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Color Imaging: Device-Independent Color, Color Hardcopy, and Graphic Arts V

Reiner Eschbach
Gabriel G. Marcu
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SESSION 1

Spectral Imaging and Sensors I

Invited Paper

Color capture, color management and the problem of metamerism: does multispectral imaging offer the solution?

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Abstract

Color management systems are being introduced worldwide to improve the color quality of digital image capture and device independent electronic color image reproduction. To be able to supply device independent color data at interfaces in imaging systems, device dependent color correction is required. The paper discusses concepts envisaged for color correction in image capturing devices with respect to fundamental requirements on color analysis. The common image capturing technology is based on the use of three color channels. Main points of the discussion are the shortcomings of this technology to analyse metameric colors correctly and the question if this will be an essential point for future imaging technology. Further parts of the paper cover the alternative multispectral technology. Multispectral cameras delivering the complete spectrum of color stimuli of each pixel of an image are available in the laboratory. This technology offers a solution to the problem of metameric color analysis and offers flexibility to match different illuminants as well, yet, the amount of additional effort is large. The paper summarizes studies and ideas on multispectral color technology and on how this technology might be introduced in future imaging and color management systems.

Keywords: color image capture, camera, scanner, multispectral color system, multispectral camera, color management

1. Introduction

The usual equipment for the capture of colors is based on the three channel technology which simulates the color capture in the human retina by three main groups of cones. For the considerations in this paper, the arrangement of Fig. 1 is considered. An object color described by its spectral reflectance $\beta(\lambda)$ is illuminated by a light source with spectral radiant power S_λ. Reflected light is falling in the eye of a human observer, activating the cones in the retina and with it producing three different color signals due to the selective spectral sensitivity curves of the cones. This basic process is described by the CIE 1931 color matching functions $x(\lambda)$, $y(\lambda)$, $z(\lambda)$ (see Fig. 4) and the definition of CIE 1931 XYZ tristimulus values[1]:

$$X = k_0 \int_{380nm}^{780nm} \varphi_\lambda \bar{x}(\lambda)\, d\lambda, \qquad Y = k_0 \int_{380nm}^{780nm} \varphi_\lambda \bar{y}(\lambda)\, d\lambda, \qquad Z = k_0 \int_{380nm}^{780nm} \varphi_\lambda \bar{z}(\lambda)\, d\lambda,$$
$$k_0 = \frac{1}{\int_{380nm}^{780nm} S_\lambda \bar{y}(\lambda)\, d\lambda}. \qquad (1)$$

The spectral function $\varphi_\lambda = \beta(\lambda) S_\lambda$ is called color stimulus and k_0 normalizes the luminance component $Y = 1.0$ in this paper for the spectral reflectance of $\beta(\lambda) = 1.0$.

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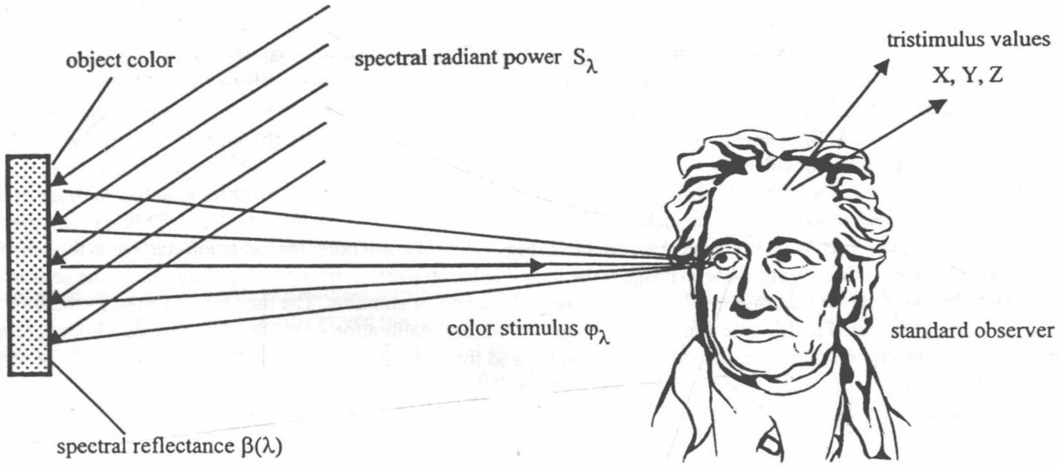

