Application Driven Design of Multi-Primary Displays

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Abstract

Implementations of multi-primary displays for home cinema, mobile screens and soft proofing are described and analyzed. The design flexibility gained by using extra primaries is discussed for each, and the different considerations are highlighted. We show that in all cases the multi-primary displays suit the requirements of the application better than RGB displays.

Introduction

Our imaging needs are varied and differ in their required "look and feel"; we want to make a movie look on our TV just like it looks at the cinema, use digital monitors for soft-proofing and achieve perfect color-match to printed paper. Translating these needs to a display's technical spec, one would find significant differences in key parameters such as color gamut, dynamic range, brightness and contrast ratio required for each application, to such degree implying that not one display can serve all. Nevertheless, up until recently the supply of electronic color displays was limited to only one type of device, CRT, whose color reproduction characteristics had almost no variance.

Practices of gamut mapping and color management have been developed to meet the different imaging needs mentioned above with the CRT gamut. However, even the most sophisticated ones have their shortcomings that derive primarily from the physical differences between the source and the target as can be seen from figure 1, which depicts the different color gamut of film, offset print on paper and the HDTV standard (Rec. 709 [1]).

In recent years, certain technological developments have facilitated the emergence of new displays. For RGB displays, these developments mostly mean that the gamut area boundary of Rec 709 may be surpassed [2]. However, one of the most significant breakthroughs is the ability to create Multi-Primary (MP) displays, which have gained a lot of interest lately [3-6]. Whereas RGB displays use red green and blue primaries to reproduce colors, in an MP display more than three primary colors are combined to create the colors.

Due to the use of more than three primaries, the three - dimensional color gamut structure of an MP display is significantly different than that of an RGB display. Furthermore, the increase in the degrees of freedom gained by the additional primaries allows a design of the gamut structure according to the application the display is intended for. The display's gamut would ideally be identical or at least very similar to the target gamut, thus enabling inherently good color match and relatively simple image processing. In the following we examine three different applications: home cinema displays, mobile displays and specialized displays for soft proofing of offset printing. We discuss the drawbacks of RGB displays and show how the use of multi-primary displays solves them.

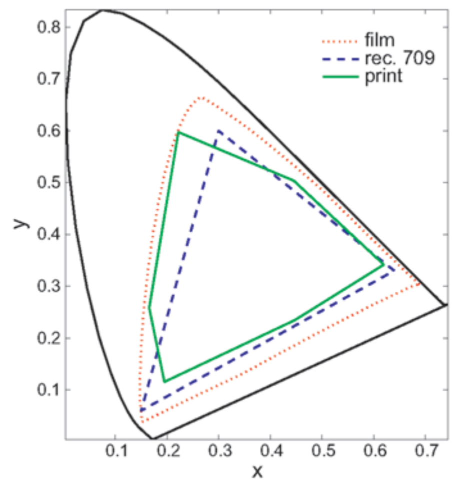

Figure 1. Film, Rec. 709 and print color gamut

Home Cinema

Home cinema is the high end niche of the TV market, and its intention is to create the cinema experience at home, both in terms of sound and image. While this has been achieved in audio, the video part is still slogging behind. Home cinema displays are usually large (front projectors and large TVs based on rear projection, plasma and recently also LCD panels), but lack the necessary color gamut and appearance of film. The film gamut is wider than Rec. 709 gamut (figure 1), in particular in the yellow and cyan color areas. The new RGB display technologies, which are not limited to Rec. 709 color gamut, still have triangular gamut shape. Thus the choice of the green point dictates the nature of the display. A green point near the edge of the chromaticity diagram, as in the case of the Sony Cineza home cinema front projector [7], provides good coverage of yellow colors, but limits the coverage of cyan (figure 2). A green inclined towards the cyan region, as in the Sony Bravia LCD [7] has the opposite effect. In both cases there is no coverage of the film gamut. The difference in color gamut between these two displays implies that their color gamut design is driven by technology rather than by the application which is common to both. A triangle that covers film gamut more closely than Rec 709 may be selected, such as the gamut defined by the DCI for digital cinema projectors [8]. Yet, a projector with such gamut will have very low brightness efficiency. Simple analysis shows that the white point luminance drops by >25%, when the color gamut of a projector with a given optical engine is extended from Rec. 709 to DCI gamut. This inefficiency is due to the fact that in order to increase the gamut in RGB displays, the spectral pass band of the RGB filters used in projectors and LCD displays to filter a white light source must be narrowed. Since a large screen with a reasonable luminance is a must for home cinema application, this implies that more light power has to be put into the engine. Although this may look like a simple solution, one must remember that more light power means more heat, implying tougher cooling requirements, resulting in more noise that should be masked so it would not disturb sound performance. As a result one ends up with a larger, more complicated system, with shorter lifetime and higher cost.

