Color calibration method providing uniform distribution of color difference throughout the whole vision gamut

Maciej Kretkowski, Yoshifumi Shimodaira, Ryszard Jabłoński

Abstract:

Accurate reproduction of colors requires methods of calibrating a digital camera. In case of a camera which employs filters with spectral characteristics deduced from the color matching functions, a set of reference calibration colors must be used to obtain a conversion matrix between raw data from imaging sensor and colorimetric tristimulus values XYZ, from which the output signal is formed. The XYZ camera used for testing of the presented calibration method is capable of acquiring colors accurately in the whole vision gamut due to its filters. However, the well-established color references, like the Macbeth Chart or other similar color checkers, are not entirely sufficient for the calibration due to their enclosure in smaller color gamut (HDTV - High Definition Television) than the whole vision gamut. The presented method is based on choosing the calibration colors by their spectral distributions, which are related with the spectral characteristics of the filters. The obtained result was found to be ΔE=1.57 for the designed colors.

Keywords: *color gamut, color difference, LED color generator, color reference.*

1. Introduction

Recent advances in digital acquisition of accurate colors have introduced a necessity of developing new methods of color calibration. In case of a colorimetric camera the problem is sophisticated, and requires tools and methods, which differ from typical commercially available equipment. The demands for a camera capable of acquiring accurate colors in whole vision gamut are more severe than for a common digital camera. A number of papers describe development of high fidelity color acquisition systems [1], [2, [3] which are reproducing device-independent output signal formed from tristimulus XYZ values in the XYZ color space [4]. In the background of our research we use XYZ digital camera with filters called S_1, S_2 and S_3 realizing the CIE's 1931 color matching functions [4], [5]. The spectral distributions of the filters are however imperfect with regard to the designed functions. Fig. 1 shows the designed and manufactured filter characteristic with marked areas in which the differences are the most significant. The Luther Condition states that if spectral sensitivities of the camera (camera color responses) are linearly related to the human eye color responses (color matching functions of a standard observer), the camera response is colorimetric and metamerism errors of the observer are minimized. Therefore, the color calibration is necessary to correct the imperfectness of the filters.

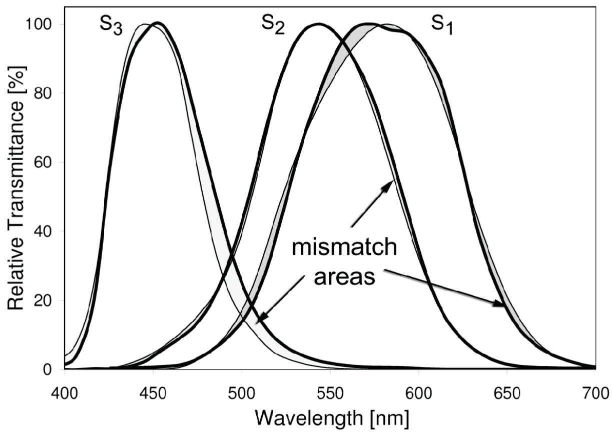


Fig. 1. Discrepancies between designed functions (thick lines) and the manufactured filters (thin lines).

Various methods can be found in literature [5], [6], [7] on subject of color calibration, however a common drawback is the fact of usage of the color checkers such as the Macbeth Chart or other similar color references. Their enclosure within HDTV gamut, which is much smaller than the whole vision gamut results with good results of the calibration inside the HDTV, but poor results (high ΔE) for colors near the border of vision gamut. The method presented in this paper describes the different approach of preparing of the reference colors, which are chosen by their spectral distribution strictly related to the spectral characteristics of the filters. By this approach, the filter errors (with regard to their designed characteristics) are minimized providing more uniform distribution of ΔE throughout the whole vision gamut.

2. Principles of color calibration

Color captured by the camera is represented by S_1, S_2 and S_3 values, corresponding to a pixel value under each filter acquisition. To provide high fidelity color reproduction, a conversion matrix between XYZ and S_1, S_2 and S_3 values must be obtained by means of least square sum analysis [2]. For estimation of the conversion matrix a color reference must be used to provide the $X_{0i}Y_{0i}Z_{0i}$ reference values (where i=1...24 - the amount of reference colors). By estimating the aii conversion matrix coefficients, the XYZ output is produced as given by equation (1).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (1)$$

The measure of accuracy and quality of color reproduction in the camera is given by color difference ΔE (CIEDE2000 standard). The ΔE coefficient is calculated for a given color between its measured $X_0Y_0Z_0$ values and XYZ values calculated by using 3x3 conversion matrix. The image acquisition flowchart is shown in Fig. 2.

