Colorimetric characterization of digital cameras preserving hue planes

Casper Find Andersen* and Jon Yngve Hardeberg**
****The Graphic Arts Institute of Denmark, Copenhagen, Denmark***
*****The Norwegian Color Research Laboratory, Gjøvik University College, Gjøvik, Norway.***

Abstract

In this paper we present a colorimetric characterization method for digital color cameras, based on hue plane and white point preservation. The present implementation of the method incorporates a series of 3 by 3 matrices, each responsible for the transformation of a subset of camera RGB-values to colorimetric XYZ-values. The method is compared to a choice of three other common characterization methods based on least squares fitting. These other methods are an unconstrained 3 by 3 matrix, a white point preserving 3 by 3 matrix and a second order polynomial.

The methods have been evaluated on real camera signals coming from an Imacon Ixpress professional digital CCD camera, under flash light. The Gretag MacBeth Color Checker and the Color Checker DC charts have been used as test set and training set (respectively). The method is evaluated in combination with a noise susceptibility estimation of the training set samples and a preliminary subdivision of the hue domain, that reduces the amount of test samples needed in the characterization. The noise estimation is based on a geometric analysis in camera chromaticity space.

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 and illuminants involved. It is a well known fact that digital cameras today do not incorporate colorimetric color 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 multi matrix based, hue plane and white point preserving method.

The hue plane preserving approach in the proposed method explores the fact that there are 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. The hue plane preserving camera characterization (HPPCC) method[6] explores that fact.

In this paper there will be a discussion of the relation between camera aquired RGB values and colorimetric XYZ values of stimuli that consist of an additive mixture of a neutral and a chromatic reflection. This leads to the presentation of the HPPCC method in its basic form as presented previously[6]. In the previous work the HPPCC method was evaluated on the basis of the Gretag MacBeth Color Checker as training set an the Gretag MacBeth Color Checker DC as test set. In the present paper the training set and the test set has been interchanged. This has resulted in a much larger number of training samples, so in order to accomodate for this large amount of training samples a selection procedure is employed in order to reduce the number of samples. The procedure will be outlined in its basic principles. The results of the evaluation of the HPPCC method compounded with the selection procedure, is presented in terms of CIELAB color difference measures of the difference between the actual colorimetric values and the estimated values of both the test and the training sets. The method is compared to a choice of a few other common camera characterization methods. The methods will also be evaluated in terms of their ability to preserve hueplanes through their respective transformations.

Hueplanes and additivity

Let the spectral reflectance *R(λ)* from an object be expressed as a linear combination of a mainly diffuse reflectance from a pigment and neutral specular reflectance, as described in the Phong[7] illumination model, with ambient and point light source having the same spectral distribution and the spectral reflection being neutral:

$$R(\lambda) = S(\lambda)\rho(\lambda) = S(\lambda)\{k_D\rho_D(\lambda) + k_S\} \tag{1}$$

where λ is wavelength, $S(\lambda)$ is the illuminant spectral power distribution, $\rho(\lambda)$ is sample reflectance consisting of a linear combination of specular reflectance (weighted by the amount k_S) and mainly diffuse pigment reflectance $\rho_D(\lambda)$ (weighted by the amount k_D). The camera responses to this stimulus will be:

$$\vec{T}_{cam} = k_{cam}\int_{\lambda} R(\lambda)\vec{t}_{cam}d\lambda \tag{2}$$

where $\vec{T}_{cam}$ is a vector of the camera responses (R,G,B) and $\vec{t}_{cam}$ is a vector containing the spectral filter sensitivities of the camera $(r(\lambda), g(\lambda), b(\lambda))$ with white-balance factors integrated. k_{cam} is a normalizing factor. The tristimulus values corresponding to this stimulus will be:

$$\vec{T}_{col} = k_{col}\int_{\lambda} R(\lambda)\vec{t}_{col}d\lambda \tag{3}$$

where $\vec{T}_{col}$ is a vector containing the tristimulus values (X,Y,Z) and $\vec{t}_{col}$ is a vector containing the standard observer color matching functions $(x(\lambda), y(\lambda), z(\lambda))$. k_{col} is a normalizing factor. Inserting Eq. 1 into Eqs. 2 and 3 yields

$$\vec{T}_{cam} = k_D(k_{cam}\int_{\lambda} S_{\lambda}\rho_D\vec{t}_{cam}d\lambda) + k_S(k_{cam}\int_{\lambda} S_{\lambda}\vec{t}_{cam}d\lambda) \tag{4}$$

and

$$\vec{T}_{col} = k_D(k_{col}\int_{\lambda} S_{\lambda}\rho_D\vec{t}_{col}d\lambda) + k_S(k_{col}\int_{\lambda} S_{\lambda}\vec{t}_{col}d\lambda) \tag{5}$$

