Spectral Gamut Characteristics based on Number of Primaries and their Characteristics

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Abstract

In applications that require spectral color information, such as fine art printing field, industry has been able to improve reproduction quality substantially in the past decade by increasing the printer gamut space and improving other print quality attributes such as metamerism. As the number of inks used in the printer is increasing and researchers are able to understand the ink and media interaction more in detail, attempting to match a color in spectral space has been possible. Similar trend is happening for electronic displays such that now there are cameras and displays with 4 or 6 color channels or filters available.

This paper focuses on the following two fundamental question in spectral color reproduction:

1. What is the optimal number of inks, and which types of inks to use?

2. How to create the ink combination that replicates a given spectral reflectance as closely as possible?

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 more general, two sets of devices are used. In one device, primaries (inks) interact with each other linearly and in the other device non-linearly.

The first part of the paper introduces the data and the models that are used in this paper. The second half of the paper compares performance of gamut coverage for different primary characteristics and interaction between the primaries. To compare performance of each device, an exhaustive hierarchical search algorithm is used.

Primary Selection

Three types of synthetic primaries were also used. The first type of reflectance used was based on square-wave reflectance as shown in Figure 1 where the edges are sharp, and thus resembles sub-sampling of the spectral reflectance. The 3 inks, as shown in Figure 1, cover the visible wavelengths 380 to 730, and are non-overlapping. The 6 inks were created by subdividing each ink in the 3-ink model into two separate square waves. The set of 9 and 12 non-overlapping inks were created similarly. The white of the print medium was taken to be the ideal white with 100% reflectance at all wavelengths.

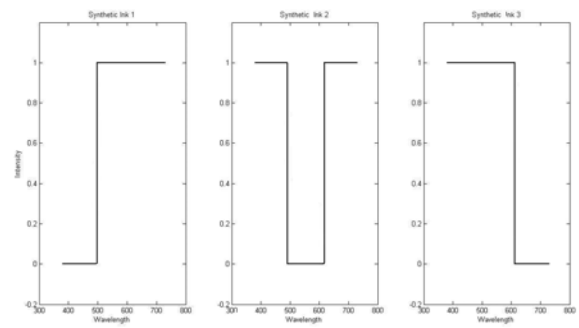

Figure 1: 3 Square wave synthetic ink reflectances covering 380 to 730 nm equally.

The second set of primaries studied has a more gradual transition from a non-absorbance region to the area of reflectance absorbance. This set of reflectances was used to compare the effect of having a tail (gradual transition between the absorptive and non-absorptive regions of each primary) on the accuracy of spectral reproduction.

Two sets of primaries with tailed overlap were considered as shown in Figure 2 and Figure 3. One set was based on modified square-wave reflectances with longer tails with the other set more sinusoidal (Figure 3).

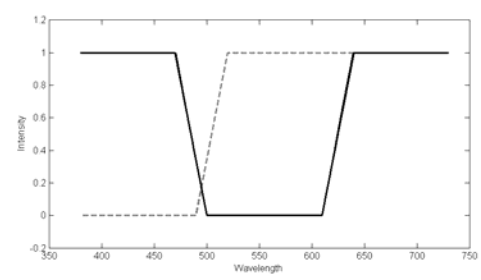

Figure 2: Two primaries with non-smooth tailed endings. The reflectances of these primaries have a gradual transition between absorptive and non-absorptive regions.

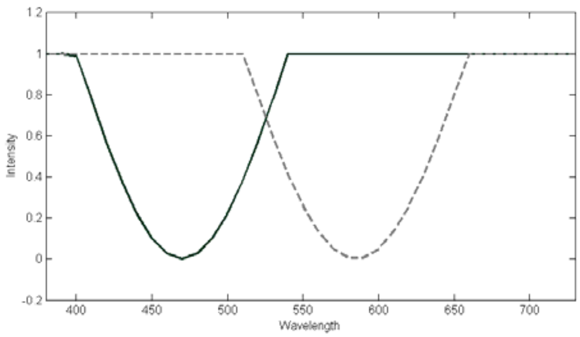

Figure 3: Two primaries with smooth tailed endings. The reflectances of these primaries have a smooth gradual transition between absorptive and non-absorptive regions.

Another contributing spectral reflectance characteristic of primaries studied was the percentage of spectral reflectance overlap. To evaluate the possible benefits of overlap for each type of reflectance, a set of 4 different reflectances in each reflectance type with 0%, 10%, 20% and 40% overlap was used.

