Spectral Reproduction--- How Many Primaries Are Needed?

Behnam Bastani*, Brian Funt**, Jeffrey DiCarlo, *Hewlett-Packard Company, San Diego, USA **Simon Fraser University, Vancouver, Canada, ***Hewlett-Packard Laboratory, Palo Alto, USA***

Abstract

Reducing metamerism is one of the main goals of spectral printing. There are three fundamental questions to answer in spectral reproduction:

1. What is the optimal number of primaries?

2. Which types of primaries to use?

3. How to find the ink combination that replicates a given spectral reflectance as closely as possible for a given set of primaries?

This paper focuses on the first question. We evaluate the extent to which metamerism is reduced as more and more inks are used. The study considers both a realistic printer and a realistic additive displaysr with both idealized and actual ink reflectances.

Introduction

One of the main goals in spectral reproduction is to match each input spectrum as closely as possible. Matching a given color in spectral space, rather than in a lower dimensional space such as CIELAB or CIEXYZ, improves metamerism of the print. To make a good spectral match, the printer gamut is expanded by adjusting the chemistry of the inks, and especially by increasing the number of the inks used in the printer.

What is a lower bound on the number of inks needed to do a reasonable job in spectral printing? We test whether the spectral matching improves noticeably as we increase the number of inks from 3 to 6 to 9 and finally 12 inks.

To make the study independent of the ink characteristics and the printer model, in the first set of experiments, an idealized linear projector model is used with reflectances having perfect square-wave reflectances. With the linear projecctor model, we can find out the minimum number of primaries required to do a spectral matching leading to almost no perceptual variation between the original and the displayed image across variations in the illumination. To determine whether real printers can be expected to follow the same trend as the linear projector, a second set of experiments was conducted using the reflectances of actual inks and synthetics ink reflectances and a printing model introduced by Tzeng [4], [5].

The study shows that, independent of number of primaries and shape of ink and primary reflectance, almost all of the scene reflectances fall outside the printer gamut. The result suggests that rather than finding whether a point is inside gamut or not, it can be assumed that all the points are out of gamut.

The first part of the paper introduces the data and the models that used in this paper. The second half of the paper compares performance of gamut coverage for different primary set and printer or projector models. To compare the accuracy of each primary and model combination (either printer or projector model) a simple manifold projection algorithm is implemented to find the closest point on the printer gamut.

Primary Selection

Two sets of primaries were used in this study. One set is based on reflectances of real inks, and the other set is synthetic ink or filter light reflectance depending on the device model used. Both synthetic and actual measurement data are used to make the result less dependent on a specific ink selection. The real ink reflectances are based on actual pigmented inks. The following 9 inks were used: Orange (O), Cyan (c), Magenta (m), Yellow (y), Green (Gr), Violet (V) and Black (K), Light Magenta (LM) and Light Cyan (LC). Two types of idealized synthetic primaries are also used. One type is based on square wave reflectance, and the other on sine wave reflectance. For square wave reflectance, varying amounts of overlap (0%, 10%, 20% and 40%) is introduced between inks. The variations in shape and overlap help determine whether either factor causes a noticeable change in gamut coverage.

Test Data

A data base of 1350 scene reflectances consisting of the Kodak data set [9], the Munsell chips, and other reflectances measured at Simon Fraser University was used to measure spectral matching accuracy of the printers. Figure 1 shows the number of PCA bases needed to represent the database accurately. It shows that in a linear space, 10 dimensions are sufficient to explain 99.5% of the variance in the data.

