Colour Separation with Dynamically Changeable Inks

L. Johansson and B. Kruse*

Keywords: Colour Separation, Dynamic Images, Spectral Model

Abstract

With dynamic image reproduction it is possible to add more information to the printed product. The print can reveal two or more images in different optical states, thus adding more attention to the final printed product. The dynamic images in this study consist of conventional process ink layers combined with dynamic ink layers that can be brought to different optical states where they display a certain colour or turn transparent, thus revealing the underlying process ink.

The dynamic images will be reproduced with more printing primaries than ordinary four process colour printing (CMYK), so called multi-colour printing, where every dynamic image requires a unique set and number of printing primaries. There are several problems common to multi-colour printing, which require more complex colour separation algorithms. The complexity of these problems increases as the number of printing primaries grows. When dealing with dynamic image reproduction, the additional requirement to be able to shift between images places completely new demands on the entire colour separation process. For example, it requires a physical model that accurately predicts how arbitrary process and dynamic inks will interact when printed together, in superposition and side by side using halftoning.

This paper addresses these challenges and focuses on finding solutions for the colour separation process when reproducing dynamic images using thermochromic inks as dynamic inks in screen printing. Although a great deal more work remains to be done before a complete colour separation model for dynamic image reproduction can be presented, this paper takes some steps towards that goal.

---

* Center for Creative Media and Technology
Department of Science and Technology
Linköping University, Sweden
Email: linjo@itn.liu.se

Introduction

By combining process and dynamic ink layers it is possible to reproduce printed dynamic images. The dynamic ink layers can be brought to different optical states where they display a certain colour or turn transparent, thus revealing the underlying process ink. When the dynamic ink layers are activated it is possible to switch between two or more printed images depending on the number of states of the used inks. The optical state of the image can be changed and controlled by conducting polymers printed on the backside of the paper substrate using different conventional printing techniques.

The dynamic image consists of image elements that can obtain two or more different states. Each image element is a function of dynamic ink layers, static process ink layers and the current image state, as summarized by equation 1:

$$\text{Image Pixel} = f(I_s, I_{d,State}, State) \qquad (1)$$

where I_s represents the process ink layers, $I_{d,State}$ represents the dynamic ink layers having two or more different states and $State$ =1,2,3,…,N represents the current state of the image pixel. In this study thermochromic inks are used as dynamic ink layers. The pigments change colour in response to temperature and they have reversible colour transitions. They are coloured in their cool state and more or less translucent in their warm state. A study of the thermochromic inks chromatic properties was presented at TAGA 2004 (Johansson, 2004).

Each dynamic image will require a unique set of colorants and the number of ink primaries will vary for different image combinations. The ink selection has to be optimized to keep the number of inks as small as possible for a particular dynamic image in order to reduce the printing costs.

A colour separation model for dynamic image reproduction requires that the colours of the different combinations of static and dynamic inks be known. A first step in finding a colour separation model for dynamic image reproduction is to derive a model for predicting spectra for different combinations of process and thermochromic inks.

Modeling Dynamic Printing Primaries

The printing primaries of the dynamic images consist of parallel-sided layers of paper substrate, process inks and dynamic inks. Additionally, the sample itself interfaces with air as shown in Figure 1. A colour separation model requires that all the colours achieved by overprinting combinations of these ink layers are known.

