Multi-spectral-based color reproduction research at the Munsell Color Science Laboratory

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ABSTRACT

The traditional techniques of image capture, scanning, proofing, and separating do not take advantage of colorimetry and spectrophotometry. For critical color-matching applications such as catalog sales, art-book reproductions, and computer-aided design, typical images, although pleasing, are unacceptable with respect to color accuracy. The limitations that lead to these errors have a well-defined theoretical basis and are a result of current hardware and software. This has led us to a re-examination of the traditional graphic reproduction paradigm. A research and development program has begun that will alleviate the theoretical limitations associated with traditional techniques. There are four main phases: 1) Multi-spectral image capture, 2) Spectral-based separation and printing algorithm development, 3) Implementation on press, and 4) Systems integration with data and image archives. This paper describes this new paradigm, summarizes recent research results, and considers implementation opportunities.

Keywords: colorimetry, spectrophotometry, multi-spectral image, multi-ink separation, metamerism, high-spatial resolution, color quality, graphic reproduction, spectral-based printing, principal-component analysis.

1. LIMITATIONS OF CONVENTIONAL GRAPHIC REPRODUCTION

Conventional graphic reproduction involves the concatenation of two reproduction processes, photography and printing. The photographic process, as an input device, is inherently noncolorimetric. It is impractical to achieve spectral sensitivities with the required large spectral overlap because photographic products consist of a "tripak" where the three layers are stacked one on top of another.[1] Furthermore, the photometric responses of film are nonlinear.[2] As a consequence, large color distortions can result during the image recording process. The variance in match equality due to the metamerism can be large, resulting in a dramatic reduction in color quality. This can be easily demonstrated by making a photographic reproduction of a metameric pair (a pair of specimens that match to a color-normal observer but have different spectral properties as a result of using different colorants during their manufacture).

The second stage in conventional graphic reproduction is scanning and image editing. The editing can correct the inherent limitations in color photography to some extent. Although scanning often results in additional color distortions, many methods[3,4] have been published to produce highly accurate scanning of photographic media. It is possible to use a conventional scanner as a colorimetric device. Thus, the colorimetric coordinates of the photographic material can be determined accurately. Color editing has also been used to minimize the color distortions resulting from the photographic process.

Conventional four-color printing results in a reproduction composed of cyan, magenta, yellow, and black inks. Optimally, the ink amounts, expressed as effective dot areas on the page, should be determined that result in the same color as the soft proof. Thus, the color print can be related back to the original object or scene to be reproduced when all the steps are concatenated. Because the original object is likely colored with different colorants than the four printing primaries, the reproduction results in a metameric match.

In summary, it is impossible to accurately reproduce original objects using the conventional techniques of photography and process printing.

2. A NEW PARADIGM: MULTI-SPECTRAL COLOR REPRODUCTION

It is well known that the only way to assure a color match for all observers across changes in illumination is to achieve a spectral match. Developing a spectral-based color reproduction system requires two critical subsystems. The first is a spectral analysis system. The spectral properties of each image element must be known. The second is the ability to print using multiple inks. If the printer has a large set of inks from which to choose from, it should be possible to select a subset of inks that achieve a spectral match to critical scene elements. There are tremendous possibilities in achieving spectral matches between original objects and their printed reproductions. Three subsystems are required: multi-spectral image estimation, ink selection minimizing metamerism, and spectral-based printing models including separation algorithms. This is shown in Figure 1. In addition to these subsystems, trichromatic-based multimedia imaging devices including CRT displays and desktop printers can be easily incorporated. Essentially, trichromatic-based systems are a subset of multi-channel-based systems.

