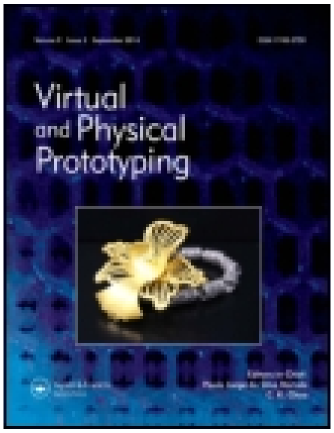

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Towards a standard experimental protocol for open source additive manufacturing

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Towards a standard experimental protocol for open source additive manufacturing

This paper proposes a benchmarking model for evaluating accuracy performance of 3D printers

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The technological development of open source three-dimensional (3D) printers is creating more affordable Additive Manufacturing (AM) machines for society in different applications. For this reason, the machines' capability should be evaluated in order to establish minimum standards of performance. This paper deals with the development, manufacture and testing of a geometrical benchmarking model (GBM) in order to evaluate the geometrical accuracy performance of open source 3D printers. The methodology is demonstrated with a case study based on fused deposition modelling (FDM). The case study positions the evaluated machine according to ANSI-ISO's International Tolerance (IT) Grades. Furthermore, root-mean-square deviation (RMSD) value is employed as an accuracy estimator, while Taguchi tools are employed to determine the control factors with the highest accuracy for the fabrication of the GBM.

Keywords: open source 3-dimensional printing; machine qualification; RepRap; benchmarking

1. Introduction

The convergence of information and communication technologies (ICT) with digital fabrication capabilities of Additive Manufacturing (AM), specifically the development of open source (OS) three-dimensional (3D) printers, is creating the appropriate knowledge-based social environments that enable independent production of modular hardware. This synergy could be transformed into a new disruptive paradigm of means of production for modular hardware (Kostakis and Papachristou 2014). In particular, material extrusion based units are widely used, thanks to the simplicity of operation, the Do-It-Yourself (DIY) approach and the open-support communities. It provides the possibility of mass diffusion of this technology, and consequently, AM is being recognised as a revolutionary technology that could up-end the last two centuries of approaches to design and manufacturing with profound geopolitical, economic, social, demographic, environmental and security implications (Garrido 2010, Campbell *et al*. 2011, Economist 2012, Rifkin 2012, Birtchnell and Urry 2013, Pearce 2014).

With the expiration of fused deposition modelling (FDM) patents (Crump 1988) in the mid-2000s, Adrian Bowyer envisioned the concept of self-replicating machines, capable of manufacturing their own parts by themselves, and so simple and easy that anyone would be able to build them (Sells *et al*. 2007, Holland *et al*. 2010, Jones *et al*. 2011). This was the start of the **RepRap** project (or **Rep**licating **Rap**id-prototyper). RepRap is a low-cost desktop rapid prototyper which manufactures approximately 57% of its own mechanical components (excluding fasteners, bolts and nuts). This project has been developed using an Open Design approach in which detailed information on the technical design and operations of the device is publicly available on the internet. In the literature, RepRaps have been proven to be useful tools in fields such as transport (Birtchnell and Urry 2013), education

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(Canessa *et al*. 2013), engineering (Sells *et al*. 2007, Kostakis and Papachristou 2014), tissue engineering (De Ciurana *et al*. 2013), chemical reaction wire, customising scientific equipment (Pearce 2012, 2014, Zhang *et al*. 2013), electronic sensors (Leigh *et al*. 2012), wire embedding (Bayless *et al*. 2010) and appropriate technology related to sustainable development (Pearce *et al*. 2010).

Characteristics of the RepRap project, such as its OS nature and its customisation and self-replication capability, open up the possibility for exponential growth for both products and 3D printer systems. The RepRap project has been an object of social experimentation, creating numerous enthusiasts and communities interested in supporting various RepRap models. Different parallel OS systems have emerged, such as Fab@Home 3D printer (Malone and Lipson 2007), the CupCake CNC and Thing-O-Matic 3D printers by MakerBot Inc (MakerBot 2014) and others. The RepRap website invites machine developers to register their project in a database in order to collect many different prototypes and projects. According to this database, there are approximately 500 models (RepRap.org 2014). This exponential growth makes it essential to evaluate the capabilities of machines in order to characterise and differentiate them. In fact, attention has been drawn to the relevance of logical evaluation tools for individuals to allow a fair comparison of the performance of a given unit to another through the use of a benchmarking process (Perez *et al*. 2013, Roberson *et al*. 2013).

In the context of commercial AM, several benchmarking propositions have been made to evaluate the performance of the techniques. Mahesh *et al*. (2006) present a methodology for identifying the best achievable quality characteristics to serve as a benchmark process using a case study involving the direct laser sintering (DLS) process. Scaravetti *et al*. (2007) worked on a benchmarking model and a procedure using a correlation matrix, in order to identify the defects of stereolithography (SL) processes for establishing whether their origins are machine or material linked. In the case of OS AM, Johnson *et al*. (2011) have evaluated an OS AM system based on the FDM technique through use of a benchmarking model in order to assess the dimensional accuracy, feature size and geometry limitation, and geometric and dimensional tolerance. The fabricated model was evaluated using a 3D laser scanning system, which has an accuracy of 0.0089 mm, far below the minimum feature size limitation of the used printer (0.08 mm). Using nearly 3 million data points, they observed a standard deviation of 0.3101 mm between the fabricated model and the computer-aided design (CAD) model, with 98.146% of the points within +/− 2 standard deviations.

Roberson *et al*. (2013) proposed a framework to evaluate the performance of a set of five 3D printer units, establishing a ranking method based on four factors (manufacturing time, cost of machine, material cost and dimensional accuracy) in order to establish a hierarchy among them. However, the authors recognised that a robust evaluation and comparison of the various AM systems are required and this research is still at an early stage. Indeed, it remains to be demonstrated that OS systems are capable of making objects in a robust way with good reproducibility. This evaluation, from the AM system user's point of view, will make it possible to know the performance of the different OS systems. On the other hand, from the point of view of an AM system developer, the evaluation of the reproducibility will enable the determination of optimal parameters of the process in order to replicate the system, ensuring the evolution of performance from generation to generation of the machines.

Following this path of research, this paper proposes an experimental protocol of geometrical performance evaluation in order to characterise OS 3D printers in a robust manner. Based on Design of Experiments (DoE) and integrating different families of geometrical objects, the dimensional accuracy of a representative 3D printer is intensively studied.

This paper is structured as follows: in section 2 an overview of the methodology is proposed. Subsequently, in section 3, the proposed methodology is applied in the case of the OS 3D printer FoldaRap. The results and the discussion are shown in section 4 and concluding remarks and perspective are given in section 5.

2. Methodology

There are two goals in the deployment of the methodology. The first is to evaluate the performance of an OS AM machine in terms of dimensional accuracy and reproducibility through statistical analysis of the set of manufactured samples. This quantitative qualification will make it possible to establish a characterisation of machine performance, in terms of four types of dimensional accuracy, as follows:

- **XY**- Plane
- **Z**-Axis.
- Circular features **-D-**
- Thin walls **-T-**

Once the degree of reproducibility of the machine is verified, the second goal is to find the parameters of the 3D printer machine, among the parameters tested, that give the lowest dimensional accuracy discrepancies possible for the fabrication of a benchmarking model. Figure 1 shows an overview of the different steps of the proposed methodology. These steps are detailed as follows:

2.1. Geometric benchmarking model

Benchmarking is a tool for comparing the performance of different similar systems (processes, organisations, machines) in order to establish standards of performance. It aims to identify the best achievable practices and processes. In this

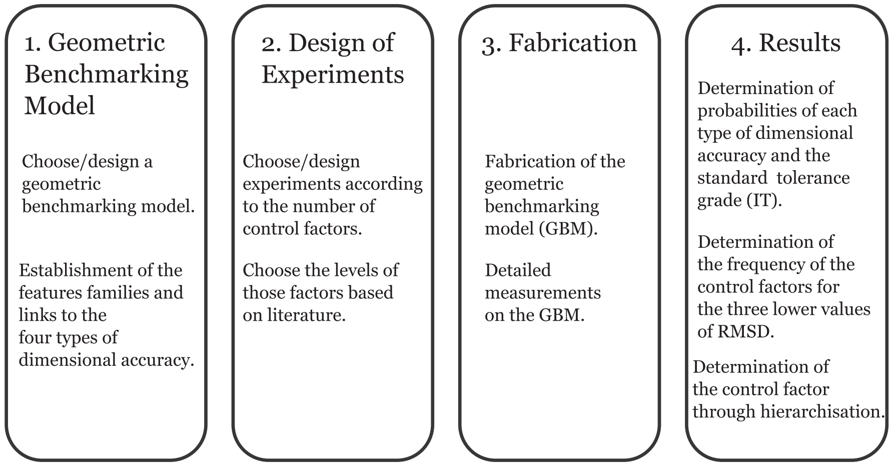


Figure 1. Overview of the proposed methodology. (RMSD = root-mean-square deviation)

step, the goal is to identify a model of reference intended for the evaluation of the OS AM system. Once a benchmarking model is adopted, it is intended to link different types of feature families with the four types of dimensional accuracies proposed.

