ANALYSIS OF THE BUILD QUALITY OF THE “DIGITAL LIGHT PROCESSING” RAPID PROTOTYPING PROCESS

P M Hackney, Northumbria University, School of Engineering & Technology

ABSTRACT

Rapid Prototyping is widely known as being able to fabricate 3D objects with complex geometries directly from accurate digital CAD data. Rapid prototyping can shorten the product development cycle and improve the design process by providing rapid and effective feedback to the designer. This paper presents the findings of an investigation into the accuracy, build strength and detail of the EnvisionTec PerFactory™ Digital Light Processing (DLP™) based system. The results will allow designers and manufacturing engineers to access the validity of the components and the range of applications for this new evolutionary system.

Key Words: Rapid Prototyping, Digital Light Processing, Accuracy

1.0 INTRODUCTION

Rapid Prototyping (RP) technologies use a layer by layer fabrication principle employing computer controlled laser, powder, print or photopolymer, together with a combination of other materials and techniques [1]. The ability to turn 3D digital Computer Aided Design (CAD) data, or other 3D data, into a physical artefact has enabled companies to reduce product development time cycles, and hence is a major factor in time compression technologies. These RP techniques complement more traditional manufacturing techniques such as CNC machining for prototype production. Several RP processes can produce functional and semi-functional components and assemblies, and can also be used as masters or patterns for tooling.

The use of RP is becoming more widespread as 3D CAD as a design tool is being used by small to medium sized enterprises (SMEs) to design and manufacture new products[2]. The advantages of RP over traditional CAM based tools are both time and cost of manufacture, ensuring the designer can hold a part designed yesterday in his/her hand today. At the moment the RP industry is split into two distinct areas:

- High cost, high precision systems - SLA, SLS, FDM, LOM,
- Low cost (<£50k) “concept modellers” - 3D “Ink Jet” Systems
    - 3DSystems ThermoJet,
    - ObJet’s Inkjet System
    - Z-Corps 3D Printer
  - Other concept modelling systems
    - Stratasys FDM Dimension
    - EnvisionTec DLP™ PerFactory

The high cost RP machines are predominantly situated in bureau companies with a range of machines to enable them to serve all their customer needs. The low cost RP machines are predominantly being installed in design houses and large OEMs to enable design verification and to serve as a communication tool. This paper will review the current concept modelling EnvisionTec DLP™ processes and benchmark these processes.

The principle of the “concept modellers” is that the parts are produced to a low accuracy of normally $\mp$ 0.5 mm, low part strength <15 M*Pa,* with limited engineering part utilisation. The benefits include: low system purchase and operating costs, low part costs, load and go capability, and fast prototype part production.

However these “Concept parts” have been used successfully in several projects as parts, sacrificial patterns or tools for production of working components. A good example is the Z-Corps 3D printer binder cartridge head cap shown in Figure 1. This component is actually produced on the same machine that made itself. The ThermoJet uses a type of investment casting wax, and is now being used regularly in the production of aluminium and steel parts via the investment casting process without expensive new processes or process modifications at the foundry.

Figure 1: Z-Corps 3D Printer, Printer Head Cap

The use of RP produced parts is restricted by three major parameters – part accuracy, part strength, and definition:

- Part accuracy is a function of the process and the interaction with the build materials, and this paper aims to further understand the interactive relationship of the two applied to the DLP™ process.
- Part strength is related to the build material or materials and the intermolecular bonds produced during the process.
- Part definition is a combination of resolution of the process and the manufacturing process constraints, i.e. green strength, support requirements etc.

Over the last decade there has been significant advancement within the RP field in the above parameters, particularly in the area of Stereolithography (SLA) process whereby both process and material improvements have led to the acceptance of parts as functional prototypes and Rapid Manufactured (RM) parts [3] [4].

3D Printing refers to a range of techniques characterised by the method of delivering build material or build adhesive via a series of nozzles that are translated across the build platform. An earlier process, Ballistic Particle Manufacture (BPM) used two heads, one for the build material and one for the support material, and a levelling machining operation was performed between layers to increase accuracy. Although this process built small accurate parts, it was slow and unreliable.

A development of the BPM process was incorporated by 3D Systems into their Actua Multi-Jet System or ThermoJet™ using wax as the build material and support material without the machining stage. They are now widely used for investment casting, but they have limited strength for prototype use. This uses 96 jets to deposit wax over the build area.

