High Quality Color Image Reproduction:

The Multispectral Solution

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Abstract

While conventional tristimulus color technology develops rapidly in commercial applications, it runs into problems if high professional color quality is required. In this paper four essential reasons why multispectral imaging should replace conventional color technology in this area are summarized. The state of the art and the way to full spectral imaging systems including multispectral image capture and multiprimary display is discussed. Particular results of research at the University of Aachen are presented. Finally, the first broad application of multispectral technology in the prepress industry for catalogue production is outlined.

Introduction

Digital color image technology and color image communication via internet have run through tremendous development during the last decade. Billions of digital color images are captured every year and all people are delighted by their colors and, the images bring the beauty of colors into their life. Nevertheless, if digitally reproduced colors are expected to match accurately the colors of an object captured or, if colors of the same object but reproduced on different media are compared with each other, everybody will be disappointed at the match -or mismatch- of colors many times. This is rooted in the use of tristimulus values to sense and describe color in the technical reproduction chain from the very beginning. Present color reproduction technology is based on the model of color vision by the CIE 1931 Standard Observer (figure 1).

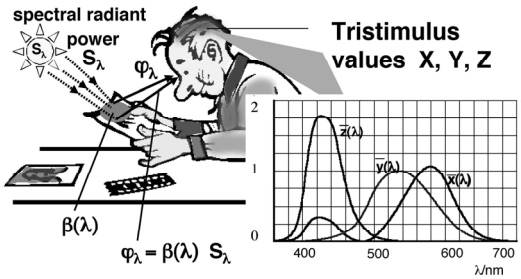

Figure 1. Color vision of the CIE 1931 Standard Observer.

The spectral color stimulus φ_λ is composed from the radiation of light with spectral radiant power S_λ, illuminating the surface of an object with spectral reflectance $\beta(\lambda)$. The Standard Observer is assumed to integrate the incident spectral components of the color stimulus via three color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ and to produce tristimulus values X, Y and Z therewith. According to this model of color vision, a camera uses also three spectral filtering channels to derive tristimulus values. Yet, there are 4 reasons, why this kind of color sensation does not provide enough accuracy with respect to high quality criteria.

Four Sources of Color Errors

1. The basic law of color reproduction for a given observer shows that color is reproduced correctly only, if the three overall spectral responsivities of a color sensor are identical with color matching functions of the observer or a linear transform of them. So, the best would be to equip a color sensor with color matching functions of the standard observer. Yet, this is not done because the captured X, Y, Z- signals have to be mixed

to compose signals necessary to control the color channels of a display or printer. Mixing of signals increases the electronic noise originating from light sensors of the camera remarkably. For that reason, transformed color matching functions r(λ), g(λ), and b(λ) related to RGB primaries of displays are used in image sensors to avoid adverse signal mixing steps in the reproduction chain (figure 2).

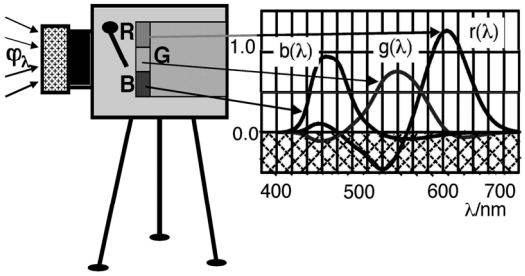

Figure 2. "Color vision" of the RGB-camera

Unfortunately, the resulting color matching functions which the camera should present, show negative parts not being physically realizable. For that reason, the negative parts are simply skipped and practically, only the positive parts are approximated by spectral responsivity curves in the camera channels. At least these three curves are well separated in the spectral domain and noise problems are minimized on the one hand, yet, errors of the "measurement" of colors are inherently produced in every digital three-channel camera on the other.

2. Present color detection in digital cameras is optimized for the Standard Observer only, though, color matching functions of human beings deviate more or less from those of the Standard Observer (figure 3). So, today`s technology does not offer correct color information for any human being.

