Color appearance in high-dynamic-range imaging

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Abstract

◆ The necessity of algorithm

– Viewing images on a monitor
  • Existence of difference of the photographed environments and viewing environments
  • Larger disconnect in HDR image than in conventional photography
    – Luminance compression not sufficient

◆ Proposed method

– Tone reproduction operators with the application of color appearance models
Introduction

- The necessity of tone mapping
  - Maturing field of HDR imaging
  - Existence of constraints on the range of luminance in conventional monitor
  - Compression the range of values to a displayable range → Tone mapping

- A problem of conventional tone mapping
  - Illumination conditions of the photographed environment
  - Illumination conditions of the viewing environment
  - Not accounted for difference
◆ Chromatic adaptation
  – Mechanism of the human visual system
    • Adaptation to colors of illumination

◆ Color appearance model (CAM)
  – Describing the environment with parameters to predict how colors appear to the observer
    • Chromatic adaptation transform
    • Prediction of relative and absolute color appearance attributes such as lightness, chroma
◆ Color appearance model in tone mapping
  – Acting as preprocessors to tone mapping operator
◆ Sample result
  – With and without appearance modeling prior to tone mapping

Fig. 1. (a) Without preservation of color appearance
(b) Color appearance is preserved
Color Appearance Phenomena

- Human visual system (HVS)
  - Operating as a nonlinear light meter
    - Small differences in illumination
      - Linear
    - Large differences in illumination
      - Causing chromatic changes complex
  - Color appearance phenomena
    - Simultaneous contrast, crispening, spreading
    - the Bezold-Brücke hue shift, the Abney effects
– Induction of perceptual effects in human visual system

Spectral response of L,M,S cone

Opponent signals (light-dark, red-green, and blue-yellow)

By the neurons of the retina (before transmitted to the brain)

– Larger difference in illumination of the original scene and the viewing environment in HDR images than in conventional images
  • Affecting of saturation and colorfulness according to brightness
  • Less saturated light and dark colors than average colors with the same chromaticity
    – Nonlinear response of our photoreceptors to linear changes in light reaching the retina
Color Appearance Models

- Appearance correlates

Table 1. Overview of appearance correlates.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness</td>
<td>The perceived quantity of light emanating from a stimulus.</td>
</tr>
<tr>
<td>Lightness (J)</td>
<td>The brightness of a stimulus relative to the brightness of a stimulus that appears white under similar viewing situations.</td>
</tr>
<tr>
<td>Colorfulness (M)</td>
<td>The perceived quantity of hue content (difference from gray) in a stimulus. Colorfulness increases with luminance.</td>
</tr>
<tr>
<td>Chroma (C)</td>
<td>The colorfulness of a stimulus relative to the brightness of a stimulus that appears white under similar viewing conditions.</td>
</tr>
<tr>
<td>Saturation (s)</td>
<td>The colorfulness of a stimulus relative to its own brightness.</td>
</tr>
<tr>
<td>Hue (h and e)</td>
<td>The degree to which a stimulus can be described as similar to or different from stimuli that are described as red, green, blue, and yellow.</td>
</tr>
</tbody>
</table>
Color Appearance Models
- Hunt’s model, RLAB7, CIELAB97s, ZLAB, and CIELAB02

Adoption of CIELAB02
- Most recent incarnation
- Simple
- Invertible
- Nonspatial
- Improved model of the CIELAB97
Color in Tone Reproduction

- Preserving chromatic content under luminance compression
  - Computing luminance $L$ for each pixel as a linear combination of the RGB channels
    \[
    L = 0.2126R + 0.7152G + 0.0722B
    \]
  - Compressing L channel with tone mapping operator
    - Reconstruction by preserving the ratio between the RGB channels
– A example of red

\[ R' = \frac{L'R}{L} \quad (1) \]

where

- \( L \); Luminance
- \( L' \); Compressed luminance
- \( R \); Red
- \( R' \); Compressed red

\[ R' = L' \left( \frac{R}{L} \right)^s \quad (2) \]

where

- \( s \); Controlling amount of saturation

Set to 1 \( \rightarrow \) tone mapping operator is to be used in combination with a CAM.
Image Preparation

◆ Outline of proposed algorithm
  – Adjustment for color appearance prior to tone mapping
  – Input data
    • Using SI units in color appearance models
      – Candela per square meter (cd/m²)
    • Calibrated input data
      – Using SI units
    • Uncalibrated input data
      – Using arbitrary units \(\rightarrow\) transform to SI units

Fig. 2. Outline of proposed algorithm.
Calibrated Input Data

- Creation HDR image from different exposure time images
  - Relative units
- Calculation of scale factor for absolute units
  - Measuring its luminance with a photometer
  - Taking the ratio of the measured luminance with the luminance recorded in the image
- Conversion of HDR image to absolute units
  - Multiplying all pixels with scale factor
Uncalibrated Input Data

