An Expanded Neugebauer formula, using varying micro-reflectance of the Neugebauer primaries

Daniel Nyström
Linköping University, Dept. of Science and Technology (ITN)
SE-60174 Norrköping, Sweden

Abstract

Modeling color reproduction in halftone printing is difficult, mainly because of light scattering, causing optical dot gain. Most available models are limited to macroscopic color measurements, averaging the reflectance over an area that is large relative the halftone dot size. The reflectance values for the full tone ink and the unprinted paper are used as input, and these values are assumed to be constant. An experimental imaging system, combining the accuracy of color measurement instruments with a high spatial resolution, allows us to measure the individual halftone dots, as well as the paper between them. Microscopic reflectance measurements reveal that the micro-reflectance of the printed dots and the paper between them is not constant, but varies with the ink area coverage. By incorporating the varying micro-reflectance values of the ink and paper in an expanded Murray-Davies model, we have previously shown that the resulting prediction errors are smaller than for the commonly used Yule-Nielsen model. Moreover, unlike Yule-Nielsen, the expanded Murray-Davies model takes into account the varying micro-reflectance for the printed dots and the paper, thus providing a better physical description of optical dot gain in halftone prints.

In this study, we further extend the proposed methodology to handle color prints, predicting tristimulus values for prints with multiple and overlapping colorants. After converting the microscopic images of halftone prints into CIEXYZ color space, tristimulus values for the paper and the different combinations of ink are computed from CIEEXYZ histograms. From the microscopic images we can also compute the physical ink area coverage for each of the Neugebauer primaries, which typically differ from the nominal one, due to physical dot gain. The result is an expanded Neugebauer model, taking into account how the tristimulus values of the paper, the primary inks and the overlapping secondary colors, vary with the total ink area coverage. Experimental results confirm the accuracy of the proposed methodology, when compared to measurements using a spectrophotometer. The results have shown that the variation of the micro-reflectance of the Neugebauer primaries is large, and depends on the total ink area coverage. The results further show that the way that the micro-reflectance vary is also strongly dependent on the surrounding inks, because of light scattering in the substrate.

Introduction

Modeling color reproduction in halftone prints is challenging, mainly because of light scattering in the substrate, causing optical dot gain. The first model to predict the output reflectance of a monochrome halftone print is the *Murray-Davies* model, published in the 1930s. The mean reflectance, R, is simply given by linear interpolation of the reflectance of the bare paper, R_p, and the full tone, R_i, weighted by the dot area fraction, a [1]:

$$R(a) = aR_i + (1-a)R_p \tag{1}$$

The famous *Neugebauer* model is then a straightforward extension of the Murray-Davies formula to handle multiple colorants, giving the average reflectance as the summation of the reflectance for the different colorants (including overlapping colorants), weighted by their fractional ink area coverage [2].

$$R = \sum_j a_j R_j \tag{2}$$

where a_j is the fractional ink area for the Neugebauer primaries, with reflectance R_j. For a three-colorant print, the eight Neugebauer primaries correspond to: the unprinted paper, the primary inks cyan, magenta and yellow, the secondary colors red, green and blue, and three color black. Since the reflected light from different areas is added to predict the overall reflectance, these models preserve the linearity of photon additivity. It is, however, well known that the performance of these linear models is very limited. The relationship of R versus a is in fact non-linear, due to light scattering in the paper substrate, causing optical dot gain.

In the 1950s, Yule and Nielsen published their work on light penetration and scattering in paper [3]. It was then shown that the nonlinear relationship could be approximated by a power function.

$$R(a) = \left[aR_i^{1/n} + (1-a)R_p^{1/n}\right]^n \tag{3}$$

The Yule-Nielsen n-factor, accounting for light scattering in the paper, is an empirically derived constant, selected to provide the best fit to experimental data. Unless other factors than optical scattering of light are involved, values of n between 1 and 2 are physically meaningful, with n=2 corresponding to a highly scattering substrate. The Neugebauer formula has later been combined with the Yule-Nielsen formula, to handle optical dot gain also for multiple colorants. The Yule-Nielsen modified Neugebauer is commonly referred to as the n-modified Neugebauer [4]. Notice that the fundamental assumption in these models is that the color for the substrate and the ink is both uniform and constant, as only the reflectance values for the full tone ink and for the unprinted paper are used.

