8 vertex HANS: An ultra-simple printer color architecture

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Abstract

The underlying non-linearity of how print colorants combine makes color control in printing significantly more complex than for other color imaging devices. While in additive systems a measurement of their few primaries and per-channel non-linearities versus luminance is a sufficient basis for predicting color output, printing typically requires the measurement of a large number of colorant combinations. This requirement for many measurements makes accurate color output more challenging and means that setting up a printing system's color control can be time consuming and costly. The solution presented in this paper involves a new use of the HANS approach, which instead of print optimization looks for simplifying print color formation and therefore also control. In a nutshell this can be achieved by only ever combining eight basic colorant patterns, which results in a display-like color gamut and allows for color control on the basis of their eight measurements and those of the printing system's optical dot gain.

Introduction

An important part of the preparing a printer or press for production is to ensure color accuracy and consistency, which are driven by having an accurate ICC color profile (or proprietary device-link) and up-to-date color calibration data respectively.

The two aspects of accuracy and consistency are typically split since the former tends to require hundreds to thousands of color patches being printed and measured while the latter can be achieved using tens to hundreds of samples, depending on the specific marking engine and printing system design. Since profiling and calibration are costly, their frequency has to be balanced against the customer complaints that they can help to avoid. Profile and calibrate too rarely and you risk more jobs that have to be re-printed with manual intervention, do it too often and you eat unnecessarily into your profits.

The underlying challenge here is that print color control requires large numbers of color patches to be printed and measured, to obtain a good characterization of what colors will result for different digital inputs. The root cause of these requirements is that printing systems are ultimately controlled in terms of colorant amounts, which are very non-linearly and multi-dimensionally related to color (Yule and Nielsen, 1951).

Furthermore, these colorant amounts are the result of a color separation mapping values from a device color space like CMYK or RGB, on top of which ICC profiles are built. Such device color spaces are even further removed from colorant patterns on media, which makes the relationship between them and print color even more complex.

As a consequence, large numbers of samples are needed to accurately represent the multi-dimensional non-linearity between either colorant or device color space vectors and print color and while there have been several attempts to optimize these (e.g., Monga and Bala, 2008; Morovič *et al.*, 2010; Bianco and Schettini, 2012), the end result is still in the high tens or low hundreds.

Instead of taking a printing system as is and looking for ways to optimize its color characterization and calibration, the approach taken here follows a fundamentally different path. It asks what printing system could be fully characterized in ways similar to those used for displays and arrives at a particular solution. The following sections will therefore first present a brief summary of Halftone Area Neugebauer Separation (HANS), which enables the new solution, proceed to describing how HANS can be used in a new way to result in a printing system characterized by eight colorant patterns and finally show results for driving a printing system using the new approach.

Halftone Area Neugebauer Separation

Instead of operating in a colorant space, the key feature of HANS (Morovič *et al.*, 2011) is that it addresses a printing system in terms of Neugebauer Primary relative area coverages. E.g., for a printer with three inks – CMY, it doesn't specify output only in terms of ink use (e.g., [C, M, Y]=[30%, 40%, 0%]), but instead determines area coverages for the system's Neugebauer Primaries: e.g., [W, C, M, Y, CM, CY, MY, CMY] = [50%, 20%, 10%, 0%, 20%, 0%, 0%, 0%] (Figure 1).

