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3D Printing in Colour: Technical Evaluation and Creative Applications

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Abstract

In this paper we report on an ongoing interdisciplinary investigation into the capabilities of colour 3D printing technologies, and present examples of the application of these technologies within art and design practice. The paper demonstrates that a quantitative investigation into colour reproduction in 3D printing can inform real-life design practice. Our research focuses on the powder-binder colour 3D printing system (Z Corporation, Burlington, MA). We present a technical evaluation which compares the colour output of the ZCorp 510 and 650 powder-binder 3D printers, through the production and measurement of colour test blocks. The investigation also compares the effect of two infiltrants (paraffin wax and cyanoacrylate) commonly used to enhance 3d printed output. The paper closes with a practical case study showing an application of colour 3D printing within art and design practice.

Introduction

3D printing is a type of rapid prototyping (RP) or solid freeform fabrication (SFF) which employs ink-jet printing technology to fabricate three-dimensional objects. In 3D printing, physical objects are “built” directly from computer aided design data, created using 3D modelling software, or acquired through 3D scanning of existing artifacts, such as hand-made models or maquettes. 3D printed objects are fabricated by depositing, fusing or solidifying material in successive layers, one on top of another, each layer corresponding to the cross-sectional shape of the objet being built. Developments in this field have led to 3D printing technologies being more widely available and affordable (Graham-Rowe, 2008; Wohlers, 2007; Gershenfield, 2005; Davey, 2003) making them accessible to a wider range of users than earlier rapid prototyping systems which were aimed principally at industrial design and engineering applications. 3D printing technologies are increasingly being exploited by a wider range of practitioners in the creative arts and design, and practical examples from within this field are included in this paper.

One common 3D printing technology is powder-binder 3D printing, developed at Massachusetts Institute of Technology (Sachs et al, 1993; MIT, 1989-2000) and licensed to Z Corporation (Burlington, MA, www.zcorp.com). In powder-binder 3D printing, layers of plaster powder are bonded together by a liquid binder (“ink”), which is printed onto a layer of powder using an inkjet print head. “Full colour” 3D printing is made possible through the inclusion of colourants within the liquid binders.

Our previous research has included the technical evaluation of the colour output of the Z-Corp Spectrum 510 3D printer (Parraman et al. 2008; Stanic, Lozo et al. 2008; Huson et al. 2008). The Z-Corp Spectrum 510 employs four ink jet print heads, with cyan, yellow, magenta and clear liquid binders. Our research investigated the colour gamut of Z Corp Spectrum 510, the accuracy and consistency of the colour output, and the effectiveness of different infiltrants to enhance colour. This research also highlighted issues relating to on-screen pre-visualision of 3D printed colour, and the influence of 3D surface orientation on colour accuracy and consistency. 3D printed colour charts were produced as a reference guide to assist in the selection of colours for 3D printed artifacts.

In the present paper, we extend our research of colour reproduction of Z-Corp Spectrum 510 printer by developing further a set of 3D colour test blocks, which can serve as real-life models to assist artists and designers in the pre-visualization process to help to achieve the desired colour output. The research is extended to include a technical evaluation of the colour output of the Z-Corp 650 3D printer, which was launched in Autumn 2008, and is the latest 3D printer in the Z-Corp range. In addition to the cyan, magenta, yellow and clear binder channels, the Z-Corp 650 has an additional print head for black binder.

Our evaluation includes examination of reproduction of basic colours, accuracy and consistency of colour output, through the production of a series of 3D printed colour test blocks. The readings are taken by a spectrophotometer and compared using the colour difference formulae. In addition, we present results comparing colour samples treated with paraffin wax and cyanoacrylate type infiltrants, which are commonly used to enhance 3D printed output and have different impact on the colour appearance.

The paper closes by presenting examples of 3D printed art and design artifacts, for which the colour test blocks served to aid colour choice. We conclude by identifying implications of this investigation in 3D printing technologies within art and design practice, and point to opportunities for further research in this field.

Review of previous research

Our previous investigations into 3D printing and colour have been reported in (Parraman et al., 2008; Stanic et al., 2008). This research will now be briefly summarised.

Research described in Parraman et al. (2008) included an evaluation of the colour output of the ZCorp Spectrum 510 powder-binder 3D printer. This involved the production of 3D printed colour charts and samples, which were finished by wax infiltration. Here colour charts were printed on flat (horizontal, upward facing) surfaces, and also on the horizontal and vertical faces of a cube. Prior to wax infiltration, the 3D printed colour charts and samples were lightly brushed with a soft paintbrush to remove any unbound powder, however their surfaces were not sanded. Following wax infiltration, uneven, strata-like effects were reported on the vertical faces of the coloured cubes. The 3D printed colours were measured using a spectrophotometer, and on average, a more than "just noticeable" colour difference was recorded between colours printed on a flat, horizontal net of a cube, and like colours printed on the vertical faces of a cube. Also identified was the slight darkening effect which occurs when the white objects, i.e. objects built with uncoloured binder, are infiltrated with wax. The colour difference between the unwaxed base colour and waxed white objects was found to be on average delta E 12. In addition, as well as providing a means to evaluate the colour output of the 3D printer, the colour charts and samples served as a useful physical reference to aid the selection of colours for 3D printed art and design artifacts (figure 1).

