Sparse Sampling for Inter-Substrate Color Prediction

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Abstract

A novel method to characterize the printer color output with few sparse samples is presented. Color measurements previously obtained on other substrates and stored in the printer are used to increase the accuracy of measurements in a new target media, thus reducing the number of samples needed. A geometrical warp is applied to the color space to adapt the differences between the two media. The warping is built with a small set of measurements on the target media and extended to the entire color. We tested the method on a HP T1100 ink-jet printer, at different levels of sampling –from 27 to 512 points– on uniform and sparse data points, and with seven different substrate families. For media as the only varying factor, mean estimation error below 1dE is obtained for less than 100 uniformly spaced color patches or 50 sparse ones. In conclusion, color space warping is proven to be an effective method to reduce the needed color samples by using previously characterized media.

Introduction

Due to physical differences between different media, such as media color, dot gain or porosity, colors appear different even when the same amount of ink is applied. Therefore, it is needed to characterize the printer's color output in order to obtain accurate colors. This operation is also known as profiling, and consists in: (i) printing and drying a color chart with various ink combinations, (ii) measuring this chart with a colorimeter or a spectrophotometer device, (iii) computing the relationship between ink combination (device space) and output color (color space), and its inverse, and (iv) formatting the result in a standard format (e.g. ICC profile). Some printers (e.g. HP Z series) make this operation simpler and faster by embedding a color sensor in the printer and performing all the steps automatically.

To obtain an accurate profile a certain number of patches need to be printed (typically more than 400). This might be a time-consuming process that impacts the user workflow, besides the waste of ink and media. Also, artifacts due to erroneous printing (banding, scratches) or erroneous measurement (poor calibration, scanning positioning), may cause the process to fail and need for repetition. Therefore, it would be convenient to reduce the number of patches needed to profile a new media in order to speed up the process.

Several approaches have been made to reduce the number of needed patches for color profiling, commonly by the use of color models. Such models describe analytically the physics of light interaction with ink and media, in order to predict which color will result from a certain ink combination. Common models include Kubelka-Munk [1], Neugebauer [2], and its various extensions like Yule-Nielsen Spectral Neugebauer [3] among others [4-6]. Certain parameters –such as colorant spectra or dot gain – need to be experimentally characterized and used along the derived analytical relationship to predict any ink combination. However, as assumptions fail, color accuracy decreases. Typically all parameters are obtained from the target media, and no use of information on other substrates is used.

Since many ICC profiles are already available in the printer, we could consider using them to increase the accuracy of the color measurement in a new media. The use of color data from another media has not received as much attention as classic color models. Shaw et al. [7] compared various color models (Beer's law, Kubelka-Munk and Neugebauer equations) to perform such operation. Also, they proposed a purely data-driven model based on principal component analysis (PCA). Interestingly, the data-driven approach performed better than analytical models, which might be an indication that actual modeling of ink-media-light interactions to highest degree if accuracy is still a challenge. The authors presented recently the basics of inter-substrate warp color prediction [8], limited to uniformly spaced color samples.

In this paper, we present a purely data-driven model to predict color measurements from few samples. We propose to geometrically warp the color measurements of the target media using the well-characterized color measurements of a reference media. The transformation is from the color space of the reference media to the color space to the target media, and it is therefore generic to any color device. This transformation is obtained from a few samples and interpolated throughout the color space.

Method

The goal is to predict color measurements for a new target media (target) from a coarse and maybe non-uniform sampling. The color measurements need to be predicted at a finer grid, to feed the color profiling process. Color measurements in a reference media (reference) are available at this finer grid, and the question remains how to use this information.

The method that we propose is as follows: (i) using the coarse sampling, determine which is the closest ICC available in the database, (ii) find the vector field that relates the target and the reference media at the coarse sampling, (iii) interpolate this vector field from the coarse to the finer sampling, and (iv) apply the interpolated vector field to the reference media data to estimate the target media data.