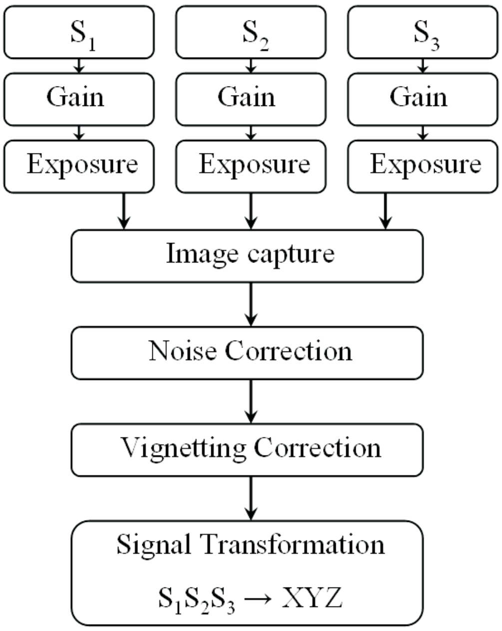
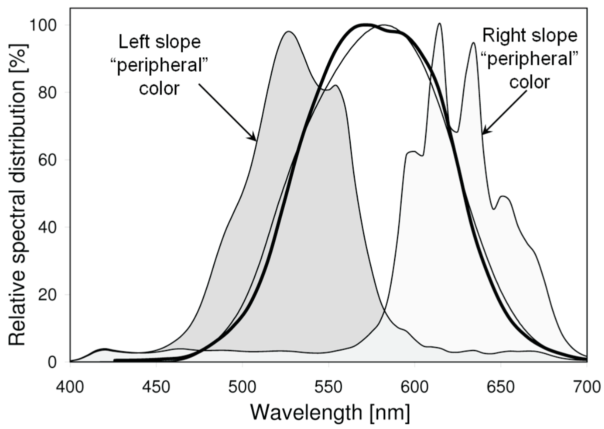


Fig. 2. Image acquisition flowchart.

3. Outline of the method

The method proposed in this paper is based on creating the reference calibration colors by LED Color Generator (LED CG) [6] with the spectral distribution designed to minimize the errors introduced by the mismatch of the manufactured filters with regard to designed characteristics. The conducted measurements and research have led to conclusion, that in areas of mismatch (as shown in Fig. 1), a calibration color sample should cover the area with overlapping of the specified filter transmittance distribution. Such samples are hereby called peripheral colors. Other group of reference colors is a group of those which spectral distribution covers whole distribution of the given filter with overlapping. The "filling" colors are designed to have a flat characteristic after passing through the filters. Fig. 3 shows the principles of the peripheral and the filling colors.

The third group of colors is composed of combinations of previous two groups and totally, set of 24 colors has been developed following those conditions. Their chromaticity coordinates are shown in Fig. 4, along with the Macbeth chart patches for comparison. As it can be seen, the distribution of the proposed colors inside the visible gamut is much more spread than those of Macbeth chart. The peripheral colors are placed near the border of the gamut (due to their narrow spectrum). The filling colors and the combinations tend to be placed closer to the center (wider spectrum). The method based on the designed color set has been called FEC (filter error compensation) method.



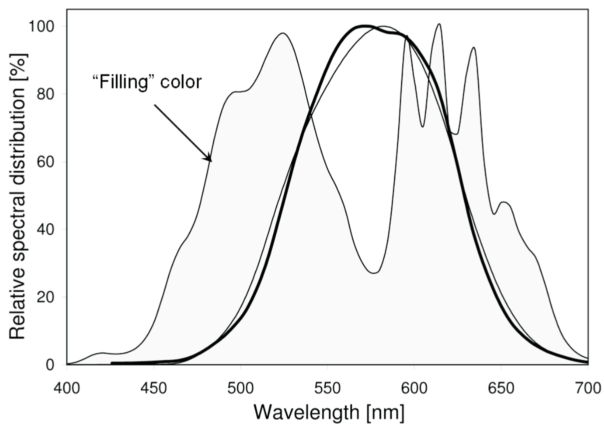


Fig. 3. Principles of designing of the "peripheral and "filling" reference colors.

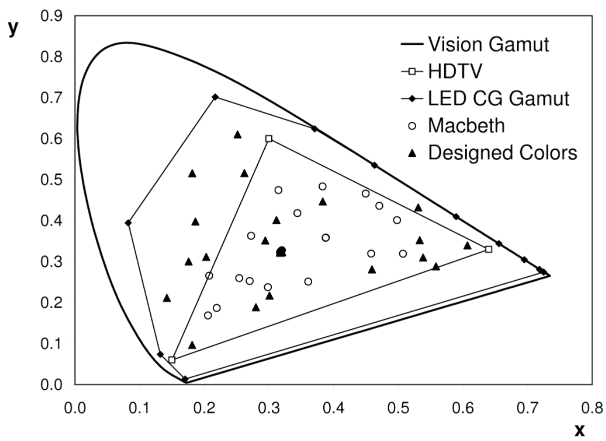


Fig. 4. x, y chromaticity coordinates of the FEC method and the Macbeth chart.