- Two steps for estimation of absolute luminances

  - Conversion from linear RGB to XYZ tristimulus space using the sRGB conversion matrix

\[
M_{sRGB \rightarrow XYZ} = \begin{bmatrix}
0.4124 & 0.3576 & 0.1805 \\
0.2126 & 0.7152 & 0.0722 \\
0.0193 & 0.1192 & 0.9505
\end{bmatrix}
\]

\[
M_{XYZ \rightarrow sRGB} = \begin{bmatrix}
3.2406 & -1.5372 & -0.4986 \\
-0.9689 & 1.8758 & 0.0415 \\
0.0557 & -0.2040 & 1.0570
\end{bmatrix}
\]
• Finding a scaling factor
  – Estimation of the absolute luminance values of an image by computing its key
  – key $k$
    » Indicating the overall dark or light appearance of an image

$$
\log L_{av} = \frac{1}{N} \sum_{x,y} \log[\delta + L(x, y)]
$$

(5)

$$
k = \frac{\log L_{av} - \log L_{min}}{\log L_{max} - \log L_{min}}
$$

(6)

where $N$ ; the number of pixels in the image
$L$ ; the relative luminance for pixel $(x, y)$
$\delta$ ; a small offset

– Normalization of log-average by the dynamic range of the image to compute its key
- Scale factor $f$

$$f = \frac{10^4 k}{L_{\text{max}}} \quad (7)$$

- Constant $10^4 \text{ cd/m}^2$
  - Based on typical maximum luminance values
- Approximation of the real-world luminance values
  - By multiplying the input with $f$
Algorithm

◆ Application of the CIECAM02 model

Table 2. The input parameters of the CIECAM02 model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>XYZ</td>
<td>Absolute tristimulus values of the stimulus</td>
</tr>
<tr>
<td>X_wY_wZ_w</td>
<td>Relative tristimulus values of the white point</td>
</tr>
<tr>
<td>L_A</td>
<td>Adapting field luminance in candelas per square meter</td>
</tr>
<tr>
<td>Y_D</td>
<td>Relative luminance of the background</td>
</tr>
<tr>
<td>Surround</td>
<td>Relative luminance level of the surround specified as dim, dark, or average</td>
</tr>
</tbody>
</table>
– Relative background luminance
  • Setting to typically 20% of the luminance of the white point
– Surround
  • Outside scene or a normally lit office using an sRGB specified monitor
    – Setting average
  • Turn off of light in room (illumination by only monitor)
    – Setting dim or dark
– Relative tristimulus values of the white point

Table 3. Relative white points $XYZ$ for common scene types and a selection of CIE illuminants and their associated correlated color temperatures $T$

<table>
<thead>
<tr>
<th>Scene</th>
<th>$T$ (in K)</th>
<th>$X_w$</th>
<th>$Y_w$</th>
<th>$Z_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>candle flame</td>
<td>1850</td>
<td>132.614</td>
<td>100.000</td>
<td>11.511</td>
</tr>
<tr>
<td>sunrise/sunset</td>
<td>2000</td>
<td>127.432</td>
<td>100.000</td>
<td>14.517</td>
</tr>
<tr>
<td>100 W incandescent</td>
<td>2865</td>
<td>109.840</td>
<td>100.000</td>
<td>35.558</td>
</tr>
<tr>
<td>tungsten (TV/film)</td>
<td>3200</td>
<td>105.975</td>
<td>100.000</td>
<td>45.347</td>
</tr>
<tr>
<td>summer sunlight at noon</td>
<td>5400</td>
<td>97.584</td>
<td>100.000</td>
<td>94.252</td>
</tr>
<tr>
<td>summer sun + sky</td>
<td>6504</td>
<td>95.047</td>
<td>100.000</td>
<td>108.883</td>
</tr>
<tr>
<td>CIE A (incandescent)</td>
<td>2854</td>
<td>109.840</td>
<td>100.000</td>
<td>35.558</td>
</tr>
<tr>
<td>CIE B (direct sunlight)</td>
<td>4874</td>
<td>109.215</td>
<td>100.000</td>
<td>75.199</td>
</tr>
<tr>
<td>CIE C (indirect sunlight)</td>
<td>6774</td>
<td>98.071</td>
<td>100.000</td>
<td>118.185</td>
</tr>
<tr>
<td>CIE D50 (noon skylight)</td>
<td>5000</td>
<td>96.396</td>
<td>100.000</td>
<td>82.414</td>
</tr>
<tr>
<td>CIE D65 (average daylight)</td>
<td>6504</td>
<td>95.047</td>
<td>100.000</td>
<td>108.883</td>
</tr>
<tr>
<td>CIE E (normalized reference)</td>
<td>5500</td>
<td>100.000</td>
<td>100.000</td>
<td>100.000</td>
</tr>
<tr>
<td>CIE F2 (office fluorescent)</td>
<td>4150</td>
<td>99.187</td>
<td>100.000</td>
<td>67.395</td>
</tr>
</tbody>
</table>