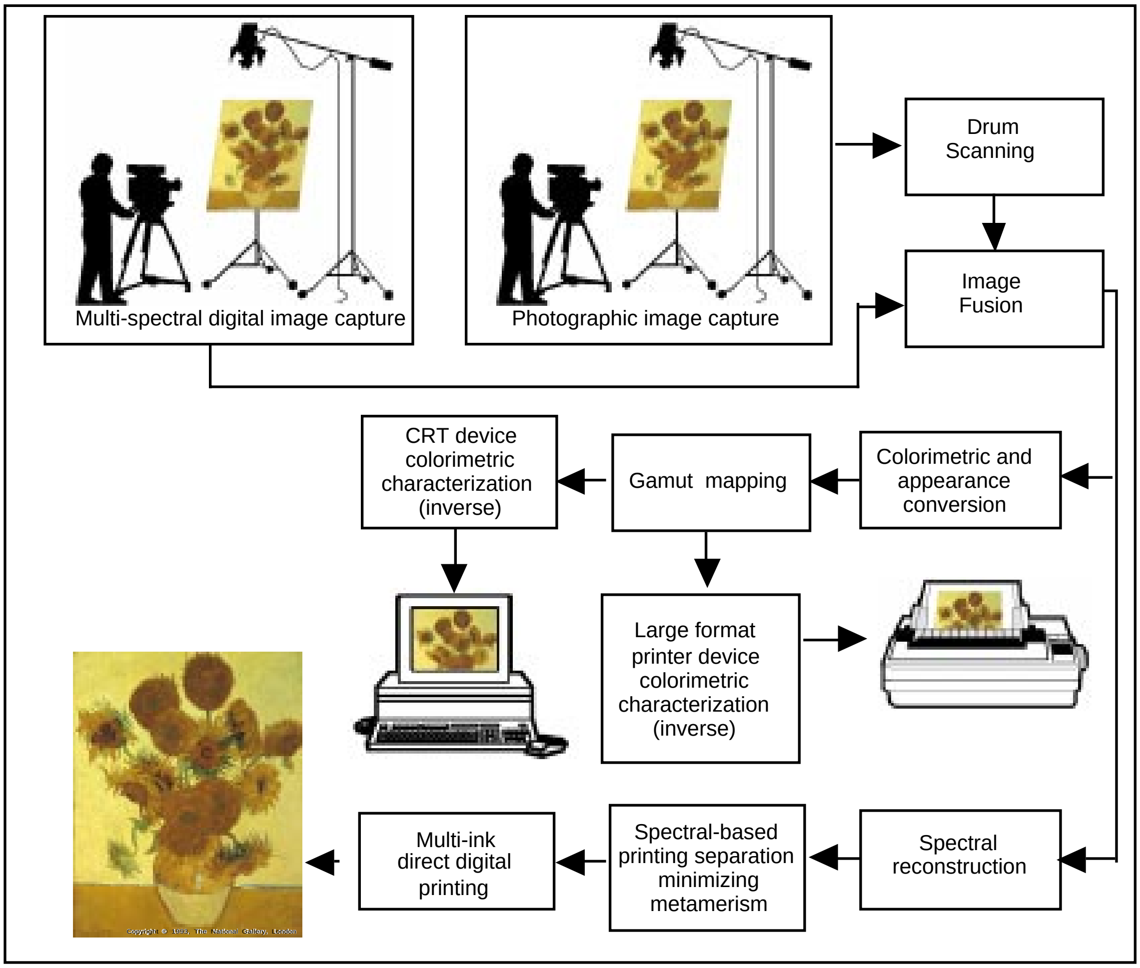

Figure 1. Multi-spectral-based multimedia flowchart. (Van Gogh image copyright of National Gallery, London.)

There is an obvious parallel to the world of color matching of materials. In the United States, many stores that sell house paint have color matching systems. These consist of a spectrophotometer, computer, and paint-dispensing system. Most manufacturers including textiles, plastics, and coatings use similar systems. A standard's spectral reflectance factor is measured using the spectrophotometer. From a data base of colorants appropriate to the particular coloration process, a subset is selected that when used to color the particular material system (e.g. paint or fabric), a match will result that is minimally metameric. The software algorithms used in these systems can be divided into two steps. The first is colorant selection. From a large database of colorants, the three or four colorant combination (the most common number of colorants used in a formulation) is selected that results in the closest spectral match (i.e. least metameric). Once the colorants are determined, their amounts, the recipe, is defined based on a color mixing model such as Kubelka-Munk turbid media theory. If an exact spectral match will result, one can combine these steps. For example, forward-selection multiple-linear regression[5] can be used to order the candidate colorants in terms of their spectral matching potential. However, if an exact spectral match is not possible, there will be residual colorimetric error; accordingly, the spectral matching algorithm might be used for colorant selection followed by a colorimetric matching algorithm to insure a close match for a primary illuminant. Alternatively, iterative methods are used where every three- or four-colorant combination is evaluated.

The multi-spectral image capture is equivalent to the spectrophotometer. A set of candidate inks is equivalent to the database of appropriate colorants. The ink-selection algorithm is equivalent to colorant selection minimizing metamerism. The spectral-printing model and separation algorithm is equivalent to determining the final color recipe.

3. MULTI-SPECTRAL IMAGE CAPTURE

Conventional image capture, both chemical and digital, is largely trichromatic. Three channels are used to record color information. Traditional color science would argue that the requirements for building input devices are straightforward. Trichromatic systems should have spectral responsivities that are linearly transformable from color matching functions (sometimes called the Luther condition). For a wide-band system, it is impossible to distinguish between metameric stimuli. Two approaches can be taken to estimate the spectral properties of scene elements.

The first, and most direct, method is to increase the sampling increment above three. Conceptually, this is equivalent to using a spectrophotometer sampling the visible spectrum at constant bandpass and wavelength interval rather than a colorimeter or densitometer. Although spectrophotometer accuracy requirements have not been universally defined, according to the CIE,[6] tristimulus errors will not be introduced when measuring materials if a 5 nm wavelength increment and bandpass are used. Ideally, one would want to sample every 5 nm with a 5 nm triangular bandpass throughout the visible spectrum. This corresponds to 61 channels. Obviously, it is necessary to reduce the number of channels. However, one should be able to decrease the sampling increment without a significant loss of spectral information, because of the absorption characteristics of both man-made and natural colorants. Spectral analysis of colored stimuli using linear modeling techniques typically result in less than ten eigenvectors.[7-9] Thus one should be able to greatly reduce the number of channels from 61.

