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ORIGINAL ARTICLE

Evaluation of geometrical benchmark artifacts containing multiple overhang lengths fabricated using material extrusion technique

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ABSTRACT – Fused deposition modelling (FDM) is a process of joining materials based on material entrusion technique to produce objects from 3D model using layer-by-layer technique as opposed to subtractive manufacturing. However, many challenges arise in the FDM-printed part such as warping, first layer problem and elephant food that was led to an error in dimensional accuracy of the printed parts especially for the overhanging parts. Hence, in order to investigate the manufacturability of the FDM printed part, various geometrical and manufacturing features were developed using the benchmarking artifacts. Therefore, in this study, new benchmarking artifacts containing multiple overhang lengths were proposed. After the benchmarking artifacts were developed, each of the features were inspected using 3D laser scanner to measure the dimensional accuracy and tolerances. Based on 3D scanned parts, 80% of the fabricated parts were fabricated within ±0.5 mm of dimensional accuracy as compared with the CAD data. In addition, the multiple overhang lengths were also successfully fabricated with a very significant of filament sagging observed.

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Multiple length overhang; geometrical benchmark; fused deposition modeling; dimensional accuracy; laser scanning

INTRODUCTION

Additive manufacturing (AM) is a recent technology that involves a process of joining materials to make objects from 3D models using layer by layer technique. Various techniques of AM is currently available including stereo-lithography (SLA), selective laser sintering (SLS), direct laser melting (DLMS), laminated object manufacturing (LOM) and fused deposition modeling (FDM). Every AM process has specific advantages and disadvantages in terms of manufacturing costs, development time and production volume. However, design constraint has been reported as a major and significant hurdle in AM due to lack of knowledge among designers to embrace designs for additive manufacturing (DfAM) concept. This is mainly because of insufficient design rules or guidelines available [1]. The same problem is also encountered by FDM users who normally repeat experiment in parts by trial-and-error techniques in order to validate design limitations and qualities of parts [2, 3]. The main objective in developing a benchmark artifact as a preliminary study is to develop a design guideline for AM. Consequently, developed and established design guidelines assist AM end-users in production processes. Design guidelines are instructions or suggestions that are dependent upon a set of circumstances. Guidelines are important as they provide design process directions in attempts to increase chances of achieving a successful objective. Guidelines require extensive research and experience as well as proven empirical evidences [4]. Beginning from the development of benchmarking artifacts, evaluation on design limitation is to be assessed in the early design stages along with the solution provided with an optimum conditions recommended.

Benchmark artifacts are also referred to as benchmark model containing various geometrical features in one base platform. A model developed to evaluate the performance of a 3D printer is also referred to as a benchmark artifact. In an AM geometric evaluation, benchmarking artifact often uses geometrical, mechanical or process benchmark. Geometrical benchmark is used to study on geometrical or dimensional performances such as accuracy, tolerances and surface finish. Meanwhile, mechanical benchmark characterizes the mechanical properties of a part in the form of tensile strength, shrinkage, warping effects and compression strength. Process benchmark focuses on the optimum process parameter available on a 3D printer machine especially for open source system including FDM [5]. Various parameter settings including layer thickness, temperature, speed, raster angle and various other parameters have been studied and optimized [6–9]. Research on benchmarking artifacts generally focuses on geometrical benchmark in attempts to evaluate dimensional or geometrical accuracy, their repeatability and minimum size on various geometric features [5]. Since FDM is built in part by using layer-by-layer method, that parts such as overhangs usually face difficulties to be printed successfully with acceptable accuracy. This process requires a support material lying below the layer to support the top overhanging layer. This has become one of the major limitations in FDM process. Studies have suggested that the design constraint needs to be identified during earlier stages of the process [10]. In order to assess FDM capabilities in producing various geometrical features with overhangs, studies on benchmarking artifacts having multiple overhang dimensions were undertaken. In FDM system, the major limiting factor of the process is the requirement for a support structure for

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overhang geometries. This is because it cannot be produced by a self-supporting structure from extruded filaments without any underneath layers. However, the use of support material incurs cost and built time [11, 12].

In order to assess the overhang length limitations that can be supported by FDM process, new benchmarking artifacts were proposed with multiple overhang length features in accordance with other manufacturing properties such as thin walls, inclined, slots, and other basic features. All of the features were fabricated in one base platform. The base platform was impossible to be constructed by using any conventional machining procedure, showing the advantage of AM technique in terms of its complexity in shape. The present study focused on fabrication of overhang structures for functional part by considering overhang quality and length limitations. Subsequent to the benchmark artifact being printed, it was inspected using laser scanner to evaluate the geometrical performance in terms of dimensional accuracy. Difficulties in the design were discussed and the consistency of tolerances between the fabricated parts and the CAD measurements were analyzed.

Benchmark Artifacts in Additive Manufacturing (AM)

The development of benchmarking artifacts in AM has become a trend among users and researchers in evaluating the performance and capabilities of their 3D printing machines. Despite the differences in manufacturing processes and material categories, artifacts have become the benchmarks to evaluate the quality of printed parts. For this reasons, various shapes and design features have been introduced and developed. The first benchmark artifacts having design features of cylinders, squares, pegs, vertical, incline and overhangs were developed. The benchmark was fabricated using three different AM techniques including selective laser sintering (SLS), laminated object manufacturing (LOM) and stereo-lithography (SLA). By comparison, the best printed part quality in terms of dimensional accuracy was SLS process [13]. However, the benchmarking artifact was not recommended because the part only contains a single part with no repeatability and replications features. Benchmark artifacts consisting of many small and medium features to produce a fine detail are presented. However, the parts with fine and small details features were difficult to measure using coordinate measuring machine (CMM) [14].