Comparing the coarse sampling to the available data (step i) is performed by colorimetric (mean dE76) difference minimization. Finding the relationship between the target and reference media measurements (step ii) is performed in the colorimetric space, e.g. CIEL*a*b*, which makes the method generic to any kind of device regardless of their ink space. The 'warping' vectors relate colormetric coordinates, as shown in Figure 1. However, the sampling (coarse or fine) is specified in device space, e.g. RGB or CMYK, which will ultimately determine the needed number of samples to characterize the system. Figure 2 shows the relationship between the device and colorimetric space, and how are these sampled.

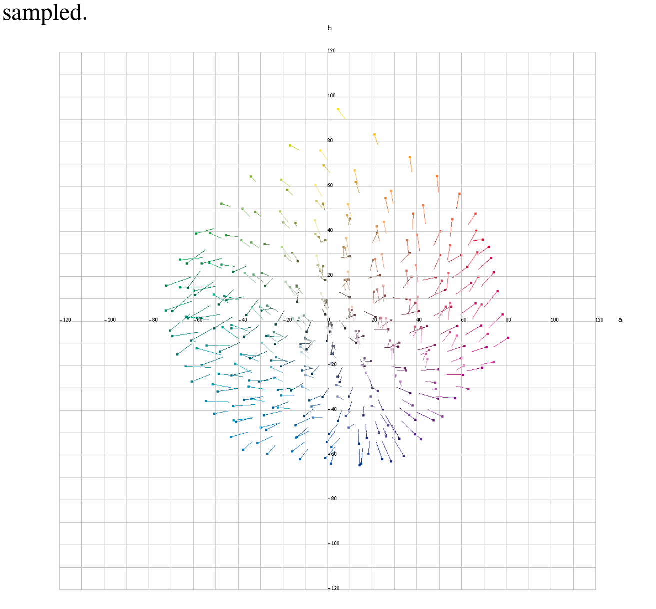

Figure 1*. Warping vectors from the reference media (points) to the target media (end of lines), projected onto a*/b* plane in the CIEL*a*b* space.*

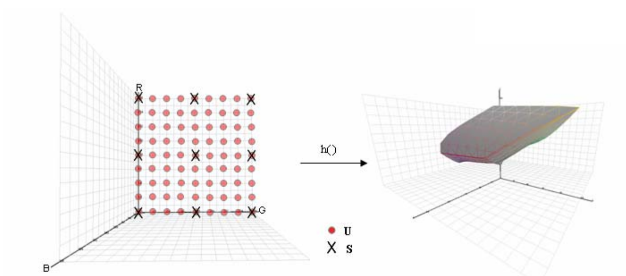

Figure 2*. A schema of the RGB cube (highlighting the RG plane), and the corresponding sampling points in CIEL*a*b* space. Dots represent the fine sampling (U) and crosses represent the coarse sampling (S).*

Interpolation of the vector filed form the coarse sampling to the finer sampling (step iii) was done with bi-harmonic interpolation [9]. This interpolation operator provides the capability to deal with sparse data while ensuring a smooth result. Once these vectors are found, they are added to the reference set (step iv) to obtain the colormetric coordinates of the estimated target set.

The described method has as end result a set of estimated color samples. In order to build a new ICC profile, these samples need to be processed by a profiling tool that might introduce further color errors than the ones reported in this paper.

Results

In this section we present the test conditions, the initial color differences between different media, the results of the warping experiments for both uniform and sparse sampling grids, and its discussion.

Test Conditions

We printed a regular grid of 8x8x8 points (total 512) in the RGB native space. We used a HP Designjet T1100 ink-jet printer, which has 6 dye-based HP Vivera inks (cyan, gray, magenta, matte black, photo black and yellow). The conversion from RGB to ink space is managed internally in the printer and it was not an input into our algorithm. Sampling in the RGB space instead of the native ink space has the benefit of sampling the color combinations that are more likely to be used, besides making the technique adaptable to any printer regardless of the number of inks used.

Targets where printed on a representative set of different media, namely: adhesive paper ("Ad. Paper"), adhesive vinyl ("Ad. Vinyl"), bright white bond paper ("Bond"), coated paper ("Coated"), natural tracing paper ("Tracing"), photo gloss paper ("Glossy") and translucent bond ("Trans"). The intention was to cover a vast spectrum of media, rather than including only those that are similar. Each media was linearized independently, and normally have different ink limits. Again, these differences were managed internally by the printer and appear transparent to our technique, which limits itself to characterize the final color output.