The ObJet System uses a similar two head system to the BPM system with a build material of Ultra Violet (UV) sensitive resin and support resin that is set at the end of each layer by a UV lamp in one step. Problems with accuracy and part strength still remain with this system, but material and process improvements have optimised the process with the new FullCure™ resins and ObJet Multihead Eden machines.

2.0 DIGITAL LIGHT PROCESSING MANUFACTURING

2.1 Traditional Stereolithography

In the Stereolithography (SL) process, a light beam is used to scan the surface of the photo-polymer according to the sliced data, and solidify a thin layer. Most machines use a UV laser beam to solidify the photo-polymer. He-Cd, argon or semi-conductor excited lasers are popular UV laser sources used in the SL process. There are several commercialised SL systems, which could also use visible-light laser as the light source.[5]

2.1.1 Photo-Polymer

In SL technology, photochemistry plays a very important role. A highly precise SL machine may not be able to produce a high accuracy model if the photo-polymer has a shrinkage problem. The properties of the photo-polymer are, therefore, very important.

2.1.2 UV Argon Laser

Ionizing atoms using electric discharge and promoting them into highly excited energy levels emit UV light emitted when the atoms fall to a lower energy state. Ionisation of

Argon requires high-density excitation energy; therefore a large current is applied onto a very thin tube to increase the current density. Due to the low efficiency, most of the UV Argon laser units are large and require water-cooling. This would make an Argon laser-based SL machine very bulky.

2.1.3 Acoustic Optical Modulator (AOM)

Since the Argon laser cannot be turned on and off frequently, the laser beam must be switched on and off by some equipment such as a shutter. However, the ordinary mechanical shutter speed is not high enough for scanning a laser beam. An acoustic optical modulator is used to control the switching of the beam.

2.1.4 Galvano-Mirrors

Although an AOM can switch the laser beam on and off immediately, the inertia of the mirrors would cause delay of movement and hence positioning accuracy. High positioning accuracy and high scanning speed are, therefore, required for the galvano-mirrors. The 'laser-on' and 'laser-off' timing parameter must be set to adjust the delay to achieve high positioning accuracy.

2.1.5 The cost and maintenance of the laser system for SLA process is a high proportion of the machine costs.

2.2 Digital Light Processing Manufacturing

EnvisionTec founded in 1999 in Marl, Germany, for the development, production and promotion of computer assisted model making for industry and bio-medical fields. Two basic versions of DLP^{TM} PerFactory system (Personal Factory) are commercially available. One for the manufacture of industrial components, "standard system", 190 x 152 x 230 mm build size, and a "mini system" 77 x 61 x 230 mm build size for 3D high accuracy/intricate objects for example in the jewellery industry. Both systems retail at 50,000 Euros and compete alongside ObJet, Z-Corps, ThermoJet and FDM Dimension processes.

3.0 BUILD PROCESS

The PerFactory system, like other commercial RP systems builds in layers directly from sliced STL triangle files. The data is cut into layers transferred to the machine to generate the slice via a DLP^{TM} technique.

The projection unit for the machine is located under the polymerisation bowl, which means the projection of the layer occurs through a silicon coated transparent contact window. The build platform is lowered to the build z-height above the polymerisation bowl, and the DLP^{TM} unit switches to display the required slice, and a light is shone onto the DLP^{TM} chip. The acrylate material is micro photo hardened by the light source. The part is peeled from the polymerisation bowl, raised, and then re-set ready for the next z-layer.

3.1 System Components

- UV Screen Cover
- Build Platform
- Polymerisation Bowl
- Build Material Vat
- Focussing Lenses (2 off)
- Digital Light Processing Chip or Digital Mirror Device^{TM} DMD^{TM} of Texas Instruments SXGA

Figure 2: Perfactory Standard System

3.2 System Specification

Resolution of picture unit – a Digital Mirror Device^{TM} by Texas Instruments – at this time the SXGA (1280 x 1024 pixel equilent to 1.3 million mirrors) chip is used. Build up time by using standard material about 36 mm/hour at 100 µm layer thickness. Two system models are available for different build accuracy and areas:

System variant	PERFACTORY® Standard SXGA I Zoom	PERFACTORY® Mini SXGA I Multi Lens	
Resolution	SXGA - 1280 x 1024 Pixel	SXGA - 1280 x 1024 Pixel	
Build envelope XYZ	190 x 152 x 230 mm to 120 x 96 x 230 mm	Lens f=60 mm 77 x 61 x 230 mm	Lens f=85 mm 41 x 33 x 230 mm
Pixel size XY	148 µm Pixel to 93 µm Pixel	60 µm Pixel	32µm Pixel
Layer thickness Z	50 µm to 150 µm	25 µm to 50 µm	

The standard material is orange, translucent acrylate, biocompatible and almost ashless burn outable (0.8% ash).

