Hue plane preserving colorimetric characterization of digital cameras

C. F. Andersen* and J. Y. Hardeberg**
The Graphic Arts Institute of Denmark, Emdrupvej 72, 2400 København NV (Denmark)
***Gjøvik University College, P.O. Box 191,N- 2802 Gjøvik (Norway)*
Corresponding author: C. F. Andersen (cfa@dgh.dk)

ABSTRACT

A hue plane preserving colorimetric characterization method for digital colour cameras is proposed and compared to a choice of three other common characterization methods based on least squares fitting. Colorimetric characterization methods deal with the transformation of linear RGB camera values to XYZ tristimulus values. These other methods are an unconstrained 3 by 3 matrix, a white point preserving 3 by 3 matrix and a second order polynomial. The proposed method employs a set of 3 by 3 matrices constrained equally to preserve the white point.

The methods have been evaluated on real camera signals coming from an Imacon Ixpress professional digital CCD camera, together with a flash light. Under The Gretag MacBeth Color Checker and the Color Checker DC charts have used as training set, and test set, respectively. The results shows that the proposed method performs better than the compared methods in terms of mean and maximum ΔE_{ab} values both on the training set and on the test set, while maintaining the hue planes defined by linear combinations of neutral and a chromatic pigment reflection.

1. INTRODUCTION

Camera characterization is an important element in digital photography since it relates the camera output values (camera RGB) to colorimetric values (i.e. CIEXYZ). This relation is not straightforward for several reasons. Two of these reasons are known as filter metamerism and light source / illuminant metamerism. In digital photography metamerism arises from sensor filter spectral characteristics and the light source / illuminants involved. It is a well known fact that digital cameras today do not incorporate colorimetric colour filters on the sensor due to manufacturing limitations and noise considerations. Therefore a linear relation between the CIE color matching functions and the sensor filter spectral characteristic does not exist. This constitutes the filter metamerism. Furthermore the light source under which the camera images are taken (i.e. flash light, tungsten etc.) differs spectrally from the illuminant to which the colorimetric values are referred. This can result in light source / illuminant metamerism.

Thus, generally no unique solution exist for the relation between camera RGB-values and colorimetric XYZ-values. Therefore optimized rather than exact solutions are usually sought for[1,2,3,5]. Among these optimized solutions a few are considered in this paper along with the proposed new method.

There are, however, some features that the digital camera and a colorimetric standard observer have in common. The standard observer is linearly responsive to exposure level (amount of light) and so is the camera, if it, by calibration, have been set up so (i.e. the CCD-device is largely linear). The calibration of the digital camera involves black offset correction (i.e. correcting for dark current and lens flare), white balancing (choosing a neutral patch, ideally a perfect reflecting diffuser, in the image, for equalization of camera RGB) and linearization of the camera RGB responses (through three independent one dimensional functions, one for each channel).

Once the camera has been black calibrated (compensating for dark noise), linearized, and white balanced, it will respond proportionally to its exposure. In fact, both the camera's and the standard observer's response to a stimulus, which consists of a linear combination of a set of physical stimuli, will be the same linear combination of the camera or observer response to each of these physical stimuli. A common situation in a real scene is that it includes objects that basically reflect light as an additive combination of the exposure of a particular pigment and the light source itself (i.e. a billiard ball or a car painted in "one" color etc.). This is parallel to the additive combination of specular (neutral) reflection and diffuse (chromatic) reflection from such objects. Defining *hue plane* as such an additive combination of neutral specular reflection and chromatic diffuse reflection, a hue plane preserving camera characterization method (HPPCC) is therefore desirable, since two colors will be enough to characterize colors corresponding to the whole hue plane. It should be noted here that hue plane in this definition is a plane in linear camera RGB space suspended by the neutral vector and a vector corresponding to the chromatic color. It is not a "perceptually related" hue plane.

Furthermore such a method should also ensure that different exposure levels of neutral (a grayscale) would be transformed to proportional luminance levels of a colorimetric grayscale.

2. METHOD

The HPPCC method proposed here can be seen as a flexible extension to a 3 by 3 matrix characterization method, constrained to white point preservation. The method incorporates a finite and flexible number of 3 by 3 matrices. Each matrix operates on the camera RGB values so that neutral camera RGB values are transformed to neutral XYZ values. Apart from that, each matrix is determined to transform two other camera colours to their respective colorimetric values. The matrices are arranged so that each of them is responsible for a subset of all camera RGB-values. The arrangement of the subsets of camera RGB values is determined in a chromaticity plane based on camera RGB values. By plotting these values in such a plane along with camera RGB whitepoint, a hue angle correlate can be constructed similar to the hue angle correlate constructed in the CIE xy-chromaticity plane (from which the dominant wavelength can be found[4]); by drawing a line from camera neutral and through a chromatic point for each of the points present. Each subset is now defined by the camera RGB values within two consecutive hue angles. There are as many matrices as there are non-neutral RGB values in the characterization set. The method can in principle employ any number of colour characterization samples. However, camera acquired samples of stimuli that are constituted by physically being different exposure levels of the same pigment or more than one linear combination with the neutral, will not add to the precision of the model, since these will either have the same chromaticity or lie on the same hue angle line.