Zhou et al. [15] developed a benchmarking artifact to improve parts' dimensional accuracy and surface roughness of SLS process. The features incorporated included rectangle, cylinder, cone and tapered structures. Major accuracy problems in SLA such as CAD/CAM induced error, laser beam with induced error, material shrinkage error, error in 3D printer parameter setup and post-processing error are discussed. Some recommendations were made such as building a square or horizontal hole vertically and providing a support for the overhang parts [15]. Besides SLS process, optimization of process parameters was also conducted where Bakar et al. [16] proposed a benchmark artifact that contains design features of ring, cube, slot and cylinder in one platform. Results showed that layer thickness had significant effect in producing optimum value of dimensional accuracy and surface finish. The optimization of process parameter was also reported by Mahesh et al. [17] where six-sigma approaches were used to determine the best tune factor that affects the printed quality in direct laser sintering process (DLS). Poor adhesion was observed between the layers of laser-sintered, primarily attributed to uneven sintering, warpage, and delamination or burnt marks. Thus, the proper selection on temperature distribution was necessary [17].

Benchmark Artifacts Studies using Multi-AM Process

Benchmarking artifacts was also used to compare the performance of multi-AM processes available that combine several AM process such SLA, SLS, LOM, FDM, material jetting (MJ) and binder jetting (BJ). For example, Mahesh et al. [5] fabricated a benchmarking artifact using four different AM techniques namely SLA, SLS, LOM and FDM. The artifacts contained various design features ranging from solid, overhangs and freeform structures. In order to assess the best AM technique to produce good quality with accurate dimensions, various standardized measurements should be used to inspect the benchmark parts. These include a measurement of elements or individual features such as holes, straight line, cylinders, cone, slots and the relation between the elements such as the distance between the centres of circular features. It was observed that SLA gave the best results in terms of dimensional accuracy and surface finish, followed by LOM and FDM. It was concluded that, FDM and LOM were least suitable in building a very fine feature [18].

Other studies by Kim and Oh [19] analyzed six multi-AM processes which included SLA, SLS, 3DP, poly jetting, FDM and LOM. The developed artifacts were evaluated based on mechanical properties, surface roughness, geometrical and dimensional accuracy, speed and costs. They proposed five artifacts models containing basic features such as small holes, thickness, ribs, bosses and planar. Tests on mechanical properties such as tensile and compressive strengths, hardness, impact strength, heat resistance, surface roughness, geometric and dimensional accuracy, manufacturing speed and material cost were performed and compared for each process and machines. It was verified that SLA process obtained the best hardness, accuracy and surface roughness values. However, FDM and LOM were superior in terms of impact strength test but the built directions significantly affected the end-results [19]. In another study by Brajlih et al. [20] MJ, SL, SLS and FDM processes were compared using a new benchmarking artifact measured by using contact or non-contact techniques [21].

Manufacturing Features of Benchmarking Artifacts

In recent years, more advanced and complex designs of benchmarking artifacts have been introduced and developed. A series of these benchmarking artifacts developments have proven that AM process is a powerful technology in producing various manufacturing features that are impossible to be manufactured using conventional techniques. For example, Johnson et al. [22] presented a qualitative and quantitative evaluations of FDM system using a custom benchmarking model. In the study, the assessment on dimensional accuracy, feature size, geometric limitations, tolerances and repeatability study were conducted. More than 50 features were developed containing various manufacturing features such as inclines, hemisphere, thin walls, circular holes, square bosses, rectangular bosses, concentric cylindrical bosses, overhangs and rectangular nocthes. All of these elements were developed in one base platform and successfully fabricated within a building time of 150 minutes [22].

In another study, complexity of benchmarking artifact was enhanced and fabricated using SLS and SLM processes. The benchmarking artifacts contained sharp vertical walls, bosses, top surfaces, overhang inclined walls and pipe details. The artifact had acceptable surface roughness and accuracy [23, 24]. Another important element to describe quality benchmarking artifact is the process repeatability. There is a necessity to study a repeated design features to evaluate the consistency of the AM process in producing the same structure with acceptable range of accuracy [25]. This was supported by a study by Fahad and Hopkinson [21] where they designed the benchmark that consisted of symmetrical repeated features such as hollow cylinders, cubes, flat bases, solid cylinders, sphere and angled surfaces and cones. It was later altered by Lonzoutti et al. [26] The two studies placed the repeated parts in a series to form side-by-side for inspection [27].

In order to establish and develop the design guidelines for AM using benchmarking artifacts, the development of artifacts refers on standards and regulations already established worldwide such as National Institute of Standards and Technology (NIST) and International Organization for Standardization (ISO). NIST has become an excellent reference for researchers when developing their benchmarking designs [25]. Moylan et al. [27] has introduced a new benchmarking artifact model by considering the regulations stated from NIST. In the new artifacts, the features such as rectangular holes, bosses, round holes, conical bosses, L-shaped bosses, ramps, overhangs, angles, side notches, thin walls and fine features, freeform structures and towers were developed [28]. Similarly, Yang and Anam [28] proposed an artifact to investigate straightness, parallelism, perpendicularity, roundness and concentricity using SLS process for design efficiency. The development of benchmark artifacts can also refer to the ISO standard. However, only few studies on AM benchmarking process were reported utilizing this standard. For example, Minetola et al. [29] designed an artifact that included several classic geometries such as planes, cylinders, spheres and cones of different sizes to cover several ranges of basic sizes as defined by ISO 286 Standard. However, these standards and regulations must be supported by the organizations themselves and the procedure is often time- consuming.

