Reprint from *Advanced in Printing and Media Technology, vol 41*. IARIGAI, pp. 19–24.

Next generation printing - Towards spectral proofing

Ludovic Gustafsson Coppel[1], Steven Le Moan[2], Paula Zitinski[3], Radovan Slavuj[1], Jon-Yngve Hardeberg[1]

[1] The Norwegian Colour and Visual Computing Laboratory
Gjøvik University College, Norway

[2] Technische Universität Darmstadt, Germany

[3] Department of Science and Technology, Linköping University, Norrköping, Sweden

E-mails: ludovic.coppel@hig.no; steven.lemoan@gmail.com; paula.zitinski.elias@liu.se; radovan.slavuj@hig.no; jon.hardeberg@hig.no

Abstract

Different printing systems can produce colours that are perceived as identical under one standard illuminant such as D50. The visual match will however fail in other illuminations if the spectral properties of the inks differs. For soft proofing, this requires the proof to be visualised in the defined illuminant. Using more proofing inks than the conventional CMYK such as RGB increases the colorimetric redundancy, that is the number of different ink combinations that produce a visual match in D50. Using a spectral workflow, the ink separation can be optimised to get a visual match in different illuminations. We test here the feasibility of multi-illuminant (spectral) hard proofing with a multi-channel inkjet printer. We compute the proof of a set of 1269 Munsell patches with an inkjet printer model and compare the performance of a colorimetric and spectral workflow in terms of multi-illuminant proof matches. We show that large colour differences in different illuminants can occur when using a colorimetric workflow only optimising ink separation for D50. Performing a spectral gamut mapping leads to significant improvements as no Munsell targets show a ΔE2000 larger than 3 for all the illuminations tested. The use of additional red, green and blue inks further increases the colorimetric accuracy in different illuminations. Spectral proofing with multichannel inkjet printers opens thus for producing proofs that can be evaluated different visual environments. This can be particularly useful for packagings that make use of several spot colours and are viewed in very different visual environments.

Keywords: colour prediction model, dot gain, Yule-Nielsen, probabilistic model

1. Introduction and background

It is possible for two different printing systems to produce colours that are perceived as identical, given a proper calibration. This visual match will however only occur under the illumination and viewing conditions used for calibration due to different spectral properties of the inks and substrates. Only when the print and proof are spectrally matched, they will appear identical in all illuminations.

Multi-channel printers were first introduced to increase the number of reproducible colours (colour gamut), which also led to colorimetric redundancy, i.e. a colour in a specific illumination can be reproduced using several different colorant combinations. This flexibility opens for minimising colour mismatch under more than one illuminant. Spectral proof reproduction can therefore remove the need for viewing booths for proof visualisation and allow comparison of print and proof in different visual environments. Although a perfect spectral match is very rarely possible, the colorant combination can be chosen so that the difference between production print and proof is minimised for more than one viewing environment (Urban and Berns, 2011). There are a variety of applications that can 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.

Within the ongoing EU Marie-Curie initial training network project Colour Printing CP7.0 – Next Generation Multi-Channel Printing, there have been considerable efforts to understand and overcome the challenge of spectral reproduction workflows: new spectral colour modelling, spectral gamut mapping and halftoning methods with the aim to improve spectral reproduction (www.cp70.org). The purpose of this paper is to address the problem of spectral proofing (i.e. simulating the rendering of a print under various viewing conditions) and to investigate the advantages of using a multi-channel printer for spectral printing. We specifically test the feasibility of multi-illuminant (spectral) hard proofing with a multi-channel inkjet printer.

2. Methods

Spectral proofing requires that the target colours are not specified in CIELAB space for one illumination and standard observer (typically D50/2). Instead, the spectral reflectance factor is required as input to the proofing workflow. Once the spectral reflectance of the target colour is known, the task is to find the ink combination on the inkjet printer that gives the lowest colour difference between proof and target in different illuminations. A similar method to the spectral gamut mapping method developed by Urban and Berns (2011) is used here.

In order to test the feasibility of spectral proofing with a 7-inks inkjet printer, a set of reference colour chips with measured spectral reflectance is assumed to be a relevant subset of all printable colours. These spectra are used as target for reproduction with the inkjet printer using its spectral colour reproduction model.