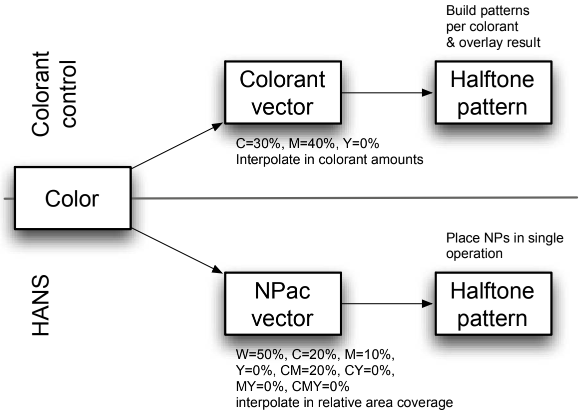

Figure 1. *HANS basics.*

The result is not only greater control and the ability to access a greater variety of halftone alternatives per color (yielding metamers even in the three colorant case (Morovič *et al.*, 2011b)), but also a fundamental additivity. Given Neugebauer Primaries of measured colorimetry and a system with measured dot gain, the color of a particular halftoned colorant pattern is the convex combination of the NPs' colorimetries in Yule-Nielsen corrected CIE XYZ. Note, that in an actual printing system, its optical and mechanical dot gain are only some of the mechanisms that are involved in color formation, and that the use of a Yule-Nielsen corrected CIE XYZ space is an approximate, whose accuracy for a test system will be reported later in this paper. While all this is on the color formation side, the key to arriving at a more easily characterizable printing system is the fact that with HANS, print is controlled in area coverage terms that do have the above, approximate additivity and convexity properties which allow for successful linear print control.

A minimal print color architecture

While HANS directly results in the potential to characterize color on the basis of printing and measuring a printing system's primaries (i.e., directly measuring the NPs within a substrate's colorant limit and inferring the colorimetry of the other NPs' colorimetries from printing and measuring their combinations with a within-limit NP, e.g., the blank substrate) and characterizing its dot gain (by printing and measuring ramps of NPs and minimizing the error between these measurements and the predictions made from NP measurements for different levels of the Yule-Nielsen n exponent), that would still result in potentially large numbers of measurements. E.g., for a printer with six inks (CMYKcm) and capable of overlaying up to 3 drops per ink per pixel, there are 4^6=4096 NPs. Furthermore there is the difficulty of printing and measuring NPs whose total ink use exceeds the limit that a given substrate is capable of supporting. With such constraints, a characterization of a printing system's full set of NPs can become even more costly than the generation of regular profiling and calibration data.

To arrive at the simple solution proposed here, it is necessary to combine two realizations – that convex combination is associative and that print color gamuts are like distorted cubes – and these will be presented in more detail next.

Associativity of convex combinations

In its most basic instantiation, halftone print color formation consists of the convex combination of the colors of the Neugebauer Primaries (NPs). E.g., a pattern C that is formed by combining some of a printing system's NPs, can be characterized by its NP area coverage (NPac) vector – $NPac_C$, which is of the following form:

$$T(NPac_C) = \sum_{i=1}^{k^n} (w_{Ci} * T(NP_i)) \quad (1)$$

where k is the number of colorant levels per colorant per pixel, n is the number of colorants, $\sum_{i=1}^{k^n} w_{Ci} = 1$ (i.e., the weights are convex), NP_i is the i-the NP, and $T()$ is color (in this case its Yule-Nielsen corrected colorimetry).

The key insight here is that this convex combination of relative area coverage weighted NP colors can also be seen as the convex combination of two constituent patterns – CA and CB (e.g., a pair of patterns that were individually determined and that can give rise to a continuum of patterns between them in the way laid out below) – such that:

$$w_{Ci} = w_{CBi} + w_{CAi} \quad (2)$$

Furthermore, each of the constituent sub-patterns of C (i.e., CA and CB) also has an equivalent, full pattern (A and B), whose weights relate to the sub pattern's weights as follows for A (and equivalently for B):

$$w_{Ai} = \frac{w_{CAi}}{\sum_{j=1}^{k^n} w_{CAi}} \quad (3)$$

Having arrived at the weights of A and B (corresponding to the CA and CB constituents of C), the pattern C can now be expressed as a convex combination not of NPs but of the NPacs A and B:

$$T(NPac_C) = x * T(NPac_A) + y * T(NPac_B) \quad (4)$$

where

$$x = \sum_{j=1}^{k^n} w_{CAi}\, , x = \sum_{j=1}^{k^n} w_{CBi} \;\; and \; x + y = 1 \quad (5)$$

As a consequence of associativity (already hinted at in Morovič *et al.* (2011)), we can therefore perform convex combinations not only of at-pixel states (i.e., the Neugebauer Primaries), but also of a pattern's sub-patterns. When approached from the other end of the process, we can construct new NPacs by convexly combining other NPacs and this process can, in principle, go on *ad infinitum*.

To illustrate this property, Figure 2 shows a transition from C=10%, CM=50% and W=40% to K=30%, M=20% and W=50%, which simply involves linearly varying the area coverages of all involved NPs. Then the mid-point between these two patterns is K=15%, M=10%, W=45%, C=5% and CM=25% CM and results in a color that is half-way between the initial patterns' colors in XYZ^n (i.e., it is an equal weighting of the initial patterns' NPacs). Furthermore, all colors obtained by transitioning between these two end points lie on a straight line.

