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A study on the dimensional accuracy of a Qidi Tech X-Max 3D printer

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***Abstract* – The world is filled with 3d printers and materials, allowing people to fulfil the fruits of their creative minds. However, certain projects require the production of objects within tight tolerances, and this can be a challenge for the majority of 3d printers. This paper aims to present a study on the dimensional accuracy and precision of a Qidi Tech X-Max 3d printer, by manufacture of three perforated plastic plates, equivalent to test sieve perforated metal plates, and measurement of these parts on an optical CMM, using a VBA program for calibration according to ISO 3310. This procedure makes it possible to calculate parameters at specific three-dimensional coordinates in the perforated plastic plate, allowing an exact characterization of the printing process. The hotbed surface height will be analysed as these printers are known for having warp issues that could be affecting the accuracy of the X and Y axes. The experimentation process yielded an original method for mechanical leveling of the hotbed.**

I. INTRODUCTION

Metrological activities for the verification of machine components require special tools for fitting and positioning standard measurement equipment. The conception of these tools can be a challenge and normally involves a trial-and-error cycle between design, production, and quality check stages, until fulfillment of the acceptance criteria. Resorting to external production on a metalworking facility can become a time consuming and expensive process. On the other hand, changing from metal to plastic facilitates production at the laboratory and provides the advantage of creating lighter tools. The Metrology Department of the Azorean Laboratory for Civil Engineering (LREC), designs and produces such tools on a Qidi X-Max 3D printer. Quality control measurements are conducted on a Mitutoyo optical CMM and results have been found to be out of tolerance. A perforated plastic plate (see Fig. 1) was designed and printed three times under different hotbed levelling adjustments, maintaining the calibration constants for all axes and extruder motor (see [1]). The aim is to measure the plate on the CMM and study its height, accuracy, repeatability, and influence between these characteristics. For reasons of similarity to a test sieve's metal wire cloth and perforated metal plate, manufactured according to [3] and [4], respectively, the printed plastic plates were measured by the same VBA program used in test sieve calibration.

Section II will present the method for the perforated plastic plate characterization of the printer.

Section III will present the method for examining the printer's hotbed.

Section IV will present the results of the hotbed surface height and plate measurements, covering an original method for the mechanical levelling of the hotbed.

II. PERFORATED PLASTIC PLATE CHARACTERIZATION METHOD

The perforated plastic plate used for the metrological characterization of the printer is presented in Fig.1.

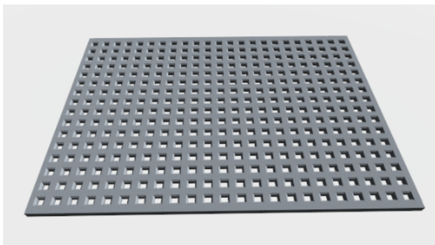

Fig. 1. Perforated plastic plate.

It consists of a part with overall dimensions of 280 mm by 200 mm and 5 mm thickness, designed with 23 apertures along the X axis and 16 apertures along the Y axis. Each aperture is square with an edge dimension of 5 mm, equivalent to a test sieve's perforated metal plate (see table 1 in [4]). The pitch between apertures is 12 mm in both directions, which differs from the 6,9 mm pitch specification in [4], for purposes of reducing the number of apertures. All internal edges where chamfered to 1 mm, in order to minimise incorrect measurements due to the expansion effects of the top and bottom layers.

An optical CMM machine was used to measure four points, namely X1, X2, Y1 and Y2 (as shown in Fig. 2), along the centre lines of each square aperture (hole), as specified in [3] and [4]. Each point has tridimensional coordinates and the X1's Z coordinate is used to evaluate the printed part height. The parameters for assessing the internal and external measurements, namely aperture dimension and aperture step, are based on [3] and [4] and calculated according to the following equations:

$$AD_{X} = \sqrt{\sum_{i=X,Y,Z} (X2_{i} - X1_{i})^{2}} \qquad (1)$$

where AD_X, $X1_i$ and $X2_i$ represent the aperture dimension and the tridimensional coordinates for the left and right edges of the aperture, respectively.

$$AS_{X}^{(n,1)} = \sqrt{\sum_{i=X,Y,Z} \left(X1_{i}^{(n,1)} - X1_{i}^{(n-1,1)}\right)^{2}} \qquad (2)$$

where AS_X stands for the tridimensional aperture step, on line 1, between columns n and n-1. Equations (1) and (2) also apply to the Y axis, by replacing X with Y. This parameter is equivalent to the pitch defined in [4]. However, the difference between the prime edges of the apertures was preferred over the centre differences, as specified in [4], so as to establish a single reference point.

