Optimizing HANS Color Separation: Meet the CMY Metamers

Peter Morovič, Ján Morovič, Juan Manuel García-Reyero
Hewlett Packard, Sant Cugat del Vallés, Catalunya, Spain

Abstract

HANS – the Neugebauer Primary based color separation and halftoning print control approach – was presented in broad terms at CIC18. The present paper provides an in–depth look at how HANS color separation can be optimized, what level of variety it provides access to and how it can be used for direct optimization of print attributes. The results show that even in the case of having only three colorants – CMY, where current approaches lead to unique solutions, HANS provides significant metamer sets that lead to variety in print attributes such as the 12.7% ink use range show in the results.

Introduction

Print has many uses, each of which has different requirements in terms of print attributes. Professional photographers tend to focus on image quality, color accuracy and color gamut while print service providers pay close attention to cost and throughput. Architects and engineers care more about line and small text quality for their drawings, while looking for pleasing appearance in prints made of rendered work. The level at which each of a print's attributes is achieved then depends on the materials used (inks, toners, substrates, varnishes, etc.), on the imaging technology and also on the color separation and halftoning algorithms used. Direct optimization of print attributes and their explicit trading–off is highly desirable, since color resources need to be tuned to individual substrate types and since a single printer model is typically aimed at more than one target use case. Having to tune resources by hand becomes costly and unreliable and also has to deal with the challenges of transitioning between individually chosen colorant combinations (Morovic, 2007). A solution to this problem is the Halftone Area Neugebauer Separation (HANS) approach presented at CIC18 (Morovic *et al.*, 2010), which both gives access to a larger set of printable halftone patterns and allows for explicit optimization of print attributes.

While the HANS approach was sketched out previously (Morovic *et al.*, 2011), details of its color separation optimization will first be presented here. A brief summary of HANS will be followed by a detailed exposition of its optimization framework and the paper will conclude with results for the simple case of a printer with CMY inks and a bi–level halftoning mechanism.

HANS

While color separation has traditionally been thought of as the process of making choices about how much of each available colorant to use for each printable color, HANS changes the domain in which choices are made. Since print properties depend not only on colorant amounts, but also on the way in which the colorants are overprinted (or not), HANS color separation specifies relative area coverages of a printing system's at–halftone–pixel states (the Neugebauer Primaries) (Figure 1). This move not only makes print control more direct, but it also unlocks a vastly greater space of printable patterns than a colorant space allows. The reason for this

is that while a bi–level printing system with CMYK inks can specify output in a 4D space when controlled in terms of colorants, a switch to HANS gives access to a 2^4=16D space where choices can be made. Having k levels to halftone to (e.g., in a printer that can deposit up to two drops at the same printed location k=3) and n inks, gives HANS a k^nD space in which to specify output. Such increased variety of printable patterns in turn leads to improved print properties such as being able to address 10% more color gamut while using 20% less ink than is currently possible on a CMYKcm printer (Morovic *et al.*, 2011).
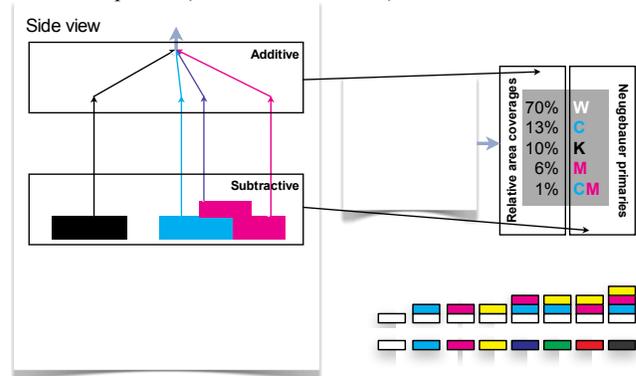
Figure 1: Print anatomy.

