Improving the Accuracy of Inexpensive Sensors for Optical Density Measurement

Behnam Bastani, Bill Cressman; Hewlett-Packard Company; San Diego, CA, USA

Abstract

A common problem in the field of color printing is closed loop color calibration, a process which generally requires a spectrometer. Light Emitting Diodes (LED) sensors are inexpensive and effective for measuring the net reflectance of certain frequencies of light. Sensor measurement of LED reflectance can be used to estimate spectral reflectance or color value (measured in CIELAB or CIEXYZ color space) of a printed patch. LED based sensors suffer from their lower accuracy in predicting color values. This paper focuses on improving accuracy of these sensors in predicting Lightness values in CIELAB color space of a single colorant by combining information from multiple LEDs with different spectrum coverage.

Introduction

The lightness linearity of RGB space is critical in getting good image quality from multiple ink printers. Therefore, a common problem in the field of color printing is closed loop color calibration, a process which generally requires a spectrometer.

Light Emitting Diodes (LED) sensors are inexpensive and effective for measuring the net reflectance of certain frequencies of light. Sensor measurement of LED reflectance can be used to estimate spectral reflectance or color value (measured in CIELAB or CIEXYZ color space) of a printed patch. However, these sensors suffer from several drawbacks:

1. Gain Control: Sensors do not receive enough light back for the color patches with high density and therefore they have a lower signal to noise ratio for dark patches. On the other hand, if the overall intensity of the LEDs is increased, the sensor may be saturated on light patches.

2. LED spectrum range is not optimized for certain types of inks, meaning that each LED may return only a portion of information about an ink density.

3. Different densities of the same ink do not necessarily have the same hue angle.

This paper starts with an introduction to a general method for using LED based sensor to measure lightness of a printed patch in CIELAB color space. A new method is introduced to improve accuracy of these sensors. This method combines prediction of each LED based on the ink density and its reflectance match with the spectrum coverage of the LED. The accuracy of this method in predicting lightness of each color patch is compared to the conventional approaches in CIELAB color space. The result shows that the accuracy of the sensors in Color Calibration improves by as much as 50% in CIELAB color space.

Close Loop Color Calibration

Closed Loop Calibration in printers is used to get perpetually uniform steps of ink ramps. Most of the known calibration procedures ([1], [2]) adjust the density of individual inks through a lookup table. The main assumption is that the hue angle for different densities of an ink is constant. This means a correction based on lightness (L* in CIELAB) can give us perceptually linear ramps in RGB space.

LED Based Sensors

Performance of the calibration process in correcting density variation amongst pens in the printer is strongly dependent on the accuracy of measurement devices. Due to cost and smaller size, LED based sensors are common to be used to measure lightness (L*).

In general, these sensors have 2 or more LEDs with different spectral range and one mono-chrome sensor that measures diffuse reflection of the light from the media. In our study we sued a sensor that is based on 4 LEDs (Red, Green, Blue and Orange) and has 2 sensors to detect diffuse and specular reflectance. Figure 1 shows position of diffuse and specular sensors respect to LED and surface.

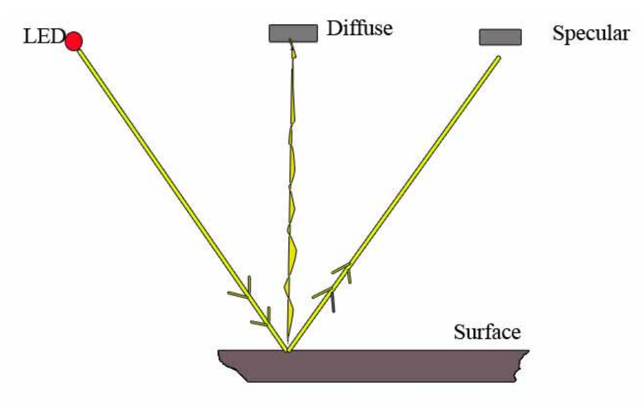

Figure 1: *Sensor Design*

Measurement of diffuse channel is used to measure color characteristic of a surface. In close loop calibration, reading from this channel is used to predict L*. In the remaining sections, some existing models for predicting L* are compared. At the end a new method is introduced to improve the prediction performance.

