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Multi-Primary Spectral Display for Soft Proofing[1]

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Abstract. *A soft proofing display that can serve as a trustworthy replacement of the hardcopy contract proof is a long anticipated missing element in the all–digital workflow of the graphic arts industry. We describe a novel approach of spectral color reproduction on screen, which combines a specially designed multi-primary projection display and spectral data processing, and discuss its application for soft proofing. The feasibility of this concept is shown, and the results of a realized system are described and analyzed. In addition, other possible configurations are simulated. The results show that the system provides a very close simulation of the print process and to the appearance and color of the printed page.* © *2007 Society for Imaging Science and Technology.*
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INTRODUCTION

Throughout the history of electronic displays, display devices have been customized to meet application specific requirements—they have been ruggedized, miniaturized, scaled-up and ultraviolet (UV) coated, to name just a few. However, one particular aspect, color performance, was taken by the display industry as a given, regardless of the vast breadth of color imaging needs, which in some cases, call for some dedicated design. As far as color reproduction is concerned, until recently the supply of electronic color displays was limited to only one type of device, a cathode ray tube (CRT), whose color reproduction characteristics had almost no variance between brands, models, or even different CRT technologies. Despite attempts to increase the color gamut of CRTs, all commercial displays, even in the most color sensitive professional markets such as the graphic arts and the cinema industries converged around the P22 conventional phosphor set gamut.[1] Liquid crystal displays (LCDs) that started to appear commercially in the 1990's did not change this picture; actually, in the first years of their market debut CRT was the target reference for LCD.

In recent years, certain technological developments have facilitated the emergence of new displays and capabilities, among them some new technologies that enable the expansion of the color gamut beyond that of CRT.[2] One of the most significant breakthroughs is the ability to create multi-primary (MP) displays.[3–6] Whereas red-green-blue (RGB) displays use RGB primaries to reproduce colors, in an MP display more than three primary colors are combined to create the colors.

In a recent publication[7] we discussed the possibility of designing a display based on its intended application. We have shown that even displays based on new technologies are designed according to the common practice of letting the technology limitations set the display performance, although these technologies provide opportunities to better fit the display to its application. We further showed how the use of MP displays allows different designs for different applications.

In this paper we focus on the application of soft proofing. We discuss the concept of multi-primary spectral display and comment on additional implementations and applications.

REQUIREMENTS FOR SOFT PROOFING SYSTEMS

Color proofing is a critical quality control process that takes place in different stages of the production chain of a print job.[8] It typically begins at the scanning station where individual images are retouched and checked for reproduction quality, then continues on to other pre-press functions until the complete job is assembled on a page and includes graphic elements, text, and pictorial material. The final page is produced on a proofing device whose output is accepted as a faithful representation of the target printing conditions (usually offset print). This proof is used for customer approval and as a reference to the press operator whose task is to render the print as close as possible to the proof. Proofs are used as a way to convey the ideas and "looks" created by the designer to other professionals downstream, and to provide the designer and other upstream personnel with feedback on the changes made in the production chain.

In order to understand the requirements from a proofing system it is instructive to examine the details of the process. Proof and print are viewed side by side in a light box, usually under D50 illumination at a level of about 2000 lux (in some stages of the process, smaller light boxes with illumination level of 800 lux are used[9]). The environment where proof viewing takes place is not uniform; scanner operators and creative artists usually work in dim light and examine proofs in small light boxes, whereas complete pages may be viewed in large viewing tables in a fully illuminated room. The proof, however, should look similar to print also under less controlled illumination, such as common office lighting where the customer may be required to approve the proof, or industrial lighting typical of the environment of

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the printing press. In many cases, several people view the proof together, and therefore the sensitivity for viewing angle should be negligible. While viewing conditions are important, color quality aspects of the proof are crucial. First and foremost is the color gamut of the proofing device, which should be large enough to cover that of the print, and colors should be close enough to that produced by an offset print so that color matching of print and proof could be achieved within reasonable tolerances. The proof should also provide suitable color gradation and visibility of details at sufficiently high resolution. Furthermore, as a quality assurance tool, proofing devices must provide color stability and reproducibility.

All of the features previously discussed are provided in a hardcopy proof, in which specialized dyes are printed on a substrate using well controlled processes, quite similar to that used in the print. The color gamut provided by these dyes is always larger or at least comparable to that of an offset print. Color gradation, detail visibility, color matching and stability, and reproducibility are provided by the process and the dyes. In some systems, such as Cromalin™ and Matchprint™, the dyes are very similar to those of offset prints. In other systems, such as ink jet based proofers, the color gamut of the proofer is larger than that of offset print and some gamut mapping should be employed. All other features required from proof are assured by the fact that the physical basis of color creation in the proof is very similar to that of the print. The main disadvantages of hardcopy proofing are its high cost and the long amount of time required to obtain it, which is the limiting bottleneck in a digital workflow.

Soft proofing, the verification of print jobs on a computer monitor, is a long anticipated missing element in the all-digital workflow of the graphic arts industry. Although partially implemented, it fails to replace the traditional hardcopy process, since many of the advantages of hardcopy proofs are lacking. The main issues are color gamut, color creation physics, color management concept, viewer variance, appearance issues, sensitivity to ambient light, and stability. As seen in Figure 1 the color gamut of CRT (and many other RGB display technologies which aim for similar gamut) does not encompass either the color gamut of devices used for proofing, such as Matchprint or Cromalin systems, or even that of offset inks. Furthermore, RGB displays create color by the additive combination of RGB primaries, a method very different from the subtractive nature of color creation on print in which the illumination is reflected from the paper and filtered through the ink layers. This has several implications. First, cyan-magenta-yellow-key (CMYK) data has no relation to RGB displays, and as a result color management is required for the CMYK to RGB transformation. This is usually done using International Color Consortium (ICC) profiles involving conversion to absolute color space. Any change in the properties of the simulated systems, such as the type of substrate used, or the illumination under which the prints are viewed, requires reprofiling. If many property combinations are required, management and update of these profiles becomes an impractical task. Furthermore, the RGB primary spectra are generally very different from that reflected from printed paper, in particular in the case of CRT phosphors emission spectra, with the spiky emission of the red phosphor. The difference in spectrum may result in interobserver variations and an inaccurate color match, since color transformations are based on an "average" human.[10,11] Moreover, since color transformations are colorimetric, additivity failures associated with the different spectra viewed from print and CRT display may cause colors that match colorimeterically to appear different.[11] Furthermore, monitors are sensitive to ambient light conditions, therefore soft proofing must take place in a dark environment, in contrast to the hard-proof to print comparison, which is usually performed in a lit environment, resulting in different visual adaptation conditions of the viewers.[12] The reflected luminance of the prints in a light box is much higher than that of most standard displays, again affecting the adaptation of the viewers in a different manner.[12] Both effects are known to affect the perceived contrast and colorfulness of the viewed images, and involve color appearance issues, which further complicate the color management. Finally, since color in RGB displays is created by additive mixing of the three different primaries based on colorimetric assumptions, variations over time of the primaries deteriorate the stability and reproducibility of the soft proof, thus requiring expert attention and frequent calibration. This is particularly evident in CRT displays, where variations in electron beam currents, phosphor aging (of the different colors and at different positions on the screen) and spatial and temporal changes of external magnetic fields affect reproduction quality.

