Color measurements using a colorimeter
and a CCD camera

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ABSTRACT

Two new techniques are introduced for measuring the color content of printed graphic images with applications to web inspection such as color flaws and measurement of color quality. The techniques involve the development of algorithms for combining the information obtained from commercially available CCD color cameras and colorimeters to produce a colorimeter system with pixel resolution.

1. INTRODUCTION

Color determination is based on the phenomenon of how a human observer perceives color. In 1931, the Commission Internationale de l'Eclairage (CIE) set forth the standards which are used to determine the human response to color. The CIE standards are based on color measurements in which human observers visually matched a given color by the mixing of three primary colors (red, green, blue). The result of the experiment was a set of observer spectral tristimulus values (x , y , z) which are the standard in color determination. There are a number of other color coordinate systems, but most of these are based on a mathematical transformation of the CIE tristimulus coordinates.

Web inspection for product quality control is the measurement of flaws and flaw features. As an example, a sketch of an imaging colorimeter system as it would be used on a graphic printing press web transport system is shown in the figure on the following page. One important aspect of web inspection is the determination of color as perceived by a human observer. In order to make color measurements, the measurements must be referenced to the 1931 CIE observer tristimulus values. Most commercially available colorimeters measure color over large regions and thus lose sensitivity for localized features of interest. To determine color at a pixel level, two criteria must be satisfied. First, one of the CIE standard Illuminants (i.e. A, B, C, or D series) must be used and second, the response functions of the sensors at each pixel must conform to the standard observer response functions as specified by the CIE standard. Filters (red, green, blue) for an off-the-shelf CCD color camera do not correspond to the standard human response functions. One of the problems involved in designing filters that duplicate the human response functions is that two filters are needed to reproduce the x CIE standard response curve. For a CCD camera this means that four filters must be used instead of just three. If an off-the-shelf CCD color camera is used to determine color at the pixel level some method must be found to correlate the camera output with the CIE standard observer response. The method described here uses on-line colorimeter measurement to standardize the CCD color camera output.

2. MODELS AND COMPUTATIONAL TECHNIQUES

One modeling approach to correlate CCD color camera outputs with the CIE tristimulus values found in the literature is to use a conversion or compensation matrix. Since there are three camera and CIE values there will be nine matrix elements in the compensation matrix which must be determined. The determination of the

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Drawing of imaging colorimeter.

compensation matrix depends upon selecting a color space and making color camera measurements on a set of color chips, such as Munsell chips, covering the color space and relating these values to the standard CIE values. This approach was taken by Suzuki et al.¹ to relate the CCD color camera output to the CIE tristimulus values. The equation for this technique is given by the following:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \begin{pmatrix} r \\ g \\ b \end{pmatrix} \quad (1)$$

where the x , y , and z are the three CIE values, the r , g , and b are the outputs from the color camera for the three filters, and the m_{ij} $\{i,j = 1,2,3\}$ elements are the matrix elements relating the camera output to the CIE tristimulus values. In the paper by Suzuki the matrix elements m_{ij} are computed by considering a color space and determining the conversion matrix using the least squares method to minimize the error between measured values and computed values. As Suzuki points out, the conversion matrix depends strongly upon the set of color samples chosen. To test the accuracy of their conversion matrix, the color differences, using the CIELAB coordinate system, for 440 color samples were computed. The average color difference was < 1.3 and the maximum was about 5. For web inspection the color differences should be about 1 or less, since this is the smallest color difference which the human observer can detect. The problem with the conversion matrix approach is the loss of accuracy when the entire color space is described by just one matrix. One method to improve the accuracy of the conversion matrix approach is to subdivide the color space of interest into smaller subspaces and determine the conversion matrices on each subspace, however, better accuracy is obtained at the expense of having a set of smaller subspaces and more conversion matrices. The obvious extension of this technique is a "look-up table", mapping the camera response to xyz color space, with standardized illumination, filters, and CCD element responses.