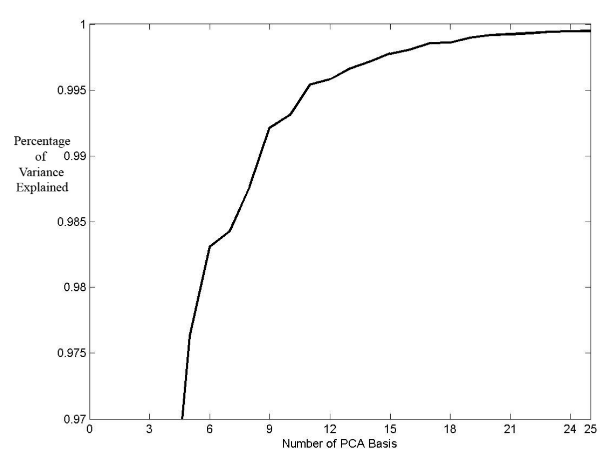

***Figure 1:** Percentage of the test data variance explained given number of PCA basis*

Device Model

Two device models, which we will denote LP (linear projector) and TK (Tzeng simple-Kubelka Munk), are used to predict the spectral reflectance resulting from printing or displaying a given primary combination. For LP, the displayed reflectance is assumed to be a linear combination of the primary reflectances. The equation below expresses how the model works:

$$R_\lambda = [\Sigma c_i R_{\lambda,i}] \quad (1)$$

$R_{\lambda,i}$ is the reflectance of primary i at 100% density, and c_i is the area coverage.

The LP model assumes that the primaries mix linearly in an additive color mixing and there is no interaction between the primaries [10]. The advantage of LP is that it makes it very easy to choose each primary percentage use, since its linearity means that simple projection can be used to compute the primary combination that best matches a given reflectance spectrum. For the LP case, we will use synthetic reflectances that are spectrally independent. Figure **2** shows the reflectance of 3 synthetic primaries for the LP model.

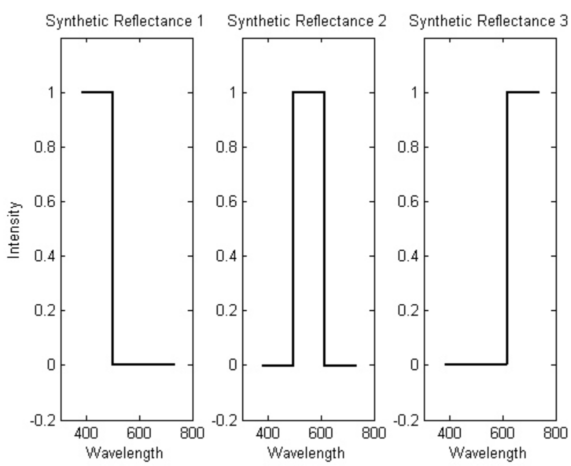

Figure 2 of 3 non-overlapping square-wave reflectances used with the LP model. The x-axis represent the wavelength of each reflectance. Y-axis represent intensity of the spectrum.

The printer model, TK, introduced by Tzeng et. al. [4], [5] is used to mimic the real ink and media reflectance. The following equations are used to predict the reflectance:

$$R_\lambda = (R_\lambda{}^{1/w}{}_{paper} - \psi_{\lambda,mixture})^w \quad (2)$$

$$\psi_{\lambda,\ mixture} = \Sigma c_i R_{i\lambda}$$

$$\psi_\lambda = R_\lambda{}^{1/w}{}_{paper} - R_{\lambda,i}{}^{1/w}$$

where w is the non-linearity weight similar to Yule-Nielsen factor [7] and $R_{\lambda,i}$ is the reflectance of the i ink as a function of wavelength. Figure 3 shows the reflectance of 3 synthetic primaries for the LP model.

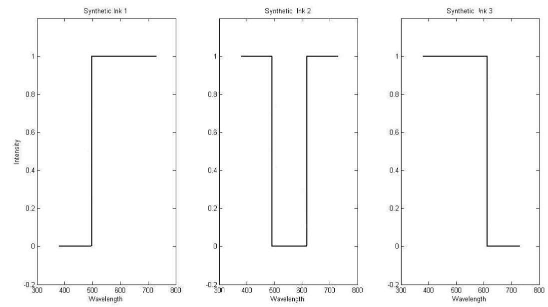

Figure 3 of 3 non-overlapping square-wave ink reflectances used with the LP model. The x-axis represent the wavelength of each ink reflectance. Y-axis represent intensity of the spectrum.

