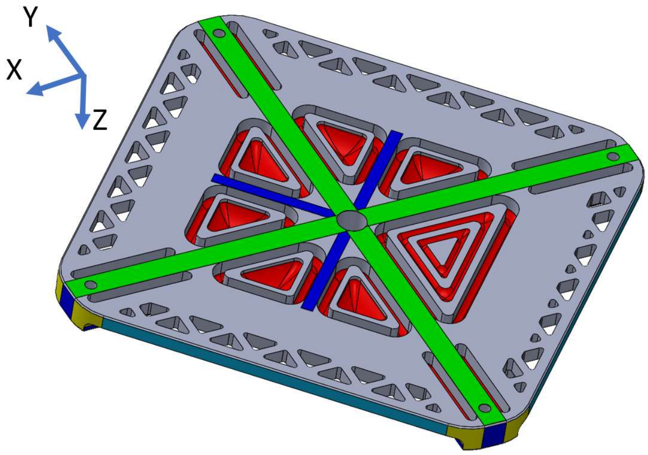


Figure 3 The self-supporting cavities of the Ultimaker 2+ GBTA.

3.1.2 - Comparison with the ISO 52902 Standard

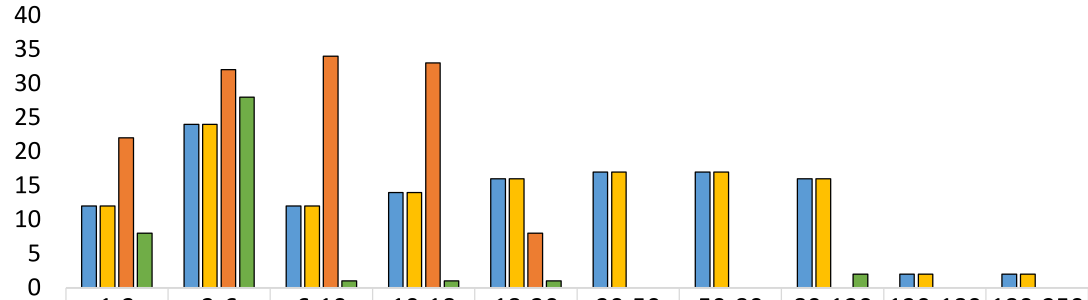
ISO 52902 standard requires realising a benchmark artefact with a sufficient coverage of the printing volume [10]. The standard requires at least 80% of the available building platform surface to be tested. The proposed design allows about 51% of the building platform for the Ultimaker 2+ part and 53% for the Pollen to be covered. Therefore, strictly speaking, the proposed design does not fulfil this requirement of the standard. Limited coverage has been chosen to guarantee relatively fast printing of the part (about 30 hours with the Ultimaker 2+ and 69 hours with Pollen).

In addition, according to the ISO 52902 [10], the GBTA should allow the evaluation of performances along the best possible coverage of the Z axis. The standard does not give a required value of the Z axis coverage. The choice was then made to enlarge the possibilities of testing along the Z axis of the Moylan *et al.* [7] GBTA, along with keeping the printing time as low as possible. This is the reason why the maximal height of the part is only 25 mm, while the Ultimaker 2+ and Pollen can generate parts of 205 mm and 300 mm high, respectively.

The ISO 52902 classifies the different test parts proposed into several categories: accuracy, resolution, surface texture, and labelling [10]. Each category encompasses several types of detail that can be added to the benchmark artefact. The proposed design followed the majority of the guidelines of the standard. However, some features were not added to the design. For example, resolution ribs to assess minimum achievable thickness and straightness of walls were not added to the benchmark artefact. Furthermore, only the tilted plane of the Moylan *et al.* [7] GBTA was added to the benchmark while the standard requires several tilted planes to assess their angularity and surface topography. The choice was made to exclude these features of the benchmark and test these characteristics with dedicated parts.

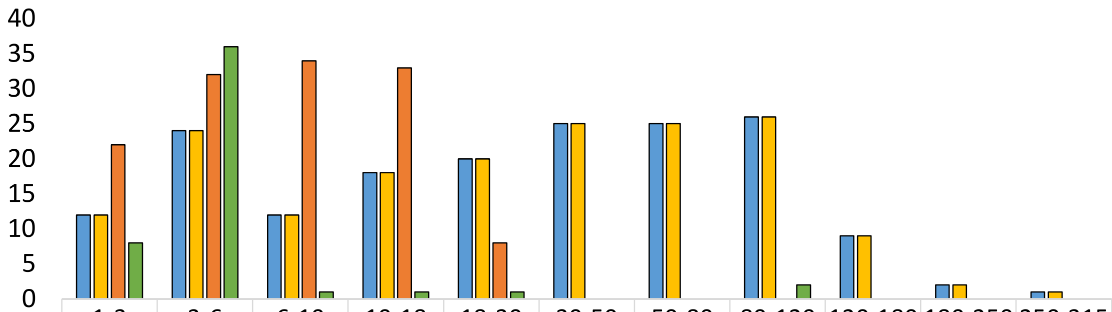
3.2 - Possible Measurements Analysis

Figure 4 shows the distribution of dimensional measurement possibilities across the machine axes (X, Y and Z) of the Ultimaker 2+ benchmark artefact according to the ISO 286-1 dimensional size ranges [12]. Figure 5 depicts the dimensional measurements distribution for the Pollen printer. The “Other” category was added to consider some listed measurements which depend on two different axes (*e.g.* X and Y in the case of the diameter of the cylinders). The total number of dimensional measurements stands at 434 for the Ultimaker 2+ and 526 for the Pollen printer. The major difference between both printers consists of the greater number of available measurements for dimensions above 10 mm for the Pollen printer. The category 250 mm to 315 mm is only available for the Pollen GBTA since the Ultimaker building platform is smaller.



	1-3	3-6	6-10	10-18	18-30	30-50	50-80	80-120	120-180	180-250
X	12	24	12	14	16	17	17	16	2	2
Y	12	24	12	14	16	17	17	16	2	2
Z	22	32	34	33	8					
Other	8	28	1	1	1			2		

Figure 4 Distribution of the possible dimensional measurements of the Ultimaker 2+ printer considering the ISO286-1 [12] dimensional size ranges (in millimetres) and the machine Cartesian axes.



	1-3	3-6	6-10	10-18	18-30	30-50	50-80	80-120	120-180	180-250	250-315
X	12	24	12	18	20	25	25	26	9	2	1
Y	12	24	12	18	20	25	25	26	9	2	1
Z	22	32	34	33	8						
Other	8	36	1	1	1			2			

Figure 5 Distribution of the possible dimensional measurements of the Pollen printer considering the ISO286-1 [12] dimensional size ranges (in millimetres) and the machine Cartesian axes.

Table 2 shows the possibilities of geometrical measurements specific to the Ultimaker 2+ while Table 3 shows the same information adapted to the Pollen printer. As previously mentioned, each geometrical type of deviation has been split according to the different axes of the printers. The “Other” category refers again to the characteristics depending on more than one axis. The features of the axes involved in the “Other” category have been added. The major difference between both printers lies in the number of positions and the number of cylindricity measurements which can be performed. Indeed, the number of cylinders is higher on the Pollen dedicated benchmark artefact. A selection of measurable surfaces was performed to ensure fast measuring of the parts by the CMM (see section 3.4.1). The Ultimaker 2+ and

Pollen benchmark artefacts allow for a total of 524 and 616 geometrical measurements to be performed, respectively.

Table 2 Number of possible geometrical measurements of the Ultimaker 2+ printer with respect to the machine's Cartesian axes.

Geometrical Measurements	X	Y	Z	Other			
				XYZ	XY	XZ	YZ
Angularity				2			
Coaxiality					2		
Cylindricity					31		
Position	132	132	129		2		
Flatness	4	4	13		4		
Parallelism	7	7	5		2		
Perpendicularity				4	18	8	8
Profile				8			
Straightness	6	6					

Table 3 Number of possible geometrical measurements of the Pollen printer with respect to the machine's Cartesian axes.