Fig. 1 Capture of color by the standard observer

The capture of color by commercial equipment is based on sensing color by three color channels (Fig. 2). Each channel is composed from an optoelectronic sensor and spectral filter with certain spectral transmissions in the red, green or blue part of the spectrum. Provided that the characteristics of the optoelectronic sensors are linear, the output of the sensors can be described by three signals S_1, S_2, S_3:

$$S_i = k_i \int_{380nm}^{780nm} \varphi_\lambda \, s_i(\lambda)\, d\lambda\,, \qquad i = 1, 2, 3, \qquad k_i = \frac{1}{\int_{380nm}^{780nm} S_\lambda \, s_i(\lambda)\, d\lambda}\,. \tag{2}$$

The spectral functions $s_1(\lambda)$, $s_2(\lambda)$ and $s_3(\lambda)$, are the overall spectral responsivities of the three channels and factors k_i are normally adjusted to maximum output signals $(S_1, S_2, S_3) = (1, 1, 1)$ for the capture of color with spectral reflectance $\beta(\lambda) = 1.0$.

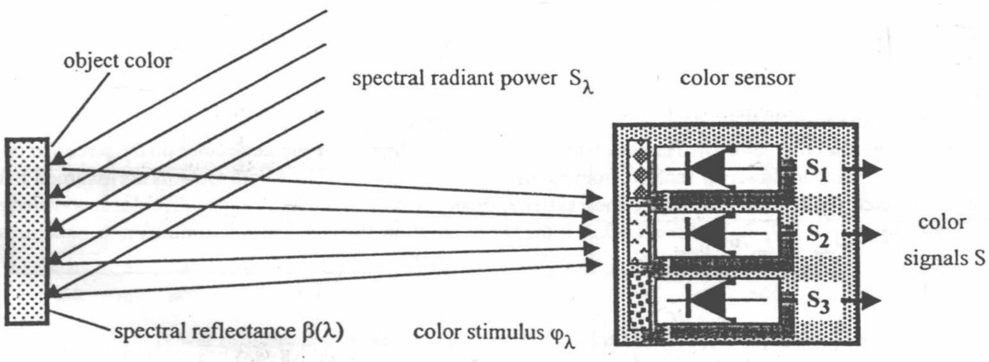

Fig. 2 Capture of color by a three channel sensor

The process of color capture as sketched in Fig. 2 is applied in color image scanners to digitize plane photographic or printed images on paper as well as in digital cameras taking images of scenes and natural object. The difference between scanners and cameras with respect to color analysis is the kind of light source used. Scanners are "closed image capture devices" equipped with a well defined built-in light source whereas a large variety of different electric light sources ranging from daylight to fluorescent lamps has to be considered for the image capture with digital cameras. Yet, both applications are facing a main problem which is rooted in the technical difficulty to develop sensors with spectral responsivities matched to those of a human being. To understand the problem, well known basic relations of colorimetry have to be considered. This is best demonstrated assuming a complete color reproduction system as sketched in Fig. 3. The chain of color reproduction starts with the sensor of Fig. 2. A cathode ray tube is added to compose an image of the sensed color on a screen from the ouput signals of the sensor. Finally, the standard observer derives tristimulus values from the reproduced color stimulus. The tube is controlled by the three signals S_1, S_2, S_3 and it is assumed in this case that internal characteristics and calibration of the display provide a linear colorimetric relation between the control signals at the input of the display and the radiant power of the three phosphors of the screen that compose the output light stimulus. Mathematically, this characteristic can be described by $(S_1, S_2, S_3) = \mathbf{C}(X, Y, Z)$, where $\mathbf{C}$ is a 3x3 matrix with elements c_{ik}.