To take advantage of the potential HANS offers, it is necessary to first have a means for assigning Neugebauer Primary area coverages (NPacs) to printable colors and then to generate halftone patterns based on those NPac specification (Figure 2). As was presented previously, the halftoning part of the process can be achieved using error diffusion, where the error is diffused in the NPac space. For the color separation stage – i.e., colorimetry to NPac mapping – the present paper will introduce a general framework next followed by results for the simplest colorant case: CMY.

Optimization framework

To find a mapping from colorimetry to NPacs, the difference in domain dimensionality between the two spaces needs to be addressed first. While colorimetry is 3D (whether in CIE XYZ, LAB or other spaces), the domain of NPacs is typically of a much higher dimension. Consequently, the mapping is one–to–many and there are numerous NPacs that correspond to the same colorimetry – *NPac metamer sets*. The set of NPacs that map to the same colorimetry will, however, vary in other attributes such as grain, ink-use, color constancy, etc. The following first looks at how to solve for the set of all metamers, which is the set over which an optimization of print attributes is then performed.

Fundamental to HANS is the assumption of a convex relationship between NP area coverages and resulting colorimetries: an NPac composed of two NPs at 50% area
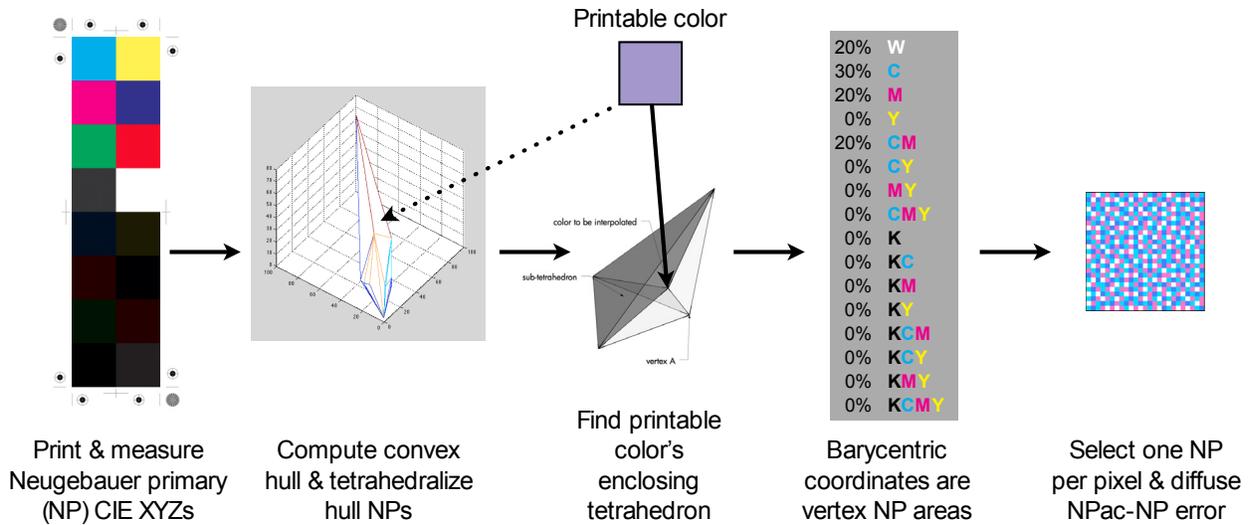
Figure 2: HANS workflow for simplest color separation setup via NP convex hull tetrahedralization and using error diffusion halftoning.

coverage each has a colorimetry that is a 50% weighted sum of the constituent NPs' colorimetries. Actual printing systems depart significantly from such a simple relationship though, due to optical and physical dot-gain, noise and drop shape. Globally and non–linearly transforming the CIE XYZ space (e.g., as in the Yule–Nielsen modification of the Neugebauer Model (Yule and Nielsen, 1951)) can greatly improve the fit between the convexity principle and colorimetry obtained from print measurements, as will be shown in the results section.