4.0 DLP^{TM} SYSTEM TEST PROCEDURE

The intention of the tests was not to optimise parameters, but to run as per manufacturers' pre-set parameters on an EnvisionTec DLP^{TM} PerFactory "standard" machine.

4.1 Repeatability

No process can be accurate if it is not repeatable. This test required the same parts to be built several times (10), and the variance between builds assessed for x, y, z build orientations.

4.2 Part Strength

Tensile test specimens were manufactured using Acrylate resin with a build increment of 0.1 mm as per Figure 3a and 3b.

Figure 3a: Orientations and Build Positions

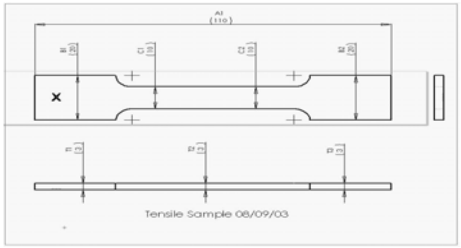


Figure 3b: Dimensional checks

Figure 3a and 3b shows orientations and build positions after x, y, and z for various build platform positions, they were tested on a Neme tensile test machine for various build orientations and build positions.

4.3 Dimensional Accuracy

The test piece as shown in Figure 4a and 4b was designed to allow the measurement of multiple build axis to be assessed, coupled with part location within the build platform in a single part. Accuracy measurements were undertaken with an International Metrology System (IMS) Impact^{TM} Coordinate Measuring Machine (CMM) – accuracy of 3 µm.

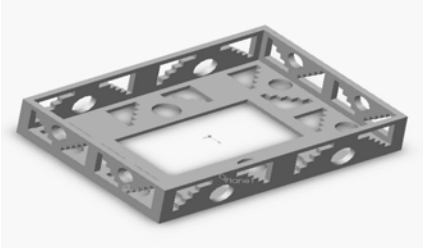


Figure 4a: Accuracy Test Pieces

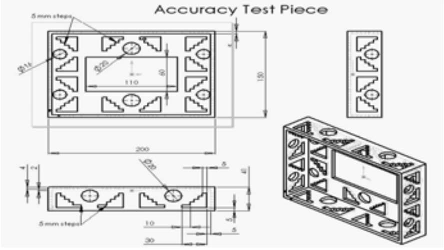


Figure 4b: Dimensional checks

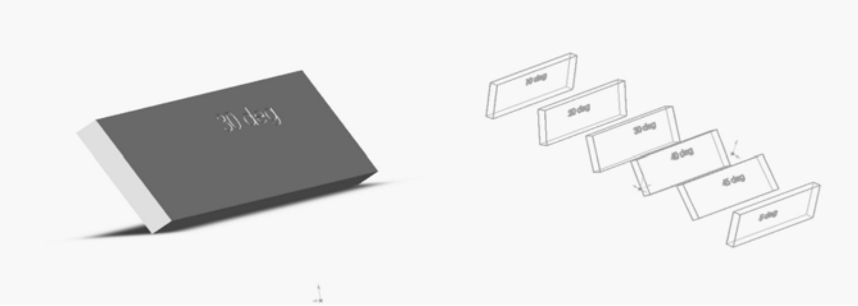
4.4 Surface Flatness

The test pieces shown in Figure 3a and 3b were evaluated for surface flatness before tensile testing using the IMS Impact CMM along the full length of each specimen.

4.5 Surface Roughness

The test pieces shown in Figure 5a were evaluated at angle of inclination of 5^{o}, to 45^{o} and 90^{o}, to assess the stair stepping effect found with all RP systems. Measurements were taken using a Taylor Hobson Surftronic 3t machine, measuring Ra volume.

4.6 Build



Detail Tests – Filigree

The sample test piece as shown in Figure 6a and 6b was used to assess the finest detail that could be manufactured using the DLP™ with filaments of 3 to 0.05 mm in the three build orientations.