In the 1990s, it was shown that the color of the halftone dots and the paper between the dots is not constant, but dependent on the ink area fraction [5]. The reflectance of the printed halftone dots, as well as the paper between them, decreases with increased ink area coverage, due to light scattering in the substrate. An expanded Murray-Davies model was then proposed [6]:

$$R(a) = aR_i(a) + (1-a)R_p(a) \quad (4)$$

This model preserves the linear additivity of reflectance, while the non-linear relation between R and a is accounted for by using the functions $R_i(a)$ and $R_p(a)$. Naturally, the difficulty with this approach is to derive $R_i(a)$ and $R_p(a)$, i.e. the way that the reflectance of the ink and paper varies with the dot area fraction. Since it is impossible to derive these components using macroscopic measurements, giving only the averaged reflectance of an area that is large in relation to the printed dots, there is clearly a need for micro-reflectance measurements of the halftone dots and the paper between them.

In previous work, we have used an experimental imaging system, combining the accuracy of color measurement instruments with a high spatial resolution, to capture microscopic images of halftone prints. From histogram data from such images, $R_i(a)$ and $R_p(a)$, were measured and characterized. The validity of the expanded Murray-Davies model was evaluated also for today's high-resolution prints, and an extension to tristimulus values was proposed, for single color prints [7]. The results have shown that the resulting prediction errors are smaller than for the Yule-Nielsen model. We have further shown that the characteristics of the varying micro-reflectance values for the dots and the paper depend strongly on the halftone geometry and the print resolution [8].

In this work, we continue the approach of micro-reflectance measurements of the halftone dots and the paper between them. The aim is to investigate if the methodology can be further developed to handle prints with multiple and overlapping colorants. We propose an expanded Neugebauer formula, similar to the previous expansion of the Murray-Davies formula. The expanded Neugebauer formula requires microscopic colorimetric measurements of the Neugebauer primaries for all ink area fractions, as well as methods to separate the different colorants in order to compute the physical ink area fractions.

Experimental Setup

Image acquisition system

An experimental image acquisition system is used, specially designed for acquiring microscopic images of prints and substrates. The images are captured using a monochrome CCD camera, with a resolution of 1360 × 1024 pixels and 12 bit dynamic range. The CCD, specially designed for scientific imaging, is of grade 0, which means no defective pixels, and uses digital temperature compensation to reduce noise. The optics used is a macro system, designed for scientific applications, allowing for images of various magnifications, up to a maximal resolution of 1.2 μm/pixel.

The substrate is placed on a table, which allows for controlled translations in two directions and for rotation around the optical axis. The illumination is provided using a tungsten halogen lamp through optical fibers, which offers an adjustable angle of incidence, as well as the possibility of using a backlight setup. Color images are captured sequentially, using filters mounted in a filter wheel in front of the light source. By using this color sequential method, there is no need for any interpolation or de-mosaicing scheme, as is the case in conventional digital cameras. Besides the conventional RGB-filters, the filter wheel also contains a set of 7 more narrow-band interference filters, which allows for the acquisition of multi-channel images. The image acquisition system has previously been thoroughly calibrated and characterized. Models have been developed, allowing for the device dependent images to be converted into the colorimetric representations CIEXYZ and CIELAB, and also to reconstruct spectral reflectance data [9].

Printed samples

The printed samples used in this study consisted of offset prints on a coated paper grade (150 gr/m2), printed with AM halftones, using clustered dots (100 lpi, 1200 dpi). The nominal dot area coverage of the patches are 0, 2, 5, 8, 10, 15,…, 90, 95 and 100% respectively. The test charts were printed with a commercial 4-color offset press, and all patches were printed using the same plate.