Since combining area coverages of NPs amounts to convex combinations of their colorimetries, the convex hull of all NPacs corresponds to the convex hull of their colorimetries. Without loss of generality, colorimetry will be referred to as being in XYZ space and behaving convexly with respect to NPacs, although convexity in a globally and non–linearly transformed XYZ may be used in practice.

The colorimetric convex hull is obtained by first defining a set of *base NPacs*. This set determines the total gamut a given system will be able to reach and serves as a set of building blocks for all patterns interior to the gamut. The base NPac set consists of:
1. The Neugebauer Primaries at 100% area coverage that are within the ink limit (i.e., the maximum amount of ink that a substrate can hold without artifacts and structural defects),
2. a mapping of the remaining NPs that are beyond the ink limit onto it (i.e., by assigning these NPs a <100% area coverage and adding other NPs to it to bring the resulting NPac to the ink limit), and
3. additional NPacs needed to span the full convex hull of possible NPacs. This convex hull is the result of intersecting the full NP simplex with a hyperplane at the ink–limit.

These base NPacs are halftoned, printed and measured to obtain their colorimetries, which then characterize a system in terms of the volume of colorimetries and volume of NP area coverages that are possible. While colorimetries of the convex hull vertices have unique correspondence with NPacs, this is not true for all colorimetries interior to the gamut or even on parts of its surface. This is analogous to what happens in image capture where monochromatic signals have single member metamer sets, while

colors towards the center of the gamut (e.g. a medium-gray) will have metamer sets of the largest volume (Morovic, 2002).

The metamer set of a colorimetric sample S in NPac space can be computed analytically as a half–plane intersection problem. However the dimensionality of this computation equals the number of base NPs (or NPacs if ink limits are in place), which can range into the hundreds and is therefore prohibitive. Therefore, NPac metamer sets are computed by a polyhedral search instead:
1. Given a set of p NPs and their measured colorimetries, form all $\sum_{n=4}^{p} \binom{p}{n}$ polyhedra with up to n vertices (n [4, p]) in the colorimetric space.
2. For a given color S with XYZ of $[S_X, S_Y, S_Z]$, whose metamer set is to be found, compute its barycentric coordinates $[b_1, b_2, ..., b_p]$ with respect to each of the polyhedra formed by vertices $[V_1, V_2, ..., V_p]$ from step 1. In the case of a tetrahedron, where $p=4$, finding the barycentric coordinates amounts to solving the following equation:

$$
\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix}^T \times \begin{pmatrix} V_{1X} & V_{2X} & V_{3X} & V_{4X} \\ V_{1Y} & V_{2Y} & V_{3Y} & V_{4Y} \\ V_{1Z} & V_{2Z} & V_{3Z} & V_{4Z} \\ 1 & 1 & 1 & 1 \end{pmatrix}^T = \begin{pmatrix} S_X \\ S_Y \\ S_Z \\ 1 \end{pmatrix}^T
$$
(2)

The matrix with the XYZ values of the tetrahedron vertices can be inverted, thus directly giving a solution vector. Equation 2 is the system formed by three equations expressing how S is the convex combination of V_1 to V_4 and the equation of b_1 to b_4 (the convex weights) summing to one. If all members of b are from [0,1], S is inside the polyhedron. Furthermore, since b represents normalized volumes of sub-tetrahedra formed by sets of three original vertices and S (for the original vertex that S substitutes), they are also the relative area coverages with which tetrahedron vertex NPs need to be combined. Note however that Eq. 2 is well formed only for tetrahedra, while it becomes under-determined for pentahedra and higher, in which case the above equation would yield a single solution out of a convex set of possible ones.
3. The set of NPacs obtained from step 2 delimits the metamer set of color S in NPac space. Note that due to the convexity of the

NPac space, the metamer set can be further sampled by generating arbitrary convex combinations of NPacs obtained from step 2.

