Image Acquisition Technique for High Dynamic Range Scenes Using a Multiband Camera

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Abstract

- Proposed method
  - Achievement of HDR imaging
    - Use of six-band camera
    - Adjustment of two camera’s sensitivity
      » Including three high sensitivity bands and three low sensitivity bands
Introduction

- High quality of digital color image
  - Satisfying several factors
    - Image resolution
    - Color reproduction
      - Multiband imaging techniques
        » Achievement of accurate color reproduction
    - Dynamic range
      - HDR imaging techniques
        » Expansion of dynamic range
    - Noise characteristics
HDR imaging techniques

- Sequential exposure change
  - Combination of valid pixels in each image
    - High exposure image
    - Low exposure image
- Multiple image detectors
  - Use of beam splitter
  - Use of image detector
    - Changing exposure time of detector
- Multiple sensor elements within a pixel
  - Use of image detector
    - Including two sensing elements of different sizes
- Adaptive pixel exposure
  - Use of novel solid-state image sensor
    - Including computational element
- Spatially varying pixel exposures
  - Use of filter array in front of CCD sensor
    - Having different exposures
Method

- Basic idea
  - Configuration of six-band camera

Fig. 1. (a) Optical configuration of six-band HDTV camera.
- Spectral transmittance of each interference filter
- Overall sensitivities with narrow bands

**Fig. 1.** (b) Schematic illustration of the principle of six-band spectral sensitivities.
Proposed method

- Use of one-shot six-band camera
  - Inserting ND (Neutral Density) filter in camera 2
    - Having relatively lower sensitivity than camera 1
- Basic concept
  - Achievement of accurate color reproduction
    - Obtaining valid information over very wide range
    - Losing information
      » Saturation in very light areas
      » Noise in very dark areas
**Fig. 2.** Schematic illustration of the modification of sensitivities and the camera responses for light and dark areas.
Wiener estimation of spectral radiance from camera response

- Expression of camera response at position \((x,y)\) in \(i\)th band image \(g_i(x,y)\)
  \[g_i(x,y) = \int h_i(\lambda)f(x,y;\lambda)d\lambda, \quad i = 1, \ldots, m\]  
  where \(h_i(\lambda)\) is the spectral sensitivity of the \(i\)th band of the camera, 
  \(f(x,y;\lambda)\) is the spectral radiance from the object, 
  \(\lambda\) is the wavelengths, and \(m\) is the total number of bands.

- Expression of Eq. (1)
  - Using vector-matrix notation
    \[\mathbf{g}(x,y) = \mathbf{h}\mathbf{f}(x,y)\]  
    where \(\mathbf{g}(x,y)\) is a \(m \times 1\) column vector representing camera responses, 
    \(\mathbf{f}(x,y)\) is a \(l \times 1\) column vector representing the spectral radiance, 
    and \(\mathbf{H}\) is a \(m \times l\) matrix in which \(i\)th row represents \(i\)th spectral sensitivity of the camera.
Achievement of Wiener estimation

- Operating matrix to observed data \( g \)
  - Applying operator \( W \) in Wiener estimation
    » Expression of estimated spectral radiance \( \hat{f} \)

\[
\hat{f} = Wg
\]  

(3)

- Minimizing ensemble average of square error between original and estimated radiance

\[
\langle \| f - \hat{f} \|^2 \rangle = \langle \| f - Wg \|^2 \rangle \rightarrow \text{min}
\]

(4)

where \( \langle \cdot \rangle \) is the ensemble average.

- Expression of Wiener estimation matrix

\[
W = \langle fg' \rangle \langle gg' \rangle^{-1}
\]

(5)

where \( [\cdot]' \) is a transposition and \( \langle fg' \rangle \) and \( \langle gg' \rangle \) denote the cross-correlation matrix between \( f \) and \( g \) and the autocorrelation matrix of \( g \), respectively.
Band selection and spectral estimation from selected band images

- Selection of suitable bands for spectral estimation from pixel value
  - Very dark areas
    - Use of bands 1, 3, and 5
  - Very light areas
    - Use of bands 2, 4, and 6
Table 1. List of bands used for HDR multiband imaging.