The second method is to perform an *a priori* spectral principal-component analysis (PCA) enabling either the optimal filter design[10-12] or a more accurate spectral reconstruction of the subsampled stimulus. This method is used routinely in photography in the conversion between integral and analytical density. Because a given photographic material uses a single set of cyan, magenta, and yellow dyes, three eigenvectors based on the absorption spectra will define the entire spectral gamut. Thus, a three-channel measurement with a logarithmic response (necessary due the linear nature of the absorption spectra, not the reflectance or transmittance spectra) can be used to estimate the spectral properties of photographic images. This technique has been used to build high-accuracy device profiles for graphic arts scanners.[4] Considerable research has been performed in determining the minimum number of channels,[12-25] their spectral response, and how the multichannel information is used for spectral estimation. Issues include colorimetric accuracy, spectral accuracy, and noise propagation. For example, research at the Munsell Color Science Laboratory[14-17] has focused on using a typical monochrome digital camera (Kodak Professional DCS 200m) in conjunction with a set of seven readily-available filters from Melles Griot. The spectral sensitivities of the seven channels are shown in Figure 2.

The method of spectral estimation was based on an eigenvector analysis of a subset of the Munsell Book of Color sampling this system's color gamut. The first five eigenvectors were used. The spectral reconstruction for a given sample is computed by

$$\mathbf{f} = \Phi\alpha + \mu_{\mathbf{f}}, \qquad (1)$$

where, $\Phi = [\mathbf{e}_1, \mathbf{e}_2, ..., \mathbf{e}_5]$, $\mu_{\mathbf{f}}$ is the mean spectral vector, and $\alpha^{\mathbf{T}} = [\mathbf{a}_1, \mathbf{a}_2, ...\mathbf{a}_5]$ is the set of five scalar weights associated with the sample to be reconstructed spectrally. The scalars can be found by

$$\alpha = [\Phi^{\mathbf{T}}\Phi]^{-1}\Phi^{\mathbf{T}}(\mathbf{f} - \mu_{\mathbf{f}}). \qquad (2)$$

The term $[\Phi^{\mathbf{T}}\Phi]^{-1}\Phi^{\mathbf{T}}$ can be interpreted as a matrix of spectral sensitivity functions that could be used to analyze a sample, $\mathbf{f}$, for subsequent spectral reconstruction. For the multi-spectral camera, however, the spectral reconstruction needs to be based on the camera signals, $\mathbf{s}$. This can be achieved by computing a least-square (5 x 7) matrix, $\mathbf{M}$, to transform the camera signals into estimates of the scalar coefficients α. The spectral reconstruction is then given by,

$$\mathbf{f} = \Phi \ \mathbf{M} \ \mathbf{s} \qquad (3)$$

where $\mathbf{s}^{\mathbf{T}} = [s_1, s_2, ..., s_7]$. Equation (3) does not include the mean vector, $\mu_{\mathbf{f}}$, since the principal components used in this reconstruction were calculated as the eigenvectors of the second moments about zero, rather than the usual covariance matrix about the mean.

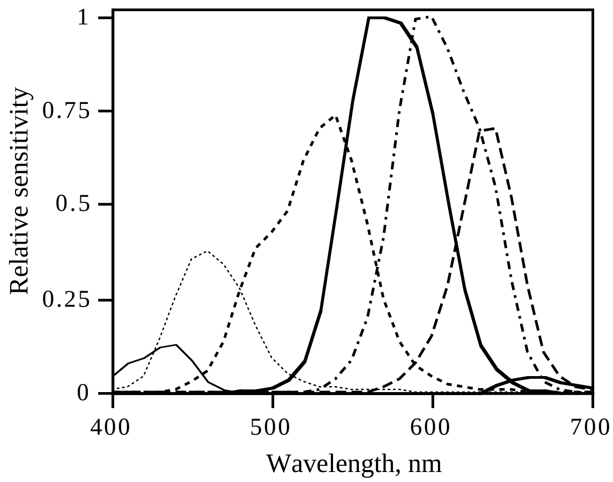

Figure 2. The spectral sensitivity of each of the seven filter/sensor channels.