In the commercial AM field, there have been several efforts to perform benchmarking studies for different processes through the use of comparative models. Kruth (1991) was the first to mention a benchmarking part for comparing AM processes, citing a study done by two Dutch companies using a U-shaped artefact with various geometric features such as circular shells (in various orientations), circular bosses, square holes and angled surfaces. This benchmark part focuses on the overall performance of the AM systems. Ippolito *et al*. (1995) worked on the development, manufacture and test of a benchmarking model in order to investigate dimensional accuracy and surface finish of various AM techniques such as SL, selective laser sintering (SLS), FDM, laminated object manufacturing (LOM) and solid ground curing (SGC). Jayaram *et al*. (1994) aimed to lay the groundwork for the development of standards to measure various performance factors such as repeatability, warpage, curl, creep, shrinkage and tensile strength in a quantitative way; test parts were designed for studying SL, SLS, LOM and FDM techniques. In 2000, Xu *et al*. (2000) presented a benchmarking model to evaluate differences in the material property, accuracy, surface finish, building cost-time, machinability and environmental effects of the SL, SLS, FDM and LOM processes. Mahesh *et al*. (2006) proposed a benchmarking model using a Six-sigma approach in order to (1) minimise process inconsistencies and defects of fabrication, and (2), to identify a best process/procedure to achieve desirable geometric accuracy and surface roughness in the DLS process. Fahad and Hopkinson (2012) proposed a geometric benchmarking part for evaluating the accuracy, tolerances and repeatability of parts produced by different AM processes. In summary, Mahesh (2004) identifies three types of benchmarking models in AM, as follows:

> *Geometric Benchmark;* used to check the geometric and dimensional accuracy of the prototype (i.e. tolerances, accuracy, repeatability and surface finish).
>
> *Mechanical Benchmark;* used to characterise the mechanical properties (i.e. tensile/compression strength, shrinkage, curling and creep characteristics.)
>
> *Process Benchmark;* used to establish process related parameters (part orientation, support structures, layer thickness, speed)

In addition, Moylan *et al*. (2012) summarise some items to consider in order to establish 'rules' for a geometric benchmarking model. Globally, benchmarking models should:

- be large enough to test the performance of the machine near the edges of the platform as well as near the centre,
- have a substantial number of small, medium and large features,
- not take long to build,
- not consume a large quantity of material,
- be easy to measure,
- have many features of a 'real' part,
- have simple geometrical shapes, allowing perfect definition and easy control of the geometry,
- require no post-treatment or manual intervention (no support structures),
- allow repeatability measurements.

Based on this literature, the objective of this step is to reach a final design of a Geometric Benchmarking Model (GBM). This design should incorporate geometric shapes and features that provide important information of the capabilities and limitations of the OS 3D printer analysed.

2.2. Design of experiments

The goal of this step is to establish the control factors to evaluate, the fixed factors to consider, and the sequence and quantity of samples to manufacture. One of the available approaches is the Taguchi method, which has been proven to be successful for improvement of product quality and process performance. This method provides an efficient and systematic approach to optimise a number of experiments and the feasibility to study the interaction effects among parameters, while maintaining valid conclusions (Fowlkes and Creveling 1995, Azadeh *et al*. 2011). In the literature of commercial AM, there have been several attempts to improve the dimensional accuracy of prototypes using adjustment of the process parameters. Using the Taguchi method, Zhou *et al*. (2000) worked on the accuracy of rapid prototyped SL parts analysing five factors, namely layer thickness, hatch spacing, overcure, blade gap and position on the build plane. They used an analysis of variance (ANOVA) approach to develop a second-order regression model establishing the best parameters to reduce the dimensional error to the smallest value. Anitha *et al*. (2001) assessed the influence of the layer thickness, road width and speed deposition on the surface roughness of the prototypes produced by the FDM process in order to minimise the surface roughness. The results indicate that layer thickness is the most influential process parameter affecting roughness, followed by road width and deposition speed. Mahesh *et al*. (2006) used the Taguchi method on the direct laser sintering (DLS) process in order to determine the setting of the key control factors for obtaining the best achievable result in terms of geometric accuracy and surface roughness for different individual geometric features such as sphere circle, cone, cylinders, square boss and wedge. Sood *et al*. (2009) investigated the effects of process parameters (orientation, layer thickness, raster angle, raster width and air gap) on FDM dimensional accuracy in order to reduce the percentage change in length, width and thickness of a test specimen. Results show shrinkage is dominant along the length and width of the test part, whereas thickness is always more than the desired value.

The authors are persuaded to adopt this method to evaluate the performance of an AM system in order to characterise the performance of the 3D printer.

2.3. Fabrication and measurement of geometric benchmarking model

The fabrication of the GBM is performed according to the instructions of the experiment design. It is intended in this protocol to use AM systems of an OS nature (less than US $1000). The selection of the machine to evaluate should be representative among the ensemble of AM systems currently in existence.

2.4. Results accuracy index and statistical analysis

The goal of this step is to quantify the dimensional accuracy of the machine, establishing a range of tolerance and confidence interval of the machine for every kind of dimensional accuracy proposed and to quantify the probability of reproducibility of the machine inside a range of deviation. The second goal is to establish an accuracy index for the control factors, which will make it possible to rank the set of combinations of control factors in order to determine those with the highest dimensional accuracy. In the next section, the approach will be illustrated by means of the evaluation of an OS AM system.

3. Application to an OS AM System: the case of the FoldaRap

3.1. Equipment

A derivative version of the RepRap machine, called FoldaRap (Gilloz 2014) (see Figure 2) was selected for this investigation. It is the first OS 3D printer designed to fold to a very small size to be completely portable. It is an OS design and it comes from a derivation of eMAKER Huxley (Giacalone 2014), VertX (Gilloz 2011a) and Pocket Laser Engraver (Gilloz 2011b). The FoldaRap machine is a representative 3D printer among the set of OS machines developed by the RepRap community. Indeed, as can be seen in the OS 3D printer family tree (Pearce 2014), the FoldaRap derives from the main branch (XZ Head, Y Bed): Darwin-Sells Mendel-Prusa Mendel.

This system can be described through three fundamental axes (Evans 2012, RepRapWiki 2014):

1. Machine architecture
2. Electronic hardware
3. Software

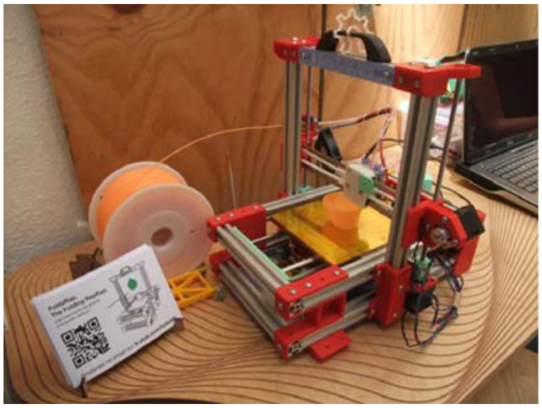


Figure 2. Open source 3D printer – FoldaRap.

Regarding the FoldaRap's architecture, it is a Cartesian 3D printer where the extrusion system can be displaced in the vertical plane XZ and the heated print bed can be displaced in the horizontal direction – Y. The work capability is 140 × 140 × 155 mm^3. Using a mechanical coupling stepper motor-drive gear, the extrusion system forces a PolyLactic Acid (PLA) polymer filament with a diameter of 1.75 mm into an aluminium melt chamber, then the filament is extruded through a 0.5 mm nozzle. The linear motion for positioning in the XY plane is achieved through machined plastics bushings and smooth rods 6 mm in diameter using a transmission mechanism of timing belts and pulleys. For *Z*-axis, threaded rods M5 and hexagonal nuts are coupled with a stepper motor with a minimum resolution of 0.00025 mm. The heated print bed is made of aluminium joined with a Peltier cell and it uses a top layer of kapton in order to improve the adherence of the piece with the print bed.

