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Methods for Multi-Layer Color Printing and Decorative Inks for Ultra-Violet Fine Art Inkjet

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Abstract. *As more robust methods for ultra-violet (UV) curable inkjet printing are being introduced to market, alternative color and decorative printing methods have been tested for the art, design, and print sectors. In order to be able to increase the density of color, and improve the ink coverage when printing onto a range of non-standard substrates, this article describes results relating to the appearance of print on different surfaces, which includes both measured data (densitometry, gamut volume, International Colour Consortium (ICC) profiles) and a visual analysis (subjective assessment, microphotography). The objective is to address the requirements of the user, to accurately print a specific color through the multi-layering of inks, and to present methods of soft previewing the appearance of a multi-pass printed color. Several case studies are presented that incorporate recent research into the capabilities of UV curing technology, which has increased the opportunities for designers to print onto non-standard materials. © 2013 Society for Imaging Science and Technology.*
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INTRODUCTION

Since its introduction to the market in the 1980s, inkjet color printing has advanced significantly: from poor-quality fugitive inks and inaccurate color management methods, to high-quality, accurate multi-colorant printing devices and high-speed presses. The current state of colorimetry, digital halftoning, and printing is part of a mature industry, and therefore technological innovation in the field of inkjet printing has begun to concentrate on more novel industrial applications, for example three-dimensional printed ceramics, biomedical sensors, and printed circuit boards.[1–3]

As demonstrated at DRUPA in 2012,[4] as a result of developments in more permanent, robust ultra-violet (UV) curable and decorative inks, the application of inkjet printing has expanded into alternative markets including packaging, publishing, textiles, and outdoor displays, and printing onto a range of substrates is now achievable. Whilst UV-curable inks have been used for more than ten years in lithographic, screenprint, and flexographic industries, it is only now possible for UV-curable inks to be ink-jetted. This has been due to improvements in print head technology and developments in the chemistry of inks. Manufacturers of UV-based hardware (Roland, HP Scitex, Durst) are now incorporating decorative inks such as white, gloss, and metallic,[5] and these new decorative inks can be considered as the most interesting and innovative challenge yet to the traditional print market.

The print quality of a traditional print is dependent on a range of factors: the gamut of the colorants, the texture, color and absorbency of the substrate, light-scattering properties, color management, halftoning methods, and viewing conditions.[6,7] Unlike conventional inkjet printers that require a wide range of paper profiles and ink limits, a benefit of the inkjet UV curing process is that a single profile can be used for a much wider range of uncoated materials, for example, cardboard, vinyl, canvas, laminates, cork, and papers. As industrial printers and designers are able to print images onto a range of alternative substrates, UV technology is increasingly more adaptable and practicable for the design market.[8]

With the addition of white, gloss, and metallic inks, the predictability of colors printed onto diffusing substrates in combination with decorative inks presents a new challenge. When non-standard materials are involved (uncoated paper, leather, plywood), some substrates are more absorbent than others and therefore require multiple passes to create an appropriate coverage of ink. Where multi-layers are used, the final printed appearance will change according to the total number of passes. It is now possible to increase the saturation and opacity of colors by using a multi-pass process;[9] for example, where a pale color that can only be achieved from a single pass, a deeper color can be obtained by using a multi-pass process.

The evolving question for this research was to address the requirements of the user, to accurately print a specific color through the multi-layering of inks, and develop methods of soft previewing the appearance of a multi-layered color prior to printing.[10] This approach is less concerned with printing photographic-based images but rather pays attention to obtaining a specific color or blend of colors.

The second evolving consideration was that of speed and cost. Although UV curing technology has enabled printing onto a range of materials, the process is slow. The investigation calculates the amount of passes to ensure the optimum physical interaction between paper and ink and its desired final appearance.

The third evolving question has centered on alternative visual approaches to ensure a multi-disciplinary understanding for all users through sector-wide collaboration,

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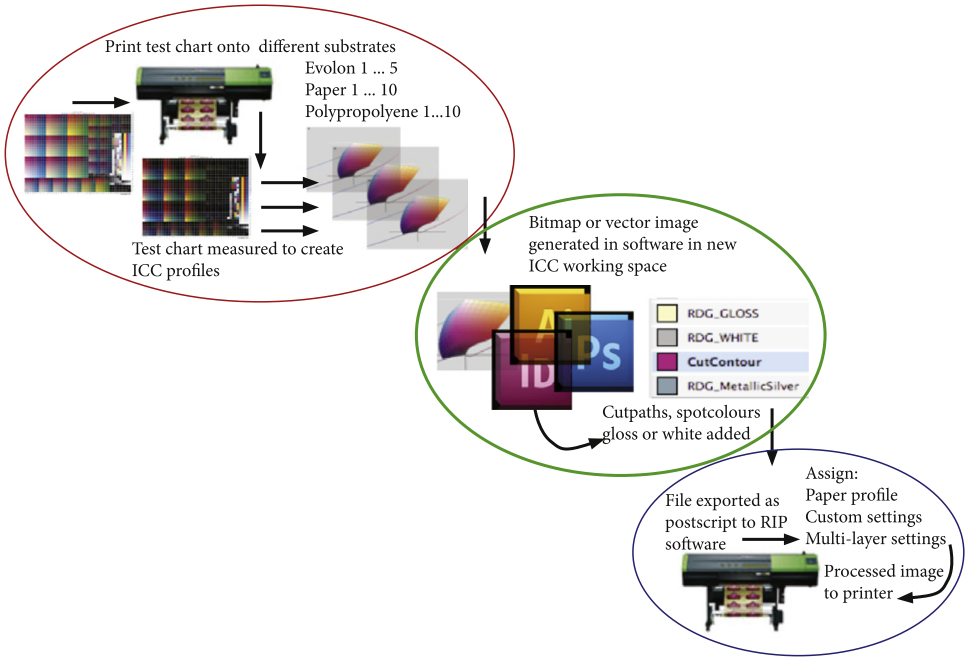


Figure 1. Demonstration of image-processing workflow: (1) measuring of multi-layering onto different substrates, (2) construction of images, (3) printing the final image.

including academic, industrial, and commercial partners. The information we are presenting therefore needs to demonstrate different ways of comparing and analyzing data that address the different requirements for users.

The article demonstrates an image-processing workflow (Figure 1), which involves (1) measuring of multi-layering onto different substrates, (2) construction of images, and (3) printing the final image. However due to the irregular three-dimensional surface properties of the multi-layering process, and based on the unique printing characteristics of UV-curable inks, the paper presents an alternative perspective in relation to the physical demonstration of the build-up of ink and the optical properties of ink and paper at the microscopic level.