Geometrical Measurements	X	Y	Z	Other			
				XYZ	XY	XZ	YZ
Angularity				2			
Coaxiality					2		
Cylindricity					39		
Position	174	174	129		2		
Flatness	4	4	13		4		
Parallelism	7	7	5		2		
Perpendicularity				4	18	8	8
Profile				8			
Straightness	6	6					

3.3 - Part Manufacturing

Five parts were manufactured in PLA on each printer. Indeed, this is the minimal number of sample parts required by the ISO 52902 [10]. The Computer Aided Design (CAD) was created in SolidWorks, version 2020. The slicing was performed under version 4.8 of the Cura freeware. An STL file format was used for the transfer file between SolidWorks and Cura, as prescribed by the ISO 52902 [10]. The Ultimaker 2+ was fed with a Ultimaker 2.85 mm diameter PLA filament while the Pollen was used with Pollen PLA pellets. Both printers were used with a 0.4 mm nozzle, a layer thickness of 0.1 mm and a first layer thickness of 0.12 mm. The same density (20%) and infill strategy (cubic) were used on both machines as well as the same adhesion strategy (8 mm wide brim). The building platform temperature was set at 60°C on both printers while the nozzle temperature was set at 220°C on the Ultimaker 2+ and 185°C on the Pollen. It should be noted that the parts were manufactured directly on the glass build platform of the Ultimaker 2+ while the Pollen glass build platform was sprayed with a 3D printing dedicated adhesive lacquer (3DLAC). Both printers manufactured the parts using a single-step process approach according to the ISO 52900 [2] (the parts are fabricated in a single operation in which the geometric shape and the material properties are obtained simultaneously). No sub-process was applied to the parts before their measurement. The print time needed for the Ultimaker benchmark artefact was nearly 30 hours while the Pollen artefact required 69 hours. Figure 6 (a) shows one of the Ultimaker artefacts on the printer building platform while Figure 6 (b) depicts one of the Pollen artefacts. The orientations of the machine axes are also represented, as well as the available space in the XY plane for the parts. As depicted, the parts occupy most of the available space on the building platform. It should be noted that a disk of only 270 mm in diameter instead of 300 mm was available for printing with the Pollen printer.

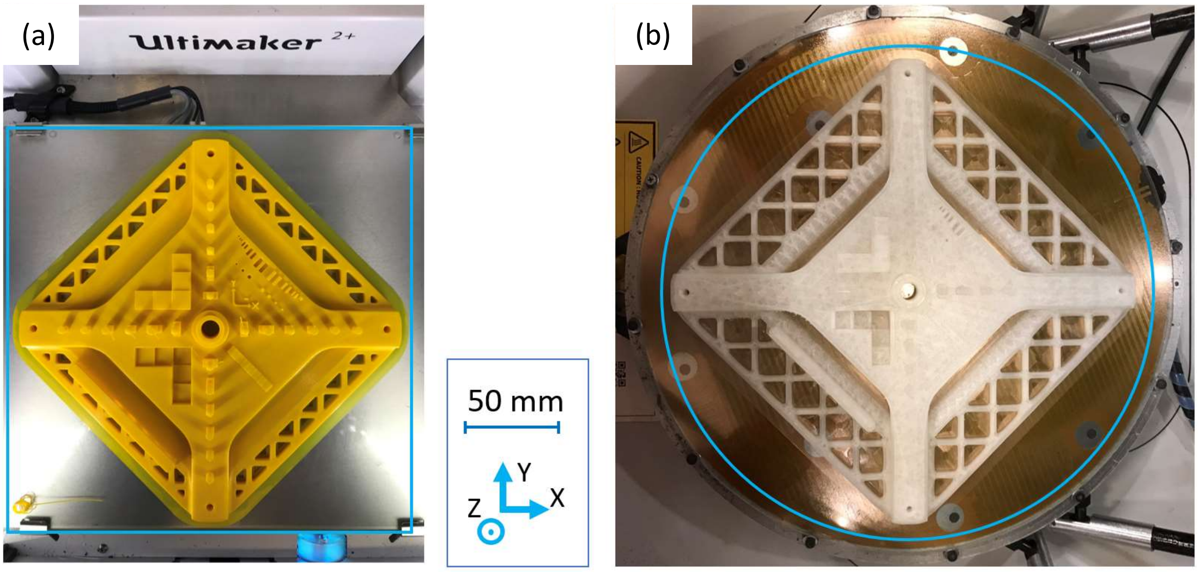


Figure 6 Final Ultimaker 2+ (a) and Pollen (b) printed parts.

3.4 - Measurements of the Parts

3.4.1 - Dimensional and Geometrical Measurements

Each part was measured with a Wenzel LH54 CMM fitted with a PH10M head from Renishaw. A dedicated measurement programme was realised for the Ultimaker 2+ and Pollen parts. Measurements were performed using a Renishaw spherical probe of 1.5 mm diameter. Each measured length L (in millimetres) had a measurement uncertainty (in micrometres) of $3 + L/300$ for the X and Y axes and $3.5 + L/300$ for the Z axis. For each measure, the total uncertainty is evaluated by a 2σ error bar. The number of probed points by geometrical feature type is summed up in Table 4. All the parts were measured at room temperature. Measuring the parts took about 40 minutes for each Ultimaker 2+ part and 60 minutes for each Pollen part. Each part was measured once. Post processing of data was performed using Metrosoft QUARTIS Measurement Software (version 2021) and Microsoft Excel.

The ISO 52902 requires testing the produced benchmark artefacts directly after fabrication [10]. As no precise value of time is given in the standard, a choice was made to test the part maximum 24 hours after their manufacture. This was evaluated as a reasonable cut-off time between manufacture and measurement. The standard also requires measuring the parts without removing them from the building platform. However, the choice was made to take a production point of view. Consequently, the separation between the part and the building platform was performed before measuring. Indeed, if a part was intended to be used in an assembly, its dimensions must fit into tolerances even after its removal. The same tools and method were used on both printers to separate the parts.

Table 4 Number of probed points by type of geometrical feature.

Geometrical features	Number of probed points
Cylinders	8 points distributed over 2 circles
Hemispheres	9 points distributed over 3 circles
Planes	6 points in general
	1 for top planes of small cylinders and their parallelepipedal base planes
	39 for the Ultimaker 2+ part top plane and 51 for the Pollen part top plane
	13 for the slope

3.4.2 - Evaluation of the Printers Dimensional Performances

The ISO 286-1 method [12] was used to evaluate the dimensional performances of each printer. Indeed, this method allows the determination of the tolerance intervals grades (IT) for each dimensional size range of the standard. Different equations can be used depending on the dimensions and IT evaluated. For the present study, all dimensions were less than 500 mm and the IT ranged from 5 to 18. A standard tolerance factor i can then be computed according to Equation 1. D stands for the geometrical average of the two extrema composing the dimensional size range considered (Equation 2). For example, D is 23.238 mm for a dimension range from 18 mm ($D1$) to 30 mm ($D2$) and 1.307 µm is the resulting i. Equation 3 allows the computation of a dimensionless number (n) called number of tolerance units. In this equation, the deviation of a measured dimension (Dm) with respect to its nominal value (Dn) is compared to the standard tolerance factor (i) associated with the nominal value.

$$i = 0.45 \cdot \sqrt[3]{D} + 0.001 \cdot D \quad (1)$$

$$D = \sqrt{D1 \cdot D2} \quad (2)$$

$$n = (1000 \cdot |Dn - Dm|) / i \quad (3)$$

Then, a maximum value of n was given for each IT grade using the ISO 286-1 standard [12]. For example, a number of tolerance units fewer than 16 is required for IT7. Table 5 gives all the maximum allowed number of tolerance units for the IT ranging from 5 to 18 according to the ISO 286-1 [12]. It should be noted that these thresholds are only applicable for dimensions of less than 500 mm.

Table 5 ISO 286-1 IT grade classification [12].

IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16	IT17	IT18
7i	10i	16i	25i	40i	64i	100i	160i	250i	400i	640i	1000i	1600i	2500i

These calculations were performed for all measured dimensional deviations, such as distances between the axes of cylinders, between planes, cylinder diameters and hemisphere radii. All the computed number of tolerance units can then be gathered into graphs with a split between the different machine axes (X, Y and Z).

3.4.3 - Surface Topography Measurements

As proposed by the ISO 52902 [10], the surface topography was analysed using a contact rugosimeter. Five measurements were taken on each printed part's top surface with a Diavite DH6. The five measurement lines were spaced by 1 mm and performed perpendicularly with respect to the deposition direction. For accessibility reasons, measurements were performed at the end of an arm, between a bore and a 4 mm cylinder. Signal acquisition and post processing were carried out using DiaSoft Standard Software on a computer. Arithmetic roughness was first estimated between 2 µm and 10 µm through a viso-tactile sample. Therefore, an evaluation length of 12.5 mm was selected and used for the measurements according to the ISO 4288:1996 [24].

4 - Results and Discussion

4.1 - Dimensional Evaluation of the Parts

The resulting graphs are given for the Ultimaker 2+ and for the Pollen in Figures 7 and 8 with 2σ error bars. A dedicated "Other" category was added to take into account the measurements relative to several axes. The diameter, for example, depends on the X and Y axes together. Each blue horizontal bar gives the maximum allowed values of the number of tolerance units for an IT of the ISO 286-1 [12]. Consequently, if a measurement, with its error bars, is below the threshold number of tolerance units, it means that it fulfils this IT.