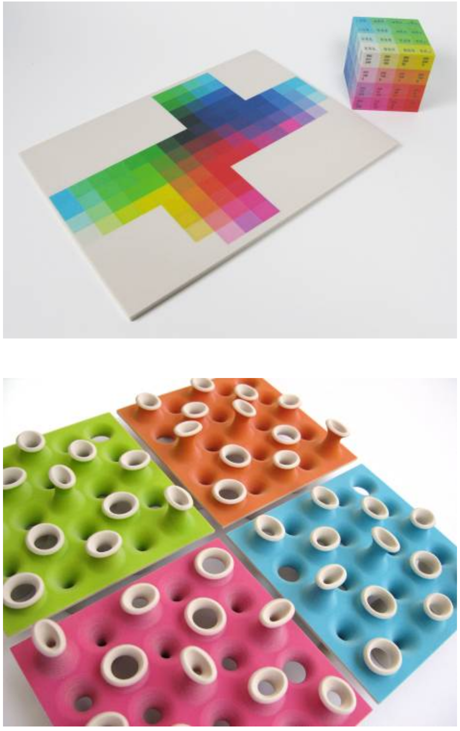

Figure 1 3D printed colour charts and design artifacts (Parraman et al. 2008)

Stanic et al. (2008) investigated the basics of colour reproduction in 3D printing, on ZCorp Spectrum 510 printer, using the zp131 powder and zb60 binders. Printed samples were separated into three groups, based on the finishing method; untreated, treated with cyanoacrylate agent (Z-Bond) and treated with epoxy-based agent (Z-Max). Two different types of colour test charts were used, one based on the ECI2002V test target and one user defined (figure 2). The work focused on two issues, the basics of 3D colour measurements methodology and the colour reproduction of basic colours and the colour gamut achievable by 3D printing. The research conclusions were that the finishing of 3D prints, influenced by the infiltrant agent used, decreases the lightness values and increase the chroma values. Infiltration with the cyanoacrylate agent, compared to the epoxy agent, contributes to the higher chroma values, while lightness and hue values do not differ much. Consequently, the gamut of cyanoacrylate finished 3D prints is larger than the epoxy infiltrated, although there are areas of the gamut that are reproduced very similarly. Due to the colour characteristics and surface topography of 3D prints, a sphere spectrophotometer (d/8° measuring geometry) was used for colour measurements.

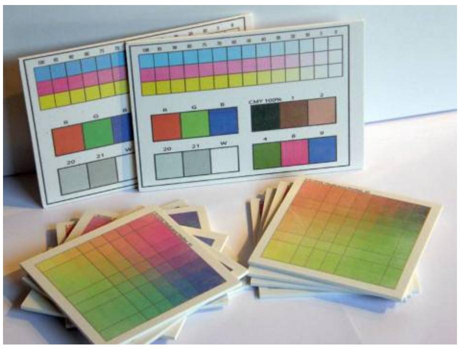

Figure 2 3D prints used for measurements, non-infiltrated sample presented (Stanic et al. 2008)

Z-Corp guidance for colour 3D printing

On their user website (www.zcentral.zcorp.com) Z-Corp provide a document “Best Practices Series Colour Quality” which gives guidance on how to achieve good quality results from Z-Corp powder-binder colour 3D printing systems, and this guidance is now summarised.

Z-Corp recommends that the 3D printer should be kept clean and well maintained. The print head service station and alignment sensor window should be cleaned. In order to ensure that the print heads are properly aligned, the auto-alignment procedure, which is accessed through the 3D printing software, should be carried out. The user should check the test pattern which is printed as part of the auto-alignment procedure, to make sure that the print heads have been aligned correctly. Within the 3D printing software, the correct powder and infiltrant type should be chosen. Z-Corp give guidance on how best to orientate the parts to be printed, and also recommend building a black witness part in front of the part to be built, to minimize “shadowing” effects and ensure best quality results.

Once 3D printed parts have been built, Z-Corp recommends that they should remain in the build bed for at least one hour to ensure they are fully dry. The parts should then be removed from the printer, loose powder should be removed, with a paint brush or with compressed air in the Z-Corp de-powdering station. Parts should be allowed to dry for a further 2.5 hours in a low humidity environment. To achieve good quality, consistent colours on the surfaces of 3D printed parts, Z-Corp recommend that the parts should be lightly sanded or brushed, with 220 or 320 grade sandpaper, or a nylon brush, to even out any inconsistencies which may occur in the 3D printed colours. All remaining loose powder should then be removed.

To achieve “uniform, vibrant” colours, Z-Corp recommends dipping parts in Z-Bond 101 Cyanoacrylate infiltrant. Protective gloves should be worn for this procedure. Parts should be completely submerged in Z-bond for 10 to 20 seconds, or until bubbles stop rising from the submerged part. The part should then be removed from the dipping container, and paper towels used wipe off any excess infiltrant. It is necessary to work quickly and to keep the Z-bonded part moving in order to avoid it sticking to paper towels and gloves. The part should then be left on a non-stick surface until the infiltrant has fully dried.

Also on its user website, Z-Corp provides a set of Sample Colour Charts for 3D printing. This set consists of nine tiles, each having 81coloured patches, making a total of 729 different colours. This offers a helpful way view, compare and select colours for 3D printing. The colour patches are flat squares, raised slightly from the upward facing surface of the tiles. In the 3D print files which can be downloaded from the Z-Corp website, the tiles are orientated horizontally in the build, with the colour patches facing upwards.

