Colorimetric Characterization of Digital Cameras Preserving Hue Planes

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Casper Find Andersen and Jon Yngve Hardeberg

School of Electrical Engineering and Computer Science
Kyungpook National University
Abstract

- Colorimetric characterization method for digital cameras
  - Hue plane and white point preservation
  - A series of 3 by 3 matrices
    - Transforming a subset of camera RGB-values to colorimetric XYZ-values
Introduction

Camera characterization

- Relating the camera output values (camera RGB) to colorimetric values (CIEXYZ)
- Not straightforward relation
  - Filter metamerism
  - Light source/illuminant metamerism
- Not unique solution
  - Optimized rather than exact solution
◆ Common things between digital camera and colorimetric standard observer
  – Linearly responsive to exposure level (amount of light)
  – Response of linear combination of a set of physical stimuli
◆ In this paper
  – Dealing with stimuli that consist of an additive mixture of a neutral and a chromatic reflection → Hue preserving
  – Selection procedure for large number of training samples
  – Hue plane preserving camera characterization (HPPCC) + selection procedure
Hueplanes and additivity

◆ Spectral reflectance $R(\lambda)$

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

- Sample reflectance
- Weight for specular reflectance
- Illuminant spectral power distribution
- Diffuse pigment reflectance

◆ Camera responses

$$\vec{T}_{cam} = k_{cam} \int_{\lambda} R(\lambda) \vec{t}_{cam} d\lambda$$  \hspace{1cm} (2)

- Normalizing factor
- Vector of camera responses (R, G, B)
- Vector of spectral filter sensitivities of camera
◆ Tristimulus values

\[
\vec{T}_{col} = k_{col} \int_{\lambda} R(\lambda) \vec{t}_{col} d\lambda
\]

(3)

Normalizing factor

Vector of camera responses (X, Y, Z)

Vector of standard observer color matching functions
Inserting Eq. (1) into Eqs. (2) and (3)

\[
\tilde{T}_{\text{cam}} = k_D (k_{\text{cam}} \int_{\lambda} S_{\lambda} \rho_{D} \tilde{T}_{\text{cam}} d\lambda) + k_S (k_{\text{cam}} \int_{\lambda} S_{\lambda} \tilde{T}_{\text{cam}} d\lambda)
\]  \hspace{1cm} (4)

\[
\tilde{T}_{\text{col}} = k_D (k_{\text{col}} \int_{\lambda} S_{\lambda} \rho_{D} \tilde{T}_{\text{col}} d\lambda) + k_S (k_{\text{col}} \int_{\lambda} S_{\lambda} \tilde{T}_{\text{col}} d\lambda)
\]  \hspace{1cm} (5)

Integrated responses (RGB and XYZ)

\[
\tilde{T}_{\text{cam}} = k_D (\tilde{T}_{\text{cam},D}) + k_S (\tilde{T}_{\text{cam},S})
\]  \hspace{1cm} (6)

\[
\tilde{T}_{\text{col}} = k_D (\tilde{T}_{\text{col},D}) + k_S (\tilde{T}_{\text{col},S})
\]  \hspace{1cm} (7)
Camera’s and standard observer’s response

- Linear combination of the responses to each of two individual physical stimuli (a diffuse and a neutral specular component)
- Geometrically planes in camera RGB space and colorimetric XYZ space (*hue plane*)
  - Projected to lines in chromaticity diagrams

Necessity of hue plane preserving camera characterization method

- Two colors are enough to characterize colors corresponding to the whole hue plane
Method

- HPPCC method
  - A finite and flexible number of 3 by 3 matrix characterization method
  - Constrained to white point preservation
  - Each matrix
    - Transforming neutral camera RGB values to neutral colorimetric XYZ values
    - Transforming two other camera colors to their respective colorimetric values
      - The least susceptible to noise color
Training target

- K chromatic samples \((R_i, G_i, B_i) \leftrightarrow (X_i, Y_i, Z_i)\)
- A near-neutral patch \((R_N, G_N, B_N) \leftrightarrow (X_N, Y_N, Z_N)\)

Multi-matrix interpolation function

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = M_i \begin{pmatrix}
R' \\
G' \\
B'
\end{pmatrix}
\]