By plotting the camera hue angle correlate against the colorimetric hue angle correlate, a monotone function should emerge. If not, then filter metamerism in the camera makes it impossible to characterize two or more consecutive, chosen pigments without a possible overlap of intermediate colorimetric values. A choice of sample elimination should then be made.

Given sampled camera RGB-values R_i, G_i, B_i from the MacBeth Color Checker (MCC): N chromatic samples (in the MCC N is maximum 18) and the near-neutral patch N8 R_N, G_N, B_N. These samples have relative colorimetric tristimulus values X_i, Y_i, Z_i and X_N, Y_N, Z_N which are defined by the illuminant under which the MCC was measured. The multi-matrix interpolation function is defined by calculating:

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = \underline{\underline{M_i}} \begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} \tag{1}$$

where the camera RGB values have been white balanced to the neutral patch (N8), and scaled to the luminance value of the same patch: $R'=Y_N R/R_N$, $G'=Y_N G/G_N$, $B'=Y_N B/B_N$ .Here the i'th matrix M_i is found by solving the following set of linear equations:

$$\begin{pmatrix} X_i' \\ Y_i' \\ Z_i' \end{pmatrix} = \underline{\underline{M_i}} \begin{pmatrix} R_i' \\ G_i' \\ B_i' \end{pmatrix}, \begin{pmatrix} X_{i+1}' \\ Y_{i+1}' \\ Z_{i+1}' \end{pmatrix} = \underline{\underline{M_i}} \begin{pmatrix} R_{i+1}' \\ G_{i+1}' \\ B_{i+1}' \end{pmatrix}, \begin{pmatrix} X_N \\ Y_N \\ Z_N \end{pmatrix} = \underline{\underline{M_i}} \begin{pmatrix} R_N \\ G_N \\ B_N \end{pmatrix} \tag{2}$$

and i is found by sorting the camera RGB samples by their hue correlates in the *rg*-chromaticity plane incrementally so that , $\theta_1 < \theta_2 < ... < \theta_N$, where

$$\theta_i = \mathrm{arctg}((g_i - 1/3)/(r_i - 1/3)) + m * \pi; \qquad m = \begin{cases} 0; & r_i \geq 1/3 \wedge g_i \geq 1/3 \\ 1; & g_i \langle 1/3 \\ 2; & r_i \langle 1/3 \end{cases} \tag{3}$$

$$r_i = R_i /(R_i + G_i + B_i) \wedge g_i = G_i /(R_i + G_i + B_i) \tag{4}$$

The transformation of any other camera R, G and B to colorimetric values is carried out by determining the hue angle θ corresponding to the RGB's by using eqs. 4 and 3 and thereafter looking up which two consecutive angles it is between. That in turn corresponds to which matrix M_i to use in eq. 1.

This basic, multi-matrix version of the method ensures C0 continuity over the hue planes (defined in the camera RGB-space by the grayscale and a color patch represented by a color vector).

3. RESULTS

The camera signals came from an Imacon Ixpress professional digital camera which from the factory had been black current corrected and linearized, but otherwise needed to be lens flare corrected and white balanced. Under a flash light source captures of the MCC and the MacBeth Color Checker DC (MCCDC) charts have been obtained in a studio with as neutral surroundings as could practically be arranged. Two flash bulbs of the same make and model provided the light source. These were arranged so that the illumination of the color charts was as spatially uniform as possible. Exposure was set so that it would match that of a typical studio exposure level, meaning that the camera RGB response on the N8 patch yielded roughly 100 8bit levels. This was done to accommodate for the film curve correction and thereby making it possible to compare with existing color characterization on the camera.

The HPPCC method is compared to an unconstrained 3 by 3 matrix (M33)[1,2,3], a white point preserving 3 by 3 matrix (M33WPP)[5] and a second order polynomial (POL2)[1,2,3]. All methods are least squares fitted in XYZ space.

Table 1: Mean and maximum ΔE_{ab} color differences between the colorimetric values of the MCC and MCCDC charts, and the estimated colorimetric values, by the four evaluated characterization methods.

	Training set (MCC)		**Test set (MCCDC)**	
Method	ΔE_{ab} mean	ΔE_{ab} max	ΔE_{ab} mean	ΔE_{ab} max
M33	4.12	11.44	5.50	20.51
M33WPP	4.19	12.57	5.65	21.96
POL2	3.48	9.34	5.95	24.62
HPPCC	0.25	1.93	4.78	18.64

As it can be seen from Table 1 the HPPCC method performs well in comparison to the other methods. It is not surprising that this method yields so low ΔE_{ab} values on the training set since it is designed to match the chromatic patch values with no error. The max ΔE_{ab} value comes from the black patch. On the training set the method performs slightly better than the other methods.