Design and production of colour test blocks

The rationale for the design of the colour test blocks was to provide a simple three dimensional form which would allow the appearance of the 3D-printed colour to be evaluated on different surfaces i.e. horizontal, vertical, diagonal and curved surfaces. The design of the colour test blocks is shown in figure 3. The blocks measure 40 x 40 x 14 mm. Colour test blocks also have small concave and convex hemispherical features which serve to provide a registration function when the blocks are stacked together. In the 3D CAD model clearance of 0.1 mm was specified between the mating surfaces of the concave and convex registration features, to allow for any dimensional variance in the 3D printing process and the application of infiltrants.

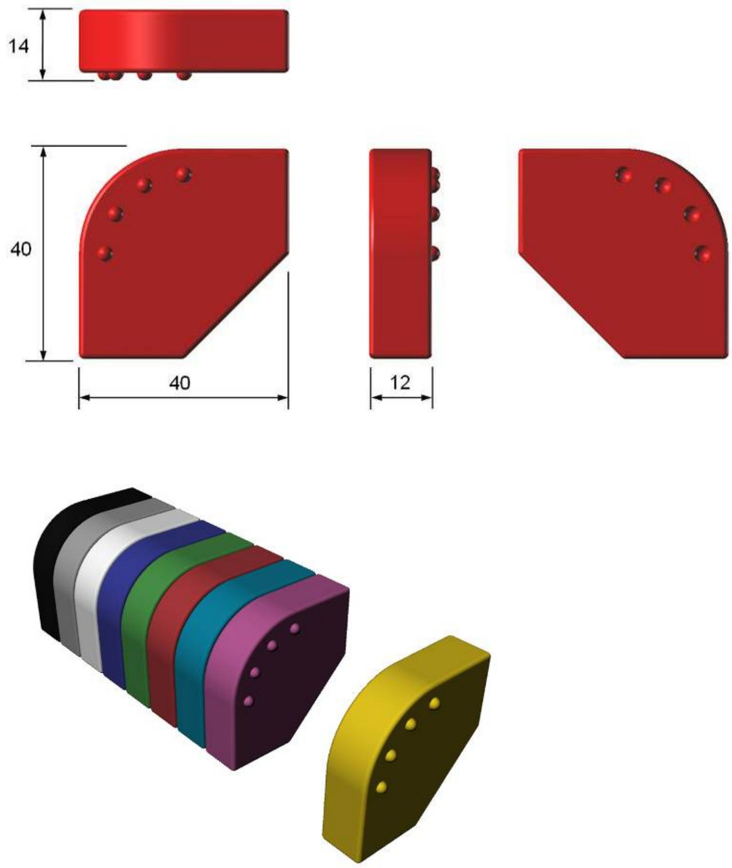

Figure 3 Design of the colour test blocks

The colours chosen for the colour test blocks were the 24 colours of the GretagMacbeth (X-Rite) “ColourChecker Classic” chart (www.xrite.com). This chart was chosen because it was thought to provide a good range of colours and grey tones and because it is often used as a standard within the colour imaging field. The colours of the colour checker chart, together with the sRGB colour coordinates are listed in figure 4, except for black, where for the colour coordinates used for the test blocks was RGB 0, 0, 0.

		sRGB						sRGB			
		R	G	B				R	G	B	
1.	dark skin	115	82	68		13.	blue	56	61	150	
2.	light skin	194	150	130		14.	green	70	148	73	
3.	blue sky	98	122	157		15.	red	175	54	60	
4.	foliage	87	108	67		16.	yellow	231	199	31	
5.	blue flower	133	128	177		17.	magenta	187	86	149	
6.	bluish green	103	189	170		18.	cyan	8	133	161	
7.	orange	214	126	44		19.	white	243	243	242	
8.	purplish blue	80	91	166		20.	neutral 8	200	200	200	
9.	moderate red	193	90	99		21.	neutral 6.5	160	160	160	
10.	purple	94	60	108		22.	neutral 5	122	122	121	
11.	yellow green	157	188	64		23.	neutral 3.5	85	85	85	
12.	orange yellow	224	163	46		24.	black	52	52	52	

Figure 4 Colours of the GretagMacbeth ColorChecker Classic chart with sRGB values.

The colour test blocks were built on Z-Corp 510 and 650 3D printers. The Z-Corp 510 3D printer used for the study is located within the 3D laboratory at the Centre for Fine Print Research, University of the West of England. The Z-Corp 510 printer is well maintained, and prior to printing the colour test blocks, it was thoroughly cleaned. New print heads were fitted, purged and auto-aligned. The type of powder and binder used were ZP 131 and ZB 60. The colour test blocks were oriented in the build as shown in figure 5. A black witness part was generated using the Z-Print 3D printer software. 3D printing of the colour test blocks on the Z-Corp 650 was carried out by a leading UK-based bureau and Z-Corp distributer. The bureau was instructed to orient the blocks in the same way as the Z-Corp 510 build, and to use the same powder i.e. ZP 131. The bureau supplied the blocks with the loose powder removed, but without any further post-processing such as sanding or infiltration.

