Colorimetric characterization of scanner
by measures of perceptual color error

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Abstract

◆ Colorimetric characterization of color scanner
  – Based on the measures of perceptual color difference error
  – First method
    • To minimize the total color difference between the actual and predicted color samples
  – Second method
    • Generalization of the existing cubic-root preprocessing technique
    • Mapping between the p’th root of scanner responses and CIELAB

◆ Experiment result
  – Second method is better than those of the traditional CIEXYZ space-based characterization methods
1. Introduction

- Goal of scanner characterization
  - Transform the device-dependent scanner response (RGB) to device-independent colorimetric value (CIELAB)

- Colorimetric characterization methods
  - Neural networks, look-up table, and polynomial regression
  - General Polynomial regression
    - Transform RGB values to the CIEXYZ values
    - Least-squares (LS) and total least-squares (TLS) methods
    - Nonlinear transform between CIEXYZ and CIELAB
    - Optimal solution in CIEXYZ space does not mean the minimization of color difference in CIELAB space
Proposed method

- Calculating the transform between RGB and CIEXYZ values by minimization of total color difference (TCDM)
- Transform the p’th root of RGB to CIELAB values using Least squares (LAB-LS)
  - Generalization of the existing polynomial regression techniques
  - Adopting the cubic root of RGB values as a preprocessing step
2. Scanner characterization

*Problem formulation*

- Scanner response $v$
  \[ v = M_s L_s r \] (1)
- Nonlinear optoelectronic conversion function of common scanner
  \[ \rho = F(v) = F(M_s L_s r) \] (2)
- CIE tristimulus values
  \[ b = M_c L_c r \] (3)
- Purpose
  - Calculating CIE XYZ values from scanner responses
- Three-order cross-terms of elements in v (M=20)

\[ a_n \equiv a_{i,j,k} = v_1^i v_2^j v_3^k, \quad 0 \leq i + j + k \leq 3, \quad 1 \leq n \leq M \quad (4) \]

- Obtaining b using transform matrix H

\[ a^T H = b^T \quad (5) \]

- Collecting the polynomial terms using K color samples

\[ AH = B \quad (6) \]

where \( H = [h_1, h_2, h_3] \) and \( B = [b_1, b_2, b_3] \)
◆ LS and TLS methods

- LS method
  • Assume that the matrix $A$ is free of error
  • Find a solution $h_j$ that minimizes equation (7)
    \[ J_{LS} = \| b_j - \hat{b}_j \| \text{ subject to } Ah_j = \hat{b}_j \]  

- TLS method
  • Considering errors in both the vector $b_j$ and the matrix $A$
  • Find a solution $h_j$ that minimizes equation (8)
    \[ J_{TLS} = \| [A; b_j] - [\hat{A}; \hat{b}_j] \|_F \text{ subject to } \hat{A}h_j = \hat{b}_j \]  
    where $\| \|_F$ is Frobenius norm
◆ TCDM and LAB-LS Methods
  
  - LS and TLS methods
    - The difference of statistical distribution for color difference error between in CIELAB space and in CIEXYZ space
    - because of the nonlinear cubic-root transform
  
  - TCDM
    - Obtaining the solution by minimizing the following error term
      \[
      J_{TCDM} = \sum_{k=1}^{K} \Delta E_{ab}^* \quad \text{subject to } AH = \hat{B} \quad (9)
      \]
    - Obtaining starting point, H, by the LS method
- LAB-LS method
  - Transform function mapping CIEXYZ to CIELAB
    \[ c = T_{Lab} (b) \]  \hspace{1cm} (10)
  - To cancel out the cubic root the transform \( T_{Lab} \)
    \[ u = T_p (v) = v^{1/p} \]  \hspace{1cm} (11)
    \( p \) is an integer such as 3,6,9, etc.
  - Calculating the high-order polynomial terms of \( u \)
  - Obtaining the transform matrix \( H \) under the LS method
3. Experimental evaluation and discussion

- **Circumstance**
  - Color target
    - Calculating the inverse optoelectronic conversion function
      - Kodak Gray Scale Q-14(Q14)
    - Evaluating the color accuracy of each characterization methods
      - GretagMacBeth ColorChecker DC(CDC) and Kodak Q60 photographic standard (IT8)
    - Epson GT-10000+ at an appropriate resolution
  - Measuring the Spectral reflectance
    - CDC and Q14 : GretagMacbeth Spectrophotometer 7000A
    - IT8 : GretagMacbeth spectrolino spectrophotometer
    - Under D65
– Samples
  • Using two-thirds of samples for training
  • Using the rest for testing purpose
– Adopting the color difference formula $\Delta E_{94}^*$
  • Close to visual perception

Table 1. Influence of the p value on color accuracy for the LAB-LS method when color target CDC was used.

<table>
<thead>
<tr>
<th>$p$ value</th>
<th>1</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average $\Delta E_{94}$</td>
<td>2.49</td>
<td>1.43</td>
<td>1.32</td>
<td>1.29</td>
<td>1.28</td>
</tr>
</tbody>
</table>
– Color difference errors of the LS, TLS, TCDM, and LAB-LS

Table 2. Color accuracies for the LS, TLS, TCDM, and LAB-LS methods in terms of means, standard deviation (Std.), and maximum (Max.) of $\Delta E_{94}$ using color targets CDC and IT8.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E_{94}$ Training</th>
<th>$\Delta E_{94}$ Testing</th>
<th>$\Delta E_{94}$ Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std.</td>
<td>Max.</td>
</tr>
<tr>
<td>CDC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS</td>
<td>1.72</td>
<td>1.82</td>
<td>12.90</td>
</tr>
<tr>
<td>TLS</td>
<td>2.73</td>
<td>6.23</td>
<td>51.66</td>
</tr>
<tr>
<td>TCDM</td>
<td>1.54</td>
<td>1.54</td>
<td>8.51</td>
</tr>
<tr>
<td>LAB-LS</td>
<td>1.33</td>
<td>1.14</td>
<td>6.65</td>
</tr>
<tr>
<td>IT8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS</td>
<td>1.24</td>
<td>1.08</td>
<td>6.73</td>
</tr>
<tr>
<td>TLS</td>
<td>1.41</td>
<td>1.25</td>
<td>6.73</td>
</tr>
<tr>
<td>TCDM</td>
<td>1.19</td>
<td>0.94</td>
<td>5.59</td>
</tr>
<tr>
<td>LAB-LS</td>
<td>0.85</td>
<td>0.49</td>
<td>2.63</td>
</tr>
</tbody>
</table>
- LS is better than TLS
  - Errors in matrix A do not satisfy the conditions required by the TLS method
  - Colorimetric values B were measured by spectrophotometers with high accuracy
- TCDM vs. LS
  - The improvement of TCDM is slight
  - TCDM failed to find the global optimal solution due to the large size of the transform matrix H
- LAB-LS
  - Better than the other methods
  - Additional advantage
    - Can be solved in a closed form and does not require iterative searching like the TCDM method
Distribution of color difference with respect to lightness range for all the samples on CDC

- The lightness CIE L is more uniform than luminance CIE Y

**Fig. 2.** Distribution of $\Delta E_{94}^*$ with respect to the lightness range of the LS and LAB-LS methods for the CDC target. The Y error bars show ±1 standard deviation.
5. Conclusion

- Proposed two methods, TCDM and LAB-LS
  - Considering the limitation of the LS and TLS
  - Using perceptual color difference error in CIELAB space
  - LAB-LS is best
  - TCDM is better than the LS and TLS methods