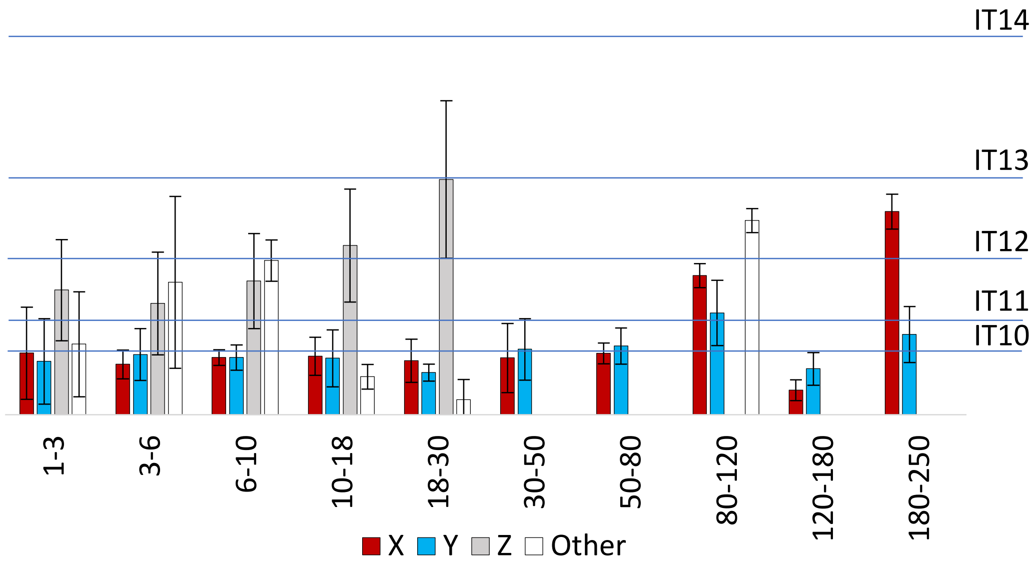


Figure 7 Dimensional analysis of the Ultimaker 2+ printer considering the ISO 286-1 [12] dimensional size ranges (in millimetres) and machine Cartesian axes.

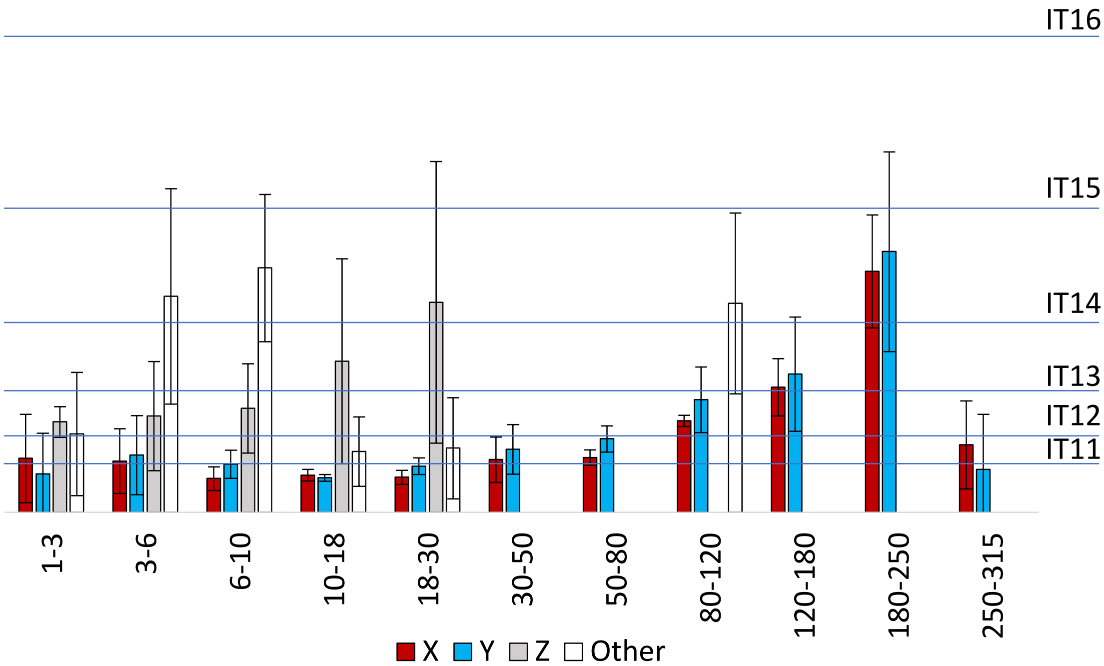


Figure 8 Dimensional analysis of the Pollen printer considering the ISO 286-1 [12] dimensional size ranges (in millimetres) and machine Cartesian axes.

4.1.1 - Features According to the X and Y Axes

As exhibited in the graphs, the Ultimaker 2+ reached a lower IT than the Pollen printer. Indeed, between 3 mm to 80 mm, the Ultimaker 2+ respects IT11 for features according to X and Y axes, while the Pollen printer is between IT12 and 13. Features ranging from 1 mm to 3 mm, fulfil IT13 on the Pollen while the Ultimaker exhibits better results by reaching IT12. Over 80 mm, the performances of the Ultimaker printer are less homogeneous but remain under IT13. The same tendency can be seen on the Pollen printer but with higher IT results, ranging from 13 to 16.

4.1.2 - Features According to the Z Axis

Both printers show lower performances for dimensional features according to the Z axis. The Ultimaker 2+ respects IT13 for dimensions ranging from 1 mm to 18 mm. Features between 18 mm and 30 mm are less accurate, and the IT is 14. For the Pollen printer, the same behaviour can be observed but with higher values of IT. Indeed, the dimensions of size ranges from 1 mm to 3 mm respect IT13. However, between 3 mm and 30 mm, the printer's achievable IT increases with the feature dimensions beginning at 14 and reaching 16 for feature sizes between 18 mm and 30 mm.

4.1.3 - Features According to a Combination of Axes

Achievable IT for features belonging to more than one axis follow the same tendency on both printers. Indeed, features between 1 mm and 10 mm show increasing IT while they decrease between 10 mm and 30 mm and then increase again for dimensions between 80 mm and 120 mm. This could be linked to the available measurements on each part for this category of features according to their size. Indeed, only one measurement is available on each part for both printers for categories of 6 mm to 10 mm, 10 mm to 18 mm and 18 mm to 30 mm, while only two measurements are available for the category of 80 mm to 120 mm. Objective conclusions about the printer performances can therefore not be drawn with this restricted number of measurements.

4.1.4 - Comparisons with Other Related Works

In the literature, another part design and printer have been evaluated with the ISO286-1 method by Minetola *et al.* [11]. The same principal author with other collaborators reused the same design and method to compare four different printers, one of which is the Ultimaker 2+ [13]. However, they did not split the results according to the machine's axes so comparisons cannot be directly made with the present work. Spitaels *et al.* [21] also used an Ultimaker 2+ but with another part design and organised the results according to the machine axes. In this study, the printer performances according to the X and Y axes are better (under IT 13 for dimensions between 6 mm and 80 mm) in relation to the Z axis (IT between 13 and 14 for the same dimensions ranges). Even if the results are better in the present work, they follow the same tendency, as shown in Spitaels *et al.* [21]. This demonstrates the adequacy of the method used in the present study.

4.2 - Geometrical Evaluation of the Parts

Geometrical measurements can be performed based on the geometrical probed features such as planes, cylinders and hemispheres. For example, the cylinders on the top surface allow the determination of cylindricity, coaxiality and position measurements between cylinders, or between cylinders and planes, while hemispheres allow the determination of profile deviation. Flatness, parallelism, perpendicularity and angularity measurements can be performed based on the probed planes. Finally, straightness measurements can be obtained from the relative positions of the different cylinder axes.

4.2.1 - Global View of Geometrical Deviations

Figure 9 gives a global view of the geometrical deviations of the Ultimaker 2+ printer with respect to the machine axes while Figure 10 gives the same information for the Pollen printer. The same chart scales were used to ease comparisons between the printers. 2σ error bars are displayed on each graph. These two graphs allow the top three geometrical deviations to be determined on the Ultimaker 2+ and Pollen printers.

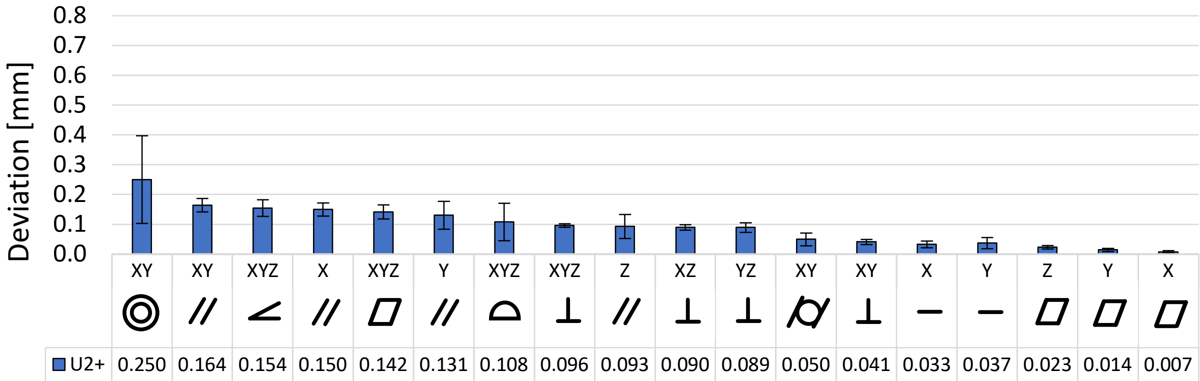


Figure 9 Global view of the Ultimaker 2+ printer geometrical deviations (in millimetres) according to the machine's Cartesian axes.