Concerning the electronic hardware and software, the FoldaRap machine uses a Melzi v2.0 controller board which makes it possible to control the machine via a USB connection (RepRapPro 2014). Marlin is used as firmware software, Slic3r software is used to convert the .STL files into G-codes, and Pronterface software is used as the system's host software. All these elements are OS.

FoldaRap has an indicated minimum value of layer height tested at 0.1 mm and it does not include the capacity to fabricate support structures. Figure 3 shows the structure of the machine schematically.

3.2. Benchmarking models in AM

Based on the discussion of section 2.1, this experiment uses a modified version of the model of the National Institute of Standards and Technology (NIST) (Moylan *et al*. 2012). The model is shown in Figure 4 and Table 1 summarises the features and characteristics. The modifications made in the benchmarking models have been in order to link different types of features with different types of accuracies of the machine proposed in this investigation.

The geometric benchmarking model is divided into 15 different types of family groups. Each family group is formed by various related features where each feature is systematically identified with a letter (A–O) and a number. Every feature is associated with at least one type of dimensional accuracy with the objective of evaluating each type of dimensional accuracy proposed. The dimensional accuracy can therefore be analysed with different features of the model; in this way, the dimensional accuracy obtained comes from a set of features. This approach will make it possible to characterise the performance of the open source 3D printer, and consequently it will make it possible to differentiate the machine from the other OS machines. Table 2 shows the allocation of the geometric features with respect to the four types of dimensional accuracy proposed.

3.3. Design of experiments

Based on the literature described in section 2.2, three control factors have been considered in this investigation. They are briefly defined as follows (Kumar Sahu 2011, Ranelluccithe 2014).

- *Layer thickness:* The thickness of a layer deposited by the nozzle, which depends upon the type of nozzle used.
- *Extrusion width:* The value of the width of the filament that leaves the printer nozzle.

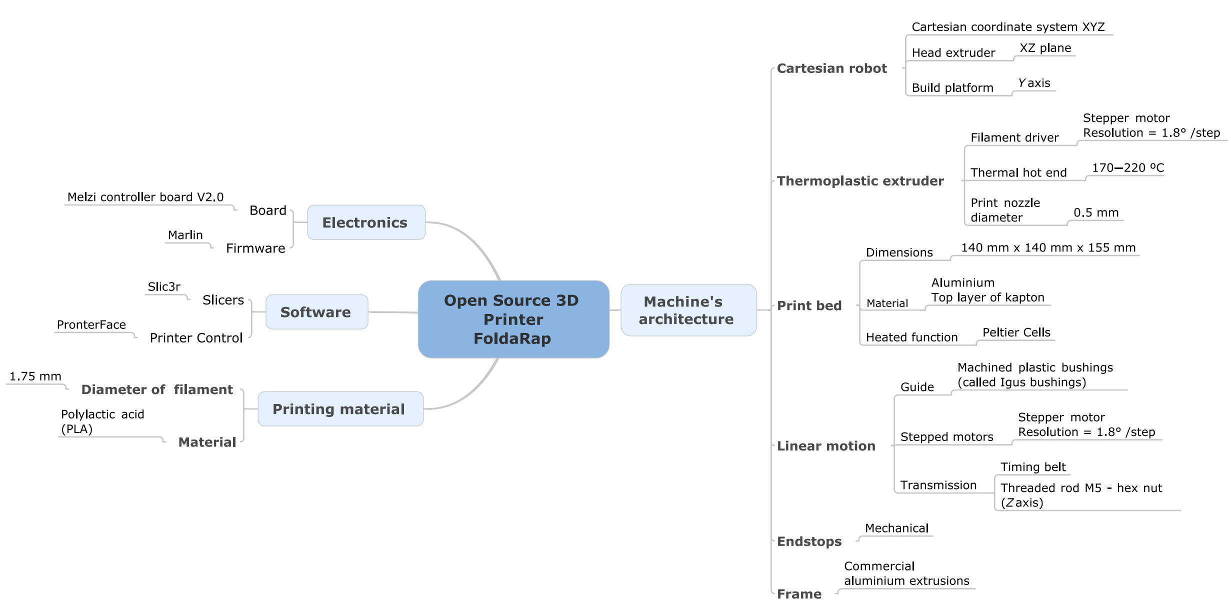


Figure 3. Main components of the FoldaRap 3D printer.

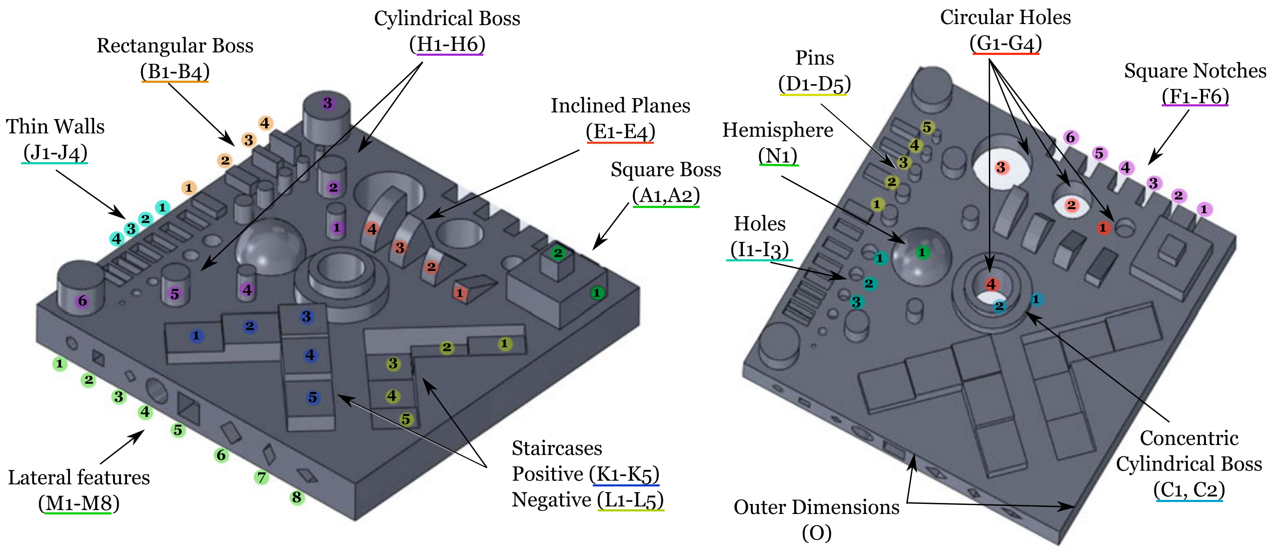


Figure 4. CAD version of benchmarking model with referenced feature identification (IDs).

Table 1. Benchmarking model feature descriptions.

ID	Family of features	Features	Description
A	Square Boss	A1–A2	A1 = 15 × 15 × 17 mm A2 = 5 × 5 × 22 mm
B	Rectangular Boss	B1–B4	B1 = 7 × 3 × 12 mm, B2 = 7 × 3 × 13mm B3 = 7 × 2 × 14 mm, B4 = 7 × 2 × 15 mm
C	Concentric cylindrical boss	C1–C2	C1 = Ø 20 mm C2 = Ø 14 mm
D	Pins	D1–D5	D1 = Ø 4 mm, D2 = Ø 3.5 mm, D3 = Ø 3 mm D4 = Ø 2.5 mm & D5 = Ø 2 mm
E	Inclines	E1–E4	E1 = 13.83 mm (15°), E2 = 17.07 mm (45°) E3 = 19.24 mm (75°), E4 = 20 mm (90°)
F	Square Notches	F1–F6	F1 = 1.5 mm, F2 = 2 mm, F3 = 2.5 mm F4 = 3 mm, F5 = 3.5 mm, F6 = 4 mm
G	Circular Holes	G1–G4	G1 = Ø 5 mm. (Prof. 5 mm) G2 = Ø 10 mm, G3 = Ø 15 mm G4 = Ø 10 mm
H	Cylindrical Boss	H1–H6	H1, H4 = Ø 4 mm H2, H5 = Ø 6 mm H3, H6 = Ø 10 mm
I	Holes	I1–I3	I1 = Ø 4 mm, I2 = Ø 3.5 mm, I3 = Ø 3 mm Prof. 5 mm
J	Thin walls	J1–J4	J1 = 2 mm, J2 = 1.5 mm J3 = 3 mm, J4 = 3 mm
K	Positive Staircases	K1–K5	Height 2, 4, 5, 6, & 7 mm width 10mm
L	Negative Staircases	L1–L5	Height 2, 4, 5, 6 & 7 mm width 10 mm
M	Lateral Features	M1–M8	M1= Ø 3 mm, M2 = 3 × 3 mm, M3 = 3 × 3 mm M4 = Ø 6 mm, M5 = 6 × 6 mm, M6 = 6 × 6mm M7 = 6 mm (Z-axis), M8 = 6 mm Features in the vertical plane.
N	Hemisphere	N1	r = 8 mm
O	Outer Dimensions	X–Y–Z	90 × 90 × 10 mm

- *Nozzle speed:* The speed of the printer nozzle when it fabricates the object. (Speed of perimeters, small perimeters, external perimeters, infill – solid, top, bottom layers).