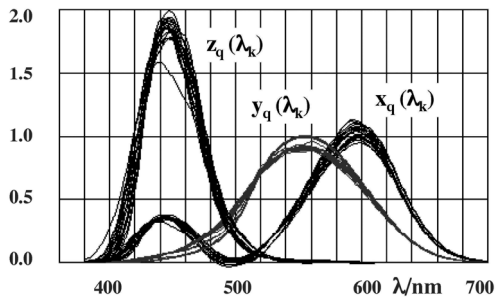

Figure 3. 24 typical human color matching functions [1].

3. Many practical applications require colors to be captured under a light source I and to be reproduced in a different viewing situation under a light source II. Both light sources typically show different spectral radiant power distribution. Moreover, the color signals delivered by a camera are inherently combined with the light source of the captured scene and the influence of the light source cannot be separated accurately from the signals. Though, there are methods available to transform colors described by tristimulus values from one illuminant to another, all these methods deliver only rough approximations to what really happens when changing a light source. The exact transformation of color stimuli when changing the illuminant requires an accurate calculation of all spectral components rather than transformations in the domain of tristimulus values.

4. Tristimulus values are the result of the integration of spectral components. So, components of different spectral distributions might sum up to the same tristimulus values. This effect is called metamerism. Metamerism causes a number of strange effects in color vision, particularly in conjunction with the change of the illuminant (illuminant metamerism) or different observers (obersever metamerism). Fig. 4 shows two different spectral reflectance curves of surface colors. Viewed under illuminant D65 for instance, they both result in the same tristimulus values of (X,Y,Z) = (0.57, 0.60, 0.65) for the CIE 1931 2^0 Standard Observer (DEoo = 0). The tristimulus values are composed from reflectance functions, spectral radiant power of D65 and color matching functions. If either the spectral radiant power or the color matching function is changed, the two surface colors will no longer match. So, there might be colors matching for one observer but appearing different for another and vice versa and, there might be surface colors matching under one illuminant but not under another. The two reflectance functions of figure 4 produce (X,Y,Z) = (0.60, 0.60, 0.32) and (0.56, 0.60, 0.34) under a fluorescent lamp D50 (DEoo = 6,8) or, (X,Y,Z) = (0.57, 0.60, 0.64) and (0.58, 0.60, 0.67) under the same illuminant D65, but assuming the CIE 1964 supplementary 10^0-Observer (DEoo = 5,0).

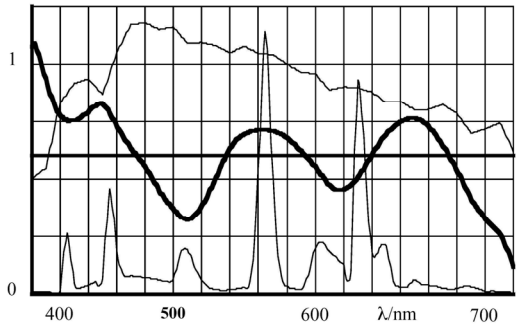

Figure 4. Two spectral reflectance functions (thick lines) that produce metameric colors under illuminant D65 (upper-) and different colors with fluorescent light D50 (lower spectrum) .

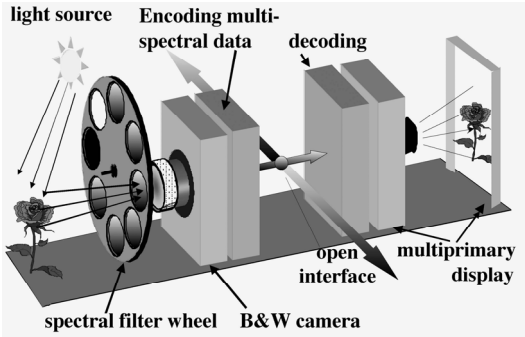

Figure 5. Sketch of a multispectral reproduction system

In technical color reproduction using three channel color sensors, we are facing the additional problem that the responsivity functions of sensors deviate from the color matching functions. Color cameras thus have their own features of metamerism not matching the metameric features of the Standard Observers nor any other. So, they deliver wrong results of color matching in many cases and colors appearing the same for a human observer might be reproduced as different colors in the technical system.

