A Feasibility Study of Spectral Color Reproduction

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Francisco H. Imai, David R. Wyble, Roy S. Berns, and Di-Yuan Tzeng

School of Electrical Engineering and Computer Science
Kyungpook National Univ.
Abstract

◆ End-to-end color reproduction system
  – Possibilities and limitations of input and output device
  – Spectrally matching between hardcopy results and original colors

◆ The approach
  – Trichromatic digital camera with multiple filtration
  – Image processing
  – Four color ink jet printing
Introduction

◆ Color management system (CMS)
  – MARC (Methodology for art reproduction in color)
    • Matched the original paintings
  – ICC color management framework
  – Multi-channel visible spectrum imaging (MVSI)
    • Minimized metamerism
    • Better accuracy
Two approaches

- Using narrow bandpass filter
  - Monochrome CCD and tunable filter
- Using conventional trichromatic digital camera
  - Possibility of decreasing the spectral sampling increment without a significant loss of spectral information

Printing for hardcopy

- Using spectral properties
- Determined an optimal ink set
  - Using Kubelka-Munk theory for overprint
Research in MCSL

- Corresponding to the various target colors
- Spectral-based ink separation
- Six color ink jet printer
- **Spectral color reproduction** in this publication
  - Developed an end-to-end spectral color reproduction system
  - Comprising a spectral image acquisition system and a spectral based printing system
  - Spectral reflectance estimated from the digital signals
    - Spectral-based color separation algorithm
Spectral color reproduction system

- Procedure
  - Figure 1

- Evaluation
  - Evaluated the spectral image acquisition and spectral based printing systems
  - Measurement of spectral reflectance
Fig. 1. Block diagram
– Estimating spectral reflectance

\[ \hat{R}_E = EA \]  \hspace{1cm} (1)

where

\[ D_S = (SF)^T PR \]  \hspace{1cm} (2)

- \( S \): measured camera spectral sensitivity
- \( F \): spectral transmittances of the filter
- \( P \): illumination spectral power distribution
- \( R \): spectral reflectance

\[ A = M_S^{-1}D_S \]  \hspace{1cm} (3)

- \( M_S^{-} \): transformation matrix
- \( D_S \): simulated camera signal
– Calculated from simulated digital signals

\[ \hat{R}_s = EM_s^{-1}D_s \]  \hspace{1cm} (4)

where \( E \) : eigenvector
\( M_s^{-1} \) : transformation matrix
\( D_s \) : simulated camera signal

– Calculated from camera signals

\[ \hat{R}_1 = EM_1^{-1}D \]  \hspace{1cm} (5)

where \( D \) : camera signal
– Estimated printed spectral reflectance

\[
\hat{r}_F = \left[ \sum_{i=0}^{16} f_i \ r_{i,\text{max}}^{1/n} \right]^n
\]

where

- \( \hat{r}_F \) : estimated printed spectral reflectance
- \( n \) : empirically fit Yule-Nielsen \( n \)-factor
- \( r_{i,\text{max}} \) : spectral reflectance of the \( i^{th} \) Neugebauer primary
- \( f_i \) : Demichel weighting

\[
f_i = \prod_{j=1}^{4} (\text{if ink } j \text{ is in Neugebauer primary } i, \text{ then } w_j \text{ else, } (1 - w_j))
\]

- \( \hat{R}_p \) is composed by the vectors \( \hat{r}_F \)

– End-to-end spectral color reproduction transformation

\[
\mathbf{M}_p^{-\mathbf{E}} \mathbf{M}_I^{-}
\]
Experimental

◆ Equipments
  – Trichromatic IBM PRO/3000 digital camera system
    • R,G,B filter wheel
    • Corrected dark current
    • Measured sensitivity
  – Epson Photo Style 1200 ink jet printer
  – Target with 55 colors sampled
– Target

Color Plate 17. Colorimetric plots for the target with 55 patches
◆ Evaluating equation

– Color difference equations
  
  • Mean color difference from the mean (MCDM)
    