PRINTING WITH UV-CURABLE INKS

New decorative inks are increasingly available for the inkjet market. These solvent or so-called ecosolvent[11] (lower solvent, slower drying) inks are hardened through UV curing and can be printed onto vinyl, fabrics, and boards. They can also be used outside, and may be subjected to a range of temperatures and weather conditions. Printing with UV-curable inks increases the opportunity to print onto a variety of uncoated materials and can also create high-quality prototypes for the packaging and pre-press industry. The conventional process of ink drying occurs when the ink carrier (water, oil, or solvent) is either absorbed by the paper or evaporates, leaving a residue of dye or pigment on the surface. The process of hardening UV-curable ink occurs as the liquid ink is printed onto the material and is immediately exposed to UV light. The difference also lies in the chemical composition of the inks, coatings, and the printers required to print them. For conventional inks, pigment or dye particles are suspended in an aqueous fluid, along with additives such as wetting agents and rheology modifiers that assist the thermal or piezo printing process.[12] The main difference between conventional inks and UV-curable inks is the addition of photo-initiators. In UV-curable inks, the photo-initiator is combined with liquid monomers (lightweight molecules that bind together to form polymers) that, when exposed to UV light, release free radicals (reactive molecules that can start rapid chain reactions). These produce polymers (that has a high molecular weight), which results in a resinous printed material. A surface printed with UV-curable ink tends to be more robust and scratch resistant than one printed with conventional inks, which are reliant on the coating of the paper to hold ink on the surface without it sinking into the fibers of the paper, and such printing can be applied to a wider range of materials (cardboard, plastic, metal, canvas). For uncoated papers, there are other problems such as the potential for damage through scuffing or accidental water damage; coated inkjet surfaces are very difficult to repair.

Although white has always been a necessary component of any artist's palette, inkjet manufacturers have been slow on the uptake. This is mainly because the particulate sizes have to be larger in order to obtain the right degree of opacity. There is a tendency for these pigments to drop to the bottom of the cartridge, and therefore they require regular agitation in order to maintain a uniform dispersion of ink. White can be used in a variety of ways, determined by the layout software as a series of commands and then processed through the RIP (Raster Image Processor). The white ink can be used as an undercoat to print vibrant images onto clear, colored, or metallic surfaces. It can also be used as a single spot color to provide highlights, for example on a dark material.

Clear inks are used as a single gloss, as a varnish to enhance areas, or to create a raised relief surface by overprinting layers of clear ink. Clear inks can either be printed as a matte varnish or a glossy varnish, the printed glossy or matt appearance of the ink can be determined. A glossy varnish finish can be achieved through a partial UV exposure (one UV light) or complete exposure (two UV lights) to create a matte finish. The two-lamp UV curing system means that clear ink can either be cured matte, or it can be cured glossy.

Metallic inks (such as those manufactured by Roland) are a recent introduction (2009). Typically, a silver base layer is printed, with the addition of CMYK spot colors as a second layer, to create a wide range of metallic colors. These inks are currently suspended in a solvent-based carrier and are printed by a conventional inkjet process.

COLOR FIDELITY AND COLOR MANAGEMENT

In order to achieve accurate color reproduction when using aqueous-based inkjet printers, each paper and printer combination requires characterization: calibration, paper linearization, and paper profiling. These profiles need to be regularly managed and updated. Generic paper profiles can result in a reduced color gamut or poor color rendering, which has caused color management problems for users in achieving accurate and consistent color reproduction.

In contrast, UV printers require only a few paper profiles; the reason is that the polymer-based ink does not rely on the composition (cellulose, cotton, vinyl, foil), texture (rough, smooth, gloss, matt), the brightness (optical brighteners, natural) or color properties of the substrate (newsprint, off-white, cream, metallic, body color, e.g., red, blue, black). If, for example, the substrate is a dark blue, then a white layer can be added to improve the brightness of a light color upon a dark colored background.

Experimental Set-Up

A diagram showing the complete workflow process is shown in the following Fig. 1. This workflow is divided into three parts: (1) multi-layer printing of test charts onto different substrates, measurement and conversion to ICC profiles; (2) construction of images, using the ICC profiles as a soft preview of how the multi-layering process will appear in the final printed image, and application of spot colors and decorative print commands, which are then exported as a PostScript file; (3) applying the printer settings, sending to print.

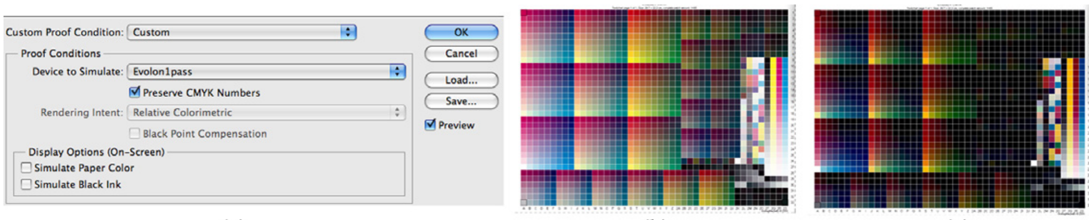
The project tested a UV curing solvent inkjet printer and cutter, the Versa UV LEC Series printer, which has the capabilities of printing full-color images, opaque-white, and multiple layers of gloss onto a variety of uncoated materials. Working with the RIP software (Versaworks version 4.1.1, firmware 4.90) for the Versa LEC, colors can be built up using a layers function; chroma and saturation can be increased through the RIP software by selecting between 1 and 10 passes. Although not undertaken in this experiment, the number of passes can be set individually to each channel, but this can be only accomplished one pass at a time. For example, to obtain a red for which two passes of magenta and one pass of yellow is required, the RIP software can be directed to print one pass each of yellow and magenta, then return to the point of origin and overprint a second pass of magenta. The appearance of the final red will differ according to the order of the inks. By building up layers in this way alternative methods for multi-pass printing can be explored.

In order to estimate the final appearance of a multi-pass image and soft preview on screen, an ICC color profile was created. This was undertaken by printing the ECI2002V CMYK color chart on the Versa LEC onto a range of papers. In the RIP software, the same profile was used (Generic II profile *Pre-Press Europe* preset: LECEcoUV_Generic2_v720x14440.icc) and the individual settings were tuned to 'high quality, 720 × 1440 dpi, halftone dither, nearest neighbour interpolation, bidirectional printing.' The choice of the profile and the individual settings were based on a trial and error basis of working with a wide range of image files onto different substrates to address different user requirements.[13] The method to undertake the multi-pass printing can be specified in the RIP software under the printer control 'use custom settings'. Ten charts were printed for each paper sample. The first color chart was printed in one pass, the second color chart contained two passes, and so on, until ten passes were completed for the tenth chart. For the purposes of this experiment, three different types of substrate were tested. Each material was considered to reflect a range of requirements for the user.

- Evolon®, a fibrous flexible cloth-like material that is made from polyester and polyamide. http://www.evolon.com/
- Paper, *Pop Set*®, Brilliant White, 320 gsm ECF Woodfree Virgin Pulp, 30% recycled, pH neutral (7.5 TAPPI 529OM) smooth surface suitable for a range of printing processes, which can be cut and folded. http://www.popsetpaper.com
- Polypropylene sheeting, 350 μm, which is a thermoplastic polymer that can be cut and folded. It is semi-opaque and therefore allows some light to be transmitted.

The charts were measured using Profile Maker Pro and the Gretag Macbeth Spectrolino with UV filter, with a standard illuminant of D50 and 2° colorimetric observer. The spectrophotometer was calibrated to its own standard white reference tile. An ICC profile was then generated from each of the measured charts. Settings used to make the profiles used a perceptual rendering intent, neutral gray, LOGO classic gamut mapping, GCR 3-40-100-400 separation, and D50 viewing light source.