Figure 6a: Filigree Test Piece

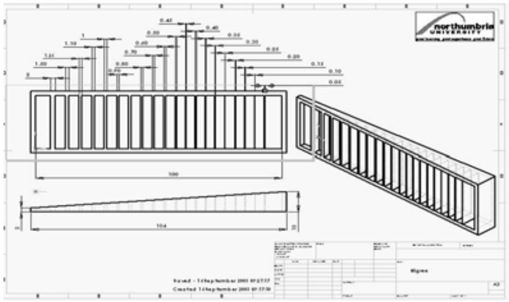


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Figure6b: Dimensional checks

5.0 DLP™ TEST RESULTS

The test results are summarised below:

5.1 Repeatability

The parts built had a standard deviation, minimum and maximum error axis as shown in Table 1.

	Std Dev mm	Min Error %	Max Error %
X	0.243	-1.318	-0.855
Y	0.148	-0.909	-0.555
Z	0.194	-0.718	0.127

Table 1: Repeatability

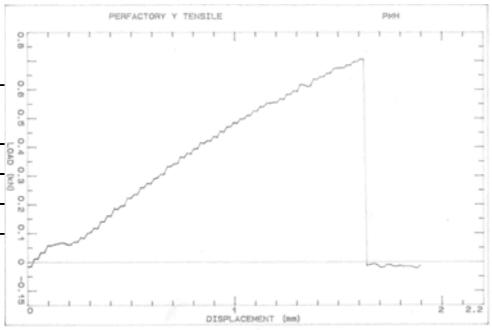
Summary: The repeatability tests show a good degree of reliability of the process. These tests were performed on two different machines over a period of 8 weeks with different settings, operators and resins. The errors in to provide repeatable results can be improved with calibration and operational knowledge of the process.

5.2 Tensile Tests

Tensile results are shown in Table 2.

	Average Tensile Stress MPa	Min Tensile Stress MPa	Max Tensile Stress MPs	Std Dev MPa
X	13.397	8.76	15.893	3.181
Y	20.693	16.197	27.1	3.710
Z	13.792	6.633	16.403	3.650

Table 2: Tensile Tests



Graph 1: Tesile Test result Y sample

Summary: The strength in x and z is similar, however the strain in z is double that in x and y showing the interlocking bond between layers has a degree of elasticity. The reason for the high y direction strength is unknown, however these samples were from a different build and could reflect the different properties of new and older resins. Brittle failure as can be seen in Graph1.

5.3 Dimensional Accuracy

Table 3 shows the results for dimensional accuracy in X, Y, Z:

X	A1	B1	B2	C1	C2	T1	T2	T3
Average	108.700	19.843	19.823	10.060	10.033	2.735	3.163	2.928
StDEV	0.243	0.059	0.154	0.067	0.090	0.274	0.035	0.293
Desired Dim	110.000	20.000	20.000	10.000	10.000	3.000	3.000	3.000
Dev	1.300	0.157	0.178	-0.060	-0.032	0.265	-0.163	0.072
ɥm Error/mm	11.818	7.875	8.875	-6.000	-3.250	88.333	-54.444	24.167
av error %	1.182	0.787	0.888	-0.600	-0.325	8.833	-5.444	2.417
Min err %	-1.318	-1.100	-1.600	0.000	-0.500	-16.667	4.333	-16.333
Max Err %	-0.855	-0.450	-0.150	1.400	1.600	3.333	6.667	4.667

Y	A1	B1	B2	C1	C2	T1	T2	T3
Average	109.213	19.920	19.996	10.041	10.037	3.051	3.150	3.133
StDEV	0.148	0.056	0.137	0.125	0.108	0.159	0.053	0.057
Desired Dim	110.000	20.000	20.000	10.000	10.000	3.000	3.000	3.000
Dev	0.787	0.080	0.004	-0.041	-0.037	-0.051	-0.150	-0.133
ɥm Error/mm	7.156	4.000	0.214	-4.143	-3.714	-17.143	-50.000	-44.286
av error %	0.716	0.400	0.021	-0.414	-0.371	-1.714	-5.000	-4.429
Min err %	-0.909	-0.800	-0.750	-0.700	-0.700	-5.333	3.000	1.667
Max Err %	-0.555	-0.100	0.750	2.800	2.600	6.667	7.333	7.333

