Spectral Digitization of Color Photographic Paper Through Dye Density Estimation

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Abstract

A methodology has been developed to digitize images from photographic color paper (reflection prints) and store the spectral information as a function of the three dye density basis functions inherent to the paper film type. The result is a highly accurate digitization of the spectral information at each spatial pixel that can be digitally stored with very little additional storage space over conventional RGB-type methodologies.

Introduction

Color film (chromes, negatives, and paper) are composed of three distinct dyes (cyan, magenta, and yellow). Each dye has unique spectral absorptance characteristics (or analytical density) and these curves are readily available from the film manufacturers. If these dye density curves are not available *(e.g.* old undocumented film), we have also developed a methodology to determine the curves from a small number of spectrophotometric measurements.

Our previous publications[1,2] introduced an alternate standard for photographic film (or prints) digitization based on the estimation of the dye concentrations for each pixel of the film rather than the color (XYZ or RGB). Thus, for each pixel the spectral transmission of the film is encoded by the storage of two types of information: 1) the analytical densities of the dyes, which must only be stored once for each film; and 2) the dye concentrations for each pixel of each frame. As a starting point we assume the film or print accurately obeys Beer's law (this is not correct for reflection prints; thus the reason we transform reflection space density measurements to transmission space). That is, we assume:

$$\tau(\lambda) = 10^{-\left[d_0(\lambda) + d_c \cdot c(\lambda) + d_m \cdot m(\lambda) + d_y \cdot y(\lambda)\right]}$$

where $d_0(\lambda)$ *is* the minimum absorption density of the film, $c(\lambda)$, $m(\lambda)$, and $y(\lambda)$ represent the spectral absorption densities of the cyan, magenta, and yellow dyes, respectively (called "dye density curves" by the film manufacturers), and the numbers d_c, d_m, and d_y represent the concentrations of each dye. Using the dye density curves as basis functions, we can then digitally store values c, m, and y for each pixel and recontruct the spectral distribution accurately.

Our published results to-date[1,2] have primarily dealt with transmission film types (chromes and negatives). With these type of film we have shown color characterization of $\Delta E < 0.1$. The excellent results from our measurement and data storage methodology, encouraged us to study the more complicated problem of color digitization of color paper (reflection prints).

Discussion

Accurate color digitization for reflection prints is a much more difficult problem; the:

- transparent coating on the paper has an index of refraction much different from unity (*i.e.* 1.53),
- paper backing is not a totally lambertian reflector nor a perfect reflector,
- each photon that ultimately is received at a sensor passes through the dyes at least twice (once going in and once more after reflection from the paper), and may pass through many times
- reflection coefficient from the paper is not constant across all visible wavelengths.

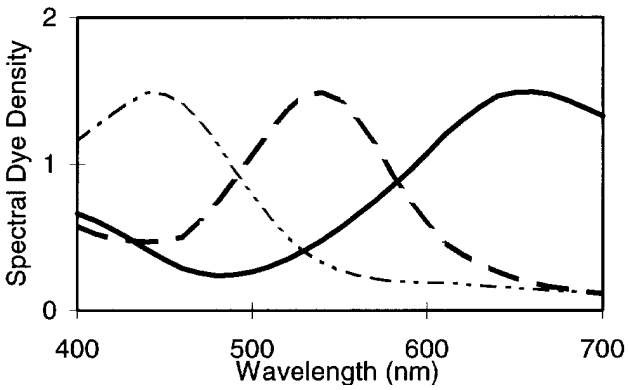

Figure 1. Kodak supplied dye density basis functions for Ultra-II paper. The three curves are the analytical dye densities for each of the three film dyes.

All of these issues (and others) result in a highly non-linear problem. However, in order to accurately digitize color reflection prints, it is necessary to determine the density of each of the dyes in the film. We have developed a methodology to translate from reflection (non-linear) to transmission (linear) density space. The methodology has two parts: (1) empirical fitting polynomial at very low densities of the data to a fourth order

and (2) raytrace analysis for high densities based partly on Fresnel's Equations.