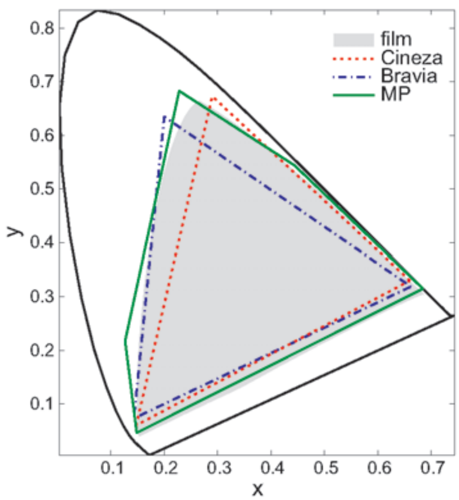

***Figure 2**. Comparison between the gamut of film (solid gray), two RGB displays- Cineza (dotted) and Bravia (dashed), and an MP display (solid line)*

Multi-primary displays can overcome both problems mentioned above. The use of more than three primaries allows a non-triangular gamut shape, thus providing coverage of both yellow and cyan regions. As an example the MP display configuration shown in figure 2 demonstrates a gamut optimized for film compatibility, larger than the DCI gamut by ~20%, yet with 30% increase in the luminance of the white point. This is achieved by adding yellow and cyan primaries and narrowing the band pass of the R, G and B primaries. For four-primary configuration, addition of yellow enhances the luminance and allows flexibility in the chromaticity of the green primary, thus again enabling better coverage of the film gamut.

The use of more primaries allows better utilization of the white light source, since the yellow region of the white light source may be included. Light sources used in the industry for projection engines, e.g. UHP and Xenon lamps, have intense yellow emission, which is not used in RGB displays, but may be fully included in a multi-primary display. Even more important factor is the spectral overlap of filters for MP displays, which results in better effective transparency than RGB filter set.

To understand the guideline for choosing the color filters and the issue of spectral overlap let us examine the MacAdam limits of the D65 optimal color stimuli depicted in figure 3 [9]. It is clear from the curve that adding a yellow primary is beneficial, since yellows may be rather saturated (i.e. very near the edge of the chromaticity curve) at relatively high luminance.

Furthermore, the black line drawn on the curve indicates the chromaticity obtained by various long wavelength transmission spectra with different cutoffs. We note that the line follows the chromaticity edge quite closely until a knee at a cutoff of 520 nm. Choosing a yellow filter corresponding to the knee point would yield a highly saturated yellow, which transmits as much as possible from the white source spectrum. Furthermore, a red filter with a cutoff at 600 nm (marked by a diamond on figure 3) is completely overlapped by the transmission of the yellow filter, thus the red part of the spectrum is transmitted twice through the system (regardless of the cutoff frequency of the red filter). Similar reasoning applies for the cyan and the blue.

