Application of Neugebauer-Based Models to Ceramic Printing

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Abstract

In the ceramic industry half-tone images are often generated from a small number of separations with the result that inks are printed over each other to achieve the final print. This study investigates whether an *n*-modified spectral Neugebauer-based model, which has been used quite successfully to predict reflectance for prints on paper substrates, can be used to predict the color of half-tone prints on a ceramic base. A set of 800 binary ink mixtures and 100 single-ink mixtures were used to test the model and it was found that best performance (median CIELAB ΔE of 2.73 units) was possible using a high value of the Yule-Nielsen correction factor (n = 20). A Kubelka-Munk model was developed to predict the reflectance factors of the overlap regions in the prints (where one ink dot lies over another). Color differences using the Kubelka-Munk model ranged from 1.8 to 10.4. However, when the measured overlap reflectance spectra were replaced by the Kubelka-Munk predictions in the Neugebauer model the median color difference increased from 2.73 to 3.40 CIELAB units.

Introduction

Images are often generated from a small number of separations with the result that inks are printed over each other in halftone patterns to achieve the final print. In the halftone process ink is deposited in small dots of approximately constant thickness. Tonal variation is not achieved by changing the thickness of the ink deposited at each dot, but, rather, by varying the frequency of the dots or their size. The pattern of dots for any ink is referred to as a screen and the ink dots are arranged in rows (Figure 1a); the screen angle is the orientation of the rows relative to the horizontal axis and the screen frequency is the number of rows of dots per inch of the resulting halftone pattern.[1] When more than one ink color is printed, the different colors are usually set at different orientations so as to minimize the visibility of artifacts (Figure 1b), or are printed so that the dots print on top of each other (so-called dot-on-dot screen printing). The individual dots are usually invisible to a human viewer under normal viewing conditions, so that the resultant color is an additive combination of the colors of the dots and of the substrate upon which they are printed. Sometimes, however, visible artifacts (so-called Moiré effects) may be visible. Halftone printing is important in the ceramic industry where, typically, three or four separations are used with the inks being selected from a library of perhaps twenty or more colors. It is useful to be able to predict the color of each pixel (where the pixel may be composed of several dots of various colors) in the ceramic image. If an accurate color-prediction model could be developed than it may be possible (by inversion of the model or via other numerical methods) to accurately reproduce the image (for proofing purposes) that would be produced by the separations for view on an RGB monitor or in hardcopy using a CMYK printer with existing ICC profile technology.

The prediction of color from the halftone separations is not trivial, but the Neugebauer model has been successfully used to predict the color of halftone systems for various printing systems on paper.[2-5] This study investigates whether the spectral Neugebauer model can be effective for the prediction of color for a halftone printing process on a ceramic base. This is interesting because the physiochemical properties of the ceramic substrate are very different from that of most paper substrates. In the ceramic tiles used in this study the base was a white-glazed material with a high gloss finish which we would expect to be far less absorbant than paper substrates and this will affect the ink-substrate interactions (ink spreading etc).

The use of Neugebauer-based models requires that the colors of not only the solid colors but also the overlap colors (see Figure 1b) be known. Although for a system with four colorants (e.g. CMYK) it is possible to measure the spectral reflectance factors of all of the overlap colors, the number of binary overlap colors may be large for a general system of m inks (where m may be, for example, 20 or more). In such circumstances, the Kubelka-Munk theory is often used to predict the overlap colors.[6] In this study a modified Kubelka-Munk theory is used to predict the overlap colors for ceramic halftone prints and the effect on color-prediction performance of the Neugebauer-based model incorporating the Kubelka-Munk theory (compared with using actual measurements of the overlap colors) is assessed.

