The Impact of Spectrally-Stable Ink Variability On Spectral Color Management

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Abstract

Typical color image processing techniques use profiles consisting of sparse multi-dimensional lookup tables that interpolate between adjacent nodes to prepare an image for rendering. It has been suggested that spectral image processing could make analogous use of these techniques. A lookup table for spectral matching will relate spectral correlates to values related to printer digital counts. Previous research has shown that within a multi-colorant printer's digital gamut there is often a large amount of spectral redundancy. Thus, without special consideration, it could be possible for adjacent nodes in a lookup table to have spectral consistency but digital count inconsistency. The colorimetric impact of lookup table interpolation within such situations was investigated.

Introduction

Research in the field of spectral hardcopy output has overcome many hurdles over the past five years.[1,2] Publications have described the process of using multiple printing inks to make reasonable spectral matches and have evaluated forward models that relate digital counts to spectral reflectance.[3,4] Investigations focusing on the implementation of the inverse model relating spectral reflectance or spectral correlates to digital counts have also been conducted. Computationally feasible methods have been reported for reducing the dimensionality of 31-band spectral sampling to a 6-ink printer via a multi-dimensional lookup table by deriving weightings from a fixed set of spectral bases.[2,5]

The abundance of spectrally-stable ink variability in multi-ink printers has recently been reported.[6] In many cases distinct ink combinations were shown to approximately produce the same spectral reflectance for linearly independent inks. This paper further explores this phenomenon of spectral redundancy by investigating how it impacts lookup tables that convert from spectra to digital counts.

Spectral Color Management

The goal of spectral color management is to accurately reproduce the spectral reflectance of the original imaged scene. The advantage of a spectral match is that a color match will be maintained for all observers across any illumination. A spectral color reproduction chain differs from an ICC color reproduction chain in that the source and destination profiles would relate digital counts to spectra instead of colorimetry. Because of the tremendous dimensionality of spectral space, implementation of the spectral color management workflow requires a stage where spectra are decomposed into a set of basis functions that are used as indices into the destination profile lookup table.[2] A diagram of a realizable spectral color management workflow is shown in Figure 1.

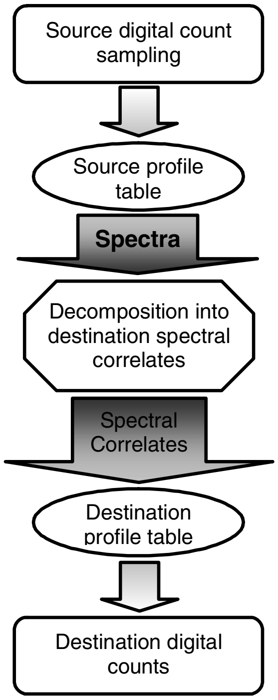

Figure 1. Realizable spectral color management workflow.

The efforts of this research are focused on the influence of spectrally-stable ink variability when developing the destination profile table.

Spectrally-Stable Ink Variability

It has recently been demonstrated that multi-ink printers can often approximately reproduce a spectral reflectance with many different ink combinations.[6,7] Due to sources of error in measurement and printing systems, two spectra are considered a match only when a tolerance range is specified. In addition to noise, two spectral curves are also considered spectrally similar when they fall within the application specific tolerance range.

To determine how spectrally-stable ink variability influences multi-dimensional lookup tables, a CMYKGO inkjet printer was spectrally characterized using a gamut-wide brute force technique that interpolates spectra from a factorial sampling of area coverages in colorant space.[4,6,7] During the characterization process, 4^6 or 4,096 samples that represent the midpoints of each six-dimensional hypercube in the characterization lookup table were also printed. The midpoints were described by the factorial design of the fractional area coverages of 12.5%, 37.5%, 62.5%, and 87.5%. The midpoint dataset was originally designed to evaluate the accuracy of the forward printer model; it was also used to reveal the relationship between spectrally-stable ink variability and the spectra prediction when interpolating between nodes in a multi-dimensional lookup table.