In Figure 1 it can be seen that hue planes in RGB-space, by the HPPCC method only, are transformed to hue planes in XYZ-space that matches the colorimetric patch values on the training set. This is accomplished by trading off continuity beyond C0. Neither of M33, M33WPP or POL2 matches any of the chromatic MCC colors exactly. M33WPP matches the neutral patch N8 perfectly which means that a series of different exposures of this color (a grayscale) will be matched exactly as well. This property it has in common with the HPPCC-method. Hue planes in the M33, M33WPP and HPPCC remain planes (planes projected to lines in the xy-chromaticity diagram) meaning that the physical relationship between the colors of such a plane is preserved through the transformation. That is not the case in the polynomial method. The hue planes are seriously curved and thereby will any physical relationship from a hue plane in camera RGB not be preserved in the colorimetric values.

Possible sources of error in the results could be related to imprecise lens flare correction, slight camera non-linearity, noise and discrepancies between actual colorimetric values and used values.

4. CONCLUSION

The presented hue plane preserving camera characterization method has been compared to three other common camera characterization methods. The comparison was based on the evaluation of ΔE_{ab} color differences and the ability of the methods to preserve hue planes defined by an additive combination of neutral specular reflection and chromatic diffuse reflection. As it can be seen from the results, the HPPCC method performs better than its competing methods, both when considering ΔE_{ab} color difference, and considering the ability to preserve the hue planes (i.e. the physically linear relationship between pigment and light). Note, however, that is done at the expense of continuity beyond C0. It is evident that more investigation into this method is needed. Firstly an evaluation based on a noise free three filter camera simulation should be conducted. This would enable a theoretical analysis of the choice of chromatic samples in the training set. It would be preferred that the simulated camera spectrally would be close to the Ixpress camera. Secondly a higher order of continuity would be desirable for example obtained through polynomial weighting of each matrix result. This would probably be obtained at the expense of colorimetric accuracy on the training set, but not necessarily on the test set.

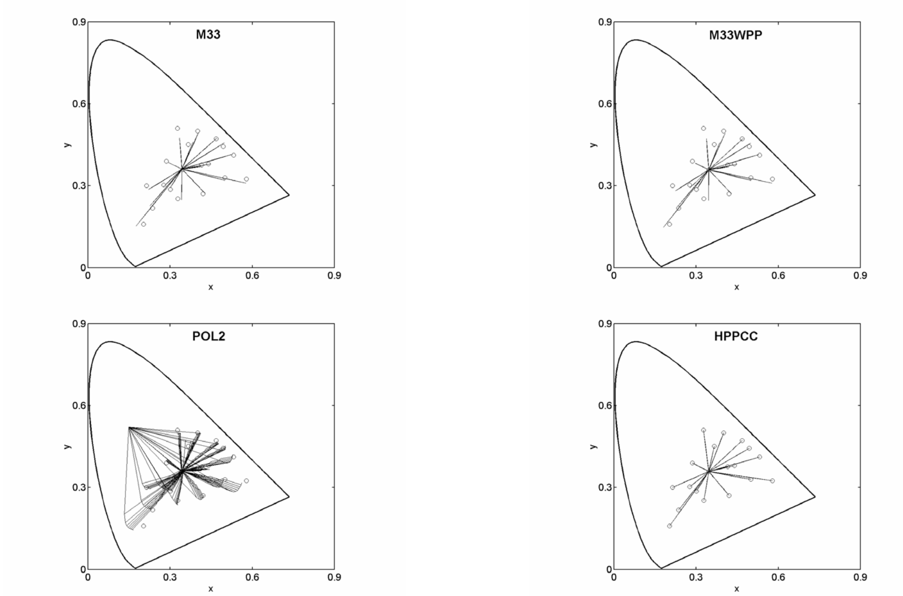

Figure 1: The figure consist of 4 xy-chromaticity diagrams, one for each of the evaluated characterization methods (M33, M33WPP, Pol2 and HPPCC). The diagrams show how linear combinations of each of the 18 MCC patches with the neutral is transformed by the methods (lines / mesh). The circles indicate the measured MCC chromaticity values.

References

1. T. Johnson, "Methods for characterizing colour scanners and digital cameras", Displays 16(4): 183-191, (1996).
2. J.Y. Hardeberg, "Acquisition and Reproduction of Color Images", Ch. 3, Dissertation.com, Parkland, FL, (2001).
3. G. Hong, M. R. Luo, P. A. Rhodes, "A study of digital camera colorimetric characterization based on polynomial modelling", Color Research and Application 26(1), 2001.
4. G. Wyszecki and W.S.Stiles, "Color Science, Concepts and methods, Quantitative data and formulae", John Wiley & sons, 2. ed. (1982).
5. G. Finlayson and M. S. Drew, "Constrained least-squares regression in color spaces", Journal of Electronic Imaging 6(4): 484-493, (1997).