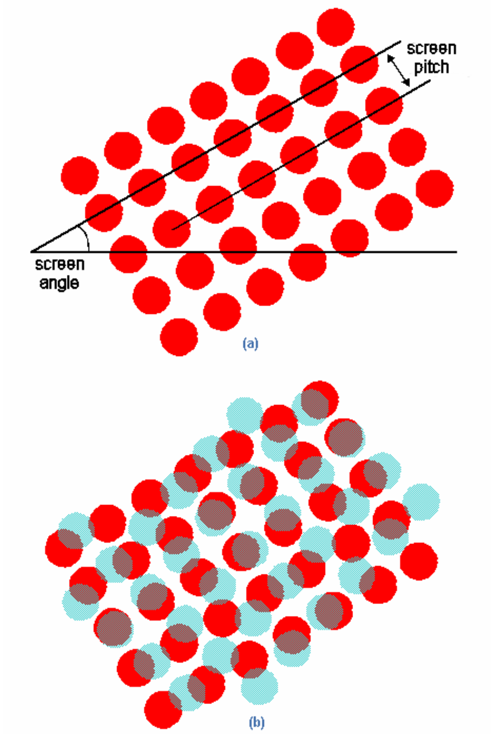

Figure 1. Schematic diagram to show the dot configuration for (a) a single ink printed at a specific angle and frequency (note that the frequency is the reciprocal of the pitch), and (b) a binary ink system where the two inks have been printed at different angles.

Neugebauer-Based Models

If we consider a single ink printed on a substrate in a halftone pattern and denote the reflectance of the unprinted (usually white) substrate by R_w and the reflectance of the solid ink by R_s, then the Murray-Davies relationship predicts the measured reflectance R of the print.[7] The value of R is related to the sum of the reflectances of the two components weighted by their fractional area coverage thus,

$$R = AR_s + (1\text{-}A)\,R_w, \tag{1}$$

where A is the fraction area of coverage of the solid ink.

Equation 1 may be inverted to predict the effective dot area A thus

$$A = (R_w - R)/(R_w - R_s). \tag{2}$$

If measurements of R_W, R_S and R are made for given a target area (digital area coverage d) and Equation 2 is used then it is generally found that $A > d$. One reason for this is that the ink tends to spread as it is applied to the substrate so that the actual dot area is larger than the target area (this is referred to as mechanical dot gain). Yule and Nielsen proposed a correction to the Murray-Davies equation, thus[8]

$$R = [A(R_s)^{0.5} + (1\text{-}A)(R_w)^{0.5}]^2. \tag{3}$$

Equation 3 results in a non-linear relationship between the effective area coverage A and the resulting reflectance R. This non-linear relationship is required to account for optical dot gain, the phenomenon that halftone prints usually appear darker than expected (based on Equation 1) because some light that strikes the unprinted substrate is absorbed by the ink dots. This primarily occurs because of scattering of light within the substrate.

The generalized Yule-Nielsen equation allows for an exponent n so that,

$$R = [A(R_s)^{1/n} + (1\text{-}A)(R_w)^{1/n}]^n, \tag{4}$$

where n is usually given a value between 1.0 (for a glossy substrate) and 2.0 (for a matt substrate).

The Murray-Davies equation can be extended for more than one color (taking into account the various overlapping binary mixtures). For example, if cyan, magenta and yellow inks are considered then the resulting reflectance will be a function of the reflectances of the unprinted substrate R_w, the three solid colors (R_c, R_m, R_y) and the four overlap color combinations of cyan + magenta (blue R_b), cyan + yellow (green R_g), yellow + magenta (red R_r), and black R_k. If the fractional areas of these eight areas are represented by A_c, A_m, etc, then we can write.

$$R = A_wR_w + A_cR_c + A_mR_m + A_yR_y + A_bR_b + A_gR_g + A_rR_r + A_kR_k \tag{5}$$

It is evident that the Neugebauer-based model (Equation 6) used in this study is an extension of the Murray-Davies equation (Equation 1) and that it assumes that the reflectance of a spatial area is the additive combination of the reflectances of the primary colors and their overlapping areas. Originally, the Neugebauer equations were used to predict the broadband reflectance in the short-, medium, and long-wavelength portions of spectrum and, indeed, modern versions of Neugebauer sometimes operate using *XYZ* tristimulus values. However, the n-modified spectral Neugebauer-based approach[9] (illustrated for a CMY system by Equation 6) has been shown to be most accurate[6] and is therefore considered in this work.

$$R = (A_wR_w^{1/n} + A_cR_c^{1/n} + A_mR_m^{1/n} + A_yR_y^{1/n} + A_bR_b^{1/n} + A_gR_g^{1/n} + A_rR_r^{1/n} + A_kR_k^{1/n})^n \tag{6}$$