Macroscopic color measurements of the prints

Macroscopic measurements of the spectral reflectance and the tristimulus values of the printed color patches were derived using a Gretag Machbeth Spectrolino spectrophotometer, equipped with a UV filter, using the 45°/0° measurement geometry. All colorimetric computations were made using the CIE standard illuminant D65.

Microscopic color measurements of the prints

RGB and multi-channel images of the test prints have been captured using the 45˚/0˚ measurement geometry. The field of view was 2.7 × 2 mm, giving a resolution corresponding to 2μm/pixel. All images are first corrected for dark current and CCD gain. The conversion to CIEXYZ color space was made by polynomial regression from RGB images, using characterization functions individually derived for each print [9].

Methodology

We propose the use of an expanded Neugebauer formula, which incorporates the varying micro-reflectance for the Neugebauer primaries, similar to the previously proposed expansion of the Murray-Davies formula (Eq. 4). Since we will use the approach to measure and predict the CIEXYZ tristimulus values in this work, we present the formula in its colorimetric form:

$$\begin{bmatrix} X_{tot} \\ Y_{tot} \\ Z_{tot} \end{bmatrix} = \sum_j a_j \begin{bmatrix} X_j(a_{tot}) \\ Y_j(a_{tot}) \\ Z_j(a_{tot}) \end{bmatrix} \quad (5)$$

In this equation, X_{tot}, Y_{tot} and Z_{tot} refer to the output tristimulus values (corresponding to the macroscopic color measurement), and $XYZ(a_{tot})$ is the micro-colorimetric values for the Neugebauer primaries, j, which will depend on the total ink area fraction a_{tot}. Naturally, the sum of the ink area fractions, a_j, for the Neugebauer primaries will sum up to unity. The reason for using the total ink area, a_{tot}, instead of the ink area fraction for the individual Neugebauer primaries, a_j, is that the ink area fractions for the primary inks will start decreasing after a total ink area coverage of 50%, due to ink overlapping (which can be seen in Fig. 5). It will also be shown that the way that the micro-colorimetric values of the Neugebauer primaries vary, is not only dependent on the ink area fraction of that colorant, but on the total ink area coverage.

From Eq. 5, we see that the use of the expanded Neugebauer formula requires for micro-colorimetric measurements of the different combinations of printed colorants and the paper between them, for each ink area fraction, a_{tot}. It will also require methods for computing the physical ink area fraction for each of the Neugebauer primaries, which may differ from the nominal ones, due to physical dot gain in the printing process.

Micro-reflectance measurements

To obtain the micro-colorimetric measurements, $XYZ(a_j)$, of the ink and paper, microscopic images are captured of printed halftones. In microscopic images the spatial resolution of the images is high in relation to the resolution of the halftone, allowing for micro-reflectance measurements. The captured device-dependent RGB-images are first converted into CIEXYZ color space, using polynomial regression techniques [9].

To capture the typical characteristics of a large population of halftone dots, which may differ in their appearance, 3D-histograms in CIEXYZ color space are computed. In a 3D histogram from images of halftone color prints captured in micro-scale, the paper and the different combinations of printed inks will appear as clusters, with the transitions between the clusters corresponding to the edges of the halftone dots. The micro-colorimetric values $XYZ(a_{tot})$, can then be computed as the centers of gravity of the clusters corresponding to the paper and the different inks, for each area coverage, a_{tot} [10].

Finding the physical ink area fractions

In the Expanded Neugebauer formula (Eq. 5) it is important that the ink area fractions of the Neugebauer primaries, a_j, correspond to the physical ink areas, which typically will differ from the nominal dot areas, due to physical dot gain in the printing process. Computing the physical ink areas involves the non-trivial task of separating of the physical and the optical dot gain in the print [11].

Computing the physical ink area fractions will first require for means to separate the different colorants. Beside the RGB images, multi-channel images have been acquired of the same halftone patches. The multi-channel images make use of 7 interference filters, covering the visible spectrum, with the center wavelengths 400, 450, 500, 550, 600, 650 and 700 nm. The spectral transmittance of the filters is displayed in Fig. 1.