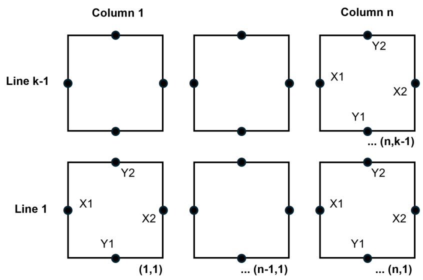

Fig. 2. Measurement scheme.

The measurement setup, shown in Fig. 3, consisted of placing a metallic ruler against two screws inserted into the CMM's table holes. The plate was placed on the glass and secured with gauge blocks on the sides and top. A 2,5 mm gauge block was placed on the lower left for reference. The Piece Coordinate System (PCS) was created on the 2,5 mm gauge block's top and right edges and the CMM's Z Axis was zeroed on this block's top edge. Both plate and reference gauge block were leaned against the ruler for alignment purposes.

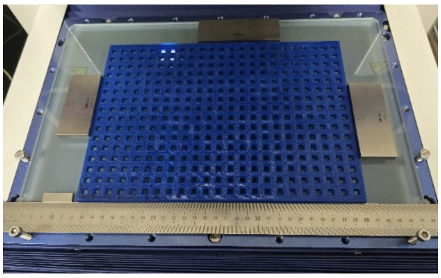

Fig. 3. Measurement setup.

Although [3] and [4] make no reference to uncertainty estimation, there will be presented two expanded uncertainties, namely U_1 and U_2. The first includes uncertainty sources due to the resolution, accuracy, repeatability and reproducibility of the CMM and measurement temperature. The second includes all the above plus the measurement repeatability, calculated by the sample standard deviation equation (STDEV.S), according to [3]. The expansion coefficient for the combined uncertainty is equal to 2.

A visual basic routine for test sieve calibration, according to [3] and [4], was used to automatically measure every aperture in the plate. This routine is implemented in the visual basic module of the Mitutoyo QVPAK software and was originally created by LREC to measure apertures within a range of 20 µm to 125 mm. Normally, the four points in each aperture are measured at the same Z level. However, major height differences between points sometimes occur due to printing defects or inadequate edge detection threshold value. A print screen from the Mitutoyo QVPAK software shows an example of a printing defect in Fig. 4. These irregular points were carefully searched, by moving the CMM to the measured point coordinates, and corrected by manual remeasurement of the edges. Alternatively, when only one point presents an abnormal Z value, it is corrected by calculating the average of the other three point's Z values.

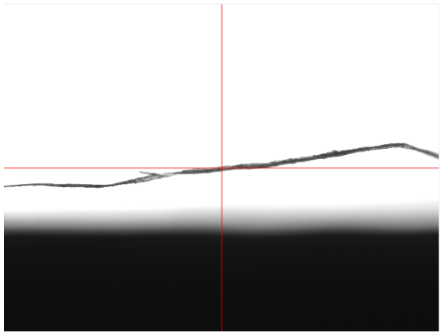

Fig. 4. Example of a printing defect on a bottom edge.

III. HOTBED EXAMINATION METHOD

The printer's extruder was dismounted from its carriage and a special holder, courtesy of [2], for a Mitutoyo digital indicator was mounted in its place, as shown in Fig. 5.

The printer was set to manual movement control, starting from the home position by moving the carriage to the upper right corner (X and Y axes) and the hotbed to the base of the printer (Z axis). Afterwards, the indicator's value was set to zero and the hotbed was moved upwards until it touched the tip of the indicator. After rezeroing the indicator, the Y axis was moved in 10 mm steps within a range of 0 to 220 mm, taking a measurement at each step, by pushbutton operation, through a digimatic data acquisition system. A series of measurements in the Y axis was completed for each 10 mm step in the X axis, within a range of 0 to 280 mm. The carriage was returned to the home position after each series of measurements and the indicator was zeroed before each series. Although the movement limits for the X and Y axis are of 303 mm and 255 mm, respectively, it was not possible to examine the whole print area due to indicator and carriage size restrictions.