While Eq. 2 is well formed and uniquely solvable for tetrahedra, it can be written for higher-degree polyhedral easily as follows:

$$
\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ \vdots \\ b_p \end{pmatrix}^T \times \begin{pmatrix} V_{1X} & V_{2X} & V_{3X} & V_{4X} & \ldots & V_{pX} \\ V_{1Y} & V_{2Y} & V_{3Y} & V_{4Y} & \cdots & V_{pY} \\ V_{1Z} & V_{2Z} & V_{3Z} & V_{4Z} & \cdots & V_{pZ} \\ 1 & 1 & 1 & 1 & \cdots & 1 \end{pmatrix}^T = \begin{pmatrix} S_X \\ S_Y \\ S_Z \\ 1 \end{pmatrix}^T \quad (3)
$$

Equation (3) is no longer well-formed and has a set of solutions by virtue of being under-determined. The set of these solutions (sets of $[b_1, b_2, b_3, \ldots, b_P]$ vectors) itself is a convex set. However, in order to have a higher-dimensional representation, a single solution can be obtained by means of a pseudo-inverse. Denoting B_p the $1xp$ column vector of barycentric coordinates on the left hand-side of Eq. 3, S the $1x4$ vector containing the sample XYZ and a 1 and V_p the $px4$ matrix of vertex XYZs padded with 1, the solution can be obtained as follows:

$$
B_p V_p = S
$$
$$
B_p V_p V_p^T (V_p V_p^T)^{-1} = S V_p^T (V_p V_p^T)^{-1} \quad (4)
$$
$$
B = S V_p^+
$$

The set of all possible barycentric coordinates within all possible polyhedra that, when combined as NPac weights, match a given colorimetry is therefore the metamer set.

Since for any one colorimetry, a single NPac has to be selected in order to construct a colorimetry to NPac mapping, the metamer sets represent the domain over which this choice is made. The choice of a metamer will depend on print-attribute considerations, such as selecting the metamer that at each colorimetry uses least ink, or the metamer that results in least grainy patterns, is most color constant, etc., or any weighted combination of these. Since this approach solves the complete set of metamers, the patterns that are the results of all possible traditional color separation and halftoning configurations are a subset of this metamer set.

Test set-up

To test the HANS optimization framework presented above, a HP Designjet Z3200 printer was used. While this printer has 11 inks: CMmYnNkKRGB (where n and N are grays – 'neutrals'), only three of them: CMY, were used. The reason for selecting three inks only is that in that case, colorant–based color separations provide no redundancy and therefore lead to single ink combinations per printable color. Any redundancy (metamerism) delivered by HANS will therefore be down to the variety it gives access to over and above current methods. The substrate on which prints were made was a HP Super Heavyweight Coated Paper and all color measurements were made using an XRite i1 0°/45° spectrophotometer embedded in the printer. All color differences were computed using the CIE ΔE2000(1:1) color difference metric (CIE, 2001) and the Yule–Nielsen modified Neugebauer model used here (with n=4) had a median error of 5.2 ΔE2000 with a 95th percentile of 12.9. Note that these model errors would not be the errors of prints made with the resulting system, since it would have an ICC profile built on top of the colorimetry to NPac mapping.

Instead they do limit the accuracy of the metamer sets and the optimality of the choices made from them.

Results

Figure 4: A visualization of 115 metamers: each row represents an NP area coverage vector where constituent color block lengths are proportional to the corresponding base NPac color's relative area coverage.

In the case of a three ink system two states per ink per halftone pixel (one or no ink drop), there are 8 Neugebauer Primaries (W, C, M, Y, CM, CY, MY, CMY) for a given ink order. However, even in this small set, some NPs will be over the ink-limit of the substrate, which will be addressed as outlined above.

For example the fourth patch in Figure 3 shows the colorimetry of a YM overprint, which at full area coverage would be over the ink-limit, combined with W in order not to exceed the ink-limit. This results in an NPac where 37.5% of halftone pixels are left blank and 62.5% have Yellow and Magenta overprinting.