Based on the reviews in the literature, it can be concluded that research on benchmarking artifacts is not new. Benchmarking artifacts is used not only to validate multi-AM performances and process parameter optimization, it also can be used to identify potential design features that have limitation to fabricate into a functional part. For example, an overhang structure had been known to be a failed part when fabricated using 3D printer. It can be manufactured using a suitable support structure. However, the bottleneck in the use of support structures is that it affects the dimensional accuracy and surface finishing of the printed part quality since it needed a post-processing treatment to reduce the support. In the present study, new design of overhang bridges was introduced and it contained multiple overhang length connected from one pillar to another like a bridge. Other manufacturing features were also designed in a one-based platform and the details are presented in Table 1. There is a need to study on the overhang structures to assist designers on the length limitation allowed in 3D printing so that they will not be spending too much time on redesigning the failed overhang part using trial and error methods.

METHODS AND MATERIALS

This section presents methodology in benchmarking artifacts and how inspection process was carried out. A schematic diagram consisting of flowchart is shown and each of the process is briefly described. An open source FDM printer was used in the experiment. The selection of parameter settings is described. Details features and their evaluation criteria are also described.

General Process Flow of Study

Figure 1 shows the flow process of the present study. The process started with the development of 3D CAD model using Solidworks software of benchmarking artifacts. The model was then converted into STL file format for the file to be processed using 3D printer software. A 3D printer model, Geetech Prusa I3, was used. The model had a build volume of 200 mm length, 200 mm width and 180 mm height with position precision of between 0.1 to 0.3 mm. The print technology used was fused filament fabrication (FFF) with the nozzle diameter of 0.3mm. The parameter settings were set up and the printing process were performed until the benchmark artifact was successfully fabricated. Finally, the inspection process was conducted using 3D scanner and the scanned part was analyzed using Geomagic inspection software.

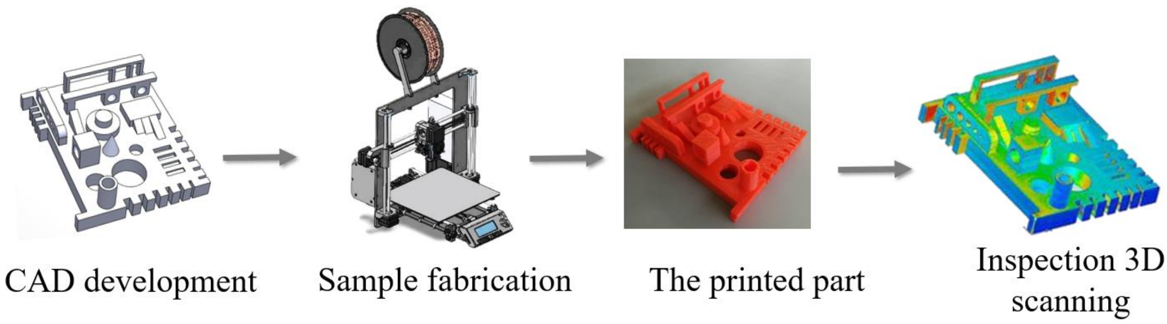


Figure 1. The process flow in experimental fabrication and inspection of dimensional accuracy

Detail Descriptions on Benchmarking Artifacts

A new benchmarking artifact has been designed to assess the dimensional accuracy, feature size, and design limitations of the fabricated part. The artifact contains manufacturing features such as overhang (BDG), square notches (XN), thin walls (YW), slots (SL), hole diameter (HD), flat base (FB), circular holes (C5, C6), and bosses. The elements inside the benchmarking artifact were inspired by Johnson et al. [22]. Some other features were added for manufacturability study including multiple overhang length. The full benchmark artifact model is presented in Figure 2, and the detail dimensions are shown in Figure 3. The study focused on the evaluation on linear accuracy, roundness, repeatability, bosses, overhangs, angularity and wall thickness. Tables 1 and 2 describe in detail all of the manufacturing features that were designed in the artifact.