The second set of reflectances is based on real pigmented ink measurements. 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). The purpose of this set to evaluate how our real inks behave compared to the synthetic inks.

Test Data

A database 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. Analysis of dimensionality complexity of the database shows that 10 dimensions are sufficient to explain 99.5% of the variance in the data.

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.

For the printer model, TK, introduced by Tzeng et. al. [4], [5] is used to model the real ink and media interaction. 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.

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. 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 1, 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

Primary Overlap

In this section, the effect of having different percentages of overlap between the primaries is evaluated. The result is repeated for each type of primary reflectance. Figure 4 shows that for the square type reflectances, as the overlap percentage increases, the accuracy of the spectral matching will decrease. Figure 5 shows similar behaviour if the performance is evaluated as ΔE_{94} colour difference under 11 different illuminations.

One hypothesis is that for square type waves, for which both the centre of the signal and the edges of the signal have similar coverage (i.e., there is no tail for the signal), having overlap on the primary reflectances causes a significant drop in reproduction accuracy. This is an indication of a drop in gamut coverage of the device.

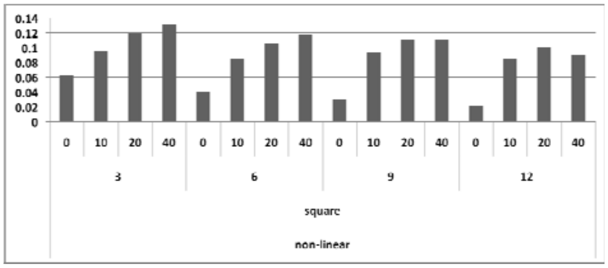

Figure 4: Spectral Gamut coverage of square wave ink given 3, 6, 9 and 12 inks evaluated as Room Mean Square difference between the database of reflectances and the closest reflectance matches that fall on the gamut. The printer model is based on non-linear (TK) model.

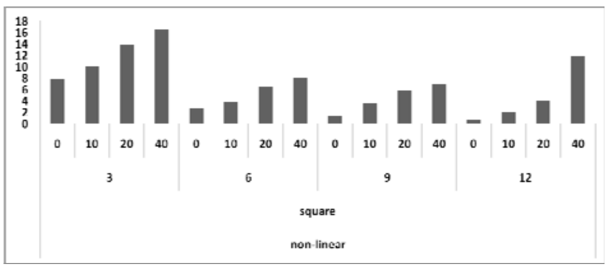

Figure 5: Spectral Gamut coverage of square wave ink given 3, 6, 9 and 12 inks evaluated as DeltaE$_{94}$ colour difference between the database of reflectances and the closest reflectance matches that fall on the gamut. The error is shown as average variation under 11 different illuminations. The printer model is based on non-linear (TK) model.

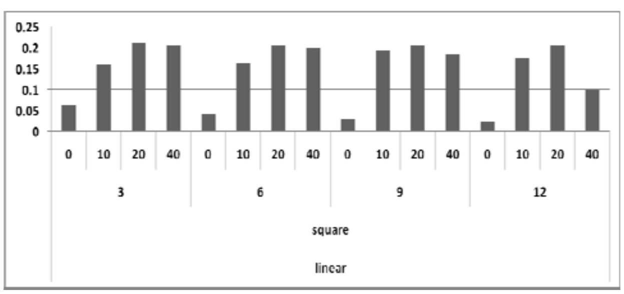

Figure 6: Spectral Gamut coverage of square wave ink given 3, 6, 9 and 12 inks evaluated as Room Mean Square difference between the database of reflectances and the closest reflectance matches that fall on the gamut. The printer model is based on linear (LP) model.

Considering trapezoidal signals (Figure 7) which have a tail (slower drop in their absorption sensitivity compared to square wave), some level of overlap improves printer spectral gamut performance. This characteristic holds for a sine wave signal as well, as shown in Figure 8 and Figure 9.