Since each of the optical filter spectral transmittance curves has a similar shape, one can think of the image collection, prior to detection, as a spectral filtering followed by a sampling operation with $\Delta\lambda$=50 nm.[26] This view of image acquisition lends itself to spectral reconstruction via interpolation schemes such as cubic-spline and modified-discrete-sine-transformation (MDST) interpolation.[22,23] The latter method relies on properties of the sine-transform (and Fourier-transform) representations of a signal. Simple extrapolation is applied to the sine transform of an input array, followed by inverse transformation. An interpolated signal can then be extracted from the resulting data. These two interpolation methods were also evaluated. Figure 3 shows that spectral estimation results in large differences on spectral-reconstruction accuracy. The poor results for the two interpolation techniques were expected given the spectral width of the seven channels which limits the high-spectral frequency components in the detected signal.

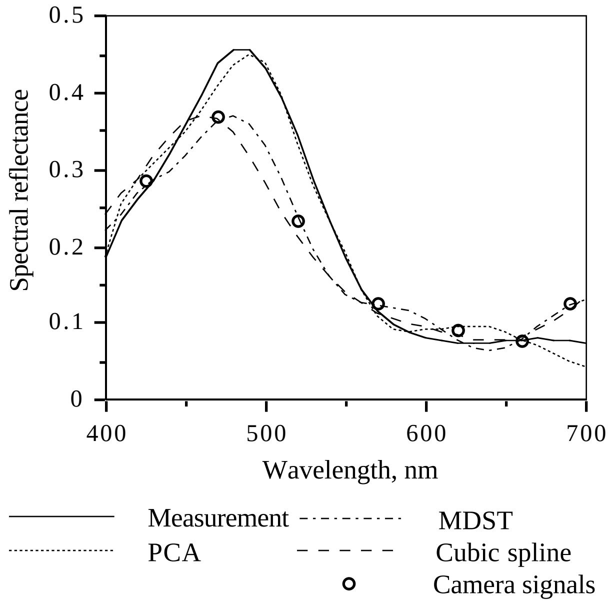

Figure 3. The spectral reconstruction using principal-component analysis (PCA), modified-discrete-sine-transformation (MDST) and cubic spline interpolation, from camera signal values, for the cyan sample of the Macbeth ColorChecker chart.[17]

In the above method, the visible spectrum was evenly sampled. It may be possible to improve the accuracy of the spectral reconstruction by unevenly sampling in order to optimize for a defined class of materials. For example, research performed at the Munsell Color Science Laboratory[11] found that different colorant systems required different spectral sampling for optimal results as shown in Figure 4 comparing an embodiment of the Munsell Book of Color (Chroma Cosmos 5000) and the Macbeth ColorChecker chart.

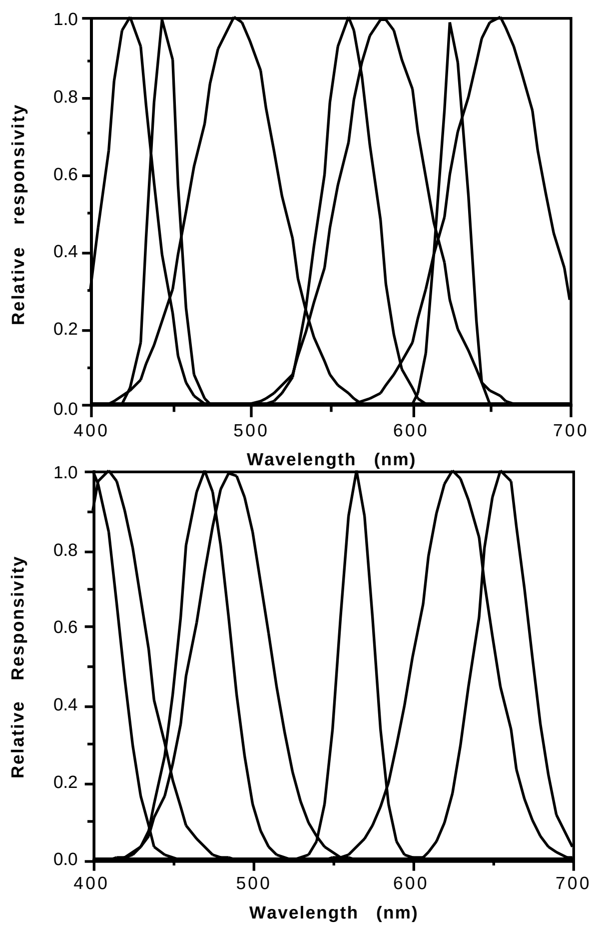

Figure 4. Optimal seven-channel spectral relative responsivities for highest colorimetric accuracy for the Chroma Cosmos 5000 (top) and a Macbeth ColorChecker (bottom).[11]

Multi-spectral image capture has been used by England's National Gallery to accurately record the colorimetric values (CIELAB) of paintings for archival and conservation purposes.[27,28] Because of the inherent low resolution of digital cameras and the large size of many paintings, they scan across the painting and use mosaic-type software to fuse the various image subspaces. After appropriate signal and spatial processing, 20K x 20K 10-bit L*, 11-bit a* and b* encoded images result. The National Gallery has been very successful in developing colorimetric image archives and using them to provide the European community with accurate color reproductions in both soft-copy and hard-copy forms under a defined set of illuminating and viewing conditions (i.e. colorimetric color reproduction).