White balanced to the neutral patch and scaled to the luminance value

\[
R' = \frac{Y_N R}{R_N}, \quad G' = \frac{Y_N G}{G_N}, \quad B' = \frac{Y_N B}{B_N}
\]
\[ \begin{align*}
\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} &= M \begin{pmatrix} R'_i \\ G'_i \\ B'_i \end{pmatrix}, \\
\begin{pmatrix} X_{i+1} \\ Y_{i+1} \\ Z_{i+1} \end{pmatrix} &= M \begin{pmatrix} R'_{i+1} \\ G'_{i+1} \\ B'_{i+1} \end{pmatrix}, \\
\begin{pmatrix} X_N \\ Y_N \\ Z_N \end{pmatrix} &= M \begin{pmatrix} Y_N \\ Z_N \end{pmatrix}
\end{align*} \] (9)

\[ \theta_1 < \theta_2 < \ldots < \theta_K \]

\( \theta_i = 0; \ r_i = g_i = 1/3 \)

\( \theta_i = \pi / 2; \ r_i = 1/3 \wedge g_i > 1/3 \)

\( \theta_i = 3\pi / 2; \ r_i = 1/3 \wedge g_i < 1/3 \)

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

\[ m = \begin{cases} 
0; & r_i \geq 1/3 \wedge g_i \geq 1/3 \\
1; & g_i < 1/3 \\
2; & r_i < 1/3 \wedge g_i \leq 1/3
\end{cases} \]

\[ r_i = R'_i/(R'_i + G'_i + B') \]

\[ g_i = G'_i/(R'_i + G'_i + B') \] (11)
Estimated colorimetric values

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

(12)

\[ \vec{T}_{col}^{Est} = k_D (\vec{T}_{col,D}^{Est}) + k_S (\vec{T}_{col,S}^{Est}) \]  

(13)

- Hue planes are preserved
  - The linear combination of the two reflection components are preserved from camera response to estimated colorimetric values

Sample elimination

- To prevent from overlap of intermediate colorimetric values
Fig. 1. Plot of the monotonically increase hue function with one 360 degree warp-around. The 12 points come from the selected training set.
Sample Selection

◆ Procedure
  – Preliminary camera hue domain subdivision in camera rg-chromaticity plane
  – Sample selection based on lowest susceptibility to noise in each domain
    • Noise $\rightarrow$ sphere in RGB space $\rightarrow$ ellipsoid by white-balancing $\rightarrow$ ellipses projected to chromaticity plane $\rightarrow$ angular span between two hue lines radiating from neutral chromaticity and being tangents to the ellipse
Experimental Setup

- Camera and charts
  - Imacon Ixpress professional digital camera
    - Several correction from factory
  - MacBeth Color Checker (MCC)
  - MacBeth Color Checker DC (MCCDC)

- Exposure
  - MCC’s N8 → level 100 (8bits)
Results

- Several methods (least square fitting in XYZ space)
  - Unconstrained 3 by 3 matrix (M33)
  - White point preserving 3 by 3 matrix (M33WPP)
  - Second order polynomial (POL2)

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

<table>
<thead>
<tr>
<th>Method</th>
<th>$\Delta E_{ab}^*$ mean</th>
<th>$\Delta E_{ab}^*$ max</th>
<th>$\Delta E_{ab}^*$ mean</th>
<th>$\Delta E_{ab}^*$ max</th>
</tr>
</thead>
<tbody>
<tr>
<td>M33</td>
<td>4.46</td>
<td>17.20</td>
<td>4.69</td>
<td>12.89</td>
</tr>
<tr>
<td>M33WPP</td>
<td>4.54</td>
<td>18.02</td>
<td>4.61</td>
<td>12.85</td>
</tr>
<tr>
<td>POL2</td>
<td>3.17</td>
<td>15.13</td>
<td>4.39</td>
<td>16.73</td>
</tr>
<tr>
<td>HPPCC</td>
<td>2.91</td>
<td>13.07</td>
<td>3.41</td>
<td>8.36</td>
</tr>
</tbody>
</table>

Number of training samples: 170
Conclusion

◆ Multi matrix based hue plane preserving camera characterization method
  – Better performance than other 3 method
    • $\Delta E_{ab}^*$ color differences and ability to preserve hue planes
  – Artifact in smooth converted image
    • Lack of continuity if they cross the hueplanes