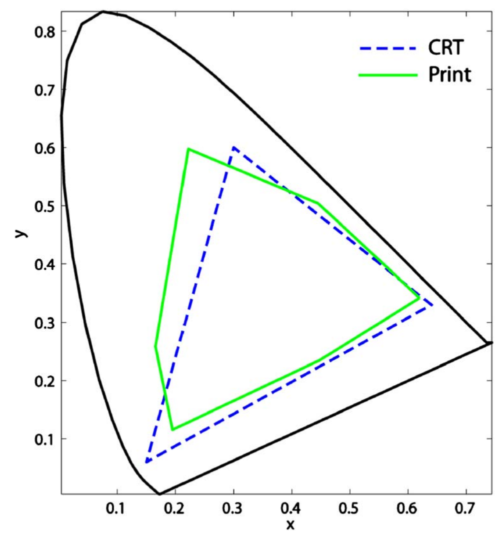

Figure 1. CRT display vs print color gamut.

Most of the issues discussed above are associated with the concept of color reproduction in RGB displays, which relies on metameric color matching, in which different spectra may represent the same color. Hard proofing, on the other hand, while still relying on colorimetry, uses substrates and dyes similar to those used in print. Thus, matching colors in print and proof implies that the physical spectra associated with the combinations of inks are also similar. Therefore, when matching is achieved under one illumination and for one observer, it is likely to be reasonably good under different illumination and for other observers. This is not true for soft proofing on RGB displays, where an attempt to predict color appearance under different illuminations, would require different colorimetric transformations. The difference between hard and soft proofing methods stems from two important factors. Hard proof relies on spectral similarity in both the ink and the illumination spectra, and is capable of separating these two elements due to the subtractive nature of color creation in print. Soft proofing, on the other hand, does not provide spectral similarity and ties illumination and inks within one inseparable colorimetric transformation.

Concept

Considering the previously stated limitations of RGB displays, a new type of display is required for soft proofing. Such a display should incorporate the underlying concepts of color creation in hard proof, namely the spectral similarity as a basis for color matching and the separation between illumination and inks. Therefore, it would be natural to choose a display technology in which a white light source is filtered by a set of color filters designed to fit the spectra of the inks. By reproducing the spectrum of the illumination and the inks rather than the color of the prints, we avoid many issues, such as observer variation, additivity failures, different illumination conditions, and change in the printing substrate, without the need for complicated color management. For example, illumination and printing substrate change may be incorporated by adjusting the display white light source spectrum to match the spectrum of light reflected from the relevant paper under the specific illumination. Moreover, colors matching on display and print would also be similar in spectra, thus minimizing sensitivity to observer variation and additivity failures. The combination of white light spectrum adjustment and spectral reproduction of the ink layers also assures a suitable color gamut for the display under various illumination conditions. Furthermore, the use of new display technologies allows for higher display luminance and wide viewing angle as required for proof approval. The use of sophisticated viewing screen technologies designed to minimize screen flare, combined with the high luminance of the displays, reduce the sensitivity to ambient light. These technologies, on the other hand, do not fit self-luminous devices, such as CRT, plasma displays and others. In addition, since the display and the print process share similar color creation physics, a simulation of printing parameters such as dot gain, ink densities, ink trapping, and paper gloss is easily achieved using rather simple processing without the need for a full device characterization and profiling.

Finally, some of the newer display technologies previously mentioned offer higher inherent stability of color performance in comparison to CRT and easier monitoring of deviation in color related performance. As an example, the only color related, age-dependent variable in a digital light processing (DLP) rear projection display is the intensity of the lamp, which can be easily monitored (and corrected, within a certain range).

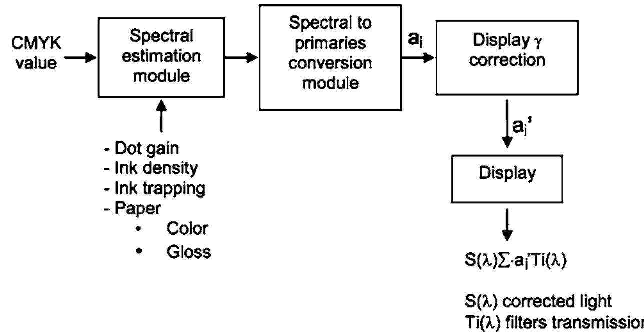

Figure 2. A schematic representation of the spectral display for soft proofing.

A complete correlation between print and display physics would require that the white light source is filtered through cyan, magenta, and yellow layers placed on top of one another in alignment. This is rather difficult to achieve and would result in a very dim display. Another approach is based on filtering white light by additive reconstruction of the required surface spectrum. This is the basic concept underlying the spectral display.