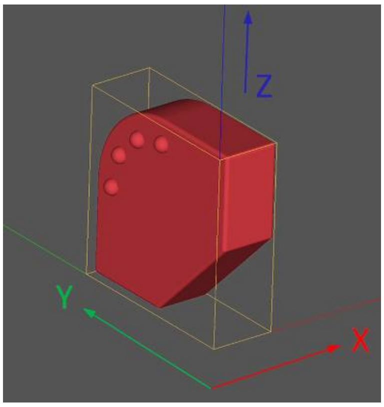

Figure 5 **Orientation of colour test block in the 3D printing software**

Two sets of 24 colour test blocks were built on the Z-Corp 510 3D printer, and two sets were built on the Z-Corp 650. The blocks built on the Z-Corp 510 were lightly sanded, using 220 grade sandpaper, applying moderate pressure for 5 to 10 strokes on the principal surfaces of the blocks. Great care was required in the area around the convex hemispherical “bumps”, to avoid damaging these features. Rather than using sandpaper, these areas were lightly brushed with a toothbrush. A soft paintbrush was used to remove all loose powder from the sanded blocks. One set of the sanded blocks was finished by wax infiltration, using a wax dipping unit (Seba Developments) and Paraplast wax, (figure 6), and the other set was finished by Z-Bond infiltration (figure 7) following the Z-Corp guidance for the dipping procedure, outlined in the previous section. Both sets of blocks built on the Z-Corp 650 3D printer were sanded and brushed, as described above. One of these sets was finished by wax infiltration, the other by Z-Bond infiltration.

Figure 6 3D printed colour test blocks, which were built on the Z-Corporation Spectrum 510 3D printer, lightly sanded and then finished with wax infiltrant.

Figure 7 3D printed colour test blocks, which were built on the Z-Corporation Spectrum 510 3D printer, lightly sanded, and finished with Z-Bond infiltrant.

Colour measurement

Measurements were made to four faces of each block: (A) top face, (B) front face, (C) side face, (D) curved surface at 45 degree angle (figure 8). A GretagMacbeth EyeOne spectrophotometer, with D50 illuminant and 2º standard colorimetric observer was employed (figure 9). Using this instrument, a single measurement was made on each of the four faces A to D. From this the measuring data was saved as spectral and CIELa*b* formats.

The Gretag Macbeth (X-Rite) "Colour Checker Classic" chart was also measured and used as the reference data for comparing the colour blocks. The colour differences are described as Delta (Δ)E CIE 2000.

Four sets of 24 colour test blocks were available for colour measurement as follows:

Set 1	Z-Corp 510	sanded	waxed
Set 2	Z-Corp 510	sanded	Z-Bond
Set 3	Z-Corp 650	sanded	waxed
Set 4	Z-Corp 650	sanded	Z-Bond

Of these sets, the colours which were measured were Cyan, Magenta, Yellow, Neutral 6.5 and black.

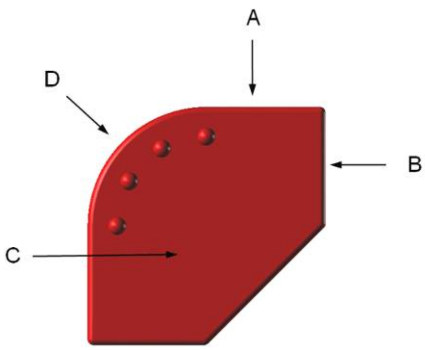

Figure 8 The surfaces A to D of the test block were measured

Figure 9 Measurements were made using a GretagMacbeth EyeOne spectrophotometer

Analysis and discussion of results

When comparing the results of samples printed on Z-Corp 510 printer and Z-Corp 650 printer, the obtained colour differences range from dE 3.07 for the cyan sample, Z-Bond infiltration, up to quite noticeable dE 7.29 for black sample, Z-Bond infiltration. Based on here discussed colours, the colour difference between samples printed on 510 and 650 printers is around dE 4, for both infiltration methods. The full results are presented in Table 1.

Wax Infiltration	DE_{00}
Yellow	3.63
Magenta	5.58
Cyan	3.13
Neutral	4.73
Black	3.54

Z-Bond Infiltration	DE_{00}
Yellow	5.23
Magenta	2.76
Cyan	3.07
Neutral	4.63
Black	7.29

Top surface, marked A, results shown.

Table 1. Colour difference between samples printed on Z-Corp 510 and 650 printers

The effect of different types of finishing, wax infiltration and Z-Bond infiltration, was also analyzed, separately for samples printed on Z-Corp 510 and Z-Corp 650 printers. These results are especially important having in mind that different finishing agents produce quite different, visually noticeable, results. Previous research (Stanic et al., 2008) have compared colour differences between cyanoacrylate based infiltrant (Z-Bond) and epoxy-based infiltrant (Z-Max), while current analysis compares wax infiltrant with Z-Bond infiltrant. The obtained colour differences range from dE 0.97 for black sample printed on Z-Corp 650 printer up to dE 4.69 for black sample printed on Z-Corp 510 printer. The full results are presented in Table 2.

Z-Corp 510 printer	DE_{00}
Yellow	3.26
Magenta	4.19
Cyan	4.01
Neutral	4.21
Black	4.69

Z-Corp 650 printer	DE_{00}
Yellow	3.17
Magenta	1.77
Cyan	2.39
Neutral	1.52
Black	0.97

Top surface, marked A, results shown.