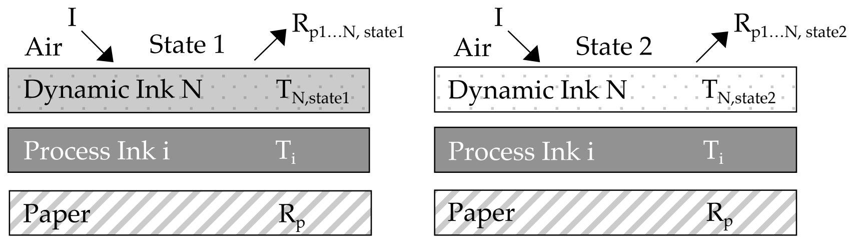

Figure 1. *Illustration of a dynamic image sample consisting of process and dynamic ink layers in two different optical states.*

The reflectance of an ink layer on paper is given by the amount of light that penetrates the ink, T_i, reflects off the paper R_p and emerges through the ink again, T_i. Some of the incident light is also reflected off the ink layer, $R_{i,state}$. In the case of dynamic ink layers, the reflectance and transmittance spectra are also dependent on the current state, thus, the reflectance spectrum of one dynamic ink layer on top of a paper substrate in the different optical states, $R_{p1,state}$, can be predicted by equation 2:

$$R_{p1,state} = R_{1,state} + T_{1,state}^2 R_p \quad (2)$$

where $R_{1,state}$ represents the reflectance spectrum of the dynamic ink layer in the current state, $T_{1,state}$ represents the transmittance spectrum of the ink layer in the current state and R_p represents the reflectance spectrum of the paper.

Apart from being reflected from the ink layer, the light can also reflect any number of times between the ink and paper before finally exiting the ink layer, making the reflectance of ink on paper an infinite sum of terms. This was modeled by Kubelka-Munk, described by (Judd and Wyszecki, 1975) and (Niskanen, 1998) among others, and the modified equation for dynamic ink layers is given by equation 3:

$$\begin{aligned} R_{p1,state} &= R_{1,state} + T_{1,state}^2 R_p \left(1 + R'_{1,state} R_p + R'^2_{1,state} R_p^2 + \ldots\right) = \\ &= R_{1,state} + \frac{T_{1,state}^2 R_p}{1 - R'_{1,state} R_p} \end{aligned} \quad (3)$$

where $R'_{1,state}$ represents the reflectance of the back side of the ink layer. The original Kubelka-Munk model works well for a single uniform ink layer on top of a backing or substrate, but provides no method for application when more than one colorant layer is present. But the model can be used for multi-ink-layers by treating each predicted layer reflectance as the substrate reflectance for the layer above it.

Modifications of this method has been used by Stollnitz (Stollnitz, 1998), for modeling multi-ink-layers images reproduced with custom inks, and Hoffman (Hoffman, 1998), for modeling multi-layer toner images, among others. Then for the N layer case the equation is given according to equation 4:

$$R_{p1\ldots N,state} = R_{N,state} + \frac{T_{N,state}^{2} R_{pN-1,state}}{1 - R_{N,state}^{'} R_{pN-1,state}} \quad (4)$$

Thus, N ink layers are modeled by treating the reflectance spectrum that has been modeled for the (N-1) ink layer as the substrate reflectance spectrum for the next ink layer. This process is further repeated for all remaining layers in order to model a final reflectance spectrum for a multi-layer sample.

The Kubelka-Munk model does not take into account the reflection losses at the sample boundaries. For example, the refractive index difference at the boundary between the sample and air give rise to a certain amount of front surface reflection. Since a certain amount of light is lost to front surface reflection, this illumination should be substracted from the total amount of light illuminating the sample. Then, according to Saunderson (Saunderson, 1942), the measured reflectance, $R_{measured}$, can be rewritten according to equation 5:

$$R_{measured} = k_1 + \frac{(1-k_1)(1-k_2)R_{corrected}}{(1-k_2 R_{corrected})} \quad (5)$$

The corrected reflectance measurements of the sample, $R_{corrected}$, that can be used in the Kubelka-Munk colour model is given by equation 6:

$$R_{corrected} = \frac{R_{measured} - k_1}{1 - k_1 - k_2(1 - R_{measured})} \quad (6)$$