We have an interest in drawing upon the European experiences and making two enhancements. The first is alleviating the need to scan across the painting. This will greatly reduce the cost and complexity of the image acquisition system. The second is to define images spectrally and use the spectral information to provide the American community with printed color reproductions that are close spectral matches to the original objects.

An imaging system is envisioned consisting of a high-resolution photographic system and a low-resolution multi-spectral digital system. In this system, each pixel of each multi-spectral image is interpolated to produce a high-spatial resolution image keeping its color information and changing the original lightness for the lightness data of corresponding high-spatial resolution image subpixels, without noticing the expected decrease of tonal resolution in the hybrid image, because the modulation of the light in the eye becomes progressively smaller as the spatial frequency increases.[29] This visual feature of human eye has been applied in photography, in television, as well as to devise very effective compression algorithms such as JPEG. The lightness and color information can be codified respectively as CIELAB L* and CIELAB a*, b* in order to allow the system to be easily optimized to have the least color difference in CIELAB ΔE_{ab}^*. Figure 5 shows a schematic diagram of this proposed method.

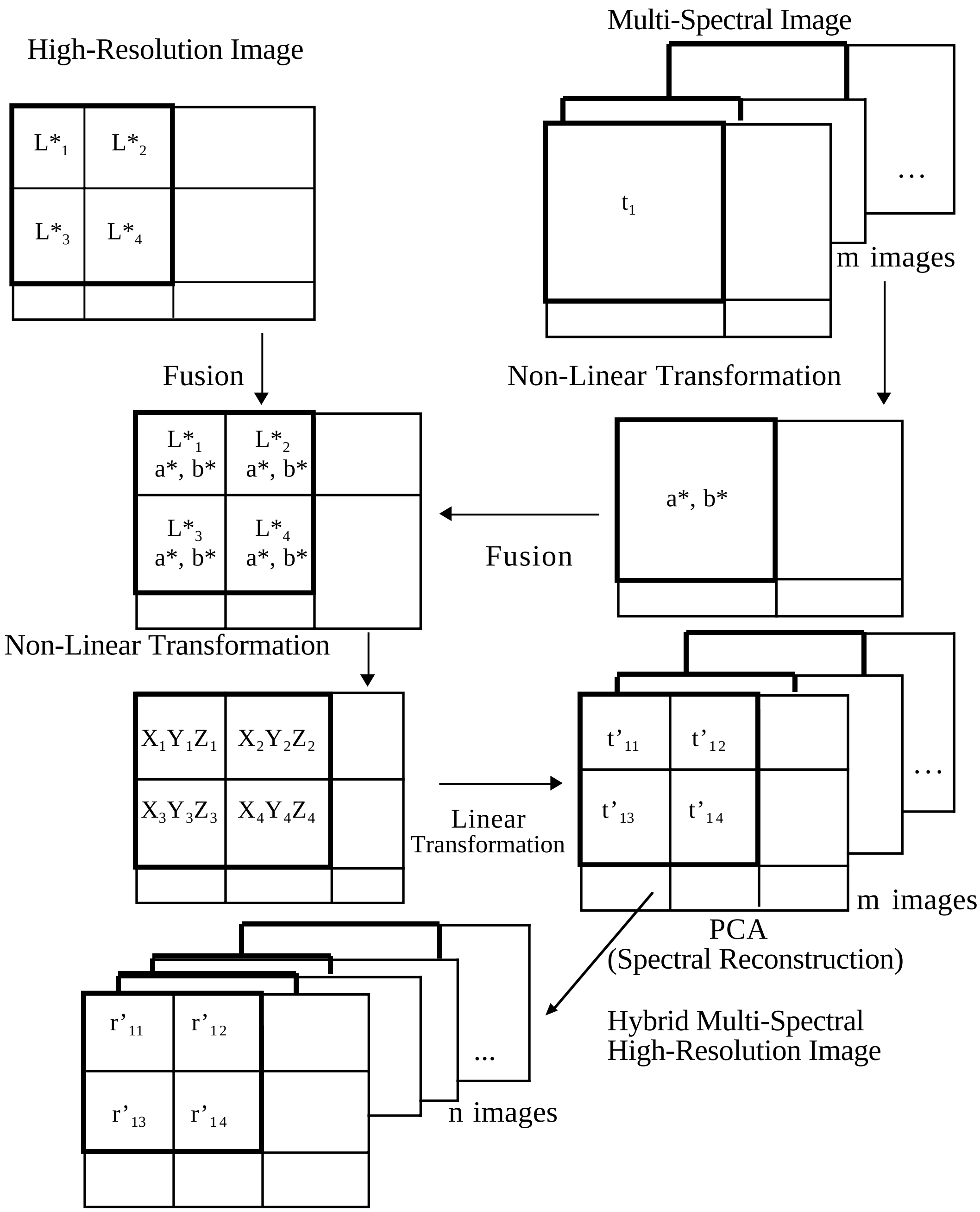

Figure 5. Diagram of proposed image fusion.