Table 2 Colour difference between wax finished and Z-Bond finished samples

The next aspect of colour reproduction which was analysed was the colour difference between different surfaces on colour block. This is of importance since, due to the mechanism of 3D printing, differences in surface appearance and in colour reproduction can occur. Previous research (Parraman et al., 2008) included colour reproduction on different surfaces of cubes and this work further elaborates the issue, dealing with more surfaces and more types of samples (see description of different sample sets in Colour Measurement). Figures 10 to 15 show the results of colour differences between top surface, marked A, and other surfaces, front, side and curved (45° angle), marked B, C, and D respectively. The results suggest that, as expected, there are visible differences between different surfaces of 3D printed objects, depending on their specific orientation in relation to the 3D printing mechanism. The issues of "banding" or the presence of visible stripes on vertical surfaces can normally be alleviated satisfactorily by carefully sanding the 3D printed objects prior to infiltration, and the "stair effect" on angled and curved surfaces can also be dealt with in this way.

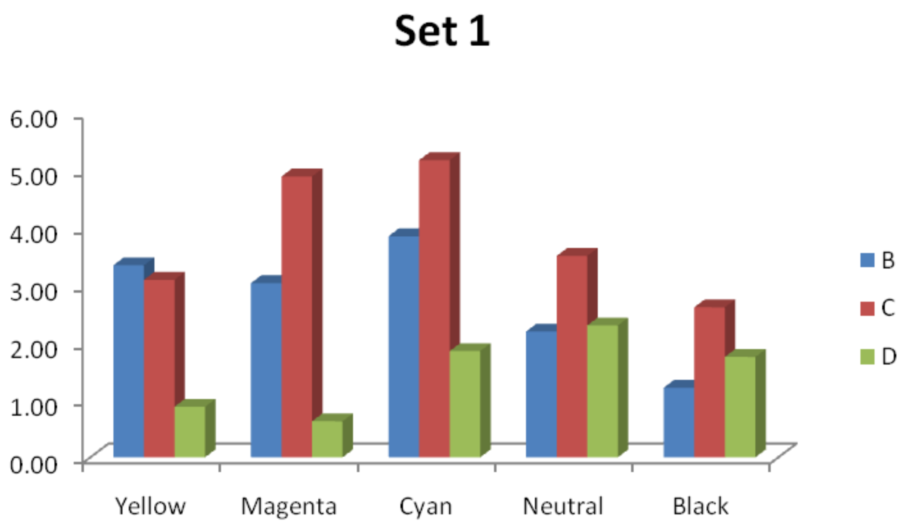

Figure 10 dE between top surface, marked A, and respective other surfaces. Set 1 (Z-Corp 510, sanded, wax infiltration)

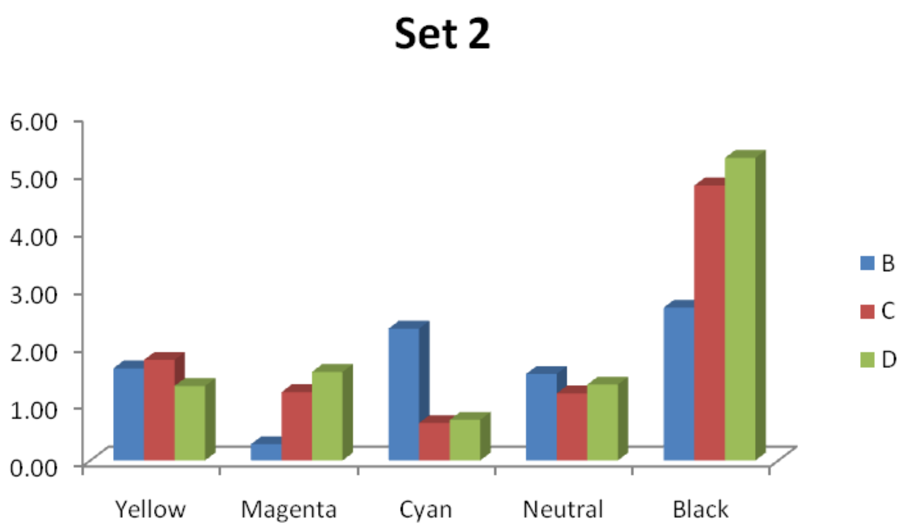

Figure 11 dE between top surface, marked A, and respective other surfaces. Set 2 (Z-Corp 510, sanded, Z-Bond infiltration)

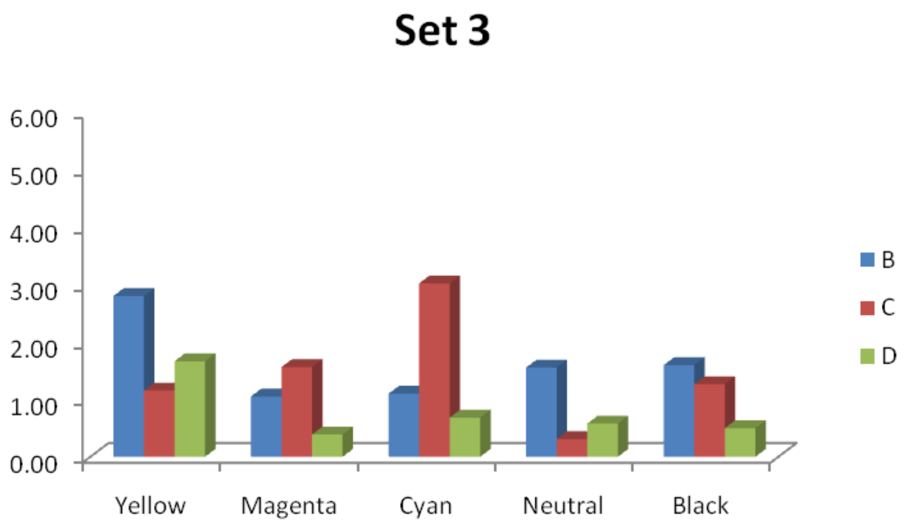

Figure 12 dE between top surface, marked A, and respective other surfaces. Set 3 (Z-Corp 650, sanded, wax infiltration)