The Multispectral Solution

The complete solution to all the problems discussed above is offered by a system reproducing spectral color stimuli information within the whole chain of color reproduction from image capture via transmission to display or printing. Presenting the complete spectral stimulus information for each pixel of digital images on displays or printers would reproduce colors correctly for any observer and moreover, any change of the illuminant could be simulated accurately in the spectral domain [1-5].

The tyical multispectral imaging system is sketched in figure 5. The spectral color stimuli to be captured are sampled by a limited number of narrow spectral bands. This is realized by a number of optical filters mounted in a filter wheel placed sequentially in front of a greyscale camera. The number of filters ranges from 6 two 32 in experimental systems. An alternative solution to the filter wheel uses an electronically adjustable filter realized by LCD technology [6]. By this way, a number of spectral separations of the image is taken sequentially and stored temporally in an image storage and encoding unit. The process of image capture normally starts by taking an image of a black image and a white reference image which reflects the spectral radiation of the light source close to 100%. The spectral separations are corrected by the black level and normalized with respect to the white reference, thus resulting in reflectance functions or spectral separations for illuminant E finally. These data are embedded in a suitable image format. In the technical committee CIE Division 8-7 various formats for international multispectral image transmission are discussed. Typically, a matrix is defined together with the set of spectral scanning values to be able to transform the values into an estimated spectral function of high resolution in steps of either 1, 5 or 10 nm. The Wiener estimation or the Smoothing Inverse is commonly used for this purpose. Finally, there is the spectral stimulus information available at the interface of the camera system for each point of the image and it is open for any color image application. A typical method for encoding is the expansion of spectral functions into basis functions [7-10]. Many proposals are available for this purpose and a particular one even includes basis functions derived as linear combination of color matching functions. Only the weights of basis functions called multispectral values are transmitted for this kind of encoding. The three first weights are tristimulus values in case of the particular encoding including color matching functions. This latter format offers direct compatibility with tristimulus applications

while all multispectral values in total define the spectral stimulus information for high quality use [9, 10].

Transmitted spectral data are decoded for display, printing or any image processing which means, they are transformed into spectral functions useful to apply a spectral illuminant for the calculation of output stimuli. For complete spectral reproduction, these stimuli are transmitted to a multiprimary display or a multichannel spectral printer. Multiprimary displays have been developed on the basis of multichannel back projection (figure 5 e.g.) and up to 6 color primaries [1, 10-13]. An essential increase of the color space and reduction of observer metamerism can be provided. The development of a spectral printer is a deep matter of research by a number of groups. As a first result, printers offering reduced illuminant metamerism are expected in the near future. Such devices using 8 to 9 color channels require very complex and sophisticated control algorithms.

The multispectral imaging technology is applied to the capture of fixed objects or even moving scenes. A field of particular interest is the goniometric imaging, where viewing angle and angle of illumination are varied. This kind of goniometric multispectral imaging has been applied to 3D-imaging of objects (virtual museum) [14] or effect pigment visualization.

From Research to Applications

The early research on spectral imaging started in the 1980s. The laboratory model of a camera system is shown in figure 6. A wheel equipped with 16 interference filters was rotated in front of a cooled greyscale CCD-camera. The use of 16 spectral sampling points over the spectral range from 400 to 700 nm featured excellent reproduction of the smooth spectral reflectance functions of surface colors illuminated by a thermal light source.

For the purpose of calibration, the image plane was automatically replaced by a white reference sheet with spectral reflectance close to 1.0. The time to record the complete image was 30 min.

A more advanced camera system finished in 1998 is shown in figure 7. The system was equipped with a CCD of either 1280x1024 or 2000x3000 pixels and the capture time was reduced to 20 s. Two years later, an industrial version was placed in the market by "ColorAIXperts" in Aachen for the first time.

Many improvements on details of the optics, geometric error correction by digital image processing and last but not least a new method of stray light compensation [15] has made the camera system a color measurement tool of rather high accuracy. The software allows for the measurement of the color of each pixel selected in a displayed image and average colors can be picked up within determinable areas. Although the geometry of illumination ($45^0/0^0$) is one directional and not circular, the results of color measurement are close to those achieved with commercial photospectrometers. A typical comparison of measured results for colors of the Macbeth Color Checker is given in figure 8. The long term stability was measured by the reproducibility. It was found to be better than CIE DEoo = 0.1.