Using LED Based Sensor to Predict Lightness

Each LED in the sensors covers specific wavelength range. Figure 2 shows the spectral range of each 4 LED for the sensor used in this paper.

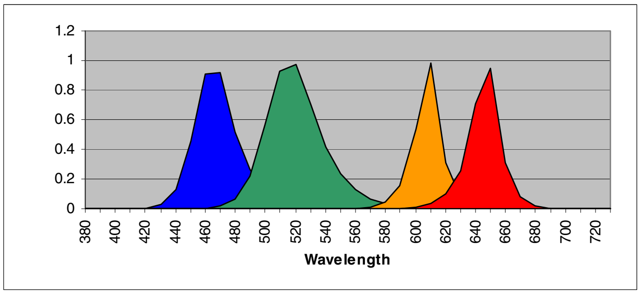

Figure 2: *Spectral Reflectance of the 4 LED in the sensor*

There are different approaches to predict lightness using off-shelf LED based sensors. For printing purposes, since individual ink are linearized in lightness space (L* of CIELAB), it is even possible to have specific mapping for predicting lightness for each ink.

1D Lookup Table

Behavior of the diffuse sensor can be represented as [5], [6]:

$$\rho(\lambda) = \int E(\lambda)S(\lambda)R(\lambda)d\lambda \qquad (1)$$

Where S( ) represents the surface reflectance at a given point, E( ) is the incident illuminant and R( ) is sensor sensitivity at wavelength.

Assuming a constant hue value, the only variation seen between different densities of a single ink is variation in intensity of spectral reflectance of the ink at a reference density. This means a look-up table should be sufficient to predict lightness of an ink given density of the ink. Figure 3 shows a sample look-up table between sensor reading of Green LED and L* for ramps of Cyan ink.

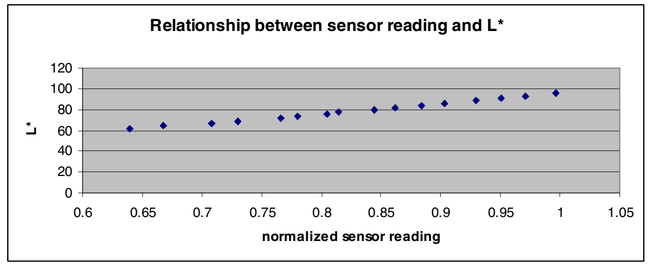

Figure 3: *Relationship between normalized sensor reading for Green LED and L* for different density of Cyan ink*

Linear Transformation of 4 LEDs

The linear model is a two-stage characterization process. In the first step, the raw sensor readings for each LED si (i=1, 2, 3, 4 for R, G, B, O) are linearized using a function Ci(si) fitted for each channel. In the second step, regression is used to determine a linear transformation, T, from linearized input value to predicted L*.

$$\begin{bmatrix} Ri \\ Gi \\ Bi \\ Oi \end{bmatrix} \times T = L^* \qquad (2)$$

This model is valid for devices that relationship between input and output values is fairly linear. For instance same model is used to calibrate monitors since relation between RGB input values and output tristimulus values can be represented as linear model after linearizing each channel [7].

Weighted Linear Model

Linear model predicts L* by applying a matrix transformation T to the linearized input values. Same matrix transformation is used for all different ranges of input values. This model is valid for printers as long as hue angle of an ink does not change for different densities of the ink. However, if hue variation is seen, this implies that maybe having different transformation matrices, T, for different ink densities can predict L* more accurately. Figure 4 shows CIELAB values for different densities of the cyan ink used in this study. Hue variation also implies that one LED with specific spectral range may see spectral variation of an ink better for specific density ranges compared to another LED.

1D lookup Table model on the other hand linearizes the ink space before applying the transformation. However, this model uses information based on one LED readings for prediction and it does not take advantage of accuracy each LED at different densities for a given ink.