Eqs. 4 and 5 can be rewritten in terms of integrated responses (i.e. camera RGB and colorimetric XYZ:

$$\vec{T}_{cam} = k_D(\vec{T}_{cam,D}) + k_S(\vec{T}_{cam,S}) \tag{6}$$

and

$$\vec{T}_{col} = k_D(\vec{T}_{col,D}) + k_S(\vec{T}_{col,S}) \tag{7}$$

where $\vec{T}_{cam,D}$ is the camera response to the diffuse component and $\vec{T}_{cam,S}$ to the specular component, and $\vec{T}_{col,D}$ is the observer response to the diffuse component and $\vec{T}_{col,S}$ to the specular component.

Thus, both the camera's and the standard observer's response to the stimulus $R(\lambda)$, which consists of a linear combination of a set of two individual physical stimuli (in this case consisting of a diffuse and a neutral specular component), will be the same linear combination of the camera or observer response to each of these individual physical stimuli. Letting k_D and k_S vary independently, from zero through positive values, will geometrically result in planes in camera RGB space and colorimetric XYZ space that contains the neutral axis. The planes will be projected to lines radiating from neutral in their respective chromaticity diagrams. The characterization method presented here will explore this fact.

A common situation in a real scene is that it includes objects that basically (not taking into account interreflections and spectral dependencies on reflection angles etc.) 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 with one pigment, but reflecting partly diffuse and partly specular light with different exposure levels). This is parallel to the additive combination of neutral specular 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 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 (or colorimetric XYZ) space suspended by the neutral vector and a vector corresponding to the chromatic color. It is not a "perceptually related" hue plane.

Method

The HPPCC method presented here can be seen as a flexible extension of a 3 by 3 matrix characterization method, constrained to white point preservation[6]. 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 colors 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 the camera RGB white point, a hue angle correlate can be constructed, similar to the hue angle correlate defined in the CIE xy-chromaticity plane (from which the dominant wavelength can be found[4]). This is done 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 can be as many matrices as there are non-neutral RGB values in the characterization set. The method can in principle employ any number of color 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. If a series of samples with that property should emerge, the sample that is the least susceptible to noise should be chosen as a representative of that particular hue angle.

Given sampled camera RGB-values from a training target captured under a chosen light source, R_i, G_i, B_i, K chromatic samples and a near-neutral (ideally a perfect reflecting diffuser) patch 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 charts was measured. The multi-matrix interpolation function is defined by calculating:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M_i \begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} \tag{8}$$

where the camera RGB values have been white balanced to the neutral patch, 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:

$$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} = M_i \begin{pmatrix} R_i' \\ G_i' \\ B_i' \end{pmatrix}, \begin{pmatrix} X_{i+1} \\ Y_{i+1} \\ Z_{i+1} \end{pmatrix} = M_i \begin{pmatrix} R_{i+1}' \\ G_{i+1}' \\ B_{i+1}' \end{pmatrix}, \begin{pmatrix} X_N \\ Y_N \\ Z_N \end{pmatrix} = M_i \begin{pmatrix} Y_N \\ Y_N \\ Y_N \end{pmatrix} \tag{9}$$

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

$$\theta_i = 0; r_i = g_i = 1/3;$$
$$\theta_i = \pi/2; r_i = 1/3 \wedge g_i \rangle 1/3;$$
$$\theta_i = 3\pi/2; r_i = 1/3 \wedge g_i \langle 1/3;$$
$$\theta_i = arctg((g_i - 1/3)/(r_i - 1/3)) + m * \pi;$$

$$\theta_i = arctg((g_i - 1/3)/(r_i - 1/3)) + m * \pi;$$

$$m = \begin{Bmatrix} 0; & r_i \geq 1/3 \wedge g_i \geq 1/3 \\ 1; & g_i < 1/3 \\ 2; & r_i < 1/3 \wedge g_i \leq 1/3 \end{Bmatrix} \tag{10}$$

and the chromaticity values are calculated by:

$$r_i = R_i'/(R_i' + G_i' + B_i') \wedge g_i = G_i'/(R_i' + G_i' + B_i') \tag{11}$$

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. 11 and 10 and thereafter looking up which two consecutive angles it is between. That in turn corresponds to which matrix M_i to use in Eq. 8.