<table>
<thead>
<tr>
<th>Lightness of area</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very dark</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Dark</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Intermediate</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Light</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Very light</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>

Note. The circles indicate bands that are used in the Wiener estimation.
– Use of different Wiener estimation matrices
  • Taking discontinuity of reproduced color
    – Application of following equation
      » Expression of spectral estimate \( \hat{f}(x,y) \) at pixel position \((x,y)\)

\[
\hat{f}(x, y) = \sum_{i=1}^{p} k_i W_i g_i(x, y), \quad k_i = n_i / n
\]  

(6)

where \( g_i(x, y) \) and \( W_i \) is multiband camera responses at \((x, y)\) and the Wiener estimation matrix corresponding to \(i\)th combination, respectively. \( p \) is the number of combination (in this article, \( p = 15 \)). \( n \) and \( n_i \) is the total number of neighboring pixels (in this article, \( n = 11 \times 11 = 121 \)) and the number of pixels of \(i\)th category, respectively.
Experimental proof of concept

- Preliminary experiment
  - Use of six-band camera
  - Arranging two sets of objects in observation booth
    - Having Macbeth color checker and doll
      - One set
        » Lower intensity of illumination than other set

**Fig. 3.** Spectral radiance of the illuminant used in the experiment.
- Capturing object twice
  - Not using ND filter
  - Capturing different exposure times
    - 1/8 second
      » Use of low sensitivity bands 2, 4, 6
    - 1 second
      » Use of high sensitivity bands 1, 3, 5
Acquisition of six-band images

- 1 second: high sensitivity bands 1, 3, and 5
- 1/8 second: low sensitivity bands 2, 4, and 6

Fig. 4. Six-band images used for the spectral estimation by the proposed method.
Expression of segmented image

- Rendering 15 kinds of band selection with pseudo colors

Fig. 5. Segmented image with pseudo-colours.
Fig. 6. Rendered images after spectral estimation. (a) The low sensitivities (1/8-second exposure time). (b) The high sensitivities (1-second exposure time). (c) Proposed method. (d) 6B-SEC method (six band sequential exposure change).
Comparison of enlarged and brightened Macbeth color charts in the dark areas

Fig. 7. Enlarged and brightened Macbeth color charts in the dark areas. (a) The low sensitivities (1/8-second exposure time). (b) The high sensitivities (1-second exposure time). (c) Proposed method.
Expressing effect of using spatial averaging of multiple Wiener estimation

Fig. 8. Effect of spatial averaging of multiple Wiener estimation. (a) A portion (bottom right corner) of the Macbeth color checker in the segmented image shown in Fig. 4. (b) Rendered color of the corresponding portion by the proposed method.
Evaluation

- Evaluating accuracy of color reproduction
  - Expression of spectral radiance and colorimetric values

**Fig. 9.** Visualization of the accuracy of spectra estimation. In each graph, the blue line denotes the measured spectral radiance and the red line denotes the estimated spectral radiance.
– Evaluating noise characteristics
  • Using normalized variance of luminance on each patch of Macbeth color checker in dark area
    – Evaluated value of $k$th patch of Macbeth color $\text{CV}^{(k)}$

$$\text{CV}^{(k)} = \sqrt{\sum_{i,j \in R^{(k)}} (Y_{ij}^{(k)} - \bar{Y}^{(k)})^2 / N\bar{Y}^{(k)}}$$ (7)