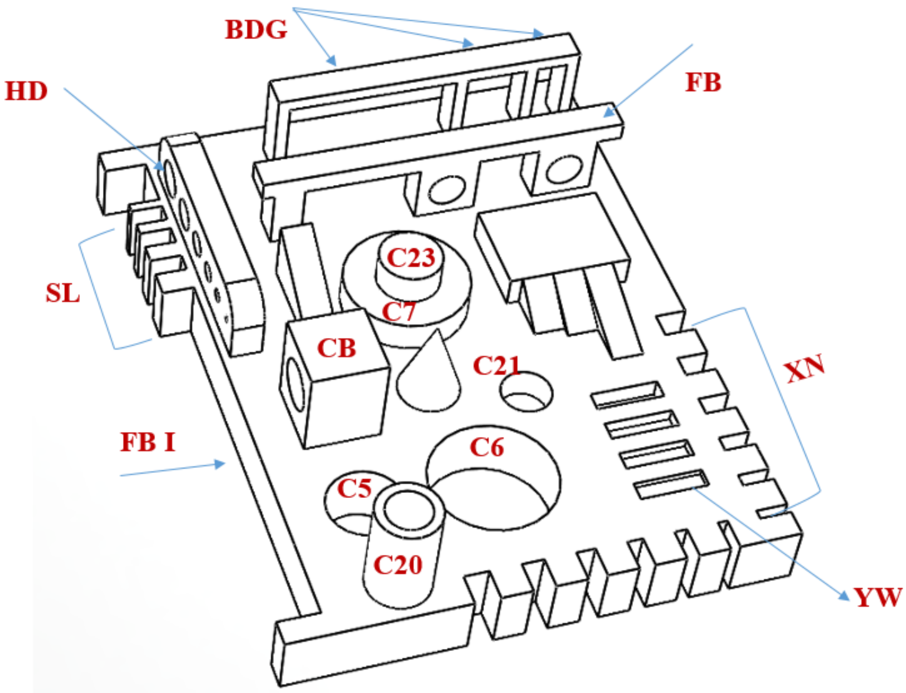


Figure 2. CAD model representation on benchmarking artifact

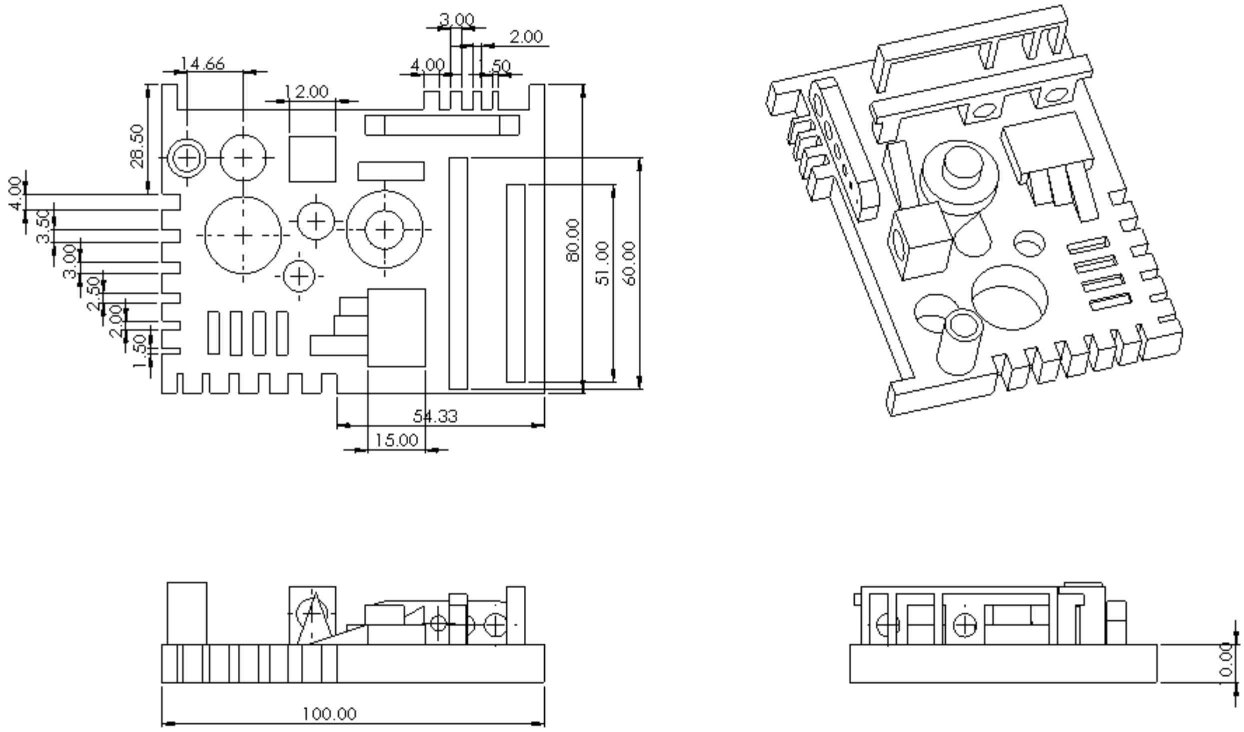


Figure 3. The detail measurements of benchmark artifacts

Table 1. Benchmarking artifacts' features for outer parts

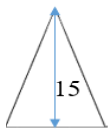
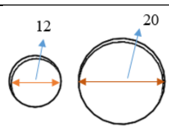
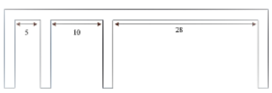
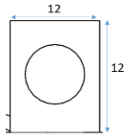
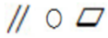
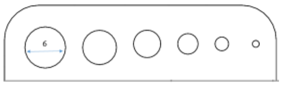
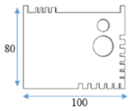
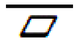
Feature	ID	Feature size, (mm)	Part evaluation	Evaluation	Symbols
Square notches	XN	The notches thickness: 1.5, 2, 2.5,3,3.5,4		Linear accuracy, symmetry	⌯
Thin walls	YW	Thin walls depth: 1-4		Wall thickness, linear accuracy and parallelism	//
Slots	SL	Slot thickness: 1.5,2.5,3,3.5		Repeatability and linear accuracy	-
Inclines	A11-A13	Angle of inclines: 35°, 60° and 90°		Accuracy	-
Cone	CN	Diameter: 9.5 Height: 15 Angle: 20°		Concity, tappers, sloping profile	-

Table 2. Benchmarking artifact features descriptions for inner parts

Feature	ID	Feature size (Mm)	Part evaluation	Evaluation	Symbols
Circular holes	C5, C6,	Circle diameter: 12, 20		Circularity, repeatability, relative position	○ ⌖
Bridges	BDG	Bridge length: 5, 10, 28		Hanging, overhang, consistency, parallelism	//

Cube	CB	length x width x height: 12mm x 12mm, 8mm		Parallelism, circularity, flatness and linear accuracy	
Hole diameter	HD	Hole dimeter: 1-6		Hollow shape, repeatability and circularity	
Flat base I	FB I	length x width x height : 100mm x 80mm x10mm		Flatness, straightness and extruded bosses	

3D Printing Process and Experimental Fabrications

The benchmarking model was fabricated using Acrylonitrile Butadiene Styrene (ABS) material. The process parameter settings are shown in Table 3. Layer thickness of 0.25 mm, infill density 40%, extruder nozzle temperature of 230°C, and default speed of 70 mm/s settings were used for fabricating the artifacts. The benchmarking artifacts took 2.5 hours to fabricate and there was no support structure generated during fabrication.