A second modeling approach introduced by Simpson and Jansen², combines simultaneous colorimeter and CCD color camera measurements to obtain pixel-level tristimulus values. This technique uses the extra information provided by the colorimeter measurement to uniquely solve for the tristimulus values at each pixel of the measurement image. A matrix approach similar to Suzuki was employed, however in this case, the camera response functions were related to the standard human response functions using a conversion matrix. Again the accuracy was limited by how well the 3 human response functions could fit the 3 camera response functions with just 9 coefficients using a least squares fit.

This paper introduces two new techniques which are designed to (1) increase the accuracy of the color measurements without relying on conversion matrices and (2) represent the entire color space of interest, without subdividing the color space into smaller subspaces. The first technique is a generalization of the technique presented in the paper by Simpson. In order to reduce the error by the conversion matrix relating the human and camera response functions, both the camera and human response functions are expanded in terms of some basis set. The error can be made as small as desired by including as many basis functions as necessary for each of the expansions. The second technique is based on a method used by authors such as Barlow³, Maloney⁴, Wandell⁵, and Chang, Liang and Hackwood⁶. The basic premise of this technique is that linear models can be used to describe the reflectance and the radiance functions (illumination).

The measurement model used in both techniques is derived by representing the color signal corresponding to each filter of the CCD color camera at each pixel location by the integrated value (over wavelength) of the products of the image spectral illumination at the pixel, the camera spectral response, and the spectral reflectance of the image at the pixel site. Mathematically, the color signal is represented by the expression²:

$$\rho_{i\text{ccd}}^x = \int_{\lambda} E^x(\lambda) R_i^x(\lambda) S^x(\lambda) d\lambda \quad (2)$$

where $\rho_{i\text{ccd}}^x$ is the color signal at the pixel location x for the i^{th} CCD camera filter, {red, green, blue} or equivalently {1, 2, 3}, $E^x(\lambda)$ is the image illumination at the pixel location x , $S^x(\lambda)$ is the spectral reflectance at pixel location x , and $R_i^x(\lambda)$ is the spectral response of the camera at the pixel location x . The measurement made by the colorimeter is the integrated color content over the whole image. The colorimeter standard tristimulus values, $S_{i\text{colorimeter}}$ are modeled as follows:

$$S_{i\text{colorimeter}} = \frac{100}{N} \frac{\sum_{x=1}^N \int_{\lambda} E_s(\lambda) r_i(\lambda) S^x(\lambda) d\lambda}{\int_{\lambda} E_s(\lambda) r_2(\lambda) d\lambda} \quad (3)$$

where $E_s(\lambda)$ is the spectral irradiance of a standard source and $r_i(\lambda)$, for $i = \{1, 2, 3\}$, corresponds to the three CIE standard response curves {x, y, z} respectively, and N is the total number of pixels. The normalized CCD color camera output, $S_{i\text{ccd}}^x$, in terms of the tristimulus values is modeled by the expression:

$$S_{i\text{ccd}}^x = 100 \frac{\int_{\lambda} E_s(\lambda) r_i(\lambda) S^x(\lambda) d\lambda}{\int_{\lambda} E_s(\lambda) r_2(\lambda) d\lambda} \quad (4)$$

The problem is to determine the normalized CCD camera output, $S_{i\text{ccd}}^x$, given the CCD color camera output, $\rho_{i\text{ccd}}^x$, and the colorimeter output, $S_{i\text{colorimeter}}$.

2.1 Linear model for human and camera responses

The first technique is a generalization of the method presented by Simpson² for determining the color and is based on the following three assumptions: (1) the image illumination, $E(\lambda)$ has the same spectral response as the standard illumination, $E_s(\lambda)$; (2) the standard human response functions and the camera response functions can be expanded in terms of a set of basis functions; and (3) $E(\lambda)$, is uniform over the image, and the CCD elements have uniform responses (i.e. independent of the pixel location x). The model in Simpson's paper was generalized for two reasons. First, by allowing the human and camera response functions to be expanded in an arbitrary set of basis functions, rather than using the compensation matrix approach, a basis set can be selected which will minimize the error resulting from the expansions. The general method assumes any number of basis functions (greater than or equal to 3) can be used. Second, additional constraints can be allowed; for example, the constraint that all the values obtained from the fit must be non-negative can be imposed.