In a spectral display the input data for each pixel represent a spectrum of light that should be emitted from that pixel. The spectral display is capable of accepting that data and presenting in each pixel of the display a spectrum similar to that required by the data for that pixel. It is well known that the reflectance or transmittance spectra of many natural and artificial colored objects can be described as linear combinations of a small number of basis functions, in the range of four to eight basis spectra.[13–17] As we will show next, the same is true for reflectance spectra obtained from offset printing inks or proofing systems such as Matchprint or Cromalin. Thus, a MP display with a small number of primaries ($4 \leq n \leq 7$), whose spectra are tailored to fit the basis functions, can be used to reconstruct spectra of natural objects and, with relevance for proofing application, the spectra of ink layers.

A schematic representation of the spectral display is shown in Figure 2. The display has a white light source with a suitable spectrum representing the illumination under which the prints are viewed. The input CMYK data for each pixel is used to estimate the spectrum $\varphi_E(\lambda)$ corresponding to that input. This estimation is based on spectral print models, such as spectral Neugebauer [linear or Yule–Nielsen (YN) modified] and others, which relates the CMYK values to dot area on paper, and then translates those areas to spectrum using the known spectra of the inks. This spectrum $\varphi_E(\lambda)$ is then approximated by a linear combination of the display filters:

$$\varphi_D(\lambda) = \sum_{k=1}^{n} a_k \chi_k(\lambda), \qquad (1)$$

where $\chi_k(\lambda)$ is the spectra of the kth filter and a_k is the linear weighted signal for the kth primary. The values of a_k may be derived from the estimated $\varphi_E(\lambda)$ and the known display filters $\chi_k(\lambda)$ using different linear algebra and optimization methods. Since the display response is not necessarily linear the value a_K is gamma corrected before driving the display.[18] The resulting spectrum from the relevant pixel is a multiplication of the white light spectrum $S_L(\lambda)$ with the filter combination $\varphi_D(\lambda)$. The white light spectrum is adjusted (e.g., by filtering the lamp) to be as close as possible to the light reflected from a given white paper, namely $S_L(\lambda) \cong S(\lambda) \cdot R_W(\lambda)$, where $S(\lambda)$ is the light impinging on the paper and $R_W(\lambda)$ is the reflectance of the paper. The result is a display which produces at each pixel, a very similar spectrum to that reflected from the paper under the relevant illumination. Note that this requires spatial light modulation (SLM) to control the amount of each primary at different positions of the image.

The advantage of the MP spectral display compared to CRT is evident. It operates in a manner very similar to the physical print and its gamut inherently matches it. Since the system is based on transmitting light through a spectral reconstruction of the inks and the overlaps, an illumination or substrate change may be done at the physical level of the display by adjusting the spectrum of the white light $S_L(\lambda)$. The model of operation does not involve profiles, and thus it is simple to change parameters. In particular, given a physical model for the spectral estimation module, changes in parameters such as ink density, trapping, dot gain, and others may be incorporated within that model.

IMPLEMENTATION

Display technologies, which are possible candidates for implementation based on these ideas, include projection displays and liquid crystal direct view displays. In these technologies white light, the spectrum of which may be adjusted to mimic the required illumination, is transmitted through a set of colored filters. The transmission spectra of the different filters are chosen, so their additive combination would span the possible normalized reflectance of ink layers on paper. The filtered light is spatially modulated according to the required amount of each of the colors at the relevant pixel. Assuming suitable spectra of the primary filters and suitable amounts of each primary at each pixel, the integration by the viewer will reproduce the required spectra at each pixel.

The choice of the primary filters and their number are important factors in the ability to create spectral reconstruction. In order to define the filters we have measured reflectance spectra of 60 patches from a Matchprint target. The target was place on an *xy* translation stage and illuminated with a wide band white light source (Xe lamp). The reflected light was measured using a PR-705 spectrophotometer. To eliminate spatial variation of the light intensity, the spectrophotometer was positioned in a fixed place and orientation, and the target was translated for each of the measurements so each of the patches measured was within the acceptance angle of the spectrophotometer. Care was taken to avoid specular reflection and change of the target angle with respect to the spectrophotometer. The size of the field was chosen to allow the isolation of a single patch on one hand and reasonable averaging over the patch area on the other hand. The light received by the spectrophotometer is reflected from the paper through transparent inks, which may partially or completely overlap. This spectrum thus represents a multiplication of the illuminating light spectrum with the reflectance spectrum of the paper and an effective transmission of the relevant CMYK ink combination. By dividing the spectrum of the light received from a color patch by the spectrum received from the blank paper, we obtain a normalized reflectance, which represents the effective transmission of that specific CMYK combination. These normalized reflectance spectra were analyzed using principal component analysis (PCA) to determine the dimensionality of the spectra space and to find basis functions. We found that more than 99% of the variance is accounted for by four or more basis functions. However, the basis functions obtained by PCA or singular value decomposition (SVD) are orthogonal, and thus necessarily have some negative reflectance at some wavelength ranges. Therefore, they cannot be used as primaries for an additive display, since the spectra must be positive to represent physical primaries. The basis functions must be rotated in the multi-dimensional space to obtain a set of all-positive non-orthogonal spectra. Examining the behavior of the subtractive color mixing provides a good initial guess for these positive spectra. When CMYK dots are placed on paper, the reflected spectrum is a combination of the light reflected from the blank paper, through the three primary inks [cyan-magenta-yellow (CMY)] and from the overlaps (blue for CM, green for CY, and red for MY).[19] Thus, to a first order the reflected spectrum is a combination of seven spectra, identical to the reflectance spectrum of the blank paper, the CMY inks and their overlaps, RGB. Thus, a possible implementation involves seven filters with transmission spectra identical to the normalized reflectance spectra of the inks and their overlaps with respect to the blank paper, in addition to a fully transparent filter segment representing the normalized blank paper reflectance, which is unity by definition. Later we will discuss the performance of a projector with a different number of primaries; however, more discussion on the choice of suitable primaries is deferred to another publication.[20]

The required filters may be produced by various methods, but for the implementation discussed below we chose interference filters. In interference filters the transmission curve is tailored by multiple interference between several subwavelength layers of materials with different indices of refraction. The number of the layers is an important factor in the complexity and the cost of the filters.[21]