Color data was captured with a spectrophotometer Gretag-Macbeth Spectrolino in spectral mode, and data was converted to CIEL*a*b* values using CIE 1931 2-degree color matching functions and D50 illuminant. Differences between CIEL*a*b* values are reported as dE76.

Initial differences among substrates

We compared how different were colors on different media without any kind of adjustment. The differences across media can be very significant, with a mean difference across all media of 12.00 / 20.26 dE (mean / 95 percentile). The two media that are closest ("Ad. paper" and "Coated") are at 2.42 / 4.43 dE. The media that is furthest away from all others ("Ad. vinyl") is at 7.05 / 16.40 dE from the one that is closest ("Glossy") to it. The two most different media ("Bond" and "Glossy") are at 20.29 / 29.71 dE, which indicates probably a bias due to the different color of the media. Figure 3 shows the a*/b* plane projections of the different color gamut contained in the database.

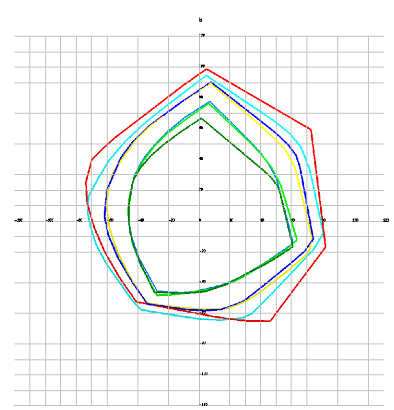

Figure 3*. Gamut projection (a*/b* plane) for the different ICC profiles in the reference database.*

These facts are consistent with the initial goal of covering a large variety of media, and stress the importance of having a specific color profile for each media.

Inter-substrate warping evaluation

We estimated the color accuracy of estimating a uniform 8x8x8 grid from: a) a uniform subset of 3, 4, 5, 6 and 7 points per axis –which contain 9, 64, 125, 216 and 343 samples respectively— (uniform) and b) a sparse optimized sampling set (sparse). This set is a sparse sampling of the device space for which minimizes the estimation error by including as sampling points the maximum contributors to this error. This optimization was performed with knowledge of the finer sampling grid, thus its objective is to find an upper bound of accuracy rather than to be a method that can be used in practice. The optimization was performed individually for every media pair. In both cases, the reference media in each case was optimized according to (step i).

Table 1 contains the results of the colorimetric estimation error for both uniform and sparse approaches. In order to put these values in perspective, it also contains the results of linearly interpolating the measurement samples, without using any information from the reference set.

Table 1: Color differences (dE76) among actual and estimated color measurements

(mean / 95 prc.)	Number of sampling points				
	27 (3^3)	**64** (4^3)	**125** (5^3)	**216** (6^3)	**343** (7^3)
Linear	4.18 / 8.26	2.37 / 4.97	1.65 / 3.62	1.24 / 2.75	0.85 / 2.00
Uniform	1.70 / 3.52	1.02 / 2.36	0.67 / 1.48	0.46 / 1.11	0.34 / 0.84
Sparse	1.49 / 3.04	0.72 / 1.57	0.35 / 0.81	0.14 / 0.41	0.03 / 0.18

It can be appreciated that color errors decrease significantly by the use of a-priori information, and this difference is larger the fewer samples used. For 3 points per axis (27 points), mean color errors are 4.18 / 8.26 dE (average / 95 percentile) for linear interpolation, 1.70 / 3.52 dE for uniform sampling warping and 1.49 / 3.04 dE for sparse sampling warping. This represents a reduction of the mean error in about a 60%. For 5 points per axis (total 125), errors for the warping method are 0.67 / 1.48 dE for uniform and 0.35 / 0.81 dE, against 1.65 / 3.62 dE of linear interpolation (again, a reduction of the mean error around 60%). This is an interesting data point if we consider 1 dE as the threshold of perceptible color difference. At the right-most part of the chart (not shown in the table), for 8 points per axis (total 512), all errors would be zero since this is our reference target. It can be summarized that color differences are reduced by the use of a-priori information for around a 60%. Figure 4 shows the 95th percentile of the estimation statistics.