At first, L^* is calculated for each pixel of the high spatial resolution image. The CIELAB a* b* values for each pixel of the multi-spectral image is computed from the camera signals t_i , $i = 1$ to m and m is the number of filters, by a non-linear transformation. The images are fused keeping L^* of the high spatial resolution image and combining with the a^*, b^*

values of the low spatial resolution image. The tristimulus values of each pixel of the hybrid image is calculated and the camera signals of each channel are calculated by linear combination. Finally the hybrid high-resolution spectral image is reconstructed by principal-component analysis. We can divide the hybrid multi-spectral generation into three parts: the spectral analysis, the image fusion, and the spectral reconstruction.

Spectral Analysis

Performance of an *a priori* spectral analysis of the sampled data is necessary to achieve an accurate spectral reconstruction for the specified sampling rate and filter system characteristics such as type, shape and number. It is possible to optimize the filters[10,13] but it is not considered in this stage of the research because such optimized filters are usually very difficult to be manufactured. The number of basis functions necessary for accurate spectral reconstruction also depends on the database used for PCA. However, 5 to 8 basis vectors seem to be sufficient for an accurate spectral reconstruction of artwork.

One can model multi-spectral image acquisition using matrix-vector notation. Expressing the sampled illumination spectral power distribution as

$$\mathbf{S} = \begin{bmatrix} s_1 & & & 0 \\ & s_2 & & \\ & & \ddots & \\ 0 & & & s_n \end{bmatrix}, \qquad (4)$$

and the object spectral reflectance as $\mathbf{r}=[r_1, r_2, \ldots r_n]^T$, where the index indicates the set of n wavelength over the visible range and ^{T} the transpose matrix, representing the transmittance characteristics of the m filters as columns of **F**

$$\mathbf{F} = \begin{bmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,m} \\ \vdots & \vdots & \cdots & \vdots \\ f_{n,1} & f_{n,2} & \cdots & f_{n,m} \end{bmatrix} (5)$$

and the spectral sensitivity of the detector as

$$\mathbf{D} = \begin{bmatrix} d_1 & & & 0 \\ & d_2 & & \\ & & \ddots & \\ 0 & & & d_n \end{bmatrix}, \qquad (6)$$

then the captured image is given by $\mathbf{t}=(\mathbf{DF})^T\mathbf{Sr}$ and the color vector can be represented as $\mathbf{c}=\mathbf{At}=(X, Y, Z)^T$ where X, Y, Z are the CIE tristimulus values. The CIELAB L^*, a^*, b^* are given by the non-linear transformation ξ, where $\xi(X, Y, Z) = L^*, a^*, b^*$.

Image Fusion

The color matrix of the hybrid image is $\mathbf{c'}=(X'\ Y'\ Z')^T$, where X', Y', Z' are the tristimulus values corresponding to the high spatial resolution subpixel L^* combined with the original multi-spectral a^*, b^* values and X', Y', Z' are obtained by non-linear transformation ξ^{-1}. The digital count for each pixel of the hybrid image is given by $\mathbf{t'}= (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^t\mathbf{c'}$**.**

Spectral Reconstruction of Hybrid Image

The reconstructed spectral reflectance for sample i is given by: $\hat{\mathbf{r}}_\mathbf{i} = \mathbf{\Phi}\alpha_i$, where $\Phi=[e_1\ e_2 \ldots\ e_n]$, where $e_1\ e_2 \ldots\ e_n$ are the eigenvectors of the second moments about the zero vector, and $\alpha_i = [a_1\ a_2 \ldots\ a_n]^T= \mathbf{\Phi r}_i$ are the associated eigenvalues. Φ is *a priori* information obtained by principal-component analysis of sampled spectral reflectance and α_i can be estimated as follows: $\alpha \approx \hat{\alpha} = \mathbf{B}\mathbf{t}'$ where $\mathbf{B}=\alpha\mathbf{t'}^T[\mathbf{t'}\ \mathbf{t'}^T]^{-1}$ where the rows of α correspond to the samples in the set of reflectance vectors for each set-illuminant combination.

