BENCHMARKING OF MATERIAL EXTRUSION ENTRY-LEVEL 3D PRINTERS

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ABSTRACT

This paper provides an insight into the level of quality of several popular Entry-Level 3D Printing (EL3DP) systems. At their best, EL3DPs are able to produce parts for conceptual models and personalised objects. As EL3DP systems continue to develop, the next generation of EL3DP machines are likely to provide low ownership costs with a more acceptable degree of quality. This paper presents results of a benchmark analysis of several low-cost material extrusion 3D printers to enable comparison with each other and with more expensive commercial systems. Benchmarking of the parts was carried out using dimensional analysis to determine key performance characteristics as well as aesthetic evaluation by users in terms of the parts being pleasing to look at and to touch. From the study, it was found that a wide variation between different entry-level systems exists, with some of them approaching the performance level of more expensive machines. Many of the EL3DP parts had horizontally aligned circular features that did not meet the geometric requirement of cylindricity and were markedly oval in appearance. Other samples that were produced had numerous “whiskers” attached to their surfaces It was also found that some samples from a particular EL3DP machine produced an extremely warped bottom surface at one corner. Some of these factors could be due to the lack of build chamber temperature control on the lower cost machines and the quality of the extruder head. In summary, it can be argued that EL3DPs are still not yet suitable for high-fidelity appearance prototypes or to build end-use parts in which functionality and aesthetic quality are required.

KEY WORDS

3D Printing, Additive Manufacturing, Entry-Level, Benchmarking, Material Extrusion

1. INTRODUCTION

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3D printing has become the most commonly used layman's term for additive manufacturing (AM) [1]. In particular, it is often used colloquially to describe the low-cost "personal" 3D printers that are proliferating in the AM market. In this paper, such systems are termed "Entry-Level" 3D printers (EL3DPs). Many of these systems are based on the extrusion of molten or semi-molten thermoplastics, making them very similar to the higher cost systems sold by Stratasys, i.e. the Fortus, Dimension and uPrint ranges and, more recently, the Mojo desktop printer. On its website, Stratasys mentions end-use parts as one of the applications for their Fused Deposition Modeling technology [2]. It could be inferred that this is due to the higher quality of the parts their systems produce compared to EL3DPs. However, the difference in quality has not been quantified, either for dimensional capability or material properties. Therefore, the aim of this research was to quantify the dimensional capability of some commonly used extrusion-based EL3DPs available in the market today through a benchmarking study. It was envisaged that the results would indicate the areas for future development that would be required for EL3DPs to be made suitable for end-use part production.

This paper gives a brief review of previous AM benchmarking, followed by an explanation of the experimental methods used for this work. Results from the benchmarking tests are then presented together with a discussion on their wider implications. Finally, some conclusions are drawn as to the feasibility of using EL3DPs for end-use parts.

2. PREVIOUS WORK

Research into the benchmarking of AM systems has been undertaken as long ago as the early 1990s. A few of the benchmarking studies have been undertaken using "real" parts, i.e. those that have a primary use outside the scope of this study, but most have used specialised benchmark parts that incorporated features particularly suitable for measurement and other methods of evaluation. By reviewing these studies, the authors sought to generate a robust methodology for this research, both in terms of the benchmark parts used, and the evaluation techniques applied to them.

2.1 Benchmark Parts for AM Systems

As the number of AM systems grew during the 1990s, users were presented with a choice of different prototyping technologies. In order to decide which system to buy or which system to use for a particular part, an objective means of comparison became necessary. In response to this, many researchers developed their own benchmark parts, often incorporating the use of various geometrical features within the designs. Some of the parts were designed with a specific characteristic in mind, such as to evaluate surface finish [3], [4], speed [5] or the effect of orientation upon mechanical properties [6]. However, most of the parts were presented as generic test pieces that could be used to evaluate the overall capability of any AM system [7], [8], [9], [10], [11], [12], [13]. As the capabilities of AM systems have improved, the complexity of the benchmark parts have also increased with more features such as overhanging features being added. Despite these attempts, a "standard" benchmark part for AM has still not been recognised and, since various features will favour different systems, achieving industry-wide agreement on a standard part will be difficult.

For this research, it was decided that selecting a benchmark part with very fine features would not be an effective method for evaluation, as they would be unsuitable for extrusion- based methods. This discounted some of the more complex parts that had been previously designed. In addition, the high complexity of some benchmark parts would make measurement of all the features very resource intensive and time consuming. Therefore, for the evaluation of geometric accuracy, it was decided that a simplified version of the generic benchmark part used by Mahesh et al [11] would suffice. The design of this part is shown in Figure 1.