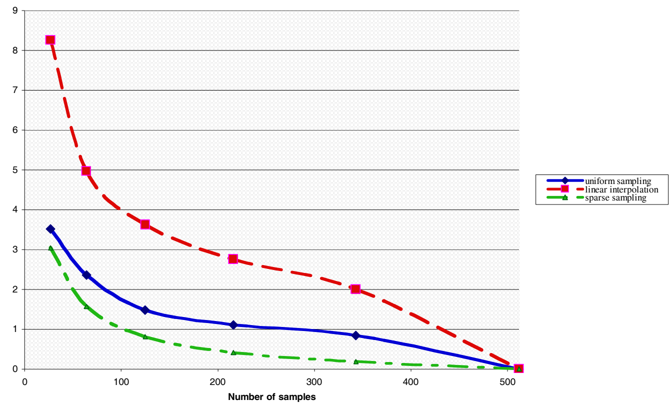

***Figure 4**. Color estimation errors (95th percentile) for linear interpolation (red, dashed), warping on uniform sampling (blue, solid) and warping on optimized sampling (green, dashed-point).*

Conclusions

We presented a technique to predict color measurements on a new media by using color measurements from previously measured and stored substrates. Results of experimental testing show significant improvement by using this technique, with a decrease in colorimetric error of about 60% when compared to linear interpolation. In absolute terms, color error reduction is larger when fewer samples are used. By optimizing the sampling, color differences can be further reduced.

The system showed to be robust to the choice of reference media, as for all cases colorimetric error was bounded. This fact leads us to be optimistic in that the system would be capable of handling a large variety of media. Anyhow, best results are obtained by using the media that is closest. Indeed, the optimal reference can be automatically found by using the small sampling set.

Future work includes the use of other color spaces such as CIECAM Jab, and other grid models, e.g. sparse sampling. Also, the measurement step is only the first step towards color profiling, and therefore the loop needs to be closed to assess the complete system accuracy. ICC profiles v4 will use a reference gamut in the perceptual intent in order to better handle gamut mapping, and might benefit of the warping technique presented in this paper.

In summary, the color space warping technique proved to be effective to improve color accuracy of prediction of a large sample from few samples.

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References

[1] C. S. Haase and G. W. Meyer, "Modeling pigmented materials for realistic image synthesis," ACM Transactions on Graphics, 11: 4, 305-335, 1992.

[2] H. E. J. Neugebauer, “Die theoretischen grundlagen des mehrfarbendruckes,” Zietschrift fur Wis-senschafliche Photographie, Photophysik und Photochemie, 36(4), pp. 73–89, 1937.

[3] J. A. C. Yule and W. J. Nielsen, “The penetration of light into paper and its effect on halftone reproduction,” in Proc. TAGA, 4, pp. 66–75, 1951.

[4] R. Rolleston and R. Balasubramanian, “Accuracy of various types of Neugebauer model,” in Proc. of the First IS&T/SID Color Imaging Conference, Scottsdale, AZ, 2413, pp. 32–37, Nov 1993.

[5] P. Emmel and R. Hersch, “Critical review of spectral models applied to binary color printing,” Color Research and Application 25(1), pp. 4–19, 2000.

[6] P. Soler and J. Arnabat, “Efficient color printer characterization based on extended Neugebauer spectral models,” Proceedings of SPIE 6493-28, San José, CA, January 2007.

[7] M. Shaw, G. Sharma, R. Bala, and E. N. Dalal, “Color printer characterization adjustment for different substrates,” Color Research and Application, 28:6, Dec. 2003, pp. 454-467.

[8] P. Soler and M. Maria, “Inter-substrate warping to predict color from reduced sample sets,” Proceedings of SPIE Vol. 6807, 68070Z (2008).

[9] D. T. Sandwell, "Biharmonic Spline Interpolation of GEOS-3 and SEASAT Altimeter Data," Geophysical Research Letters, 14:2, 139-142, 1987.

Author Biography

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