Table 3 shows the respective levels of each factor.

On the other hand, fixed factors considered in this investigation are shown in Table 4.

In classical Design of Experiments (DoE), the study of three factors at three levels would require 27 (3^3) experiments. Using Taguchi's approach, a reliable estimation of the effect of factors can be obtained by using an *orthogonal array* with fewer experiments. The appropriate orthogonal array for this experiment is L_9 (3^4). This array consists of nine rows for the experiment conditions of the control factors and four columns for assigning the factors or interactions. Table 5 shows the columns and the disposition of the control factors used in this investigation.

3.4. Fabrication

Using Taguchi's array proposed in the previous section, and the geometric benchmarking model developed in section 3.2, the OS 3D printer 'FoldaRap' manufactured a total of 18 samples. That means that two samples were fabricated for each row of the array. Figure 5 shows the coordinates system used by the 3D printer for manufacturing the samples. It is at 45° with respect to the outer edges of the model.

The total time consumed by the machine was approximately 60 hours. Figure 6 shows the time for each sample.

The results show that control factors for sample #1 (Layer thickness = 0.13 mm, Raster width = 0.54 mm and Nozzle speed = 25 mm/s) are the most time-consuming during fabrication. By contrast, control factors for sample #8 (Layer thickness = 0.25 mm,

Table 2. Corresponding geometric features of each type of dimensional accuracy.

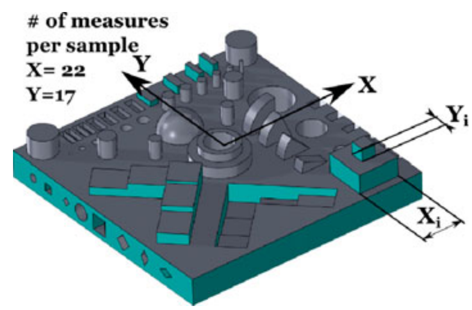
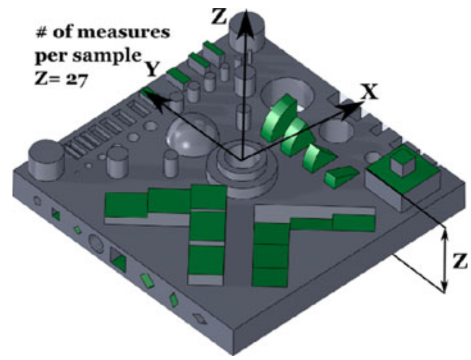
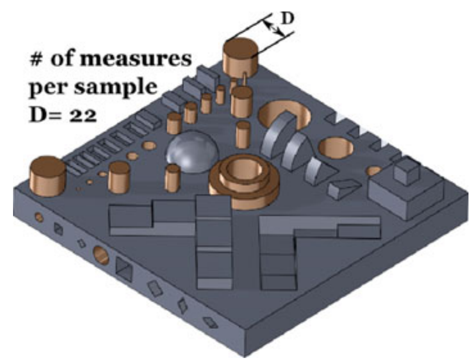
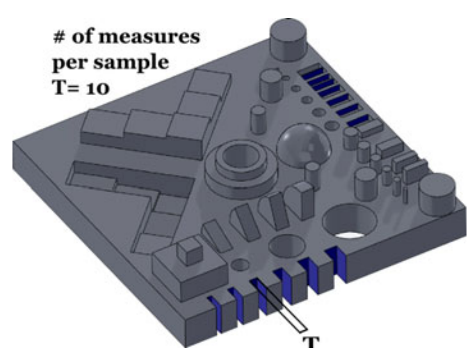
Dimensional Accuracy	Features	
XY Plane	A1, A2 B1–B4 K1–K5 L1–L5 M2, M3, M5, M6, M8 O	
Z-Axis	A1, A2 B1–B4 E1–E4 K1–K5 L1–L5 M2, M3, M5, M6, M7 N1 O	
Diameters	C1, C2 D1–D5 G1–G4 H1–H6 I1–I3 M1,M4	
Think walls	F1–F6 J1–J4	

Table 3. Control factors.

Control factors	ID	Levels 1	2	3	Units
Layer thickness	A	0.13	0.18	0.25	mm
Raster width	B	0.54	0.62	0.71	mm
Nozzle speed	C	25	50	75	mm/s

Table 4. Fixed factors

Parameters	Value	Units
Bed temperature	52	°C
Nozzle temperature	190	°C
# of perimeters	2	
Top solid layers	2	
Bottom solid layers	2	
Fill density	30	%
Material	PLA	
# of repetitions	2	
Travel speed	200	mm/s
Nozzle diameter	0.5	mm
Filament diameter	1.75	mm
Support	Non	
Slic3r software for generation of G-code		

Raster width = 0.62 mm and Nozzle speed = 75 mm/s) were systematically the fastest. However, the samples fabricated show that the finish surface is not the same for both control factors. These parameters have a major influence on this as shown in Figure 7.

This time consumption criterion is a relevant factor in a tool for selection and characterisation of an OS 3D printer.

4. Results and discussion

In this part, we will first present a statistical analysis of all the previous measurements. Then we will compare the dimensional accuracy obtained with our OS 3D printer and professional 3D printers.

As explained in the methodology (section 3), we considered three control factors (A, B, C) leading to the set of combinations shown in Table 3. In order to obtain the best set of

Table 5. Taguchi's L_9 (3^4) orthogonal array.

# Sample	Control factors A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

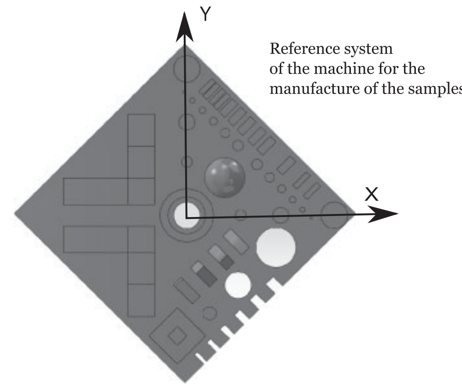


Figure 5. Coordinate system used in the manufacturing of the samples.

parameters regarding the geometrical accuracy, two approaches will be proposed.

4.1. Statistical analysis

Upon completion of the fabrication of samples, the measurements were performed using a digital Mitutoyo caliper with a measurement degree of 0.01mm. Each feature of the benchmarking model was measured twice, reducing the incertitude of the measurement. Therefore, a total of 3528 measurements were taken from the 18 samples fabricated. For each feature of the benchmarking model (A_i–N_i), mean percentage deviation value $Y1$ for the first repetition and $Y2$ for second repetition were found using Equation (1):

$$\%\Delta Y = \frac{|Y - Y_{CAD}|}{Y_{CAD}} * 100\% \tag{1}$$

Figure 8 shows the histogram of the database.

Using the classification of section 3.2, it is possible to establish the probability of the machine for making features that fall within a particular range of dimensional percentage change. This is achieved by using the probability density function for each type of dimensional accuracy proposed and for the total of data. In this way, it is feasible to compare each accuracy level in order to characterise the performance of the machine.