The measurement data can be found on the author's web page, "UV curable inkjet printing and the wallpaper project": http://www.uwe.ac.uk/sca/research/cfpr/staff/carinna_parraman/colour_print_workflow_and_multi_layer_printing.html. This data contains separate files for each



(a) (b) (c)

Figure 2. (a) The dialog box in Photoshop showing the custom proof profile. A soft preview demonstrating the difference in the printed color on Evolon using one pass (b) and five passes (c).

printed pass. For example, file "1passPolypropLab.txt" contains CMYK, XYZ, and LAB data; file "1passPolyprop.txt" contains CMYK and spectral reflectance data (380 nm–730 nm); and file "1passPolyprop.icc" contains the ICC profile showing the gamut of multi-pass printing, and which can also be used to preview the colors in design software. In order to accurately preview the colors and gain a complete experience of the color differences, the monitor was calibrated (in this case to D50 illuminant, and a white point of X: 0.964; Y:1.000; Z0.827).

Each profile was imported to the system software libraries. Designers can use these profiles in any imaging application, for example, Adobe Illustrator, InDesign, and Photoshop. In order to soft preview an image in Photoshop using a profile, the following procedure was employed: View, Proof Set-up, Custom, then select "*name of profile*", with 'Preserve CMYK numbers' and 'Preview' buttons checked (Figure 2).

The ICC profiles can be used to visually evaluate the changes in the printed color patches and identify which colors are out of gamut. The first method is to apply an ICC profile as the CMYK working space and then any CMYK images that are opened can be viewed in the working space. The second approach is to assign the profile in the 'colour settings' menu and then click on 'gamut warning'. Sections that are out of gamut will show as gray. Users can also preview their artworks or specific colors—which they have themselves by ICC profiling in order to gain a better understanding as to how colors will appear after multi-pass printing.

Results from the Printed Samples

Qualitative and quantitative approaches were employed to compare the printed samples. An initial visual inspection of all the printed samples during the printing process showed that, in order to provide a good surface coating on a porous, fibrous, or textured surface, more than one pass was necessary; and when compared to two passes, the colors after one pass appeared desaturated. However, after five passes, the Evolon substrate had reached a maximum level of what could be considered as an acceptable surface quality; the darker patches on the fourth and the fifth charts revealed an unappealing hard fibrous surface, which resulted in a stiff non-flexible material. It was considered unnecessary to print further samples. A visual inspection of the ninth and tenth printed patches on polypropylene showed small bubbles, where the ink was beginning to delaminate from the plastic. These were easily detectable without the need for a microscope. Furthermore, in chart 10, color patches that contained the highest combination of CMYK had begun to appear lighter than the surrounding color patches. The maximum amount of printed passes of ink that was applicable for the Evolon, paper, and polypropylene differed depending on whether a lighter color or a darker color might be preferred. The polypropylene could also be used with back-lighting, and therefore a chart with a greater number of passes was considered useful. In order to view the polypropylene with a back-light, the charts were placed on a light box with 65 W fluorescent lighting.

Results from the Measured Data

The measurement data can be found under the 'Current Research' section of the author's web page: UV curable inkjet printing and the wallpaper project. http://www.uwe.ac.uk/sca/research/cfpr/staff/carinna_parraman/colour_print_workflow_and_multi_layer_printing.html.

Comparison of Ink Densities Using Densitometry

The density of the black ink patches at 40% print coverage were measured and compared across all the printed charts. The objective was to plot and compare the multi-pass layers of ink and their relative densities. The density of ink is dependent on the pigment, relationship of ink on paper, dot structure, and thickness of inks; it provides only a measure of the ink thickness, and does not measure the color or tonal value. According to Fogra, color control bars containing 40% and 80% patches are most widely used by printers as a means for density comparison.[14] As the ink thicknesses were too high at 80% to provide any comparable data, in this case only 40% patches were measured. The density of the patches was measured using an RT120 Techkon densitometer. The *R-DEN mode* measures the densities in reflection. The densitometer was calibrated to the paper's whiteness and then a measurement of the 40% black patch, which corresponds to color patch 2P19 on the EC12002V CMYK test chart was taken. The different substrates were measured and compared. Measurements in transmission mode were taken from 40% black patches on the polypropylene samples. The densitometer was calibrated to the chart upon the light box with 65 W fluorescent lighting. The following Figure 3 shows the comparison of 40% black patches for each of the substrates.

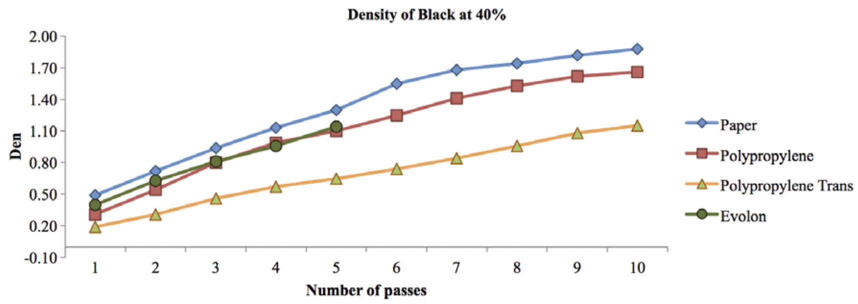


Figure 3. Comparison of densities of 40% black from one to ten passes.

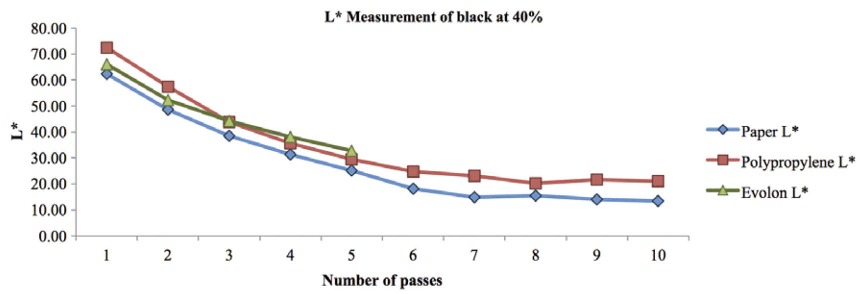


Figure 4. Comparison of ink densities using L^* measurements from the CMYK, XYZ, and LAB .txt files.

Figure 4 shows the L^* measurements from the measured .txt files (CMYK, XYZ, and LAB), and which are the same 40% black patches as measured by the densitometer. Figs. 3 and 4 demonstrate a comparison between the different substrates. As shown in the paper and polypropylene samples, the density and L^* values begin to plateau and show little difference at around the seventh pass.

Comparison of Multi-Pass Printing

Using the 'compare' function in Profile Maker, colorimetric variations of each of the ICC profiles generated from the printed color test charts were analyzed (observer angle 2° and illuminant D50). The software provides a statistical analysis and a visual display of each of the measured color charts. In Figure 5, a comparison was made between the first pass print and the subsequent passes. Figure 5 shows the ΔE_{2000} differences between paper, polypropylene (1 pass and 10 passes inclusive) and Evolon (1 pass and 5 passes inclusive), where each print pass was compared to the reference data contained in the first pass (Fig. 5). The plotted lines—containing circular marker points—indicate the maximum total ΔE difference. The plotted lines—containing star marker points—indicate the average differences.

Comparison of Gamut Volume

In order to analyze and compare the printed gamut of the color charts, the ICC profiles were imported into ColorThink Pro. (www2.chromix.com/colorthink). A comparison was made between the first pass print as the reference data. Figure 6 shows a comparison of the total volume for each gamut and their percentage differences (Table II). The number listed in the vertical axis indicates the gamut volume, and the number of passes is indicated in the horizontal axis.