This basic, multi-matrix version of the method ensures C0 continuity over the hue planes since any RGB color on a hue plane will transformed to the same XYZ values by using the matrix belonging to either side of the plane.

Letting a matrix M_i from Eq. 8 operate on the camera responses defined by Eq. 6 to obtain estimated colorimetric values yields:

$$\vec{T}_{col}^{Est} = M_i(k_D(\vec{T}_{cam,D}) + k_S(\vec{T}_{cam,S})) \tag{12}$$

which can be rewritten:

$$\vec{T}_{col}^{Est} = k_D(\vec{T}_{col,D}^{Est}) + k_S(\vec{T}_{col,S}^{Est}) \tag{13}$$

In Eq. 13 it can be seen that the hue planes have been preserved since the linear combination of the two reflection components have been preserved from camera response to estimated colorimetric values. In the chosen training set sample points the estimated colorimetric values for each of the two components are the same as the real colorimetric values and therefore the estimated colorimetric values for any linear combination is colorimetrically correct. This result is shown in figure 5 in which the HPPCC method has operated on the chosen training set samples and their corresponding hueplanes.

The method also ensures that different exposure levels of neutral (a grayscale) would be transformed to proportional luminance levels of a colorimetric grayscale. Furthermore the method degenerates to a 3 by 3 matrix if the camera filters are linearly related to the color matching functions and the measurement illumination is the same as the light source under which the target is captured (i.e. a unity matrix if the camera filters are in fact the color matching functions).

By plotting the camera hue angle correlate against the colorimetric hue angle correlate (see figure 1), a monotone function should emerge (i.e. no hue change reversal in colorimetric hue angle correlate must occur, except one representing 360 degree wrap around). If not, then metamerism 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. In this paper that choice is based on an evaluation of the relative susceptibility to noise in the sample and a preliminary subdivision of the camera chromaticity hue domain, as described in the following section.

Sample selection

The sample selection procedure that pertains to the results in this article, consists of a preliminary camera hue domain subdivision, a sample selection based on relative susceptibility to noise, addition of specific samples, and hue overlap control. The goal of the selection procedure is to eliminate sample colors that overlap each other in the colorimetric hue correlate while retaining samples of low susceptibility to noise, obtaining samples representative of hue angles in all chosen hue directions and keeping an overall low color difference in both the test and the training set.

In order to obtain a sample representative of a chosen interval of hues in the camera rg-chromaticity plane, the 360 degrees of possible hue directions are subdivided into a number of equally sized hue intervals. In each interval a sample is chosen on the basis of lowest susceptibility to noise.

It is assumed that noise can be modeled geometrically in camera RGB space as a sphere around the position of the sample. The center of the sphere corresponds to the sample RGB value and the radius models the noise. Any such spheres have identical sizes independent of the position. After white-balancing of the camera, the spheres will be transformed to ellipsoids, again of identical sizes. When these ellipsoids are projected to the chromaticity plane they will depict ellipses with geometric centers not generally being the position of the sample chromaticity. The ellipses will now have different sizes depending on sample saturation and distance to black origin. By calculating the angular span between two hue lines radiating from neutral chromaticity and being tangents to the ellipses a measure of relative susceptibility to noise is established for each sample. The measure being the angle span. The closer to neutral or the closer to black the wider the span and thus the more susceptible to noise. Given a choice between samples belonging to the same hue subsection, the sample with the narrowest span is chosen.

To eliminate the possibility of reversal in the colorimetric hue correlate, the hue function is plotted and any sample that reverses in hue is eliminated or exchanged with another sample in the hue interval.

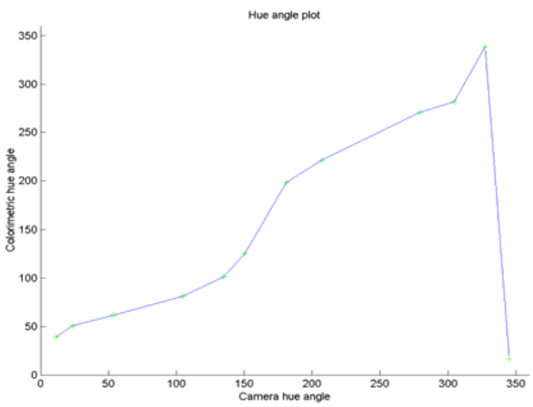

Figure 1. Plot of the monotonically increasing hue function with one 360 degree wrap-around. The 12 points come from the selected training set.