In Figure 9, the area under the curve of each type of accuracy gives the probability of the machine for manufacturing the geometric benchmarking model within a specific range of deviation. In this research, a range of (−5%, 5%) with respect to a target measurement is selected as the initial criteria. The ideal machine is one whose probability is 100% within an infinitesimal range close to zero. In this case, the results show that the overall probability of the machine is 82.14%. Similarly, the probability to obtain a measurement in this range is 87.53% in the XY plane, 88.16% in the Z-axis, 76.64% in diameters and 56.94% in thin walls. It should be emphasised that each of those probabilities was obtained from a different quantity of data N.

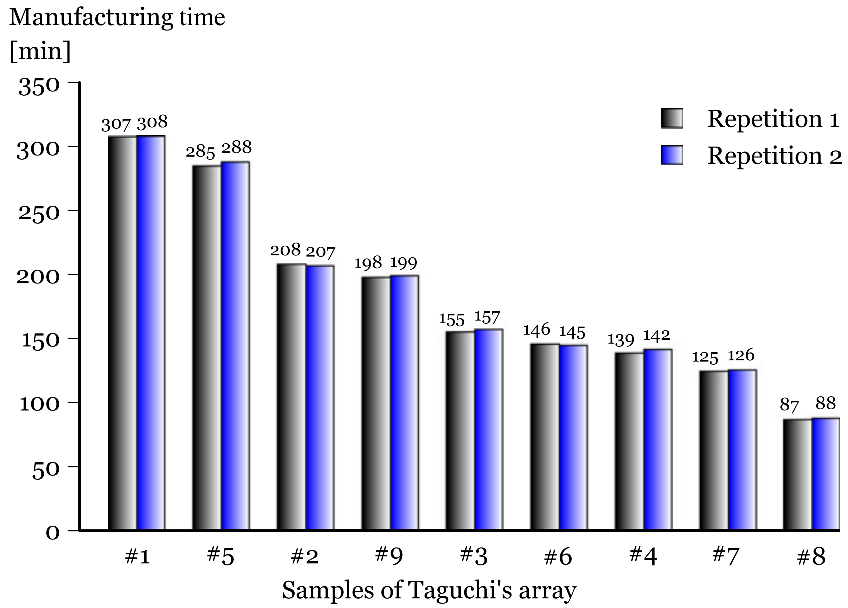


Figure 6. Fabrication time of the control factor sorted in descending order.

The features of the geometric benchmarking model were divided into the four types; however, this division was not equal in the number of data obtained.

4.2. International tolerance for the FoldaRap

Introducing the International Tolerance (IT) grade established by ISO-ANSI standards UNI EN 20286-I (1995) based on the total set of measurements taken and the corresponding deviations, the maximum tolerance grade obtained for the samples is calculated. This value places the dimensional performance of the FoldaRap machine with respect to the performance of other AM techniques. The standard tolerance value considers a tolerance factor 'i' (µm) indicated by Equation (2):

$$i = 0.45\sqrt[3]{D + 0.001D} \qquad (2)$$

where D is the geometric mean of the range of nominal size in mm. In this case, the standard tolerance value is calculated for a

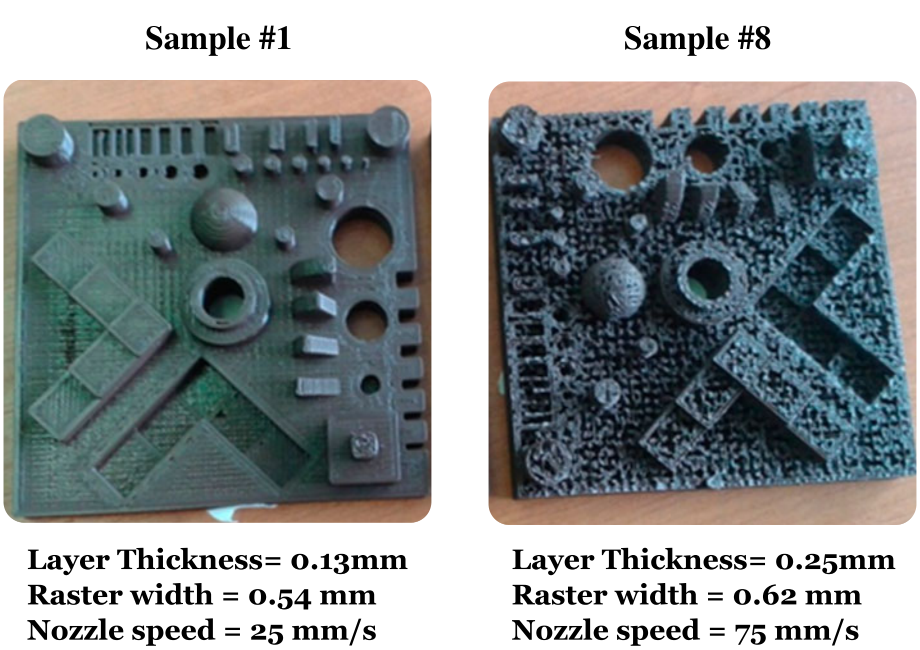


Figure 7. Surface finish of Sample 1 (slowest manufacturing time) and Sample 8 (fastest manufacturing time).

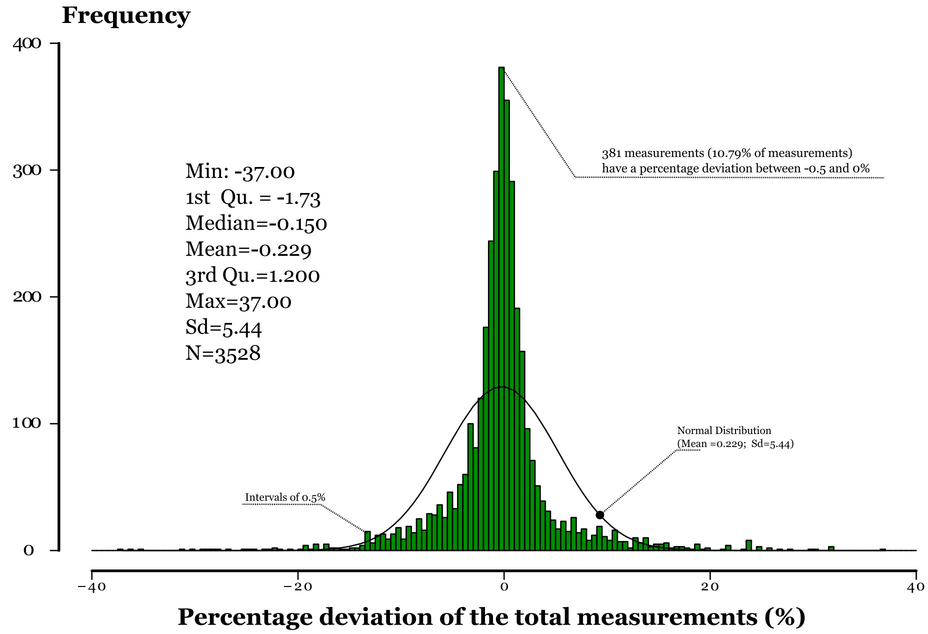
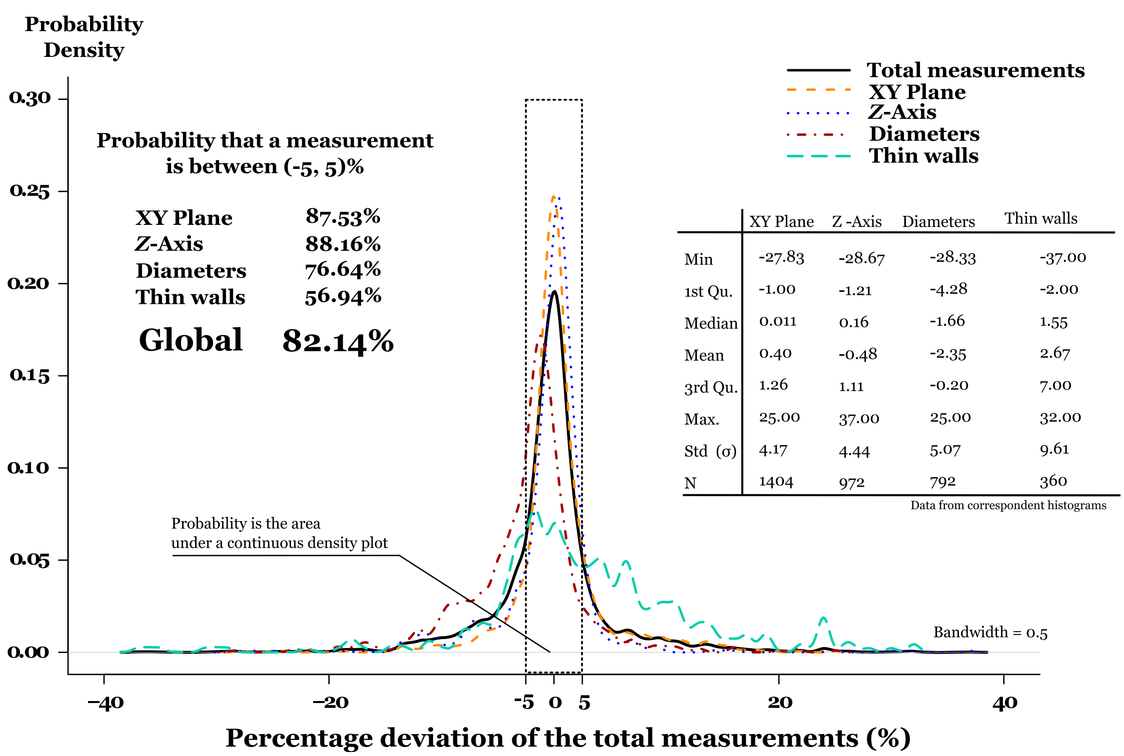