4. SPECTRAL-BASED SEPARATION AND PRINTING ALGORITHM DEVELOPMENT

Reducing metamerism between objects and their printed reproductions implies spectral matching. The color of the output device is defined by its spectral reflectance factor rather than colorimetric coordinates. In spectral-based research, it is more common to develop models rather than build *mxn* dimensional look-up tables where *m* counts the number of measured samples and *n* counts the number of wavelengths. The first step in developing a spectral-based printing system is the derivation of an accurate spectral model of color printing. There are many representative color printings models.[30-40]

As an example Iino and Berns[34,36] used the Yule-Nielsen modified Neugebauer equations to model process printing, shown in Eq. (7) where a_i are the effective dot areas of the 16 Neugebauer primaries for four-color printing, described in the usual manner by the Demichel equations, R_i are the reflectance factors of each *ith* Neugebauer primary, c, m, y and k, are dot areas of each primary ink, and n_l is the Yule-Nielsen n value defined as a function of wavelength. Typical spectral model fits are shown in Figure 6.

$$\begin{aligned} R_\lambda = (& a_c R_{\lambda,c}{}^{1/n_\lambda} + a_m R_{\lambda,m}{}^{1/n_\lambda} + a_y R_{\lambda,y}{}^{1/n_\lambda} + a_k R_{\lambda,k}{}^{1/n_\lambda} \\ & + a_r R_{\lambda,r}{}^{1/n_\lambda} + a_g R_{\lambda,g}{}^{1/n_\lambda} + a_b R_{\lambda,b}{}^{1/n_\lambda} \\ & + a_{ck} R_{\lambda,ck}{}^{1/n_\lambda} + a_{mk} R_{\lambda,mk}{}^{1/n_\lambda} + a_{yk} R_{\lambda,yk}{}^{1/n_\lambda} \\ & + a_{rk} R_{\lambda,rk}{}^{1/n_\lambda} + a_{gk} R_{\lambda,gk}{}^{1/n_\lambda} + a_{bk} R_{\lambda,bk}{}^{1/n_\lambda} \\ & + a_{cmy} R_{\lambda,cmy}{}^{1/n_\lambda} + a_{cmyk} R_{\lambda,cmyk}{}^{1/n_\lambda} + a_w R_{\lambda,w}{}^{1/n_\lambda})^{n_\lambda}, \end{aligned} \tag{7}$$

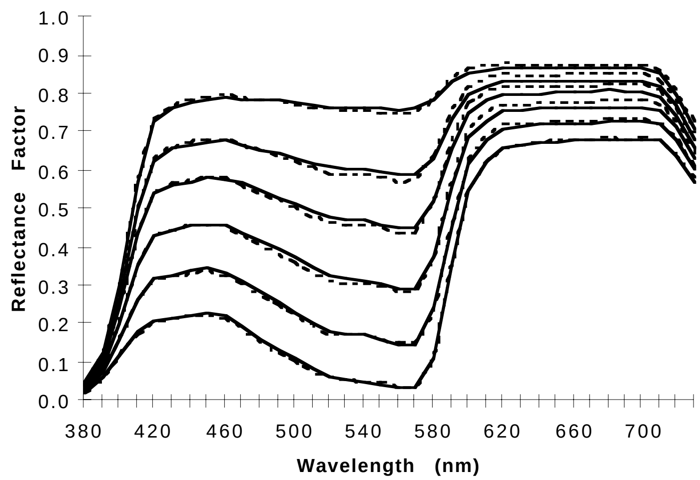

Figure 6. Measured spectral reflectance factor (dashed line) and predicted spectral reflectance factor (solid line) of the magenta ramp based on Eq. (7).[36]

One difficulty often encountered in using the Demichel equations to predict the entire color gamut is a discrepancy between predicted and actual area coverage caused by optical interactions. Recognizing that the Yule-Nielsen modification is empirical, this can be removed in favor of increasing the number of Neugebauer primaries. This approach is more in line with the true optics of ink paper interactions. The number of primaries can be increased to i^2 where i counts the number of primaries or to infinity.[39,40] Alternatively, the empirical equation is used with an augmentation where the optical interactions are accounted for in the conversion between theoretical and actual area coverages.[34,36,41] Iino and Berns described this using Eq. (8). Their colorimetric performance was, on average, ΔE^*_{ab} of 2.2 with a maximum of 5 for independent colors sampling a printer color gamut represented by Matchprint III.

$$
\begin{aligned}
q_c &= f_{c\_m}(d_{t,m}) f_{c\_y}(d_{t,y}) f_{c\_k}(d_{t,k}) \\
q_m &= f_{m\_c}(d_{t,c}) f_{m\_y}(d_{t,y}) f_{m\_k}(d_{t,k}) \\
q_y &= f_{y\_c}(d_{t,c}) f_{y\_m}(d_{t,m}) f_{y\_k}(d_{t,k}) \\
q_k &= f_{k\_c}(d_{t,c}) f_{k\_m}(d_{t,m}) f_{k\_y}(d_{t,y})
\end{aligned} \tag{8}
$$

where q_i is coefficient q for the overlapped ink i, the function $f_{i\_j}(d_{t,j})$ is the decreasing effective dot gain function of the secondary color (overlapped ink i by overlapping ink j), and $d_{t,j}$ is the theoretical dot area of each overlapping primary color.