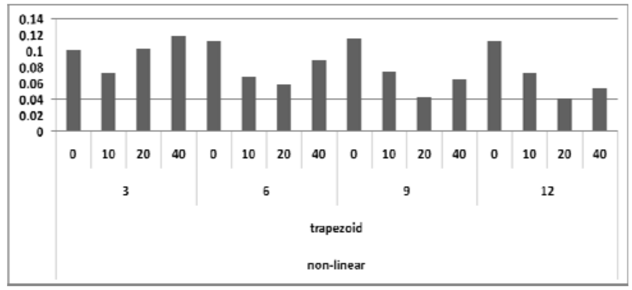

Figure 7: Spectral Gamut coverage of trapezoidal wave ink given 3, 6, 9 and 12 inks evaluated as Room Mean Square (RMS) difference between the database of reflectances and the closest reflectance matches that fall on the gamut. The printer model is based on a non-linear (TK) model.

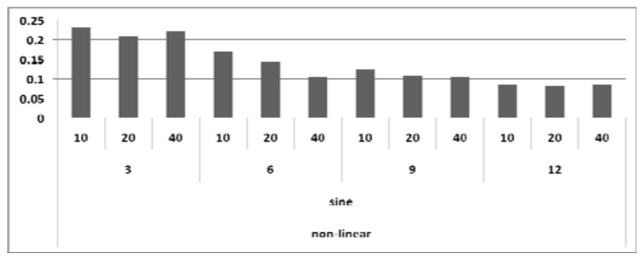

Figure 8: Spectral Gamut coverage of sine wave ink given 3, 6, 9 and 12 inks evaluated as Room Mean Square (RMS) difference between the database of reflectances and the closest reflectance matches that fall on the gamut. The printer model is based on a non-linear (TK) model.

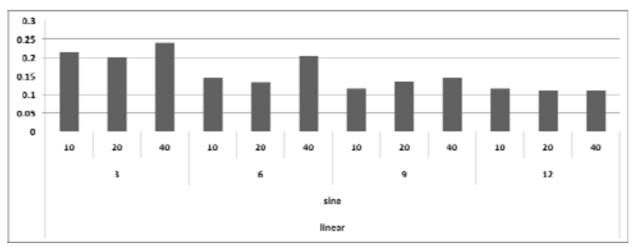

Figure 9: Spectral Gamut coverage of sine wave ink given 3, 6, 9 and 12 inks evaluated as Room Mean Square (RMS) difference between the database of reflectances and the closest reflectance matches that fall on the gamut. The printer model is based on a linear (LP) model.

Primary Interaction Model

Figure 10 Compares gamut coverage of the two primary interaction models for square waves. Previous data showed that for the square wave functions, the more the two primaries overlap the lower the gamut coverage becomes (Figure 4). It can be derived that, if the primaries have optimal spectral overlap percentage, then the two interaction models (linear and non-linear) have similar gamut coverage. However, once there is more overlap between the primaries' absorption sensitivity regions than what is optimal, then a non-linear system has better performance.

Similar behaviour is seen for the sine and trapezoid shape signals that have longer tails. Figure 11 and Figure 12 show that for signals with not enough overlap between the primaries, a linear model performs better. When there is enough overlap (e.g. 10% for trapezoid signal or 20% for sine wave), then both linear and non-linear models have overall similar coverage. On the other hand, when there is more than optimal overlap between signals, primaries with non-linear interaction result in a better reproduction than if they had linear interaction.

Typical inks used in the printers are a good example of primaries with long tails. Based on observations using synthetic inks, the expectation is that these inks (real inks) would have better spectral gamut coverage in a non-linear system than a linear system. Figure 13 confirms the expectation, where 3, 6 and 9 real ink reflectances were used.

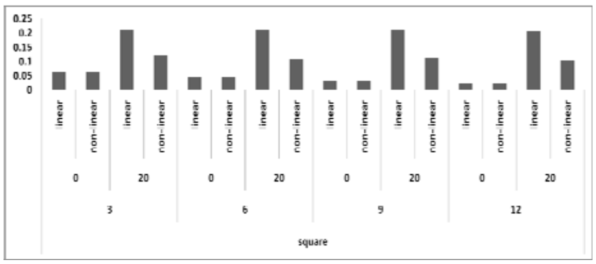

Figure 10: Performance of square wave primary evaluated as RMS of match between scene reflectance and the closest match on the system gamut.