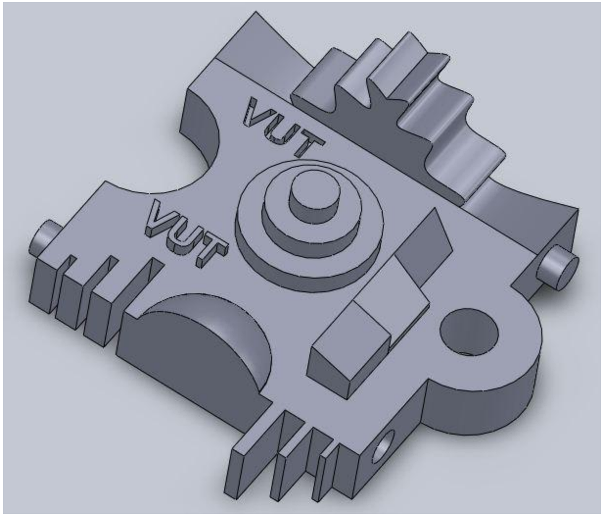

Figure 1. Geometric benchmark part used for this study.

2.2 Evaluation of Popularly Used Entry Level 3D Printers

Most of the previous studies undertaken have excluded EL3DPs from their benchmarking exercise. An exception is the work of Johnson et al [14] who developed a “benchmark” part specifically to evaluate the capabilities of the MakerBot machine. However, the part was not used to compare the machine to other systems, although this was alluded to as “future work” that would be undertaken. In previous work by three of the authors of this paper, a shape complexity analysis of parts from a RapMan 3D printer was undertaken [15]. Although this assessed the ability of EL3DPs to create complex geometries, it did not provide any quantitative analysis of the parts or the capability of the EL3DP in detail. Therefore, the novelty of this paper is to provide a quantitative approach to EL3DP capability.

Taking a step further, the authors wanted to look at both the functional and aesthetic aspects of EL3DP system capability. The functional aspects are typically related to engineering design which is covered through the evaluation of dimensional and positional accuracy. However, aesthetic aspects, typically associated with industrial design, require an evaluation of visual and tactile perception from an end-user’s point of view. Therefore, the authors believed that there was a need to use an additional level of benchmarking that would be a true representative of the “non-engineering” products currently being designed and produced by many in the “Maker Community" services such as Shapeways, Sculpteo and Thingiverse. For this reason, a second benchmark part was introduced (see Figure 2). This was a “real” part that was created from a scan of a bust sculpture of Sappho, an ancient Greek poet, available as a downloadable STL file from Thingiverse [16]. This part was chosen because it contained numerous freeform surfaces that could not be measured very easily, but whose aesthetic impact could be assessed and recognised by ordinary users.

Figure 2. Sculptural benchmark part used for this study.

3. PART BUILD AND EXPERIMENTS

The geometric benchmark part was fabricated on six widely-used consumer EL3DPs that were available in the Idea to Product™ (I2P) Laboratory at Vaal University of Technology, the DREAM (**D**esign **Re**search in **A**dditive **M**anufacturing) Lab at Loughborough University and the CREAMI (**C**enter of **R**everse **E**ngineering and **A**dditive **M**anufacturing **I**nnovation) Lab at the University of Naples. The software for some of the printers could accept STL files directly, whilst for others, conversion into a printer-specific file format was required. In addition, for the purpose of benchmarking, the part was also built on Stratasys Mojo and Dimension SST machines. Therefore, a total of eight geometric benchmark parts were built. After the build process, all eight parts were removed from the printers and inspected visually to make sure that the fabrication was complete. Support structures were carefully broken off (Dissolved in the case of the Dimension part). The eight geometric benchmark parts are shown in Figure 3.

Figure 3. Geometric benchmark parts, from top left to bottom right are as follows:
BFB 3000 Touch, Cube Generation 1, Cube Generation 2,
PowerWasp01, RepRap, Up!, Dimension SST, Mojo.

All eight parts were carefully measured to an accuracy of +/- 0.05mm using a set of professional-grade Vernier callipers across the 25 linear and diameter dimensions that are shown in Figure 4. Care was also taken to ensure that parallax error was avoided and all readings were recorded systematically by means of a log book. The readings were then compared to the nominal dimension values taken from the original CAD model and used to calculate dimensional deviations. Maximum oversize and undersize dimension values were noted for all eight parts and the average deviation from nominal values was calculated. It should be noted that some features failed to build in some of the machines. Additional observations were made including any pronounced ovality of the circular features, the presence of burrs and the reason for failed features. A summary of results for the eight parts is shown in Table 1.