Table I. A visual survey of the charts demonstrated the optimum number of passes.

Substrate	Indicative maximum passes of spot color
Evolon	2 passes
Paper	2 passes
Polypropylene	3 passes
Polypropylene on light box	5 passes

Table II. Comparison of volume percentages.

	2	3	4	5	6	7	8	9	10
Evolon	27%	3%	−5%	−5%					
Paper	24%	0	−9%	−4%	−11%	−4%	−13%	−4%	−6%
Polypropylene	42%	−2%	−6%	−5%	−6%	−8%	−7%	−6%	−4%

As demonstrated in Table II, the volume of the gamut for all substrates increases dramatically between the first pass and the second pass by 24% for paper and polypropylene, and there is a 27% difference for Evolon. As shown in the graph, the percentage values flatten and then decrease after the second and third pass.

Visualizing the Printed Gamut

The primary objective of the experiment was to demonstrate a visual shift in the gamut of the multi-pass printed colors, and to demonstrate how the printed color charts could be compared to the existing printed colors. In order to show the shape and the configuration of the resulting color space, the differences between the different multi-passes, and which colors could be attained, a method of visualizing and comparing the printed gamut was adopted. The ICC profiles

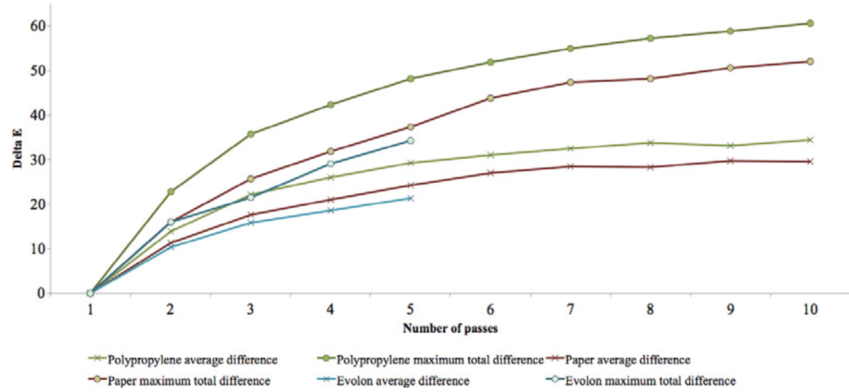


Figure 5. Comparison of multi-pass printing on paper, polypropylene, and Evolon, showing the difference between one pass and ten passes inclusive for paper and polypropylene, where print passes 2–10 were compared to the reference data contained in the first pass. Evolon shows the difference between one pass and five passes.

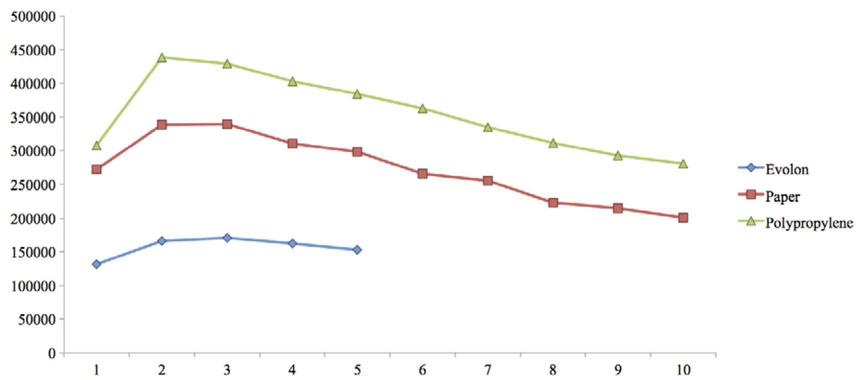


Figure 6. A comparison of the size of the gamut corresponding to the different number of passes. Their percentage increase and decrease is shown in Table II.

generated from the printed color charts were compared using ‘Apple ColorSync’. This comparison was undertaken in order to visualize the relationship between the first-pass print and the subsequent multi-pass prints. Figure 7 illustrates the printed and measured colors onto Evolon, Figure 8 those onto paper, and Figure 9 those onto polypropylene. The figures show the side elevations of the primary hue colors with the white point at the top and the darkest point at the bottom. The first-pass print is shown at the top of the column (Figs. 7–9). This pass is then used as the reference data, which is then indicated as a white wire frame in the subsequent frames. The colored shapes correspond to the data measured in multi-pass mode.

In Fig. 7 (Evolon), the subsequent images in columns a and b show both side elevations, where print passes 2 and 5 are compared to the reference data contained in the first pass (white wire frame). In Figs. 8 and 9 (paper and polypropylene), the side elevations of passes 1, 2, and 10, are shown. It is interesting to visualize how the expected shape of the space, as more layers are printed, expands and shifts towards the darker points. The multi-pass printing does not necessarily expand the gamut, as what is gained in some areas is lost in others. However by combining the different passes (as described above), then a much wider range of colors, and, more significantly, a diverse richer color, can be achieved.

A comparison between the visual survey and the measured data has demonstrated similar findings: by using multi-pass printing the gamut can be increased by double printing, and by a small amount for a third pass (Fig. 6). Fig. 5 shows that, where the curve begins to plateau in the measured data, it tends to correspond to the number of passes that were visually judged to be the maximum amount of printed passes (Table I). Figs. 7–9 provide a visual overview and comparison of the shift in gamut. As described in the introduction, the research has considered how the user could print a specific color through the multi-layering of inks, and, furthermore, the ability to soft preview the appearance of a multi-pass color prior to printing. The methods have demonstrated that, whilst the gamut is not expanded beyond the second pass, it is possible to achieve other colors that go beyond the existing gamut.

MULTI-PASSES UNDER MAGNIFICATION

In order to provide a better understanding of the relationship between ink on the different substrates, the printed samples were examined under a stereo microscope.[15] The front-on images were captured using a Nikon SMZ800 stereo zoom microscope with a P-ED Plan 1.5× objective (with zoom ratio of 6.3:1), attached to a G-US2 universal table stand so that larger samples could be examined. The samples

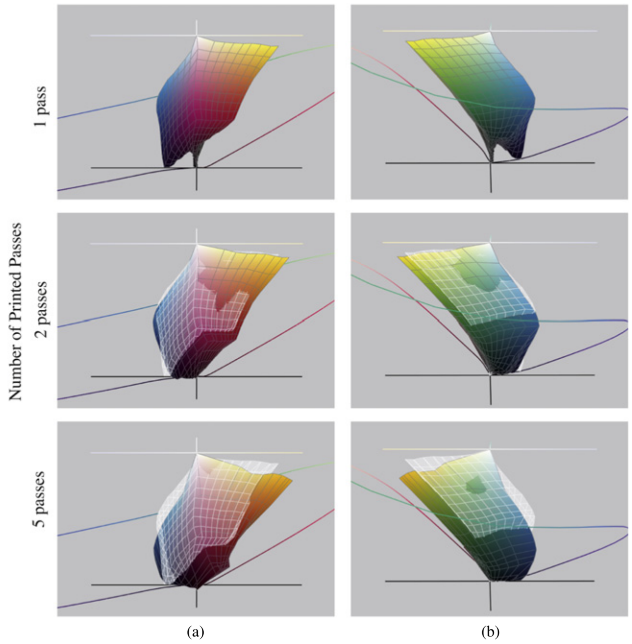


Figure 7. Showing the gamut of multi-pass printing onto Evolon. The columns (a and b) show side elevations, where print passes 2 and 5 are compared to the reference data contained in the first pass (top row 1 of columns a and b). The reference gamut is indicated as a white wire frame in the subsequent frames.

