Colour Printing 7.0: Next Generation Multi-Channel Printing

Ludovic Gustafsson Coppel, Aditya Sole and Jon-Yngve Hardeberg; The Norwegian Colour and Visual Computing Laboratory, Gjøvik University College, Norway

Abstract

Colour Printing 7.0: Next Generation Multi-Channel Printing (CP7.0) is a training and research project funded under the Marie Skłodowska-Curie Initial Training Networks (MCITN) call in EU's seventh framework programme (FP7) . The project is led by Gjøvik University College in collaboration with five full network partners and six associated partners from academia and industry. The project addresses a significant need for research, training and innovation in the printing industry. The main objectives of this project are to train a new generation of printing scientists who will be able to assume science and technology leadership in this established technological sector, and to do research in the colour printing field by fully exploring the possibilities of using more than the conventional CMYK inks. The research focuses particularly on spectral reproduction (new spectral colour modelling, spectral gamut mapping, halftoning and image quality assessment) and on multilayering printing methods to control ink mixing, relief (2.5 D prints) and surface properties. This paper reviews the achievements of the project so far in conjunction with a topical workshop at the 22nd Colour and Imaging Conference on "Next generation colour printing".

Introduction

Multi-channel printers were first introduced to increase the number of reproducible colours and also led to colorimetric redundancy, meaning that a colour in a specific illumination can be reproduced using several different colorant combinations. This flexibility opens for spectral reproduction that gives the same visual experience as what a reproduction will in any viewing environment, as opposed to colorimetric reproduction that is optimised for one specific lighting and one specific standard observer. Although a perfect spectral match is very rarely possible, the colorant combination can be chosen so that the difference between production print and original is minimised for more than one viewing environment.

Additive manufacturing (or 3D-printing) is in an expansive development phase in prototyping but 3D printing systems generally have a restricted palette of colours and materials, and do not afford the range of surface appearance possibilities that are available in 2D conventional printers. A new technology hybrid has recently emerged, which builds on 2D print capabilities but uses 3D multi-layer methods to generate surface relief. This technology is often referred to as 2.5D printing (or relief printing), and makes it possible to reconstruct the texture and appearance of a wide range of surfaces. This process is carried out by digital offset presses or by using ink jet technology with wax or UV curing inks. This layer-by-layer technique also offers the possibility to apply more ink and different ink mixings thus extending the colour gamut, especially in the dark tones, and to control the gloss of 2D prints.

Unlike 3D printing, 2.5D and multilayer printing have the capability of being a mass-market technology, as it is relatively fast, and can be integrated with existing 2D printing technologies and workflows. A variety of applications could benefit from considering multiple viewing conditions, such as catalogue or packaging printing, security-driven applications (e.g. watermarking), fine art, material appearance modelling and 3D printing.

CP7.0 Project

Colour Printing 7.0: Next Generation Multi-Channel Printing (CP7.0) is a training and research project funded under EU FP7 Marie Skłodowska-Curie Initial Training Network call. The project is co-ordinated by Gjøvik University College and has six full project partners including Canon/OCE (France), Linköping University (Sweden), Voxvil AB (Sweden), Technische Universität Darmstadt (Germany) and the University of the West of England (UK). The project involves seven postgraduate students and two postdocs at the project partners. The project addresses a significant need for research, training and innovation in the printing industry. The main objectives of this project are:

- to train a new generation of printing scientists who will be able to assume science and technology leadership in this established technological sector;
- to do research in the colour printing field by fully exploring the possibilities of using more than the conventional four colorants (CMYK) in printing.

While many aspects of these objectives are well known and extensively studied, there are four key areas of science and technology where this project has the focus:

- Spectral modeling of the printer/ink/paper combination.
- Spectral gamut prediction and gamut mapping.
- Optimal halftoning algorithms and tonal reproduction characteristics of multi-channel printing.
- Non-conventional inkjet printing employing multilayering to control ink mixing, relief and surface properties.

This 4-year project will end in September 2015 and the purpose of this paper is to review the achievements of the project so far in conjunction with a topical workshop held at the IS&T 22nd Colour and Imaging Conference on "Next generation colour printing".

In addition to the research activity reported here, the project provides a targeted professional and technical skills development programme for the involved researchers, focusing on multi-disciplinary theoretical and practical understanding of the field of multi-colorant printing, outreach and networking (see `www.cp70.org` for more information).

