Accurate Estimation of the Non-Linearity of Input-Output Response for Color Digital Camera

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Abstract

◆ Estimation of the non-linearity of the channels
  – Different techniques
    • Based on the luminance of samples
    • Based on the mean reflectance of samples
    • Based on the spectral sensitivities of the channels
  – Experimental results
    • Small difference between each method
Introduction

◆ Traditional device characterization
  – Ascertaining sensor values for targets with known color characteristics
  – Transforming the sensor values to match the target CIE values

◆ Recent research
  – In order to estimate the non-linearity it is necessary to know the spectral sensitivities of each color channels
Background

- **Raw channel responses**

\[
R = \sum E(\lambda)S_R(\lambda)P(\lambda) \\
G = \sum E(\lambda)S_G(\lambda)P(\lambda) \\
B = \sum E(\lambda)S_B(\lambda)P(\lambda)
\]  

(1)

where  
- \(P(\lambda)\) : Known spectral reflectance of a uniform surface  
- \(E(\lambda)\) : Known spectral power distribution  
- \(S_R(\lambda), S_G(\lambda), S_B(\lambda)\) : Spectral sensitivities
◆ Input-output non-linearity function

\[ B' = f(B) \] (2)

where \( B' \) : Actual output response

◆ Luminance for each surface

\[ L = \sum E(\lambda)V(\lambda)P(\lambda) \] (3)

where \( V(\lambda) \) : Luminous efficiency function
Reflectance spectra invariant to wavelength

- Ratio of the luminance for each surface

\[ B_1 : B_2 : B_3 = L_1 : L_2 : L_3 \]  

- Reflectance spectra invariant to wavelength

![Graph](image)

Fig. 1. Reflectance spectra of three hypothetical grey surfaces with equal spectral reflectance across the wavelength spectrum.
◆ Typical reflectance spectra
  – Typical reflectance spectra

![Graph showing reflectance spectra of three hypothetical grey surfaces with spectral reflectance that varies with wavelength.]

Fig. 2. Reflectance spectra of three hypothetical grey surfaces with spectral reflectance that varies with wavelength.
Experimental

- Characterization procedure for each technique of estimating the non-linearity

1. Estimate the non-linearity for the system using the Munsell grey samples.
2. Apply the estimates of the non-linearity to the measured system outputs for the Macbeth DC ColorChecker to yield the linearized $RGB$ values.
3. Compute the coefficients of a polynomial transform that maps $RGB \rightarrow XYZ$ based upon the $RGB$ and $XYZ$ values of the Macbeth DC ColorChecker samples.
4. Compute the CIELAB color difference between the actual $XYZ$ values and the $XYZ$ values obtained from steps 1-3 for the Macbeth DC ColorChecker samples.
5. Use the polynomial transform obtained from the Macbeth DC ColorChecker samples to compute $XYZ$ values for the samples in the Macbeth ColorChecker and compute CIELAB color differences between the actual and predicted values.
– Computing camera output values by a power law with exponent $\gamma = 1.8$

$$R' = R^\gamma, \ G' = G^\gamma, \ B' = B^\gamma$$

(5)

– Spectral sensitivities of the three channels

Fig. 3. A set of known spectral sensitivities of a camera system.
– Using the luminance or mean reflectance of the samples

\[ R' = L', \quad G' = L', \quad B' = L' \]

\[ R' = P', \quad G' = P', \quad B' = L' \]
Results

- Estimated non-linearity

### Table 1. Non-Linearity Estimations Under Illuminant D_65

<table>
<thead>
<tr>
<th></th>
<th>R channel</th>
<th>G channel</th>
<th>B channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral sensitivities</td>
<td>1.8000</td>
<td>1.8000</td>
<td>1.8000</td>
</tr>
<tr>
<td>Luminance</td>
<td>1.8087</td>
<td>1.8044</td>
<td>1.8146</td>
</tr>
<tr>
<td>Mean reflectance</td>
<td>1.7708</td>
<td>1.7644</td>
<td>1.7729</td>
</tr>
</tbody>
</table>

### Table 2. Non-Linearity Estimations Under Illuminant A

<table>
<thead>
<tr>
<th></th>
<th>R channel</th>
<th>G channel</th>
<th>B channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral sensitivities</td>
<td>1.8000</td>
<td>1.8000</td>
<td>1.8000</td>
</tr>
<tr>
<td>Luminance</td>
<td>1.8177</td>
<td>1.8044</td>
<td>1.8135</td>
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<tr>
<td>Mean reflectance</td>
<td>1.7768</td>
<td>1.7615</td>
<td>1.7695</td>
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</tbody>
</table>

### Table 3. Non-Linearity Estimations Under Illuminant F_11

<table>
<thead>
<tr>
<th></th>
<th>R channel</th>
<th>G channel</th>
<th>B channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral sensitivities</td>
<td>1.8000</td>
<td>1.8000</td>
<td>1.8000</td>
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<tr>
<td>Luminance</td>
<td>1.7938</td>
<td>1.8076</td>
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<td>Mean reflectance</td>
<td>1.7539</td>
<td>1.7657</td>
<td>1.7658</td>
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</table>
Characterization performance

Table 4. Comparison of Memorization Performance With Different Linearization Techniques

<table>
<thead>
<tr>
<th></th>
<th>Spectral sensitivities</th>
<th>Luminance</th>
<th>Mean reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median $\Delta E_{ab}$</td>
<td>0.1039</td>
<td>0.1041</td>
<td>0.1056</td>
</tr>
<tr>
<td>Maximum $\Delta E_{ab}$</td>
<td>0.6178</td>
<td>0.6195</td>
<td>0.6252</td>
</tr>
</tbody>
</table>

Table 5. Comparison of Generalization Performance With Different Linearization Techniques

<table>
<thead>
<tr>
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<th>Luminance</th>
<th>Mean reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median $\Delta E_{ab}$</td>
<td>1.5807</td>
<td>1.6775</td>
<td>1.6931</td>
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<tr>
<td>Maximum $\Delta E_{ab}$</td>
<td>2.6699</td>
<td>2.8270</td>
<td>2.8726</td>
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</table>
Characterization performance with random noise SD=0.025

Table 6. Comparison of Memorization Performance With Different Linearization Techniques (With Random Noise SD = 0.025)

<table>
<thead>
<tr>
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<th>Luminance</th>
<th>Mean reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median $\Delta E_{ab}$</td>
<td>0.2427</td>
<td>0.2429</td>
<td>0.2441</td>
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<tr>
<td>Maximum $\Delta E_{ab}$</td>
<td>0.7105</td>
<td>0.7149</td>
<td>0.7304</td>
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</tbody>
</table>

Table 7. Comparison of Generalization Performance With Different Linearization Techniques (With Random Noise SD = 0.025)

<table>
<thead>
<tr>
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<th>Luminance</th>
<th>Mean reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median $\Delta E_{ab}$</td>
<td>1.6501</td>
<td>1.7417</td>
<td>1.7597</td>
</tr>
<tr>
<td>Maximum $\Delta E_{ab}$</td>
<td>3.1059</td>
<td>3.3054</td>
<td>3.3188</td>
</tr>
</tbody>
</table>
Discussion

◆ Computational model of a camera system
  – Known channel spectral sensitivities and non-linear response
  – Using different techniques to estimate the non-linearity

◆ Experimental results
  – Small difference between each method