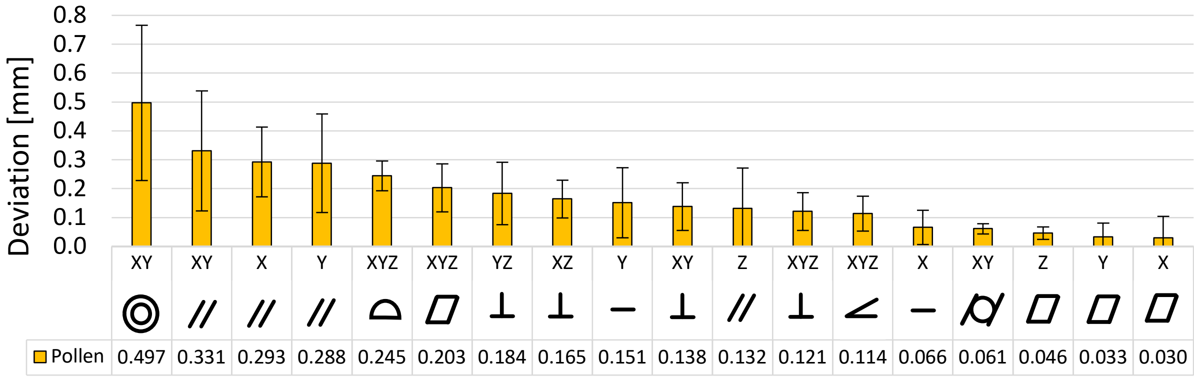


Figure 10 Global view of the Pollen printer geometrical deviations (in millimetres) according to the machine's axes.

For the Ultimaker 2+, the coaxiality in the plane X and Y is the first deviation observed with average values reaching 0.250 mm. As shown by the 2σ error bars, the dispersion of measurements is also higher than for other geometrical deviations. This shows non-homogeneous values of coaxiality among the different parts produced. The parallelism of planes with a normal belonging to more than one machine axis is the second-highest deviation observed, with an average value of 0.164 mm. The angularity comes third, with average deviation values of 0.154 mm. The parallelism of planes with a normal parallel to the X and Y axes of the printer follows closely, as does the flatness of planes with a normal non-parallel to the machine Cartesian axes. This form error can justify the second place of the parallelism of planes with a normal belonging to more than one machine. Indeed, these planes suffer then from a non-negligible form error.

The coaxiality is also the highest geometrical deviation observed on the Pollen printer with values two times higher than the Ultimaker and a wide dispersion among the measurements. This is followed by the parallelism of planes with a normal belonging to more than one machine axis (average deviation of 0.361 mm). The top three are then completed with the parallelism of planes with a normal parallel to the X axis (average deviation of 0.293 mm). Its equivalent for the Y axis follows closely in fourth position, followed by the profile deviation of the hemispheres.

On comparison, it is more difficult for both printers to ensure the coaxiality of cylinders and the parallelism of planes, regardless of their normal direction. It should be noted that the Pollen printer exhibits values two times higher than the Ultimaker 2+ printer on average. This is partly due to the higher dimensions of the Pollen benchmark artefact. Moreover, only two measurements of coaxiality deviation are performed on each part of both printers.

4.2.2 - Link with the ISO 2768-2

A link can be made with the ISO 2768-2:1989 [25] for the parallelism, perpendicularity and flatness. The link between the standard and other deviations is detailed in the next section. Even if the application domain of this standard relates to subtractive processes, it makes for a comparison, since no equivalent standard currently exists for additive processes. Figures 11, 12 and 13 detail the parallelism, perpendicularity and flatness deviations of the Ultimaker and Pollen printers according to the different related machine axes and main dimensions of the planes considered. 2σ error bars are represented on each graph.

The parallelism deviations vary with respect to the principal dimensions of the evaluated planes. Indeed, between 10 mm and 30 mm, the parallelism of the X and Y planes for the Ultimaker 2+ respects an L class (large), while a K class (middle) is respected for the Z planes.

Between 30 mm and 100 mm, the X and Y planes respect a K class (middle) while the planes with a normal depending on different machine axes reached an L class (large). For the main dimensions between 100 mm and 300 mm, the Z planes reached a K class (middle). Almost all the parallelism deviations for the Pollen printer were higher than the Ultimaker. Thus, between 10 mm and 30 mm, the X and Y planes were far higher (0.728 mm and 0.420 mm respectively) than the L class (large) threshold (0.2 mm). The X planes exhibited a very high measurement dispersion. The Z planes for the main same dimension interval fit into an H class (fine). Between 30 mm and 100 mm, the X and Y planes respect an L class (large) while the planes with a normal depending on different machine axes exceeded the L class (large). Finally, the Z planes for dimensions between 100 mm and 300 mm exhibited a high measurement dispersion and could not respect the threshold of the L class (large). The Pollen performances in terms of parallelism were therefore worse than the Ultimaker 2+.

The perpendicularity deviations exhibited different values according to the type of planes, main dimensions and printer considered. However, all measurements on Ultimaker 2+ fit into an H class (fine) of ISO 2768-2 [25]. On the other hand, the Pollen respects a K class (middle) for all measurements. It should be noted that the dispersion of measurements, as well as the absolute average values, were, again, higher for the Pollen printer than for the Ultimaker 2+.

The same link to ISO 2768-2 [25] can be made for flatness deviations. The Ultimaker 2+ respects an H class (fine) for the Z planes, with main dimensions between 0 mm and 10 mm. For the dimensions between 10 mm and 30 mm, the Z planes respect a K class (middle). Between 30 mm and 100 mm, the X and Y planes reach an H class (fine), while planes having a normal belonging to more than one axis reached a K class (middle). The Z planes with main dimensions between 100 mm and 300 mm fit into an H class (fine). For the same type of planes and main dimensions, the Pollen reaches a K class (middle). The planes of the same printer having a normal belonging to more than one axis and main dimensions between 30 mm and 100 mm respect an L class (large), while the X and Y planes respect an H class (fine). Finally, the Z planes between 10 mm and 30 mm fit into an H class (fine), while the Z planes of dimensions between 0 mm and 10 mm belong to a K class (middle). Again, the Pollen exhibited lower performances than the Ultimaker 2+ to reproduce flat surfaces.

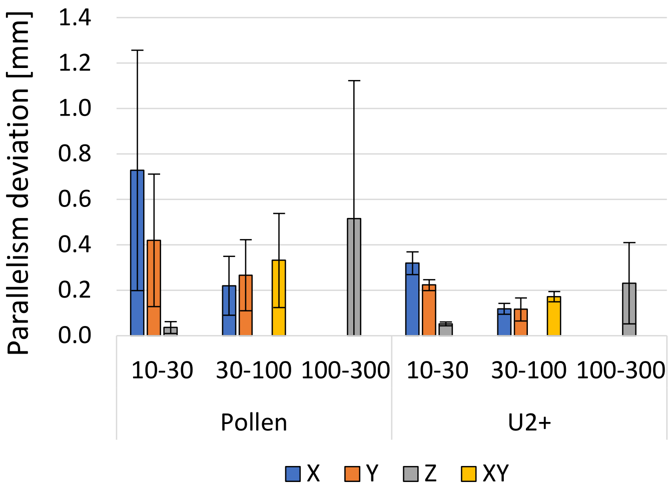


Figure 11 Parallelism deviation (in millimetres) according to the ISO 2768-2 [25] dimensional ranges (in millimetres) and the machine's axes.

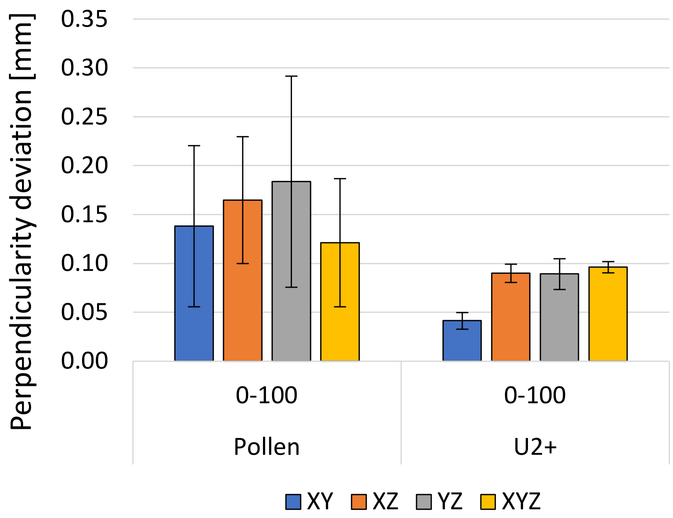


Figure 12 Perpendicularity deviation (in millimetres) according to the ISO 2768-2 [25] dimensional ranges (in millimetres) and the machine's axes.