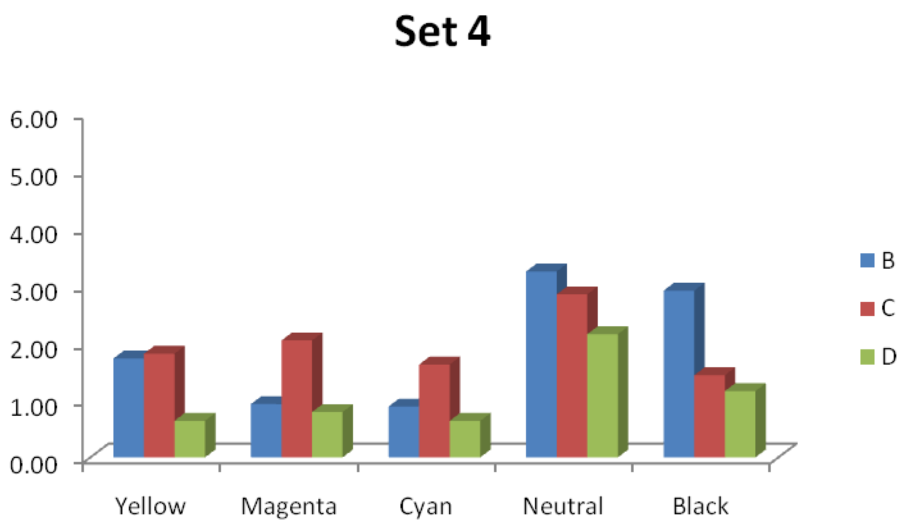

Figure 13 dE between top surface, marked A, and respective other surfaces. Set 5 (Z-Corp 650, sanded, Z-Bond infiltration)

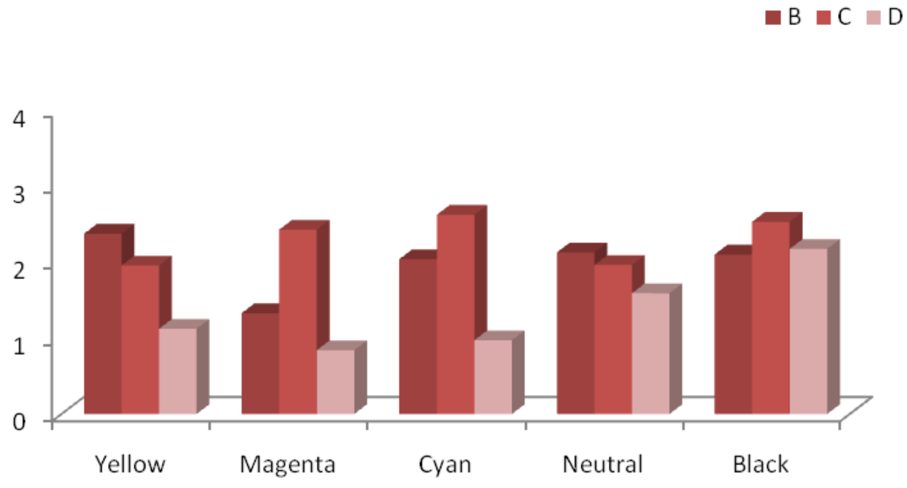

Figure 14 dE between top surface, marked A, and respective other surfaces, expressed as average for all the samples

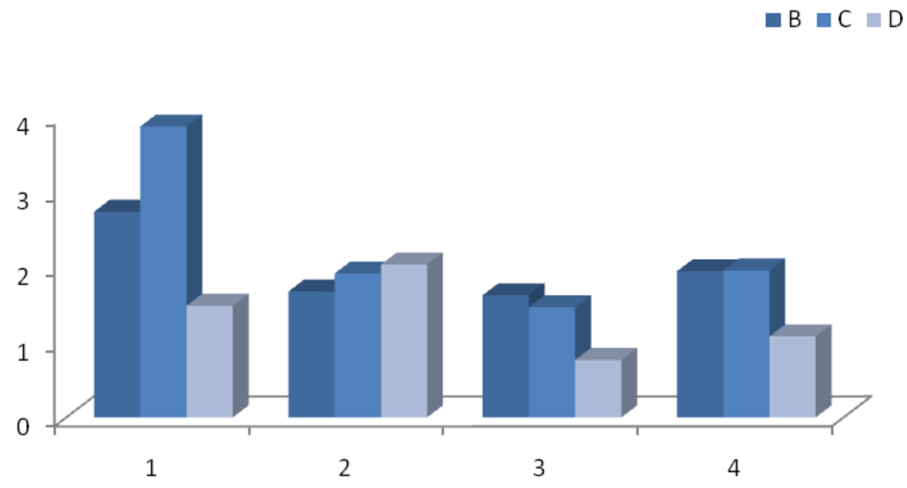

Figure 15 dE between top surface, marked A, and respective other surfaces, expressed as average all the colours on sets 1 to 4 of printed samples (see Colour Measurement section for description of sets)

The analysis also compared the measured values of the colours on the GretagMacbeth ColorChecker chart with those of the top surface, marked A, of all the sets of 3D printed colour test blocks (figure 16). This comparison is of particular importance since it shows the scale of colour difference between the “target” colour and the colour achieved in 3D printing, having in mind that there was no profiling or any alterations of the colour reproduction workflow. These results show the resulting differences between the “target” values and resulting values of samples finished in different methods. The results also show the need of development of unique visualization aids or, in the end, profiles for different finishing methods. This is in agreement with the suggestion from the Z-Corp, which advises that differently finished sets of Z-Corp Sample Color Chart for various finishing combinations should be used.