Before Equation 6 can be used to predict reflectance the areas of the primary, secondary and tertiary colors need to be determined. For the three-color example, the proportional areas of the eight color regions can be computed using Demichel's equation,

$$\begin{aligned} A_w &= (1\text{-}c)(1\text{-}m)(1\text{-}y) \\ A_c &= c(1\text{-}m)(1\text{-}y) \\ A_m &= m(1\text{-}c)(1\text{-}y) \\ A_y &= y(1\text{-}c)(1\text{-}m) \end{aligned} \tag{7}$$

$$A_b = cm(1\text{-}y)$$
$$A_g = cy(1\text{-}m)$$
$$A_r = my(1\text{-}c)$$
$$A_k = cmy,$$

where c, m and y are the proportional dot areas (corrected for dot gain) of the three primary colors.[10] Demichel's equation has been shown to work reasonably well for rotated halftone screen configurations where the screens for cyan, magenta and yellow are placed at different angles, carefully selected to avoid moiré artifacts.[9] It is important to note, however, that Equations 7 make certain assumptions concerning the amount of overlap between the primary colors. The relationship between the screen angles is one of several factors that could affect the degree of overlap. The dot-on-dot halftone configuration, for example, places the primary dots at the same screen angle and phase so that they maximally overlap. In practice it has been shown that a weighted combination of the Demichel model and the dot-on-dot model can give good performance.[6] In order to use the n-modified spectral Neugebauer-based model (Equation 6), not only is it necessary to make assumptions about the degree of overlap of the dots but, as mentioned previously, it is also necessary to measure (or predict) the reflectance of an area (the overlap color) where a dot of one color is printed over a dot of another color.

If the number of inks in the system is small then the best approach to determine the overlap color reflectance is by direct measurement of every combination. However, for systems containing many inks such an exhaustive approach may be prohibitive and alternatively the Kubelka-Munk model can be used to predict the color of the overlap areas. The number of binary overlap colors is $m!/[(m\text{-}2)!2!]$ or, if the print order of the inks can be changed, $m!/(m\text{-}2)!$ which corresponds to 190 and 380 respectively when $n = 20$. Of course, in practice it may also be necessary to consider tertiary (or higher) overlap areas but this work is restricted to the use of just two inks at any one time.

Experimental

A set of ceramic tiles were obtained from Typemaker* and were measured using the Color Eye 7000A spectrophotometer to generate reflectance data between 400 and 700 *nm* at 10 *nm* intervals. The spectrophotometer used an integrating sphere and this allowed the specular component to be excluded. Measurements were taken for a set of ten inks each printed over white and black tiles (although the main glaze used was white, inks were also printed on ceramic tiles with a black glaze). Tonal variation of each ink was obtained by varying the dot frequency (FM halftoning) to provide a step-wedge with 10 digital coverage areas (0.1, 0.2, 0.3 … 1.0) for each ink. Each of the tiles (referred to as calibration tiles) therefore was composed of 10 separate areas where the digital coverage of the ink was known in each case.

In addition, tiles were available for eight printed binary combinations of the individual inks. For each combination a tile was printed with a step-wedge of one ink and then with a step-wedge of a second ink (printed at 90^o to the first) to generate 100 squares arranged in a grid. Since each ink was printed at each of 10 digital coverage areas (0.1, 0.2, 0.3 … 1.0) a total of 100 unique combinations resulted for each of these tiles. The eight combination tiles formed a set of test data so that in total there were 800 measured samples each with known digital coverage areas for each ink in a binary mixture. One of the squares in each of these tiles corresponded to where the two inks were both printed at coverage 1.0 and the reflectance of this square was used as the reflectance of the overlap region for the inks in subsequent computations.

Measurements from the calibration tiles were used to build a model that was then used to predict the reflectance of each of the 800 test samples.