For the above set-up we then have 14 base NPacs – 8 corresponding to the 8 NPs – some of which are single NPs at 100% area coverage (such as all inks by themselves), others are combinations of two or three NPs as a consequence of ink-limiting, and 6 more that make sure the convex hull is represented. Figure 3 shows their measured colorimetries (represented in sRGB for preview purposes):

Figure 3: The colorimetries of the base NPac set, from left to right.

Within this set of XYZs corresponding to the base NPacs there are 15,914 polyhedra (from tetrahedra up to a single 14-vertex polyhedron). Limiting minimum NP area coverage to 1/64 (for visualization purposes) 115 metamers are obtained for an achromatic stimulus using between 5 and 11 NPacs at a time (out of 14 available ones). They are visualized by coloring as many of the 64 pixels in a row with the color of a measured base NPac as is its area coverage in multiples of 1/64s (i.e., 32 pixels of a given NPac's color represent a 50% area coverage for it). Each row therefore represents one of the metamer set's NPacs.

The variety shown in Figure 4 shows how many different halftone pattern NP area coverage statistics match a single color, for which colorant–based color separation results in only a single CMY ink combination. For this example case the difference in magnitude between the HANS separation and any colorant space separation is 115:1.

Halftoning in a HANS pipeline amounts to spatially distributing NPacs - NPs with proportional area coverages over a unit area. Figure 5 is an example of the halftoned patches of some of the metamers shown in Figure 4. The left-most patch corresponds to the NPac metamer that uses 11 base NPacs (out of 14) – the most in this set, while the remaining patches correspond to some of the metamers with 5 base NPacs – the smallest number in this set.
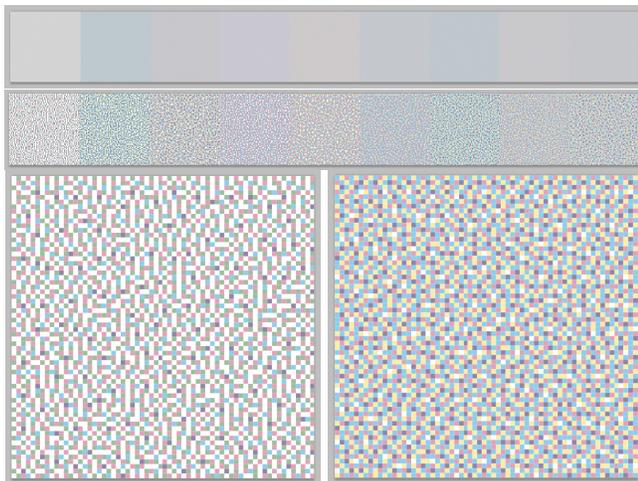
Figure 5: Some of the metamers halftoned and displayed as a pseudo-colored preview). Top row shows them halftoned at 720 x 720 pixels, the middle row at 64 x 64 pixels and the bottom two samples are the two left-most ones halftoned at 64 x 64 pixels, magnified.
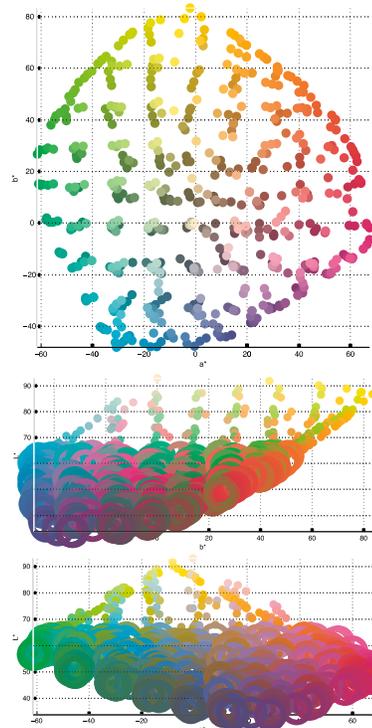
Figure 6: The set of 544 samples spanning the color gamut available using the CMY ink-set, printed and measured from the least-ink-using optimized NPacs.