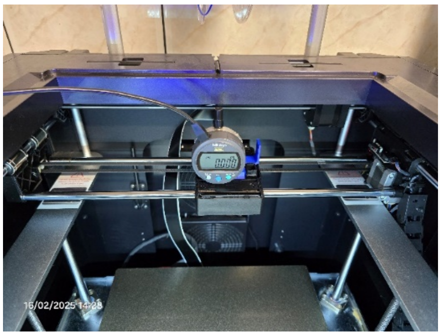

Fig. 5. Mitutoyo digital indicator mounted on the printer's carriage.

The uncertainty sources include the accuracy and repeatability of the digital indicator and the standard deviation of the measurements. The expansion coefficient for the combined uncertainty is equal to 2.

IV. PERFORATED PLASTIC PLATE AND HOTBED VERIFICATION RESULTS

A first plate was printed, for reference purposes, before the hotbed adjustments. From Fig. 6 and Table 1, it's possible to verify that the plate has a maximum height of 1,6 mm at the center, and that the aperture's dimension and step average errors are very small for both axes. However, the values of U_2 for both axes show a poor repeatability, which is confirmed in Fig. 7.

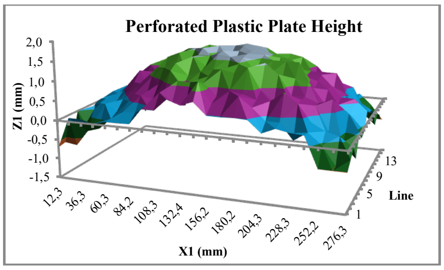

Fig. 6. First perforated plastic plate height.

From Table 2, it is observable that both axes present an equal variation range of 0,32 mm for the aperture dimension error. The asymmetry between the extreme values in the X axis shows an offset of -0,05 mm, in relation to the Y axis, which is equal to the aperture dimension error value in Table 1. The Y axis shows no significant divergence between its aperture dimension error extreme values, presented in Table 2, and the average step error in Table 1 is equal to zero in both axes. This means that the X axis presents a larger difference between internal and external dimensions error values than the Y axis. The aperture step error variation displays close values between axes. Nevertheless, Fig. 7 shows that this variation is not uniform along the X direction.

Table 1. Results for the aperture dimension and step.

Parameter	Value (mm)						
AD	Max	Min	U_1	Avg	s	U_2	Error
X	5,098	4,777	0,015	4,95	0,06	0,12	-0,05
Y	5,154	4,829	0,014	4,99	0,06	0,10	-0,01
AS							
X	12,178	11,848	0,015	12,00	0,07	0,14	0,00
Y	12,202	11,848	0,014	12,00	0,05	0,10	0,00

Table 2. Results for the error variation limits.

Axis	Aperture Dimension Error (mm)			Aperture Step Error (mm)		
	Max	Min	Range	Max	Min	Range
X	0,10	-0,22	0,32	0,18	-0,15	0,33
Y	0,15	-0,17	0,32	0,20	-0,15	0,35

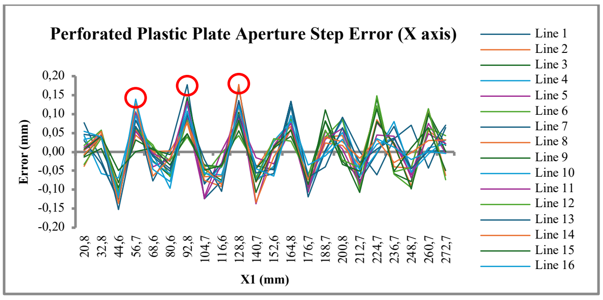

Fig. 7. First plate aperture step error (X axis).

After this first plate print, the height of the hotbed was measured. From Fig. 8, it's possible to verify that the front and left sides of the hotbed were more elevated than the home position. The maximum measured height value was 0,328 mm.

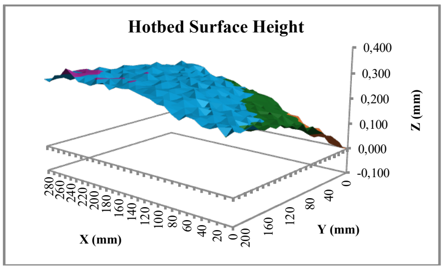

Fig. 8. First hotbed surface height measurement.