The parameter k_1 (external reflection) depends on the refractive index of the two media comprising the surface, and can be calculated according to the Fresnel equations, given by equation 7, using the refractive index ration of the two media and the angle of incidence of the illuminating light (Judd and Wyszecki, 1975):

$$\rho_T = \frac{\rho_{II} + \rho_{\perp}}{2}$$

$$\rho_{II} = \left[\frac{\cos i - \sqrt{(n_2/n_1)^2 - \sin^2 i}}{\cos i + \sqrt{(n_2/n_1)^2 - \sin^2 i}} \right]^2 \tag{7}$$

$$\rho\perp = \left[\frac{(n_2/n_1)^2 \cos i - \sqrt{(n_2/n_1)^2 - \sin^2 i}}{(n_2/n_1)^2 \cos i + \sqrt{(n_2/n_1)^2 - \sin^2 i}} \right]^2$$

where i is the angle of incidence, n_1 is the refractive index of the surrounding medium and n_2 is the refractive index of the object. The parallel and perpendicular subscripts refer to the polarization of the incident beam. The two equations can simply be averaged to describe the total reflectance ρ_T for unpolarized light.

The internal reflection loss, k_2, can be calculated by integrating the Fresnel equations over all incident angles under the assumption that the light becomes totally diffuse as soon as it enters the ink layer. This loss occurs as the light travels downward through the sample, is reflected off the sample-substrate boundary and travels back upward toward the sample-air boundary as if it were to re-emerge from the sample. However, a fraction of this light is again reflected off the sample top surface back down into the sample and travels back towards the sample-substrate boundary. This cycle may continue several times, and a fraction of the light, k_2, never re-emerges from the sample.

Modeling Dynamic Colour Halftoning

To model the dynamic colour halftone prints the Yule-Nielsen modified spectral Murray-Davies model (Yule and Nielsen, 1951) is used. For dynamic colour halftoning the reflectance spectra of the inks are also dependent of the current state, thus the modified Yule-Nielsen equation for dynamic inks is given by equation 8:

$$R_{state}(\lambda) = \left[w_i R_{i,state}(\lambda)^{\frac{1}{n}} + (1 - w_i) R_p^{\frac{1}{n}} \right]^n \tag{8}$$

where R_{state} represents the resulting reflectance spectrum of the halftoned printed area, w_i represents the weight of the current ink and $R_{i,state}$ represents the reflectance spectrum of the current ink in a given state, R_p represents the reflectance spectrum of the paper and n represents the Yule-Nielsen-factor which is derived from the best fit of the model to the training data set. Viggiano (Viggiano, 1985) extended the Yule-Nielsen equation to the case of colour halftones and obtained the following Yule-Nielsen modified spectral Neugebauer equation (Neugebauer, 1989) given by equation 9.

$$R_{state}(\lambda) = \left[\sum_{i=1}^{N} a_i R_{i,state}(\lambda)^{\frac{1}{n}} \right]^n \tag{9}$$

The fractional area coverage a_i is estimated using the Demichel equations (Demichel, 1924).

Experimental Setup

To verify the model eleven steps from 0% to 100% area coverage in 10% intervals were printed for each ink along with the overprint combinations. A total of six hundred colours were printed and measured spectrally. The inks used were process cyan, process magenta, process yellow and thermochromic blue. The thermochromic blue ink has an activation temperature of 31°C. The colour charts were printed using a flatbed screen printing press with a mesh of 120 threads per inch and a screen ruling of 80 lpi. The printing parameters are collected in Table 1.

Press	Flatbed Screen Printing Press
Mesh	120 threads/inch (15µm thread thickness)
Screen Ruling	80 lpi
Inks	UV-screen ink (Cyan, Magenta, Yellow) Thermochromic blue pigments (20-30%) mixed with a UV-screen printing base
Substrate	Uncoated card, 220g

Table 1: *Printing specifications.*

The printed samples were measured with a spectrophotometer with an optical geometry of 45°/0°. Measurements were done with D50 illuminant, 2° observer and UV filter. To transform the thermochromic ink to the warm state a radiator was used together with an aluminum plate to separate the test prints from the radiator and make the heat distribution more even. The temperature was set to 40°C. The temperature was measured against the paper on top of the plate.