Table 3. Selected parameter settings of 3D printing machine

Parameter indicator	Unit	Settings	Descriptions
Layer thickness	mm	0.25	Measure of height of layer on each consecutive addition of material
Infill density	%	40	Percentage of filament deposition that fulfils inside the cross section of built pats
Extruder nozzle temperature	C	230	Temperature used for filament extrusion
Travel speed	mm/s	70	The speed at which the print head moves while extruding the filaments
Material	kg	ABS	Material commonly used in FDM process

Inspection Method Using 3D Scanner

According to Johnson [22], a laser scanning is an alternatively method to do an inspection for the parts especially for AM considering the possibility of layer-wise deviations. A 3D scanner was used to inspect dimensional accuracy of the artifact. The scanned part was analyzed using Geomagic qualify reverse engineering (RE) software. The main reason on the use of RE software was to obtain deviations between the scanned part (printed part) and the CAD data. The measurement of scanned part is referred to as printed part measurement, meanwhile, the CAD data were referred to as the CAD measurement. The general procedure of the inspection process is shown in Figure 4. In Figure 4, the scanned part was placed on the scanner platform. The blue ray light functions to capture the part. By using this technology, even the smallest size and the finest features can be captured. The scanner was connected to computer devices so that the scanned part can be analysed using RE software. The special features of the 3D scanner are the blue LED, having 2.0 mega pixels twin camera, automatic 3D scanning process and active synchronization and automatic calibration.

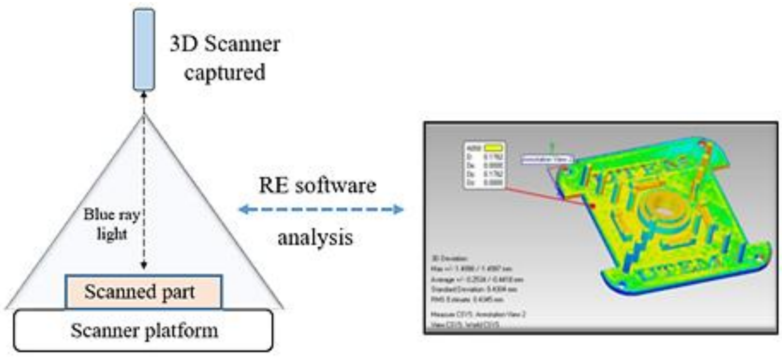


Figure 4. Schematic diagram of scanning process

RESULTS AND DISCUSSION

In this section, results of the scanned benchmarking artifact data were evaluated. The evaluation included straightness, circularity, overhang, bosses, thin walls, tapered and other features. The evaluation metric was also for dimensional accuracy, staircase effects, warpage effects, and dimensional tolerances using standard deviations technique.

3D Scanning Results and Discussions

The benchmarking artifact was displayed using a color map distribution after the analysis was conducted. The analysis presented through map error distributions and color segment, is shown in Figure 5.

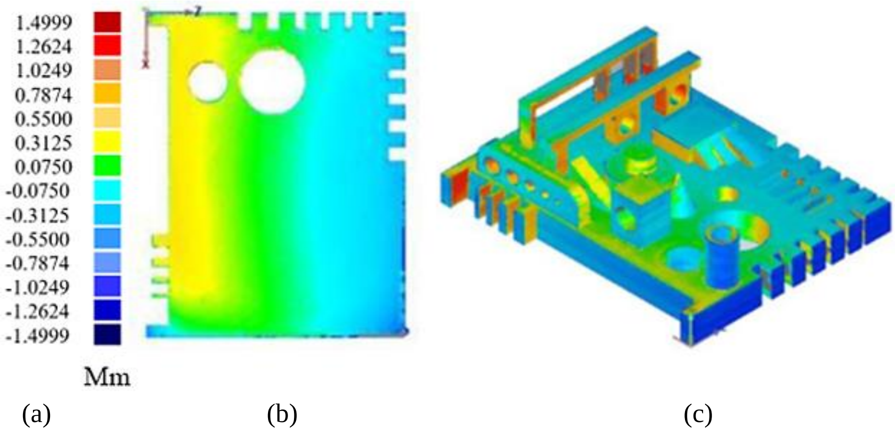


Figure 5. (a) Color segment (b) Error map analyses of benchmarking artifacts in back view (c) Error map analyses of benchmarking artifacts in isometric view

Figure 5(a), (b) and (c) represent overall results from the inspection analysis conducted using the RE software. In Figure 5(a), the deviation segments had a range of between -1.4999 to +1.4999 mm. Meanwhile, Figure 5(b) and 5 (c) show the back and isometric views of the error map analysis presented according to their color representatives respectively. For example, the hole diameter (HD, 1 to 6 mm) had light blue and light green colors. By referring to the color segment in Figure 5(a), the deviation between the CAD measurements and printed part measurements of the features was approximately between -0.0750 to -0.5500 was expected. However, in order to obtain the actual deviations between CAD and printed part, an annotation process was conducted. The full measurements and tolerances for every feature were also provided in the Tables 4, 5 and 6.