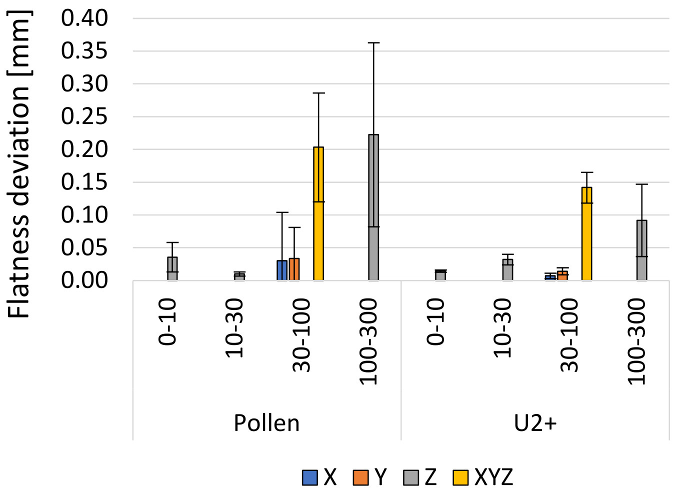


Figure 13 Flatness deviation (in millimetres) according to the ISO 2768-2 [25] dimensional ranges (in millimetres) and the machine's axes.

4.2.3 - Detailed Geometrical Deviation Analysis by Zone

Geometrical deviations could then be split into different categories depending on their X and Y positions on the part's top surface. The deviations computed from the cylinders distributed across the top surface can be classified into five different zones (X-, X+, Y-, Y+, centre), as depicted in Figure 14 in the case of the Pollen benchmark artefact. Two other categories (Z- and Z+) were also created for planes coming from negative and positive stairs. The average deviation value was compared to the ISO 2768-2 standard [25].

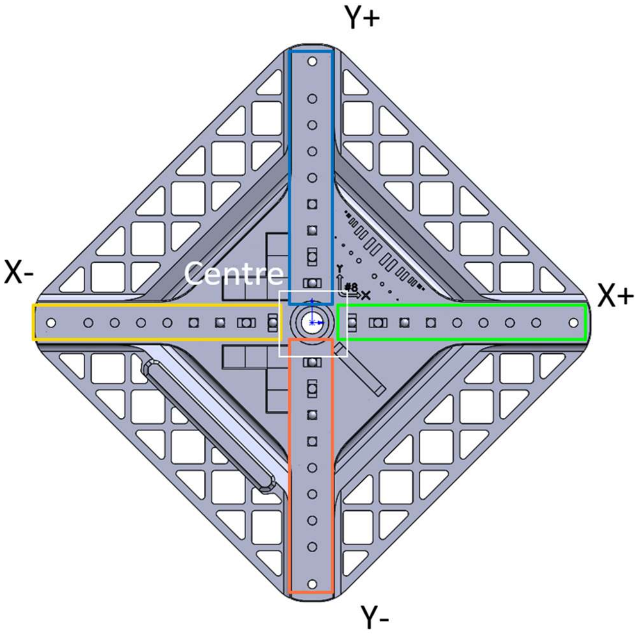


Figure 14 Part zones in the case of the Pollen GBTA.

Figures 15, 16, 17 and 18 depict the average straightness, diameter, cylindricity and profile deviations across the different part zones. Figure 20 shows the distance deviations between cylinders and planes or between cylinders and cylinders, while Figure 21 gives the average distance deviation between planes with a normal parallel to the Z axis. All graphs exhibit 2σ error bars.

The average straightness deviation in the different zones of the Ultimaker 2+ printer parts, as depicted in Figure 15, remains at the same average of about 0.035 mm. This is not the case for the Pollen printer. Indeed, the Y+ zone shows much higher values with the average deviation reaching 0.190 mm followed by the Y- and X- zones with their respective deviation values reaching 0.113 mm and 0.088 mm. This inhomogeneity of results may be a consequence of the parallel architecture [1]. However, the Ultimaker 2+ and Pollen printers respect, on average, the same H class (fine) of the ISO 2768-2 [25]. The different deviation values of both printers can be explained by the higher dimensions of the Pollen part compared to the Ultimaker. However, the non-homogeneity exhibited is due to the axes' positioning performances of the Pollen printer. Finally, the dispersions of straightness deviations observed in the case of the Pollen printer are higher than the Ultimaker 2+. The performances of the Pollen printer are therefore less homogeneous.

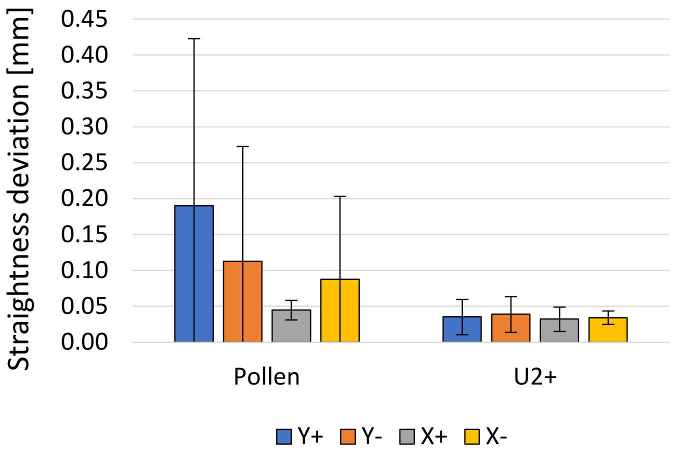


Figure 15 Straightness deviation (in millimetres) according to part zones.

Through the different part zones, the average diameter deviation of the Ultimaker 2+ is quite identical, as shown in Figure 16. Only the centre benefits from a better performance (0.069 mm of deviation instead of 0.103 mm on average for other zones) even if the central bore and cylinders have higher diameters (10 mm for the central bore, and 15 mm and 20 mm for the central cylinders). The Pollen printer exhibits higher diameter deviations (0.318 mm on average), also with a better performance for the central cylinders (0.258 mm). The diameter deviation of the Ultimaker 2+ fulfils the *c* class of ISO 2768-1:1989 (rough) [26] while the Pollen's average deviations lead to *v* class, meaning a worse quality (very rough). The central cylinders of the Ultimaker 2+ reach an *f* (fine) class while the Pollen respects a *c* class (rough).

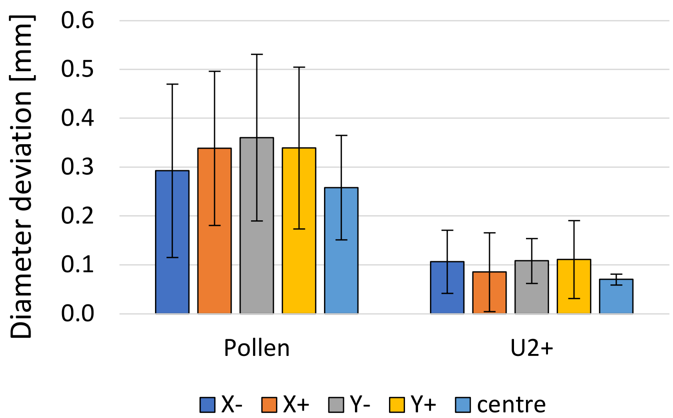


Figure 16 Diameter deviation (in millimetres) according to the part zones.

Figure 17 represents the cylindricity deviation of the Pollen and Ultimaker 2+ printers. They reach about the same values with 0.057 mm and 0.047 mm on average, respectively, for all zones, except the centre. The centre zone exhibits higher deviations on both printers with average values reaching 0.074 mm for the Ultimaker 2+ and 0.114 mm for the Pollen. No link to the ISO 2768-2 standard [25] can be established since there is no prescription of cylindricity in this standard.

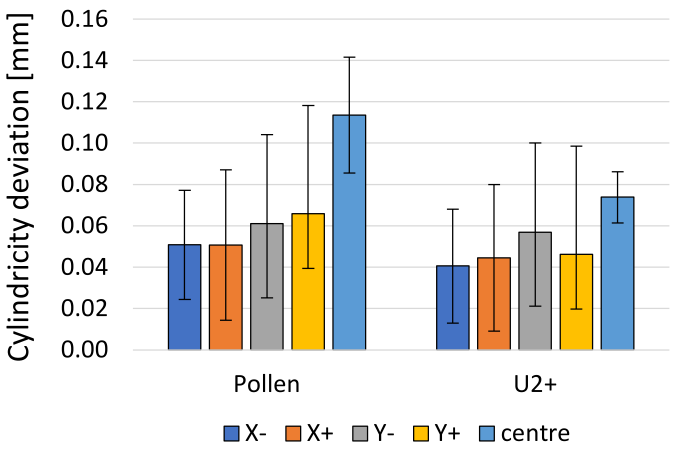


Figure 17 Cylindricity deviation (in millimetres) according to the part zones.