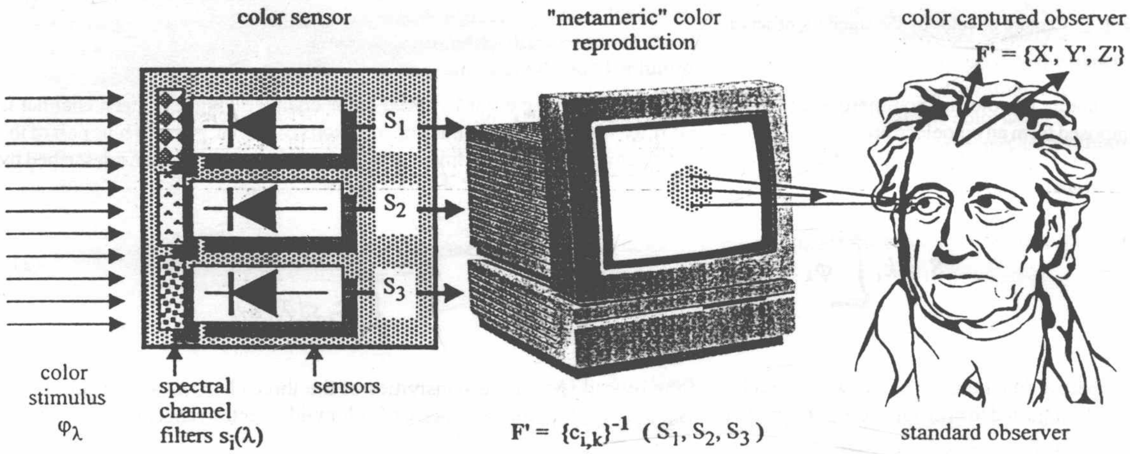

Fig. 3 Color reproduction system with additive color mixture on the screen of a cathode ray tube.

It is also assumed, that the reproduction system of Fig. 3 is facing the same color stimulus as the arrangement in Fig. 1, where the standard observer views the color directly. The aim of the experiment is to reproduce the same color on the screen of the cathode ray tube as the color the standard observer receives from the arrangement of Fig. 1. Since both systems are assumed to be linear, the essential condition can be derived with help of linear systems theory from the transfer of a spectral color at wavelenght λ with the stimulus given by $\varphi_{\lambda o} = \delta(\lambda-\lambda_0)$, where $\delta(\lambda-\lambda_0)$ is the Dirac function. Introducing this stimulus into equations 1 and 2, relation $(S_1, S_2, S_3) = \mathbf{C}(X, Y, Z)$ simplifies to:

$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} k_1 s_1(\lambda_0) \\ k_3 s_2(\lambda_0) \\ k_2 s_3(\lambda_0) \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{pmatrix} \begin{pmatrix} k_0 \bar{x}(\lambda_0) \\ k_0 \bar{y}(\lambda_0) \\ k_0 \bar{z}(\lambda_0) \end{pmatrix} . \qquad \left(Note: \int \varphi_{\lambda_0}\, s_i(\lambda)\, d\lambda = \int \delta(\lambda-\lambda_0)\, s_i(\lambda)\, d\lambda = s_i(\lambda_0) \right) \quad (3)$$

Thus, the comparison requires the spectral responsivities of the color sensor to be a linear combination of the color matching functions.

This well known requirement is not fulfilled in technical color imaging sensors for a number of technical reasons. In many commercial scanners or cameras, the output signals are interpreted as colorimetric RGB signals. A standardized transformation from the CIE 1931 XYZ system to standardized RGB values is, e.g., the sRGB color space defined by the transformation of color matching functions from IEC 61966-1:

$$\begin{pmatrix} \bar{r}(\lambda) \\ \bar{g}(\lambda) \\ \bar{b}(\lambda) \end{pmatrix} = \begin{pmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{pmatrix} \begin{pmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{pmatrix} . \tag{4}$$

The input functions and the results of the transformation are shown in Fig. 4. Since the transformation to the sRGB color space is based on a real primary stimulus system derived from the phosphors of the screen of a cathode ray tube, negative parts of the color matching functions are unavoidable. Color matching functions without any negative part admit imaginary primary stimuli that cannot be realized in a practical reproduction system. If RGB tristimulus values have to be delivered by a color sensor, the spectral responsitivies of the sensor must be identical or at least approximate the shape of the color matching functions of the sRGB or similar colorimetric color space. Sensors of scanners or cameras are not only unable to realize negative parts of responsivities but also deviate more or less from desired shapes due to technological difficulties of fabrication. Hence, a typical set of responsitivity curves looks more or less like the one given in the lower part of Fig. 4.