Experiment Setup

To determine how the number of primaries affects the accuracy of spectral reproduction in terms of reproducing spectra, we calculate spectral matches for 3-, 6- and 9-primary device (printer and a projector). In case of using TK, the 3 realistic inks considered are the most common 3 inks used in practice, namely, cyan, magenta, and yellow. For the 6-ink case, the initial 3 inks are the retained, and 3 more complementary inks are added, namely, orange, green, and violet. Light cyan, black and Light magenta are added to these 6 for the 9-ink case.

A problem with the TK model is that it is not easily invertible, especially for large ink sets. In other words, there is no simple way to determine the best ink combination matching a given reflectance spectrum. This presents a problem for its use in printers; however, for our purposes a simple brute-force search algorithm will suffice. The search is based on partitioning the printer's ink space by a uniform grid, and finding the partition that represents the printable spectrum with the lowest RMS (root mean squared) error to the input spectrum. To improve the accuracy and reduce the search time, the partitioning is broken down into a hierarchy of grid coarseness.

For the LP case, 3, 6, 9, and 12 inks were used. The 3 inks, as shown in Figure 3, cover the visible wavelengths, and are non-overlapping. The 6 inks are created by subdividing each ink in the 3-ink model into two separate square waves. The set of 9 non-overlapping inks are created similarly. The white of the print medium is taken to be the ideal white with 100% reflectance at all wavelengths. For the additive mixing model (LP) the 3, 6 and 9 non-overlapping synthetic reflectances are created similary.

The ink-separation problem is particularly easy in the LP case with inks of non-overlapping reflectance, since simple projection of the input spectrum onto the ink-reflectance basis yields the required ink separation. In addition to square wave inks, we also included sine wave ink reflectances. For both cases, we also allowed the inks to overlap to varying degrees.

Result

Two error measures are used to evaluate the accuracy of the spectral match between the predicted closest reflectance and the reflectance of the spectrum to be reproduced. The first is the Root Mean Square difference (RMS) between the two spectra calculated as follows, where N is the number of samples in the spectrum measurement:

$$DIST = (\Sigma(S_i - S_i')^2/N)^{1/2} \quad (3)$$

The second error measure is intended to capture the degree of metamerism between the two spectra. The measure is the maximum CIE ΔE_{04} difference between the two reflectances found under any of the 11 illuminants in the Simon Fraser University database of illumination sources [7]. Table 1 lists the 11 illumination sources, which are a combination of daylight, tungsten, and fluorescent lights.

Table 1 The 11 illumination sources used to calculated ΔE94

11 illumination types used for ΔE94 comparison
Sylvania 50MR16Q (12VDC)-A basic tungsten bulb
Sylvania 50MR16Q (12VDC) + Roscolux 3202 Full blue filter
Solux 3500K (12VDC)-Emulation of daylight
Solux 3500K (12VDC)+Roscolux 3202-Emulation of daylight
Solux 4100K (12VDC)-Emulation of daylight
Solux 4100K (12VDC)+Roscolux 3202-Emulation of daylight
Solux 4700K (12VDC)-Emulation of daylight
Solux 4700K (12VDC)+Roscolux 3202-Emulation of daylight
Sylvania Warm White Fluorescent (110VAC)
Sylvania Cool White Fluorescent (110VAC)
Philips Ultralume Fluorescent (110VAC)

Tables 2 and 3 show the performance of the TK and LP models. Both models show that the accuracy improvement tails off beyond 6 primaries. As expected, LP performs better than TK, and indicates the best we can do for any given number of inks.

Figure 1 visualizes the performance of the LP model.

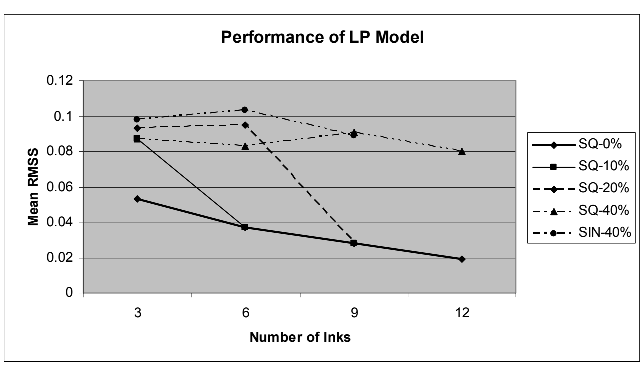

Figure 1. Performance of LP model.