Results

The reflectance spectra of the three process inks are shown to the left in Figure 2 (C=solid line, M=dashed line, Y=dotted line), and the spectra of the thermochromic blue ink in the cold state (solid line) and the warm state (dashed line) are shown to the right in Figure 2. The black dotted line represents the reflectance spectrum of the paper. It is clear when comparing the reflectance spectrum of the paper with the reflectance spectrum of the thermochromic blue ink in the warm state that the ink film do not turn completely transparent. The ink still exhibit a certain colour even in the warm state.

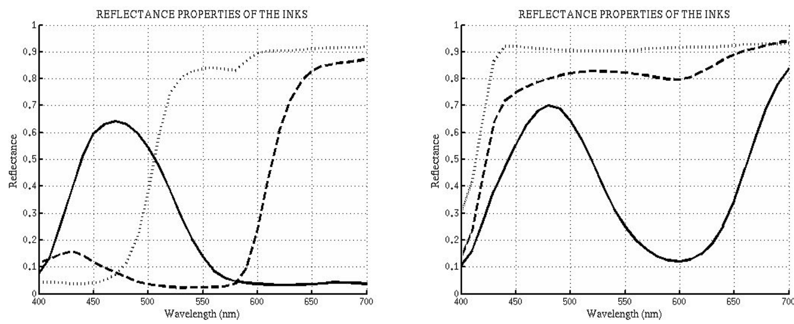

Figure 2. *Reflectance spectra of the process inks (left) and thermochromic ink (right).*

The dot gain curves for the three process inks are shown to the left in Figure 3 (C=solid line, M=dashed line, Y=dotted line), and the dot gain curve for the thermochromic blue ink is shown to the right. There is a small dot gain for magenta and thermochromic blue. For cyan and yellow the dot gain is relatively high, around 20% in the midtone area.

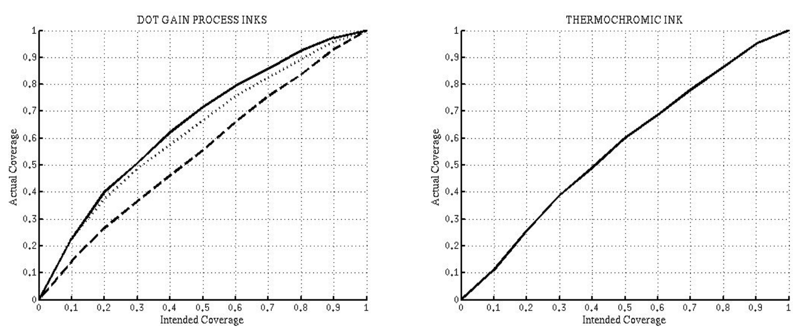

Figure 3. *Dot gain curves for process inks (left) and thermochromic ink (right).*

The Saunderson correction parameters, k_1 and k_2, for the air-paper boundary and for the air-ink boundary are shown in Table 2. The parameter k_1 correspond to the external reflection loss and k_2 correspond to the internal reflection loss. In this case 2.5% of the illumination is lost by reflection at the air-paper and air-ink boundary, and 32.3% of the illumination is lost by internal reflection inside the ink layer and also inside the paper substrate. The refractive index for the paper substrate and the inks is assumed to be 1.2.

Media Boundaries	k_1	k_2
Air/Paper Boundary	0.0248	0.3228
Air/Ink Boundary	0.0248	0.3228

Table 2. *Saunderson correction parameters.*

The results from the model for the primaries in state 1 (cold state), i.e. when the thermochromic ink layer is coloured, are shown in Figure 4. The results are compared to the measured reflectance spectra represented by solid lines in the figure.

