LETTER

Development of an XYZ Digital Camera with Embedded Color Calibration System for Accurate Color Acquisition

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SUMMARY Acquisition of accurate colors is important in the modern era of widespread exchange of electronic multimedia. The variety of device-dependent color spaces causes troubles with accurate color reproduction. In this paper we present the outlines of accomplished digital camera system with device-independent output formed from tristimulus XYZ values. The outstanding accuracy and fidelity of acquired color is achieved in our system by employing an embedded color calibration system based on emissive device generating reference calibration colors with user-defined spectral distribution and chromaticity coordinates. The system was tested by calibrating the camera using 24 reference colors spectrally reproduced from 24 color patches of the Macbeth Chart. The average color difference (CIEDE2000) has been found to be $\Delta E = 0.83$, which is an outstanding result compared to commercially available digital cameras.

key words: *color difference, color gamut, color calibration, XYZ camera*

1. Introduction

The development of digital camera systems with highly accurate color acquisition capabilities is important to follow the rapid growth of the multimedia technologies and communication systems. Wide spread accessibility to the internet allows for convenient commerce in various merchandise, real-time visual data exchange like telemedicine and many other applications. The large variety of color systems, however, has caused problems with color management. Commercially available digital cameras usually produce device-dependent color outputs (RGB, sRGB, AdobeRGB etc.). In the case of applications that require ultra high quality of the visual information, device-independent color data is needed [1]–[3]. The target of this research is the ability to develop a relatively inexpensive camera system with outstanding color acquisition performance.

The tri-chromatic camera system presented in this paper is based on filters with spectral transmittance derived from the CIE color matching functions [4] as shown in Fig. 1. Theoretically, the camera satisfies the Luther Condition [5] and is capable of accurate acquisition of colors within the whole vision gamut. The outputs of the camera are linearly transformed into device-independent XYZ tristimulus values by using 3×3 conversion matrix. The conversion matrix is derived from a set of $X_iY_iZ_i$ measured values ($i = 1 \ldots 24$) of reference color samples and their equivalent imager outputs with regard to the filters of the camera (S_{1i}, S_{2i} and S_{3i}) by multiple regression analysis.

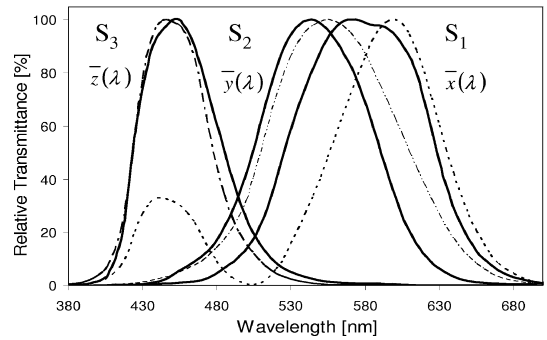

Fig. 1 $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ color matching functions (dotted lines) and S_1, S_2, S_3 filters (thick lines) spectral transmittance characteristics.

The XYZ camera incorporates embedded color calibration system comprised of integral spectrophotometer mounted inside the optical system of the camera and the developed external calibration device called LED Color Generator (LED CG) [6]. The LED CG is an emissive device for displaying reference colors with unique function of generating colors with user-defined spectral distribution for calibration purposes. The developed color calibration system is digitally controlled by a PC and the color calibration is performed automatically resulting with high-fidelity color acquisition and outstanding accuracy of the color in the acquired image.

2. Outlines of the XYZ Camera

The principle of operation of the XYZ camera is shown in Fig. 2. The CCD (1) is a monochrome sensor with active pixels of 4008(H) by 2672(V) and 43.3 mm diagonal (3 : 2 ratio). The S_1, S_2 and S_3 filters are put on a revolving wheel (2). Between the camera lens (3) and the CCD, a glass plate (4) splits the image into two mutually orthogonal paths. The reflected image is fed through a fiber optic probe (5) into the internal spectrophotometer (6) for the reference measurement. The glass plate and the probe have positioning mechanisms (7) allowing for measurement of selected parts of the image along x and y axes. The image passing through the glass plate and the filters is captured by the CCD.

