Sparse Cellular Neugebauer Model for N-ink Printers

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Abstract

The number of colorants used in printers is growing to improve quality of the prints in terms of gamut size, grain and metamerism. In this paper we demonstrate a modification to the existing models (Cellular Neugebauer Model, with Yule Nielson Correction) to simulate spectral reflectance of an N-ink printer. This is achieved by imposing a constraint for the media ink limit, the modified model is shown to reduce the required number of training points by as much as 97 percent. Imposing this constraint leaves us with sparse training data set and the modified Yule-Nielson Neugebauer Spectral model is shown to handle the sparse data well with average error of 1.48 ΔE_{94}.

In this paper, two standard dot placement models (Dot-on-dot v.s. Demichel) are implemented and compared.

Introduction

Color printers with low number of inks (4 or 6) can be metameric and have limited color gamut. Previous work done by Kohler and Berns 0 and Tzeng [2] and Tzeng and Berns [1] used a larger number of inks to minimize metamerism. In these papers it was shown that reflectance of an ink combination could be predicted accurately using a modified Yule-Nielsen Spectral Cellular Neugebauer (YNSCN) model. One of the main challenges with the Yule-Nielsen Neugebauer model is that the computational complexity grows exponentially with number of inks. One approach by Taplin and Berns [3] was to developed a color reproduction model for 6 color inkjet by combining 10 4-color Neugebauer models.

In this paper we introduce a modified YNSCN model developed to model an N-color printer. Its computational complexity is compared on an 8 ink printer. By imposing a media ink limit constraint, the modified YNSCN model is shown to reduce the required number of training points by as much as 97 percent. In this paper, two standard dot placement models (Dot-on-dot and Demichel) are implemented and compared. Also the effect of linearizing the sampling space based on CIELAB color variation and spectral variation is studied.

When applying the proposed ink limit constraint to the printer model it will result in the reduction of the number of training points, this reduction leaves the model with a sparse matrix of training data. The modified YNSCN model is shown to handle the sparse data well with average error of 1.48 ΔE

Yule-Nielsen Spectral Modified Neugebauer Equation

The Cellular Neugebauer Model is essentially an interpolation within a set of test patches that cover the printable colorant space. The interpolation is based on the neighboring points of the hypercube surrounding any requested index, and is generally based on one of two standard dot placement models (Demichel and Dot-on-Dot), both of which have equations that can be extended to n-dimensions.

In this paper, the YNSCN model is used and modified to handle large data of ink combinations. YNSN model is defined below for an N-color:

$$\widetilde{R}_\lambda = [\Sigma W_i R^{1/n}{}_{\lambda,i}]^n \qquad (1)$$

Where the weights Wi are computed using the Demichel or dot-on-dot equations, n is the empirical value for Yule-Nielsen model to correct for physical and optical dot gain, and $R_{\lambda,I}$ is the spectral reflectance of the ith primary. For more information we would like to refer the reader to reference [13].

It has been shown that in order to improve Neugebauer model performance, one can provide more primaries within printer gamut. This approach is called Cellular Neugebauer, which was shown by Heuberger [8] and others [4],[9].

Reducing Complexity of Cellular Neugebauer Model

The Cellular Neugebauer model is based on sampling a subdivision of the Neugebauer primaries. For instance, if we have N inks with K samples along each of primary axis, we must print and measure K^N training patches to use in the model. This means the number of patches grows exponentially with the number of inks used in the printer. For instance for an 8 ink printer, to sample only 4 samples along primaries, would require 4^8 = 65,536 patches to print and measure for use in the interpolation.

To reduce the complexity of the model, we use two concepts: First, the printed patches are subject to ink limiting so only a small number of the potential patches actually need to be printed. Second, linearization of each ink before printing the test patches to keep the Neugebauer cells of a uniformly spaced and further reduce the necessary number of steps per colorant.

Linearizing Training Patches

In essence the Cellular Neugebauer model is a piecewise linear model, and the Yule-Nielsen correction reduces nonlinearity related to dot gain, but does not capture all of the possible curvature caused by ink interactions, etc. Increasing the sampling size (printing more patches in each dimension) reduces the need for the YN correction. If cells are not printed using uniform perceptual steps with each ink, then the perceived cell spacing at one end of the space can be much larger than the other – and lead to a large color error. By printing patches that are linearly spaced in a perceptual color space such as CIELAB or CIECAM02, one can keep the perceptual spacing of interpolation cells roughly equal.

Ink Limiting

Printing substrates are commonly faced with a certain ink limit beyond which the page is too saturated to print – in the inkjet realm this leads to issues such as cockle, bleed, dry time and gloss uniformity. It is not reasonable to print and measure patches that violate the ink limit of the substrate media. This observation significantly reduces the complexity of the problem. By imposing the constraint that we do not need to print or measure patches that violate the ink limit, the number of data points to measure for the model can be reduced by up to of 97%.