where $Y_{ij}^{(k)}$ is the luminance value at $(i, j)$ of the $k$th patch of Macbeth color checker and $\bar{Y}^{(k)}$ is the mean luminance value over an area $R^{(k)}$ with $N$ pixels on the $k$th patch.
Table 2. Quantitative evaluation of accuracy of color reproduction and the noise characteristics of the reproduced image.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Evaluation area</th>
<th>Six low sensitivities</th>
<th>Six high sensitivities</th>
<th>Proposed</th>
<th>6B SEC</th>
</tr>
</thead>
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<tr>
<td>RMSE in spectral estimation</td>
<td>Dark</td>
<td>0.37</td>
<td>0.29</td>
<td>0.26</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Light</td>
<td>0.07</td>
<td>0.56</td>
<td>0.16</td>
<td>0.07</td>
</tr>
<tr>
<td>Color difference</td>
<td>Dark</td>
<td>9.1</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Light</td>
<td>2.9</td>
<td>35.4</td>
<td>6.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Noise</td>
<td>Dark</td>
<td>0.324</td>
<td>0.043</td>
<td>0.045</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Note. 6B SEC stands for the sequential exposure change using all six bands.
Table 3. Details of accuracy of color reproduction described in Table 2.

<table>
<thead>
<tr>
<th>Patch No.</th>
<th>Dark area</th>
<th></th>
<th>Light area</th>
<th></th>
<th></th>
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<tr>
<td></td>
<td>6 L. S.</td>
<td>6 H. S.</td>
<td>Proposed</td>
<td>6 L. S.</td>
<td>6 H. S.</td>
</tr>
<tr>
<td>1</td>
<td>6.3</td>
<td>3.7</td>
<td>2.1</td>
<td>3.5</td>
<td>1.7</td>
</tr>
<tr>
<td>2</td>
<td>8.9</td>
<td>2.0</td>
<td>4.7</td>
<td>1.1</td>
<td>19.8</td>
</tr>
<tr>
<td>3</td>
<td>8.0</td>
<td>2.0</td>
<td>2.2</td>
<td>1.6</td>
<td>28.3</td>
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<td>4</td>
<td>10.5</td>
<td>1.7</td>
<td>1.4</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>12.9</td>
<td>2.4</td>
<td>1.4</td>
<td>1.1</td>
<td>36.4</td>
</tr>
<tr>
<td>6</td>
<td>13.5</td>
<td>3.3</td>
<td>2.3</td>
<td>4.5</td>
<td>40.4</td>
</tr>
<tr>
<td>7</td>
<td>9.2</td>
<td>1.5</td>
<td>4.1</td>
<td>2.5</td>
<td>32.0</td>
</tr>
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<td>0.9</td>
<td>0.7</td>
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<td>84.5</td>
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<td>17</td>
<td>8.7</td>
<td>1.7</td>
<td>2.9</td>
<td>2.2</td>
<td>66.8</td>
</tr>
<tr>
<td>18</td>
<td>16.2</td>
<td>3.6</td>
<td>2.2</td>
<td>6.3</td>
<td>48.8</td>
</tr>
<tr>
<td>19</td>
<td>6.8</td>
<td>3.9</td>
<td>4.2</td>
<td>2.5</td>
<td>51.6</td>
</tr>
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<td>2.3</td>
<td>1.0</td>
<td>42.4</td>
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<tr>
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<td>2.0</td>
<td>0.5</td>
<td>32.3</td>
</tr>
<tr>
<td>22</td>
<td>10.1</td>
<td>2.5</td>
<td>2.6</td>
<td>1.9</td>
<td>22.7</td>
</tr>
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<td>23</td>
<td>11.5</td>
<td>1.6</td>
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<td>2.3</td>
<td>12.7</td>
</tr>
<tr>
<td>24</td>
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<td>1.4</td>
<td>2.2</td>
<td>3.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Mean</td>
<td>9.1</td>
<td>2.5</td>
<td>2.5</td>
<td>2.9</td>
<td>35.4</td>
</tr>
</tbody>
</table>
Discussion and conclusions

- Proposed method
  - Purpose
    - Expansion of dynamic range
      - Use of six-band camera consisting of three high sensitivity bands and three low sensitivity bands
    - Result of preliminary experiment
      - Providing reasonable color reproduction
      - Providing low noise