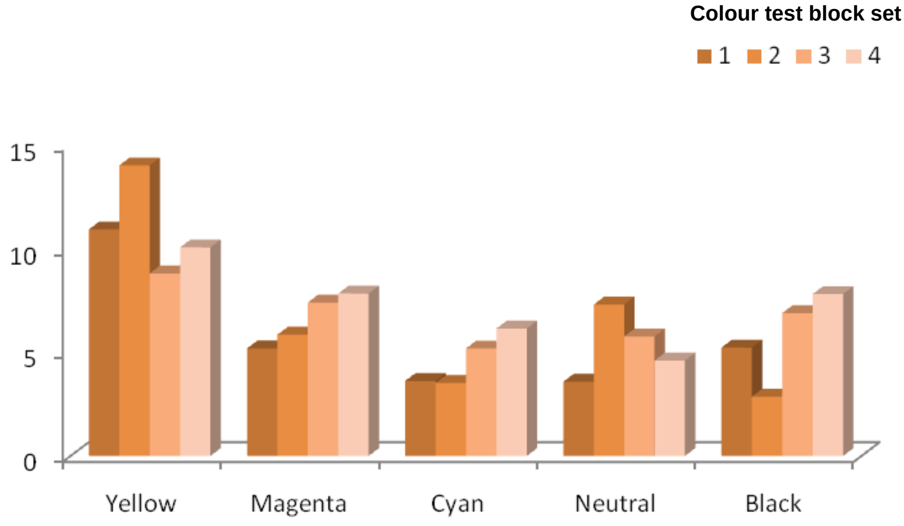

Figure 16 dE between measured values of GretagMacbeth ColorChecker chart and top surface, marked A, of sets 1 to 4 (see Colour Measurement section for description of sets)

In addition to the results presented above, further measurements were taken from the two sets of colour test blocks produced on the Z-Corp 650 3D printer. Spectral and dE measurements were taken from the top face A, and the results for colour test blocks with Z-Bond and Wax infiltration were then compared. The spectral curves in figure 17 indicate an overall difference in waxed samples, which appear lighter. There a slight shift in the blue area with a dE difference of 7.5 (CIE 2000), in the green dE of 5.7 greater magnitude difference in the Da* (green region); and for the red a dE of 4.8 again appearing lighter in the red region. The two yellow samples yield the greatest magnitude difference of 11.7 dE. Overall, the slight gloss of the ZBond appears to create a more homogeneous colour. Both ZBond and Wax infiltration help to reduce the stripy effect of the ink strata and create a more pleasing finish.

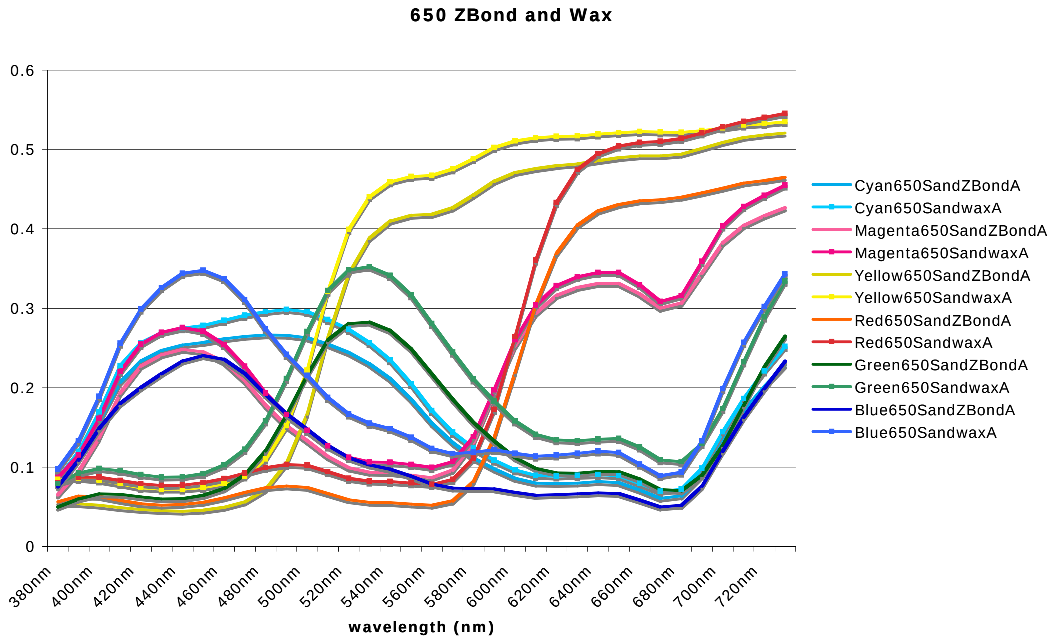

Figure 17 Z-Corp 650 colour test blocks. Surface A measured.
Z-bond infiltration and wax infiltration compared.
(x axis = wavelength, y axis = reflectance)

Design study

To demonstrate how colour test blocks were used to assist in the selection and previewing of colours for 3D printing of art and design artifacts. Form and colour studies were created: “Undersea Machines” and “Trumpet Spheres”. A palette of five colours was first generated in Photoshop. The sRGB values for these colours were applied to test blocks in Z-Edit software. The test blocks were 3D printed, sanded and brushed, and infiltrated with wax. Following infiltration, the coloured test blocks were found to be slightly darker than expected, so the colour values were adjusted and a second set of blocks was printed and post-processed. This time the colours were satisfactory (figures 18 and 19).