Table 2: Performance of the LP printer as a function of the number of inks, ink type, and degree of ink overlap measured in terms of mean RMS and mean ΔE94 of input spectra to the corresponding closest printable spectra. The format of the left-hand column labeling is: number of inks, ink type, percentage overlap. SQ indicates square wave inks; SIN indicates sine wave inks; and R indicates real inks. The percentages indicate the percentage of overlap between the inks in a given ink set.

	RMS (mean/max)	ΔE94 (mean/max)
3 SQ-0%	0.053/0.152	6.67/29.67
6 SQ-0%	0.037/0.104	2.6/15.7
9 SQ-0%	0.028/0.073	1.06/7.53
12 SQ-0%	0.019/0.052	0.5/3.16
3 SQ-10%	0.087/0.247	8.37/40.7
6 SQ-10%	0.037/0.104	2.6/15.7
9 SQ-10%	0.028/0.073	1.06/7.53
3 SQ-20%	0.093/0.271	10.95/43.65
6 SQ-20%	0.095/0.27	3.73/11.49
9 SQ-20%	0.028/0.073	1.06/7.53
3 SQ-40%	0.087/0.243	11.62/49.67
6 SQ-40%	0.083/0.225	2.38/9.8
9 SQ-40%	0.091/0.257	2.97/9.91
12 SQ-40%	0.08/0.228	2.41/12.54
3 SIN-40%	0.098/0.241	6.54/24.29
6 SIN-40%	0.103/0.284	4.04/16.78
9 SIN-40%	0.089/0.24	2.4/11.15

Table 3: Performance of TK printer. Labeling is as for Table 2.

	RMS (min//mean/max)	ΔE94 (min/mean/max)
R 3	.09/.2/.6	2.1/29.38/78.8
R 6	.03/.18/.45	1.9/23.49/60.23
R 9	.019/.134/.37	1.2/18.39/56.38
3 SQ-0%	.002/0.095/0.271	.08/15.6 / 51.9
6 SQ-0%	.001/.07/.198	.54/10.87/35.80
3 SQ-10%	.01/0.117/0.463	.43/16.6 / 71.7
6 SQ-10%	.002/.089/.213	.41/12.61/47.46
3 SQ-20%	.014/.131/.431	.3/18.45/68.93
6 SQ-20%	.016/.125/.311	.44/14.85/46.54
3 SQ-40%	0.02/0.147/0.386	.72/21.45/67.5
6 SQ-40%	.018/.126/.32	.52/16.3/48.32
3 SIN-40%	.08/.167/.41	1.2/24.3/72.3
6 SIN-40%	.02/.13/.38	.78/20.2/52.23

Conclusion

Spectral Reproduction accuracy improves as a function of number of primaries in both additive and subtractive models. They both models show that the accuracy of the reproduction improves when the primaries are more independent from each other (less overlap).

The main observation is that independent of the number of inks, almost all of the scene reflectances fall outside of the model spectral gamut space.

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Author Biographies

Behnam Bastani received his B.S. degree in Computing Science with a minor in Business from Simon Fraser University in 2003. He completed his Masters degree in Computing Science at SFU in 2004, where his research was focused on gamut mapping and characterization of digital color displays. He joined Hewlett-Packard Company in 2004, where his research is on designing models for calibrating high-end ink-jet printers. He is also a PhD candidate at Simon Fraser University.

Brian Funt received the Ph.D. degree in computer science from the University of British Columbia, Vancouver, BC, Canada, in 1976. He is a Professor with the School of Computing Science, Simon Fraser University, Vancouver, where he has been since 1980. He has published widely in color, color constancy, retinex, color calibration, and illumination estimation.

Jeffrey DiCarlo received his B.S. in electrical engineering from Case Western Reserve University in 1994, and he earned his M.S. and Ph.D. in electrical engineering from Stanford University in Palo Alto, California in 1996 and 2003. He is a research scientist and manager at HP Laboratories in Palo Alto, California, where he researches topics in color science, device characterization, color reproduction, spectral imaging and image processing.