Color Reproduction and Beyond

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- "Is research in color reproduction not completely outdated? Since anyone can print perfectly looking color pictures, hasn't everything been solved ?"

In reply to these questions, let us give an overview about the current state of the art in classical color reproduction and outline both solved and unsolved problems. We then describe actual and future challenges.

The fundaments of color reproduction have been laid out at the end of the 19th and beginning of the 20th century. They rely on the decomposition of a scene imaged onto 3 separate "red", "green" and "blue" color separation negatives and on the reproduction of that scene by the subtractive primaries "cyan", "magenta" and "yellow". The amounts of cyan, magenta and yellow inks are respectively controlled directly or indirectly by the intensity of the registered red, green and blue color negatives [1].

Today's approach for computing the amounts of cyan, magenta and yellow inks from the red, green and blue intensity values of a displayable color image consists in characterizing both the input red, green and blue imaging device and the cyan, magenta, yellow and black output device in respect to a device-independent color connection space such as CIELAB. An explicit mapping between the input color gamut and the printer's output color gamut is established [2].

Printer manufacturers embed into an ICC profile the correspondence between input colors expressed for example as CIELAB colors and output CMYK ink dot surface coverages. This mapping incorporates the mapping of the input gamut, generally a display gamut, into the printer gamut. Such a profile is only valid for a given printer using a given set of inks and a given substrate [3]. Changing the substrate (paper type) or the inks requires recreating a printer profile. This is often carried out by a robot measuring the spectral reflectance of more than thousand different uniformly printed color halftone samples. Printer profiles may be recreated more easily with a spectral prediction model that can be calibrated with only a few dozens of measured reflectance samples.

Recent professional printers such as large format inkjet printers or offset printing machines incorporate a spectrophotometer. This spectrophotometer scans the printed page and measures reflectances. With the feed-back obtained in respect to the printed colors, control software may modify print parameters such as the amount of ink flow. These spectral measurement devices enable the online recalibration or possibly re-characterization of the printer, but are rather expensive. For low-cost home printers, cheap solutions for online re-characterization may be achieved by combining model-based spectral prediction approaches and inexpensive multi-channel sensors.

Since the first part of the 20th century, attempts have been made to establish models predicting the reflectance and therefore the color of uniformly printed samples incorporating given amounts of inks. The spectral Neugebauer prediction model predicts the reflectance $R(\lambda)$ of a halftone as a weighted average of the reflectances $R_i(\lambda)$ of the colorants (primaries) contributing to that halftone, the weights being proportional to the relative surfaces a_i covered by these colorants. In order to account for the lateral propagation of light induced by the multiple reflections between the paper substrate and the print-air interface, the spectral Neugebauer model was modified by carrying out the weighted average in the reflectance space raised to the power of $1/n$:

$$R(\lambda)^{\frac{1}{n}} = \sum_i a_i \cdot R_i(\lambda)^{\frac{1}{n}} \qquad (1)$$

where n is a scalar value generally higher than 1, optimized on a limited number of representative halftone samples.

In the case of independently printed three cyan, magenta and yellow ink layers with respective surface coverages c, m and y, one obtains the 8 colorant surface coverages white a_w, cyan a_c, magenta a_m, yellow a_y, red a_r, green a_g, blue a_b, and chromatic black a_k, according to the Demichel equations:

$$\begin{aligned} a_w &= (1-c)(1-m)(1-y), & a_c &= c(1-m)(1-y) \\ a_m &= (1-c)m(1-y), & a_y &= (1-c)(1-m)y \\ a_r &= (1-c)my, & a_g &= c(1-m)y \\ a_b &= cm(1-y), & a_k &= cmy \end{aligned} \qquad (2)$$

The resulting Yule-Nielsen modified spectral Neugebauer reflectance prediction model (YNSN) [4] is further improved by accounting for the spreading of each ink independently of the superposition condition (independent ink spreading: IIS) [5]. An improved superposition-dependent ink spreading model (SDIS) relies on the specific spreading of each ink superposed with each colorant formed by each of the other solid inks, each superposition of the other solid inks and paper white. For ink-jet printers, the SDIS-YNSN model provides prediction accuracies [6] that yield average color CIELAB ΔE_{94} differences between measurements and predictions in the range between 0.8 and 1.6. For 3 inks, that model requires at least 8+12=20 sample measurements for its calibration. A slightly higher precision accuracy is achieved with 8+36=44 calibration samples. For the 4 CMYK inks, the model requires at least 16 + 20 = 36 samples for its calibration [7]. A slightly higher prediction accuracy is achieved with 16+60=76 calibration samples.

The prediction accuracy can be further improved by cellular subdivision of the YNSN model [8]. For 3 inks, it requires the spectral measurement of 3^3 = 27 Neugebauer primaries. At the center of each of the 8 subcubes, one additional measurement is needed in order to simultaneously fit the effective surface coverages of the 3 inks. This additional measurement provides the three superposition independent ink spreading curves of the considered subcube. In total, for 3 inks, the resulting IIS-CYNSN model [9] requires 27+8=35 sample measurements and for 4 inks, it requires 34 + 16 = 97 measurements. For ink-jet printers, average prediction accuracy of the IIS-CYNSN model expressed as average color CIELAB ΔE94 difference is between 0.5 and 1.2.