Figure 8. Distribution of the total measurement percentage deviation.



	XY Plane	Z -Axis	Diameters	Thin walls
Min	-27.83	-28.67	-28.33	-37.00
1st Qu.	-1.00	-1.21	-4.28	-2.00
Median	0.011	0.16	-1.66	1.55
Mean	0.40	-0.48	-2.35	2.67
3rd Qu.	1.26	1.11	-0.20	7.00
Max.	25.00	37.00	25.00	32.00
Std (σ)	4.17	4.44	5.07	9.61
N	1404	972	792	360

Data from correspondent histograms

Figure 9. Density plot of the types of dimensional accuracy with the respective probability values in the range (−0.5%, 0.5%).

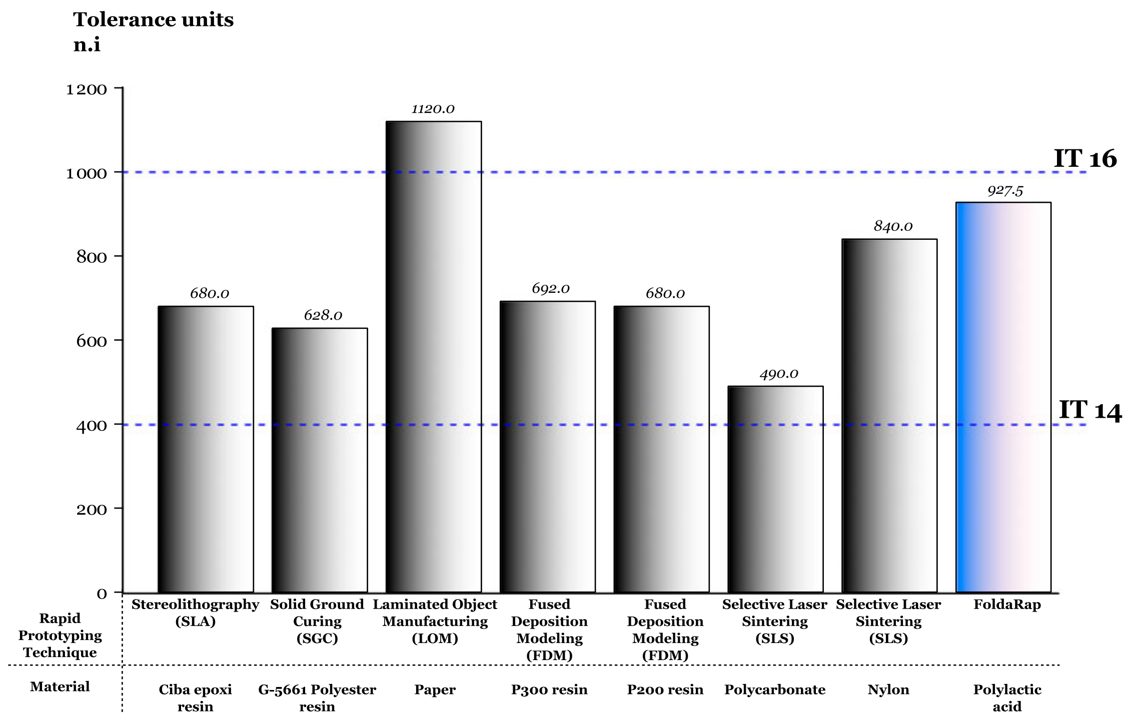


Figure 10. Comparison of the maximum tolerance grade among different AM processes.

range of nominal size. For a generic nominal dimension D_{CAD}, the number of tolerance unit n is evaluated as follows (Singh 2011).

$$n * i = 1000(D_{CAD} - D_{mea}) \tag{3}$$

where D_{mea} is the measured dimension. Using Equation (3), the maximum value ni among the set of measures obtained from the fabrication of the 18 samples is yielded. On a global scale, this value makes it possible to compare the performance of the OS machine 3D printer with the other AM technologies. Figure 10 positions the results of the FoldaRap's case with regard to the work developed by Ippolito *et al*. (1995).

Table 6 shows the comparison of IT grades for conventional manufacturing processes, including the AM techniques (Singh 2011).

We can see through Figure 10 that, though the precision level of the FoldaRap machine is lower with respect to the different commercial AM techniques, the performance of the machine is within the range of standard tolerance grades (IT14–IT16). This means that the tolerance of the machine is from IT14=400$i(\mu m)$ to IT16=1000$i(\mu m)$, where i is calculated based on Equation (2).

Table 6. Tolerance grades for various manufacturing processes.

	IT GRADES										
Process	6	7	8	9	10	11	12	13	14	15	16
Sand Casting											
Die Casting											
Hot Forging											
Material Removal Processes											
Rapid Prototyping Techniques											

4.3. Optimal control factors for the GBM

4.3.1. Using the DoE approach to select the most relevant control factors

Quantifying the effect of the control factors identified in section 3.3 with the DoE method, should help to reduce the number of measurements required to evaluate the performance of the 3D printers. The nine experiments listed in the Taguchi table L_9 (3^4) gave the following results concerning the mean percentage deviation value $\Delta\tilde{Y}_1$ for the first repetition and $\Delta\tilde{Y}_2$ for the second repetition showed in Table 8.

Calculating the mean effect of the control factors gives the following results shown in Figure 11.

At first glance, there is no overriding effect of control factors and it does not seem possible to reduce the model of the accuracy of the 3D printers. In order to provide a correct interpretation of the effect of factors, an ANOVA analysis is necessary. This provides a significance rating of the relative influence of each factor analysed in this study. Factors which significantly influence the percentage deviation of the model can be identified. A variable possessing the maximum value of variance is said to have the most significant effect on the

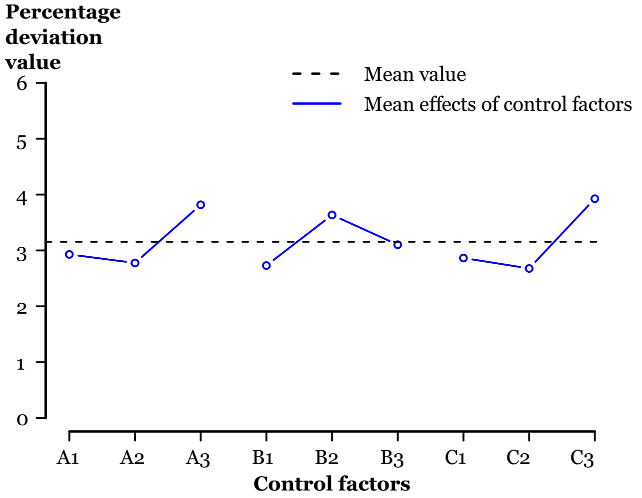


Figure 11. Variation of the percentage deviation value depending on the control factors.

experiment. Therefore, based on the responses of the mean percentage deviation values $\Delta\tilde{Y}_1$ and $\Delta\tilde{Y}_2$ showed in Table 7, the ANOVA computations were carried out.

ANOVA results (Table 9) show that the only significant control factor is the nozzle speed, but more importantly, that there are unusually large residuals (contribution: 32.9%). This confirms that the noise produced by this type of machine has more impact than the effect of the control factors. Elements of noise that can affect the experimentation are shown in Figure 12.