2.1 Proofing printer

A Hewlett-Packard HPZ3200 ink-jet printer is used as proofing printer in a CMYKRGB mode. However, the proofs are actually not printed but simulated with the printer model. In order to reduce the number of training samples needed for calibration of the model and limit ink bleeding, the number of colorant overprints is limited to 4, as proposed by Tzeng and Berns (2000). Hence, only 4-ink combinations such as CMYK or CMRB are used, leading to 35 different 4-ink combinations. The printer is modelled with the cellular Yule-Nielsen modified Neugebauer (cYNSN) model, described e.g. by Wyble and Berns (1999), using two cells between 0 and 0.5 apparent ink coverage and between 0.5 and 1 apparent ink coverage. For calibration of the printer model, 35 charts with 625 patches are printed. This set includes all 4-ink combinations at 5 apparent ink coverages (0-100% with 25% step) including training samples (0, 0.5 and 1 apparent coverages) and test samples (0.25 and 0.75 apparent coverage). A highly white non fluorescing paper (200 g/m^2 offset proof 9200 semimatt, EFI) is used as substrate and the printed patches are measured with an i1-Pro spectrophotometer (X-rite Inc.).

2.2 Proofing targets

The spectral gamut of all printable colours is unknown and will depend on the printing method and inks used. For testing the spectral printing capability of the inkjet printer, the matte Munsell colour chips can however be considered as a relevant subset of all printable colours. The spectral reflectance factor of 1269 matte Munsell chips was obtained from the spectral colour database published online by the University of Eastern Finland, Joensuu (Joensuu, 2014; Kohonen et al., 2006).

2.3 Illuminations

The spectral separation used to determine the colorant combination of the proofing system is optimised to get the best colorimetric reproduction in D50 illuminant while reducing the colour mismatch in other illuminants using spectral gamut mapping (Urban and Berns, 2011; Samadzadegan and Urban, 2013). Five illuminations are considered in this experiment: D50, A, and F11 standard illuminants, a Lamina WW-NB light-emitting diode (LED) and a Luxina EXZ-CG-M250 tungsten halogen lamp. These illuminations shown in Figure 1 are chosen to minimise the pairwise similarity of their spectral power distributions (Blahová, 2013; Le Moan and Urban, 2013). The spectral power distribution of the two real illuminations is available from the National Gallery, London (2014).

2.4 Calculations and Analysis

The spectral separation uses the cYNSN forward model for the inkjet printer and optimises the ink coverages to match the target colour. First, all 4-ink combinations leading to ΔE_{2000} less than 1 between target and proof in D50 are determined. In order to reduce the number of computations, this is done with an additional constraint on the apparent ink coverages that are only allowed to vary with 0.01 steps. The next step is to select the ink combinations leading to ΔE_{2000} less than 1 between target and proof in D50 that lead to the lowest ΔE_{2000} in A. Finally the ΔE_{2000} in the two other illuminations is computed. This optimisation is performed for all possible 4-ink combinations. The best spectral reproduction is then compared to the "worst case" colorimetric reproduction for which one selects the ink combinations that provide a match in D50 with the largest ΔE_{2000} in A.

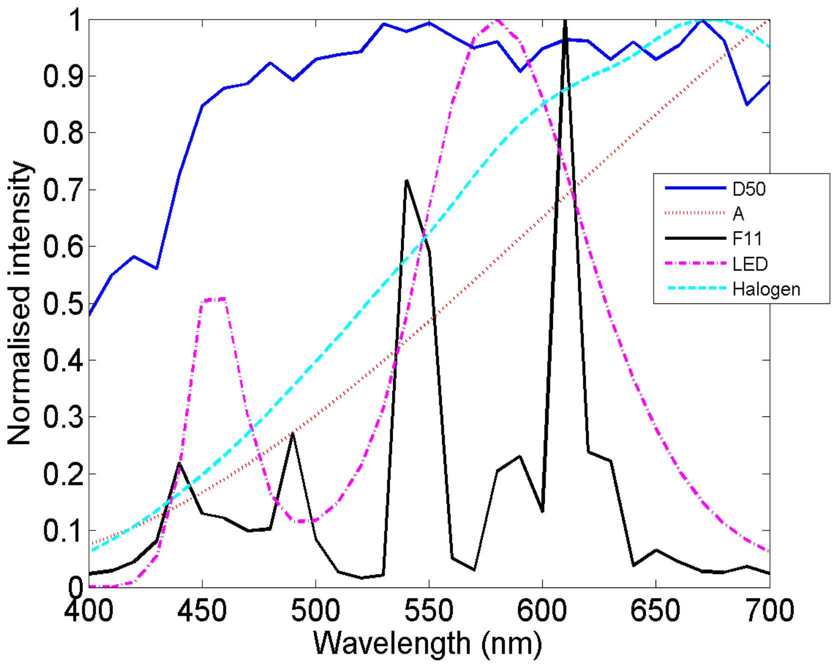

Figure 1. Normalized spectral power distribution of the used illuminations.