An algorithm was developed to systematically uncover how much individual ink could be varied from its original amount and still maintain spectra.[6,7] The analysis was performed for each measured spectral reflectance of the midpoint dataset. Initially, one of the six inks is selected and systematically incremented or decremented by 1 digital count (depending on the starting digital count value) from its initial value. The nonlinear optimization routine inverted the characterization lookup table and was allowed to vary the other five inks to attempt to make the best spectral match possible while keeping the area coverages of the unconstrained inks between 0 and 1. This process was repeated until every ink was constrained at every digital count value from 0 to 255 for the entire midpoint dataset. The ink combination that produced the smallest spectral difference was returned from the routine. The advantage of this algorithm is that it is independent of the spectral difference metric. For this analysis, spectral RMS was used as the spectral difference metric, although many others could have been selected.[8]

The Influence of Spectrally-Stable Ink Variability on Multi-Dimensional Lookup Tables

Typically, the forward printer model that relates digital counts to spectra is not easily invertible. To populate a multi-dimensional lookup table that relates spectra to printer digital counts, search methods are used to accurately guess the digital counts that produce a requested spectral reflectance. Spectrally-stable ink variability can cause unexpected results at this step in the spectral color management chain.

Figure 2 shows the process for populating a multi-dimensional lookup table that relates spectra to digital counts. This diagram assumes that the dimensionality of the input spectra has been reduced and the multi-dimensional lookup table will relate spectral correlates to printer digital counts.

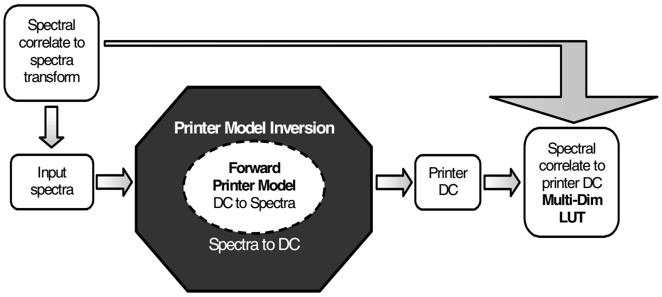

Figure 2. The process needed to produce a spectral reflectance to digital count multi-dimensional lookup table.

Because of spectral redundancy, it is possible that a variety of digital count combinations could be used to match a given spectrum. The consequence of this is that adjacent nodes in spectral space could have widely varying six-ink digital count combinations.

Experimental

To demonstrate the outcome when adjacent LUT nodes are inconsistent in output digital counts, the results of the spectrally-stable ink variability analysis on the midpoint dataset were used. For each node in the midpoint dataset, the maximum digital count distance an ink could be moved while maintaining the measured spectral reflectance within a 0.02 spectral RMS was chosen for each ink. Therefore, every node in the midpoint dataset had six sets of digital count combinations where one set corresponded to each of the six inks.

Ramps of spectral interpolations were computed between an original six-ink combination at a node and the original six-ink combinations at every adjacent node. The interpolation distances selected were 25%, 50%, and 75% of the entire distance between the nodes. Adjacent nodes here had digital count consistency.

Similar ramps were then computed for adjacent nodes that did not have digital count consistency. This was accomplished by using the digital count combinations that were derived from the spectrally-stable ink variability analysis explained above. Spectral interpolations were made at the same intervals between each of the six selected digital count combinations from the spectrally-stable ink variability analysis and the original six-ink combination at every adjacent node.

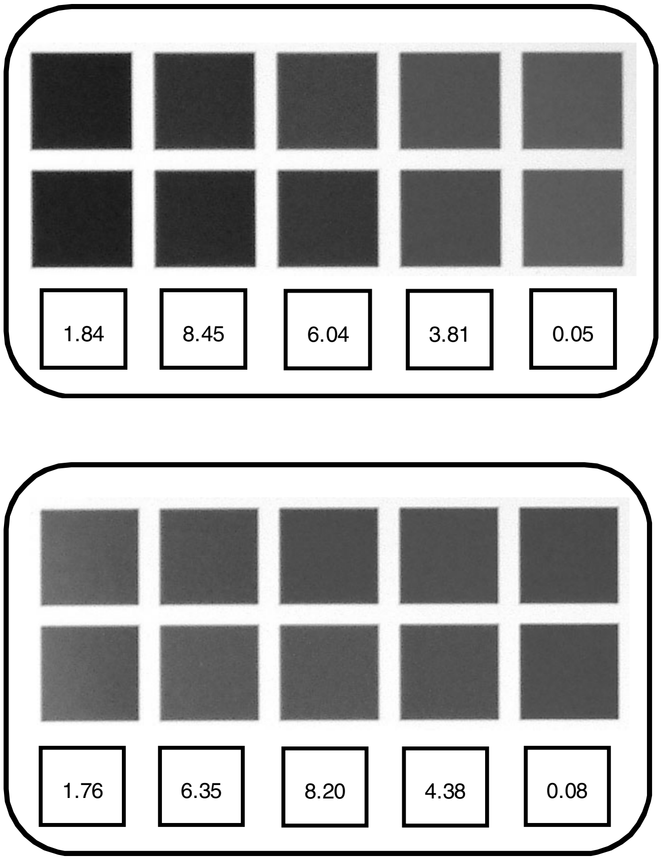

Figure 3. Demonstration of colorimetric errors for two ramp sets that occur when adjacent nodes do not have consistent digital counts. The top row ramp was made from patches with inconsistent digital count combinations between end nodes. The bottom row ramp has consistent digital count combinations. Colorimetric error is reported in ΔE_{00} units.