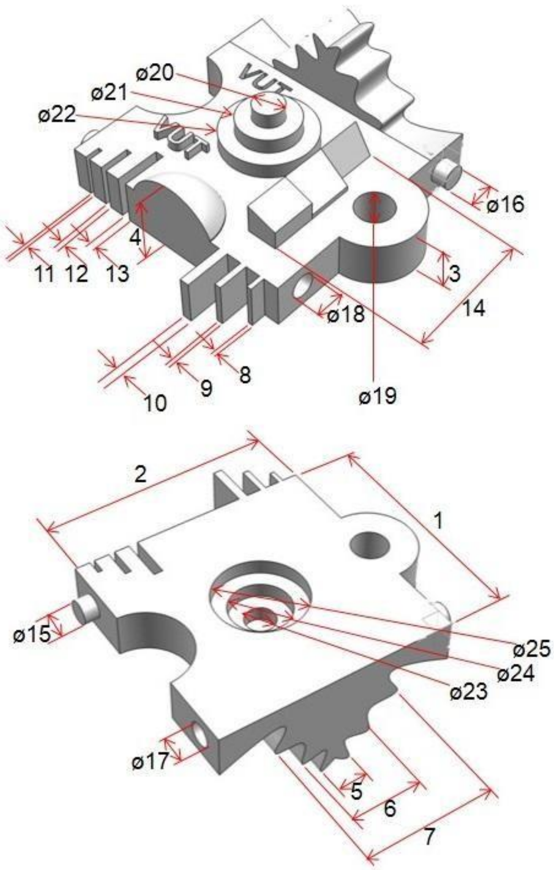

Figure 4. Dimensions measured for all eight geometric parts.

Table 1: Summary of results from dimensional analysis

Results => System	Max Under-size Dim (mm)	Max Over-size Dim (mm)	Average under - size error (mm)	Average over-size error (mm)	Std Dev for under-size (mm)	Std Dev for over-size (mm)	Root Mean Squared Average (mm)
BFB 3000 Touch	3.00	0.70	1.08	0.36	0.61	0.16	0.89
1st Generation Cube	1.50	0.60	1.01	0.33	0.35	0.20	0.84
2nd Generation Cube	0.60	1.70	0.24	0.42	0.14	0.58	0.47
PowerWasp01	1.6	0.55	0.50	0.55	0.44	Only 1 value	0.65
RepRap	0.60	0.80	0.28	0.41	0.17	0.37	0.34
UP! Printer	1.00	1.40	0.42	0.72	0.20	0.68	0.48
Dimension SST	0.45	0.95	0.20	0.44	0.12	0.33	0.28
Mojo	0.45	0.10	0.21	0.09	0.10	0.03	0.19

In addition to the qualitative results above, a number of quantitative statements could be made about the part and some of their features. The most important of these are as follows:

- Many of the EL3DP parts had horizontally aligned circular features that did not meet the geometric requirement of cylindricity and were markedly oval in appearance, this was also true for the Dimension and Mojo machines
- The parts from the BFB 3000 Touch and Dimension machines had numerous "whiskers" attached to their surfaces which could potentially be due to the retraction settings
- The part from the BFB 3000 Touch machine had an extremely warped bottom surface at one corner, evidence that there was an occurrence of uneven material shrinkage (see Figure 5).

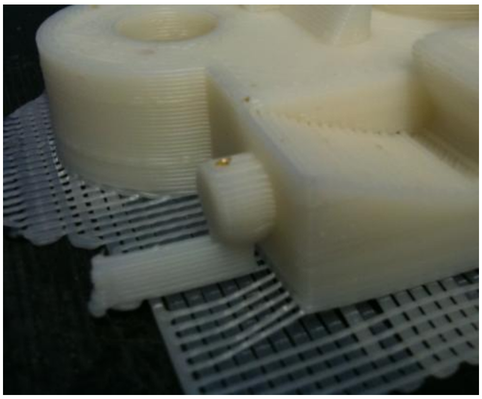

Figure 5: Extreme warping seen on part from BFB machine

For the second part of the evaluation, four of the EL3DP's were used for an aesthetic evaluation by users. The EL3DPs used were the first and second generation Cube machines [17], an UP! machine [18]) and a BFB 3000 Touch [19]. Key specifications and build times are given for these machines in Table 2.

Table 2: Key Specifications and build times.