For proofing targets outside the colorimetric gamut of the inkjet printer, ΔE_{2000} is larger than 1 in D50/2 and the minimum ΔE_{2000} integer is determined instead. Some targets will be reproducible in D50/2 with CMYKRGB but not with CMYK, due to the smaller colorimetric gamut of CMYK as compared to CMYKRGB. To further investigate the spectral proofing capability of the inkjet printer we therefore select the targets whose reproduction with CMYK for D50/2 does not provide a colorimetric match for the A illuminant and compare the reproduction in the other illuminations for the two CMYK and CMYKRGB modes. From this analysis we can conclude on the improvements in terms of spectral printing when adding the RGB ink channels.

3. Results

The result of the colorimetric optimisation in D50/2 with CMYK mode is compared to the results with the CMYKRGB mode in Table 1. Almost all Munsell targets (99%) are reproducible with CMYK with a ΔE lower than 3, which may be acceptable in many applications. On the other hand, the number of Munsell targets reproducible under 1 ΔE increases from 95% to 99% when adding the RGB inks.

Table 1. Comparison of the estimated colour difference between proof and 1269 Munsell targets under D50 illumination obtained with CMYK and CMYKRGB proof printing. Percentage of Munsell targets in different ΔE classes.

	$\Delta E_{2000} < 1$ (%)	$1 < \Delta E_{2000} < 3$ (%)	$\Delta E_{2000} > 3$ (%)
CMYK	95	4	1
CMYKRGB	99	1	0

Figure 2 shows a typical Munsell target whose CMYK colorimetric reproduction for a D50 illumination leads to ΔE less than one but to a large colour difference between proof and target in an A illumination. For this specific sample, using the red and blue inks (YKRB) provides a colorimetric match in both illuminations. Two curves are shown for the CMYK case. These corresponds to the best and worst colorimetric match in D50 for which the colour difference between proof and target in A is the lowest and the largest, respectively.