In Figure 3 we compare the required transmission spectra with those obtained from the filter manufacturer. Table I summarizes the ΔE and spectral root mean square (RMS) values between the required and realized filters for six primaries, CMYRGB display. There is a good spectral and colorimetric match for all primaries, but for the red and magenta filters the deviation is larger than for other colors. The red

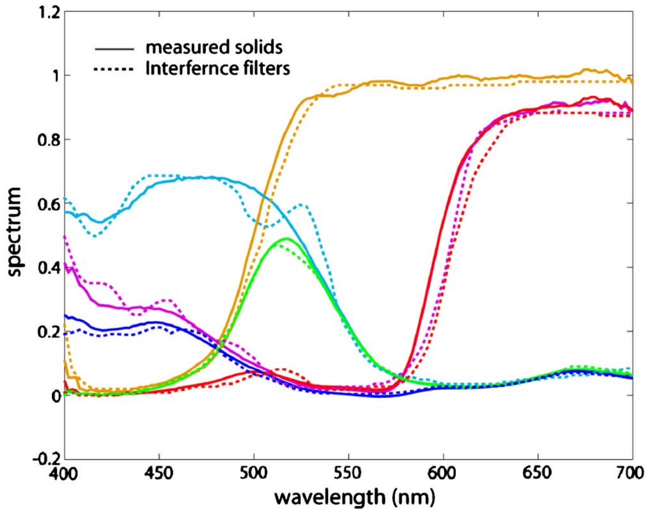

Figure 3. Required vs manufactured filter spectra.

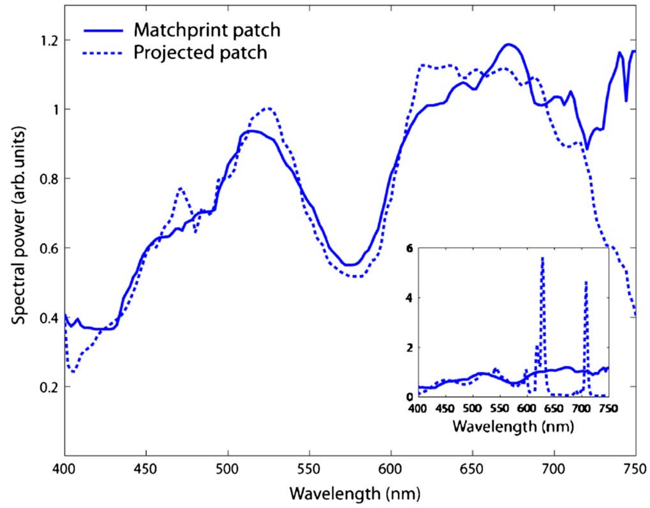

Figure 4. A comparison between the spectrum measured from a Matchprint patch (CMYK=50,41,41,0) and that measured from the spectral display screen. The inset shows the same comparison for a CRT screen under the condition of $\Delta E=0$ between screen and print (note that the scale of the inset is 5 times larger than the scale of the main figure).

Table I. ΔE values between the required and realized filters for six primaries.

	C	M	Y	R	G	B
ΔE	1.9	6.0	2.8	6.5	1.6	2.0
RMS	0.040	0.045	0.030	0.053	0.008	0.010

part of the spectrum is very sensitive to changes in the cutoff wavelength; a change of 2 nm may result in $\Delta E \sim 2.5$ (2 if only the $a^* b^*$ components are taken into account). Since a very high accuracy in the red region would require a large number of layers increasing the complexity (and cost) of the filters, we choose to set the cutoff wavelength deliberately toward the red so that even within the manufacturing tolerances the resulting gamut would be larger than the required one. Although this reduces the spectral accuracy of the primary itself, it allows for colorimetric correction. As an example, note that the shift in the red filter cutoff means less light would pass through it, thus reducing its relative luminance. This may be compensated by increasing the pass band transmission from $\sim$90% of the solid ink overlap transmission to $\sim$100% in the filter. For the red filter this reduces ΔE from 6.5 to 2.8, which is comparable to the other filters. Alternatively, the effective transmission can be compensated for by modifying the relative segment size of the red filter. The magenta case is more complicated since the ratio between the red and the blue regions of the filter is a critical factor, which limits the ability to tweak the filter's transmission. Therefore, tighter tolerances should be applied in the production of this filter and/or colorimetric adjustment has to be performed in order to correct the color.

In practice we design the filters to have the maximum possible transmission (within the requirement for spectral shape) and luminance is adjusted by controlling the SLM gray level signal. The advantage of this approach is that the luminance of the display is maximized (for example, when we create white by a combination of filters), however, its disadvantage is that it reduces the effective bit depth for the different spectra because some of the available bits are used for compensation of the extra luminance.

We have constructed two different projector implementations. In the first one, we have used a Xenon lamp to illuminate a mask with eight rectangular holes, seven for each of primary filters (CMYRGB and transparent filter for W) and another transparent hole through which light is passed to illuminate the paper. The mask is attached to a small transparent liquid crystal (LC) modulator, in which eight rectangular areas are defined digitally in correspondence with the position of the holes. The light filtered by the mask and the modulator is projected by a long focal length lens on a set of eight rectangular mirrors, in such a way that the light coming from each one of the holes falls on a single mirror. The mirrors are tilted so that the light from the seven regions overlap in registration on a screen, and the additional mirror is used to reflect the white light on a paper for comparison. This setup allows for the presentation of patches (because of its rather low resolution), but ensures that the spectrum of the light used for viewing the print and for the display is identical. Figure 4 shows an example of spectral fit using this type of implementation.

Another implementation, closer to a "real life" display, is that of a sequential rear projection MP display. In a sequential projector white light is transmitted through color filters mounted on a rotating color wheel. During the rotation of the wheel, the white light is sequentially filtered by the color filters. The colored light is spatially modulated to set its required luminance as a function of position. A projection lens images a SLM on the rear side of a viewing screen creating a single color image. For fast enough updating the temporal stream of different single color images is merged by the human visual system to create a full color image.