Benchmarking Artifact Evaluation

Benchmarking artifact were successfully fabricated using an open source 3D printer. Table 4 shows the deviations of three features; flat base, square notches and slots. The first evaluation was on the flat base (FB1) thickness, length and width of the base part. The CAD measurement was 100mm x 80mm x 10mm, meanwhile the printed part produced was 98.7453mm x 78.7599mm x 8.5976mm. Overall, the printed part measurements were lower compared to the CAD data. The low value was indicated by the negative symbol. This suggests that, after the printed part was fabricated, the part underwent warpage effects and shrunk during the printing process. The warping effects were visible along the edges of the base part especially on the notches side. Features such as flat base, slots, square notches and overhangs are briefly described below.

Deviations of Flat Base, Square Notches and Slots Features

In this section, the design manufacturability is discussed. It involves flat base, square notches and slot features. Table 4 shows the comparison between CAD and printed part measurements of the three mentioned features. The inspection of the square notches features also underwent shrinkage after being fabricated. However, the trend was different in which the gap was between -0.4 to -0.7 mm, respectively for the six fabricated samples. Since the features located at the edges of the base part, the features were also affected by the warpage effects. Figure 6 shows the deviation values between the CAD and printed part.

Table 4. Overall dimension and deviations of flat base (FB), square notches (XN) and slots (SL)

Feature	Feature ID	CAD measurements, (mm)	Printed part measurements (mm)	Deviations, (mm)
Flat base (Thickness)	FB (T)	10.00	8.5976	-1.4024
Flat base (Length)	FB (L)	100.00	98.7453	-1.2547
Flat base (Width)	FB (W)	80.00	78.7599	-1.2401
Square notches :				
- Notches 1	XN1	1.50	1.0611	-0.4389
- Notches 2	XN2	2.00	1.5218	-0.4782
- Notches 3	XN3	2.50	1.9970	-0.5030
- Notches 4	XN4	3.00	2.4616	-0.5384
- Notches 5	XN5	3.50	2.8283	-0.6717
- Notches 6	XN6	4.00	3.2198	-0.7802
Slots :	SL	-	-	-
- Slot 1	SL1	1.50	0.8406	-0.6594
- Slot 2	SL2	2.50	2.0864	-0.4136
- Slot 3	SL3	3.00	2.5889	-0.4111
- Slot 4	SL4	4.00	3.5641	-0.4359

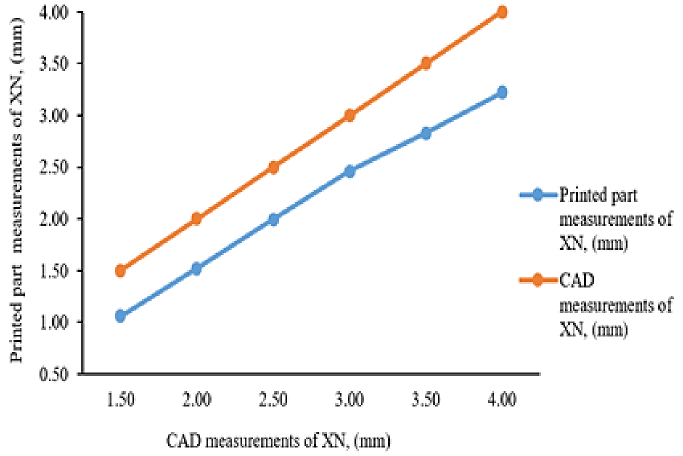


Figure 6. Printed parts and CAD measurements of XN, (mm)

In Table 4, the overall dimensions of feature base were described. The results from printing showed that the overall printed part measurements for the flat base is below the dimensions assigned in the CAD data. One of the major contributions to these problem is the corners of the base become sort of rounded instead of sharps. The rounded corners are mainly cause by the two reasons which are; over extrusion and higher extrusion temperature. Firstly, minor over extrusion happens when printing speed was slowly down at the corners, meanwhile there is still a pressure on the filament kept extruding from the nozzle. Secondly, when the printing speed was slowly down at the corners, the temperature was heating up seeking the shorter round path rather than a tight corner. Therefore, it is not recommended to design the sharp corners in FDM process especially for the precision parts.

Other than that, the square notches design was also discussed in this sections. Figure 6 described the results of the printed square notches and CAD measurements. Notches were developed along the edges at the flat base and it is crucial part in the benchmarking artifacts that have the highest possibilities to undergoes warping effects especially at the sharp corners of the part. Warping occurred due to material shrinkage, especially on thermoplastic material such as ABS causing the corners of the print to lift and become detached from the build platform. This happened because the plastic material contracted extensively during cooling down especially when the part's size was large and caused the print to bend up from the built plate. There are another few reasons observed in this study causes the warping developments. Firstly, the 3D printer does not have the cover, thus, the cold air blowing over the printers can cause the sudden cold breeze to the printing process and affected the printing part. Secondly, the edge of the bed platform is cooler than the centre. As the results, the plastic at the cooler edges will contract more and when it happens repeatedly, when the fresh layer was retracting, it pulls together the layer underneath up slightly. The solutions to these, the temperature around the 3D printer environment need to be stabilize and enclose chamber is an ideal solution to encounter this matter.