The DoE approach is therefore not relevant for machines with this precision level. Consequently, another methodology to obtain the best combination of control factors for fabrication of the GBM is proposed.

4.3.2. Proposed method

The objective is to rank the control factors according to Taguchi's array proposed in section 3.3, in order to find within the nine combinations those control factors with the highest accuracy. As an estimator parameter, the root-mean-square deviation (RMSD) is used. This was calculated as follows:

$$RMSD_i = \sqrt{\left(\sum_{i=1}^{m} \frac{x_i - \tilde{x}}{m}\right)^2 + \left(\frac{\sum_{i=1}^{m} x_i}{m} - Y_{CAD}\right)^2} \quad (4)$$

where the first term is the variance (σ^2) of the measurements obtained and the second term is the deviation of the mean value A with respect to the target value (Y_{CAD}). The m value is the quantity of measurements taken for each feature. If the RMSD value of a feature is zero, this would mean that every measurement taken is always the same ($\sigma^2 = 0$) and this measurement is always equal to the corresponding CAD model measurement ($\bar{x} = 0$), thus, the lower the RMSD value, the more accurate the feature. Using this approach, the RMSD value of each feature gives an estimation of the machine's performance when it uses a control factor of the Taguchi array. In this way, the RMSD measurement makes it possible to rank, from best to worst, every control factor for every feature of each manufactured sample.

It is intended to collect in a database the three control factors with the minimum value of RMSD for each feature. Figure 13 schematically shows the proposed strategy. The aim of this

Table 7. Mean value of percentage deviation.

# Sample	Factors			Response	
	A	B	C	$\Delta\tilde{Y}_1$	$\Delta\tilde{Y}_2$
1	1	1	1	3.307	2.113
2	1	2	2	2.398	2.752
3	1	3	3	2.678	4.213
4	2	1	3	2.476	3.053
5	2	2	1	2.328	3.202
6	2	3	2	2.308	3.178
7	3	1	2	2.498	2.930
8	3	2	3	5.227	5.901
9	3	3	1	2.935	3.299

Table 8. Mean effect of the control factors.

Control factors	Level	Mean value	Effect
Layer Thickness (mm)	1	2.91	−0.25
	2	2.76	−0.40
	3	3.80	0.64
Raster width (mm)	1	2.73	−0.43
	2	3.63	0.48
	3	3.10	−0.05
Nozzle speed (mm/s)	1	2.86	−0.29
	2	2.68	−0.48
	3	3.92	0.77

Table 9. ANOVA analysis.

	Factors	DOF	SS	V	F value	Pr (>F)	Contribution
Y1	Layer thickness [mm]	2	3.791	1.895	3.629	0.061	21.7%
	Raster width [mm]	2	2.483	1.241	2.377	0.138	14.2%
	Nozzle speed [mm/s]	2	5.430	2.715	5.198	0.025	31.1%
	Residuals	11	5.746	0.522			32.9%
	Total	17	17.450				

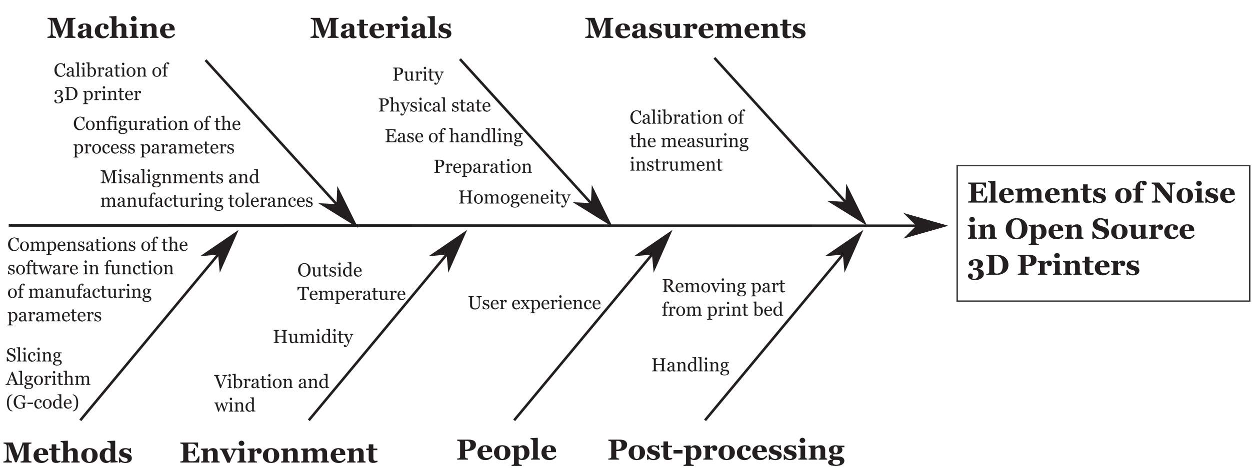


Figure 12. Ishikawa diagram of the factors that could affect the open source 3D printers.

strategy is to obtain the frequency of every control factor when they are selected as the most accurate, the second most accurate and the third most accurate. Using this frequency, we can establish a link between the performance of the 3D printer in terms of dimensional precision and the process parameters of the process. Figure 14 shows the histograms of the control factors for each type of frequency.

Through the use of these frequencies, the purpose is to determine a hierarchy of the control factors in order to find out which of them has systematically been the most accurate throughout the set of measurements of the benchmarking model. As a result, a *Global Index* of performance is established with three relative weights w_i for pondering the significance of each type of frequency, giving more importance

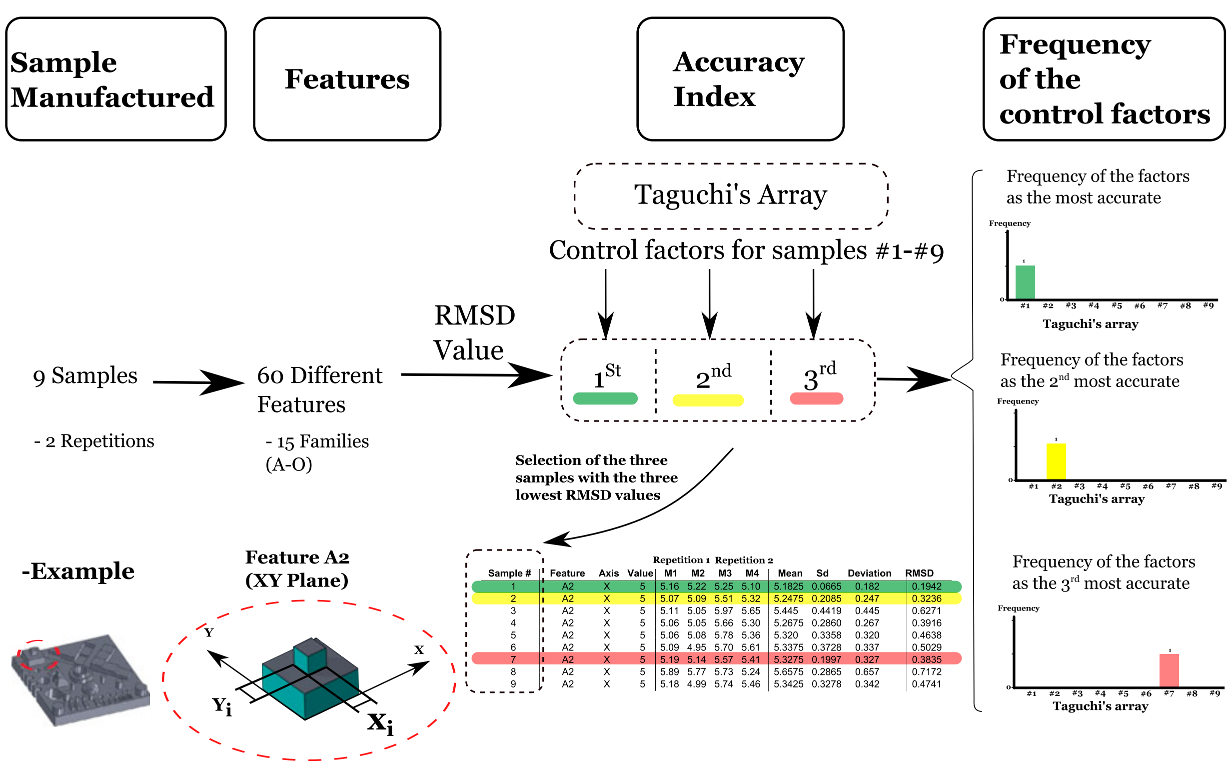


Figure 13. Methodology of selection of the three best control factors.