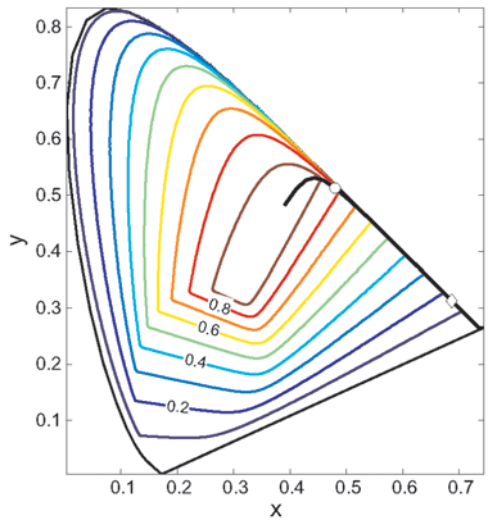

***Figure 3**. The MacAdam limits for optimal color stimuli under D65*

Moreover, parts of the green transmission spectrum are overlapped by the cyan and the yellow filters. As a result, although each of the filters in an n-primary display (where n>3) occupies 1/n of the pixel area (in an LC display) or on average 1/n of the time [10], the average transparency is higher than that of an RGB system since most of the white light spectrum transmits through two of the filters. Finally, although the analysis here is done in terms of D65 illumination it may be also done for other light sources (such as CCFL, UHP Xenon lamp or white LED) with similar conclusions.

Important considerations determining the choice of primaries are the required white point color temperature and the relative luminance of the primaries with respect to the white. Cinema look and feel implies "warm" (low) color temperature, typically 5000 – 6500K. In the CRT age, TV color temperature was pushed to significantly higher levels typically 9000 – 12000K, thus rendering a much "cooler" appearance. Here again, additional primaries mean additional degrees of freedom. The introduction of a yellow primary means a much warmer device white point, between 5000 – 6500K. Thus, a very important aspect affecting cinema look and feel is achieved at the physical level of the display, rather than at the image processing level. As an example, the white point color temperature of the MP display shown in figure 2 is 5400K, typical for film.

In figure 4, luminance – excitation purity [11] curves representing cross sections of the color gamut of film and MP display along different hue lines (straight lines connecting two saturated colors with opposite hues through the white point on an x-y chromaticity diagram) are shown. It can be seen that a good match is achieved between MP performance and cinema envelope, in contrast to Rec 709 which falls short in saturated colors and throughout the whole range in yellow.

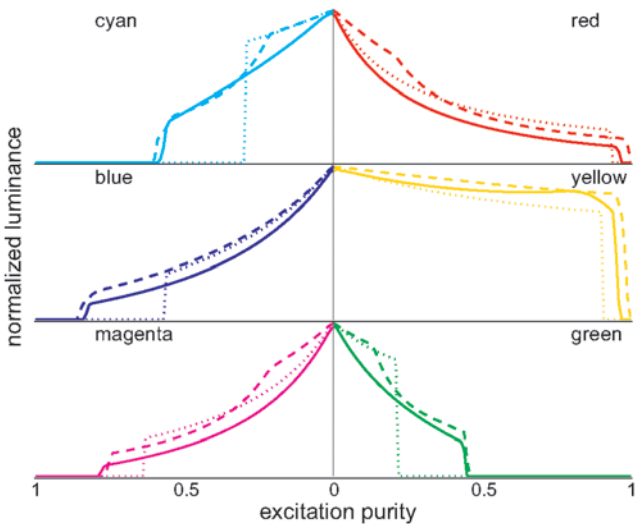

***Figure 4**. Luminance vs. excitation purity for the principle hues, for film (solid lines), Rec. 709 display (dotted) and MP display (dashed)*

Nevertheless, as home cinema products are used for viewing not only feature films but also other types of content (typically Rec 709), other color spaces and their 3 dimensional volumes have to be considered. This consideration pertains mainly to the relative luminance of the primaries with respect to the white point, which may be essential to the compatibility with the color space represented by the data. The chromaticity of a primary usually trades-off with its luminance; therefore a suitable choice of a primary should represent an optimum between both aspects.

Currently, color data is given in terms of device dependent RGB data. The Rec. 709 standard for example, maps this device dependent RGB to absolute color space within the Rec. 709 triangle. To make use of the benefits of the MP display a suitable color rendering and gamut mapping method has been developed, as well as color conversion from a three dimensional color space into MP signals. The conversion is performed by transferring the incoming device dependent data into an absolute color space where color rendering and mapping are performed, and at the last stage the resulting XYZ data is converted to multi-primary signals. The use of absolute color provides a reference to which the primary signals may be aligned by calibration. The conversion from three to n>3 channels is a problem with a multitude of solutions and for video applications the solution must be chosen at real time speed, sufficient for processing 1080P data, implying about 6 ns total processing time per pixel.