By using a Standard Illuminant, $E_s(\lambda)$, the resulting image illumination, $E(\lambda)$ will be proportional to the source, thus

$$E(\lambda) = K E_s(\lambda) \quad (5)$$

where K is the constant of proportionality. Assumptions (1) and (3) require that the image illumination and the camera response functions be uniform across all pixel locations. Using these assumptions equation (2) can then be written in the form

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$$\rho_{i\text{ CCD}}^x = K \int_{\lambda} E_s(\lambda) R_i(\lambda) S^x(\lambda) d\lambda \quad (6)$$

The third assumption involves choosing a basis set $\{\phi_1, \phi_2, \dots, \phi_n\}$ and expanding both the human response functions and the camera response functions in terms of this basis set as follows:

$$\begin{aligned} R_i(\lambda) &= \sum_{j=1}^n a_{ij} \phi_j(\lambda) \quad \text{for } i = 1, 2, 3 \\ r_i(\lambda) &= \sum_{j=1}^n b_{ij} \phi_j(\lambda) \quad \text{for } i = 1, 2, 3 \end{aligned} \quad (7)$$

For generality, an arbitrary number of basis functions, n , has been assumed. If three basis functions are chosen and there are three camera filters, then there will be a unique solution to the problem. However, if more than three basis functions are used with three filter functions, then a mathematical technique such as singular value decomposition must be applied to the problem in order to obtain a solution. When equation (7) is substituted into equations (6), (3), and (4), the resulting new equations are given by

$$\rho_{i\text{ CCD}}^x = \sum_{j=1}^n a_{ij} K \int_{\lambda} E_s(\lambda) \phi_j(\lambda) S^x(\lambda) d\lambda \quad (8)$$

$$S_{i\text{ colorimeter}} = \frac{1}{NP} \sum_{x=1}^N \sum_{j=1}^n b_{ij} \int_{\lambda} E_s(\lambda) \phi_j(\lambda) S^x(\lambda) d\lambda \quad (9)$$

$$S_{i\text{ CCD}}^x = \frac{1}{P} \sum_{j=1}^n b_{ij} \int_{\lambda} E_s(\lambda) \phi_j(\lambda) S^x(\lambda) d\lambda \quad (10)$$

where

$$P = \frac{1}{100} \int_{\lambda} E_s(\lambda) r_2(\lambda) d\lambda \quad (11)$$

To simplify the notation, I_j^x is defined by the equation

$$I_j^x = K \int_{\lambda} E_s(\lambda) \phi_j(\lambda) S^x(\lambda) d\lambda \quad (12)$$

When explicitly writing the matrices in this paper 3 basis sets will be used. Generalization to more than 3 basis sets is straightforward. The procedure now is to solve a series of linear equations to determine the normalized CCD camera output, $S_{i\text{ CCD}}^x$. Equation (8) can be written in matrix form as follows:

$$\bar{\rho}_{\text{CCD}}^x = \bar{A} \bar{I}^x \quad (13)$$

where

$$\vec{\rho}_{CCD}^x = \begin{pmatrix} \rho_{1\ CCD}^x \\ \rho_{2\ CCD}^x \\ \rho_{3\ CCD}^x \end{pmatrix} \quad \vec{I}^x = \begin{pmatrix} I_1^x \\ I_2^x \\ I_3^x \end{pmatrix} \quad \vec{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \quad (14)$$

In order to relate the colorimeter values and the camera values, it is convenient to introduce the average values of the quantities over all the pixels as follows:

$$\bar{\rho}_{i\ CCD} = \frac{1}{N} \sum_{x=1}^N \rho_{i\ CCD}^x \quad (15)$$

$$\bar{I}_i = \frac{1}{N} \sum_{x=1}^N I_i^x$$

where N is the total number of pixels.