The other feature inspected was slots (SL). Slots were inspired from the study by Pham et al. [14] and the benchmark consisted of slots, recessed fine and cantilevers. These types of features were not easily assessed by CMM . In the present study, slot measurements were successfully taken by using the 3D scanning technique. The relatively small sample size suggests that there were some levels of repeatability by involvement of square and bosses in the fabrication of the features. The slots also had negative deviations as compared to the square notches (XN). However, the results in the present study were in contrast with the results reported by Bakar et al. [16] where slots feature had an increment tolerance of 0.127 mm. These results were affected from the parametric optimization study that was conducted by variation settings such as layer thickness that influenced the fabrication of the slots samples. The deviations of the slot features are shown in Figure 7. In this study, the slots (SL) were designed to investigate on the potential of the snap-fits design using FDM. Therefore, the smallest slots were designed using measurements of 1.5 mm. However, it was observed that the fabricated slots having a negative deviation (lower) than the CAD data. Therefore, the tolerances of ±0.5 mm was suggested to ensure the fabrication process of slots is successfully within the CAD data.

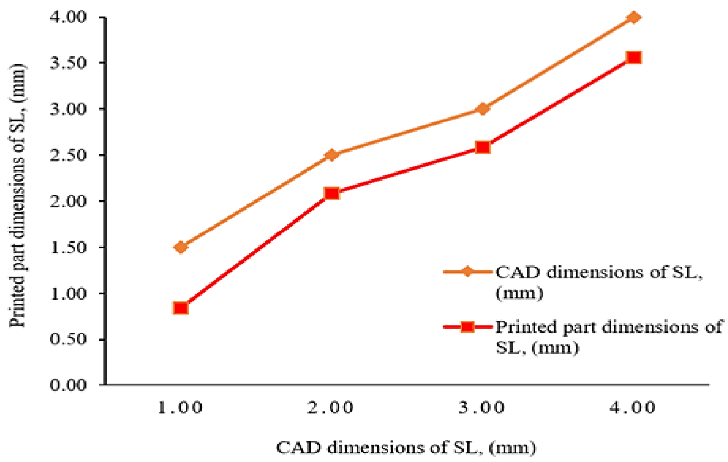


Figure 7. CAD and printed parts measurements of SL, (mm)

Comparison of CAD and Printed Part Deviations of Overhang Features

Results of CAD and printed part deviations of overhang (bridges) structures are discussed. Table 5 shows the overall dimensions and deviations. The table shows the dimensions of overhang types, containing multiple overhang lengths, known as bridges. Bridges were known as the flat sections that have a span for some area. A bridge is described as an overhang that is connected to another part of a surface. Generally, a 3D printer can fabricate overhang without support. However, the quality of the printed part not satisfactory and there is always length limitation. However, this problem can be overcome with proper settings adjustment. As shown in Table 5, the printed part measurements were lower than the CAD measurements since the deviations of the part was presented by (-) symbol. In the study, the span length of 5 mm, 10 mm and 28 mm were designed and fabricated. Each of the length was decreased by -1 mm. Figure 8 shows the process in bridge construction using a 3D printer.

Table 5. Overall dimensions and deviations of bridges features

Feature	Feature ID	CAD measurements, (mm)	Printed part Measurements (mm)	Deviations, (mm)
Bridges span 5	BDG 5	5.00	3.9898	-1.0102
Bridges span 10	BDG 10	10.00	8.8982	-1.1018
Bridges span of 28	BDG 28	28.00	26.8126	-1.1874
Bridges height	BDG (H)	15.00	13.9757	-1.0243
Bridges thickness	BDG (T)	2.00	1.0111	-0.9889

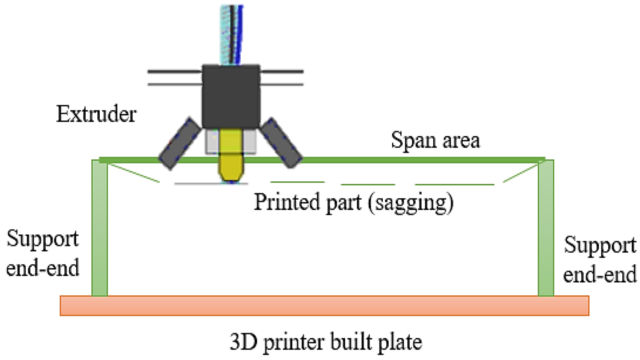


Figure 8. Process diagram of bridge fabrications using a 3D printer

In Figure 8, the bridging process started after the support located end to end, was fabricated. The material was extruded, and the thin strands of filaments along the span area were stretched. The sagging filament was likely to occur since there was no support structures generated and the defect was likely to occur. The 3D model that has exceed the 45 degrees and approaches to horizontal will be difficult to fabricate. Such overhangs had high possibility to have defects like curling, sagging, delamination or collapsing that explained the reason for under sizing on the printed part measurements of the bridges. Therefore, in order to ensure each of the successive layer has enough support to depend too, the angle of overhang should not exceed 45 degrees. For example, in the bridges (overhangs types) the tension on both ends (such as Figure 9) of the strings keeps it from damage, therefore, it was recommended to design the length of bridges shorter to prevent the filament collapsing and crumpling. Nevertheless, there is some recommendations to improve the bridges. Such as, increasing the cooling environment, decrease the flow rate of material extrusion and decrease the printing speed.

Therefore, in this study, new findings on the overhang results were established where the structure was successfully fabricated with only minimal sagging effects. The scenario occurred because the overhang structures were designed in a minimal thickness of the span area and they were designed in different compartments of overhang length as shown in Figure 9. The overhangs differed in Sections A, B and C by 5, 10, and 28 mm respectively. The various overhang length proved the ability of the 3D printer machine to fabricate the structures in different measurements at the same time. Findings showed that the three sections were successfully fabricated without filament sagging.