Gamut mapping is required because the color gamut of the MP display is different from that of Rec. 709, and most available color content is prepared to comply with Rec 709 standard. Therefore, the extended envelope of performance will not be utilized without color re-mapping. Color is hence re-mapped to the full gamut of the display, while appearance heuristics constrained by image quality aspects are applied. The integrity of neutral, natural and other memory colors is protected, and out of device - gamut colors are re-mapped inside, preserving color differentiation and smooth transitions.

Mobile Displays

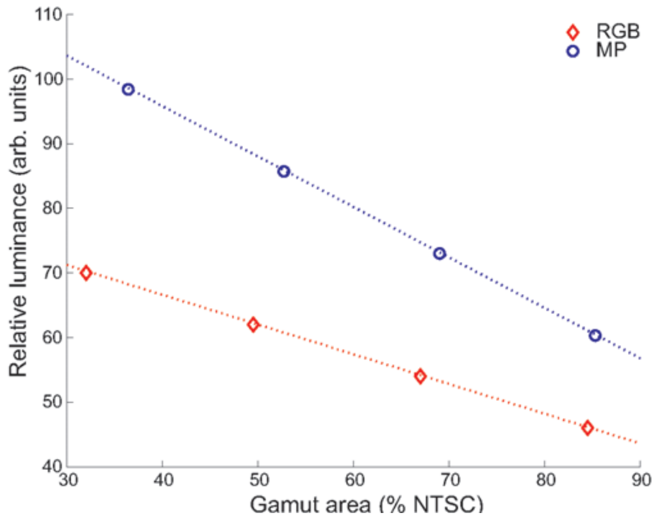

***Figure 5**. Relative luminance vs. gamut area for RGB displays (diamonds) and MP displays (circles). Lines are added for reference only.*

Mobile displays have some similarity to other TV applications (including Home Cinema discussed above) in the sense that they are also used for presentation of video and image data. However, they differ from these applications in several important aspects. First and most crucial is the fact that they rely on battery operation, and thus power consumption is a major issue. Furthermore, they are usually viewed outdoors or in lit environment where ambient light is the main factor in determining the dark level of the display. As a result, contrast is determined by the luminance of the display and color saturation is usually limited.

As discussed before there is a close relation between gamut size and white luminance in RGB displays; larger color gamut implies lower luminance when all other parameters are equal. Therefore, the approach taken by most cellular mobile display manufactures for example is to reduce gamut in order to obtain higher luminance (and higher apparent contrast). The smaller color gamut is even further reduced by the presence of flare light, resulting in poor colors.

The flexibility of MP displays provides a solution to this problem, by applying the concepts discussed above to a different design. As in the case of RGB display there is a relation between color gamut and luminance, however the better efficiency of the MP display places it at a better starting point. Figure 5 describes the relation between the size of the color gamut (measured as area in the xy chromaticity plane with respect to the NTSC triangle) and the luminance of the white point, for RGB and MP liquid crystal displays, both with a white LED backlight. The color matrix filters used for this evaluation are those available and compatible with current LCD technology. We see that for the same gamut size the luminance of the multi-primary display is higher by a factor ranging from 1.45 to 1.3. This extra luminance may translate to either higher apparent contrast (hence better image quality) or alternatively the apparent contrast may stay the same and the amount of power fed into the backlight reduced, thus prolonging battery lifetime. Another approach is to opt for similar luminance and contrast without power saving, and to obtain the larger color gamut the MP display offers. This would result in a better color image, which may be important in many video applications.

Spectral Soft Proofing

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 hard copy process, the main reasons being color gamut, viewer variance, color management concept and sensitivity to ambient light. As seen in figure 1 the color gamut of CRT does not encompass neither the color gamut of devices used for proofing such as Matchprint or Cromalin systems, or even that of offset inks. In addition, 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 ICC profiles involving conversion to absolute color space. This color transformation suffers from several problems. First, any change in the properties of the simulated systems, or the illumination under which the proofs are viewed, requires re-profiling. If many system combinations are required, management and update of these profiles becomes an impractical task. Furthermore, the color transformations are based on an "average" human, and thus inter-observer variations may be of great concern [12]. CRT 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 light box.