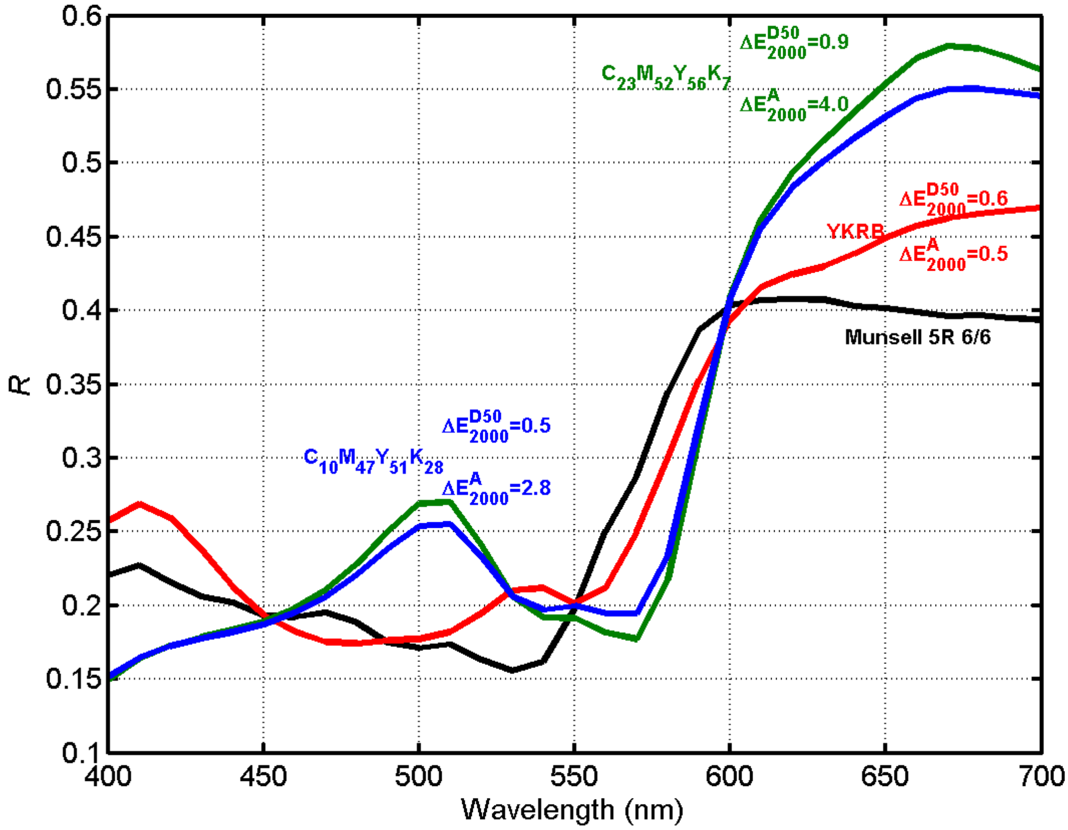

Figure 2. Original and reproduced spectra of the Munsell 5R 6/6 target. The reproduction are optimised to minimize ΔE_{2000} . in both D50 and A illuminations using CMYK inks or the optimal mix of CMYKRGB (red line, YKRB). The green line is the worst CMYK colorimetric match under D50 (leading to the largest ΔE under A). The blue line is the best CMYK D50 match leading to the lowest ΔE under A.

Of the 1269 Munsell targets included in this study, 340 can be reproduced in CMYK so that a colorimetric match is made in D50 ($\Delta E_{2000} \leq 1$) but not in A ($\Delta E_{2000} > 1$). This corresponds to the worst case in which a colorimetric optimisation is performed under D50 so that the colour difference between proof and target is maximal under A. For these targets, Table 2 reports the results of the comparison of the spectral reproduction accuracy obtained with the CMYK mode to the one obtained with the CMYKRGB mode. All the reproductions are optimised to get a colorimetric match in D50 illumination. Hence, ΔE between proof and target is less that 1 for all targets irrespective of the printing mode. From all possible reproductions that give a colorimetric match under D50, the two leading to the lowest and largest ΔE between proof and target under A are chosen. Table 2 shows that 85% of the selected targets that do not have a colorimetric match under A with CMYK get a match with CMYKRGB. The colorimetric math is also significantly improved for the LED and halogen illuminations when adding the RGB channels. It can also be noticed that a multi-illuminant workflow in CMYK already can significantly improve the colorimetric match in different illuminants (here D50 and A). Although no targets optimised in CMYK for D50 get a perfect match in A ($\Delta E \leq 1$), the number of targets with $\Delta E \leq 3$ in A can increase from 15 to 82% between a (worst case) colorimetric and a multi-illuminant workflow.

4. Discussion

The results in Table 1 show that using 7 inks instead of only four overall improves the colorimetric accuracy although CMYK already provides acceptable proofs of the 1269 Munsell chips used in this study (95 % are under 1 ΔE_{2000} and 99 % under 3 ΔE_{2000}). On the other hand, a colorimetric match of a proof target for one single illumination can be achieved with different ink mixtures of the 4 process inks. For production prints, additional goals such as minimizing ink consumption or graininess are utilised in the ink separation. Table 2 shows however that a colorimetric separation (here for D50) can lead to large colour deviations (up to 9 ΔE_{2000}) between proof and target in other illuminations. For almost 50% of the Munsell targets, a colorimetric match in D50 can lead to ΔE_{2000} larger than 6 under the LED illumination. Performing the spectral gamut mapping described in Section 2.4 allows to choose the colorimetric reproductions that minimise colour difference under A illumination. This leads to significant improvements as no Munsell targets show a ΔE_{2000} larger than 3 for all the illuminations tested, even without using the extra RGB inks. Our findings show that a spectral workflow can lead to a much better colorimetric match for different illuminants than a D50 colorimetric workflow. This is in contradiction with the findings from Morovic et al. (2012) who concluded that no significant improvement was obtained with a spectral workflow. It should however be emphasised that a colorimetric workflow has several degrees of freedom and will lead to different ink separations depending on its implementation.

The addition of the red, green and blue inks further improve the proof-to-target colour match in different illuminations. This confirms a larger spectral variability and therefore a better suitability of multi-channel printers for spectral colour management. The performance of the spectral gamut mapping algorithm is very dependent on the order of the illuminants for which colorimetric match is optimised for. This is why the results in Table 2 are (after D50) best for the A illuminant. The order of illuminants could be change if a colorimetric match in F11 is for instance weighted higher than a colorimetric match in A. This approach to proofing allows specifying a number of illuminants that are particularly relevant for a given application. When this number becomes large, representative illuminants can then be created by means of a PCA-based approach (Le Moan and Urban, 2013).