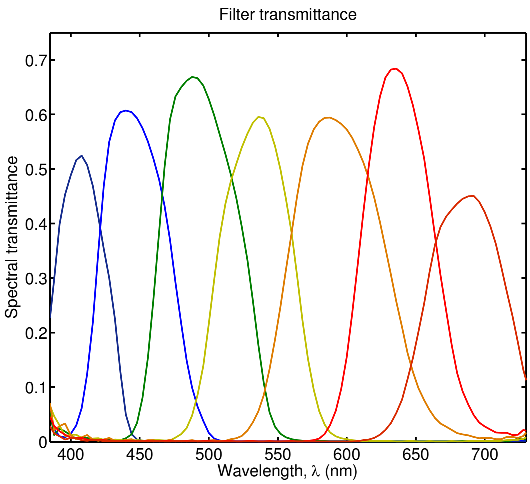

Figure 1. *Spectral filter transmittance for the seven interference filters.*

Since the different primary inks absorb and reflect the light in different wavelength bands (see Fig. 2), we can use the multi-channel images to separate the inks [12]. For example, by using the filter around 700 nm for a blue print, only the cyan ink will be visible in the image, since this spectral region belongs to the absorbing wavelength band of cyan, but to the reflecting wavelength band of magenta.

This is illustrated in Fig. 3 for a 40% blue halftone patch. The upper half displays a part of the microscopic RGB image. The lower left image shows the same halftone patch captured using the 700 nm interference filter, where the magenta dots are no longer visible. The lower right image shows the image captured using the 500 nm filter, where the magenta ink appears clearly while the cyan dots only appears as shadows, which are easily separated from the magenta ink.

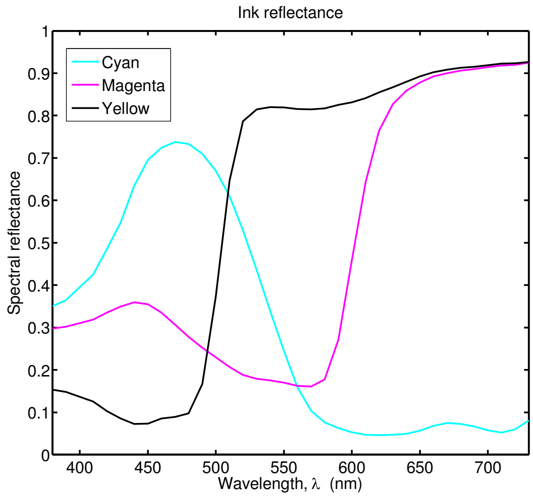

Figure 2. *Spectral reflectance of the primary inks Cyan, Magenta and Yellow.*

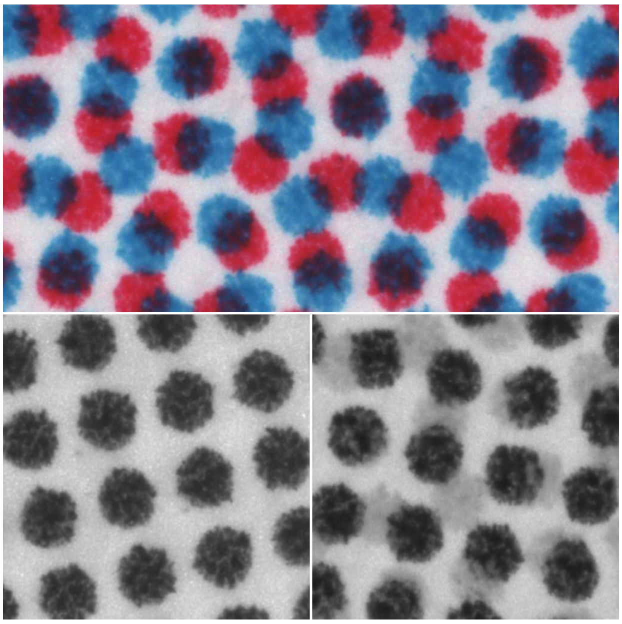

Figure 3. *Separation of the cyan (lower left) and magenta (lower right) colorants.*