While the other applications discussed in this paper concern colorimetric reproduction, for soft proofing the MP approach shows its inherent strength, by providing a new display concept – a spectrally matched color display. Many natural spectra [13] can be described as linear combinations of a small number of basis functions. The same is true for reflectance spectra obtained from offset printing inks or proofing systems such as Matchprint or Cromalin. We have measured reflectance spectra of 60 patches from a Matchprint target, analysed them using PCA and found that more than 99% of the variance is accounted for by 4 or more basis functions. An MP display with a small number of primaries ($4 \leq n \leq 7$), whose spectra are tailored to fit the basis functions, is thus able to provide spectral reconstruction of print. However, the basis function obtained by PCA or SVD are orthogonal, 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 behaviour 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 (CMY) and from the overlaps (blue for CM, green for CY and red for MY) [14]. 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 (BGR for blue, green, red, not to be confused with additive display RGB).

Possible implementation based on these ideas is a sequential rear projection MP display, where the filters are chosen in such way that they reproduce the normalized reflectance spectra of the inks and their overlaps with respect to the blank paper. In addition a fully transparent filter segment is included to represent the normalized blank paper reflectance, which is unity by definition. The light source is further filtered to obtain the same light spectra as that impinging on the paper. Thus, during the rotation of the color wheel the light transmitted through the relevant filter is identical to that reflected from the paper through the corresponding ink (or ink overlap or the blank paper). The filtered light illuminates the SLM, and each pixel is switched to the required level according to the amount of reflectance of that specific spectrum needed for this pixel. This amount is determined to a first approximation by applying Demichel equations to the dot gain corrected CMYK data values for the relevant pixel. The spatial halftone of the print is replaced by a temporal additive combination of the different primaries.

The projector operating in this mode is producing for each pixel a spectrum according to Murray-Davis spectral Neugebauer model. The Murray-Davis (MD) spectral Neugebauer model estimates the spectrum of a CMYK pixel by [15]:

$$\varphi(\lambda) = \sum_i F_i R_i(\lambda) \qquad (1)$$

Here $\varphi(\lambda)$ is the estimate of the spectrum reflected from a specific printing dot on the substrate, $R_i(\lambda)$ are the spectral reflected intensities of a set of elementary colors, i= CMY BGR KW. $R_i(\lambda)$ depends on the illumination conditions and substrate properties via $R_i(\lambda) = S(\lambda)R_W(\lambda)T_i(\lambda)$, where $S(\lambda)$ is the spectrum of the incident light, $R_W(\lambda)$ is the reflectance of the white paper and $T_i(\lambda)$ is the transmission of the i^{th} elementary color (ink or overlap of inks). The white transmission curve $T_W(\lambda)$, is assumed to be flat and equal to 1 and the transmission of black layer $T_K(\lambda)$ is assumed zero over the whole spectral range. Overlaps of black with other inks, and the overlap of C, M and Y results also in zero transmission, however, correction for finite small transmission and for 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. Within this model $0 \leq F_i \leq 1$ and the sum of all F_i is 1 [16].

Figure 6 depicts the a*,b* coordinates of a set of patches as measured from a Matchprint proof of a color target, under D50 illumination, and a simulation of corresponding colors obtained by the projector described above. 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.

The advantage of the MP spectral display compared to CRT is evident. The projector operates in a manner very similar to the physical print and its gamut inherently matches it. Its model of operation does not involve profiles, and thus it is simple to change parameters, either at the physical level of the projector or by simple manipulation of input data. As an example, since the system is based on transmitting light through a spectral reconstruction of the inks and the overlaps, an illumination change would be obtained at the physical level of the projector, by inserting additional filter between the light source and the filter wheel that would convert the source spectrum to the required one.

