A Method to Separate Ink/Paper Interaction Effects from Halftone Effects in the Study of Inkjet Prints

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Abstract

The development of analytical models that predict measured reflectance spectra of halftoned printing has progressed for over half a century. Most of the published work has focused on the contribution of the halftone pattern to the measured reflectance, either through the development of the half-toning algorithm itself, or through the optical and physical dot gain resulting from the process. However, the non-ideality of the ink/paper interaction is also a key contributor to the measured reflectance. This non-ideality is partially addressed by perturbations to existing models, such as the cellular Neugebauer equations, or more directly with Kubelka-Munk descriptions. These effects can be especially large in inkjet printing, as the round ink dots require overlap and therefore variable ink laydowns across even a single-color nominally constant density patch, something that is not true of graphic arts printing. This work illustrates the contribution of the ink/paper interactions to the measured reflectance, and describes a workable method to separate the ink/paper effects from the halftone effects, to allow the direct study of the ink/paper interaction. The inks are applied in continuous layers using hand-coating rollers, and the ink laydowns are quantified by weighing under carefully controlled conditions. Finally, we demonstrate with reflectance measurements that the half-tone effects are removed, and the remaining unusual spectral features reproduce those seen in inkjet prints.

Introduction

Models designed to predict the color output of halftone printing systems have been studied for over 60 years, most building on the Murray-Davies equation first published in 1936.[1] Such models typically predict the spectral reflectance of a printed area, given input values for the inks to be printed, and are utilized in color calibration or system development. The inaccuracy of these halftone color models has led to continued extensions and improvements over the last six decades.

$$R_T = a_i R_i + a_s R_s = a_i R_i + (1 - a_i) R_s \qquad (1)$$

Murray-Davies and Neugebauer Models

The first successful halftone model, formulated by Murray, is shown in Eq. 1. It simply states that the total light reflected from a printed region (patch) is the sum of the light reflected from the unprinted paper (substrate): the reflectance of unprinted substrate (R_s) scaled by the fraction of the region with bare substrate showing (a_s); and the light reflected from the printed area: the reflectance of the full coverage ink (R_i) weighted by the fractional coverage of the ink (a_i). Neugebauer extended the Murray-Davies model to color printing the following year (Eq. 2).[2] The Neugebauer equation reflectance values (R_i), called Neugebauer primaries, are measured from the full coverage printed patches, and the fractional coverages (a_i) are calculated using the Demichel equations (assuming random laydown of ink spots) and the coverage of each individual color ink. The model is appealing in its simplicity, as the 8 Neugebauer primaries (cyan (c), magenta (m), yellow (y), black (cmy), red (my), green (cy), blue (cm) and white (paper or substrate)) are the only colors that an ideal 3-color press can produce (16 colors for a 4-ink press), and these primaries can be quickly printed and measured for a given ink set and receiver. The model predicts a system that can only produce reflectance spectra that are linear combinations of these Neugebauer primaries.

$$R_T = \sum_{i=1}^{8 or 16} a_i R_i \qquad (2)$$

Nonlinearity from Optical Dot Gain

Although the above models are simple and intuitive, it was soon found that the measured reflectance of printed patches was consistently lower than that predicted by Eqs. 1 and 2. The prints behaved as if the dots printed were larger than what was intended, giving rise to the term dot gain. Some of this gain is due to actual spreading of the ink on the receiver (mechanical or physical dot gain), but when the actual size of the dots is carefully accounted for, the measured reflectance is still less than that predicted by the actual size dots. Optical dot gain arises from light that impinges upon the unprinted substrate in a printed sample, scatters within the substrate below the ink, and exits the sample through a printed ink area, and vice versa. The body of literature dealing with the optical dot gain effect can be divided into three main categories: empirical, probability or first principles approaches.