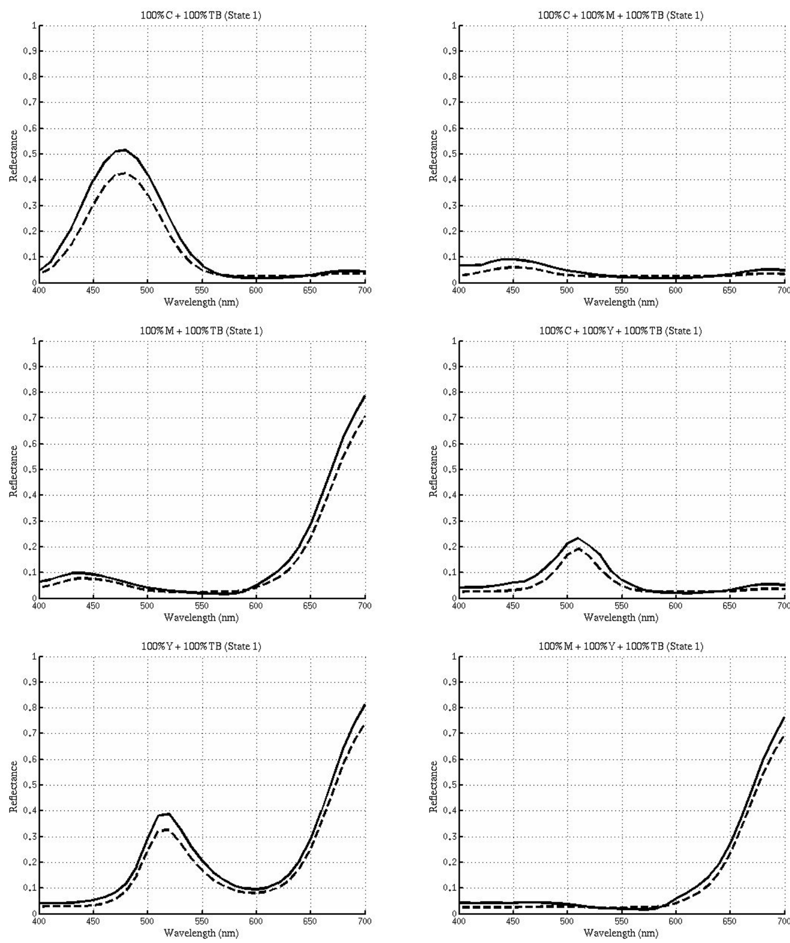

Figure 4. *Predicted (dashed lines) and measured (solid lines) spectral reflectance for the printing primaries in state 1.*

Both measured and modeled spectra have been converted to their colour coordinates in CIELAB colour space. The mean colour difference ΔE^*_{ab} (D50, 2° observer) is 8.8 ΔE^*_{ab}, and the mean RMS spectral error is 3.1%.

The results from the model for the primaries in state 2 (warm state), i.e. when the thermochromic ink layer turns transparent, are shown in Figure 5. The results are compared to the measured reflectance spectra represented by solid lines in the figure. The mean colour difference ΔE^*_{ab} (D50, 2° observer) is 4.7 ΔE^*_{ab}, and the mean RMS spectral error is 1.6%.