Figure 1. Spectral printing. A scene or an original reflects different amount of light at different wavelengths. Traditional metameric (colourimetric) workflow optimises the perceived quality under one specific illuminant, though the appearance can change drastically with the illuminant. A spectral workflow aim at minimising colour differences in more than one illuminant.

Research summary

Within the ongoing EU Marie-Curie initial training network project Colour Printing CP7.0 Next Generation Multi-Channel Printing, considerable efforts are made to understand and overcome the challenge of spectral reproduction workflows: new spectral colour modelling, spectral gamut mapping, halftoning and image quality assessment with the aim to improve spectral reproduction. Another part of the project develops non-conventional inkjet printing methods using multilayering to control ink mixing, relief and surface properties. Focused applications include textile colour reproduction, multi-illuminant hard proofing, fine arts reproduction and new appearance effects for printed products.

Spectral colour prediction models

Many spectral colour prediction models have been proposed over the years to relate nominal ink coverages to the output measurable colour. Most of the models need to be calibrated on printed samples and the number of calibration patches grows tremendously when adding additional ink channels. A review of the available models for prediction of multi-channel printing is given by Slavuj et al. [1].

Reducing the number of training samples requires a better understanding and modelling of the ink-paper interactions and the light scattering in paper and inks. In this aspect, Rahaman et al. [2] use micro-scale images to directly characterise the size of halftone dots. A segmentation method is proposed in [3] to separate micro-scale images into ink, paper and ink/paper areas, the latter including the observed dot blurring due to lateral propagation of the light in the substrate (dot gain). Accounting for the change of reflectance from the paper between ink dots, they propose an extended Murray-Davis model [4]. In a study on dot gain, Namedanian et al. [5] show that the physical dot gain depends on ink penetration and ink spreading properties. The effect of optical dot gain depends on the lateral light scattering within the substrate, the size of the halftone dots, and on the halftone dot shape, especially the dot perimeter.

Ideally, a spectral colour prediction model should accurately separate mechanical and optical dot gain to allow for predictions without the need for a full model calibration when changing either ink, printing conditions, or substrate. For practical applications, the model parameters should also be determined with fast and affordable measurement methods. While the empirical n-factor in the Yule-Nielsen (YN) model can account for many different effects, probabilistic models allow~~s~~ explicit modelling of the optical dot gain. Coppel [6] compares a probabilistic approach to the YN model. The results show that the probabilistic approach performs as well as the YN model in predicting the colour of single halftone patches and that for multiple ink prediction, the probability of lateral propagation from paper to ink dot can be described as a linear function of the apparent coverage. A non-zero offset at zero coverage suggests however that other effects than lateral light propagation are affecting the model parameter. The ongoing research focuses on modelling ink dot thickness variation, ink penetration into the substrate and the effect of fluorescence on the colour reproduction under different illuminants. Coppel et al. [7] discuss the impact of the spectral power distribution of the light source in the fluorescence emission band on the total radiance factor.

Conventional spectral prediction models such as the widely used Yule-Nielsen modified Neugebauer model can yet be applied to multi-channel printing that uses more inks than the conventional CMYK. Besides the problem of large number of calibration patches required when using more than four channels, one problem with multi-colorant printing is the fact that large amount of inks eventually leads to artefacts such as bleeding. This prevents the determination of the so-called Neugebauer primaries in the calibration of spectral colour prediction models. Slavuj et al. [8] propose a method to estimate these primaries from the reflectance of single ink patches using radiative transfer theory. In a feasibility study for textile reproduction, Slavuj et al. [9] use inkjet to reproduce a set of 4872 textile colour samples. They found that going from CMYK to CMYKRG increases the number of reproducible colours from 60% to 90% (Figure 2) and show that further improvements could be achieved using a spectral ink separation workflow [10]. Most of the textile colours outside the printable gamut are found in the darker region of the colour space.