Some approaches have been purely empirical, the best known of which is the Yule-Nielsen equation[3] (Eq. 3). This approach fits measured data using a single exponent "n", the Yule-Nielsen parameter. This parameter has been shown to be dependent upon a wide range of factors, including screen ruling, dot size and shape, paper spread function, and area coverage. This model successfully corrects some of the nonlinearity in the data, but gives little or no explanation as to the dependence on the materials and printer, and still does not explain all of the nonlinearity.

$$R_T = \left[a_i R_i^{1/n} + (1 - a_i) R_s^{1/n}\right]^n \qquad (3)$$

The second approach describes optical dot gain using a probability description. The initial work was done by Huntsman,[4] and was later greatly extended by Arney and coworkers,[5] based upon the observation[6] that reflectances of white paper and inked regions are functions of their fractional coverages. Equation 1 applies once again, except R_i and R_s are not constant, measured values, but must be calculated as a function of a_i. The dot edge hardness is also included in this model, and the screen ruling, dot size and shape, paper spread function, and area coverage are included more specifically. This semi-empirical model does not, in general, fit the measured reflectance data any better than the YN equation, but does give significantly more insight into the physical workings of the system.

The third general category of optical dot gain research is the first principles approach taken by Kruse and coworkers.[7] They have expressed the reflectance as the convolution of the paper spread function with a description of dot location and ink transmittance. This approach is potentially more accurate, and certainly more informative for design of ink/paper systems, but the computational cost to accurately fit the data is currently prohibitive.

All of these attempts to correct for optical dot gain fall short of accurately describing the color produced in an actual printed patch. This is to be expected, as there are other nonlinearities in the printing process, in addition to optical dot gain.

A different, more general approach to describing the nonlinearities of the color space of the output of a color printer is to empirically generate additional "Neugebauer primaries" by printing and measuring sample patches in addition to those of 0% and 100% coverage of each ink.[8,9] This effectively allows interpolation in smaller areas of color space, thereby reducing the magnitude of errors caused by nonlinearity of the system, without describing any of the sources of this nonlinearity. The downside of this approach lies in the loss of insight into the behavior of the system, and the large increase in the number of patches that must be printed and measured in order to apply the method. Other approaches[10] such as regressing the Neugebauer primaries to minimize the error in a training set, and combinations of all the above methods, have been used to further improve the description of measured data sets.

Additional Sources of Nonlinearity

Additional inherent sources of nonlinearity in halftone systems that limit each of these models are usually assumed to be small. Most printing inks/receiver systems are non-ideal, in that the ink reflectance density is not a linear function of the amount of colorant printed. The Neugebauer model skirts this problem, by assuming that the laydown of a given ink is constant wherever that ink is printed. This assumption fails to varying degrees, depending upon the printing method used. For example, in lithographic printing, the ink is often thicker near the perimeter of the printed area than in the middle. Therefore, the true "Neugebauer primaries" change across the dot, and the net reflectance of a dot is a function of dot size. This effect is confounded with the optical dot gain effect in halftone prints, and both are treated together, for example, in the cellular Neugebauer model.

The ink non-ideality is likely to be a much larger contributor in non-impact printing than in traditional graphic arts applications, due to the required overlap of round dots printed on a square grid. A sizable fraction of the area of a nominally constant colored inkjet patch can have multiple layers of ink overlapping. Several publications[11] have described a dot-overlap-model or printer model, which describes the overlap of dots in non-impact printing, but the purpose of these models has been to describe the fractional coverage of unprinted substrate, and of multicolor areas. The region of overlap of two dots of the same color has been assumed to have the same reflectance as the original dots. This assumption has not been adequately tested.

The non-ideal behavior of colorants, mostly dealing with pigmented paints, has been described using Kubelka-Munk theory.[12] Kang applied this to printed ink on paper in one publication,[13] and Arney used this description to explain deviations from his probability model in at least one case.[14]

The purpose of this paper is to describe a method that can be used to separate effects arising from the halftone nature of the print, specifically optical dot gain, from those effects that arise from ink/paper interactions. The separation is achieved by coating inkjet inks on inkjet receivers, in uniform layers of controllable thickness. The laydown of ink needs to be quantifiable, and the reflectance density uniform, across a defined area. Various properties of these coatings can be compared with inkjet prints utilizing the same inks and receivers. We will demonstrate the capability of making and characterizing useful coatings of this sort.