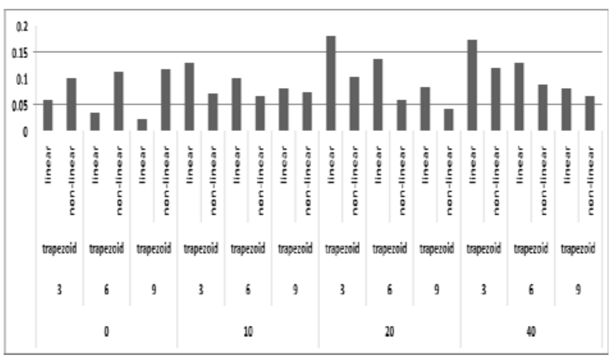

Figure 11: Performance of square wave primary evaluated as RMS of match between scene reflectance and the closest match on the system gamut.

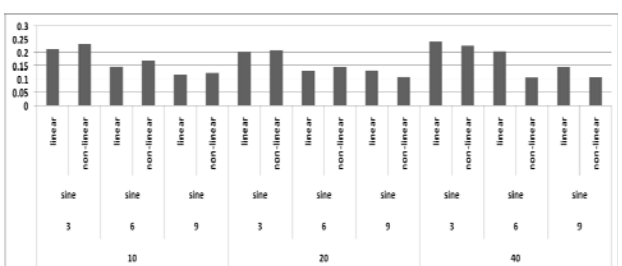

Figure 12: Performance of square wave primary evaluated as average RMS of match between scene reflectance and the closest match on the system gamut.

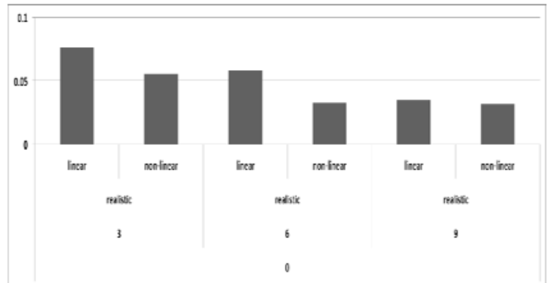

Figure 13: Performance of real ink reflectances as average RMS of match between scene reflectance and the closest match on the system gamut (both linear and non-linear models are evaluated).

Number of Primaries

The focus of this study was to understand whether the spectral gamut coverage of the device is improved when more primaries are made available in an output device.. The result in this section tries to explain how many primaries are needed in a device to get an accurate spectral colour reproduction system when the reflectance or absorption characteristics of the primaries are, or are not, optimized for reproduction purposes.

Figure 14 and Figure 15 show, for close to optimum square wave primaries, the spectral coverage of a device gamut improves noticeably as the number of primaries increases (whether the error is measured in RMS or DeltaE). On the other hand, if the overlap percentage for the same type of primaries is larger than what is desired (having non-optimum primaries), then the gamut coverage of the output device does not improve continuously as the number of primaries increase (Figure 16). The data shows that for non-optimized primaries, the gain from having a higher number of primaries (especially after 6 primaries) is cancelled by the noise in spectral reproduction from having a higher than optimized overlap amount. Similar behaviour is seen for output devices with linear primary interaction (Figure 17).

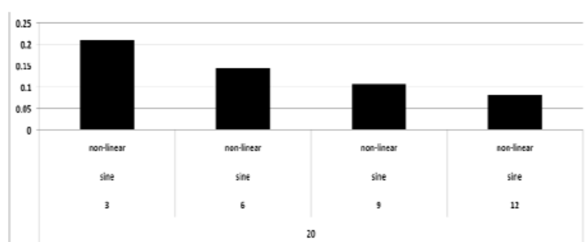

Figure 14: Spectral Gamut coverage of sine wave ink at 20% overlap (the better overlap amount) for 3, 6, 9 and 12 inks evaluated based on mean RMS difference between the closest match on gamut and the goal reflectance. Mean RMS is on Y axis.

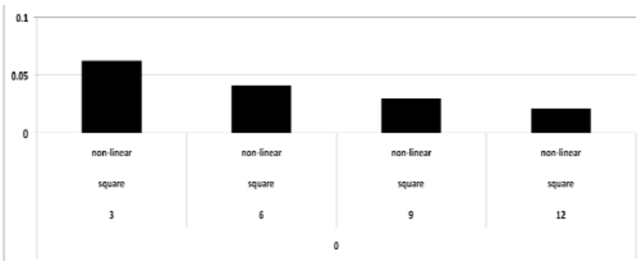

Figure 15: Spectral Gamut coverage of square wave ink at 0% overlap (the better overlap amount) for 3, 6, 9 and 12 inks evaluated based on mean RMS difference between the closest match on gamut and the goal reflectance. Mean RMS is on Y axis.