Figure 5 shows same measurements but in spectral space. The overlap of cyan spectral variation with the 4 LED sensors shows that there are multiple candidates and each may be a better choice for a range of density.

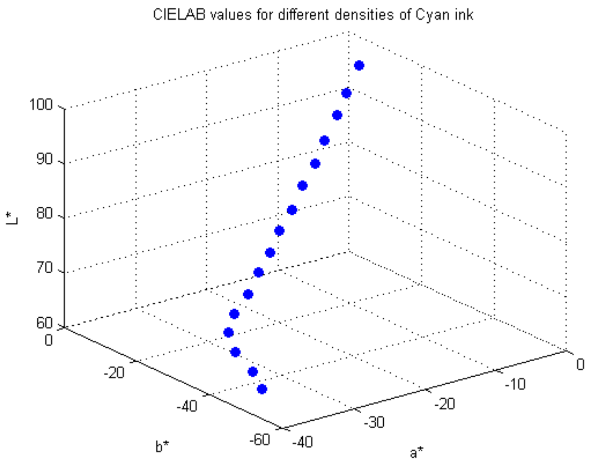

Figure 4: *different densities of cyan ink measured in CIELAB color space.*

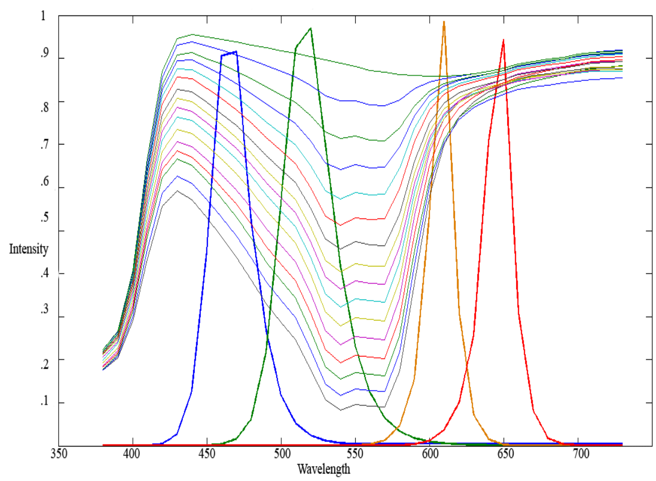

Figure 5: *overlap of spectral variation of cyan against each LED coverage*

Since each LEDs' accuracy in predicting L* is different for different ink density, a weighting function is proposed to combine prediction of the LEDs. The weighting function is based on the resolution of the LED to see neighboring densities of an ink and signal to noise ratio of the measurements at the given density. Equation 3 shows the calculation of the weighting function. M_i^{LED} represent measurement for density i from for a given LED. $M_{0\text{-end}}^{LED}$ is the measurement range for a given LED along all different ink densities.

$$R_i^{LED} = \frac{mean(M_i^{LED}) - mean(M_{i-1}^{LED})}{\max(M_{0-end}^{LED}) - \min(M_{0-end}^{LED})}$$

$$w_i^{LED} = \frac{R_i^{LED}}{\sum_{L\in\{R,G,B,O\}} R_i^L} \qquad (3)$$

$$W_i^{LED} = \alpha . w_i^{LED} + (1-\alpha) Si$$

After calculating the weighting function, prediction from each LED is combined together (equation 4).

$$P_i = \sum_{L\in\{R,G,B,O\}} W_i^L . p_i^L \qquad (4)$$

For the 4 LED based sensor used in this study, 4 1D Lookup tables are created for each ink and one weight function to combine prediction of each LED. *Figure 6* shows the weight function for Green and Orange LED to scan Cyan ink. The gray bars in the background represent the weight function.