The first step is to solve equation (13) for the value I_i^x and its average value over all the pixel locations. Using the average values of I_i^x equation (9) can be written as

$$S_{i\ colorimeter} = \frac{1}{PK} \sum_{j=1}^n b_{ij} \bar{I}_j \quad (16)$$

and using equation (12) in equation (10), $S_{i\ CCD}^x$ can be expressed in terms of I_j^x as:

$$S_{i\ CCD}^x = \frac{1}{PK} \sum_{j=1}^n b_{ij} I_j^x \quad (17)$$

Now taking the ratio of equations (16) and (17) and solving for the normalized camera values, the final results are obtained:

$$S_{i\ CCD}^x = \frac{\sum_{j=1}^n b_{ij} I_j^x}{\sum_{j=1}^n b_{ij} \bar{I}_j} S_{i\ colorimeter} \quad (18)$$

As an example, choose the basis set to be CIE standard response functions, $r_i(\lambda)$. The coefficients a_{ij} in equation (7) can be determined by a least squares fit to the standard response functions. The coefficients b_{ij} become the Kronecker delta function, having a value of 1 for $i = j$ and 0 otherwise. For this basis set, equation (18) reduces to the same form derived by Simpson and Jansen².

$$S_{i\text{ CCD}}^x = \frac{I_i^x}{\bar{I}_i} S_{i\text{ colorimeter}} \quad (19)$$

2.2 Linear model for illumination and reflectance

The second technique is based on the method by Maloney⁴ and Wandell⁵ in which they demonstrate that the illumination and the reflectance can be expanded in a linear combination of basis functions. This approach is unique in that the actual camera and colorimeter response functions are used as opposed to fitting the curves with a conversion matrix. The advantage of expanding the illumination and the reflectance functions, rather than the response functions, is that the illumination and the reflectance spectra are more slowly varying functions with respect to wavelength and thus higher accuracy is obtained with fewer basis sets. Also, the illumination and reflectance, being band-limited, do not depend on the selection of a color space for their determination and the method is uniformly applicable to the entire color space. A further benefit of this approach is that the spectral reflectance, the image illumination, as well as the xyz values are obtained at each pixel of the image. Assumptions used in the second approach are as follows: (1) the image illumination and the reflectance can be expanded in terms of basis functions, and (2) the measurement illumination, $E(\lambda)$, and the CCD element responses, $R_i(\lambda)$, are uniform over the image.

The mathematical procedure for this method is very similar to the procedure for the first method, except that three different sets of basis functions are used; one each for the reflectance, the average reflectance, and the image illumination. Expanding the illumination and the reflectance in terms of basis sets $\{u_1, u_2, \dots, u_m\}$ and $\{v_1, v_2, \dots, v_n\}$ respectively using an arbitrary number of basis sets for each basis function,

$$\begin{aligned} E(\lambda) &= \sum_{j=1}^m e_j u_j(\lambda) \\ S^x(\lambda) &= \sum_{k=1}^n \sigma_k^x v_k(\lambda) \end{aligned} \quad (20)$$

Substituting the expansions in equation (20) into equation (2) and noting from the second assumption that image illumination is uniform over the entire region of interest and the camera response functions are uniform (i.e. independent of the pixel location, x), the color signal is then given by the expression:

$$\rho_{i\text{ CCD}}^x = \sum_{j=1}^m \sum_{k=1}^n e_j \sigma_k^x G_{jk} \quad (21)$$

where

$$G_{jk} = \int_{\lambda} u_j(\lambda) R_i(\lambda) v_k(\lambda) d\lambda$$

Substituting the expansions given in equation (20) into equation (3)

$$S_{i\text{ colorimeter}} = \frac{1}{PN} \sum_{x=1}^N \sum_{k=1}^n \sigma_k^x g_{ik} \quad (22)$$

where

$$g_{ik} = \int_{\lambda} E_s(\lambda) r_i(\lambda) v_k(\lambda) d\lambda$$

$$P = \frac{1}{100} \int_{\lambda} E_s(\lambda) r_2(\lambda) d\lambda$$

The color signal, $\rho_{i, \text{CCD}}^*$, averaged over all the pixel locations, x , can be related to the colorimeter measured values, $S_{i, \text{colorimeter}}$. This procedure involves using an expansion for the average reflectance. The average reflectance is related to the average color signal and the colorimeter values, as demonstrated by the following two equations. The colorimeter values from equation (3) can be written in the form:

$$S_{i, \text{colorimeter}} = \frac{1}{P} \int_{\lambda} E_s(\lambda) r_i(\lambda) \bar{S}(\lambda) d\lambda \quad \text{where} \quad \bar{S}(\lambda) = \frac{1}{N} \sum_{x=1}^N S^x(\lambda) \quad (23)$$

and the average color signal, using equation (2) and the definition of the average value over all the pixel locations, gives the equation:

$$\bar{\rho}_{i, \text{CCD}} = \int_{\lambda} E(\lambda) R_i(\lambda) \bar{S}(\lambda) d\lambda \quad (24)$$

Expanding the average reflectance in terms of some basis set $\{w_1, w_2, \dots, w_p\}$ the average reflectance becomes:

$$\bar{S}(\lambda) = \sum_{k=1}^p \bar{\sigma}_k w_k(\lambda) \quad (25)$$

Note that the three basis sets that have been introduced, can in general, all be different. The procedure is to solve for each set of coefficients. When the expansion for the image illumination (equation (20)) and the expansion for the average reflectance (equation (25)) are substituted into equation (24) the average color signal is given by the equation:

$$\bar{\rho}_i = \sum_{j=1}^m \sum_{k=1}^p e_j \bar{\sigma}_k Q_{ijk} \quad \text{where} \quad Q_{ijk} = \int_{\lambda} u_j(\lambda) R_i(\lambda) w_k(\lambda) d\lambda \quad (26)$$

Substituting equation (25) into equation (23) gives the colorimeter values in terms of the basis sets

$$S_{i, \text{colorimeter}} = \frac{1}{P} \sum_{k=1}^p q_{ik} \bar{\sigma}_k \quad \text{where} \quad q_{ik} = \int_{\lambda} E_s(\lambda) r_i(\lambda) w_k(\lambda) d\lambda \quad (27)$$

Equation (27) involves the coefficients for mean reflectance and can be written in matrix form as

$$\bar{S} = \frac{1}{P} \bar{Q} \bar{\sigma} \quad (28)$$

where

$$\vec{S} = \begin{pmatrix} S_{1 \text{ colorimeter}} \\ S_{2 \text{ colorimeter}} \\ S_{3 \text{ colorimeter}} \end{pmatrix} \quad \vec{\sigma} = \begin{pmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_3 \end{pmatrix} \quad \bar{Q} = \begin{pmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{pmatrix} \quad (29)$$

Matrix equation (28) can now be solved for the unknown coefficients (σ_i for $i = 1, 2, 3$). As stated earlier, if there are three basis functions and three camera filters, then a unique solution for the coefficients is obtained. Otherwise, mathematical techniques such as singular value decomposition must be used.

The next step is to determine the coefficients, e_j , in the expansion for the image illumination using equation (26). Equation (26) can be written in matrix form as shown below:

$$\bar{\rho} = \bar{H} \vec{e} \quad \text{where} \quad H_{ij} = \sum_{k=1}^p \bar{\sigma}_k Q_{ijk} \quad (30)$$

and

$$\bar{\rho} = \begin{pmatrix} \bar{\rho}_1 \\ \bar{\rho}_2 \\ \bar{\rho}_3 \end{pmatrix} \quad \vec{e} = \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix} \quad \bar{H} = \begin{pmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \\ H_{31} & H_{32} & H_{33} \end{pmatrix} \quad (31)$$

Equation (30) describes a linear system of equations with unknown coefficients, e_j , whose values can be determined straightforwardly or by using singular value decomposition in the overdetermined case as discussed previously.