The profile deviations of both printers are depicted in Figure 18. The Ultimaker 2+ printed parts exhibit lower average values of profile deviation than the Pollen parts. The average stands at 0.107 mm while the Pollen printed parts reach 0.244 mm on average. The Pollen printer allows homogeneous deviations, while the Ultimaker 2+ printer exhibits 50% higher values for the Y- zone. No prescription in the ISO 2768-2 exists for this kind of deviation [25]. However, compared to the radius of the elements (2 mm), the form error is non-negligible.

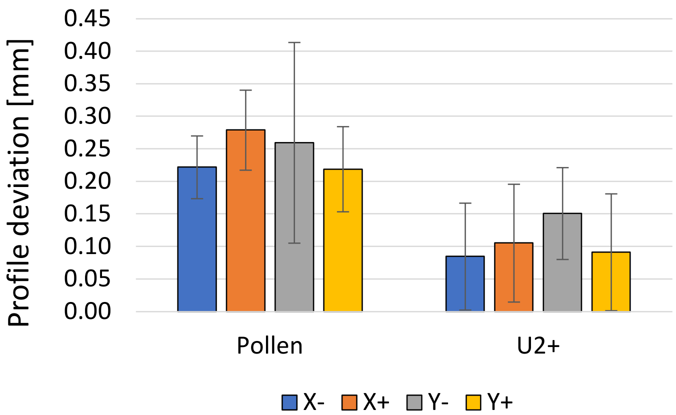


Figure 18 Profile deviation (in millimetres) according to the part zones.

The position deviations of the top surface little cylinders can be studied for the Pollen and Ultimaker 2+ printers. Figure 20 shows the position deviations of the cylinders in the X and Y plane, while Figure 21 gives the same information for the planes depending on the Z axis. These are the planes composing the positive stairs (Z+ zone) and negative stairs (Z- zone) on the GBTA, as shown in Figure 19. At first glance, in Figure 20, the Pollen printer exhibits lower performances than the Ultimaker 2+ since the average position deviation reaches values at least two times higher than the Ultimaker 2+ printer. Homogeneous results can be observed for this printer while the Pollen machine exhibits better results for the zones X+ and Y-. The Pollen performances in the X- and Y+ zones are quite similar. With respect to the Z axis, as depicted in Figure 21, the same tendency can be observed with better values for the Ultimaker 2+. However, both printers show better results for features belonging to the Z+ zone. This means that the positive stairs were reproduced with a better accuracy than the negative stairs. As the same behaviour can be observed on both printers, it means that this tendency perhaps comes from the benchmark part design itself. Indeed, dedicated cavities (to reduce the risk of warping) have been added below the negative stairs. They may influence the accurate reproduction of negative stairs since the thickness of that zone of the part is reduced.

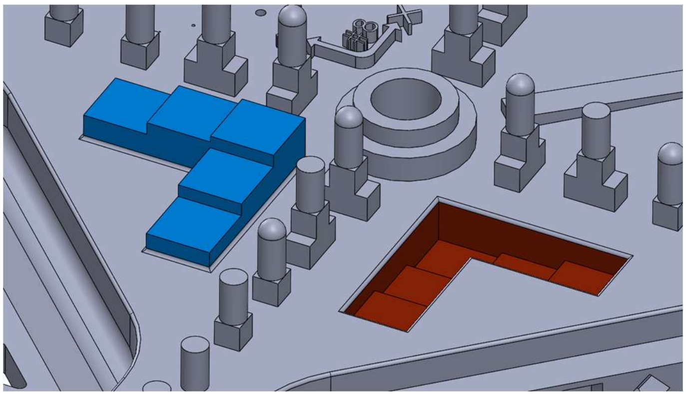


Figure 19 Positive stairs (in blue) and negative stairs (in red).

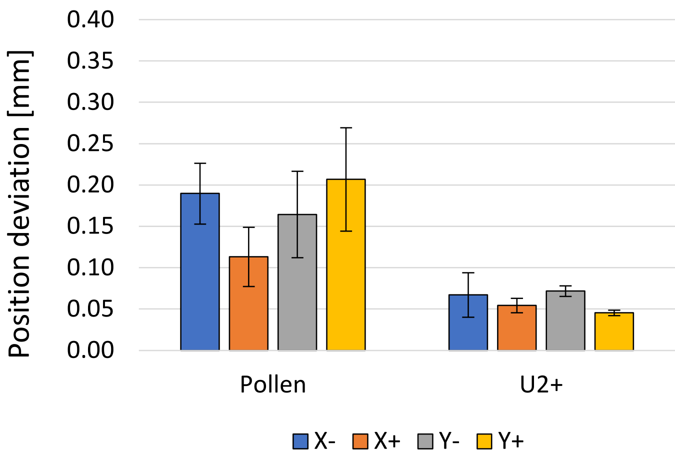


Figure 20 Position deviation (in millimetres) according to the X and Y part zones.

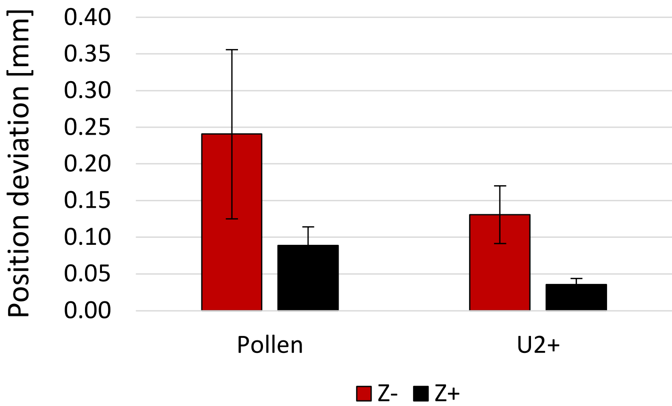


Figure 21 Position deviation (in millimetres) according to the Z part zones.

Finally, as shown by Moylan *et al.* in [7], the position deviations of the top surface cylinders can be split following the X and Y axes of the GBTA. The resulting graphs are shown in Figure 22 (a) and (b) with absolute values. These give the X and Y position deviations of the top surface cylinders along the Y axis. Figure 23 (a) and (b) depicts the same information for the top surface cylinders along the X axis. The same tendency can be seen in each graph: the absolute position deviation increases along with the distance from the centre of the building platform. Again, the Pollen printer exhibited higher deviations than the Ultimaker machine. Moreover, the bores located at the ends of the benchmark artefact arms exhibited a very high position deviation. Some reached nearly 1 mm of deviation from the nominal position. No error is displayed in the graphs to ease their comprehension. Nevertheless, the average error (2σ) reached about 0.7 mm for the Pollen parts, while the Ultimaker 2+ average error stood at about 0.3 mm.

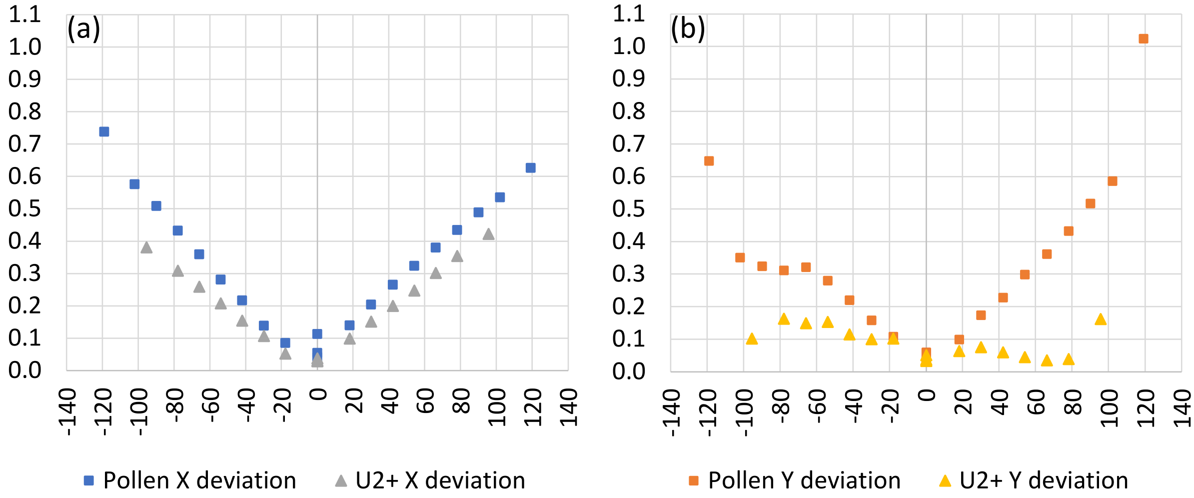


Figure 22 Absolute values of the X position deviation (a, in millimetres) and Y position deviation (b, in millimetres) of the top surface cylinders along the Y axis (in millimetres).