– Degree of adaptation $D$
  • Change with the luminance level of the surround
- Estimation for light source detection
  - Computation of a threshold $L_T$
    \[
    L_T = L_{\min} + [0.6 + 0.4(1 - k)](L_{\max} - L_{\min})
    \] (8)
  - Varying $D$ smoothly between 10% below and 10% above threshold
    - Using Hermite interpolation
      - 10% below threshold
        \[
        L_{T_0} = \max[L_{\min}, L_T - 0.1(L_{\max} - L_{\min})]
        \] (9)
      - 10% above threshold
        \[
        L_{T_i} = \min[L_{\max}, L_T + 0.1(L_{\max} - L_{\min})]
        \] (10)
• Degree of adaptation $D'$
  - $L_{T_1} < L$ \(\rightarrow\) not change
  - $L < L_{T_0}$ \(\rightarrow\) 0
  - $L_{T_0} \leq L \leq L_{T_1}$ \(\rightarrow\) $D' = D(1 - 3s^2 + 2s^3)$ (11)

$$s = \frac{L - L_T + 0.1(L_{\max} - L_{\min})}{L_{T_1} - L_{T_0}}$$ (12)

Fig. 3. The degree of adaptation as the value of $s$ changes

Fig. 4. (a) Without applying a CAM (b) Using the CIECAM02 model with chromatic adaptation applied to all pixels (c) Interpolation scheme
– Environment of experiment

- Using an sRGB monitor in a room lit by fluorescent light
- Adapting luminance $L_A = 16 \text{ cd/m}^{-2}$
- $Y_b = 20$
- Surround parameter average

– Luminance reset

- Dynamic range compression in CIECAM02 model
Results

- Performance of experiments
  - A example of calibrated HDR image

Table 4. Environment parameters of the calibrated HDR image

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_A$</td>
<td>240 cd/m²</td>
</tr>
<tr>
<td>$X_Y Z_w$</td>
<td>95.45, 100.00, 129.22</td>
</tr>
<tr>
<td>Surround</td>
<td>average</td>
</tr>
<tr>
<td>$T(K)$</td>
<td>7969 K</td>
</tr>
</tbody>
</table>

Fig. 5. Separate exposures used to create the calibrated HDR image.
• Results for the calibrated HDR image

![Calibrated HDR Image](image)

Fig. 6. (a) Only tone-mapped image (b) Display white point was set to D65 (c) Display white point was set to a weighted average of D65 and F2 (d) Display white point was set to a weighted average of D65 and A

Table 5. The viewing environment parameters used for producing Images.

<table>
<thead>
<tr>
<th></th>
<th>Upper Right</th>
<th>Lower Left</th>
<th>Lower Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_A )</td>
<td>16 cd/m²</td>
<td>16 cd/m²</td>
<td>16 cd/m²</td>
</tr>
<tr>
<td>( X_w, Y_w, Z_w )</td>
<td>95.05, 100.00, 108.88</td>
<td>96.71, 100.00, 92.29</td>
<td>100.97, 100.00, 79.55</td>
</tr>
<tr>
<td>Surround</td>
<td>average</td>
<td>average</td>
<td>average</td>
</tr>
</tbody>
</table>
• Effect of changing the surround of the display environment
  – Increasing contrast and the colorfulness of the images with darkening surround
  – Contrary to Hunt effect

Fig. 7. Effect of changing the surround of the display environment. The surround is set to (a) average, (b) dim, and (c) dark.
– Demonstration of the accuracy of light source detection
  
  • Detected some small highlights as light sources
    – Excluding by using a minimum area threshold

Fig. 8. Image in (b) depicts the detected light sources in (a) as white pixels.
– The overall effect

**Fig. 9.** The overall effect
- Results created with and without proposed approach to color appearance for different tone mapping operators

**Fig. 11.** Parking garage without (a) and with our preprocessing (b) is compressed
– Using different color appearance models

Fig. 12. Using different color appearance models
– Further results

Fig. 13. Further results with and without appearance preserving reprocessing for viewing under fluorescent light.
Discussion

- **Proposed method**
  - Larger difference in illumination of the original scene and the viewing environment in HDR images than in conventional images
  - Preserving color appearance in HDR imaging by combining CAMs with tone reproduction operators
  - Decouples color appearance from tone reproduction
    - Operating as a preprocess to tone reproduction

- **Doing active research in tone reproduction**