The acquired image consists of three 12-bit channels

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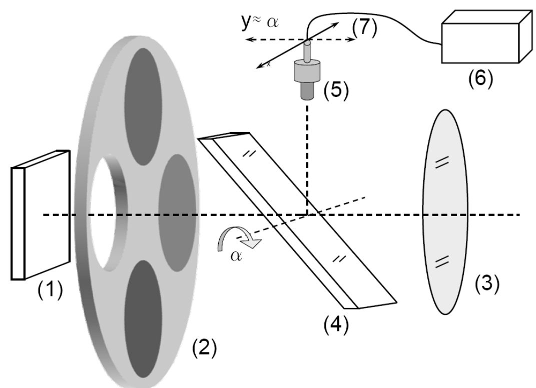

Fig. 2 Principle of the XYZ camera: (1) CCD, (2) filter wheel, (3) lens, (4) glass plate, (5) fiber otpic probe, (6) spectrophotometer, (7) positioning mechanisms.

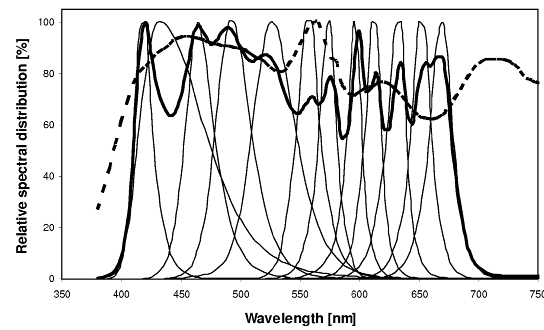

Fig. 3 Spectral distributions of the primary colors of LED color generator (thin lines), D65 standard illuminant (dotted line) and its equivalent produced by LED CG (thick line). Peak wavelengths of the primary colors: 418, 432, 464, 493, 526, 556, 574, 595, 612, 632, 652 and 671 [nm].

formed from triple acquisition performed under one filter exposure at a time, hence the expression "S_1, S_2 and S_3 image".

3. Embedded Color Calibration

The employment of the spectrophotometer inside the XYZ camera allows for precise measurements of the colors contained in the photographed scene. However, for calibration purposes a color reference of high quality is required. Common color references such as the Macbeth Chart are not sufficient for accurate calibration [7] therefore we developed a method of calibration based on spectrally reproduced colors produced by the LED Color Generator and the algorithm of automated color calibration of the XYZ camera.

LED CG is an emissive device composed of 12 primary colors. Each primary color consists of a certain amount of light-emitting-diodes of narrow-band spectral distribution with the shift of the peak wavelengths between two neighboring primaries by approximately 20 nm (Fig. 3). The intensities of each one of the primary colors are digitally controlled by a microcontroller system coupled with a PC. LED CG is optimized for D65 standard illuminant [8] by means of the spectrum and the x, y chromaticity coordinates and it produces colors with user-defined spectral distribution by varying intensities of the primary colors. This approach distinguishes the LED CG from the other researches in the field which use LED's as a monochromatic light sources for sampling of the imager's color response [7].

The embedded color calibration system (shown in Fig. 4) operates on algorithm shown in Fig. 5. The process of color calibration begins with the white balancing. The filters of the XYZ camera are optimized for the D65 standard illuminant therefore proper white balancing with an emissive color reference requires reference D65 white. The LED CG reproduces D65 with chromaticity coordinates of $x = 0.3159$, $y = 0.3294$ and spectrum distribution as shown in Fig. 3. The system automatically adjusts the gains for each acquisition channel (S_1, S_2 and S_3) to give the output of the channels at the same level. The level is set to max-

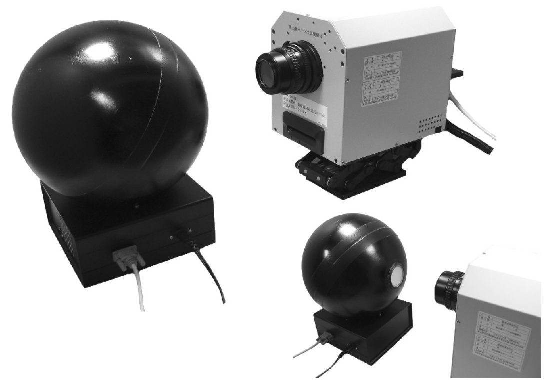

Fig. 4 Accomplished prototype of the XYZ camera with embedded color calibration system based on the LED Color Generator.