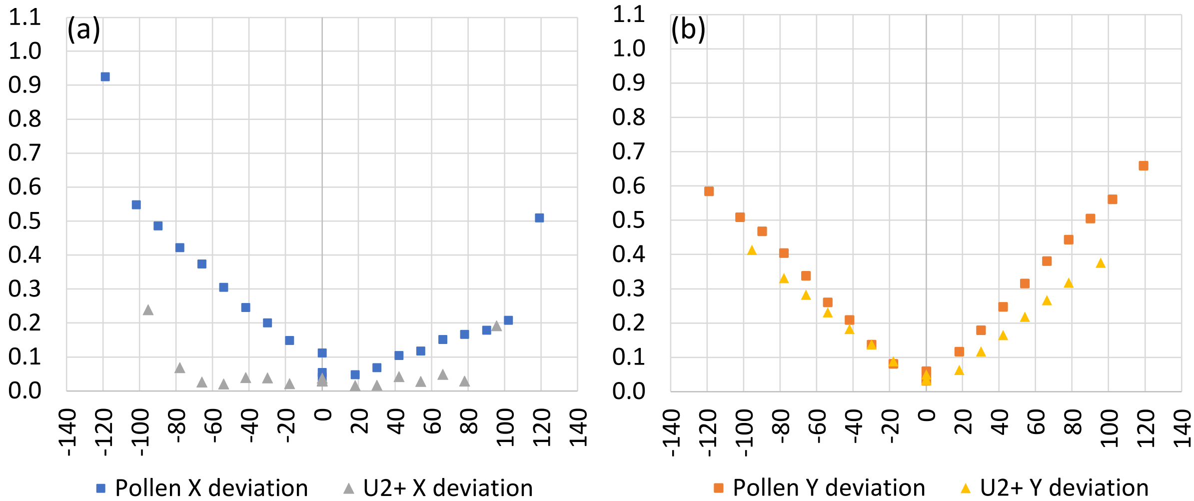


Figure 23 Absolute values of the X position deviation (a, in millimetres) and Y position deviation (b, in millimetres) of the top surface cylinders along the X axis (in millimetres).

4.2.4 - Surface Topography Analysis

Figure 24 depicts the average arithmetic (Ra) and total roughness (Rt) for the Ultimaker 2+ and Pollen printers on the considered top surface area according to the ISO 4288 [24]. A better surface topography with lower average values of Ra and Rt could be achieved on the Ultimaker 2+ (Ra = 4.9 µm) than on the Pollen (Ra = 13.7 µm). The dispersion of the measurements was higher for the Ultimaker 2+, showing a less homogeneous behaviour of the printer.

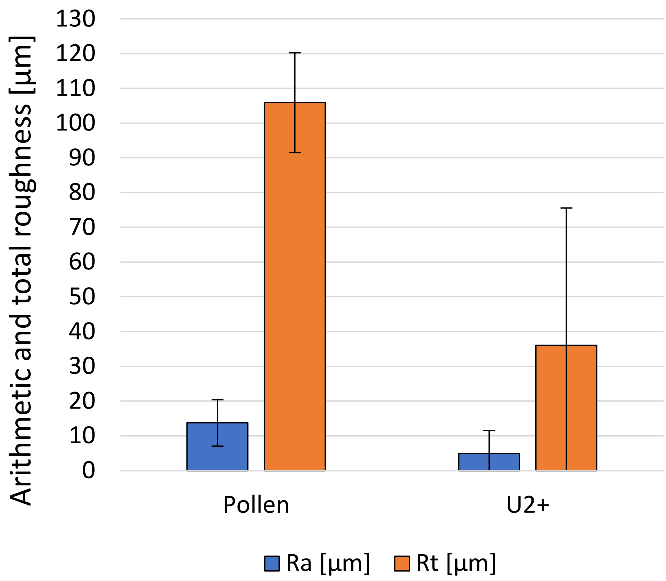


Figure 24 Average arithmetic (Ra) and total (Rt) roughness (in micrometres) for the Ultimaker and Pollen printers.

4.3 - Qualitative Evaluation of the Parts

Specific decreasing spaced parallelepipeds and cylinders of decreasing diameter, allowing the minimum achievable size of positive and negative features by the printers to be determined, are available on the GBTA of Moylan *et al.* [7]. The proposed GBTA design also exhibits these features. Since all the parts exhibited the same results, only one of each printer is presented. Figure 25 depicts the positive and negative features reproduced by the Ultimaker 2+ printer while Figure 26 gives this information for the Pollen printer. Table 6 also gives the qualitative analysis of the picture for the Ultimaker 2+ while Table 7 gives it for the Pollen printer. The successful reproduction of the features is indicated by "OK" in the tables while "NOK" shows the impossibility for the machine to reproduce the detail. The Pollen and Ultimaker 2+ have the same difficulties except for negative and positive cylinders of 0.5 mm, which the Pollen cannot reproduce.

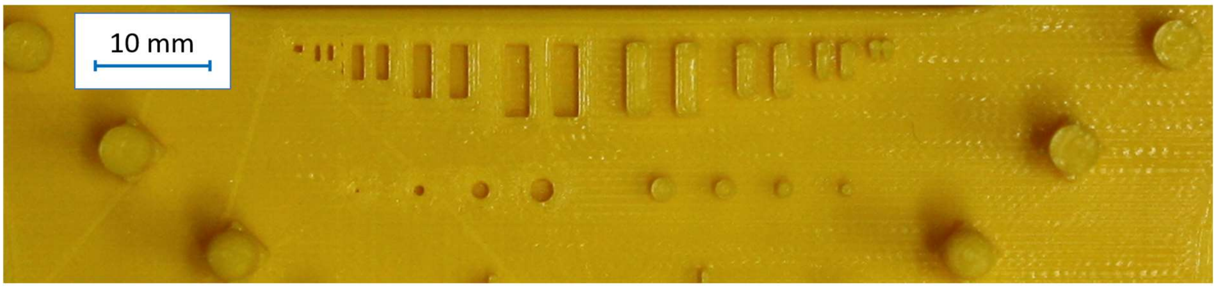


Figure 25 Minimum achievable feature size analysis for the Ultimaker 2+ printer.

Table 6 Minimum achievable feature size analysis for the Ultimaker 2+ printer.

Rectangular parallelepipeds – Ultimaker									
Negative					Positive				
0.25	0.50	1.00	1.50	2.00	2.00	1.50	1.00	0.50	0.25
NOK	OK	OK	OK	OK	OK	OK	OK	NOK	NOK
Cylinders – Ultimaker									
Negative					Positive				
0.25	0.50	1.00	1.50	2.00	2.00	1.50	1.00	0.50	0.25
NOK	OK	OK	OK	OK	OK	OK	OK	OK	NOK

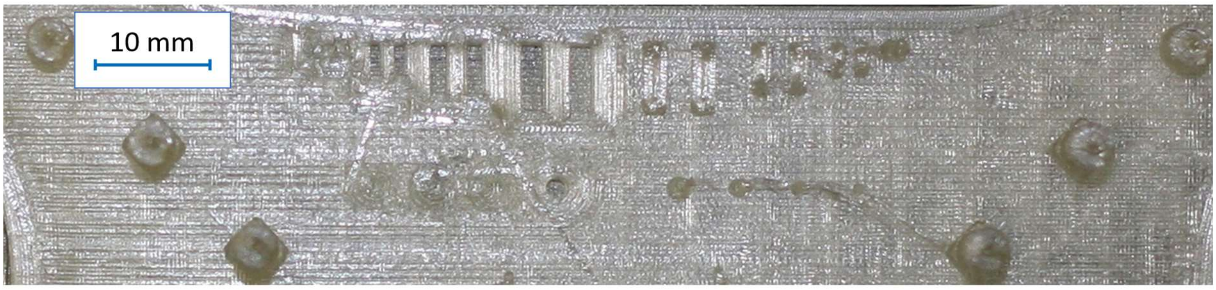


Figure 26 Minimum achievable feature size analysis for the Pollen printer.

Table 7 Minimum achievable feature size analysis for the Pollen printer.

Rectangular parallelepipeds - Pollen									
Negative					Positive				
0.25	0.50	1.00	1.50	2.00	2.00	1.50	1.00	0.50	0.25
NOK	OK	OK	OK	OK	OK	OK	OK	NOK	NOK
Cylinders – Pollen									
Negative					Positive				
0.25	0.50	1.00	1.50	2.00	2.00	1.50	1.00	0.50	0.25
NOK	NOK	OK	OK	OK	OK	OK	OK	NOK	NOK

Finally, the overhang features coming from the initial design of Moylan *et al.* [7] were reproduced on the proposed GBTA design. Figure 27 shows the CAD target (a), the overhang printed features for the Ultimaker 2+ (b) and for the Pollen printer (c). Since all the parts of each printer exhibited the same behaviour, only one picture is given. The top surfaces of the overhang features were better reproduced by the Ultimaker, with even the negative big cube being well reproduced and without collapsing. The Pollen printer showed lower performances with less quality in the overhang features' top surfaces.