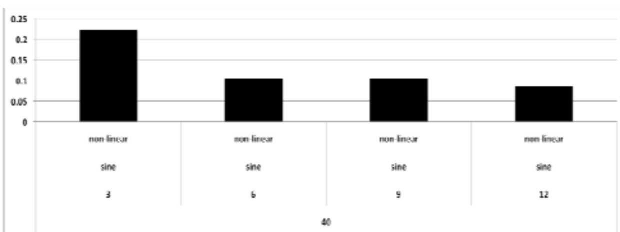

Figure 16: Spectral Gamut coverage of sine wave ink at 40% overlap (the undesired overlap amount) for 3, 6, 9 and 12 inks evaluated based on mean RMS difference between the closest match on gamut and the goal reflectance. Mean RMS is on Y axis.

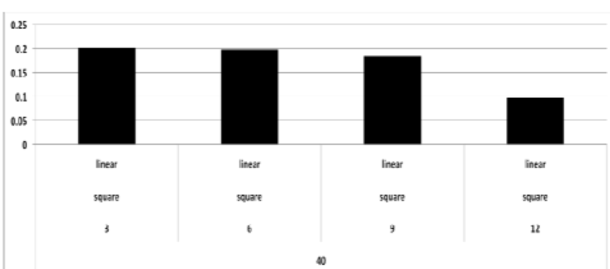

Figure 17: Spectral Gamut coverage of square wave ink at 40% overlap for a linear system. 3, 6, 9 and 12 inks evaluated based on mean RMS difference between the closest match on gamut and the goal reflectance. Mean RMS is on Y axis.

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). For primaries that are more independent (square wave inks), we prefer less overlap on their absorption sensitivity region.

The real ink reflectances are not optimized for spectral reproduction. However, the inks do better spectral reproduction on devices where primaries interact with each other non-linearly.

References

[1] N. Katoh and M. Ito, "Applying Non-linear Compression to the Three-dimensional Gamut Mapping" ,*The Journal of Imaging Science and Technology* July/August, vol. 44, no. 4; pp. 328-333, 1999

[2] R. S. Gentile, E. Walowitt and J. P. Allebach, "A comparison of techniques for color gamut mismatch compensation", Journal of Imaging Technology., vol. 16, pp. 176-181, 1990.

[3] J. Morovic, M. Lou, "The fundamental of Gamut Mapping: A Survey", *Journal of Imaging Science and Technology*, vol. 45, no. 3, 2001

[4] DY. Tzeng and R. Berns, "Spectral-Based Ink Selection for Multiple-Ink Printing II. Optimal Ink Selection", *Proc. IS&T/SID Seventh Color Imaging Conference: Color Science, Systems and Applications*, Scottsdale, Nov. 1999. pg. 182-187.

[5] DY. Tzeng., Spectral-based color Separation algorithm development for multiple-ink color reproduction, Ph.D. Dissertation, Rochester Institute of Technology, 1999

[6] G. Finlayson, S. Hordley and I. Tastl, "Gamut Constrained Illuminant Estimation", *International Journal of Computer Vision* Volume 67 , Issue 1, 2006

[7] Wyble, D., Berns, RS., A Critical Review of Spectral Models Applied to Binary Color Printing, Rochester Institute of Technology, Color Research and Application , Volume 25, Issue 1 , Pages 4 - 19, 1999

[8] Barnard, K. Martin, L., Funt, B.V. and Coath, A., "A Data Set for Color Research," *Color Research and Application*, Vol. 27, No. 3, (2002), pp.148-152 (Data available from www.cs.sfu.ca/~colour)

[9] M.J., Vrhel, R. Gershon, R. Iwan, L. S. "Measurement and analysis of object reflectance spectra," *Color Res. Appl*., 19(1) pp. 4-9, 1994.

[10] B. Bastani, B. Cressman, B. Funt, "Calibrated Color Mapping Between LCD and CRT Displays: A Case Study", Color Research and Application, Volume 30, Issue 6, Date: December 2005, Pages: 438-447

Author Biographies

Behnam Bastani received his PhD degree in Computing Science at SFU in 2009, where his research was focused on Spectral Color Reproduction and Gamut Mapping in higher dimensions. He joined Memjet Photo Retail in 2008, where he works as a senior image scientist in designing the next breakthrough printing technology. Previously he worked at Hewlett-Packard where his research was on designing models for calibrating high-end ink-jet printers.