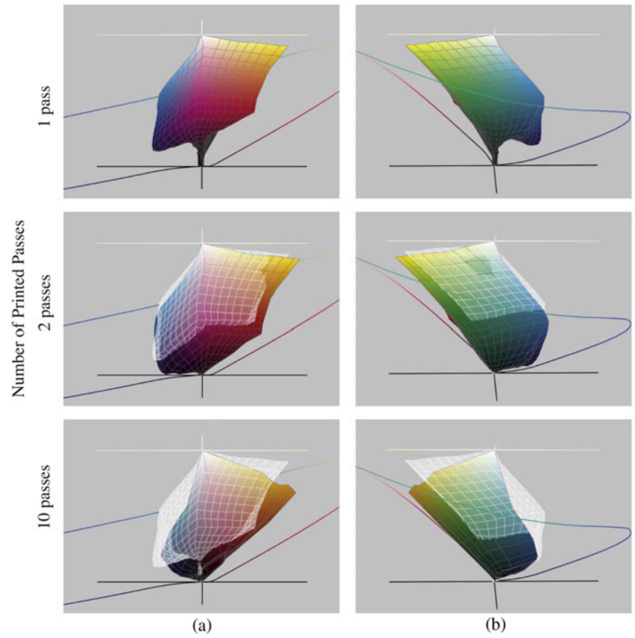


Figure 8. Multi-pass printing onto paper. The columns (a and b) show side elevations, where print passes 2 and 10 are compared to the reference data contained in the first pass (top row 1 of columns a and b). The reference gamut is indicated as a white wire frame in the subsequent frames.

were illuminated using a C-FPS fluorescent ring illuminator attached to the bottom of the objective. A Nikon DS-Fi1 digital camera was attached to the microscope, and Nikon's NIS-Elements imaging software was used to observe and capture the samples.

Figure 10(a) shows the image printed onto paper. In order to examine and illustrate the surface topography of the ink and the resinous properties of the UV cure, the print was tilted at an angle of 45° and photographed. As shown in Fig. 10(b), the illuminated foreground demonstrates how some areas have a build-up of ink and a perceptible resinous surface texture in the printed areas.

Figure 11 compares a small section of the three printed samples: Evolon, polypropylene, and paper. The images are captured looking straight on at the prints, at low magnification. The figures shown here, in relation to the original printed test image, are magnified approximately 11×. Here one can examine the structure of the substrate and its impact on the image. The texture and fibers of the Evolon are clearly discernable (Fig. 11(a)) and increase the appearance of scattering in the print. In order to gain a better understanding of the build-up of ink, we used a Bausch and Lomb stereo zoom microscope. The samples were illuminated using a flexible fiber optic light, which also provided repositionable and directed light for the tilted samples to an angle of 45°. The images were captured at its lowest magnification (7×), and the illustrations are shown here at approximately 5× magnification. Figure 12 illustrates a range of printed samples that are described in the corresponding table, Table III.

The example above shows the color print and multi-layers of gloss onto polypropylene and the build-up of layers of gloss onto a blue sublayer to create Fresnel lenses. Figure 13 (right) shows a straight-on view of the edge at the lowest magnification (5×) using the stereo microscope. The left illustration shows a cross section of the printed Fresnel lens, which is cut with a razor blade; the edge is viewed in reflected light with a Zeiss Universal microscope with a tungsten halogen light source, with a 4× objective and a 10× eyepiece. The compound microscope provides a better view of the thickness, but shows only a small portion of the section. Here, one can clearly see the build-up of the layers. The stress fractures are possibly due to the removal of the layers from the polycarbonate base. The cross-sectional view in Fig. 13 (left) has been stitched together from five micrographs. The field width of the composite image is approximately 5 mm. An individual micrograph is 1595 μm horizontal field width (the composite here is approximately 4785 μm).

METHODS FOR MULTI-LAYERING COLOR, WHITE, AND GLOSS

In order to understand how the printed color charts and profiles might work in a design scenario, the charts were used as a visual reference, and profiles were tested for soft previewing colored wallpaper designs. The following case studies demonstrate a range of multi-layering methods employed by artists.

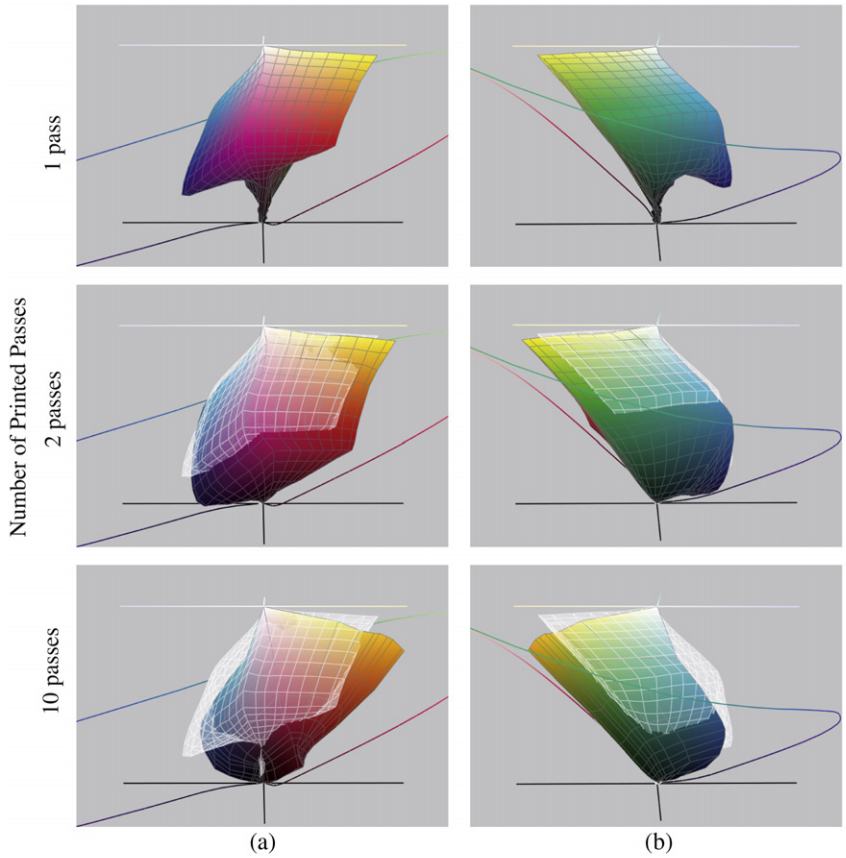


Figure 9. Multi-pass printing onto polypropylene. The columns (a and b) show side elevations, where print passes 2 and 10 are compared to the reference data contained in the first pass (top row 1 of columns a and b). The reference gamut is indicated as a white wire frame in the subsequent frames.

Figure 10. (a) The test image and the sections of the image that are microphotographed. (b) Printed sampled tilted at an angle of 45°.

Table III. A visual description of the different samples from Fig. 12.