In 1962, Pinney and Voglesong published[3] a paper defining a fourth order polynomial to translate from reflection density to transmission density. The coefficients of the polynomial were based on empirical, experimental results. Our work is based not on experimental results but on estimation theory. We employ a least squares methodology to minimize the error between actual spectral measurements and a linear combination of dye density curves (in transmission space—not reflection space). We define a non-linear transform that maximizes the power of three basis functions obtained using a KL (Karhunen and Loeve) transform[4]. The coefficients we derive match very closely with those of Pinney and Voglesong—an interesting conclusion given that our data is based on current (1995) film paper and their's was based on 1962 film paper. The curves are valid only to a reflection density of ~1.5, only because the 1962 paper did not extend the analysis beyond D = 1.5. Our derived curve fit is shown in the equation below:

$$D_t = -0.014 + 0.1116D_r + 0.2801D_r^2 - 0.09D_r^3 + 0.011D_r^4$$

At higher densities, we have found that a raytrace program we have written matches quite well up to high densities (~2.4). The program is based on Fresnel's Equations along with optical reflection estimates at each surface of the paper/coatings. In effect, the only variable parameters are the:

- index of refraction of the coating,
- paper reflection,
- variation in Lambertian scattering on paper surface, and
- coating surface BRDF that results in scattering from the light source into the detector.

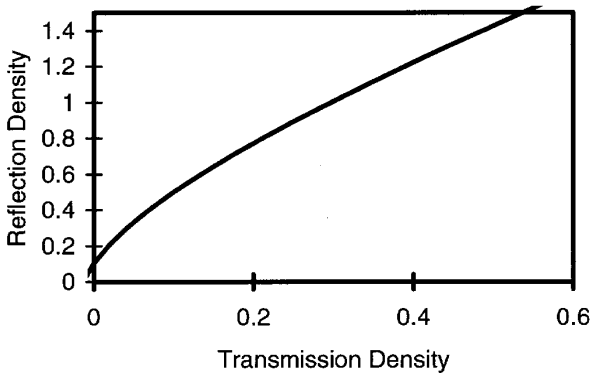

Figure 2. Predicted translation from reflection density to transmission density based on estimate theory and error minimization. It assumes a functional form given in Reference 2.

We have found extremely good agreement with the only problem areas at extremely high densities (>2.4) in the yellow and cyan. However, we are currently studying these problem areas and believe that at the short wavelengths there is a spectral dependence on paper reflection and at the long wavelengths there is a spectral dependence on the BRDF scattering from the coating surface. The results are discussed in the next section below.

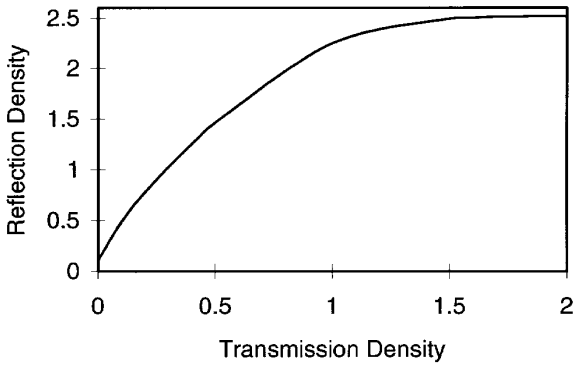

Figure 3. Raytrace model results using Fresnel's Equations and best fit parameters. At high to mid densities, the prediction is quite good. At lower density the Figure 2 curve gives slightly better results.

We are currently studying other modification to the raytrace analysis to give more accurate prediction at low densities. While the predictions are good, they are not as good as the empirical least squares model described above. The intent is to develop one raytrace model with only a few adjustable, measurable parameters that is accurate at all densities. Currently, the raytrace model can be summarized by the equation below (all angles are in degrees), where the

- $Fr(\theta)$ is the Fresnel factor
- T0 and T45 are the transmission fractions at zero and 45° (our measurement instrument is a Gretag SPM55 which has a 45/0 measurement geometry),
- 1.53 is the assumed index of refraction,
- 41.1 is the critical angle inside the film's transparent coating,
- DT is the transmission density,
- 27.7° is the light angle within the transparent coating of a 45° externally incident light,
- 0.895 is the assumed paper reflectance,
- 0.002025 is an assumed parameter to give a maximum reflection density of 2.5,
- 1.19 assumes that the paper reflection within the critical angle is 19% higher than Lambertian, and
- 0.81 is 1-19%.

Results

Figures 4, 5, and 6 show the results of our analysis. In each figure, the

- upper solid curve is the actual measured reflection density;
- lower solid curve is the predicted (from the above described methodology) transmission density;
- lower dashed curve is our best spectral match to our estimated three basis functions; and finally
- upper dashed curve is our translation from our best transmission space spectral match to reflection space (from the above described methodology).