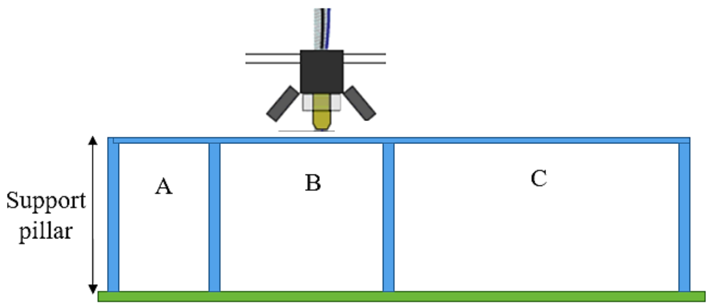


Figure 9. Fabrication of multiple overhang length using 3D printer

Comparison of CAD and Printed Part Deviations of Hole Diameter, HD

In benchmarking artifacts, the hole diameter was designed in a vertical axis orientation and had a diameter of 1 to 6 mm. The overall dimension and deviations of hole diameter was tabulated. Table 6 presents the deviations of hole diameter between the printed part measurements and CAD measurements. Meanwhile the plotted graph of hole diameter is shown in Figure 10.

Table 6. Dimensions and deviations of hole diameter

Feature	Feature ID	CAD measurements, (mm)	Printed part measurements, (mm)	Deviations, (mm)
Hole diameter 1	HD 1	1.00	0.5546	- 0.4454
Hole diameter 2	HD 2	2.00	1.7893	- 0.2107
Hole diameter 3	HD 3	3.00	2.8815	- 0.1185
Hole diameter 4	HD 4	4.00	3.6498	- 0.3502
Hole diameter 5	HD 5	5.00	4.7194	- 0.2806
Hole diameter 6	HD 6	6.00	5.5256	- 0.4744

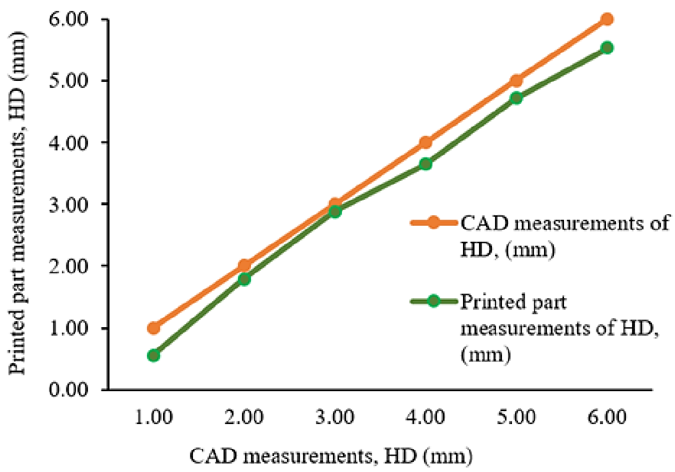


Figure 10. Printed part and CAD measurements of HD, (mm)

For hole diameter fabricated in vertical axis, the features can be manufactured but the recommended diameter was only from 2.00 mm and above. The hole diameter of 1.00 mm was not perfectly rounded because the fabricated hole was covered by the agglutinated filament around the layer. Referring to variations in measurements in Figure 10, the measurements of printed part were smaller than the CAD measurements by the cumulative deviations of -0.3133. The reduction in diameter occurred because a new layer compressed the existing layer of the structured part to improve the layer adhesions during printings. Thus, the compressing force from the upper layer turned the existing layer (round shape) into a flat shape. For this reason, the adhesions layer was improved. It also increased the width of the extruded filaments which resulted in decreasing the hole diameter of the printed parts. In order to develop a part that consists of a hole feature using 3D printer especially on the FDM process, larger diameter was recommended.

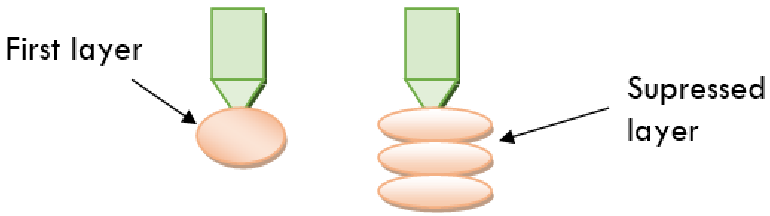


Figure 11. The first layer and suppressed layer of the small hole diameter

It can be summarized that a total of 2,999,987 data points were used to determine the deviations from the printed part and CAD measurements after the scan data was aligned using the best fit approach annotation. The average deviation for the benchmarking artifacts was +0.483/-0.5535 mm. Meanwhile, the standard deviation of the data collected in the study was 0.6159 mm.

CONCLUSIONS AND FUTURE WORKS

Benchmarking artifact has become one of the most important aspects in evaluating performance or characteristics of various AM processes. In the present study, a new benchmarking artifact was developed to investigate the performance of an open source polymer-based 3D printer machine in fabricating various design features such as multiple overhang structures. The benchmarking model developed had a square base of 100x80x10 mm and included features such as slot, square notches, thin walls, inclines, overhangs and bridges, hole diameter, cone and circular holes. The warpage effect was also being studied. The part was successfully fabricated; however, noticeable warping effects occurred along the bottom edges of the benchmarking base. Based on the 3D scanned parts, most of the points had negative deviation (shrinkage), but overall, 80% of the points were within ±0.5 mm of the CAD measurements. Another 20% of the feature measurements was more than ±0.5 mm and the major contributions to this value is the overhang structures. In conclusion, future works should focus on obtaining optimal combination of parametric optimization involved in bench marking artefact with more complex features.

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