If certain samples are desired they can be added to the training set if they do not result in hue overlap. Fictive samples can be inserted and edited or the samples themselves can be edited with only a local impact on the overall characterization.

Experimental setup

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 MacBeth Color Checker (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 to the MCC's neutral patch N8 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 camera capture images were stored in 16 bit tiff.

The RGB-values gathered in the experiment corresponding to the two targets are: On the MCC, K = 18 chromatic samples and patch N8 as the near neutral patch. On the MCCDC K=154 (excluding the glossy patches in column 'S' in the chart) and the average of patches J5, J6, K5 and K6, as near-neutral patch values. The RGB-values are obtained in the target images by averaging no less than a 100 by 100 pixels area from each patch.

Results

Preliminary results of the HPPCC method[6] were based on the MCC as training set and the MCCDC as test set without sample elimination. In the present work, the training and test set have been interchanged so that the MCCDC is the training set and the MCC is the test set. Because of the large number of training samples, the HPPCC method is tested here in conjunction with the sample selection procedure. The 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]. The M33, M33WPP and the POL2 methods were least squares fitted in XYZ space. The results of the CIELAB color difference evaluations are summarized in Table 1. The M33, M33WPP and the POL2 methods where trained on all 170 MCCDC samples, whereas the HPPCC method, due to the selection procedure, was trained on 12 MCCDC colors, 11 of which came from a preliminary hue subdivision, one of which was interchanged because of hue reversal and one was added as desired extra color. The added color was chosen, because its colorimetric estimate resulted in unwanted high color difference when the HPPCC method was trained only on the original 11 samples. The white reference sample for the HPPCC and the M33WPP methods where the near-naeutral MCCDC patch values.

Training the HPPCC method on all 154 chromatic samples has been tried with the result that the ΔE^*_{ab} values were equal to zero on the training set samples. But the test set ΔE^*_{ab} values were very large because matrix conditioning was poor and there were many large hue reversals.

As it can be seen from Table 1 that even though only a relatively few samples from the training set has been used to train the HPPCC method, it performs well in comparison to the other methods. The ΔE^*_{ab} values from the the HPPCC-method on both the training and the test set are consistently lower than the ΔE^*_{ab} values from the competing methods.

Table 1: Mean and maximum ΔEab 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 (MCCDC)		Test set (MCC)	
Method	ΔE^*_{ab} mean	ΔE^*_{ab} max	ΔE^*_{ab} mean	ΔE^*_{ab} max
M33	4.46	17.20	4.69	12.89
M33WPP	4.54	18.02	4.61	12.85
POL2	3.17	15.13	4.39	16.73
HPPCC	2.91	13.07	3.41	8.36

The 4 CIE xy-chromaticity diagrams, Figures 2 to 5 pertains to the transformation of training set samples and corresponding hue planes for each of the 4 methods. The circles are the chromaticity points af the 12 chosen HPPCC training samples from the MCCDC). The lines/meshes are the hueplanes after transfomation. The hueplanes (eq. 6) are constructed by letting k_D and k_S vary independently through 9 discreet values between 0 and 1, thus forming a mesh of RGB values spanned by the neutral vector and the chromatic sample vector.

In Figure 5 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 training set colors exactly. M33WPP matches the neutral patch 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, meaning that the physical relationship between the colors of such a plane is preserved through the linear matrix based transformations. 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 estimated 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.

In future work it is planned to work with the optimization of the sample selection and the trade-off between continuity and color difference.

Conclusion

The presented multi matrix based hue plane preserving camera characterization method has been compared to four 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. The results show that the HPPCC method compounded with a sample selection procedure based on hue angle representation, noise susceptibility and elimination of hue reversal, performs better than its competing methods, both when considering ΔE^*_{ab} color difference, and considering the ability to preserve the hue planes. Note, however, that is done at the expense of continuity beyond C0. Depending on the specific situation the loss of higher order continuity can lead to artefacts in the converted images. Smooth sweeps of stimuli can be affected by this lack of continuity if they cross the hueplanes. Part of a the smooth series of colors from a rainbow could be an example of this, since it is highly probable that this series of colors would cross one or more hue sections. Another example less likely to be affected is sky regions with varying elevation/azimuth angles, since that sweep mainly lies within one hue subsection sweeping from highly chromatic sky blue to misty neutral in the horizon. The problem of higher than 0 order continuity will be adressed in the further investigation into the HPPCC method.