    $\sum_{i=1}^{N}\left(\frac{(L_i^* - \bar{L}^*)^2 + (a_i^* - \bar{a}^*)^2 + (b_i^* - \bar{b}^*)^2}{N}\right)^{1/2}$
    
    $MCDM = \frac{1}{N} \sum_{i=1}^{N} \left( (L_i^* - \bar{L}^*)^2 + (a_i^* - \bar{a}^*)^2 + (b_i^* - \bar{b}^*)^2 \right)^{1/2}$
    
  
  – Goodness-of-fit coefficient (GFC)
    
    $GFC = \frac{\left| \sum_j R_m(\lambda_j) R_e(\lambda_j) \right|}{\sqrt{\sum_j \left[ R_m(\lambda_j) \right]^2 \left[ R_e(\lambda_j) \right]^2}}$
    
    $GFC = \frac{\left| \sum_j R_m(\lambda_j) R_e(\lambda_j) \right|}{\sqrt{\sum_j \left[ R_m(\lambda_j) \right]^2 \left[ R_e(\lambda_j) \right]^2}}$
    
  
  – Metameric index
    
    $MI = \sqrt{(\Delta L_{n1} - \Delta L_{n2})^2 + (\Delta a_{n1} - \Delta a_{n2})^2 - (\Delta b_{n1} - \Delta b_{n2})^2}$
Results and Discussions

◆ Evaluation of the MVSI acquisition system
  – Performance of eigenvectors in the reconstruction of original spectra
    • Comparing $\hat{R}_E$ and $R$
    • Reconstructions using six eigenvectors
• Table I. Resulting colorimetric and spectral accuracy

<table>
<thead>
<tr>
<th>Number of eigenvectors</th>
<th>Cumulative variance contribution (%)</th>
<th>Mean $\Delta E_00$ (D50, 2°)</th>
<th>Mean Spectral rms error (%)</th>
<th>Mean GFC (%)</th>
<th>Mean Metameric Index ($\Delta E_00$) (D50 -&gt; A, 2°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>98.10</td>
<td>5.1</td>
<td>2.7</td>
<td>97.53</td>
<td>1.4</td>
</tr>
<tr>
<td>6</td>
<td>99.97</td>
<td>0.4</td>
<td>0.8</td>
<td>99.77</td>
<td>0.2</td>
</tr>
<tr>
<td>9</td>
<td>99.99</td>
<td>0.1</td>
<td>0.4</td>
<td>99.95</td>
<td>0.03</td>
</tr>
<tr>
<td>12</td>
<td>100.00</td>
<td>0.1</td>
<td>0.2</td>
<td>99.93</td>
<td>0.01</td>
</tr>
</tbody>
</table>

• Spectral difference

Fig. 2. Spectral difference between $\mathbf{R}$ and $\hat{\mathbf{R}}_E$, using six eigenvectors
– Estimation of spectral reflectance using simulated camera signals

\[ \hat{R}_S = EM_S D_S \] (4)

\[ D_S = (SF)^T PR \] (2)

- Using Kodak Wratten filter 38 (light blue)
- Tested the performance of the estimation system under noiseless environment

Fig. 3. Spectral sensitivity
• Spectral difference

Fig. 4. Spectral difference between measured spectral reflectance and estimated spectral reflectance

• Table II. Colorimetric and spectral accuracy of reflectance estimation by simulated camera signals

<table>
<thead>
<tr>
<th>Number of eigenvectors</th>
<th>$\Delta E_{00}$ (D50, 2°)</th>
<th>Spectral rms error (%)</th>
<th>GFC (%)</th>
<th>Metameric Index ($\Delta E_{00}$) (D50 → A, 2°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.3</td>
<td>1.0</td>
<td>99.84</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum or Minimum (GFC)</td>
<td>0.8</td>
<td>2.9</td>
<td>98.70</td>
<td>0.5</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.2</td>
<td>0.3</td>
<td>0.34</td>
<td>0.1</td>
</tr>
</tbody>
</table>
– Estimation of spectral reflectance using actual camera signals

\[ \hat{R}_1 = EM_i D \] (5)