Spectral printing

Adding the RGB channels to CMYK increases the number of degrees of freedom when it comes to combining inks. This flexi-

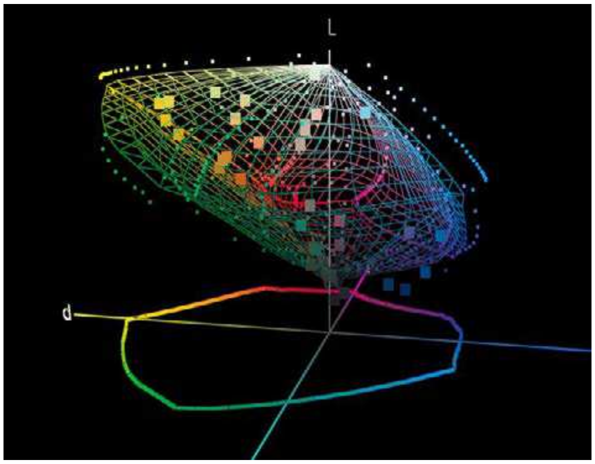

Figure 2. Printable gamut with CMYK (wireframe) and CMYKRGB (smaller squares) and representative colours from a set of textile samples (larger squares). [9].

bility can be used not only to increase the colour gamut in one illuminant but also to minimise colour differences in different illuminants. This requires on the other hand advanced ink separation methods to determine the reproducible spectrum that best fit the appearance of the original in different illuminations. Coppel et al. [11] make use of the perceptual paramer-mismatch based spectral gamut mapping method to test the feasibility of multi-illuminant hard proofing of colour patches. They show that spectral proofing with multichannel inkjet printers opens for producing proofs that can be evaluated in different visual environments.

When applied to images, the ink separation leads however to banding artefacts because similar neighbouring pixels can be mapped to completely different colourant combinations. In order to remove these artefacts, Samadzadegan and Urban [12] take into consideration the spatial information of the original image along with the colourimetric differences in the spectral gamut mapping. The results achieved show much smoother separations when compared with the pixel wise approach (Figure 3).

Besides the addition of colorant like RGB, multi-channel printers also use inks at different saturation levels. Light cyan and light magenta are for example mainly used to reduce perceived halftone patterns in light tones. Qu et al. propose a model based colour separation for CMYLmLc [13]. Žitinski Elías et al. introduce a multilevel halftoning approach to optimally use three black ink levels [14]. In addition to the colorant separation issue, research is being conducted on halftoning for multi-channel printers. Žitinski Elías et al. tested elliptic dot shapes for AM halftoning [15] and dedicated algorithms are being implemented for spectral reproduction of textiles, for which the most critical colours are found in the darker region of the colour space as mentioned above [10].

Multilayer printing

Rendering of a wide range of black colours is also an issue in the fine art area. By controlling the order of inks printed on top of each other, Olen and Parraman [16] show significant print density increase and significant colour difference between colour overlays using multilayer inkjet printing (Figure 4). This process is similar to the application of layering of pigments as demonstrated in old master paintings and allows reproducing a painted original with high dynamic range by improving colour variation in the shadow regions [17].

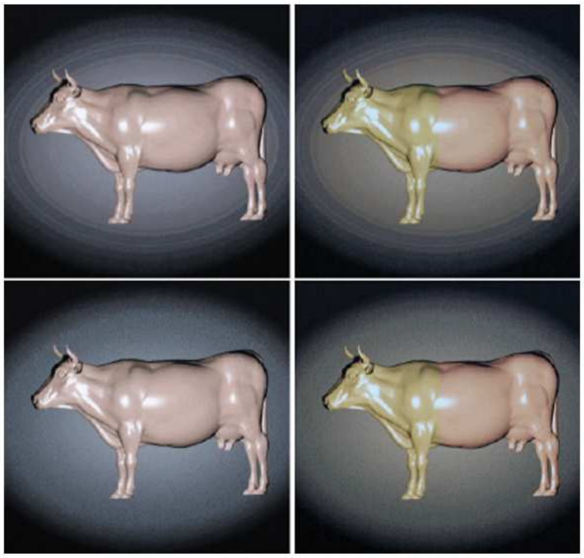

Figure 3. Cutout of the METACOW image rendered for illuminant (left) D65 and (right) A. Top: Resulting from a pixelwise paramer mismatch-based spectral gamut mapping computation. Bottom: Resulting from a pixelwise paramer mismatch-based spectral gamut mapping computation after adding noise to the a^* and b^* channels of the input images [12].