After the different colorant inks have been separated into separate images, these images need to be segmented in order to compute the physical ink areas. This requires for a proper threshold value, defining the limit between the ink and the paper. When microscopic images of the prints are available, one possibility is to derive the threshold from image data, by using line scans across the halftone dots, and defining the threshold value as the region of maximum rate of change in reflectance values, dR/dx [6]. In this work, however, we make use of a thresholding algorithm minimizing the interclass variance of black and white pixels [13]. The resulting binary images give the physical ink areas for the primary inks. By combining these binary images, the area for the secondary color is given where the primary inks overlap.

The principle is displayed in Fig. 4 for a 40% blue print, where the binary images are used as masks in combination with the RGB images to display the physical dot areas for the four Neugebauer primaries. The physical ink area fractions corresponds to 34.2% for paper, 23.7% for cyan, 22.2% for magenta and 19.9% for the secondary blue.

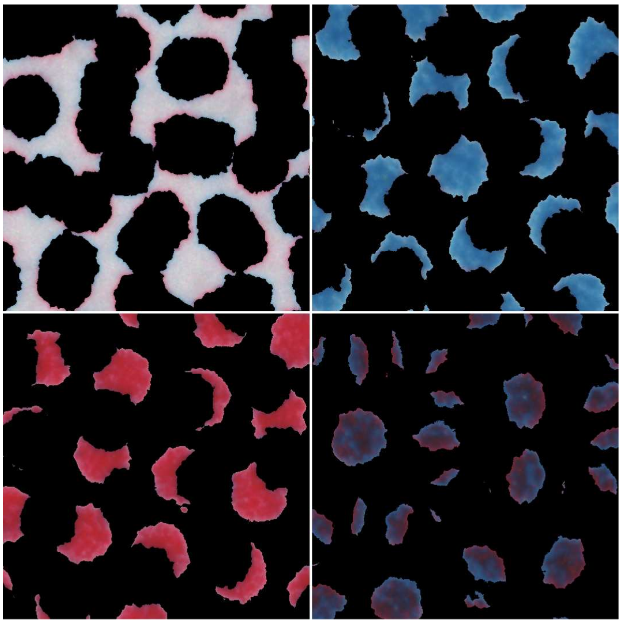

***Figure 4**. Physical ink areas for the Neugebauer primaries, Paper, Cyan, Magenta and Blue. Nominal ink area 40% for Cyan and Magenta.*

The only colorant combination that is not easily separated using the available interference filters, is the combination of yellow and magenta. By using the filter around 550 nm, the magenta ink is easily separated from the yellow, since this spectral region belongs to the absorbing wavelength band of magenta but to the reflecting wavelength band of yellow. However, there is no spectral region where the yellow overprint on magenta is easily separated. To overcome this, and still be able to estimate the physical ink area fractions, we assume that the physical dot gain for each colorant in a two colorant print is similar to that of the single color print for the same colorant. By computing the physical ink area as a function of the nominal ink area for single colorant prints, we can use the famous *Demichel* equations to compute the physical ink areas for the Neugebauer primaries in the two colorant prints [14].

To test and verify the accuracy of the methodology, it is first evaluated for blue prints, where the cyan and magenta inks are easily separated and segmented. Figure 5 depicts how the physical ink area fractions computed using the Demichel equations agree reasonably well with the corresponding areas, measured using the described methodology.