4. Experimental and results

The FEC method provides variety of colors some of which have relatively narrow spectral distribution (peripheral colors). Due to employment of three filters in a camera with monochrome CCD sensor, during of acquisition of such colors a situation may occur that the spectrum of the color is captured by only one filter at the time, while others are basically cutting it off. This causes to acquire noise by the filters, which are not "seeing" the color. Therefore, the S_1 S_2 S_3 data is affected by random error, and the results of calibration are very poor (average ΔE=2.64). For this reason, in the parts of the spectrum, which are cut-off by the specified filter characteristics, a small amount of white light is introduced to increase signal to noise ratio (SNR). This simple operation reduces the average color difference to ΔE=1.57. The amount of white light is typically around 2% of the total intensity of the white color that LED Color Generator can produce. Figure 5 shows the principle of such compensation.

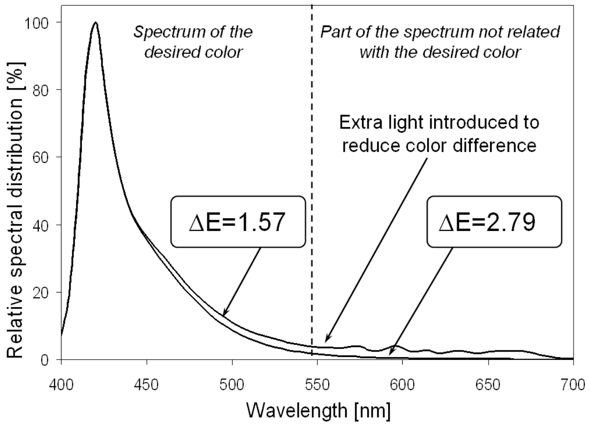


Fig. 5. Addition of white light to the colors with narrow spectral distribution and its influence on the color difference.

It is worth noticing that the addition of a small amount of white light doesn't result with a significant shift of the coordinates of the compensated colors towards white. Therefore the overall gamut of the color of the FEC method is much bigger than that of the Macbeth chart as it was shown in Fig. 4.

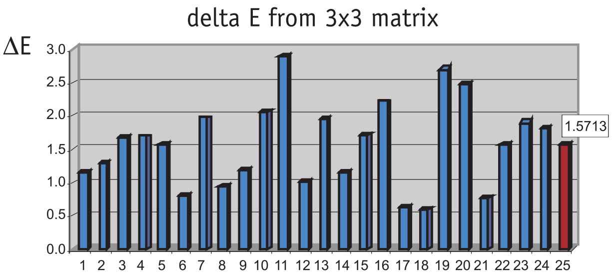


Fig. 6. Color difference ΔE of the experimental FEC colors.

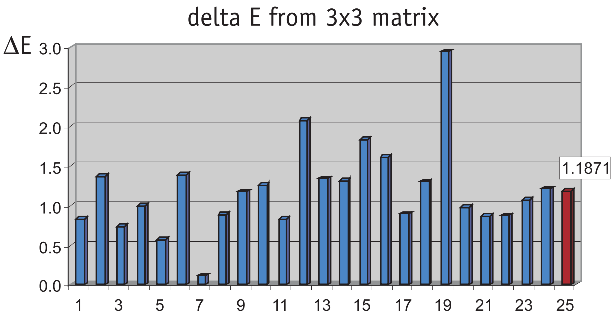


Fig. 7. Color difference ΔE of the Macbeth chart colors.

The obtained average color difference for 24 reference colors of the FEC method was found to be ΔE=1.57. The color difference chart for the colors is shown in Fig. 6. For comparison of the obtained results with results obtained by using the Macbeth chart, an experiment was conducted to check the performance of the conversion matrix derived in the described method. The conversion matrix A (average ΔE=1.18) obtained by Macbeth chart (color difference chart shown in Fig.7) was applied to the colors of the new method. The result was found to be average ΔE=1.82 for designed colors. However the opposite transformation with matrix B (average ΔE=1.57) obtained by the FEC method, applied to the Macbeth chart (MBC) gave average color difference ΔE=1.22.

5. Conclusions

The cross transformations presented in previous section, have significant meaning. They show that the conversion matrix obtained by using FEC method allows for more uniform distribution of the color difference ΔE throughout the whole vision gamut Within small gamut (HDTV), both FEC and Macbeth give similar results. However the gamut of FEC colors is bigger than Macbeth's. In this case the FEC colors transformed by Macbeth gave ΔE=1.82 and FEC method gave ΔE=1.57. Above results show, that the presented method is significantly improving quality of the calibrated image.

In practice the color difference between two colors below ΔE=1.2 is difficult to distinguish by an untrained eye. However the saturated colors placed close to the border of the vision gamut, they are difficult to acquire with such good accuracy. The common color references like Macbeth Chart and similar are not sufficient for color calibration of a high-accuracy color acquisition capable digital camera. The FEC (filter error compensation) method presented in this paper allows for accurate calibration within whole vision gamut. The method can be applied to any camera with known spectral characteristics of the filters however the reference colors produced by LED Color Generator would differ for each given type of a camera.

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