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).
6. C. F. Andersen and J. Y. Hardeberg, Hue plane preserving characterization of digital cameras, in AIC Colour 05 Proceedings Book, 287-290 (2005).
7. James Foley et al., Computer Graphics, principles and practice, 2nd edition in C, (Addison-Wesley, 1996) pg. 730

Author Biography

Casper Find Andersen obtained his M.Sc. degree in 1993 from the Danish Technical University (DTU) with a specialization in Computational Fluid Dynamics and Descriptive Geometry. From 1995 until 1998 he was employed by DTU as research assistant specializing in color theory and color management until 1998. From 1998 to 2001 he was senior researcher at the R&D department of Phase One dealing with color management and image manipulation. From 2001 he has been working as teacher, consultant and researcher at the Graphic Arts Institute of Denmark. At the moment he is working towards a PhD-degree on the topic of characterization of digital color cameras with Prof. Jon Yngve Hardeberg, Gjøvik University College, Norway, as de facto supervisor..

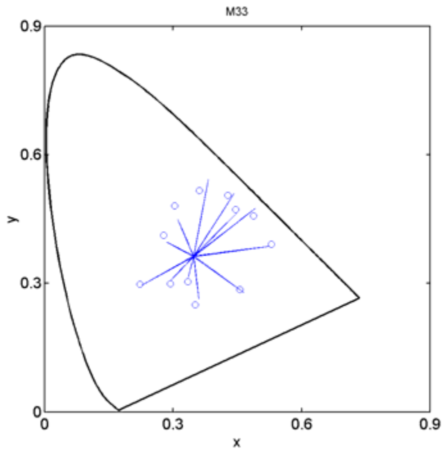

Figure 2. Plot of the hueplanescorresponding to the M33 method.

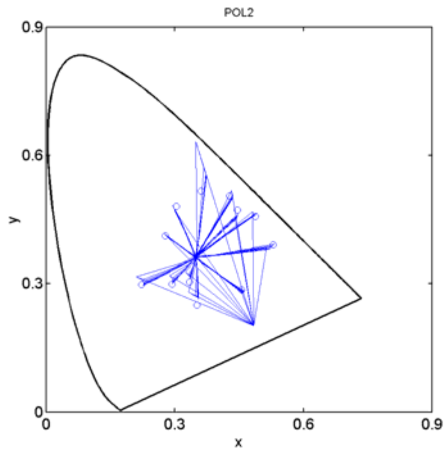

Figure 3. Plot of the hueplanescorresponding to the POL2 method.

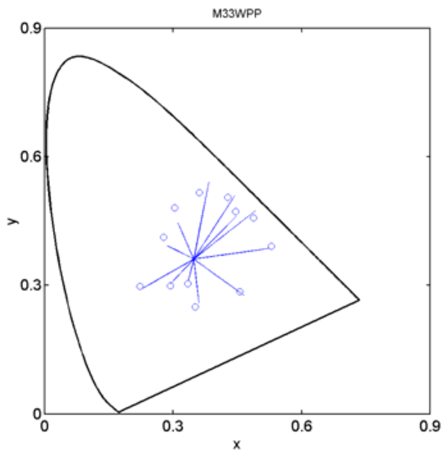

Figure 4. Plot of the hueplanescorresponding to the M33WPP method.

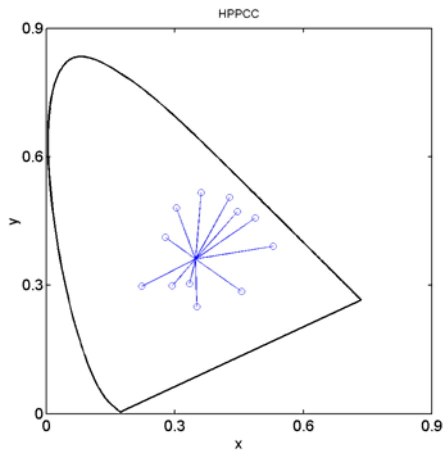

Figure 5. Plot of the hueplanescorresponding to the HPPCC method.