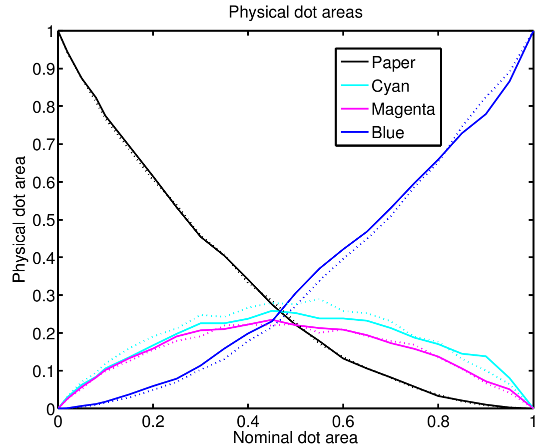

***Figure 5**. Physical ink areas for the Neugebauer primaries Paper, Cyan, Magenta and Blue. Full lines: measured ink areas. Dotted lines: computed ink areas, using DeMichel.*

Experimental results

The expanded Neugebauer formula has been evaluated using offset prints of AM halftones, with the two-colorant combinations cyan and magenta, cyan and yellow, and magenta and yellow. The nominal ink area coverage of the printed halftone patches are 0, 2, 5, 8, 10, 15,…, 90, 95 and 100%, for both the primary inks. For all halftone patches, the physical ink area fractions, as well as the micro-colorimetric values, have been derived according to the described methodology.

The result when combining the estimated physical ink area fractions with the micro-colorimetric measurements to compute the tristimulus values according the expanded Neugebauer formula (Eq. 5), are displayed in Figs. 6-8, for the different colorant combinations. Included for comparison are the corresponding values, measured by a spectrophotometer.

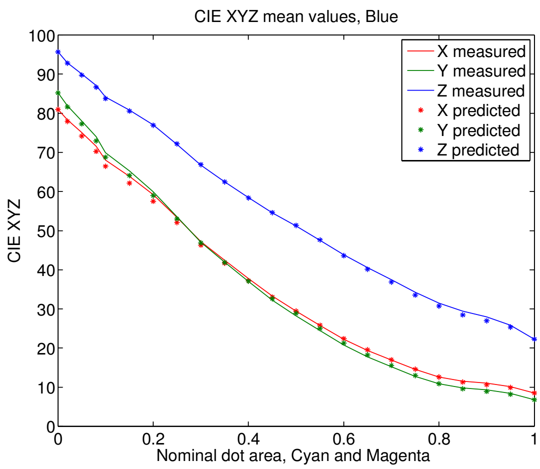

***Figure 6**. Measured and predicted tristimulus values for a blue print (cyan and magenta inks).*

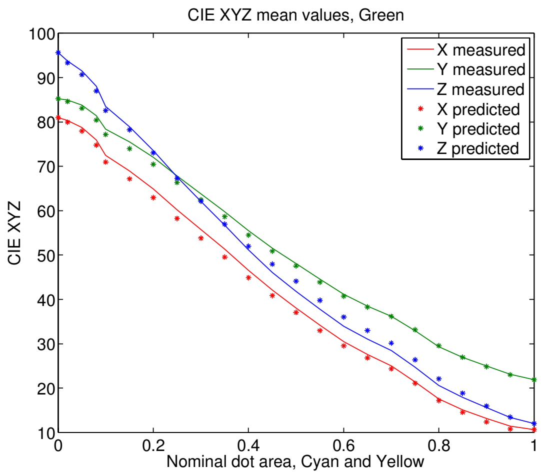

Figure 7*. Measured and predicted tristimulus values for a green print (cyan and yellow inks).*

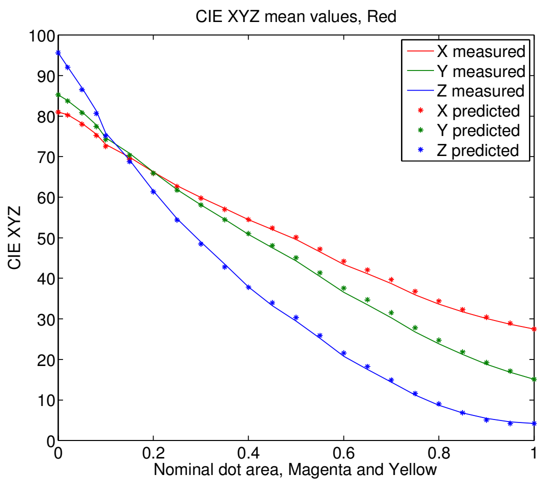

Figure 8*. Measured and predicted tristimulus values for a blue print (magenta and yellow inks).*