(Top Left) Evolon, rough surface, fine details obscured.	(Top Middle) Evolon, tilted, showing a specular reflection. We see only tiny glints of light off single fibers.	(Top Right) Polypropylene, tilted, specular reflections off each area.
(Bottom Left) Polypropylene, showing a lower density, a pattern of small circles in every area.	(Bottom Middle) Paper, good density, nice smooth white surface, details are preserved.	(Bottom Right) Paper, tilted. We see specular reflections off the built-up of the printer polymer on the darker areas, but no specular reflection off the white paper.

Case Study: The Wallpaper Project

The aim of this collaborative research between creative professionals and industry was to analyze, from an empirical perspective, new inkjet printing methods, in this instance towards the production of digitally printed wallpaper. The research was undertaken in collaboration with industrial

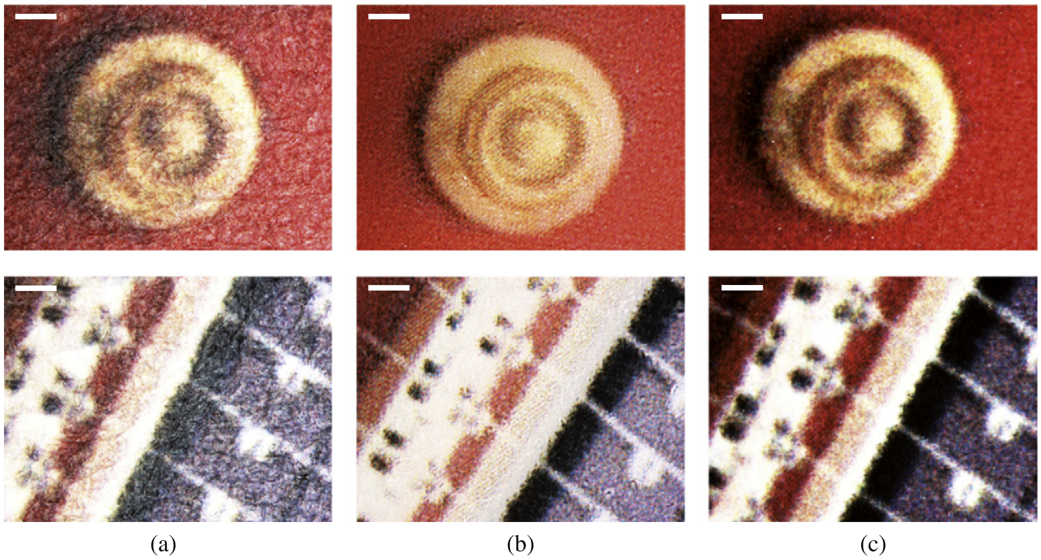


Figure 11. Printed samples of (a) Evolon, (b) polypropylene, and (c) paper. The samples show a horizontal field of approximately 8 mm of the print (the white bar represents 1 mm).

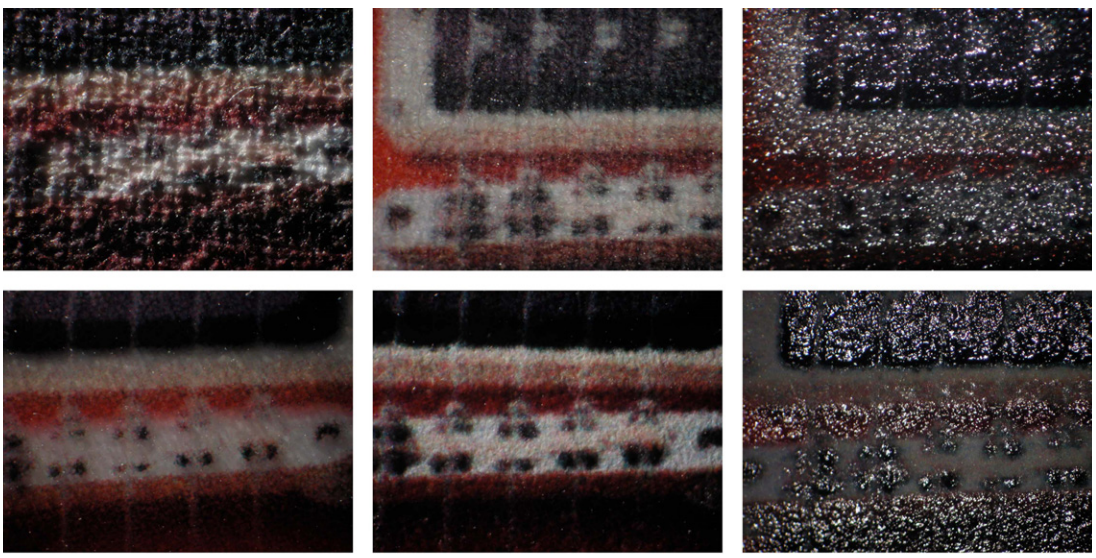


Figure 12. Sections of different samples printed at 5× magnification, captured at 7× magnification. The horizontal field in each image shows approximately 10 mm of the print.

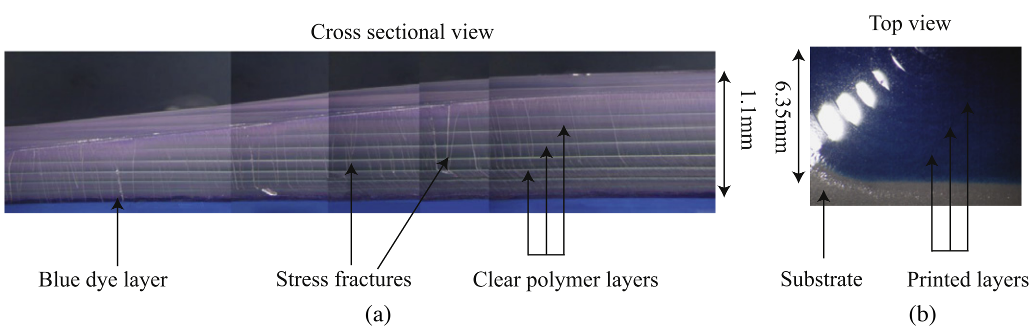


Figure 13. (a) Fresnel lens cross-sectional view. The printed layers have been removed from the substrate. Each polymer layer is 0.1 mm; Fig. 13. (b) Top view showing the build-up of printed layers.

partner Roland DG (UK) Ltd., which manufactures UV-curable and solvent-based inkjet printers for the poster, signage, and packaging market.

The objective of the Wallpaper Project was to develop a range of printed materials and surfaces that could be developed either as print on paper, or on textiles, and then

Figure 14. The completed sample book from the Wallpaper Project.

applied to walls that would evolve to be interactive with the viewer by incorporating, for example, moveable parts, or removable stickers, sections that could be folded to conform to different structures, or contain embedded lighting, or that could change color or surface appearance.[16] The long-term vision is to address how we currently design, think, and construct the materials in our environment; to operate a bottom-up approach to the development of technologies and design tools that allow us to imagine, design, and create materials, surfaces, and textures in a way that benefits human well-being; and to design materials that enhance our environment.[17–19]

Set-Up of the Wallpaper Project

The remit for the artists was to create a wallpaper design that first reflected their practice, but would also test a range of materials and print processes. It was not necessary to design a traditional wallpaper composition, such as a repeat pattern, but artists were asked to incorporate more innovative approaches to surface design, pattern, and materials. The finished wallpaper might include a range of materials or combine hand-drawn elements with photographic, vector, cut lines, and embossed surfaces.