Given this large variety in NP composition, the variation of one of the print-attributes – ink-use – is looked at next. Metamer sets for 544 XYZ samples, chosen to be uniform in CIE LAB space and spanning the color gamut (Figure 6), were combined next. For each metamer set an ink-use metric (counting the number of drops of ink it costs to produce a pattern) was computed for all of it's members and the minimum and the maximum ink use patterns were stored for comparison. The ink-use over all 544 samples was next summed for both the least and most ink–using NPacs respectively, resulting in an ink-use range of 12.66%. The optimization used 244 NPac samples (the base NPacs and a finer sampling of the gamut surface), over which the tetrahedral search was performed, amounting to an exhaustive search through 14,4 million tetrahedra.

Note that this variety compares to a single possibility for a current, non-HANS pipeline with no flexibility in terms of ink-use.

Conclusions

The color separation optimization approach presented here allows for access to all possible digital halftone patterns that can be formed using a printing system's Neugebauer Primaries. Furthermore, it provides a way to explicitly optimize any attribute that can be predicted from a halftone pattern, including ink use, grain and color constancy. Nowhere are the benefits from HANS more obvious than in the case of a CMY printing system, where it provides a significant number of metamers where current colorant–space approaches only yield unique results.

In future work, the challenges from dealing with systems that have many more NPs as well as the effective and efficient accounting for ink limits will be addressed as well as the optimization of the halftoning needed for NPac content.

Acknowledgements

References

[1] Morovič, J. (2007) Multi-primary printing, NIP23: The 23rd International Congress on Digital Printing Technologies, 16–21 September 2007, Anchorage, Alaska, pp. 10–13.

[2] Morovič J., Morovič P. and Arnabat J. (2010) HANS – A New Color Separation and Halftoning Paradigm, IS&T/SID 18th Color Imaging Conference, pp. 359–364.

[3] Morovič P. (2002) *Metamer Sets*. PhD. Thesis, University of East Anglia, School of Information Systems.

[4] J A C Yule, W J Nielsen, "The penetration of light into paper and its effect on halftone reproduction." 1951 TAGA Proceedings, p 65-76

[5] CIE (2001) CIE 142:2001: Improvement to industrial colour difference evaluation, CIE Central Bureau, Vienna.

[3] Morovič J., Morovič P. and Arnabat J. (2011) HANS – Controlling Inkjet Print Attributes Via Neugebauer Primary Area Coverages, IEEE Transactions on Image Processing, accepted for publication.

Author Biography

Peter Morovič received his Ph.D. in computing sciences from the University of East Anglia, UK in 2002 and holds a B.Sc. degree in theoretical computer science from Comenius University, Slovakia. He has been a Color Imaging Scientist at Hewlett–Packard S. L., Spain since 2007. He has published over 40 scientific articles and his research interests include color vision, color reproduction, image processing and computational geometry. Dr. Morovič received the IS&T's Raymond Davis Scholarship (2001) as well as a JSPS Post-doctoral Fellowship (2005).

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 later Master Technologist at Hewlett-Packard in Barcelona, Spain and has been there since 2003. He is currently the Director the CIE's Division 8 on Image Technology and Wiley and Sons have published his book entitled 'Color Gamut Mapping.'

Juan M. García-Reyero received his Ph.D. from the Polytechnical University of Catalonia (UPC, Spain) in 2000, and holds an MD in Mechanical Engineering from UPC. He has worked as an engineer specializing in inkjet writing systems at Hewlett-Packard in Barcelona since 1996. From 2007 to 2010 he managed an R&D team at HP. In 2010 he became an HP Master Technologist