The key here is that such transitions are linear and yield a convex color gamut, unlike the result that would be obtained from attempting the same in a colorant space instead of the area coverage space used here (measurements for an transition in ink space are also plotted at the top of Figure 2).

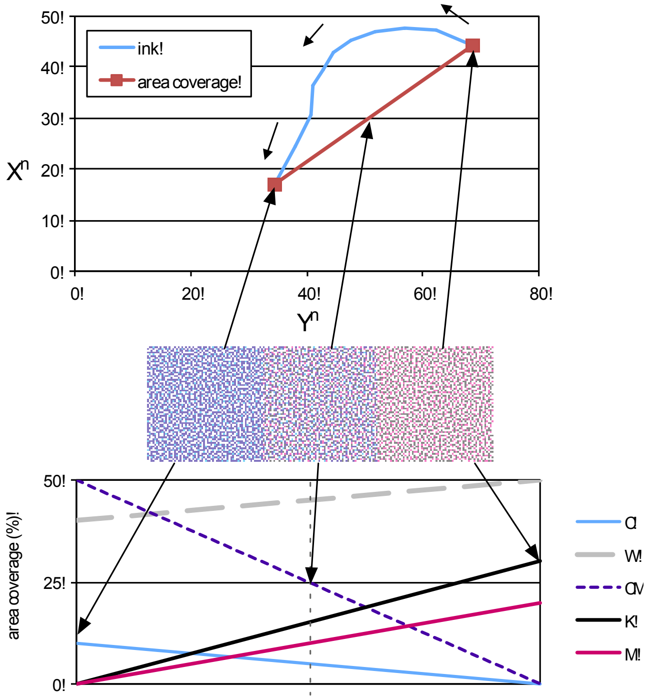

Figure 2. Transitioning in Neugebauer Primary area coverages: (top) Non-monotonicity of ink space v. linearity of area coverages, (center) halftones corresponding to area coverage transition (bottom) area coverage transition.

Cube-shaped gamut

The second piece that is needed for exercising efficient print color control is the realization that the color gamut of imaging devices resembles a distorted cube. This insight was already made by Herzog (1998), who took advantage of it for the purposes of color gamut computation, while here it allows for the formation of a well-behaved color gamut that is the convex hull of only eight vertices.

The eight–pattern printer

Armed with the above concepts, HANS can be used to construct NPac combinations, each aimed at providing a color that will serve as the white, black, red, green, blue, cyan, magenta and yellow of a color gamut, with the expectation that their combinations will form a convex, well-behaved device color gamut. The result then is a way of controlling print such that every color is printed with a weighted combination of up to four of these eight basic NPacs. To determine these eight NPacs, the following one-off process can be applied to any set of print colorants (Figure 3):