Z	A1	B1	B2	C1	C2	T1	T2	T3
Average	109.806	20.041	20.092	10.144	10.124	3.049	3.029	3.054
StDEV	0.266	0.131	0.053	0.221	0.070	0.062	0.043	0.065
Desired Dim	110.000	20.000	20.000	10.000	10.000	3.000	3.000	3.000
Dev	0.194	-0.041	-0.092	-0.144	-0.124	-0.049	-0.029	-0.054
ɥm Error/mm	1.760	-2.036	-4.607	-14.429	-12.429	-16.429	-9.762	-17.857
av error %	0.176	-0.204	-0.461	-1.443	-1.243	-1.643	-0.976	-1.786
Min err %	-0.718	-0.950	0.050	0.300	0.400	-1.667	-0.667	-0.333
Max Err %	0.127	1.450	1.000	9.000	2.700	4.667	3.667	8.333

Table 3: Dimensional Test Results

Summary: Maximum error of 0.19 mm similar in all planes. The percentage error for smaller dimensions is higher than for larger dimensions as would be expected.

5.4 Surface Flatness

The surface flatness results are shown in Table 4 where performed on the thin tensile test pieces shown in Figure 3a.

	Deviation mm
X	1.065
Y	0.956
Z	0.060

Table 4: Surface Flatness

Summary: The thin 3mm width samples shown, curl due to shrinkage in the x and y planes during plane change. This is over a 100mm length test piece. The z direction is virtually flat. A new release of resin is due to be released in October 2003 with significantly less shrinkage characteristics which will improve this problem.

5.5 Surface Roughness

Surface Roughness Ra

	0 deg top	0 deg Bot	5 deg top	5 deg Bot	10 deg top	10 deg Bot
Average Ra	0.475	3.325	23.300	25.950	27.050	23.350
Std Dev	0.096	0.096	1.183	1.136	1.063	0.985

	20 deg top	20 deg Bot	30 deg top	30 deg Bot	40 deg top	40 deg Bot	45 deg top	45 deg Bot
Average Ra	24.550	16.750	24.800	18.500	21.800	14.450	21.200	14.250
Std Dev	0.252	0.100	1.689	0.600	1.166	0.870	0.432	1.482

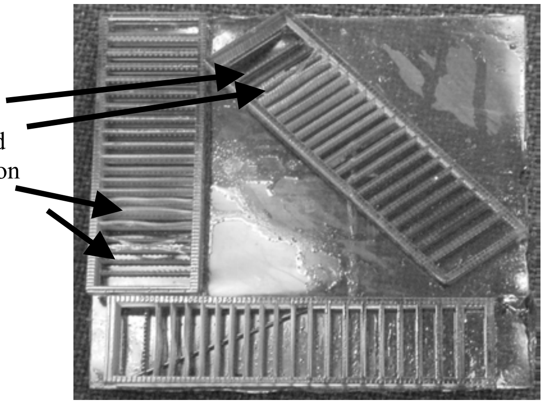
Table 5: Surface Roughness

Summary: The top of each sample, from 20° to 45°, showed a lower value of surface roughness to the lower side. This is due to the curing by the light through the thickness of the build layer being defined by the polymerisation both on the top side providing a well defined step, and through the resin curing to various depth on the liquid side.

The vertical and horizontal build planes showed excellent surface finish, showing good light mask alignment and controlled vertical curing of the resin.

5.6 Build Detail – Filigree

The samples in various build orientations are shown in Figure 8



Failed to build required section

Figure 8x: Samples x-axis, y-axis and xy axis

Summary: The smallest detail feature built perfectly was 0.3 mm thick rib. Features below this size are not self supporting during removal from the polymerisation bowl during build operation. The 0.1 mm rib did build in y direction, but lacks stability.

6.0 CONCLUSIONS

This study was not intended to be a full investigation into the EnvisionTec Perfactory Standard System, but an "out of the box" analysis of the key characteristics of the parts built from it. No calibration other than standard machine setup has been undertaken to improve results.

The results of the tests revealed the following:

Repeatability:	Yes, within 0.2mm for x, y and z planes.
Strength:	Fair – brittle failure at a stress of 14 MPa, z strain twice, x and y strains.
Dimensional Accuracy:	Majority of error less than 1% of desired dimension, improving with the size of the sample.
Surface Flatness:	Excellent in z, but due to large shrinkage of resin during curing with current materials, poor in x and y for thin sections.
Surface Roughness:	Excellent horizontal and vertical build directions up to Ra of 27 at 10% inclination with better underneath surface.
Detail:	The system can reliably manufacture thin walled features up to 0.05mm thick.

The above results are an indication of performance of the PerFactory System during the period of testing. Improvements have been made to the set-up, operation calibration, and materials used. The process can only improve with iminant release of the new build resin.

7.0 ACKNOWLEDGEMENTS

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