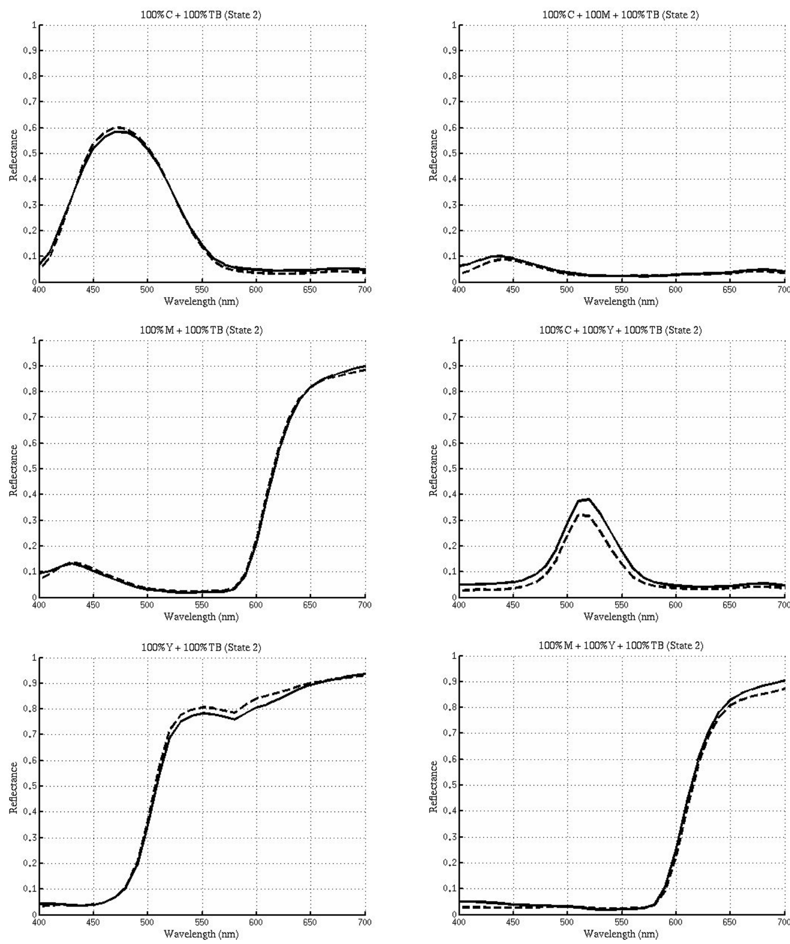

Figure 5. *Predicted (dashed lines) and measured (solid lines) spectral reflectance for the printing praimaries in state 2.*

Some of the spectra from the model for dynamic colour halftones are shown in Figure 6 (two ink layers) and Figure 7 (three ink layers). The results are compared to the measured reflectance spectra represented by solid lines in the figure. The mean colour difference ΔE^*_{ab} (D50, 2° observer) is 7.3 ΔE^*_{ab} in state 1, and 5.0 ΔE^*_{ab} in state 2. The mean RMS spectral error is 3.6% in the cold state and 3.5% in the warm state.