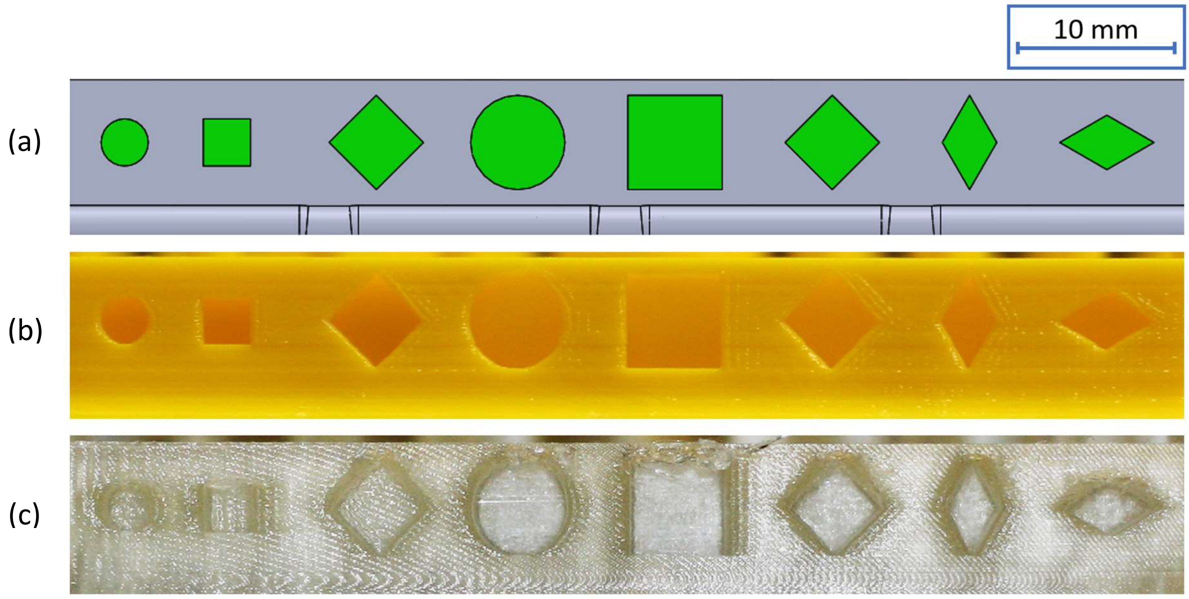


Figure 27 CAD target of the overhang features (a), printed features with the Ultimaker 2+ (b) and Pollen printer (c).

4.4 - Discussion of Results

Off-line metrology using GBTA makes it easier and cheaper to evaluate the performances of 3D printers compared to on-machine metrology [7]. However, this method does not allow an error to be directly linked to its source [7]. The Ultimaker 2+ showed better performances than the Pollen machine on every dimensional size range considered both for the dimensional and geometrical performances, as well as for the surface topography and qualitative evaluation of the minimal achievable feature size. These differences can come from diverse causes (*e.g.* printer architecture, axes misalignment, backlash, irregularity of the extrusion flow). Even if the proposed method does not directly link the deviations observed to their source, some assumptions based on the major differences between both printers can explain these performances differences.

One of the printers' major differences is their architecture. Indeed, the Ultimaker 2+ exhibits a Cartesian (serial) architecture, while the Pollen is based on a vertical linear Delta (parallel) architecture [27]. In the case of parallel structures, the positioning error observed at the end effector is the average of the errors of each individual axis [27,28]. This architecture of the printer should then be more accurate than serial structures which cumulate, rather than average, the positioning errors of each individual axis at the end effector [28]. Higher stiffness is also expected from parallel architectures compared to serial structures [27,28]. However, these advantages are highly influenced by the quality of the components (tolerances of manufacturing, stiffness) and their assembly, as well as the calibration of the whole machine to compensate the deformations due to gravity, inertial forces and thermal expansion [27,28]. The wear in passive joints (such as ball-and-socket) can lead to backlash and results in a lower positioning accuracy of the printer. Therefore, the lower performances observed for the Pollen printer may be caused by its different architecture and the quality of its actuators and joints.

Another major difference between both printers is their feed mechanism. The Ultimaker 2+ uses a filament driven by friction (ram extrusion), while the Pollen uses pellets and an extrusion screw (helical extrusion) [29]. The accuracy of the deposited material flow can be affected by the type of feeding. Indeed, the pellet additive manufacturing requires an

adequate mixing of the feedstock to ensure a constant feeding of the extrusion screw, while sufficient friction and pressure are required in ram extrusion to avoid the slippage and the irregular feeding of the extruder [29].
However, as explained before, the method in this article only observes the deviations and cannot link them directly to their source. Using on-machine metrology could be the solution to assess and verify these assumptions, but this requires other measurements means (*e.g.* laser trackers). These are not available in all industrial workshops and can be impossible to integrate in an existing machine [7].

5 – Conclusion

An innovative GBTA design was developed and applied to commercial printers (Ultimaker 2+ and Pollen AM Series MC) with two different architectures to assess and compare their dimensional and geometrical performances.

The main findings of the study are the following:

- In the wide variety of the existing GBTA, none can adapt to any AM printer to test the maximum available space of its building platform. The proposed GBTA solves this problem by exhibiting an adaptive design.
- Innovative cavities and lattice structure to reduce the risk of warping were developed and applied to the proposed design.
- On every size range considered, the Ultimaker 2+ exhibited dimensional performances below IT13 while the Pollen machine reached a higher IT, such as 15 or 16. Lower dimensional performances were observed for the features according to the build direction (Z axis) on both machines.
- Both printers exhibited the same difficulty to create cylindrical features with low coaxiality deviations and parallel planes involving different machine axes with low parallelism deviation.
- Depending on the part zones, the Pollen printer exhibited non-uniform geometrical performances. The Ultimaker 2+ was more homogeneous.
- The average surface topography was better for the Ultimaker 2+ (Ra = 4.9 µm) than for the Pollen printer (Ra = 13.7 µm).

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References

[1] Rebaioli L and Fassi I 2017 *Int. J. Adv. Manuf. Technol.* **93** 2571-2598

[2] International Organization for Standardization 2015 ISO 52900

[3] Bourell D, Kruth JP, Leu M, Levy G, Rosen D, Beese AM and Clare A *CIRP Ann. - Manuf. Technol.* **66** 659-681

[4] Mallikarjuna U. 2013 *Sci. Eng. Compos. Mater.* **2** 1426-1432

[5] Leach RK, Bourell D, Carmignato S, Donmez A, Senin N and Dewulf W 2019 *CIRP Ann.* **68** 677- 700

[6] de Pastre MA, Toguem Tagne SC and Anwer N 2020 *CIRP J. Manuf. Sci. Technol.* **31** 14-24

[7] Moylan S, Slotwinski J, Cooke A, Jurrens K and Donmez MA. 2014 *J. Res. Natl. Inst. Stand. Technol.* **119** 429-459

[8] Mahesh M 2005 *PhD Thesis* National University of Singapore

[9] ASTM International 2014 - ASTM D638

[10] International Organization for Standardization 2019 - ISO 52902

[11] Minetola P, Iuliano L and Marchiandi G. 2016 *Procedia CIRP* **41** 1027-1032

[12] International Organization for Standardization 1988 - ISO 286-1

[13] Minetola P, Calignano F and Galati M. 2020 *Addit. Manuf.* **32** 101103

[14] Kruth J-P, Vandenbroucke B, Van Vaerenbergh J and Mercelis P. 2005 *International Conference Polymers & Moulds Innovations*

[15] Krishna AV, Faulcon M, Timmers B, Reddy VV, Barth H, Nilsson G and Rosén B G 2020 *Surf. Topogr. Metrol. Prop.* **8** 014001

[16] Pandey PM, Reddy NV and Dhande SG. 2003 *J. Mater. Process. Technol.* **9** 323-331

[17] Thompson MK et al. 2016 *CIRP Ann.* - Manuf. Technol. **65** 737-760

[18] Yang L, Hsu K, Baughman B, Godfrey D, Medina F, Menon M and Wiener S 2017 *Addit. Manuf*. **10** 81-160

[19] Booth JW, Alperovich J, Chawla P, Ma J, Reid TN and Ramani K. 2017 *J. Mech. Des. Trans. ASME* **139** 1-9

[20] Bracken J, Pomorski T, Armstrong C, Prabhu R, Simpson TW and Jablokow K 2020 *Addit. Manuf.* **35** 101163

[21] Spitaels L, Rivière-Lorphèvre E, Demarbaix A and Ducobu F. 2021 *21st International Conference & Exhibition*

[22] Siciliano B and Khatib O 2008 *Springer Handbook of Robotics* (Berlin: Springer).

[23] Scaravetti D, Dubois P and Duchamp R. 2008 *Int. J. Adv. Manuf. Technol.* **38** 683-690

[24] International Organization for Standardization 1996 - ISO 4288

[25] International Organization for Standardization 1989 - ISO2768-2

[26] International Organization for Standardization 1989 - ISO2768-1

[27] Weck M and Staimer D. 2002 *CIRP Ann.* **51** 671-683

[28] Briot S and Bonev IA. 2007 *Trans. Can. Soc. Mech. Eng.* **31** 445-455

[29] ASM International 2020 *Additive Manufacturing Processes*. vol 24 ed DL Bourell, W Frazier, H Kuhn, M Seifi ASM International