The final stage in this process is to determine the coefficients, σ_k^x . Equation (21) can be written in terms of matrices and is given by the mathematical expression:

$$\vec{\rho}_{CCD}^x = \bar{M} \vec{\sigma}^x \quad \text{where} \quad M_{ik} = \sum_{j=1}^m e_j G_{ijk} \quad (32)$$

where

$$\vec{\rho}_{CCD}^x = \begin{pmatrix} \rho_{1 \text{ CCD}}^x \\ \rho_{2 \text{ CCD}}^x \\ \rho_{3 \text{ CCD}}^x \end{pmatrix} \quad \vec{\sigma}^x = \begin{pmatrix} \sigma_1^x \\ \sigma_2^x \\ \sigma_3^x \end{pmatrix} \quad \bar{M} = \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{pmatrix} \quad (33)$$

Equation (32) can now be solved for the coefficients, σ_k^x , at each pixel location. The normalized camera output can then be determined by substituting the expansion for the reflectance, $S^x(\lambda)$, into equation (4) and using assumption 2, to obtain the results:

$$S_{i \text{ CCD}}^x = \frac{1}{P} \sum_{k=1}^n \sigma_k^x \int_{\lambda} E_s(\lambda) r_i(\lambda) v_k(\lambda) d\lambda \quad (34)$$

Equation (34) can also be written in matrix form as

$$\bar{S}_{CCD}^x = \frac{1}{P} \bar{J} \bar{\sigma}^x \quad (35)$$

where

$$\bar{S}_{CCD}^x = \begin{pmatrix} S_1^x \\ S_2^x \\ S_3^x \end{pmatrix} \quad \bar{J} = \begin{pmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{pmatrix} \quad J_{ik} = \int_{\lambda} E_s(\lambda) r_i(\lambda) v_k(\lambda) d\lambda \quad (36)$$

2.3 Choice of Basis Functions

The minimization of the error in both techniques depends upon the choice of basis functions. The first technique uses a linear model for the human and camera response (Sect 2.1) and determines the respective coefficients from basis expansions of the camera and colorimeter response functions. The choice of the basis functions and how well the response functions can be fit by a finite number of basis functions determine the accuracy of this representation. The second method, the linear model for illumination and reflectance (Sect. 2.2), determines coefficients for the basis expansions from the CCD camera and colorimeter measurements. The technique is more general than the first method and uses the actual response functions $r_i(\lambda)$ and $R_i(\lambda)$ rather than relying on a fit, however, again the accuracy is determined by the number and choices for the basis functions, fitting the illumination and, more importantly, the reflectance by a finite number of basis functions.

One possibility for a choice of basis function is to use the Karhunen-Loeve (K-L) expansion. The K-L expansion is based on statistical analysis⁷ using an ensemble of color signals and solving for the eigenvectors. Any color signal can then be represented by a linear combination of these eigenvectors. Using Munsell color chips, Maloney determined the K-L eigenvectors for the reflectance and image radiance functions. Maloney concludes that when five or more basis functions are used, the error was < 1%. In many cases, excellent fits to the data were obtained using as few as three or four coefficients.

Another choice for basis functions was suggested by Stiles et al.⁸, who showed that frequency-limited (band-limited) functions can be applied to spectral reflectance functions. This appears to be a natural choice because the reflectance and illumination functions are band-limited in wavelength space; i.e., the color signals are constrained to be positive and wavelength-limited (400 - 700 nm). Chang et al., point out that under real-world conditions, the K-L expansions may not be easy to obtain; instead, they suggest that wavelength-limited functions may be a better choice for the basis functions. One such set suggested was the digital prolate functions⁹.

3. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

Two new approaches, both based upon linear models, have been introduced to produce an imaging colorimeter from off-the-shelf components. Both methods are expected to enhance the accuracy over previous color measurement techniques with CCD color cameras by eliminating the need for compensation matrices and taking advantage of the extra information provided by a parallel colorimeter measurement. The first approach uses a standard illumination source and models the colorimeter and human response functions with basis functions, yielding the computationally simpler procedure. The second approach uses actual human and camera response functions and models the illumination and reflectivity from basis expansions. The second approach has the added advantage of providing estimates of the illumination spectrum and the reflectance spectrum at the pixel level from the camera and colorimeter measurements. It is desirable to use as few basis functions as possible for the expansions, since there are only 3 camera filters. Our initial results indicate that band-limited functions such as the digital prolate functions

are a good choice for the basis functions.