The participants were shown how to create and layout patterns in Adobe InDesign and Illustrator software; each software can incorporate bitmapped images, vector lines, cut paths, color blends, and spot colors. The participants were also shown how to export files so that all the command printing features would be recognized by the RIP software. The Roland LEC series printer/cutter supports CMYK + white and clear ink configurations. The white ink can be used as an undercoat to print vibrant images on clear or metallic substrates. The clear ink can be used as a gloss or matte spot varnish for highlights or for simulating embossing effects by overprinting multiple layers of ink. These special printing features are accomplished by using specific spot colors in the design.

A Description of the Work by Artists in the Wallpaper Project

Each artist explored their ideas and methods, incorporating very different materials and effects with the UV printer. Each had quite specific requirements and objectives, but did not quite know what to expect in the final result. A process of trial and error, an empirical approach, was the most interesting part of the exploration. Each artist had no experience or expectation as to how the finished image would appear. However, by printing both the color charts and using the profiles to preview how colors might appear, we have provided the artists with a better understanding of the final printed color.

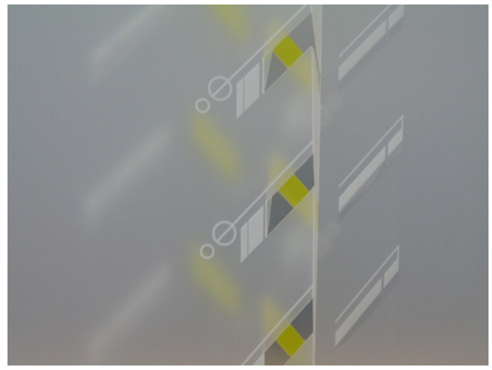


Figure 15. Sophie Adams-Foster. Title: *Structural interventions*. A printed, cut, and folded panel is placed in front of another. The semi-opacity of the material allows for subprinted layers to show.

Sophie Adams-Foster

Adams-Foster's work explores the forms found when moving into and around architectural structures, as represented by folds, cuts, lines, and print (Figure 15). Using a semi-opaque polypropylene plastic, given its ability to hold folds when cut, the relationship between the surface grain and the addition of a gloss varnish was key in the development of her idea. By creating moveable wall panels, with the potential to layer, the objective was to enable the user to create their own three-dimensional wall arrangements that could also be used to hide unsightly features such as pipes or cables. Having developed previous works using laser cutting technologies, Adams-Foster was especially interested in the opportunity to print, layer, and cut simultaneously. Drawing on existing Illustrator skills to create complex designs was very important, but the knowledge and understanding of the software used in conjunction with this particular printer was a challenge. All the commands for gloss, white, spot color, and the cut path were layered in the Illustrator file (Figure 16).

Sarah Barnes

In her design, Barnes explored the theme of architecture and the urban environment. She was interested in how wall coverings in particular could enhance the way we interact with the spaces around us. As a result, she investigated how interactive, three-dimensional, colored, and layered elements could be incorporated in the design. The wallpaper was designed in Illustrator and comprised three layers that were printed onto two different weights of paper. All images were printed using a double pass. The image was soft previewed to gain an idea of how the image would appear (Figure 17).

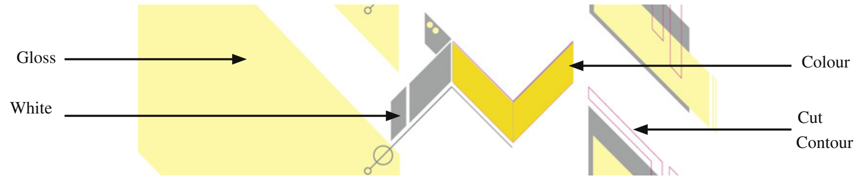


Figure 16. Layout in Illustrator showing the combination of gloss, white, cut contour, and CMYK spot color.

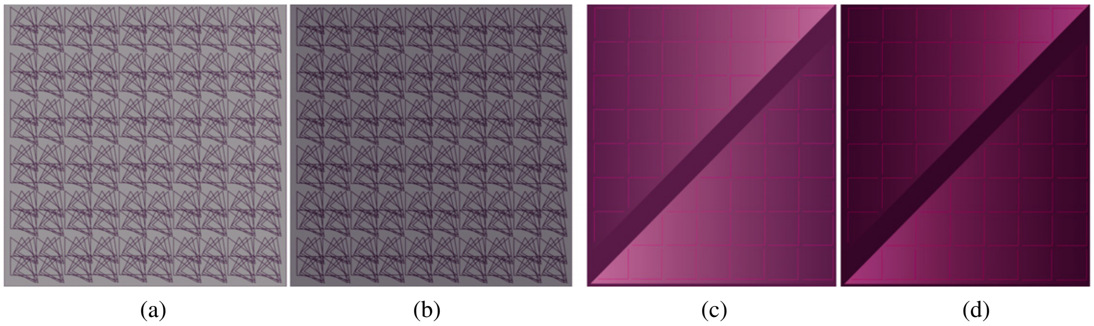


Figure 17. Underlayer and verso showing (a and c) the one-pass proof and (b and d) the double-pass soft proof.

The first paper, a lightweight laid paper, was printed on both sides, using a mint-green color on the top side, with a gradient color of purple to pink on the underside. Because of the limits of the cutting tool on the printer, the paper was then cut by a laser cutting machine. The cut paths that had been originally designed for the printer software in the image file could also be used for the laser cutter. Laser cutting was used on the first layer to cut and engrave small triangular flaps as an interactive and three-dimensional element. The second, using a heavier weight paper, was printed with a geometric triangular design in gray and purple. This was placed underneath the first paper (Figure 18).

Through the unfolding of the triangular flaps the user could interact with the design, revealing not only the printed pattern beneath but also the gradient color on the underside of the triangles. The number of triangles that could be folded back were based on individual choice, allowing the finished wallpaper to be unique. These unfolded elements provided a tactile, textured, and very multi-dimensional wall-covering solution, which changed in appearance as one passed in front with the color reflected at different angles.

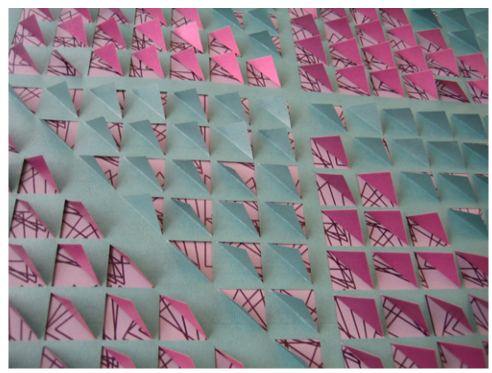


Figure 18. Sarah Barnes. Title: *Triangular*. Laser-cut triangles in combination with printed panels.

Verity Lewis

Playing with the idea of text, and specifically well-known lyrics to classic movies, Lewis used the theme tune to the ‘Spy Who Loved Me’ as the inspiration for her wallpaper. Working with the layering capabilities of the Versa LEC, Lewis printed layers of both white ink and clear matt varnish to create lettering in high relief. The text was created as a spot color in Illustrator and then assigned the various combinations of passes (Figure 19). After trialling different layering combinations, the resulting 25-pass image comprised layers of white (two passes), matt (ten passes), gloss (ten passes) and white (three passes) to build up each layer. The objective for printing two passes of white first was to ensure a hold onto the paper. The subsequent ten passes each of matt and gloss increased the height of the letters and the last three layers of white ensured the letters appeared as an opaque white.