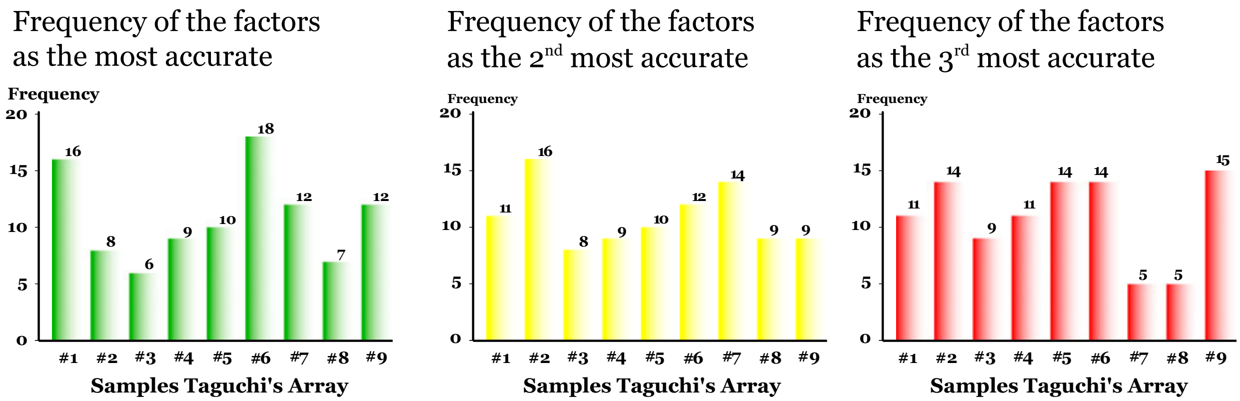


Figure 14. Frequencies of the control factors.

$$Global\ Index = I_j = \sum_{i=1}^{n} w_i * f_{j,n}$$

$$w_1 = \frac{1}{2}, w_2 = \frac{1}{3}, w_3 = \frac{1}{6}$$

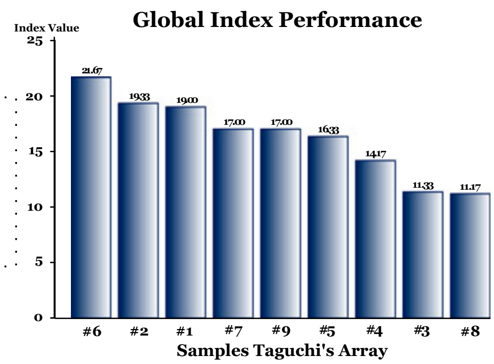


Figure 15. Performance index of each control factor tested according to Taguchi's array.

to a set of frequencies of the factors qualified as the most accurate.

Figure 15 shows the results of this approach. Taguchi's control parameters for sample #6 (Layer thickness = 0.18 mm, Raster width = 0.71 mm and Nozzle speed movement = 50 mm/s) were identified as the best parameters within the total parameters established through the use of the Taguchi array.

4.4. Discussion

The first comment can be made with regard to build time needed for the 18 samples. In fact, it has taken nearly 60 hours to print all the samples. In order to reduce this time, it will be interesting to simplify the GBM. In Figure 16, the RMSD value is calculated for every feature (A–O) of each sample (Table 1). In this figure, dimensional accuracy in the XY plane and the Z-axis for the lateral features are those having the lowest geometrical performance. Further experimentation is then needed in order to determine whether this weakness is specific to the FoldaRap 3D printer or if it could be generalised to the Cartesian family of printers.

5. Conclusion

In the present work, an experimental protocol to evaluate OS 3D printers regarding dimensional accuracy has been proposed. We use the proposed protocol on a representative 3D printer: the FoldaRap. It was found that the International Standard Tolerance Grade of this machine is situated between IT14 and IT16.

On the other hand, the process parameters that give the highest accuracy for the fabrication of the geometric benchmarking model have been obtained using the Taguchi approach coupled with the root-mean-square deviation (RMSD) value as an accuracy estimator. The results of this approach show that the following parameters: Layer thickness = 0.18 mm, Raster width = 0.71 mm and Nozzle speed movement = 50 mm/s have been systematically present with a low RMSD value in the fabrication of the 18 samples of the geometrical benchmarking model.

Furthermore, results regarding deviation of the features used suggest that the proposed protocol could be optimised in order to reduce the overall experimental time (60 hours).

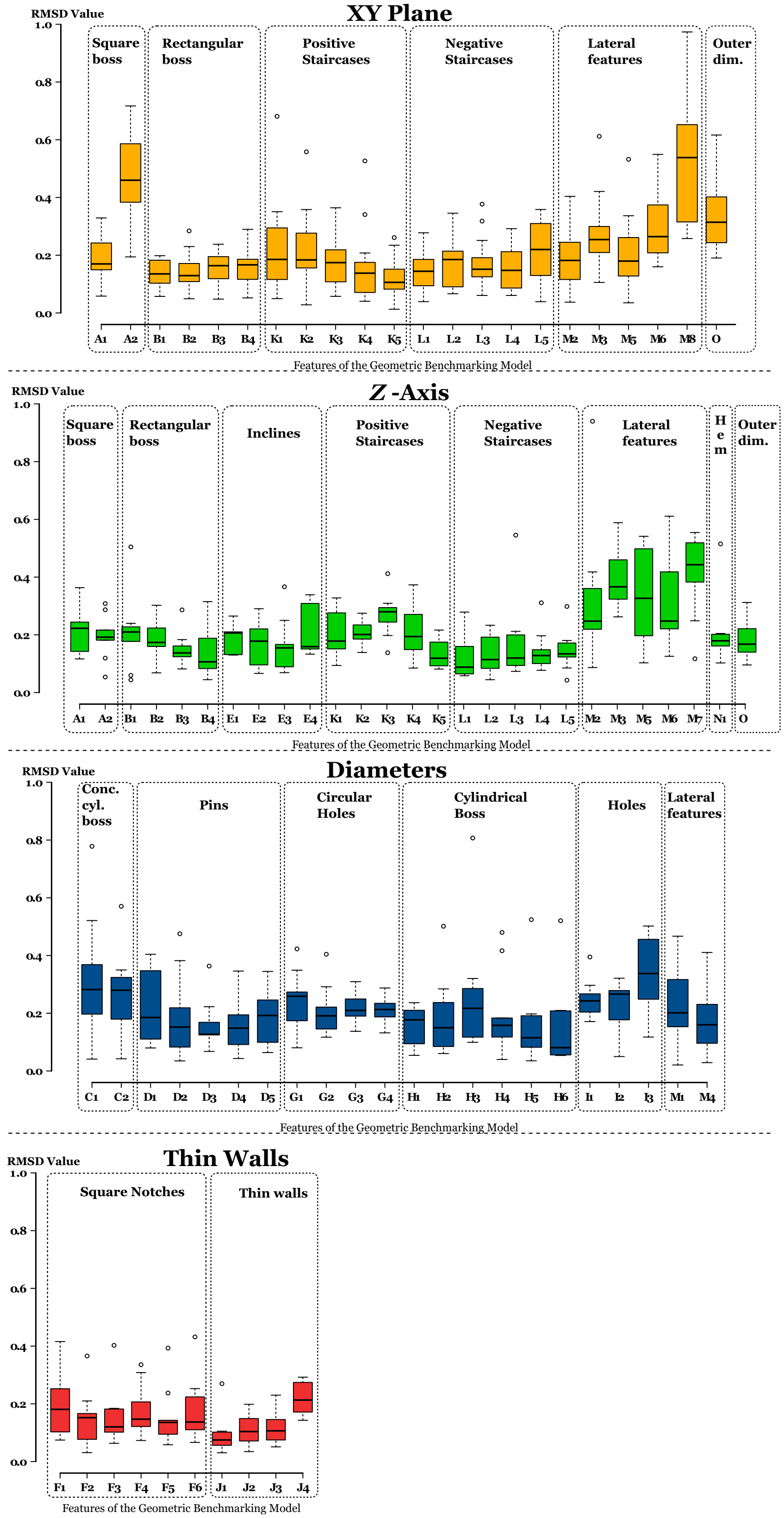


Figure 16. Variation of the RMSD value of each feature of the GBMs according to the four types of accuracy.

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