In an inkjet printer, the maximum dispensable weight-per-unit-area W^i for each colorant i is defined by factors such as drop size, nozzles per inch, and number of passes. This value varies for each ink, and is generally between 50% and 100% of the overall media ink limit. Define the "percent under limit" for each ink i as $U_i = W_i$/InkLimit) for each ink.

Given the number of colorants k, the number of steps per colorant n, and the percent under limit U_i we can compute the complexity subject to the ink-limit constraint. For simplicity, assume that $U = \min(U_i)$ for all inks, which will error on the side of over-estimating the complexity.

First, consider the case where U = 1. This is the case where the printer is capable of delivering exactly the media ink limit with each ink individually. In two dimensions, the valid sample space is a triangle defined by (0,0), (n,0), (0,n) as shown in Figure 1.

In general, the space of printable patches can be represented by a k-simplex defined by the origin and the points along each colorant axis at a distance of n. The area of such a region is:

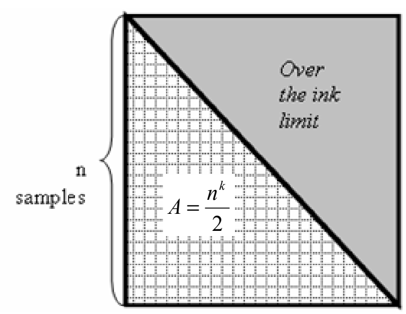

Figure 1: Valid Patches for 2 inks with U=1

$$A_{U=1} = \frac{n^k}{k!} \qquad (2)$$

Now, consider the case where U_i is between 0.5 and 1. In this case the valid space is a hyper-cube with sides of length n, and one corner removed by the ink-limit hyper-plane, as shown in Figure 2.

The volume of this region can be computed by calculating the area of the k-simplex formed by the ink-limit hyper-plane and subtracting the corners that are outside the printable hypercube, resulting in the following equation:

$$A_{U=(0.5,1)} = \frac{\left(n/U\right)^k}{k!} - k\left(n/U - n\right)^k \qquad (3)$$

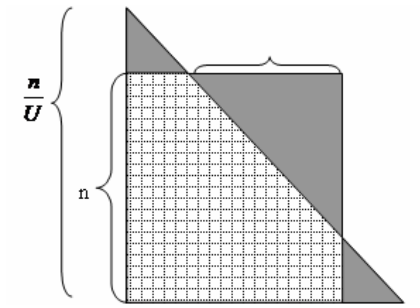

Figure 2: Valid Patch Space for ½ ≤ U ≤ 1

For values of U less than 1/k, the ink limited hyper-plane does not intersect the dispensable ink hyper-cube, so the complexity reverts to n^k. Computations for 1/k < U > 1/2 are more complex, and are not generally needed since the colorants are generally defined with U ≥ 1/2.

This constraint was implemented on two training sets, one on glossy photo media and the other on plain media. In the case of glossy media, 4 steps along the primaries on an 8 ink printer required 6048 patches – a reduction of 91% over n^k. On plain media, the same test required 2175 patches – a reduction of 97%.

The cause for the difference in savings between glossy and plain media was related a difference in the definition of the primary ink axes on those two media. One of the inks was not intended for use on glossy media, so its linearization table on glossy media was defined such that very little ink would be dispensed even at 100% fill. As a result, the U-value for that ink was very low and no clipping occurred in that dimension.

Handling Missing Points

The YNSCN model is based on interpolation between neighboring primaries, some of which may have missing data because of the ink limit constraint. This poses a challenge to the interpolation operation.

To enable the YNSCN model for N ink with missing neighbors, the weights for all neighbors are computed, the sum of weights for missing neighbors are recorded as a "missing score" or M-score value for each interpolated point. The missing weights are then set to zero and the remaining weights redistributed using a factor of 1/sum(weights) to re-normalize the sum back to 1.

To redistribute the weights more accurately, the original Neugebauer model is modified so that weights are calculated based on the linearized distance of the neighbors in CIELAB color space. For instance, if variation along Yellow primary is smaller than Gray primary, neighbors with gray primary will get a larger portion of the weights from missing neighbors.

Another method considered in this paper for handling missing points is to extrapolate Neugebauer primaries so that the training data set is populated enough to cover missing neighbors for a given data set. Spectral-reflectance of a missing point is predicted using linear interpolation of existing values along each Neugebauer primary.

In the result section, the correlation between the model error and the number of missing points is studies for each of the above three methods.

Data Collection

An 8 ink printer with the following inks was used to study performance of the model: Cyan, Magenta, Yellow, Light Cyan, Light Magenta, Black, Gray, and Light Gray. The results are based on 6048 patches for training and 939 patches for testing. The patches are printed on glossy media with ink limit either 1.5 or 2 drops of ink (depending on the ink type).

A GretagMacbeth Spectralino was used to measure the spectrum reflectance of the printed patches. 10nm sampling from 380nm to 730nm.

The Spectralino has an accuracy of around 0.30 ΔE_{94} between two different sets of measurements under D50 illuminant. The printer has an average 0.75 ΔE_{94} page to page variation (including instrument variation).