The Euclidian distances in CIEXYZ color space between the predicted and measured values for all the printed patches are given in Tab. 1, together with the CIE 1994 color difference, Δ^*E_{94}. Notice that the predicted values are computed from microscopic images of the prints, while the reference values are measured by a spectrophotometer. This means that the color differences also include the error from the polynomial regression from RGB to CIEXYZ color space. Considering this, one must say that a mean prediction error of 1.1 Δ^*E_{94} and a maximum of 2.0 Δ^*E_{94} indicate that the proposed model is accurate.

Table 1. Estimation errors between measured and predicted tristimulus values.

ΔXYZ max	ΔXYZ mean	ΔE^*_{94} max	ΔE^*_{94} mean
2.25	0.98	1.98	1.09

The measured micro-colorimetric values, $XYZ(a_{tot})$, for the Neugebauer primaries with respect to the total ink area are displayed in Fig. 9, for the blue color patches. Clearly, there is a large variation of the micro-colorimetric values for the different combination of inks and the paper, with the total ink area.

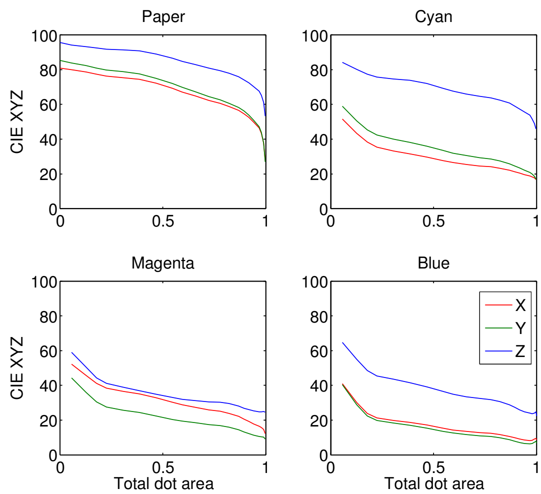

Figure 9*. Micro-colorimetric measurements of the Neugebauer primaries Paper, Cyan, Magenta and Blue.*

The experiments further reveal that the way that the micro-colorimetric values of the Neugebauer primaries vary is not only dependent on the total ink area, but also on the surrounding inks. Figure 10 compares the micro-colorimetric measurements for the unprinted paper with magenta (full lines) and cyan (dotted lines) single colorant prints. Clearly, the color of the paper between the dots is strongly dependent on the color of the printed dots. From Fig. 10, we see that the *Z* value for the paper is higher with the cyan ink, which has higher reflectance in this spectral region compared to the magenta ink (see Fig. 2). For the same reason, the *X* value for the paper is higher with the magenta ink. The curves in Fig.10 can be compared with the curves in Fig. 9a, showing the corresponding values for the paper with both cyan and magenta inks, where the reflectance of the paper is decreased even more.

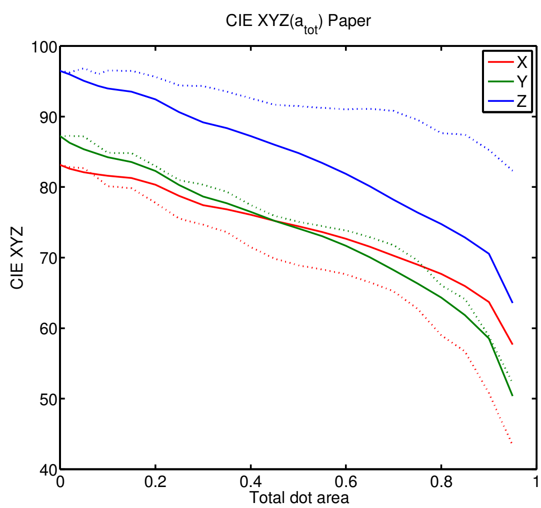

Figure 10*. Micro-colorimetric measurements for the paper between the dots. Full lines: Magenta prints. Dotted lines: Cyan prints.*

The way that the surrounding areas affect the colorimetric values for the Neugebauer primaries is also evident in the case of the printed colorants. Figures 11 and 12 displays the tristimulus values for the magenta ink, when printed together with cyan and yellow, respectively. Included for comparison are the micro-colorimetric measurements for magenta as a single colorant (dotted line). It is obvious that the largest effect occurs for the tristimulus values where the second colorant has its absorption wavelength band, i.e. *X* and *Y* for the cyan ink, and *Z* for the yellow ink.