For a spectral proofing application, the standard RGB sequential projector needs to be modified; the light source

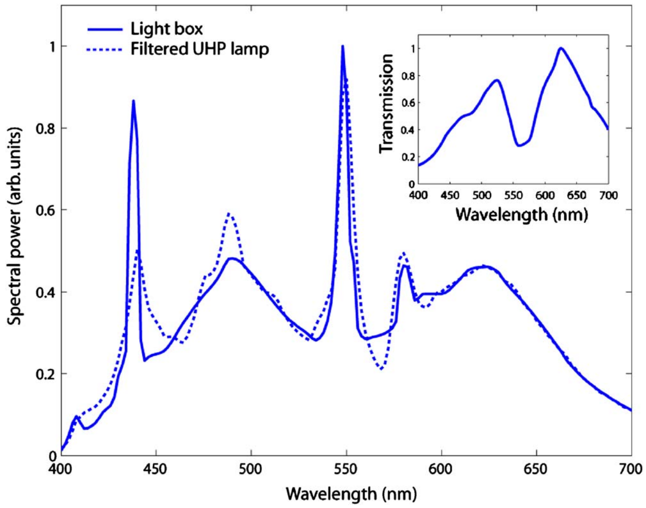

Figure 5. Typical spectrum of a D50 fluorescent light box and the filtered UHP lamp of the projector. The inset depicts the characteristics of the filter.

unit is modified so that the spectrum of the white light would reproduce the spectrum of the light reflected from the paper, for example by inserting a suitable optical filter (not to be confused with the color filters on the wheel) in the light path. Different filters may be used in order to reproduce different illuminations and substrates; the spectra of the filters on the color wheel are designed to fit the required display filters $\chi_k(\lambda)$. The input data are also handled differently. Instead of RGB data, CMYK data are used as input and are converted by the spectral estimation and the conversion units to the amount a_k of each specific spectrum needed for each pixel. The result of these modifications is that the temporal additive combination of the different display primaries (spectra) reproduces at each point the spatially integrated local light spectrum reflected from the paper through the halftone dots of the print, because the white light spectrum of the projector is spectrally matched to the white light reflected from the paper, and the temporal addition of the different display filters at each pixel resembles the effective transmission spectrum of the CMYK ink combination.

Rather than designing a completely new projector we have used two RGB DLP projectors, in which we have replaced the filters on the color wheels with filters of our design. The projectors have been stacked in a mechanical jig, which allowed the registration of their output on a screen. Each of the projectors provided three of the colors so that their combination on the screen resulted in a six-color display.

In order to adjust the white light spectrum, an additional filter was placed in the light path of each projector. The projectors use an ultrahigh-pressure (UHP) mercury lamp. Many light boxes use a "D50" fluorescent lamp, a typical spectrum of which is shown in Figure 5. For that illumination the UHP lamp is rather suitable, since it also has a spiky spectrum. The filter shown in the inset of Fig. 5 converts the UHP lamp spectrum so that it would better fit that of the fluorescent lamp. We have calculated the color rendering index between the UHP converted light and D50 standard illuminant based on the measured 60 patches and found it to be 97.2%, and between the converted light and the fluorescent lamp to be 98.3%.[22] This is a satisfactory result that compares to 97.4% between the lamp and a D50 standard illuminant. We note that this filter may also be used to correct for varying substrate reflectance. By using various filters to adjust the light source, the display can provide simulation of the print under different illumination lights and for different substrate spectra.

The extension of this system to a real sequential integrated projector is straightforward, and entails the replacement of the standard three-primary color wheel with an MP one, as well as the adjustment of the electronics that control the data formatting to the spatial light modulator to accept more than three colors.[23] Similarly to a hardcopy proofing device, the projected image should allow presentation of A3 size page $(42\times 29.7\ \mathrm{cm}^2)$. However, most high resolution SLMs have a 16:9 format, thus the projected image would be at least $52.8\times 29.7\ \mathrm{cm}^2 \cong 0.15\ \mathrm{m}^2$, equivalent to a 24 in. screen. At illumination of 2000 lux, the projection engine should provide about 300 lumens, assuming a screen gain of 1, which is required for wide viewing angle. For luminance maximization, a six primary configuration is favored over seven primaries, where only the transparent segment is used to create the white. For print resolution of 175 printing dots per inch (DPI), the SLM resolutions should be of the order of 3640×2046. This is achievable today, but at rather high price. Full HD SLM with a resolution of 1920×1080 would provide 90 and 130 DPI for A3 and A4 pages, respectively.

The required contrast is determined by the luminance ratio between the substrate and the darkest black that can be printed on it. The luminance of various black patches (K, CMY, CMYK, and other black overlaps) is measured to be a factor of 200 smaller than the blank substrate luminance and thus a contrast better than 200:1 is required, which is easily obtained with a well designed projection engine. The required dynamic range is influenced by several factors. The difference between different black colors is about a factor of 5 smaller than the luminance of the black, requiring a minimum increase of 0.1% or less of the white luminance. Furthermore, for brighter colors the relative change of luminance between adjacent codes should be smaller than 1% in order to preserve smoothness. Assuming a 2.2 power gamma behavior, this translates to eight or more nonlinear bits, and a linear dynamic range better than 1000:1.

To enable consistent image reproduction under bright room illumination and in total darkness, a low reflectance $(\leqslant 0.5\%)$ screen should be used, which, coupled with the system's high brightness would provide the display with high ambient light immunity.

A similar spectral display may be based on LCD. The scope of this paper does not allow in-depth review of this application; however, the main challenges toward such implementation should be mentioned:

- Color filter choice for LCD is far more limited than that of projection technologies. Whereas projectors use interference filters, which can be quite tightly designed to provide a desired transmission, LCD color filters are actual dyes whose spectral characteristics are not easy to engineer. Further limitations are imposed on the filter design by the constraints of the LCD panel manufacturing process.

- The spectral transmission of an LCD cell varies as a function of the voltage applied to it, and therefore a designated correction for the resultant color shift must be performed. This correction may be added to the data processing or could be performed by the device hardware electronics.
- The current state of LCD technologies does not enable high performance sequential implementation of MP. MP implementation would therefore have to be spatial (i.e., across the filter plane),[24] and require a very high resolution panel in order to provide the requirement of a soft proofing device.