Recently, the model of a goniometric version of the multispectral camera to view plane objects under varying viewing angles and different directions of the illumination has been realized in the laboratory. The model allows for the recording of a series of images of car paintings with effect pigments and demonstrates their color change (cis-trans).

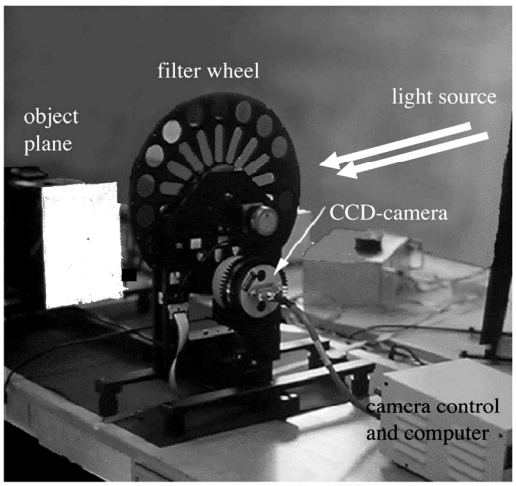

Figure 6. Experimental set up of a laboratory trial at the University of Aachen, Germany, in 1990

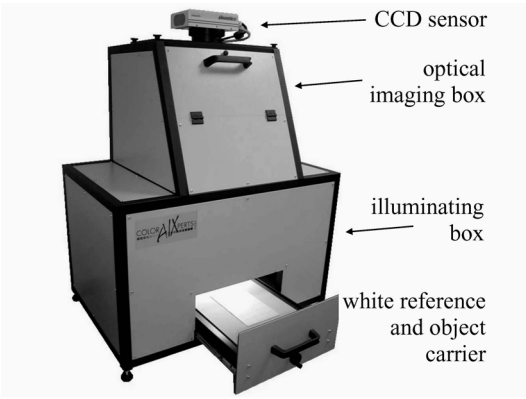

Figure 7. Multispectral Repro-Camera introduced in 2000

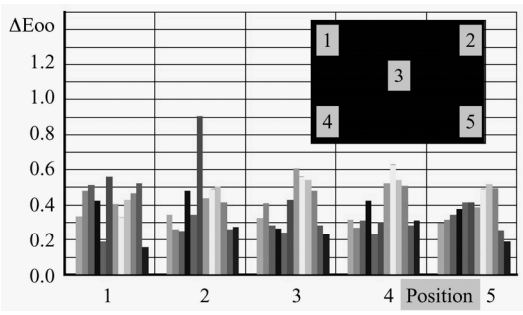

Figure 8. Color differences between measured results of the multispectral camera and a commercial photospectrometer (EyeOne) for 5 various positons of colors in the image field

The 16-channel multispectral repro-camera features high color reproduction quality on one hand but is stationary on the other. To fill the gap between the low quality of tristimulus cameras and the 16-channel device, a mobile camera using 7 spectral bands of 50 nm has been developed (figure 9) [16]. Although it still uses a mechanically rotated filter wheel, the time to capture an image has been brought down to 1 s.

The estimation of captured color stimuli from 7 spectral bands is an interesting matter of research. Moreover, calibration and with it the estimation of the light sources in natural scenes is studied intensively for various applications. The color reproduction error of 240 color patches yields CIE DEoo = 2.4 in a maximum and most of the errors are below 1.4 (figure 9).

Compared with three channel cameras, a big step is performed by the multispectral image capture.

The display or printing of spectral information is not that far developed. The laboratory model of a 6 primary display is shown in figure 10 [10, 12, 13].

The laboratory model is built from two LCD projectors. The spectral channels inside the projectors have been limited to 50 nm each by introducing additional band edge filters. Hence, primary colors of the display are determined by 6 spectral bands of 50 nm between 400 and 700 nm. Accordingly, the space of colors is enlarged remarkably compared to RGB displays as shown in the CIE 1976 UCS diagram (figure 11).