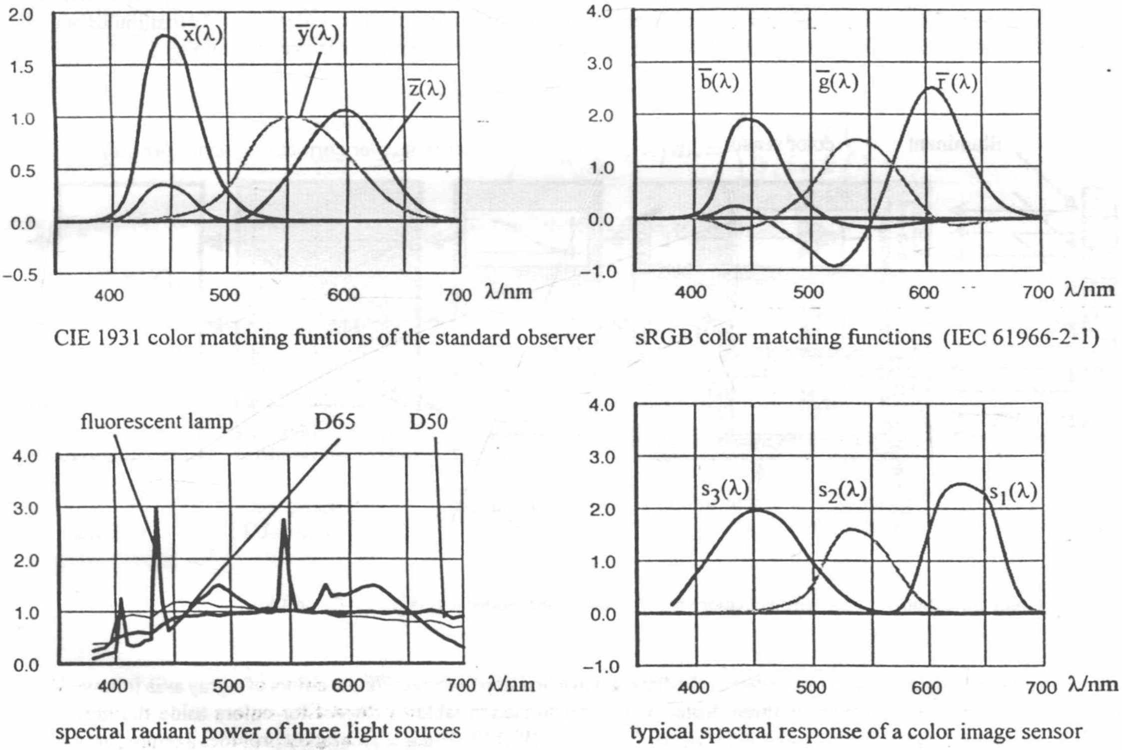

Fig. 4 **Color matching functions of the CIE 1931 standard observer (top leftside), of the sRGB color space (top right side) and typical spectral responsivities of color imaging sensors (bottom right side). Spectral radiant power of some illuminants (bottom left side)**

Commercial three channel color measurement equipment usually uses spectral responsitivies approaching the CIE 1931 color matching functions with imaginary primary stimuli. So, why is not at all the same done with scanners and cameras? The answer is found in the necessity to convert the sensed color signals to a color space derived from real primary stimuli for display or printing and in electronic noise problems amplified by the transformation to real primary stimuli. Electronic noise is present in any optoelectronic sensor; but it is reduced to acceptable values in measurement equipment by averaging versus time which is realized by using long integration times. However, capturing color information in electronic imaging is done fast and the electronic noise therefore has to be considered. In addition, this noise is supplementarly amplified by the conversion of XYZ-values to a color space for real primary stimuli. In the transformation to sRGB (equation 4), the measured XYZ- together with their noise values are multiplied by factors up to 3.2, and a linear combination of all the components X, Y, Z is formed in addition by the transformation. This increases random noise due to the fact that noise sums up according to a square root law.