Reflection Density =

$$-\log\left[\frac{\frac{T0\cdot T45}{1.53^2}10^{-\left(1+\frac{1}{\cos(27.7)}\right)DT}\cdot 1.05}{1-0.895\left\{1.19\int_0^{41.1}Fr(\theta)\cdot 10^{-\frac{2DT}{\cos(\theta)}}\cdot 2\cdot\cos(\theta)\cdot\sin(\theta)\cdot d\theta+0.81\int_{41.1}^{90}10^{-\frac{2DT}{\cos(\theta)}}\cdot 2\cdot\cos(\theta)\cdot\sin(\theta)\cdot d\theta\right\}}+0.002025\right]$$

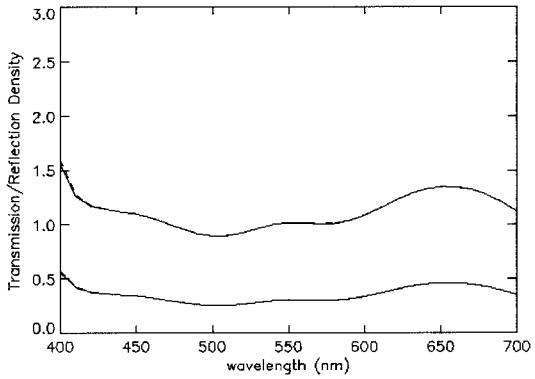

Figure 4. Medium density example showing excellent agreement between methodology and actual measurements

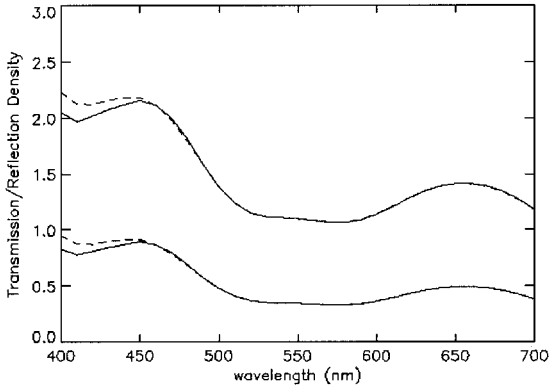

Figure 5. High density example illustrating that our methodology is incomplete at densities greater than ~2

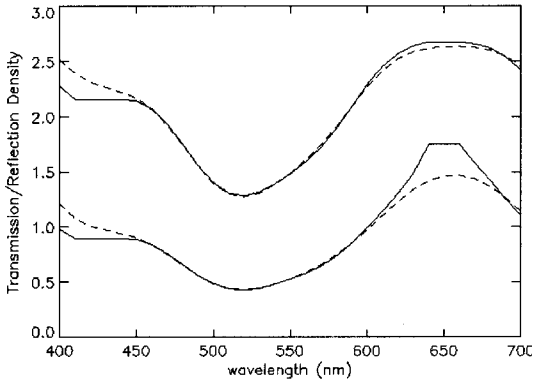

Figure 6. Very high density example illustrating that our methodology over-predicts in the blue and under-predicts in the red regions (while not shown the high density green matches very well). Implication could be a wavelength dependence not yet incorporated into the methodology.

The colors used to present the data in the figures are representative of mid, high, and very high densities, respectively.

As can be seen for reflection densities less than ~2, our analysis methodology predicts quite well the transmission and reflection densities. At reflection densities greater than ~2, the methodology does not perform well. We believe this is because our model does not account for parameters being a function of wavelength (*e.g.* paper reflection, surface scattering). Note in particular that our methodology over-predicts the density in the blue region, under-predicts the density in the red region, and (while not shown) has an excellent match in the green region.

Our future efforts are to incorporate wavelength dependence into our model and to improve the raytrace modeling at lower densities. Accurate theoretical modeling with fitted parameters should results in a sound basis to extrapolate this work to other paper and film types. With this in mind, more accurate color photographic film and paper digitization and reproduction is possible in the near future.

Concluding Remarks

We have developed a methodology to digitize color film as a function of dye densities. To ensure accurate color digitization of reflection prints, we have developed a relatively simple transformation from reflection to transmission densities that is a function of measurable quantities such as index of refraction and paper reflectance. Our methodology essentially linearizes the color digitization issues associated with reflection prints. This linearization allows for more accurate dye concentration estimation and consequently more accurate color digitization of reflection prints.

Acknowledgements

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