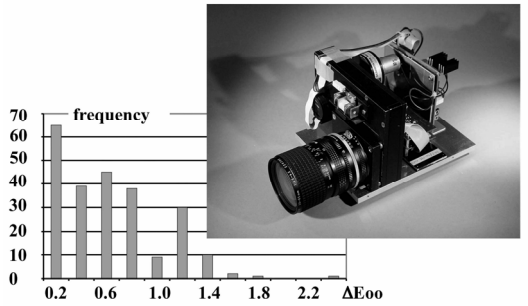

Figure 9. Seven channel mobile multispectral camera and typical error distribution of reproduced colors

Figure 10. Laboratory model of a 6 primary display using back projection of spectral bands from two three-channel projectors.

Due to a number of strong peaks originating from the light sources of projectors, the spectral distribution of the 6 spectral bands is not well shaped and hence, a good direct spectral approximation of original color stimuli is not yet possible. Nevertheless, there is the opportunity to optimize the reproduction for more than one observer. Stochastic optimization of the control of color primaries has been applied with the aim, to minimize the color reproduction errors for 24

observers shown in figure 3. Maximum errors below CIE DEoo = 2 can be expected for any observer [10]. Since stochastic optimization is rather time consuming, fast control algorithms have been developed on the basis of a real time selection process between a number of different linear matrices to map spectral information onto the 6 control signals of the channels. This method offers maximum errors of 2.5 [17].

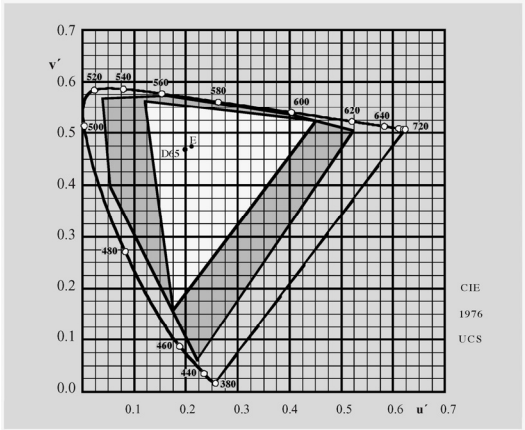

Figure 11. Color space of the 6 primary display in the CIE1976 UCS diagram dark gray area and sRGB triangle inside

The Industrial Use

Multispectral technology has found its first industrial application in the prepress industry. For the production of catalogues offering clothing of warehouses and mail order companies, multispectral systems are now used to digitize and display textile samples.

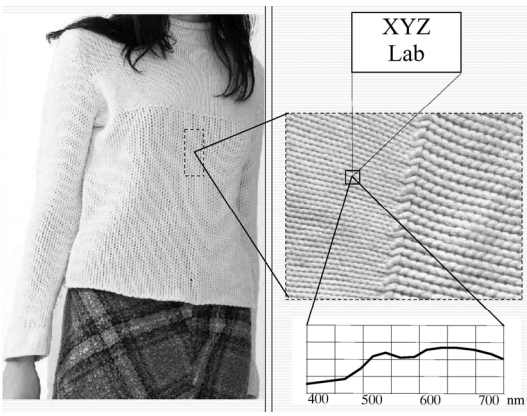

Fig. 12. Use of digital fabrics in catalogue production and selection of areas of color measurement

Digital samples of thousands of fabrics are stored in large data bases or made available for the design of new collections. Instead of retouching colors within the process of catalogue design completely by hand, digital samples with their reliable (multispectral) color patterns are inserted into images of clothing by special software (figure 12). This use of multispectral technology is saving much working time and provides more consistency in the process of catalogue production. Moreover, digital samples featuring true color texture can be sent throughout the world without loss of quality to design centers, fabrication workshops or customers instead of transporting them physically.

Conclusions and Outlook

Four essential reasons why high quality color reproduction forces the change from conventional "tristimulus color technology" to multispectral imaging have been outlined. The state of the art of realized systems shows the feasibility of multispectral technology and its benefit in industrial applications. Further essential steps aiming at commercial products require the development of non-mechanical camera systems with 6 or more color channels integrated on a chip and integrated multiprimary displays.

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