System => **Parameters**	**1st Generation Cube**	**2nd Generation Cube**	**UP! Printer**	**BFB 3000 Touch**
Material	ABS	PLA	ABS	ABS
Filament diameter/mm	1.75	1.75	1.75	3.0
Layer thickness/mm	0.2	0.2	0.15	0.125
Platform	Heated	Not heated	Heated	Not heated
Firmware version	1.09	2.04	6.07	5.4.2
Build time for part	5h 57m	3h 49m	6h 39m	6h 08m
Price of machine/US$	1399	1399	1499	4370

The four sculptural benchmarks (seen in Figure 6) were evaluated in a markedly different way from the geometric benchmark part. Rather than being treated as functional models that needed to be geometrically accurate, they were considered as aesthetic models that needed to be pleasing to look at and to touch. Therefore, the parts were presented to 51 first, second and third year undergraduate students from the Product and Furniture Design course at De Montfort University in the United Kingdom. They were first asked to visually inspect the parts without touching them to score the visual quality. Next, they were asked to observe and handle the parts and score their perception of tactile and overall quality of the test pieces. In both cases, the scoring was from most acceptable (score 1) to least acceptable (score 4). All the scores for each part were then averaged and the results are shown in Table 3 (lower scores showing a higher level of quality).

Figure 6: Sculptural parts, left to right, 1st Cube, 2nd Cube, UP!, BFB

Table 3: Average ranking results for sculptural parts

System => Rankings	1st Generation Cube	2nd Generation Cube	UP! Printer	BFB 3000 Touch
Visual quality	2.4	2.8	3.7	1.1
Tactile quality	2.8	2.9	3.0	1.2
Overall quality	2.5	2.8	3.5	1.2

4. DISCUSSION

In the measurement of dimensional accuracy, there was a wide variation in quality between the systems that were evaluated. In the case of the BFB 3000 Touch, the warping that was seen on the base of the geometric component was unacceptable for a functional part. This would seem to disqualify this system from making functional models, at least those with anything but a very small basal area

For all the systems, the dimensional errors seen on the linear and diametrical features were very similar to each other. In terms of the overall root mean squared (RMS) error for the six EL3DP machines, the BFB 3000 Touch performed worst with a value of 0.89mm and the RepRap performed best with a value of 0.34mm. These values do not compare very favourably with the RMS values for the two professional-grade Stratasys machines, i.e. 0.28mm for the Dimension and 0.19mm for the Mojo. However, in terms of maximum oversize errors seen, the Dimension SST performed worse than four of the EL3DPs. This may be related to the "whisker" effect that was seen on this machine. The oversize dimension in question (0.95mm) may have been due to a local whisker being present on the feature being measured. On closer inspection, it was determined that four of the Dimension SST errors (all of them oversize between 0.40mm and 0.95mm) deviated significantly from the majority of results for this machine, which were sometimes slightly oversized but usually undersized. Removing these "outliers" actually gives the Dimension SST machine very similar results to the Mojo. Taking this into account, it would appear that none of the EL3DPs evaluated in this work are able to match the level of accuracy exhibited by the two more expensive Stratasys machines.

In terms of aesthetics, it was clear that the BFB 3000 Touch part came out on top, the two Cube machine parts were closely scored for 2nd and 3rd, and the UP! Machine part was placed last. This is in contrast to the poor performance of the BFB machine under the geometric dimension valuation, which was effectively in last place. The visual and tactile qualities of each model were given similar scores. It would seem that the user evaluation of aesthetic quality relied largely upon the quality of surface finish of the parts. A general point to be learned here is that the choice of EL3DP machine to use must always consider the target user of the parts and their specific requirements, whether functional, aesthetic, or a combination of both factors.

From this study, it was found that the accuracy available from the best performing EL3DPs is approaching the capabilities of higher-priced machines but not yet equivalent to it. The authors speculate that this could be potentially due to the lack of build chamber temperature control on the lower-cost machines and the quality of the extruder head. It can be argued, therefore, that if functional prototype parts are required, EL3DPs are not yet fit-for-purpose.

5. CONCLUSIONS AND FUTURE WORK

This paper has provided aninsight into the level of quality that is currently available from several EL3DP systems. At their best, EL3DPs are providing parts that are suitable for conceptual models and perhaps as personalised objects. However, they are not yet suitable for high-fidelity appearance-critical prototypes or for use as end-use parts, where both functionality and aesthetic quality are required. However, as EL3DP systems gain popularity in the market, this may lead to higher revenue for the manufacturers and increased machine development. The authors believe that the next generation of EL3DP machines will continue to provide low ownership costs but will exhibit a more acceptable degree of quality. For example, some EL3DP vendors such as Makerbot are already offering heated build chambers and other features that were previously the protected intellectual property of Stratasys. When this happens, it may be difficult to see how the major players such as Stratasys will be able to maintain their current price premium, unless they also introduce improved build quality and new features.

A limitation to this study was that the experiments did not undertake repeated trials on each system and therefore the findings do not provide insight into the aspect of process variability. Further research could investigate the use of different materials to examine its impact upon warping and also the use of different filament diameters and the nozzle sizes. Future work on a larger scale should examine how other parameters such as the temperature of the material, the fill density and the build pattern could affect the build quality of parts produced from EL3DPs.

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