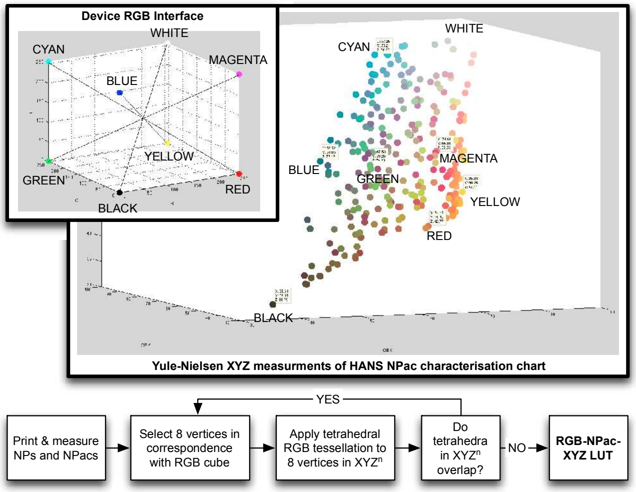

Figure 3. *Determining the eight vertices of a minimal color separation.*

1. Print and measure a set of representative NPacs. These can be a set of all Neugebauer Primaries or have other NP combinations added to the (e.g., to exercise control over the lightnesses at which patterns are available in the CMYKRGB regions where patterns are sought).
2. The measurements from step 1 represent the full color gamut of the printing system and the pool from which eight patterns can be selected to correspond directly to vertices of an RGB cube (black, red, green, blue, cyan, magenta, yellow and black). This can be done by hand (choosing based on XYZ^n) or algorithmically, as follows:
   a. Select the darkest XYZ^n as the black, the lightest as the white.
   b. Sequentially choose pairs of "opposite colors": Blue and Yellow (Red–Green and Cyan–Magenta) by selecting XYZ^n measurements that are far from each other, perpendicular to the White-Black axis and that maximize angles relative to the other opposite color axes. Keep evaluating alternatives until the largest volume is enclosed by the convex hull of the eight vertices.
   c. Assign each of the eight selected patterns to a vertex of an RGB cube.
   d. Perform a tessellation of the above eight vertices in RGB such that each tessellating tetrahedron is aligned with the RGB space's black to white axis. Ensure that no inversions are present when the RGB tessellation is applied in XYZ^n either.

The resulting 8 vertices (with their colors and NPacs) correspond to vertices of the RGB cube and form the full color separation. Transitions between them will be smooth, since they correspond to transitions in area coverages and if the printer or press changes over time, it is only necessary to print these eight vertex NPacs to either calibrate for variation from a previous state or to generate an accurate ICC profile.

To apply the resulting color separation, the following process is used:

1. For an input RGB value, find its enclosing tetrahedron from among the six tetrahedra that span the full RGB cube (each tetrahedron having the following vertices: white, black, a primary (R,G or B) and a secondary (C, M or Y)).
2. Compute the input RGB's barycentric coordinates inside its enclosing tetrahedron as follows:

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix}^T = \begin{pmatrix} S_R \\ S_G \\ S_B \\ 1 \end{pmatrix}^T \times \left(\begin{pmatrix} V_{1R} & V_{2R} & V_{3R} & V_{4R} \\ V_{1G} & V_{2G} & V_{3G} & V_{4G} \\ V_{1B} & V_{2B} & V_{3B} & V_{4B} \\ 1 & 1 & 1 & 1 \end{pmatrix}^T \right)^{-1}$$

   where V_i ($i \in [1,4]$) are the enclosing tessellation's vertex RGBs, S is the input RGB and b_i are the resulting barycentric coordinates.
3. Compute the area coverages of the system's NPs as follows:

$$ac_i = \sum_{n=1}^{4} b_n * ac_{n,i}$$

   where ac_i is the output area coverage of the i-th NP, b_n is the barycentric coordinate of the n-th vertex of the enclosing tetrahedron from step 2, and $ac_{n,i}$ is the area coverage of the nth vertex's i-th NP.

For more detail of how NPacs are computed from a tetrahedron, see a previous journal article (Morovic et al., 2011).

Experimental setup

To test the above approach, prints were made on a HP Designjet Z6200 printer using pigmented CMYK inks on a 90 g/m^2 HP Coated Paper substrate. Measurements of an 8^3=512 color test chart were made using the printer's embedded 45°/0° spectrophotometer under D50 illumination and color differences were computed using the CIE ΔE2000 color difference equations between the chart's measurements and their predictions using the eight RGB vertex measurements + an estimate of the printer's dot gain alone.

Results

The first point to note about the 8-vertex color separation is that it results in a very well behaved printing system, with very smooth transitions and a color gamut that has the hallmarks of traditional print color gamuts. Figure 4 shows both a photo of the test chart, where each patch is the combination of at most four of the eight basic NPacs, and the color gamut of its measurements.

What is noteworthy about this 8-vertex print color gamut is the convexity of its entire boundary, which also results in gamut mapping to it being free of the challenges and likely artifacts that mapping onto concavities brings (e.g., having to deal with the absence of a unique difference minimizing mapping).