Multilayer printing can also change the gloss properties and it can be used to add an extra dimension in the form of relief that controls the angular dependent reflection properties. Baar et al. [18] use 2.5D printing to produce lenticular effect that reveal different images in different directions without the need for a system of lenses. The quality of the lenticular prints is significantly improved by modelling and compensating for ghosting effects that lead to some parts of one source image remaining visible for the illumination or viewing direction corresponding to the other source image (Figure 6). In another application, Baar et al. [19] control the printout roughness by manipulating the way the ink is deposited in a layer-by-layer basis. By changing the deposition time in between two layers of white ink and the order on which the pixels are printed, they achieve different gloss levels from a matte to a glossy appearance that can be controlled locally (Figure 5). Samadzadegan et al. [20] make use of this novel way of controlling gloss to investigate the impact of colour on gloss for low to medium gloss levels. Their results show a decrease of the magnitude of perceived gloss with increasing lightness. On the other hand, the change of surface gloss is known to significantly affect perceived colour in the off-specular directions because of different (white) surface reflectance contributions. Baar et al. successfully use separate ICC-profiles to tackle the problem [21].

To predict the reflectance of multilayer and relief prints require modelling the light scattering in multilayer materials and the lateral propagation in different layers. Coppel [22] uses Monte Carlo methods to simulate the spatial- and angle resolved re-

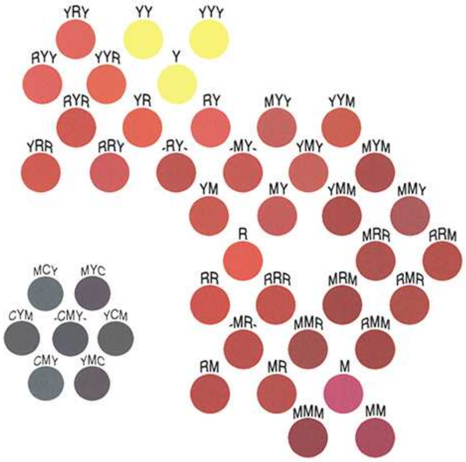

__Figure 4.__ Multi-pass prints with inkjet. The swatches include all colour variables and orders for up to three layers where one ink colour is applied to the paper twice in conjunction with a layer of an additional ink colour (e.g. YYR, YRY, RYY, RRY, RYR, YRR). There variations are constructed for all possible combinations of CMYRGB ink colourants [16].

flectance of turbid media for different scattering and absorption coefficients, phase functions and surface topographies representative for uncoated paper grades.

Quality assessment

Reproducing relief or 2.5D surfaces brings out the challenge of evaluating the quality of the outcome. Baar et al. review the progress of the assessment of image quality metrics of 2.5 and 3D prints [23] and propose a simple method using a flatbed scanner for capturing surface texture and reflection properties [24].

For spectral images, the main challenge is how to compare two images with dozens of channels in terms of perception and determining to which extent one can apply traditional (colour) image difference measures and pool the results over a variety of renderings corresponding to different viewing conditions. Le Moan and Urban [25, 26] conducted a series of experiments on the variations of image difference under various illuminants . They observe that achromatic image-difference features are overall far less sensitive to illuminant changes compared to chroma and hue, even when chromatic adaptation is considered. These sensitivities are quantified in terms of Shannons information (entropy). These observations are used to create a spectral image difference measure that does not require to compute all image difference scores under all viewing conditions. It is observed that over a dataset of 74 illuminants, only 2 of them are sufficient to accurately represent achromatic discrepancies under any other [27]. These findings lead to an efficient design of a Profile Connection Space (PCS) which will allow a high-dimensional spectral image representations using limited features [28] that is efficiently used in the design of look-up tables for spectral color management [29].

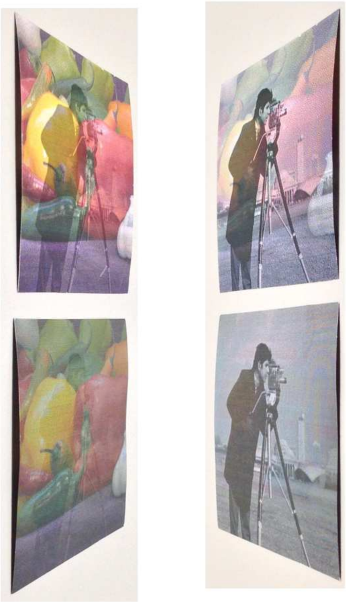

__Figure 5.__ Comparing a printout as seen from the left (left images) and from the right (right images) side, with (bottom) and without (top) ghosting effects compensation [18].