As an example, figure 1 shows the elements of the ink spreading enhanced Yule-Nielsen modified Spectral Neugebauer reflectance prediction model (SDIS-YNSN), followed by the part calculating CIELAB colors from reflection spectra.

In forward mode, a calibrated spectral prediction model predicts the colors of samples printed with given surface coverages of the inks (Figure 1). The predictions are accurate for the printer, set of inks and paper that were used for the calibration of the model. In backward mode, i.e. by a gradient descent procedure, one may obtain the surface coverages of the inks enabling printing a given color. In respect to the generation of ICC profiles, the model in forward prediction mode enables creating the relationship between surface coverages of the inks and the device-independent color (CIE-XYZ or CIELAB). In backward mode, the prediction model enables obtaining ink surface coverages as a function of a desired color. This may be useful in filling the table which maps device-independent colors to ink surface coverages.

Prediction models are specially useful for dynamically adapting the reproduction workflow to the printer operating conditions. With a few spectral measurements or by obtaining the response from a few sensors, a printer can be completely re-characterized and if needed an appropriate ICC profile can be regenerated. This is particularly useful in environments where operating parameters such as temperature or humidity may vary or if the inks and the paper come from different suppliers.

When printing with a large choice of custom inks, e.g. Pantone inks, prediction models can be enhanced by additional constraints such as the minimization of metamerism [10], the maximization of color constancy [11], the minimization of the amount of ink used [12] or the avoidance of false boundaries due to custom ink halftoning [13]. In this context, the question arises if a single prediction model should incorporate all candidate custom inks. Such a model could be set up by extending the Demichel equations to all suitable ink superpositions and by measuring the corresponding primaries. Or is it preferable to subdivide the available set of inks into subsets of 3 to 4 inks, and associate to each subset of inks a separate prediction model?

Generally, the second solution is preferred. With different subsets of inks capable to print a given color, we can select the one that is the most appropriate at a given position within a specific image according to either general considerations or to considerations which depend on the color image to be reproduced and on the current position within that image. This approach was successful in creating wide-gamut prints relying on daylight fluorescent inks [14] as well as in creating invisible daylight fluo watermarks revealable under blue light [15].

Let us note that YNSN color prediction models have the limitation that no exact method exists to predict the reflectances of solid colorants (primaries) formed by superpositions of solid ink layers. For high prediction accuracy, all considered primaries need to be measured.

The issues mentioned above are relevant for classical color reproduction, where inks are printed on a white diffusing "Lambertian" substrate. There are however new approaches for creating attractive prints on non Lambertian substrates. One of these approaches uses a substrate formed by a specularly reflecting layer of silver [16]. When printing with classical inks on top of such a specularly reflecting substrate, many new problems arise. The image creator needs to decide if the image is to be viewed in specular mode, i.e. at aspecular angle zero or at another aspecular angle. At the selected illumination and observation angle, there is a need to establish a relationship between classical ink surface coverages and perceived color. This is not trivial, since both the CIE-XYZ and the CIELAB colorimetric systems were established for diffuse emitting or reflecting surfaces. In addition, when converting from CIE-XYZ to CIELAB one needs to define a reference "white" stimulus on which the eye adapts. Is it the unprinted metallic surface ? A further issue concerns the colorimetric "error" introduced when a color image printed to be viewed under specular reflection is viewed under some aspecular angle. Is there a way to generate a color image that would look good both under specular reflection and under a significant range of aspecular angles ?

Spectral prediction models are extremely useful when trying to solve problems raised in connection with specularly reflecting prints. The cellular ink-spreading enhanced Yule-Nielsen modified spectral Neugebauer model provides accurate spectral predictions under the same illumination and observation conditions for which it was calibrated. For the three cyan, magenta and yellow inks printed on a silver substrate, it reduces the number of samples that have to be measured from many hundreds to 35 samples at each selected illumination and observation geometry.

Beyond color reproduction of images on flat media, there is today the possibility of printing images in 3D by combining both flat and relief image elements. Such 3D printers theoretically allow selecting different substrates on which the colorants are printed. Using non-planar structures offers many new opportunities as well as challenges for color image design and reproduction.

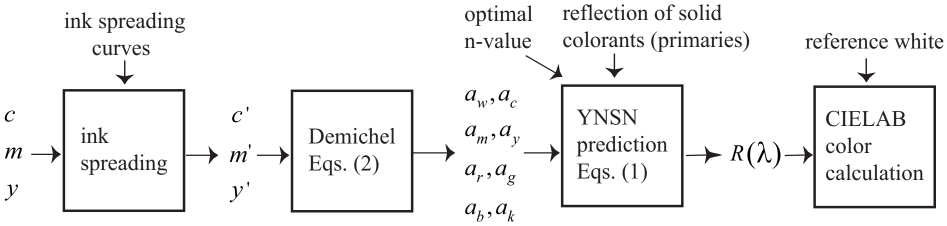

***Figure 1**. Ink-spreading enhanced Yule-Nielsen modified Spectral Neugebauer model (SDIS-YNSN) followed by CIELAB color calculation, with c,m,y and c',m',y' expressing respectively the nominal and effective surface coverages of the inks and with a_w, a_c,, … a_k expressing the effective surface coverages of the colorants (Neugebauer primaries).*

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