Experimental

Coatings of pigmented and dye based inkjet inks were applied to three different receivers: a photoglossy inkjet paper (*glossy*), a clay-coated inkjet paper (*CC*), and a standard laser printer paper (*LP*), using an anilox, hand-coating roller from Pamarco, Inc. A range of laydowns of the inks was obtained by applying multiple coatings, one layer at a time, with a short time for partial drying in between coatings.

Quantifying the ink coated is a difficult problem, as the change in weight of the strips of receiver with changes in the relative humidity can be greater than the total dry weight of ink coated. This problem was overcome by weighing the strips in a constant environment room. Uncoated strips were allowed to equilibrate in the controlled environment room (23 ± 0.4 °C/50 ± 1% RH) before being tared on a Mettler Toledo balance. The strips were coated, and returned to the controlled environment room to dry and equilibrate, during which time they were weighed frequently to quantify the equilibration process. The final weight increase for each strip was divided by the area of the coated patch to yield dry ink laydown. The same procedure was applied to patches printed by an Epson Stylus Color 900 ink jet printer. 100% red areas were printed on tared *LP* and *glossy* media, each paper printed using "photoglossy" and "plain paper" settings from the Epson print driver. The 100% red was chosen to give a laydown near the upper limit that the printer would apply. These prints were allowed to dry and equilibrate, dry ink weight was measured, and laydown calculated.

The uniformity of the ink coatings was studied by measuring multiple reflectance density spectra (at 40 uniformly spaced sample areas) of representative samples of the hand coated strips and the inkjet printed sheets using a Gretag Macbeth Spectrolino/Spectroscan spectrophotometer.

Results

Equilibrium Rate

Figure 1 shows the equilibration / drying process for receiver strips having 1, 2, 5, and 10 layers of dye-based ink coated on *glossy* (A) and *LP* (B) media. In each case the symbols are the measured weights of the inked strips (averaged for three strips), from which the weights of uninked strips of like material have been subtracted to account for slight changes in the controlled environment room. The lines in Fig. 1 are fits using the parameters listed in Table 1, and described below.

The *LP* receiver drying is well described with a single exponential weight loss, with the "Δ ink weight" approaching the dry ink weight. The *glossy* receiver drying curve requires a fast process in addition to a slower process, similar in rate to that found for the *LP* receiver. The reason for the difference in kinetics was not explored, however, the *LP* receiver is homogeneous throughout, while the *glossy* receiver has a paper base coated with several additional layers. The more complicated structure may be responsible for the two-phase drying kinetics.

Despite the different drying kinetics, the two receivers are both well behaved, and the final dry laydowns of the ink are reliably obtained, and listed in Table 2, along with the laydowns from the inkjet prints. Note that less ink is transferred to the *glossy* receiver, in comparison to the *LP* receiver, probably because of the smoother, less porous surface of the *glossy* receiver.