__Figure 6.__ Resulting image of a print with local gloss effects [19].

Conclusions

The Colour Printing CP7.0 Next Generation Multi-Channel Printing project aims at improving spectral colour reproduction, with contributions from new spectral colour modelling, spectral gamut mapping, halftoning to image quality assessment methods. Using non-conventional inkjet printing methods like multilayering enables controlling ink mixing, relief and surface properties. The models and methods developed within the project find applications in e.g. textile colour reproduction, multi-illuminant hard proofing and spectral image quality asssessment. Layering process similar to traditional printing and painting processes is expected to improve colour output when printing inkjet reproductions of original artworks.

Acknowledgments

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References

[1] R. Slavuj, P. Nussbaum, and J. Y. Hardeberg, “Review and analysis of spectral characterization models and halftoning for multi-channel printing,” in “Advances in Printing and Media Technology, Digitalization of Print,” (IARIGAI print and media research, 2013).

[2] G. M. A. Rahaman and O. Norberg, “The effect of media interac-

tions in predicting spectral reflectance by color prediction models," in "AIC Colour," (2013), pp. 593 – 596.

[3] G. M. A. Rahaman, O. Norberg, and P. Edström, "Microscale halftone color image analysis: perspective of spectral color prediction modeling," in "Proc. SPIE Vol. 9015," (2014), pp. 901506–901506–15.

[4] G. M. A. Rahaman, O. Norberg, and P. Edström, "Extension of Murray-Davies tone reproduction model by adding edge effect of halftone dots," in "Proc. SPIE Vol. 9018," (2014), pp. 90180F–90180F–13.

[5] M. Namedanian, D. Nyström, P. Žitinski Elías, and S. Gooran, "Physical and optical dot gain: characterization and relation to dot shape and paper properties," in "Proc. SPIE Vol. 9015," (2014), pp. 901509–901509–10.

[6] L. G. Coppel, "Dot gain analysis from probabilistic spectral modelling of colour halftone," in "Advances in Printing and Media Technology (accepted)," (IARIGAI print and media research, Swansea, UK, 2014).

[7] L. Coppel, M. Andersson, O. Norberg, and S. Lindberg, "Impact of illumination spectral power distribution on radiance factor of fluorescing materials," in "Colour and Visual Computing Symposium (CVCS)," (2013), pp. 1–4.

[8] R. Slavuj, L. G. Coppel, M. Olen, and J. Y. Hardeberg, "Estimating Neugebauer primaries for multi-channel spectral printing modeling," in "Proc. SPIE Vol. 9018," (2014), pp. 90180C–90180C–8.

[9] R. Slavuj, K. Marijanovic, and J. Y. Hardeberg, "Feasibility study for textile colour simulation with multichannel printing technology," in "AIC Colour," (International Colour Association (AIC), NewCastle upon Tyne, UK, 2013), pp. 379 – 382.

[10] R. Slavuj, K. Marijanovic, and J. Y. Hardeberg, "Colour and spectral simulation of textile samples onto paper: a feasibility study," Journal of the International Colour Association **12**, 36 –43 (2014).

[11] L. G. Coppel, S. Le Moan, P. Žitinski Elías, R. Slavuj, and J.-Y. Harderberg, "Next generation printing - towards spectral proofing," in "Advances in Printing and Media Technology (accepted)," (IARIGAI print and media research, Swansea, UK, 2014).

[12] S. Samadzadegan and P. Urban, "Spatially resolved joint spectral gamut mapping and separation," in "IS&T 21st Color and Imaging Conference," (2013), pp. 2–7.

[13] Y. Qu, P. Žitinski Elías, and S. Gooran, "Color prediction modeling for five-channel CMYLcLm printing," in "Proc. SPIE Vol. 9015," (2014), pp. 901508–901508–11.

[14] P. Žitinski Elías, S. Gooran, and D. Nyström, "Multilevel halftoning applied to monochromatic inks in multi-channel printing," in "Advances in Printing and Media Technology (accepted)," (IARIGAI print and media research, Swansea, UK, 2014).