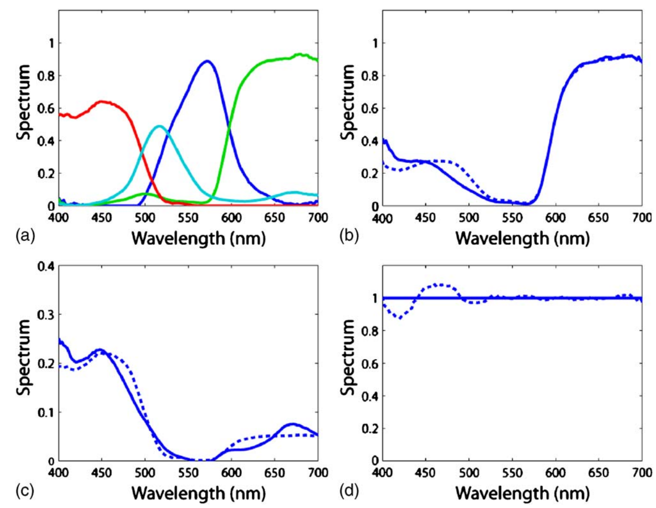

Figure 6. (a) Spectra of the four primaries and (b)–(d) reconstruction of magenta, blue, and white with these four primaries. The other spectra (C, Y, R, and G) are perfectly reconstructed since the primaries spectra are linear combinations of them.

DATA PROCESSING

Data processing in the spectral display is very different from that of current RGB displays, including profile based CMYK to RGB color conversion. As mentioned before, the processing involves two main modules: a spectral estimator unit and a conversion unit. In the simplest spectral Neugebauer approach, the reflectance spectrum corresponding to a certain CMYK value is given by:[25]

$$\varphi_E(\lambda) = \sum_i F_i R_i(\lambda). \tag{2}$$

Here $\varphi_E(\lambda)$ is the estimate of the reflectance spectrum from a specific printing dot on the substrate, and $R_i(\lambda)$ is the normalized spectral reflectance of a set of elementary colors, i=CMY BGR KW. The normalized white reflectance curve $R_W(\lambda)$ is assumed to be flat and equal to unity (by definition of the normalization procedure) and for simplicity the reflectance of black layer $T_K(\lambda)$ is assumed to be zero over the whole spectral range. Overlaps of black with other inks, and the overlap of C, M, and Y are also assumed to have zero reflection; however, correction for finite small reflection and different black colors can also be implemented. The mixing proportions F_i are given by Demichel equations, calculating the relative areas of the inks, the overlaps, and the blank paper:

$$\begin{aligned}
F_C &= C'(1-M')(1-Y')(1-K'),\\
F_M &= M'(1-C')(1-Y')(1-K'),\\
F_Y &= Y'(1-C')(1-M')(1-K'),\\
F_R &= M'Y'(1-C')(1-K'),\\
F_G &= C'Y'(1-M')(1-K'),\\
F_B &= C'M'(1-Y')(1-K'),\\
F_K &= K' + C'M'Y'(1-K'),\\
F_W &= 1 - \Sigma_{i\neq W} F_i.
\end{aligned} \tag{3}$$

Here C′M′Y′K′ are the dot gain corrected CMYK input data and the black component includes all nine types of black. Within this model $0 \leqslant F_i \leqslant 1$ and the sum of all F_i is 1.[26]

Given the estimated spectrum, the conversion unit should provide the display signals a_K that would yield a reproduced spectrum $\varphi_D(\lambda)$ [according to Eq. (1)] as close as possible to the estimated spectrum $\varphi_E(\lambda)$. In the case of the linear spectral Neugebauer model of Eq. (2), this conversion is simplified. Since the spectra $\chi_k(\lambda)$ of the k display filters are chosen to span the print reflectance space for each of the elementary reflectances $R_i(\lambda)$ (Neugebauer primaries) we can write:

$$R_i(\lambda) = \sum_k b_{ik}\chi_k(\lambda). \tag{4}$$

Inserting that into Eq. (2) and comparing with Eq. (1) we obtain:

$$a_k = \sum_i F_i b_{ik}, \tag{5}$$

which implies that in the case of linear models it is not required to perform the spectral estimation on a wavelength basis, but rather the Demichel coefficients may be converted directly to display signals via matrix multiplication. This approach is very suitable for cheap hardware implementation, since the matrix coefficients b_{ik} depend on the reflectance functions $R_i(\lambda)$ and display filters spectra $\chi_k(\lambda)$, which are known beforehand, but not on the varying values of the CMYK input data. In the simplest case in which the k display filter spectra $\chi_k(\lambda)$ are identical to the seven reflectance spectra, $R_i(\lambda)$, the matrix is reduced to unity and no conversion is required. The matrix conversion is mandatory, however, in cases where the number of display primaries is different from the number of Demichel coefficients. This may happen if the display uses less than seven primaries, as shown in Figure 6, when only four filters [see Fig. 6(a)] are used to reconstruct the seven reflectance spectra $R_i(\lambda)$ functions [see Figs. 6(b)–6(d)]. Alternatively, it may also occur in situations in which we still use seven (or less) display filters but the number of Demichel coefficients [and the corresponding reflectance spectra $R_i(\lambda)$] increases, such as when we take into account the nine different types of blacks (which increases the number of coefficients to 16), or when we use linear cellular models in which more reflectance spectra are used, corresponding to the points in the CMYK color space, where the ink levels are taken as, e.g., 0, 0.5, and 1.[25] In this later example the number of Demichel coefficients is $3^4=81$ if all types of black are considered, or $3^3-1=26$ if all blacks are assumed to have zero reflectance. However, for each unique CMYK input only eight values are different from zero, so the matrix operation could, in principle, stay reasonable in size using some additional logic.