We are now testing both approaches using mosaics of Munsell chips. Both CCD camera measurements and colorimeter measurements have been taken of a large set of Munsell chips. Mosaics consisting of approximately 16 Munsell chips are then constructed digitally from CCD color camera measurements of the individual chips. The colorimeter input to the model is then the average xyz CIE values for the entire mosaic. The normalized camera values are then computed using both approaches and compared with the individual colorimeter values made on each separate Munsell chip to determine the errors. The questions that remain, then, are: 1) How well does each model fit the measured data if only three basis functions are used in each basis set (therefore unique solution)? and 2) If more basis functions are used, what are the regions in color space where anomalies may exist (multiple solutions, similar to the phenomena of color metamerism)?

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David L. MacAdam

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- **Metals**
- **Ceramics**
- **Paints and Coatings**

IMAGING COLORIMETRY EXTENDS CONVENTIONAL COLOR MEASUREMENT TECHNOLOGY TO EXAMINE FINE DETAILS OR STRUCTURE ON AN OBJECT OR WEB

- Color quality control of features and details
- Defect detection and evaluation
- Feature Isolation and Extraction

Fig.1 Imaging Colorimeter

THERE ARE THREE TECHNIQUES PRESENTLY USED TO CONVERT CCD CAMERA OUTPUT TO THE STANDARD CIE COORDINATES

- Use of a conversion matrix to relate the camera values (r, g, b) to the tristimulus values (x, y, z)

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{pmatrix} \begin{pmatrix} r \\ g \\ b \end{pmatrix}$$

-Uses a finite sample color space and a least squares fit.

-Error increases as the size of the color space increases

- Use of a customized color camera

-Requires 4 filters

-Pixel registration problems

- Use of "look-up" tables

- Highly system dependent

- CCD response

- filter response

- illumination

- Sensitive to shifts in calibration

Research Instruments Section

1931 CIE Standard Observer Curves

**WE PROPOSE A NEW APPROACH USING SIMULTANEOUS CCD
CAMERA AND COLORIMETER MEASUREMENTS WHICH
ELIMINATES SOME OF THE PROBLEMS INVOLVED WITH THE
OTHER METHODS**

- No conversion matrix required
- Technique spans the entire color space
- No calibration of filter responses required
- Fitted parameters are determined directly from the CCD camera and colorimeter measurements

THE PROBLEM OF TRANSLATING THE CCD COLOR SIGNAL
 INTO STANDARD XYZ VALUES IS NOW CAST IN THE
 FOLLOWING FORM:

Given:

$$S_{i \text{ Colorimeter}} = \frac{100}{N} \sum_{x=1}^N \frac{\int_{\lambda} E_s(\lambda) r_i(\lambda) S^x(\lambda) d\lambda}{\int_{\lambda} E_s(\lambda) r_2(\lambda) d\lambda}$$

$$\rho_{i \text{ CCD}}^x = \int_{\lambda} E^x(\lambda) R_i^x(\lambda) S^x(\lambda) d\lambda$$

Find:

$$S_{i \text{ CCD}}^x = 100 \frac{\int_{\lambda} E_s(\lambda) r_i(\lambda) S^x(\lambda) d\lambda}{\int_{\lambda} E_s(\lambda) r_2(\lambda) d\lambda}$$

TWO NEW APPROACHES, USING LINEAR MODELS, ARE INTRODUCED TO CONVERT CCD COLOR CAMERA MEASUREMENTS TO CIE COORDINATES

- Linear model for human and camera responses.
 - A standard illumination source is used
 - The CIE human response functions and the CCD camera response functions are expanded in terms of a basis set
- Linear model for illumination and reflectance
 - The illumination and the reflectance spectra are expanded in terms of basis functions
 - The actual CIE human and camera response functions are used in the calculations

THE LINEAR MODEL FOR HUMAN AND CAMERA RESPONSES DETERMINES THE NORMALIZED CAMERA OUTPUT BY FITTING PARAMETERS TO THE MEASURED DATA.