The loss of negative parts in the real spectral responsivities of color sensor channels causes a desaturation of the colors represented by the sensor signals and it introduces a nonlinear distortion of the respective signal space in comparison to a linear tristimulus color space. The result is a systematic error which is present in any three-channel color sensor equipment. In a closed color reproduction system, these errors are reduced by processing the color signals in combination with all the processing necessary for final reproduction. However, the open system of worldwide image communication (Internet) requires a different management. Color Management Systems have therefore been developed [2] and a device-independent color space is recommended for color representation at interfaces [3]. This makes color correction within any component of the system necessary. Device-dependent color correction for the case of color scanners or cameras uses so called color profiles that consist of rules, transformations or look up tables to transform the sensed color signals into approximate values of a tristimulus or a uniform color space [3] at the interface. The usual method for color correction of a color sensor is sketched in Fig. 5.

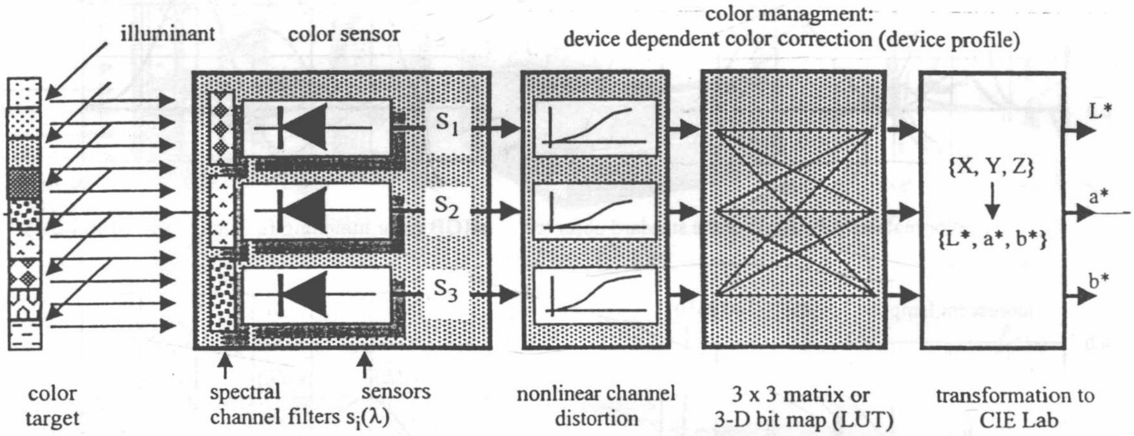

Fig.5 Color correction of a three channel color sensor in a color management system (device profile)

The three channel signals (Fig. 5) are nonlinearly distorted in a first step to correct for the colors of a gray axis followed by a 3 x 3 linear transformation or a complete three-dimensional transformation table to correct for colors aside the gray axes. The correction requires a target of test colors at the input of the device (ISO 12641 e.g.). This target provides a printed gray scale and a selected number of colors. The colors of the target are measured first by spectral color measurement equipment and afterwards compared with the respective signals delivered by the three channel color sensor. From this comparison, the nonlinear channel distortion is calculated in such a manner, that the gray scale of the target delivers e.g. equal values for the gray axis of the sRGB space. If numerical tables are used for the transformation, exact correction is achievable. Afterwards, the elements of the 3 x 3 matrix are optimized by minimizing chromatic errors for the capture of the test colors of the target.