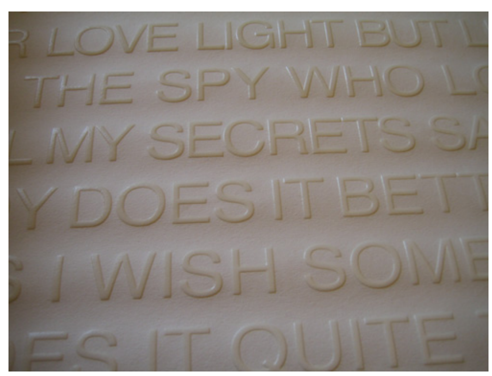


Figure 19. Verity Lewis. Title: *Text'ured*. Combining 25 passes of white, matte, gloss, then white to create a raised surface.

Figure 20 shows the letter O captured by a Nikon microscope under oblique illumination. The over layering of ink and minute misregister of the layers can be seen. The

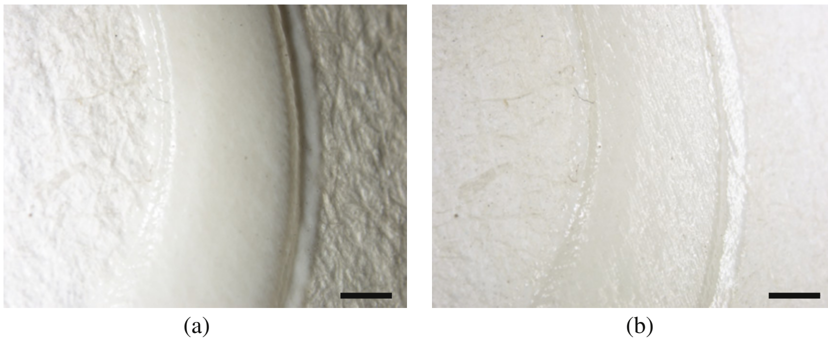


Figure 20. Microphotographs were made of the surface structure of the letter O: (a) under oblique illumination; (b) under homogeneous illumination. The black bar represents 1 mm of the surface.

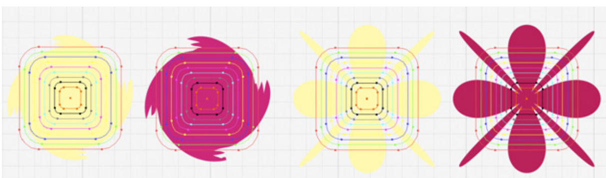


Figure 21. Showing the layout and layering of the gloss. Each layer represents two passes, resulting in 22 layers of gloss.

shadow on the right shows the edge of the matt passes (seen as a more yellowish layer) and the fibrous texture of the paper. The printed surface under diffuse light shows the direction of the print heads and the glossy reflectance of the edges.

Carinna Parraman

Working with hypotrochoid shapes, a series of layers was generated in Illustrator to create Fresnel lenses. Each shape was reduced in size, layer by layer, at either a fixed central point or an offset point. The first layer (which appears on the bottom) was printed as a colored blend (Figure 21), and the following ten layers were printed in gloss and printed at two passes per layer to a create high surface relief. The colors and gloss were printed onto a clear polypropylene (Figure 22). The translucency of the color and gloss means that the light is diffused through the lenses to create soft patterns and scattering of color (Figure 23) onto the surface below.

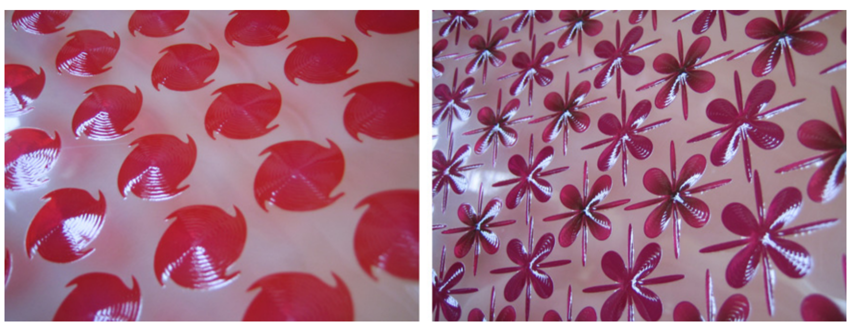


Figure 22. Carinna Parraman. Title: *Subsurface Scatter*. Showing the results of the printed layers of color and gloss.

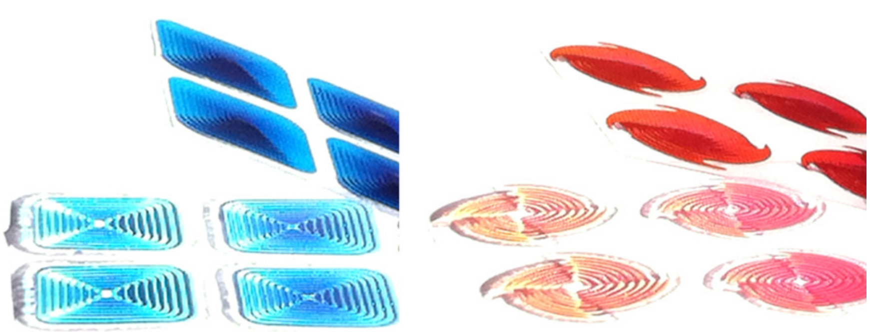


Figure 23. Showing the scattering effect of the printed Fresnel lenses (photograph courtesy of John and Mary McCann).

CONCLUSION

This research and supporting case studies sought to test methods for multi-layer printing. The objective of the testing was to print color charts onto three different surfaces, which simulated different types of surface that an artist might choose, such as smooth, hard, gloss, plastic, textured, fabric, flexible, semi-opaque. Through the process of multi-pass printing the test charts, the objective was to identify the maximum number of printed ink passes that were applicable for the chosen substrate. In most cases a two-pass process was required to achieve an optimum quality and coverage of ink. For printing onto more translucent surfaces, a further layer was necessary.

The printed color charts were used first as a hard-copy print to demonstrate the relationship of ink onto a range of substrates, and second, by measuring the test charts, to provide the artist with a method of soft previewing the appearance of a multi-printed color in different design software.

In this study, we used the capabilities of the Versa LEC UV printer to test the strengths and weaknesses of both the printer hardware and artists' methods for generating designs. As illustrated in Figure 14, a wallpaper sample book was devised to demonstrate to stakeholders the range of materials, processes, and ideas that were applied by artists. All the designs have been described and illustrated on the CFPR website, comprising a unique artifact and work of art in its own right; the site can be accessed at: http://www.uwe.ac.uk/sca/research/cfpr/research/wideformatprinting/research%20projects/wallpaper.html.

The website will also be used as a way of offering open-source designs for use by others. In this way the designs can be modified and printed by another user, in exchange for their ideas and contribution to the website. An important objective is to increase market awareness of the application of paper-based and cutting technologies in industry. Through open-source communities developing novel software and hardware technologies, there are opportunities to increase and share knowledge through online communities.

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