- Camera and human response functions are expanded in terms of basis functions $\{\phi_1, \phi_2, \dots, \phi_n\}$

$$R_i(\lambda) = \sum_{j=1}^n a_{ij} \phi_j(\lambda) \quad i = 1, 2, 3$$

$$r_i(\lambda) = \sum_{j=1}^n b_{ij} \phi_j(\lambda)$$

- The fitted parameters I_i^x and $\bar{I}_i$ are given by

$$I_i^x = K \int E_s(\lambda) \phi_i(\lambda) S^x(\lambda) d\lambda$$

$KE_s(\lambda)$ - standard illumination source, K is a constant

$S^x(\lambda)$ - reflectance at pixel location x

$$\bar{I}_i = \frac{1}{N} \sum_{x=1}^N I_i^x, \quad N \text{ is the total number of pixels}$$

LINEAR MODEL FOR HUMAN AND CAMERA RESPONSES

(CONTINUED)

- The normalized CCD camera values are given by

$$S_{i \text{ CCD}} = \frac{\sum_{j=1}^n b_{ij} I_j}{\sum_{j=1}^n b_{ij} \bar{I}_j} S_{i \text{ colorimeter}}$$

SCHEMATIC OF THE LINEAR MODEL FOR HUMAN AND CAMERA RESPONSES

THE LINEAR MODEL FOR ILLUMINATION AND REFLECTANCE DETERMINES THE STANDARDIZED CAMERA OUTPUT BY DETERMINING THE EXPANSION COEFFICIENTS USING THE MEASURED DATA

- The image illumination, the reflectance at each pixel location, and the average reflectance (averaged over all pixel locations) are expanded in terms of basis functions
- The colorimeter measurements are used to determine the expansion coefficients for the average reflectance
- The illumination coefficients are determined from the average CCD camera measurements (average over all pixel locations) and the average reflectance coefficients
- The reflectance coefficients at each pixel location are determined from the illumination coefficients and the CCD camera measurements at each pixel location
- The normalized CCD camera values are determined from the reflectance coefficients at each pixel location.

ILLUMINANT C

TYPICAL SPECTRAL REFLECTANCE CURVE

SCHEMATIC OF THE LINEAR MODEL FOR ILLUMINATION AND REFLECTANCE

TWO ISSUES INVOLVED IN USING THE LINEAR MODELS ARE THE CHOICE OF BASIS FUNCTIONS AND THE NUMBER OF BASIS FUNCTIONS REQUIRED

- Some choices for the basis functions are
 - Karhunen - Loeve (K-L) expansions
 - Band-limited basis functions
 - Orthogonal Polynomials
- Several researchers have shown reasonable fits to reflectance and illumination curves with 3 or 4 basis functions
- If more than three basis functions are chosen, then a mathematical technique such as singular value decomposition must be employed.

TO TEST AND VERIFY THE TWO APPROACHES, EXPERIMENTS USING MOSAICS OF MUNSELL COLOR CHIPS ARE BEING USED

- Measurements using a CCD color camera and a colorimeter have been made for several Munsell color chips and stored digitally
- Mosaics consisting of approximately 16 Munsell chips are constructed digitally from the CCD color camera measurements of the individual chips
- The colorimeter values for the entire mosaic are the average XYZ CIE values for all the individual chips on the mosaic.
- Comparison of computed CIE XYZ values for each chip with colorimeter XYZ values will be made for each chip in the mosaic to determine the error.

CONCLUSIONS AND FUTURE WORK

- Two new approaches, based upon linear models, have been introduced to produce an imaging colorimeter using off-the-shelf components
- Both approaches are designed to eliminate the need for conversion matrices between camera output and standard CIE XYZ values
- The second approach allows a determination of the illumination and reflectance spectra.
- We are currently performing experiments to determine
 - How well each model fits the measured data using only three basis functions (unique solution)
 - To determine regions in color space where anomalies (multiple solutions) may occur if more than three basis functions are used

**DATE
FILMED**

6 / 23 / 92