The first step in applying the model was to build a tone-reproduction curve that be used to transform the target area coverage values d into effective coverage area values A. Based upon the n-modified spectral Neugebauer-based model, for given values of d and P, the optimum area coverage A may be computed using

$$A = \Sigma(P_S(\lambda)^{1/n} - P(\lambda)^{1/n})(P_S(\lambda)^{1/n} - P_W(\lambda)^{1/n}) \,/\, \Sigma(P_S(\lambda)^{1/n} - P_W(\lambda)^{1/n}) \qquad (11)$$

where it is assumed that there are no inter-colorant interactions.[6] Thus, the reflectance P was measured for a number of levels d and Equation 11 was used to determine A. This procedure yielded pairs of $[d_j\ A_j]$ from which a continuous function (referred to as a tone-reproduction curve, TRC) was derived that maps digital area coverage d to dot area coverage A. Some alternative methods for determining dot areas that minimize the error in CIELAB color-difference units are also available.[4]

The steps involved in the application and testing of the model were

- A value of n was selected for the model (Equation 6). For each of the 10 inks the data from the calibration tiles were used to derive the TRC. The measured reflectance data were used to predict the dot area coverage A for each digital area coverage d (Equation 11) and the TRC was constructed using a second-order polynomial fit to the $[d_j\ A_j]$ pairs.
- For each of the 800 binary mixtures (and for the 100 single ink prints) the dot area coverage A for each ink component was computed from the TRC for that ink and the digital area coverage d.
- The Dimechel model (Equation 7) was used to predict the coverage areas of the primary and secondary colors. The reflectance data for the primary and secondary colors were taken directly from measurements.
- For each of the 900 prints the reflectance was predicted using the n-modified spectral Neugebauer-based approach (Equation 6).

The above steps were repeated with different values of n.

In the first part of the work the reflectance for the overlap region (where one ink dot is printed over another) or secondary colors was measured using the spectrophotometer. However, as was previously mentioned, for many practical applications of this work it would be too time consuming to measure the overlap color for all possible individual pairs of inks. Therefore, in the second part of the work a version of the Kubelka-Munk theory was used to predict the reflectance for the overlap regions.

The version of the Kubelka-Munk theory[11] that was used exploited the fact that the inks are not mixed together, but, rather, are printed in layers (one over the other). Thus, the first ink printed was treated as a colored, but opaque, substrate and the Kubelka-Munk theory was then used to predict the color of a layer of the second ink printed over the first. Since only eight binary mixtures were used it is necessary to predict the reflectance spectra for only eight overlap regions to be able to use these in the predictions (using Equation 6) for the 900 test samples.

Results

The performance of the *n*-modified spectral Neugebauer-based model was tested for different values of *n* (Figure 2) by computing the CIELAB color difference (illuminant D65 and 1964 standard observer) between the predicted reflectance and the measured reflectance for each of the 900 test samples. It is evident that the performance of the model increases with *n* but for large values of *n* the increase in performance levels off. For $n = 20$, the median color difference between the model predictions and the measurements was 2.73 and the maximum color difference was 9.02. Figure 3 shows the frequency distribution of CIELAB ΔE values for the case of $n = 20$.

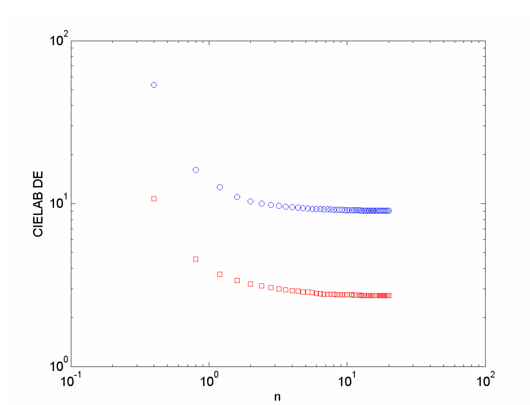

Figure 2. Effect of n on the median (squares) and maximum (circles) CIELAB ΔE values for 900 test samples using the n-modified spectral Neugebauer-based model.

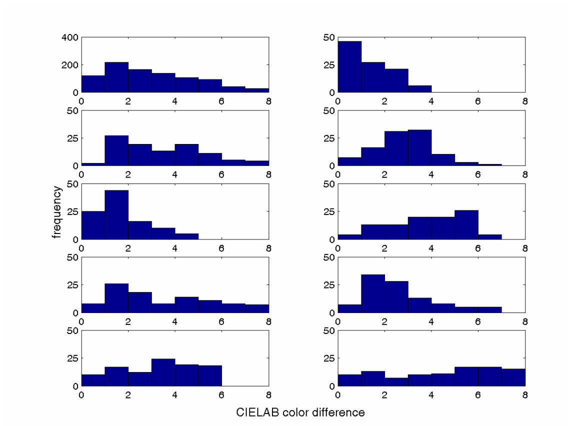

Figure 3. Frequency histograms (n = 20) for the combined test samples (top left pane) and for the nine binary ink pairs considered separately.