Results

Both Demichel [10] Dot-on-Dot [11] models were implemented. The Dot-on-Dot model assumes perfect dot placement during printing, whereas the Demichel equations assume a more random dot placement, which is more suited to ink-jet printers.

Three different methods for handling missing points in the model (missing neighbors) are implemented and studied. The three models are as follows: Distributing weights for missing neighbors with and without some linearization or extrapolating Neugebauer primaries to fill in missing neighbors. These three approaches are referred to as Lin=0, Lin=1, Extrap=1.

In all the experiments, a search was done to find the best Yule-Nielsen correction factor. The search is stopped if the prediction accuracy is within 0.10 ΔE_{94} for the subsequent Yule-Nielsen values.

shows accuracy of the model for both dot-on-dot and Demichel dot placement approaches. The result is shown both in ΔE_{94} and spectral RMS.

Table 1: YNSCN Performance for 8-ink printer with missing Neighbors. Mean, Max and Std represent average, maximum and standard deviation of error respectively.

		ΔE_{94}	RMS
Demichel, YN=5.2 Lin=0	Mean	2.43	0.0072
	Max	10.92	0.048
	Std	1.49	0.0057
Demichel, YN=5.1 Lin=1	Mean	2.31	0.0064
	Max	10.73	0.0613
	Std	1.34	0.00542
Demichel, YN=4.1 Extrap=1	Mean	1.48	0.0037
	Max	5.12	0.0284
	Std	0.81	0.00299
Dot-on-Dot, YN=7.5 Lin=0	Mean	8.54	0.0363
	Max	37.46	0.2848
	Std	5.42	0.0367
Dot-on-Dot, YN=7.3 Lin=1	Mean	7.87	0.0313
	Max	29.38	0.257
	Std	5.08	0.0326
Dot-on-Dot, YN=7.1 Extrap=1	Mean	3.00	0.00584
	Max	11.75	0.0471
	Std	1.56	0.00465

shows that YNSCN model has the best performance when Demichel dot placement model is used with extrapolation of Neugebauer primaries.

To understand effectiveness of each of the methods for handling missing neighbors, correlation between the number of missing neighbors and resulting error is studies. Table 2 and Figure 3 show the correlation between percentage of missing neighbors and error in the model for each of the 3 methods (Lin=0, Lin=1 and Extrap=1) based on Demichel dot placement model. The result shows that extrapolating Neugebauer primaries not even improves the YNSCN performance but also has a very low correlation between the number of missing neighbors and error (R^2=.38) .

Table 2: Correlation between missing score (percentage of missing neighbors) and error in the model (ΔE94)

Method	Correlation
No Extrapolation, No Linearization	.63
No Extrapolation, with Linearization	.48
With Extrapolation, No Linearization	.38

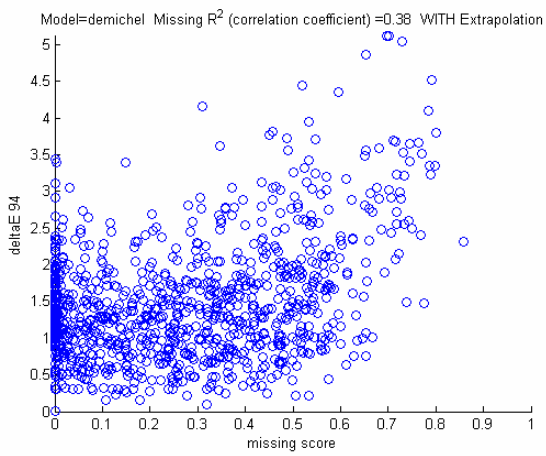

Figure 3: Correlation of Missing Neighbors and error for Extrap=1 method, R2=.38

Table ***3*** shows the top 10 ink combinations that the model (with extrapolation) had the worst error in prediction.

Table 3: Ink density for the 10 ink combinations with highest prediction error in ΔE_{94}

C,M,Y,CL,ML,g,G,K	RGB	ΔE_{94}
4,121,147,139,133,34,36, 2	83,70,60	5.12
4,16,8,7,3,58,11,1	160,165,171	5.12
4,82,126,177,126,6,11,3	77,87,81	5.04
25,162,129,166,25,37,5,3	73,70,71	4.86
9,215,156,134,0,6,0,3	96,66,64	4.51
233,77,141,20,9,19,88,5	25,62,63	4.44
72,5,61,30,16,118,36,3	74,98,89	4.36
31,153,113,119,128,43,5,5	81,65,71	4.16
20,5,70,15,44,86,5,9	113,119,99	4.10
62,26,32,43,41,27,16,6	100,121,133	3.95

Conclusion

A modification to Yule-Nielsen Spectral Cellular Neugebauer model for printers with large number of inks is presented. It is shown that by imposing ink limiting constraint the number of measurement points can be reduced substantially (around 95%). Three different methods are studied to handle missing points because of ink limiting. Performance of these methods is presented on an 8 ink printer. It is shown that extrapolating Neugebauer primaries has the best performance.

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