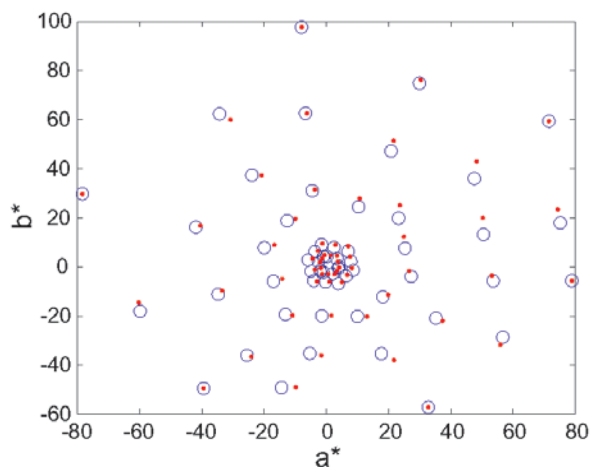

***Figure 6**. Match between measured and reproduced colors*

Dot gain is easily manipulated by affecting the Demichel coefficients, and other parameters such as density and ink trapping are also included within the model as will be discussed later. Furthermore, since spectra are reconstructed rather than colors, inter-observer variability is of less concern. Finally, the color stability is determined by the relation between the color filters and the spectral stability of the light, both of which are very stable. This is in contrast to CRT in which different aging of the red, green and blue phosphors or external electromagnetic fields may cause colors to deviate significantly.

A more general approach splits the system into two parts, a spectral display with n primaries (the filters) and spectral estimation and conversion unit. Since the display is additive in nature, the resulting spectrum for a certain pixel is defined as:

$$\varphi_D(\lambda) = \sum_{k=1}^{n} a_k \chi_k(\lambda) \tag{2}$$

Here $\chi_k(\lambda)$ is the spectra of the display primaries and $\varphi_D(\lambda)$ is the spectrum reproduced by the display when derived by the signals a_k. The spectral estimation and conversion unit obtains the CMYK data for the specific pixel, evaluates the spectrum $\varphi_R(\lambda)$, which should be reproduced for this input, and from that calculates the corresponding a_k's.

The spectrum $\varphi_R(\lambda)$ can be represented as a set of coefficients β_j representing the weights of predefined spectral functions $\Psi_j(\lambda)$, namely:

$$\varphi_R(\lambda) = H\left(\sum_{j=1}^{L} \beta_j \Psi_j(\lambda)\right) \tag{3}$$

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 a unity transformation $H(x_\lambda)=x_\lambda$, and $\Psi_j(\lambda)$ are the inks, the overlaps and the blank paper spectra, than eq. 3 represents the Murray-Davis (MD) Neugebauer spectral model (and β_j are the Demichel coefficients). Another example is a Yule-Nielsen (YN) spectral model, where $H(x_\lambda)=x_\lambda^{m}$, and $\Psi_j(\lambda) = (S(\lambda)R_W(\lambda)T_j(\lambda))^{1/m}$, where m is a parameter determined by experiment, which is about 1.5 for offset printing. Other examples include cellular models in which more spectral functions 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, or models in which the spectrum of black ink is not assumed zero, and the overlaps of black and other inks may be taken into account. Furthermore, within this spectral estimation the influence of lower density or a change in ink trapping may be taken into account by affecting the functions $\Psi_j(\lambda)$.

Having calculated the spectrum to be reproduced $\varphi_R(\lambda)$ as discussed above, the coefficients a_k should be determined based on the estimated $\varphi_R(\lambda)$ 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 $\varphi_R(\lambda)$, and under the requirement that all a_k must be in the range 0 – 1. If $H(x_\lambda)$ is linear, then the a_k's are obtained from the β_j's via linear matrix manipulation, without a need to fully evaluate the spectrum $\varphi_R(\lambda)$, an approach which is very suitable for cheap hardware implementation, since the matrix coefficients depend on the choice of spectral functions and display primaries, but not on the values of the CMYK input data.

Figure 7 demonstrates the spectral similarity between several spectra as measured from a Matchprint (normalized by reflection from white) and the simulated spectra obtained from a seven primary display. The estimation is based on Yule-Nielsen model, and the conversion is performed by constrained least square error fit. In table 2, colorimetric results for different systems are shown. The systems differ in the number of primaries of the projector (7 or 6, where the white is left out) and their spectra ("ideal" means spectra are identical to those measured on paper, "real" are interference filters that were designed for us based on our requirement for ideal filters, thus representing typical manufacturing tolerances). The systems also differ in the estimation and conversion modules used.