Figure 4 illustrates the predicted reflectance spectra for the overlap areas using the Kubelka-Munk theory. The CIELAB color differences between the measured and predicted reflectance spectra of the eight overlap regions ranged from 1.77 to 10.43 with a mean value of 4.20. Although the performance of the Kubelka-Munk model is relatively poor for one of the samples, the effect of using the model to predict the overlap reflectance spectra might be expected to be relatively small on the overall model since the overlap region is only a fractional part of the total area. Indeed, when the Kubelka-Munk model is used in the *n*-modified spectral Neugebauer-based model (with $n = 20$) the overall errors increase only marginally.

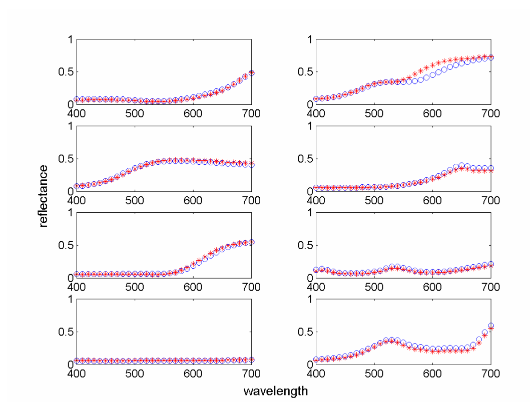

Figure 4. Reflectance spectra of the eight overlap regions, measured (circles) and predicted (stars) using the Kubelka-Munk theory.

Table 1 shows the performance of the *n*-modified spectral Neugebauer-based model both using the measured overlap reflectance spectra and those predicted by the Kubelka-Munk model.

Table 1. Color difference statistics for the n-modified spectral Neugebauer-based model using measurements and estimates for the overlap reflectance

	Mean ΔE	Median ΔE	Maximum ΔE
Neugebauer-based Model ($n = 20$) using measurements of overlaps	3.02	2.73	9.02
Neugebauer-based Model ($n = 20$) using K-M	3.56	3.40	10.79

Although the difference between the use of measured values and the use of values predicted by the K-M model for the overlap reflectance is small, it is statistically significant ($p < 0.01$) using the Wilcoxon Matched-Pairs Signed-Ranks test.[12] Note that this statistical test is non-parametric and therefore does not rely upon the color differences being normally distributed.

Discussion

The Neugebauer model has been applied to the prediction of reflectance for a set of half-tone prints on a ceramic substrate. Performance of the n-modified spectral Neugebauer-based model[10] increased with the size of n but stabilized at about $n = 20$. For $n = 20$, the model gave a median CIELAB ΔE of 2.73 (maximum ΔE = 9.02) when tested on a total of 900 samples of which 800 were binary ink prints. Although the value of n should, according to theory, be between 1 and 2, other studies have also found optimal values of n much greater than 2. A possible reason for the large value of n observed in this study is that the dots may not have sharp edges, but rather, the thickness of the ink may slope off towards zero. It is also possible that the Neugebauer-based model is not a good description of the behavior of inks when printed on a ceramic surface which will have very different surface properties than a typical paper substrate. However, average ΔE values of around 2 CIELAB values would probably give an acceptable performance when printing an image on a ceramic base (it is known that for images, as opposed to spatially uniform stimuli, the magnitude of ΔE that is visually acceptable is between 3 and 5 CIELAB units).[13] A Kubelka-Munk model was developed that treated a binary ink mixture as a translucent ink printed on a colored, but opaque, background. The average color difference of this model, when tested on a small number of samples, was around 5 CIELAB units. However, when used in the n-modified spectral Neugebauer-based model the effect of replacing direct measurement of overlap colors with predictions using a Kubelka-Munk model was relatively modest (though statistically significant) with an increase in the median color difference from 2.73 to 3.40. It would be possible to extend the Kubelka-Munk to deal with prints that contain 3 or more color separations. It might be expected that the effect of replacing direct measurements with Kubelka-Munk predictions would be more serious for prints where the area of the overlap region is high (for example, with dot-on-dot printing) or for dark prints.

Acknowledgment

The authors wish to thank Typemaker Ltd for a research grant that partially funded this work.

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