The simple linear Neugebauer method is known to be less accurate than more complex models. In particular, a better estimation may be obtained by nonlinear models. The spectrum $\varphi_E(\lambda)$ can be represented as a set of coefficients β_j representing the weights of predefined spectral function $\Psi_j(\lambda)$ namely:

$$\varphi_E(\lambda) = H\left(\sum_{j=1}^{L} \beta_j \Psi_j(\lambda)\right). \tag{6}$$

Here $H(x_\lambda)$ is a pre-defined function operating on each of the wavelengths separately. The spectral estimation thus involves the determination of the coefficients β_j for each CMYK input value. The number of functions $\Psi_j(\lambda)$ and their spectra is determined by the ease of calculation of the β_j. As an example if $H(x_\lambda)$ is linear we return to the previous discussion about simple Neugebauer spectral models and β_j are the relevant Demichel coefficients. A well known nonlinear example is the YN modified spectral Neugebauer model, where $H(x_\lambda)=x_\lambda^m$, and $\Psi_j(\lambda)=\{R_j(\lambda)\}^{1/m}$, where m is a parameter determined by experiment, which is about 1.5 for offset printing. Other examples include the Lambert–Beer model, where $H(x_\lambda)=\exp(-x_\lambda)$, $\Psi_j(\lambda)=D_j(\lambda)$ are the spectral density functions (absorption curves) and β_j are the effective densities.

Having calculated the spectrum to be reproduced as discussed above, we can determine the coefficients a_k based on the estimated $\varphi_E(\lambda)$ and the known primaries $\chi_k(\lambda)$ such that the spectrum on the display $\varphi_D(\lambda)$ will be as close as possible to the required spectrum $\varphi_E(\lambda)$ and under the requirement that all a_k must be in the range of zero to one.

The main advantage of the models discussed above for data processing in the spectral display is their direct relation to the print process. Unlike ICC profiling in which a mapping function is evaluated between one set of measurements to another without any relation to the physical parameters of the print process itself, the models discussed here are tightly connected with the physics of printing, and thus can be easily manipulated to simulate changes in printing parameters. These changes are done within the spectral estimation module, where dot gain variations are easily incorporated by affecting the Demichel coefficients, and other parameters such as ink densities and trapping are taken into account by affecting the functions $\Psi_j(\lambda)$ (or in the linear models by affecting the matrix coefficients b_{ik}).

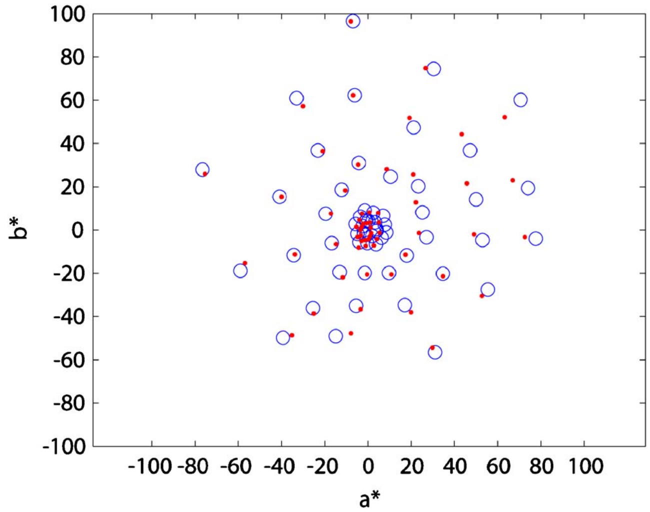

Figure 7. Comparison of color coordinates of measured Matchprint patches and results obtained by the spectral display system.

RESULTS AND DISCUSSION

Figure 7 depicts the calculated a*, b* coordinates of a set of patches as measured from a Matchprint proof of a color target, under D50 equivalent light box illumination, and a simulation of corresponding colors obtained by the projector described above with a filtered UHP lamp (Fig. 5), six realized filters (Fig. 3), and using the simple Neugebauer estimation and linear matrix conversion. Although the matching is not perfect, it is obtained based only on the physical properties of the projector filters, the measured dot gain curves and the known Demichel equations. We note that the errors seen in the figure may be associated with at least four different factors:

1. The difference between the light sources used for display and hard proof
2. The difference between the normalized measured spectra and the estimated spectra
3. The difference between the estimated spectra and the displayed spectra due to the limited number of basis functions
4. The difference between the estimated spectra and the displayed spectra associated with the realization of the display

The first and the fourth factors result from the realization of the display, the first related to the type of light source used in the display and the fourth to the accuracy at which the transmission spectra of the display filters span the estimated spectra space. The second involves the ability to estimate the correct spectrum reflected from the paper using the corresponding CMYK input values. This second factor has no relation to the display itself, but rather to the print model in use, e.g., YN modified or simple linear Neugebauer models. The third factor involves the conversion of the estimated spectra to display signals. This is related to the number of display primaries and the accuracy of converting the estimated spectra to display signals. As discussed above this may be as simple as linear matrix operation, other linear methods such as constrained least squares optimization, or more complex methods. We note that the third and the fourth factors are strongly associated and it is rather difficult to separate their influence.

In order to evaluate the contribution of each parameter, we use a simulation of the display and the print, which is based on spectral measurements we have performed on Matchprint color patches, as previously discussed. The measurements provide us the normalized reflectance spectra as well as the light source used for viewing them. Based on the normalized reflectance spectra, we have designed the filters shown in Fig. 3, and using the light source we have designed the correction filter for the UHP lamp shown in Fig. 5. A comparison of the print with the display is given in Fig. 7. However, in the simulation we can set the display in such a way as to eliminate part of the error factors, for example the light source may be identical to that used to view the print, thus eliminating the first error factor. We can further eliminate all other error contributing factors except for the one considered, and examine the residual error compared to the total system error. As a measure of error we use ΔE averaged over all patches even though the ΔEs contributed from the different factors are not additive. The ΔE values are always calculated with respect to measured white from the Matchprint, when display is referred to its own white ΔE values are usually lower. We evaluate the error of each factor alone in two ways: First by eliminating the errors of the other factors and obtaining the ΔE associated with this factor, and second by eliminating the error of the relevant factor and checking the change of ΔE of the whole system.

The results are summarized in Table II. In the first row, the influence of the light source is given. By setting the displayed reflectances equal to measured reflectances and examining the use of the two different light sources we obtain $\Delta E = 0.369$ (a value indicating the high color rendering index of the two light sources). On the other hand, when we set the simulation so that the light sources are identical (but leave all other aspects of the system unchanged) we obtain $\Delta E = 4.08$ which should be compared to $\Delta E = 3.96$ of the whole system. Thus, the influence of the light source on the accuracy of the system seems to be negligible.