Table 2. Estimated colour difference expressed as ΔE_{2000} between proof and Munsell targets in different illuminations for CMYK (D50 worst case colorimetric and multi-illuminant optimisation) and CMYKRGB proof printing, for targets within CMYK gamut ($\Delta E \leq 1$) under D50 but not under A. The addition of the RGB channels leads to a significant improvement of the colour match in different illumination.

		mean ΔE	**max ΔE**	**DE ≤ 1 %**	**DE ≤ 3 %**	**DE > 6 %**
D50	CMYK col	0.8	1	100	0	0
	CMYK	0.7	1	100	0	0
	CMYKRGB	0.6	1	100	0	0
A	CMYK col	4.7	8	0	10	15
	CMYK	2.4	3.9	0	82	0
	CMYKRGB	0.5	2.2	85	15	0
F11	CMYK col	3.7	8.6	4	38	15
	CMYK	1.9	5.9	22	60	0
	CMYKRGB	1.7	5.9	32	54	0
Lamina LED	CMYK col	5.7	9	0	5	46
	CMYK	3.1	6.3	0	52	0
	CMYKRGB	1.8	5.9	24	69	0
Luxina halogen	CMYK col	4.6	7.5	0	10	11
	CMYK	2.4	4	0	81	0
	CMYKRGB	0.5	2.2	85	15	0

It should be noted that fluorescence, which has so far been neglected in spectral printing, will occur in many commercial prints. This is a main challenge in conventional proofing and becomes even more problematic for spectral proofing since the amount of UV is different for different illuminations. The tested method can however be extended to fluorescing substrates by including fluorescence in the reflectance factor computation (Coppel et al., 2012). This would allow estimating multi-illuminant colour matches for different proofing substrates.

5. Conclusions

We tested the feasibility of multi-illuminant (spectral) hard proofing with a multi-channel inkjet printer. Unlike conventional colorimetric reproduction that optimises the proof to match the target in one illumination (typically D50), the proof is optimised to get the best colorimetric reproduction in D50 while reducing the colour mismatch in other illuminants. For conventional printing, colour mismatch between proof and target is more likely to occur for spot colours than for process inks. For a large set of matte Munsell chips, all colours can be proofed under 3 ΔE_{2000} using multi-illuminant spectral gamut mapping. The use of additional red, green and blue inks further increases the colorimetric accuracy in different illuminations. Spectral proofing with multichannel inkjet printers opens thus for producing proofs that can be evaluated different visual environments. This can be particularly useful for packagings that make use of several spot colours and are viewed in very different visual environments. One of the main challenges in proofing is fluorescence whose impact on multi-illuminant could be evaluated by including fluorescence in the calculations.

Acknowledgments

This work was supported by the Marie Curie Initial Training Networks (ITN) CP7.0 N-290154 funding.

References

Blahová J., Le Moan S. and Urban P. (2013), “The Impact of Illumination on the Perceived Quality of Spectral Reproductions,” in Proc. 19th Workshop Farbbildverarbeitung,1-3.

Coppel L. G., Anderson M., Neuman M. and Edström P. (2011), “Fluorescence model for multi-layer papers using conventional spectrophotometers,” Nord. Pulp. Pap. Res. J. 27(2), 418-425. Joensuu (2014/06/15), “Spectral database”: http://www.uef.fi/fi/spectral/munsell-colors-matt-aotf-measured

Kohonen O., Parkkinen J. and Jääskeläinen T. (2006), “Databases for spectral color science,” Col. Res. Appl. 31(5), 381-390.

Le Moan S. and Urban P. (2013), “Evaluating the perceived quality of spectral images,” in Proc. IEEE International Conference on Image Processing, 2024-2028.

Morovic P., Morovic J., Arnabat J. and Garcia-Reyero J. M. (2012), “Revisiting spectral printing: a data driven approach,” in Proc. IS&T 20th Color and Imaging Conference, 335-340.

National Gallery (2013/06/15), “Spectral power distribution curves,” The National Gallery: http://research.ng-london.org.uk/scientific/spd/.

Samadzadegan S. and Urban P. (2013), “Spatially Resolved Joint Spectral Gamut Mapping and Separation,” in Proc. IS&T 21st Color and Imaging Conference.

D.-Y. Tzeng and R. S. Berns (2000), “Spectral-based six-color separation minimizing metamerism,” in Proc. IS&T/SID, Scottsdale, AZ, 342–347.

Urban P. and Berns R. S. (2011), “Paramer Mismatch-Based Spectral Gamut Mapping,” IEEE Transactions on Image Processing 20(6), 1599-1610.

Wyble D. R. and Berns R. S. (2000), “A critical review of spectral models applied to binary color printing”, Col. Res. Appl. 25(1), 5-19.