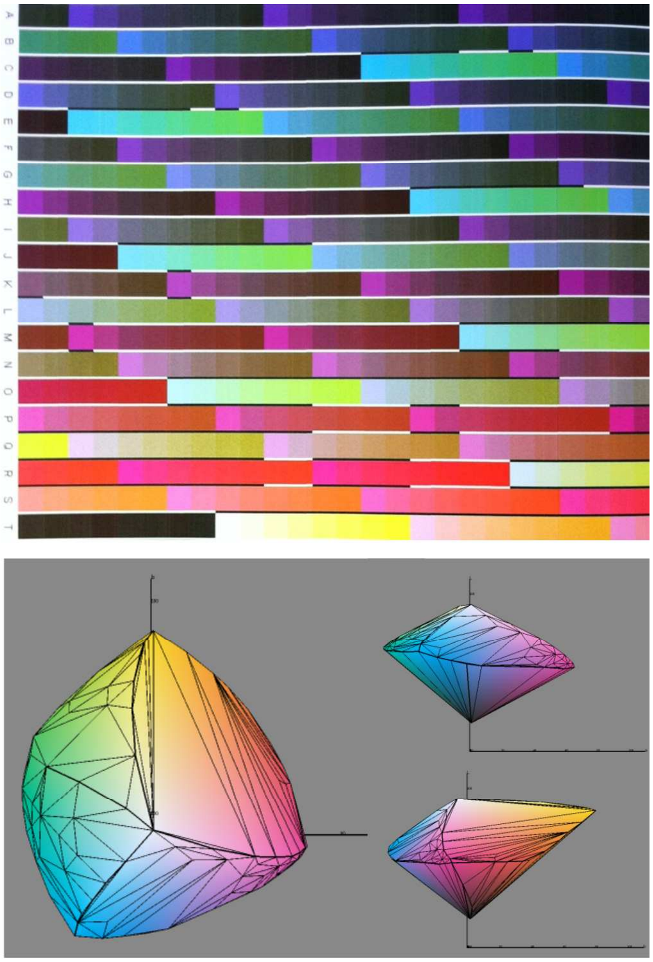

Figure 4. *(Top) photo of printed chart sampling full gamut and (bottom) gamut of its measurements in CIE LAB.*

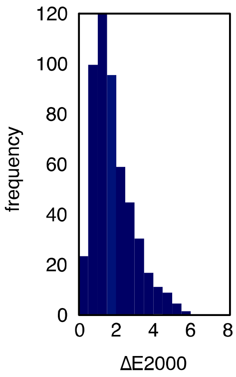

Figure 5. *Distribution of color differences between 512 measured color patches and their predictions from the measurements of the eight vertices of the device RGB cube.*

Turning to colorimetric accuracy, the results depend very strongly on how well the dot gain of the system can be characterized. When this is done by taking into account a broad variety of colorant-substrate interactions, the ΔE2000 distribution shown in Figure 5 can be obtained, with a mean of 1.59, a 95^{th} percentile of 3.96 and a maximum of 5.54.

If the non-linearity of the systems is less well characterized, color differences can easily exceed 10 ΔE. However, the characterization of a printing system's non-linearity only needs to be performed once per substrate type as it is a consequence of a printer's marking engine, halftoning and colorant properties. Once non-linearity is characterized, color control can be exercised successfully on the basis of measuring only the eight basic colorant halftone patterns that are the basis of forming all of the printing system's colors.

Conclusions

The aim of this paper was to introduce an ultra-simple approach for print color formation and control that allows for an entire printing system to be characterized by eight halftone patterns and the system's dot gain. The results of a prototype of the system show the potential for great accuracy and consistency at minimal set-up cost.

Finally, it is worth noting a limitation that this approach introduces, which is that it does not use the full color gamut of a printing system, but only its largest eight-vertex convex subset. However, in many cases this theoretical constraint represents little or no loss. E.g., in the case of only having CMYK inks to being with, the gamut is already close in shape to the constraint. Also, in the case of standards-based workflows, printers already don't use all of their native gamuts and it is then the relationship between the standard reference and the eight-vertex gamut rather than versus the full, native gamut that matters.

The benefits of the ultra-simple pipeline, with minimal color setup requirements (being the printing and measurement of only eight color patches) and with a convex, 'flat-faced' gamut, obtainable using an 8-node look-up table, in many applications (e.g., general commercial printing, signage, transactional) outweigh the loss of some of the system's potential color gamut. Where production efficiency and reliability are key, this extreme case of simplicity adds clear value.

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Ján Morovič received his Ph.D. in color science from the Colour & Imaging Institute of the University of Derby (UK) in 1998. After working there as a lecturer in digital color reproduction, he became senior color scientist and later master technologist at Hewlett-Packard in Barcelona, where he has been since 2003. He is also the director of the CIE's Division 8 on Image Technology and Wiley and Sons have published his 'Color Gamut Mapping' book.

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