• **Table III.** Colorimetric and spectral accuracy of reflectance estimation by camera signals

<table>
<thead>
<tr>
<th>Number of eigenvectors</th>
<th>( \Delta E_0 ) (D50, 2°)</th>
<th>Spectral rms error (%)</th>
<th>GFC (%)</th>
<th>Metamer Index (( \Delta E_{10} )) (D50 -&gt; A, 2°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.0</td>
<td>1.4</td>
<td>99.55</td>
<td>0.4</td>
</tr>
<tr>
<td>Maximum or Minimum (GFC)</td>
<td>2.1</td>
<td>2.6</td>
<td>97.91</td>
<td>1.2</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.4</td>
<td>0.4</td>
<td>0.40</td>
<td>0.3</td>
</tr>
</tbody>
</table>

• Poor result
  – Noise, quantization, and typical experimental uncertainty
– Evaluation of three ways

Fig. 5. Spectral difference $\hat{R}_E$, $\hat{R}_S$, $\hat{R}_I$
◆ Evaluation of the spectral-based printing
  – Evaluation of the spectral-based printing model
    • Using Yule-Nielsen $n$–factor

![Graph showing spectral reflectance comparison](image)

**Fig. 7.** Comparison of spectral reflectance

• **Table IV.** Colorimetric and spectral evaluation

<table>
<thead>
<tr>
<th>Number of eigenvectors</th>
<th>$\Delta E_{uv}$ $(D65, 2^\circ)$</th>
<th>Spectral rms error (%)</th>
<th>GFC (%)</th>
<th>Metameric Index ($\Delta E_{uv}$) $(D65 \to A, 2^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.8</td>
<td>0.1</td>
<td>99.996</td>
<td>0.05</td>
</tr>
<tr>
<td>Maximum or Minimum (GFC)</td>
<td>0.7</td>
<td>0.4</td>
<td>99.98</td>
<td>0.3</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.1</td>
<td>0.1</td>
<td>0.004</td>
<td>0.1</td>
</tr>
</tbody>
</table>
– Evaluation of the spectral-based printing system
  • Using the printer inverse model

![Graph showing spectral difference](image)

Fig. 8. Spectral difference

• **Table V**. Colorimetric and spectral evaluation of the spectral based printing system

<table>
<thead>
<tr>
<th>Number of eigenvectors</th>
<th>ΔE∞ (D65, 2°)</th>
<th>Spectral rms error (%)</th>
<th>GFC (%)</th>
<th>Metameric Index (ΔE∞) (D50 -&gt; A, 2°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.9</td>
<td>0.7</td>
<td>99.91</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum or Minimum (GFC)</td>
<td>4</td>
<td>2</td>
<td>99.57</td>
<td>0.4</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1</td>
<td>0.5</td>
<td>0.07</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Evaluation of the spectral color reproduction system from original to hardcopy

– Evaluated end-to-end spectral reproduction system

\[
\begin{align*}
M_p \quad &EM_l \\
\end{align*}
\]

(8)

Fig. 9. \(\Delta E_{00}\) histogram
Table VI. End-to-end system colorimetric and spectral evaluation

<table>
<thead>
<tr>
<th>Number of eigenvectors</th>
<th>$\Delta E_{ab}$ (D50, 2°)</th>
<th>Spectral rms error (%)</th>
<th>GFC (%)</th>
<th>Metameric Index ($\Delta E_{ab}$) (D50 -&gt; A, 2°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.5</td>
<td>0.9</td>
<td>99.79</td>
<td>0.2</td>
</tr>
<tr>
<td>Maximum or Minimum (GFC)</td>
<td>5.5</td>
<td>2.8</td>
<td>98.67</td>
<td>0.6</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.1</td>
<td>0.5</td>
<td>0.26</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Comparison of spectral reflectance curve

Fig. 11. Compared two ways
Conclusions

- Tested end-to-end spectral color reproduction
  - Spectral analysis
  - Spectral reconstruction using simulated camera signals and actual camera signal

- Evaluated printing system
  - Spectral based printing model and system
  - Good performance