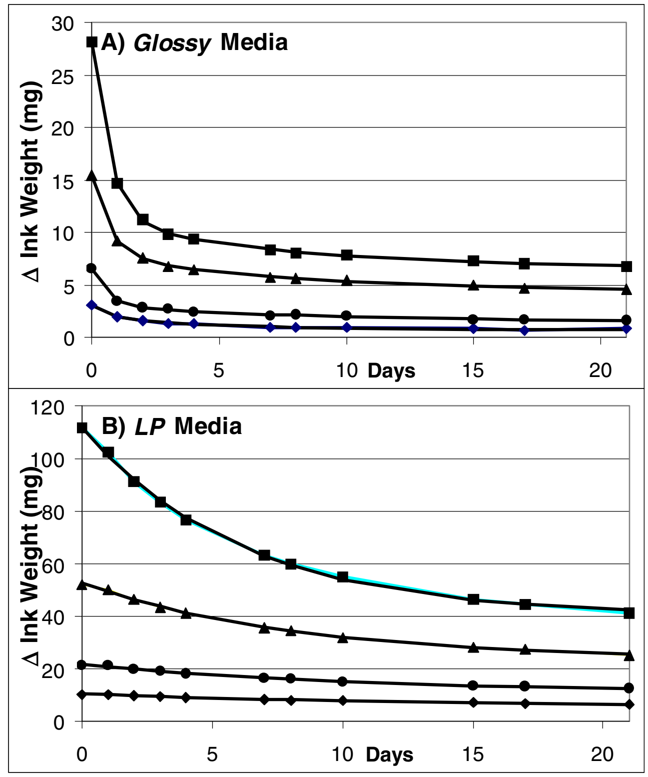

Figure 1. Weight of ink coated on glossy *(top) and* LP *(bottom) receiver as a function of time, during equilibration / drying. Data points are shown for 10 layers (■), 5 layers (▲), 2 layers (●) and 1 layer (◆), and the solid line is fit to the data as described in the text.*

Table 1. Drying / Equilibration of Coatings

Number of Layers	Fast Drying Rate (day^{-1})	Fast Weight (mg)	Slow Drying Rate (day^{-1})	Slow Weight (mg)	Dry Ink Weight (mg)
		***Glossy* Receiver**			
1	-1.58	1.14	-0.23	1.22	0.74
2	-1.76	3.54	-0.11	1.59	1.44
5	-1.46	7.59	-0.12	3.53	4.31
10	-1.42	16.96	-0.13	4.61	6.55
		***LP* Receiver**			
1			-0.09	4.62	5.75
2			-0.09	11.04	10.55
5			-0.12	29.48	23.06
10			-0.16	72.15	39.72

Table 2. Measured Dry Ink Laydowns

Sample Description	Dry Ink Laydown (mg/cm^2) *Glossy* Receiver	*LP* Receiver
1 Layer Hand Coating	0.0077	0.0596
2 Layer Hand Coating	0.0148	0.1088
5 Layer Hand Coating	0.0444	0.2390
10 Layer Hand Coating	0.0679	0.4086
100% Red Inkjet Print "Plain Paper" Setting	0.2527	0.2135
100% Red Inkjet Print "Photo Paper" Setting	0.1967	0.1385

Laydowns of Hand Coatings vs Inkjet Prints

Figure 2 shows the ink laydowns for *LP* receiver, from Table 2, plotted for each number of layers. The ink laydowns from the inkjet prints have been plotted on the same curve. Note that measurably different ink laydowns are produced depending on driver settings. For the *LP* receiver, the 100% red laydown is equivalent to roughly 2.5–4.5 layers of hand-coated ink, depending upon driver setting, while the printed sample on the glossy receiver has a greater laydown than the 10 layers hand coated on the same media. Note that the ink distribution on the inkjet prints are not uniform, so some areas of the printed region have ink laydowns greater or less than the previously mentioned 2.5-4.5 hand-coated layers.

Uniformity

Table 3 shows the spatial uniformity of roller generated and inkjet printed samples, using dye-based inks. The standard deviation of a single wavelength reflectance density measured at 40 positions across the sample is calculated as a percentage of the average density at that wavelength. The calculation is repeated at 10 nm intervals, and the percent standard deviation is averaged across the visible spectrum and listed in Table 3. The hand-coated samples are seen to be only slightly less uniform than the printed samples.