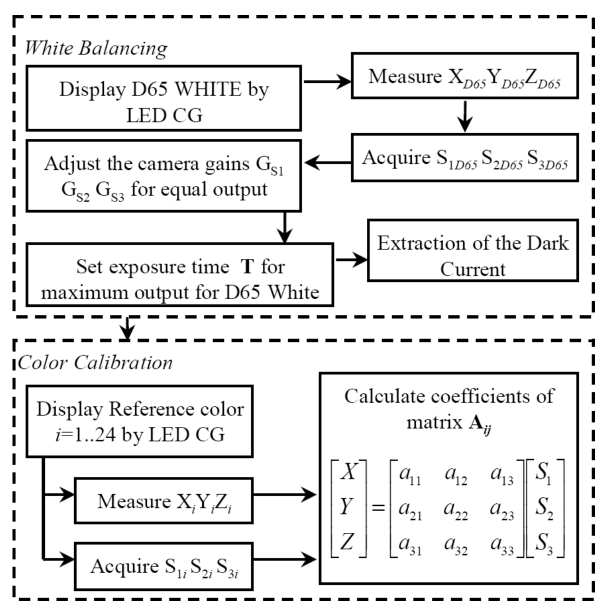

Fig. 5 Algorithm for automated color calibration of the XYZ camera with use of the LED Color Generator displaying spectrally reproduced reference colors.

imum by adjusting of the exposure time. During the color calibration, the reference colors are displayed in sequence and their XYZ values are measured by the spectrophotometer. The corresponding output values of S_1, S_2 and S_3 for the given color are acquired simultaneously and the coefficients of the conversion matrix A are calculated to provide minimal color difference ΔE (CIDE2000 standard) between the measured color and the acquired color [9].

The measurement of the reference colors during each consecutive calibration assures the stable and repetitive results over a long period of time. The fluctuations of the colors produced by LED CG observed over a one year period are less than 0.5% in terms of chromaticity coordinates. In practice such change is negligible because it is compensated by the measurement process and does not affect the result of the calibration.

4. Results and Discussion

The system was tested using 24 color patches of the Macbeth Chart spectrally reproduced by LED CG. It provided reliable comparison in image quality (in terms of CIEDE2000 color difference) of the camera calibrated by the described method with the results obtained by typical color calibration. The average of 10 consecutive calibrations gave the results of $\Delta E = 0.83$ with standard deviation $\sigma = 0.23$. In case of the calibration with regular Macbeth the corresponding results were $\Delta E = 1.41$, $\sigma = 0.43$.

The results obtained by our system have been compared with commercially available digital cameras from leading camera manufacturers. The obtained results of average color difference of the 24 colors produced by the LED CG were: for camera #A $\Delta E = 4.88$, for camera #B, $\Delta E = 6.08$, for camera #C $\Delta E = 8.17$. In comparison with the XYZ camera described in Ref. [2] which according to the authors gives average $\Delta E = 1.86$ and the camera presented in Ref. [1] (ΔE between 1.05 and 5.5), the increase of accuracy of the XYZ camera presented in this paper is significant. The quality of the image acquired by the presented camera system is characterized by its color fidelity. Real scene images are reproduced with satisfactory accuracy in terms of color. The research shows that calibration with an emissive device (LED CG) with single output window provides better results than with using common color references such as the Macbeth Chart. The reasons of increase of the accuracy are the negligible influence of the vignetting characteristics of the input optics and stable emission of light provided by LED color generator during the calibration process.

5. Conclusions

The XYZ camera with embedded color calibration system presented in this paper features ultra-high quality of the acquired image. The application of the filters related to the CIE color matching functions allows for representation of the pixel values by tristimulus XYZ values per pixel. The output is device-independent, so the color information is not corrupted by device-dependent color acquisition. The embedded color calibration system comprised of emissive device displaying colors with user-defined spectral distribution allows for precise and repetitive calibration of the XYZ camera. The obtained average color difference of $\Delta E = 0.83$ shows the outstanding capability of accurate color acquisition.

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