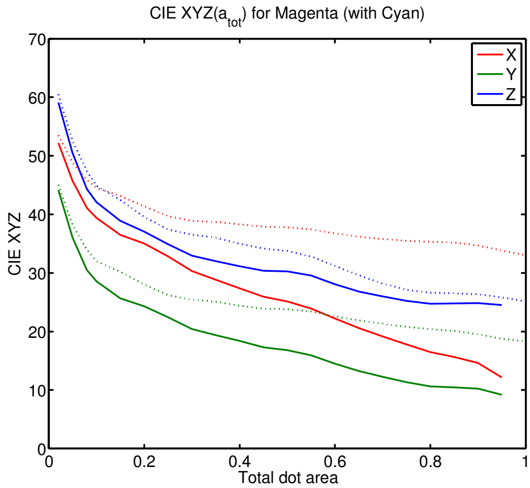

Figure 11. *Micro-colorimetric measurements for magenta ink. Full lines: two colorant prints with cyan. Dotted lines: single colorant prints.*

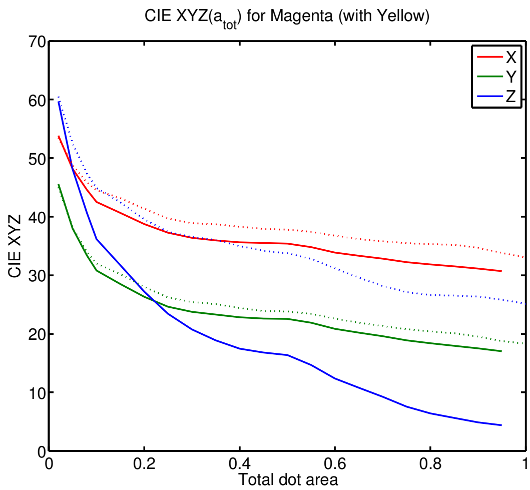

Figure 12. *Micro-colorimetric measurements for magenta ink. Full lines: two colorant prints with yellow. Dotted lines: single colorant prints.*

Summary and Conclusions

We have proposed an expended Neugebauer formula, incorporating the variation of the micro-reflectance of the Neugebauer primaries with respect to the total ink area. The methodology has been evaluated using offset prints of AM halftones with the colorant combinations: cyan and magenta, cyan and yellow, and magenta and yellow. The experimental results show that the method works well, giving only small prediction errors. More importantly, the results have shown that the colorimetric variations for the Neugebauer primaries with respect to the ink area are substantial. These results clearly indicate that every model that assumes constant reflectance of the inks and paper, are not physically correct.

We know from earlier work on single color prints that the way that the micro-reflectance of the ink and paper vary with the ink area coverage is related to the halftone geometry and the print resolution. The results from this work further prove that the surrounding inks have a strong impact. Because of the practical difficulties of microscopic color measurements, models for how the micro-reflectance of the ink and the paper varies with the ink area are needed, to make the expanded Neugebauer formula useful in practice. Especially, focus should be on relating these models to properties of the printing process, such as the paper substrate, the printing method and the halftoning employed. However, the results from this work clearly illustrate the complexity of such models, where also the effect of surrounding inks must be taken into account, because of light scattering in the substrate.

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Author Biography

Daniel Nyström received his M.Sc. degree in Media Technology from Linköping University, Sweden, in 2002 and his Ph.D degree from the same university in 2009. He is currently working as a research associate in the Media and Information Technology group at the Dept. of Science and Technology, Linköping University. His research interests include color science, paper optics and image processing.