The hotbed has three levelling points. Originally, these points were supported by springs, which led to frequent misalignments of the hotbed. The springs were substituted by silicone columns in 2022. After this first surface height verification, experimentation led to two bed adjustment setups, by placing more silicone columns at strategic positions. The adjustment made on 20-03-2025 consisted of placing a silicone column at the rear right, but not directly under the home position, and an extra at the left front, as pointed out by the red circles in Fig. 9. Height results for this configuration (see Table 3 and Fig. 10) show a regular increment of 10 µm on the maximum values from 20-03-2025 to 25-03-2025, until stabilisation on 26-03-2025. The average value also confirms the hotbed's steadiness on the last day.

Table 3. Results for the hotbed surface height.

Date	Value (mm)				
	Max	Avg	Min	s	U
20-03-2025	0,090	0,042	-0,035	0,026	0,053
22-03-2025	0,100	0,051	-0,047	0,025	0,050
24-03-2025	0,109	0,057	-0,018	0,025	0,050
25-03-2025	0,119	0,066	-0,015	0,026	0,052
26-03-2025	0,120	0,067	-0,009	0,026	0,052

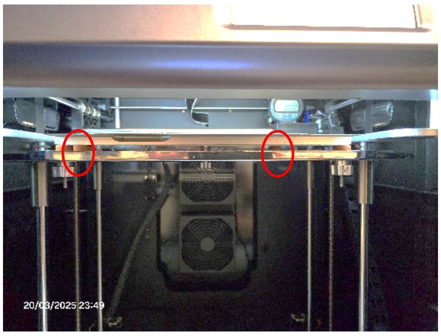

Fig. 9. Hotbed levelling adjustment.

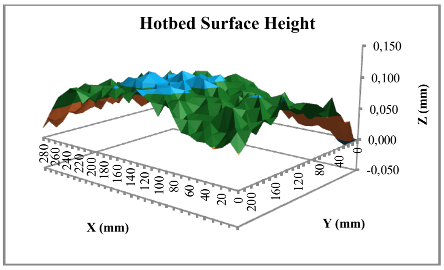

Fig. 10. Hotbed height measurement on 26-03-2025.

Comparing Fig. 8 and 10, it is visible that the hotbed is straighter, and surface height maximum value decreased from 0,328 mm to 0,120 mm. However, deformation in the hotbed's corners started to become noticeable. The results for the perforated plastic plate printed with this hotbed configuration (20-03-2025) are presented in Fig. 11 and Table 4.

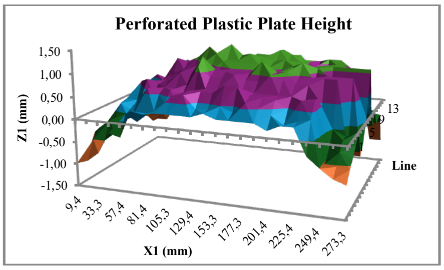

Fig. 11. Perforated plastic plate height (20-03-2025).

Table 4. Results for the aperture dimension and step (hotbed configuration from 20-03-2025).

Parameter	Value (mm)						
AD	Max	Min	U_1	Avg	s	U_2	Error
X	5,136	4,798	0,015	4,96	0,06	0,13	-0,04
Y	5,149	4,870	0,014	5,01	0,05	0,11	0,01
AS							
X	12,129	11,841	0,015	12,00	0,07	0,13	0,00
Y	12,136	11,873	0,014	12,00	0,05	0,11	0,00

Comparing Fig. 6 and 11, it is visible that the new plate is flatter in the middle section. The maximum height value decreased from 1,6 mm to 1,4 mm. There are no significant changes between the errors presented in Tables 1 and 4.

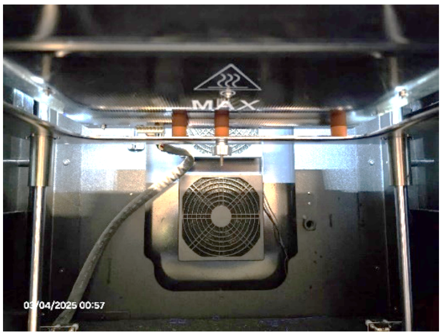

Fig. 12. Final hotbed levelling adjustment.

The best and final configuration is presented in Fig. 12, showing two extra silicone columns at the rear. One column was placed to the far right, directly below a screw, near the home position. The left column was more difficult to install, and its position had to be decided by trial and error, through the measurement of the surface height. The front columns level had to be compensated by washers, placed at the bottom of the silicone, and the extra column on the left was removed. This adjustment was made on 02-

04-2025 and surface height was measured for three days (see Table 5).