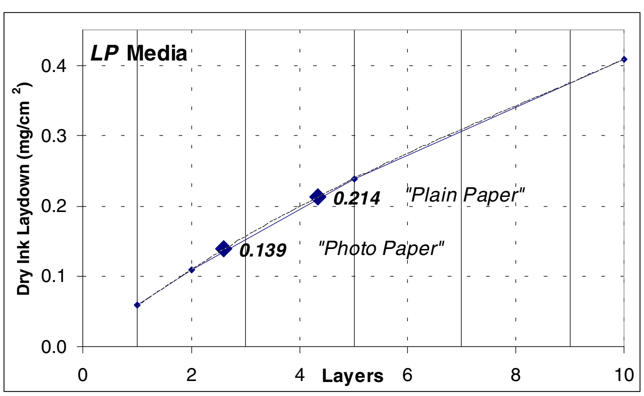

Figure 2. Dry ink laydowns (♦) of hand coatings of dye based ink on LP receiver. The laydowns for the 100% red inkjet print using the same ink and receiver are plotted (♦) on the same curve. For the glossy media the inkjet laydowns are equivalent to greater than 10 layers. See text for details.

Table 3. Uniformity of Hand Coatings and IJ Printers

Method	Receiver	Standard Deviation
Roller	*CC*	1.96%
Roller	*glossy*	2.42%
Roller	*LP*	2.16%
IJ (low laydown)	*glossy*	1.53%
IJ (high laydown)	*glossy*	1.74%

Comments on Usability and Limitations

An example of the use of these hand coatings is shown in Fig. 3. The reflectance density spectra are plotted for a range of laydowns of a pigmented cyan ink on *CC* receiver, generated with an inkjet printer (dashed lines), and by hand coatings (solid lines). The unusual spectral shape at high laydowns are clearly reproduced with the hand coatings, while the differences in peak widths at lower laydowns can be shown to be due to the reflectance of the paper in the inkjet print. Therefore, the hand-coating technique successfully generated samples having a uniform distribution of desired inks, the properties of which can be studied in the absence of halftone effects.

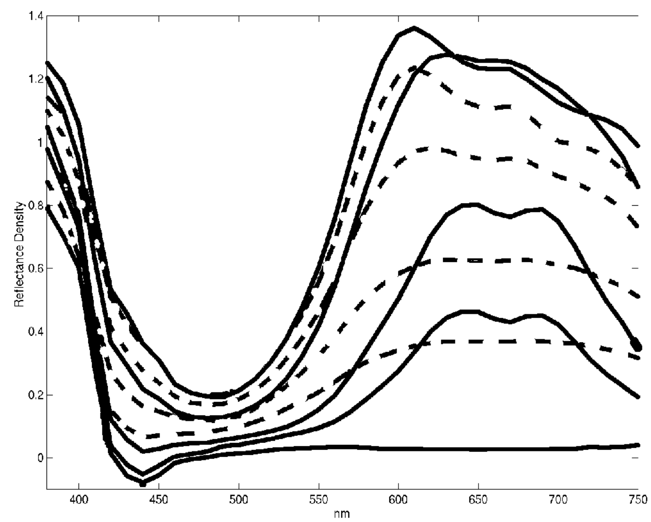

Figure 3. Reflection density spectra of a range of laydowns of pigmented ink on CC receiver printer with inkjet printer (dashed and coated with hand roller (solid).

The utility of this method is slightly limited by three factors. The experiments are time consuming, and require some skill to generate the coatings. The time lapse between successively applied layers of ink is significantly different than between drops from an inkjet printer, meaning some differences may arise because of the different processes. Finally, for some glossy media, it is difficult to reach the full laydown levels achieved with the inkjet printer.

Conclusions

We have shown that we can generate uniform samples of inkjet inks on inkjet receivers, with similar ink laydowns to those produced by inkjet printers. With careful work, the ink laydowns can be quantified for further study. These samples allow one to study the nonlinearity in halftone color models that arise from ink non-ideality, independently from the nonlinearity that arises from halftone effects, such as optical dot gain.

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Biography

Richard Reem received his B.S. degree in Chemistry from the University of Illinois in 1981, and Ph.D. in Inorganic Chemistry from Stanford University in 1986. His research efforts involved spectroscopic studies of Bioinorganic systems. He has worked at Eastman Kodak Company research labs since 1986, working first on spectroscopic studies of pharmaceutical products, then working on photographic systems and new product concepts, before moving on to the inkjet modeling field. E-mail: richard.reem@kodak.co