Figure 18 Palette of colours chosen for 3D printing

Figure 19 Colour palette previewed using 3D printed colour test blocks

These colours were then applied to the form and colour studies “Undersea Machines” and “Trumpet Spheres”, shown in figures 20 to 22. For the “Undersea Machines”, the inner sea urchin-like form was built separately to the outer circular frame so that the inner part could be infiltrated with wax, whilst the outer frame was left as the base white colour. This was to avoid the slight darkening effect which can occur with wax infiltration, as described earlier. Sea urchin-like form was carefully brushed with a soft toothbrush prior to wax infiltration, to alleviate the slight variation in colour which was present over the curved surface, and this resulted in a much more satisfactory appearance when waxed. Two sets of Trumpet spheres were produced, one set was waxed, and the other set was left untreated, because with untreated surfaces, the appearance of the object was also pleasing to the artist.

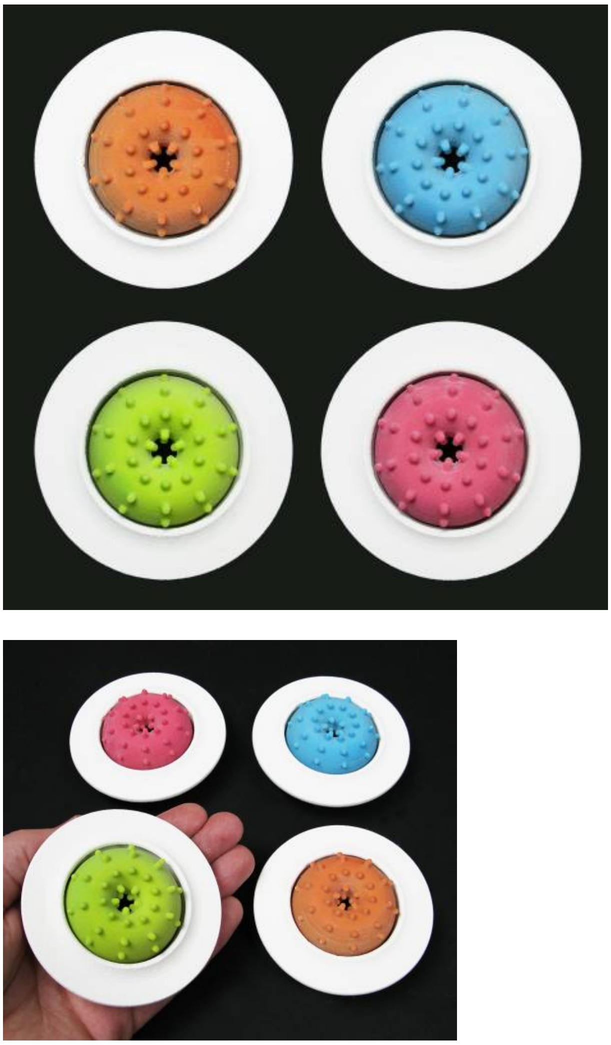

Figure 20 Undersea Machines. 3D printed form and colour study (Peter Walters, 2009)

Z-Corp Spectrum 510 powder-binder 3D print, inner forms infiltrated with wax, outer frames not infiltrated.

Figure 21 Trumpet Spheres. 3D printed form and colour study (Peter Walters, 2009)

Z-Corp Spectrum 510 powder binder 3D print, wax infiltrated

Figure 22 Trumpet Spheres. 3D printed form and colour study (Peter Walters, 2009)

Z-Corp Spectrum 510 powder binder 3D print, wax infiltrated

Discussion and Conclusions

The technical study of colour reproduction in 3D printing, as based on the analysis of selected basic colours, has shown that the reproduction of colours is dependable on the position and orientation of the surface, finishing method and type of printer used. The colour difference, expressed as dE, was presented for all described cases. The findings are indicative of the issues which contribute to differences in colour appearance of objects produced by powder-binder 3D printing. The results presented in the technical investigation are based on single measurements taken from four surfaces of the 3D printed colour test blocks, using a GretagMacbeth EyeOne spectrophotometer. This is clearly a limitation of the present study, since a spot reading at a single location does not show up any variations in colour which may be present on the surrounding surface. Nevertheless, we consider that the quantitative results presented here do give some indication of the nature of colour variations which can occur with powder-binder 3D printing.

The use of colour test blocks as pre-visualization tools was also demonstrated, and study presents the possibilities of creating unique, tailor-made solutions, according to user preferences, for example, to assist in the selection and pre-viewing of a palette of colours for specific art and design applications.

In conclusion, it may be stated that like all technologies, the Z-Corp powder-binder 3D printing process has certain capabilities and limitations. By developing a practical understanding and sensitivity to the materials and process parameters, it is possible for artists and designers to obtain pleasing creative outcomes.

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