Illustrations of results from printed samples are shown in Figure 3. When comparing the interpolation ramps reproduced in Figure 3, the patches on the left end have spectrally similar reflectances, and the patches on the right end had exactly the same digital count combinations. The left and right end patches for the second row had consistency between digital count combinations. The left and right end patches for the top row were digitally inconsistent. Colorimetric differences between patches for the two ramps are reported in the boxes below the patches. The small colorimetric errors between the patches on the right for both ramp sets are caused by printer engine variation.

Shown in Figure 4 are the associated colorimetric plots in the CIELAB a*, b* plane for each ramp set. Note that the largest colorimetric difference does not necessarily occur at half the interpolation distance.

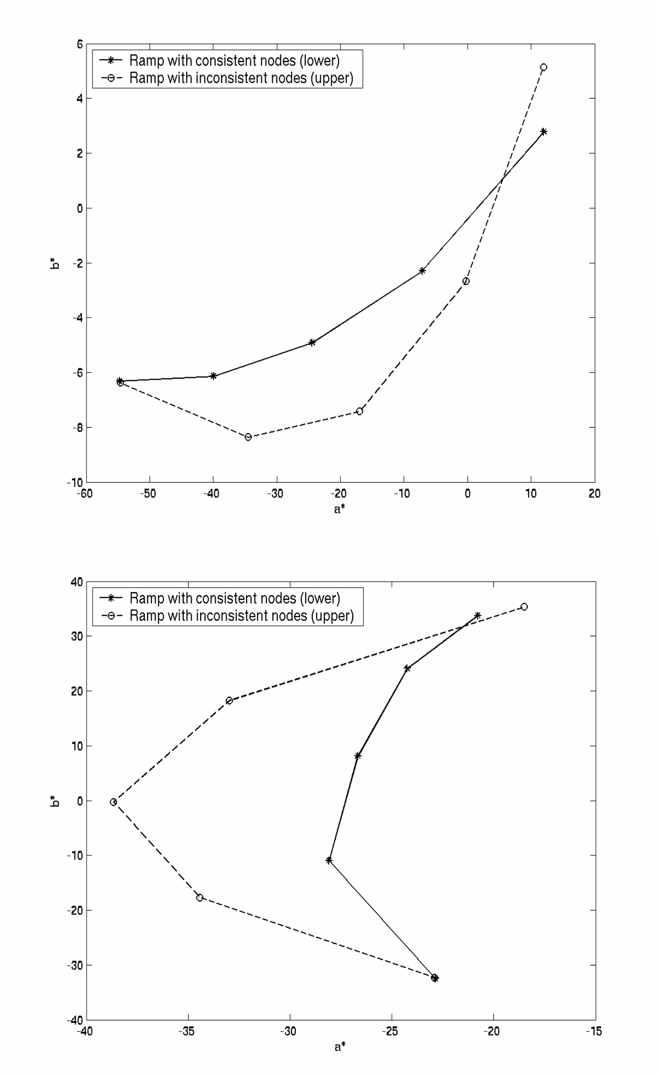

Figure 4. Colorimetric plots associated with the ramps in Figure 3. The first plot corresponds to the first interpolation example shown in Figure 3.

Conclusions

The importance of having digital count consistency between nodes in a spectral color management lookup table has been demonstrated. An algorithm developed to uncover spectrally-stable ink variability was effective in identifying examples where inconsistent digital count combinations at spectrally adjacent nodes could cause troublesome colorimetric results. Demonstrated were errors exceeding 8 ΔE_{00}. These findings highlight the fact that when building lookup tables for use in spectral reproduction, consistency in the digital domain must be maintained.

References

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Biography

Edward F. Hattenberger received his B.S. degree in Environmental Resources and Forest Engineering in 1999 from SUNY College of Environmental Science and Forestry and his M.S. degree in Color Science from the Rochester Institute of Technology in June of 2003. In July, he retired from the academic world and began working at Hewlett Packard in Idaho as a Color Scientist.