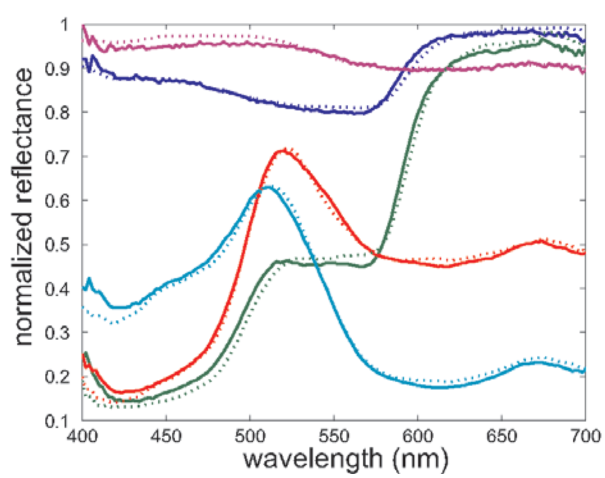

***Figure 7.** Comparison between measured and reproduced spectra*

The display accuracy of an ideal 7 filter set in the case of MD estimation is determined by the estimation itself. For YN estimation, the conversion of the estimated spectra to display coefficients is the major source of inaccuracies. However, as we move to a 6 primaries display, or to the real filters, the accuracy is determined by the conversion stage for both models, and it is limited by the possibility to fit the basic spectra with the available filters.

Table 2: Colorimetric results for different systems

System	Avg. ΔE	Max ΔE
7 "ideal" filters, MD estimation no conversion $F_i=\beta i$	2.65	7.6
7 "ideal" filters, YN estimation Conversion: constrained LSE minimization	1.95	6.4
7 "real" filters, MD estimation Conversion: matrix	3.30	10.9
6 "ideal" filters, MD estimation Conversion: matrix	3.40	7.6
6 "real" filters, YN estimation Conversion: constrained LSE minimization	3.80	10.9

We have implemented the concept described here by stacking two DLP sequential projectors whose color filter wheels were replaced by custom made wheels outfitted with "real" filters. The image was split into RGB and CMY channel sets that were each fed into the corresponding projector to form an integrated image on the screen. We have used a high transmission (>50%), low reflectance (<0.4%) gain 1 screen, which, coupled with the system's high brightness rendered the display high ambient light immunity, allowing consistent operation under both bright room illumination and total darkness. The measured color difference in black, between a dark and a fully illuminated room is ΔE=1.2 for the spectral display compared with ΔE=18 for CRT.

MD estimation was used, however allowing different blacks (black ink and its overlap with C, M, and Y inks) which were well differentiated due to the contrast of the display (>300:1). The conversion step was done by matrix. The spectral match yielded by this system was not perfect (especially for highlights) as white filter was not used, however the colorimetric results were good, averaging ΔE<4.5.

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[10] In a sequential projector the ratios are not necessarily identical to 1/n since they are determined by the sizes of the color wheel segments.

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[16] Note that the print gamut is limited by the requirement that the sum of all F_i is 1, while the projector gamut does not have this constrains. Thus the projector gamut encloses the print gamut.

Author Biography

Dan Eliav has been a developer of color management applications and algorithms for the Graphic Arts industry since 1992. Holding various positions with Scitex Corporation, his work covered the full color chain from capture (scanners and digital cameras) to output (monitors and print). Dan has also been an independent consultant for color management and pre-press integration until co-founding Genoa Color Technologies in 2000.

Shmuel Roth received his Ph.D in Physics from the Bar Ilan University, Ramat Gan, Israel. From 1981 to 2000 he worked in El-Op, Electro-Optical Industries (a subsidiary of ELBIT, NASDAQ: ESLT), in the fields of laser and thermal imaging research and other defense and aviation related systems. Shmuel joined Genoa in 2001, as VP of technologies. In Genoa, his professional responsibilities include the electro-optical design of the multi primary displays.

Moshe Ben Chorin received his Ph.D. in Physics from the Hebrew University of Jerusalem, Israel in 1992. Until 1998 he was holding research positions as a post-doc fellow and as a research associate, at the Technical University of Munich, Germany and at the Weizman Institute of Science, Israel. His research was mostly in the fields of semiconductor physics and optical spectroscopy. Later, he was working on different aspects of image quality, including color, in Karat Digital Press, until he co-founded Genoa Color Technologies in 2000, where he holds the position of Chief Scientist.