Basically, it is not possible to correct for the chromaticity errors for all the colors completely by a 3 x 3 matrix. Yet, a complete correction for the colors of the test target becomes possible, if a numerical transformation table is used instead of the matrix assigning the correct colorimetric value to each of the signals sensed from the test colors. Interpolation of such table must be applied to map each possible combination of digital sensor signals to corresponding RGB values or directly to CIE Lab-values[3] via a look up table.

In a first view, it seems that all the problems of three-channel color capture discussed above are solved by this technology. Yet, this is true only for the colors of the test target and originals printed by the same technology, with the same colorants and on the same kind of paper as the test target used to develop the look up table. The reason is the metamerism problem of colors which is discussed in the following section.

2. Effects of sensor metameric colors

The color signals (S_1, S_2, S_3) of the sensor and corresponding tristimulus values (X,Y, Z) of the standard observer as well are the result of the integration of spectral functions versus wavelength (equation 1, 2). Due to the integration, there exist different spectral distributions resulting in the same integrated values. Colors originating from different color stimuli but resulting in the same (X,Y, Z) values are called metameric colors[1,4,5]. Metameric colors are not differentiated by the standard observer. The three channel color sensor is facing the same problem as the standard observer. Different color stimuli might generate the same output signals (sensor metameric colors). Yet, the colors being metameric for the standard observer are not the same like those being metameric for the sensor. So, there are colors not differentiated by the sensor but differentiated by the standard observer and vice versa. To study this effect, it is appropriate to expand the spectral reflectance of a color into a series of orthogonal functions[6] with the first three functions being a linear and orthogonal transform of the spectral responsivities of the sensor[15]. The expansion exemplified below is based on effective responsivities including the distribution of the spectral radiant power of the illuminant:

$$\beta(\lambda) = \sum_{k=1}^{K} W_k \, w_k(\lambda) , \qquad \int_{380nm}^{780nm} w_i(\lambda)\, w_k(\lambda)\, d\lambda = \begin{Bmatrix} 1 \, , i = k \\ 0 \, , i \neq k \end{Bmatrix} . \tag{4}$$

Values W_k are the weigths of the basis functions $w_k(\lambda)$ and the first three are given by:

$$\begin{pmatrix} w_1(\lambda) \\ w_2(\lambda) \\ w_3(\lambda) \end{pmatrix} = \begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} \begin{pmatrix} s_1^*(\lambda) \\ s_2^*(\lambda) \\ s_3^*(\lambda) \end{pmatrix} = (\mathbf{T}) \begin{pmatrix} s_1^*(\lambda) \\ s_2^*(\lambda) \\ s_3^*(\lambda) \end{pmatrix} , \tag{5}$$

where $s_i^*(\lambda)$ are the effective responsivities under the illuminant: $s_i^*(\lambda) = s_i(\lambda)\, S_\lambda$. There are many possibilities to derive the higher order basis functions. In this paper, they have been derived from the metameric parts of colors of various printing processes which opens an easy way to construct realistic device metameric colors. The expansion allows to split the spectral reflectance of a color into a sensor visible part and a sensor invisible part:

$$\beta(\lambda) = \underbrace{W_1\, w_1(\lambda) + W_2\, w_2(\lambda) + W_3\, w_3(\lambda)}_{\text{sensor visible part}} \quad + \underbrace{\sum_{k=4}^{K} W_k\, w_k(\lambda)}_{\text{sensor invisible part of the spectrum}} . \tag{6}$$

sensor visible part .... sensor invisible part of the spectrum

An example of the splitting of a spectral reflectance of a leaf of a plant into a sensor visible- and the invisible part is given in Fig. 6. All the reflectance spectra with the same values (W_1, W_2, W_3) but with different weights W_K, $k > 3$, determine the sensor metameric colors. All combinations of values W_K with $k > 3$ can accordingly be used to construct sensor metameric colors as long as the reflectance spectrum does no exceed the range $0 <= \beta(\lambda) <= 1.0$. An example is given in Fig. 7 for the illuminant D50. The natural color of a plant is given by its reflectance spectrum 1. Two other colors 2 and 3 are printed colors composed from different inks and all the three colors are sensor metameric. The table below summarizes the corresponding sensor signals, the