Table 5. Results for the hotbed surface height (Final Adjustment).

Date	Value (mm)				
	Max	Avg	Min	s	U
02-04-2025	0,057	0,000	-0,058	0,021	0,042
03-04-2025	0,053	-0,005	-0,071	0,023	0,047
04-04-2025	0,060	0,000	-0,061	0,021	0,043

Results in Table 5 reveal a significant improvement in the maximum height value measured in 02-04-2025, since there is a decrease from 0,328 mm to 0,057 mm. The levelling is stable because there is no significant variability on the extreme values and the average is practically equal to zero. The surface height chart in Fig. 13 shows that the front corners are at the lowest height. This presents a problem when executing the printer's standard four-point levelling because the adjusting screws can no longer be touched, and levelling can only be done by manual control of the printer's Z axis, in 0,05 mm steps, meaning that the center will have to be one step higher to compensate the front corners.

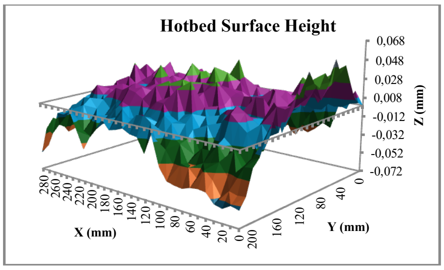

Fig. 13. Hotbed height measurement on 02-04-2025.

The results for the perforated plastic plate printed with this hotbed leveling adjustment (02-04-2025) are presented in Fig. 14 and Table 6.

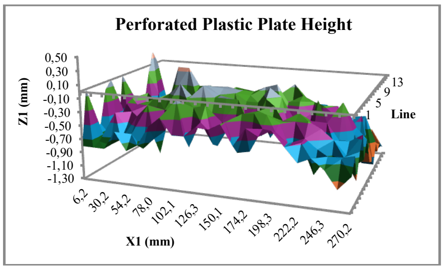

Fig. 14. Perforated plastic plate height (02-04-2025).

From Fig. 14, it is possible to see that this new plate is even flatter than the last one (see Fig. 11). Comparing with the first plate (see Fig. 6), it is visible that the height maximum value decreased from 1,6 mm to 0,20 mm. Comparing tables 1 and 6, a major decrease in the aperture dimension error is clear. This was caused by a change of printing filament from the same type (PLA PRO) but from a different brand. The extruder motor was not calibrated for this new filament and was over extruding by 2 mm. Therefore, the extra filament expanded to the inside of the aperture and reduced its dimensions. Nonetheless, Table 6 shows that the aperture dimension error has a difference of -0,05 mm between axes, which was already verified in Tables 1 and 4. Hence, this internal dimension difference between axes proves that the X axis offset verified in Table 2 is not dependent on extrusion flow calibration. On the other hand, aperture average step errors remained equal to 0,00 mm, which means that over-extrusion had no effect on the external dimension average error, although uncertainty has slightly risen due to the variation range increase of 0,09 mm shown in Tables 7 and 8.

Table 6. Results for the aperture dimension and step (hotbed configuration from 02-04-2025).

Parameter	Value (mm)						
AD	Max	Min	U_1	Avg	s	U_2	Error
X	4,991	4,473	0,015	4,68	0,07	0,15	-0,32
Y	4,971	4,537	0,014	4,73	0,08	0,15	-0,27
AS							
X	12,261	11,839	0,015	12,00	0,08	0,17	0,00
Y	12,198	11,756	0,014	12,00	0,07	0,14	0,00

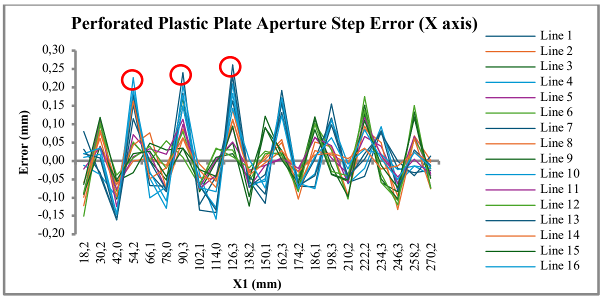

Fig. 15. Last plate aperture step error (X axis).