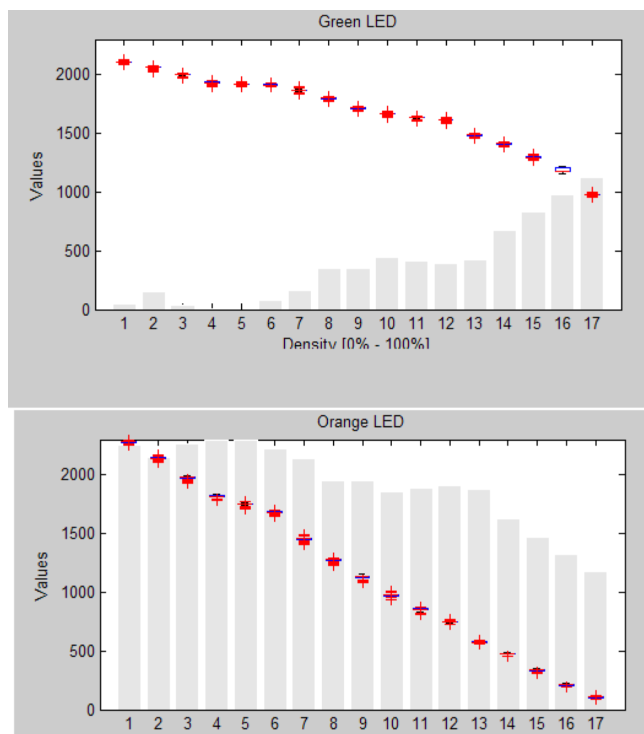

Figure 6: *measurements of each LED for Cyan ink and applied weight function. The red bars show the signal to noise ratio of each LED. The gray bars represent weight function of each LED for different densities.*

Results

Table 1 compares accuracy of the weighted linear model with linear model for three different inks using 2 LEDs. For each ink, 10 densities was used during training and 36 densities were used (including the training data point) for testing purpose.

The result shows that by taking advantage of each LED resolution at different densities, accuracy of the model in predicting L* has improved by as much as 50%.

Table 1: Accuracy of the weighted linear model (G+B) v.s. linear model (G or B) for 3 different inks.

Ink	LED	μ	max	σ
Light Magenta	G	1.085	1.882	0.443
	B	1.575	4.998	1.394
	G+B	0.921	1.939	0.54938
Gray	B	1.3395	3.5615	0.94754
	G	1.532	2.945	0.7125
	G+B	0.96483	2.924	0.63034
Black	R	1.197	5.6402	1.293
	G	0.993	3.685	0.8593
	R+G	0.7122	3.3253	0.70151

References

[1] Huanzhao Zeng, CMYK transformation with black preservation in color management system, Proc. SPIE Vol. 4663, p. 143-149. (2001).

[2] Anoop K. Bhattacharjya, Closed-loop color calibration for the home user, Proc. SPIE Vol. 3018, p. 138-146. (1997).

[3] M. Has and T. Newman, Color management: Current Practice and the Adoption of a New Standard, http://www.color.org.

[4] G. Braun and M. Fairchild, Color Gamut Mapping in a Hue-Linearized CIELAB Color Space, Proc. IS&T/SIC 6th Color Imaging Conf., 163-168 (1998).

[5] L. Maloney, B. Wandel, Color constancy: a method for recovering surface spectral reflectance, Journal of the Optical Society of America, A3:29-33, (1986)

[6] G. Finlayson, M. Drew, and B. Funt, Spectral Sharpening: Sensor Transformations for Improved Color. J. Opt. Soc. Am. A, 11(5):1553-1563, (1994)

[7] B. Bastani, B. Cressman, B. Funt, Calibrated Color Mapping Between LCD and CRT Displays: A Case Study, Journal of Color Research and Application, Volume 30, Issue 6 , pg. 438 – 447, (2005)

Author Biography

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 2005, where his research is on designing models for calibrating high-end ink-jet printers. He is also a PhD candidate at Simon Fraser University.

Bill Cressman received his B.S. degree in Mechanical Engineering from Rice University in 1993, and a Masters in Business Administration from the University of California at Irvine in 2002. He completed his Masters degree in Computing Science at SFU in 2003 where his research is focused on calibration and testing of digital displays. He has worked for Hewlett Packard since 1993, in the field of manufacturing data system design.

.