In the second row we look at the influence of the spectral estimation. In order to eliminate all other error factors we compare the measured reflectance spectra with the estimated ones. Using a Neugebauer estimation the error is $\Delta E = 2.66$, while for a YN model the error is $\Delta E = 1.79$ (having $m = 1.4$). On the other hand, keeping all error factors unchanged and setting the estimated spectra equal to the measured spectra, we obtain $\Delta E = 3.27$, a small difference with respect to the total system error.

The results in the third row represent the effect of the number of filters, their spectra and the conversion of the estimated spectrum to the display primaries on the display accuracy. In order to evaluate these errors we have taken the measured spectra and calculated the basis functions using PCA, and then reconstructed the spectra using only the few first basis functions. We obtained $\Delta E = 2.58$, 0.90, 0.44, 0.28 for 4,5,6,7 basis functions, respectively. As mentioned above, PCA basis functions cannot be used as display primaries; therefore, we have also estimated the errors when we have used the seven ideal primaries (CMYBGR measured solids and W), six primaries (CMYBGR, no white) and four primaries (linear combination of measured solids). For these we have obtained $\Delta E = 2.13$, 2.43, 0.86 for 4,6,7, respectively. Note that the error for six primaries is larger than that for four and that the four and the seven primary errors are relatively comparable to the PCA errors of similar number of primaries. This indicates that the use of solid colors and transparent filters is a relatively good basis for spanning the spectra space, and the same is true for the four filters indicated in Fig. 6. The spectra of the six solids, however, are not as optimal, given for example the difficulty associated with spectral reproduction of white. We have also examined the use of real manufactured filters as opposed to the ideal primaries. In this case we examined four different conversion methods: the first, where the F_i values derived from Demichel equations are used as signals for the display (i.e.,

Table II. Summary of color errors associated with different factors. The numbers in parentheses are spectral errors of filter combinations measured in terms of average RMS error of all 60 spectra.

		ΔE Only examined factor, all others set to zero influence			ΔE Perfect factor, all others unchanged
Influence of light		0.369			4.08
Influence of estimation		**Neugebauer** 2.66 (0.0285)	**YN modified** 1.80 (0.0161)		3.27
Influence of number and spectra of filters		**Four filters**	**Six filters**	**Seven filters**	2.74
	PCA	2.58 (0.0161)	0.44 (0.0058)	0.28 (0.0044)	
	Ideal[a]	2.13 (0.0293)	2.43 (0.0336)	0.86 (0.0093)	
	Real[b]		3.65 (0.0581)	3.09 (0.0366)	
	Real[c]		4.03 (0.0574)	3.48 (0.0353)	
	Real[d]		2.94 (0.0965)	2.94 (0.0386)	
	Real[e]		3.34 (0.0456)	2.02 (0.0192)	
Total system					3.96

[a]Spectral transmission identical to the spectral reflectance of the measured C,M,Y,R,G, and B solids and the blank substrate.

[b]The F_i values calculated from Demichel equations are used as the display signals a_i' (in the six primaries, white signal is reproduced by linear combination of other primaries).

[c]Matrix conversion applied on the F_is. Matrix coefficients determined by best spectral match of real primaries to ideal primaries.

[d]Matrix conversion applied on the F_is. Matrix coefficients determined by best colorimetric match of real primaries to ideal primaries.

[e]Best spectral match for each of the data points.

neglecting the difference between ideal and real filters); the second, in which matrix correction as indicated by Eq. (5) is applied and the coefficients are derived by spectral fit as in Eq. (4); the third is with similar matrix correction, but where the coefficients of the matrix are determined colorimetrically: and the fourth, where constrained least squares optimization is used for each spectrum. The level of error is similar for all conversion methods, indicating that a major error factor is the spectral mismatch of the real filters. Note that the matrix correction provides the same results for both six and seven primaries, since both configurations contain the Matchprint gamut entirely. The colorimetric matrix improves color accuracy, but slightly compromises spectral accuracy. Nevertheless, since the primaries have similar spectra to that of the Matchprint, a good spectral fit is maintained. We also examined the change of ΔE when the influence of the conversion module is eliminated, i.e., assuming perfect conversion, implying the displayed spectra are identical to the estimated ones. For Neugebauer estimation we have $\Delta E = 2.74$, while for YN estimation we obtain $\Delta E = 1.82$.

Examining Table II, we find that the major factor affecting accuracy is the inaccuracies of the real filters. When comparing the achievable accuracy obtained with the real filters to that of the ideal filters, we find that improvement in filter characteristics would contribute a lot in the case of seven filters, but less in the case of six filters. This is a possible indication that the set of the six ideal filters is not optimal, a fact supported by the comparison to the results obtained with the artificial filters derived by the PCA approach.

Similar conclusions are derived when examining the spectral error. The spectral error is calculated between the combinations of display primaries and the measured spectra, and thus it neglects the influence of light. We see that using the real filters increases the spectral error with respect to the situation where more ideal filters are used. As expected, when the conversion algorithm is aimed at best spectral match the spectral error is minimized. When matrix conversion is used [Eq. (5)] and the matrix coefficients are derived by spectral fit, the spectral error is lower than when matrix coefficients are determined by colorimetric match. At the same time, the colorimetric error is increased. The choice of conversion algorithm therefore depends on the desired spectral or colorimetric requirements. In any case the spectral display would provide a reasonably good level of both spectral and colorimetric match compared to standard RGB displays, in which only colorimetric considerations are taken into account.

Nevertheless, when considering the performance of the overall realized system, with its different light source, six real filters, and the simple Neugebauer estimation and linear matrix conversion, the average $\Delta E = 3.96$ and maximum error over all patches of $\Delta E = 10.9$ is fairly reasonable.

In conclusion, the novel concept of an additive spectral display is proven to be very suitable for accurate color reproduction, and in particular to the application of soft proofing previously discussed. The spectral display concept can be easily adapted to other color critical domains, such as the simulation of film.

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