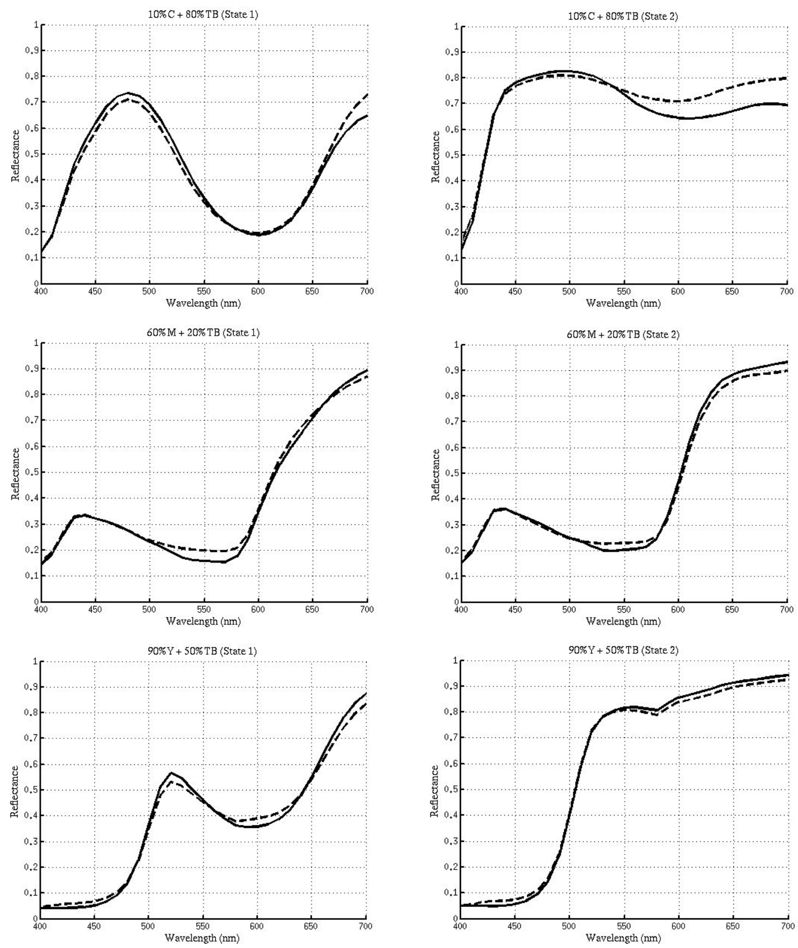

Figure 6. *Predicted (dashed lines) and measured (solid lines) spectral reflectance for some of the two ink dynamic colour halftones in state 1 (left) and state 2 (right).*

Some of the ink samples with printed halftones were poorly printed and had to be discarded from the reference sample set. This is probably due to an excessive stencil thickness in some parts of the screens that prevents an efficient transfer of ink through the screen to the substrate.

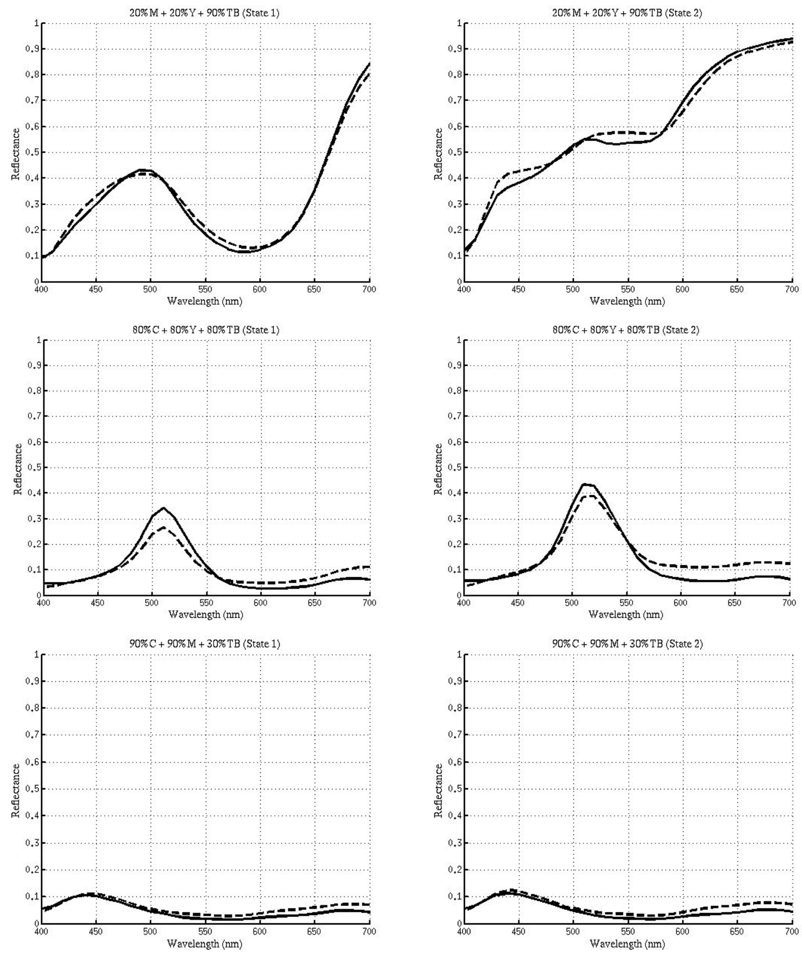

Figure 7. *Predicted (dashed lines) and measured (solid lines) spectral reflectance for some of the three ink dynamic colour halftones in state 1 (left) and state 2 (right).*