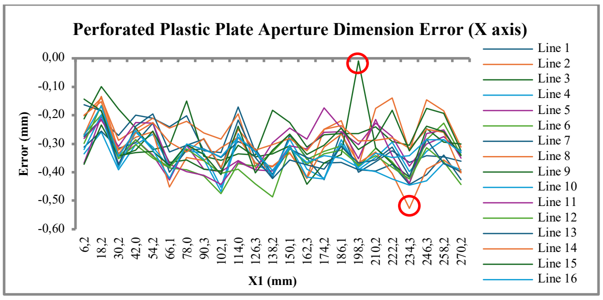

Fig. 16. Last plate aperture dimension error (X axis).

Comparing Fig. 7 and 15, it is possible to verify a pattern in the upper peak values of both prints, especially noticeable in the ones referenced by the red circles. These peak values are found in approximately the same X1 positions, within the range of 42 to 138 mm, in both plates and are probably caused by local deviations in the X axis structure.

Table 7. Variation comparison for the first and last plates (X Axis).

X Axis Variation (mm)						
Plate	Aperture Dimension Error			Aperture Step Error		
	Max	Min	Range	Max	Min	Range
First	0,10	-0,22	0,32	0,18	-0,15	0,33
Last	-0,01	-0,53	0,52	0,26	-0,16	0,42
	Difference		**0,20**	**Difference**		**0,09**

Table 8. Variation comparison for the first and last plates (Y Axis).

Y Axis Variation (mm)						
Plate	Aperture Dimension Error			Aperture Step Error		
	Max	Min	Range	Max	Min	Range
First	0,15	-0,17	0,32	0,20	-0,15	0,35
Last	-0,03	-0,46	0,43	0,20	-0,24	0,44
	Difference		**0,11**	**Difference**		**0,09**

V. CONCLUSIONS

The first surface height measurement presented in Fig. 8 showed an unbalanced hotbed with a maximum height value of 0,328 mm. This was a consequence of using the printer's normal bed levelling function, which consists of adjusting the distance between the bed and the extruder nozzle at four position points, utilising a sheet of paper to establish the levelling criteria. This method produced a plate with a significant deformation of 1,6 mm at the center, concluding that it will not accomplish bed surface height correction nor prevent print warping.

Through experimentation with the placement of silicone columns in strategic points under the hotbed, and validation of these positions by surface height measurement, it was possible to reduce the maximum height value of the hotbed from 0,328 mm to 0,060 mm, thus creating an original and effective mechanical adjustment method that produced straighter parts.

Results for the last printed plate showed a significant decrease in the aperture dimension error, caused by over-extrusion. However, the low error values shown in Tables 1 and 4 show that the extruder motor was calibrated, and this is periodically checked. The extruder was not recalibrated when changing the filament because it was PLA PRO, which was equal to the previous filament. The over extrusion was unexpected, and experience taught that filament brand has a significant impact on extrusion.

The aperture step average maintained a value of 12 mm in all plates, thus proving that the hotbed surface height, in this case, had no influence in the accuracy of the X and Y axes. Nonetheless, surface height minimization is important to fulfill quality requisites and for aesthetic reasons. Extrusion however was found to have a strong impact on internal dimension accuracy and should be the next characteristic to study. It also had a slight effect on repeatability for both internal and external dimensions.

The 0,2 mm increase in X axis aperture dimension error, shown in table 7, is not representative of the whole interval as there are two peak values, referenced in the red circles in Fig. 16, that overshoot. Considering the other difference values in Tables 7 and 8, it is possible to conclude that the over-extrusion caused a global increment of about 0,10 mm in axes variation range. This value is confirmed by comparison of the U_2 values in Tables 1 and 6, where uncertainty differences vary between 0,03 mm to 0,05 mm, approximately half of the 0,10 mm range value.

The patterns found in Fig. 7 and 15 show positioning errors along the X axis. It is important to find these errors by calibration with a standard equipment, like a linear ruler or an interferometer.

Finally, the perforated plastic plate production based on [3] and [4], allowed the successful characterization of the printer's X and Y axes, over a large hotbed printing area. Tables 1 and 4 show maximum values of -0,05 mm and 0,14 mm for accuracy and uncertainty, respectively, concluding that the printer has a good accuracy due to the calibrations of the axis and extruder, performed before this study. However, repeatability is one of the printer's weak points and is the reason of non-compliance to LREC's criterion of 0,10 mm, despite the 0,19 mm deviation value conformity to the commonly accepted accuracy tolerance of 0,20 mm.

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