[15] P. Žitinski Elías, D. Nyström, and S. Gooran, "Multi-channel printing by orthogonal and non-orthogonal AM halftoning," in "AIC Colour," (2013), pp. 597 – 600.

[16] M. Olen and C. Parraman, "Exploration of alternative print methodology for colour printing through the multi-layering of ink," in "AIC Colour," (2013), pp. 573 – 576.

[17] M. Olen, J. Padfield, and C. Parraman, "Reproducing the old masters: applying colour mixing and painting methodologies to inkjet printing," in "Proc. SPIE Vol. 9015," (2014), pp. 901507–901507–9.

[18] T. Baar, M. Shahpaski, and M. V. Ortiz Segovia, "Image ghosting reduction in lenticular relief prints," in "Proc. SPIE Vol. 9018," (2014), pp. 90180N–90180N–7.

[19] T. Baar, S. Samadzadegan, H. Brettel, P. Urban, and M. V. Ortiz Segovia, "Printing gloss effects in a 2.5D system," in "Proc. SPIE Vol. 9018," (2014), pp. 90180M–90180M–8.

[20] S. Samadzadegan, J. Blahova, and P. Urban, "Color-printed gloss: Relating measurements to perception," in "IS&T 22nd Color and Imaging Conference, Boston, MS, USA (accepted)," (2014).

[21] T. Baar and M. Segovia, "Colour management of prints with variant gloss," in "IS&T 22nd Color and Imaging Conference, Boston, MS, USA (accepted)," (2014).

[22] L. G. Coppel, "Lateral light propagation and angular variation of the reflectance of paper," in "Proc. SPIE Vol. 9018," (2014), pp. 90180L–90180L–7.

[23] T. Baar, H. Brettel, and M. Segovia, "A survey of 3d image quality metrics for relief print evaluation a survey of 3d image quality metrics for relief print evaluation a survey of 3d image quality metrics for relief print evaluation," in "Colour and Visual Computing Symposium (CVCS)," (2013), p. 6.

[24] T. Baar and M. V. Ortiz Segovia, "Colour and texture appearance modelling of 2.5D prints," in "AIC Colour," (2013), pp. 585 – 588.

[25] S. Le Moan and P. Urban, "Evaluating the perceived quality of spectral images," in "Image Processing (ICIP), 2013 20th IEEE International Conference on," (2013), pp. 2024–2028.

[26] S. Le Moan and P. Urban, "Image quality and change of illuminant: An information-theoretic evaluation," in "IS&T 21st Color and Imaging Conference," (Society for Imaging Science and Technology, 2013), pp. 102 – 107.

[27] S. Le Moan and P. Urban, "Image-difference prediction: From color to spectral," Image Processing, IEEE Transactions on **23**, 2058–2068 (2014).

[28] S. Le Moan and P. Urban, "A new connection space for low-dimensional spectral color management," in "Proc. SPIE Vol. 9018," (2014), pp. 90180E–90180E–6.

[29] S. Le Moan and P. Urban, "Spectral printing with a CMYKRGB printer: a closer look," in "IS&T 22nd Color and Imaging Conference, Boston, MS, USA (accepted)," (2014).

Author Biography

Ludovic Gustafsson Coppel received his PhD in Applied Physics from Mid Sweden University in 2013. Currently he is a postdoc fellow at the Norwegian Colour and Visual Computing Laboratory at Gjvik University College. His research focuses on spectral printing and on modelling the interaction of light with paper and inks.

Aditya Sole completed his bachelors from PVGs College of Engineering and Technology, Pune University, India in year 2005. In 2007 he completed his MSc in Digital Colour Imaging from London College of Communication. From 2008 till 2012 he worked as a Laboratory Engineer at the Norwegian Colour and Visual Computing Laboratory. Since 2012 he is working as a Project Manager for the EU funded CP7.0 project and as a PhD researcher at the Colourlab.

Jon Y. Hardeberg received his PhD from the ENST in Paris in 1999. After a short industry career in the US, he joined Gjvik University College in Norway in 2001, where he is Professor of Colour Imaging and member of the Norwegian Colour and Visual Computing Laboratory. His broad research interest within the field has resulted in more than 150 papers. He currently leads several large research projects, including the Initial Training Network CP7.0.