Discussion

The model shows fairly good agreement with measured data. The results would probably be improved if the tests were made using another printing method, for example flexo or offset printing. The screen printed samples with several ink layers are inhomogenous in some parts of the samples which of course influence the measurements, and thus the accuracy of the model. This inhomogeneity is probably due to an excessive stencil thickness that prevents an efficient transfer of ink through the screen to the substrate.

A more accurate model of the ink layers can be achieved with a better characterization of the ink layers. This can be obtained by printing an identical ink layer on different paper grades. Then the additional ink parameters $R_{1...N,state}$ and $R'_{1...N,state}$ can be characterized for the different ink layers in addition to $T_{1...N,state}$. These parameters can then be included in the model. This also makes the model less dependent on the paper substrate.

Conclusions

The first steps in building a colour separation model for dynamic image reproduction has been presented. A method for predicting the reflectance of multi-layer combinations of static and dynamic ink layers was derived based on the Kubelka-Munk model. Each ink layer combination is predicted by treating the predicted reflectance of each ink layer as the substrate reflectance of ink layers above it. Dynamic colour halftones were predicted using the Yule-Nielsen modified Neugebauer equations. The model was verified by printing two- and three ink-layer combinations of process and thermochromic ink with screen printing.

Results show the model for predicting dynamic printing primaries and dynamic colour halftones to be quite accurate. Colour difference (ΔE^*_{ab}) values between results predicted with the model and actual physical samples were used as a means to characterize the accuracy of the model. The mean colour difference was 8.8 ΔE^*_{ab} and 4.7 ΔE^*_{ab} in state 1 (cold state) and state 2 (warm state), respectively, for the printing primaries, and 7.3 ΔE^*_{ab} and 5.0 ΔE^*_{ab} in state 1 (cold state) and state 2 (warm state) for the colour halftones.

Acknowledgments

The work presented here has been performed within the national research program T2F. The financial support is greatly acknowledged.

Literature Cited

Demichel M.E., Procédé 26, 17-21, 26-27, 1924.

Hoffman, K., Applications of the Kubelka-Munk Color Model to Xerographic Images, B.S. Thesis, Rochester Institute of Technology, 1998.

Johansson L., Chromatic Properties of Thermochromatic Inks, Proc. TAGA, 2004.

Judd D. B., Wyszecki G., Color in Business, Science, and Industry, John Wiley and Sons, New York, 1975.

Kubelka P., New Contributions to the Optics of Intensely Light-Scattering Materials. Part I, J. Optical Society of America, 38, pp. 448-457, 1948.

Niskanen, K., Paper Physics, Fapet Oy, Helsinki, Finland, 1998.

Neugebauer, H. E. J., Die Theoretischen Grundlagen des Mehrfarbendrucks, Zeitschrift fuer wissenschaftliche Photographie, Vol. 36, pp. 73-89, 1937 (Reprinted as Neugebauer Memorial Seminar on Color Reproduction, Proc. SPIE Vol. 1184, pp. 194-202, 1989).

Saunderson J. L., Calculation of the Color of Pigmented Plastics, J. Optical Society of America, Vol. 32, pp. 727-736, 1942.

Stollnitz E.J., Ostromoukhov V., Salesin D. H., Reproducing Color Images Using Custom Inks, Proc. SIGGRAPH 98, pp. 267-272, 1998.

Viggiano J.A., The Color of Halftone Tints, Proc. TAGA, pp. 647-661, 1985.

Yule J.A.C., Nielsen W.J., The Penetration of Light into Paper and Its Effect on Halftone Reproduction, Proc. TAGA, pp. 66-75, 1951.