In order to fully develop a multimedia system that is analogous to the color matching of paints or textiles, a large database of inks is required. The purpose of the database is to provide sufficient spectral variability, such that one can "tune" a spectral reflectance factor, thereby matching the spectral properties of an object requiring color reproduction. This requirement is different from typical multi-ink systems, largely concerned with increasing color gamut.[41-51] Published research where minimizing metamerism is the goal rather than increasing color gamut has been limited to preliminary research by one of the authors.[52]

Using a small-aperture spectrophotometer, the spectral reflectance factor of 100 positions across a landscape painting was measured, plotted in Figure 7. Transforming the spectral data to absorption and scattering ratios using Kubelka-Munk turbid media theory, performing principal-component analysis, and rotating the significant characteristic vectors to an all-positive representation, a statistical set of pigments results, shown in Figure 8.[51] This statistical set of pigments will predict the 100 measurements to an average ΔE^*_{94} of 0.8 and a maximum of 1.8. The degree of metamerism,[52] expressed in CIE94 units, is 0.1 on average with a maximum of 0.3. Once a printing system is defined and spectrally modeled, the optimal ink set can be determined that minimizes metamerism compared with the statistical pigment set.

5. SYSTEM EVALUATION

Once the spectral-based multimedia system has been developed, quality metrics are required. These should include CIE94 color difference metric[53], special indices of metamerism,[52,54,55], indices of color inconstancy[55], and indices that include the human visual system's spatial properties.[56,57]

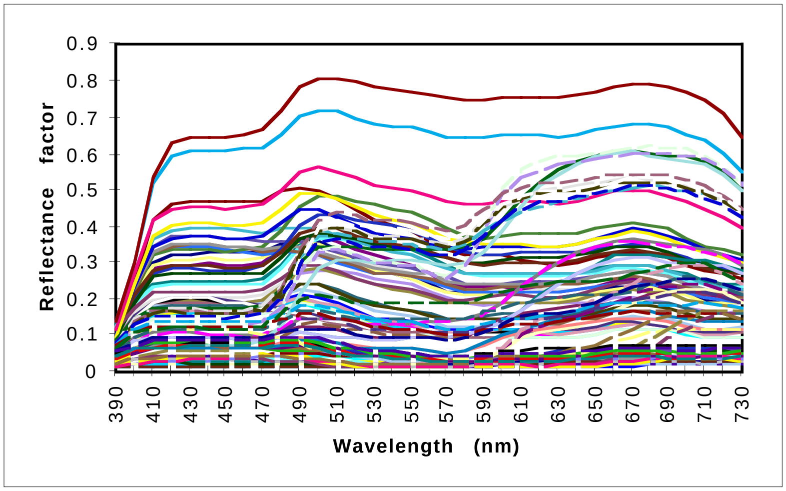

Figure 7. Measured spectral reflectance factors of 10x10 grid sampling a landscape painting.

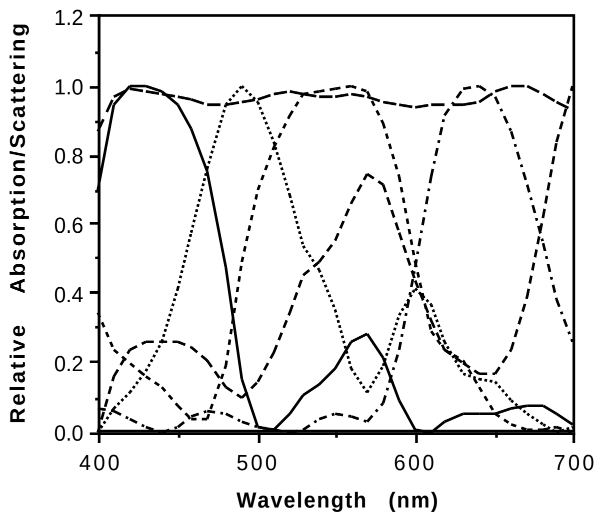

Figure 8. Statistical colorants representing a painting.[51]

6. CONCLUSIONS

Evaluating multimedia imaging as one of many applications of color science can result in a new paradigm for color imaging, multi-spectral-based imaging. However, developing multichannel multimedia systems will likely cause a dramatic increase in cost (hardware, software, personnel training, data storage, image access, etc.). If only an increase in color accuracy compared with the current state of multimedia imaging was the benefit, a cost-benefit analysis would probably not result in a favorable outcome. Fortunately, there are many additional benefits that result from spectral data bases and color printing that minimizes metamerism. Perhaps most important is the potential to define and thereby archive objects using the most fundamental definition, spectral reflectance factor. As an analogy, the U.S.'s National Institute of Standards and Technology only provides spectral definitions for their standard-reference materials used for spectrophotometers. Matching spectra minimize the need for controlling lighting, viewing conditions, and observers. The benefits we take for granted when having our automobile refinished after a collision or when we purchase clothing can be applied to multimedia.

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