A Relative Perceived Visual Contrast Model for High Dynamic Range Photography

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Abstract

- Proposed method
  - Relative perceived visual contrast (RPVC)
    • Assumption of RPVC
      - Equivalence of perceived visual contrast HDR and LDR
    • HDR tone mapping function
      - Compensating luminance change in HDR environment
      - HDR tone mapping function
      - Derived by experiment
  • Feature
    - Previous method incorporated
    - Efficiency HDR modeling method compared with others
Introduction

- Background knowledge of HDR
  - HDR image
    - Photo taken in extreme condition
  - Problem of photographic
    - Missing details of high light or shadow
    - Limitation of recording medium
  - Requiring tone mapping operators (TMOs)
    - Compressing dynamic range globally or locally

- Previous Method
  - Pre-visualization
    - Visualizing complex scene before reproducing
  - Retinex-based HDR image-reproduction
    - Image processing on center/surround characteristics
- Miller’s Method
  - Mapping by constant brightness ratio
- Bilateral filtering
  - Edge-preserving and smoothing filter
  - Pixel weighted by average of intensity values from nearby pixels
- Photographic operator
  - Mapping by local contrast equivalence
- Photoreceptor
  - Modeling light adaptation of human photoreceptor
- ICAM06
  - Edge-preserving filtering with human vision photoreceptor response
  - To predict viewer’s perception in real environment
  - Better performance than other model
- Other methods

**Table 1.** Sampling of prior HDR image-processing models.

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>Miller</td>
<td>Mapping by constant brightness ratio</td>
</tr>
<tr>
<td>1993</td>
<td>Tumblin—Rushmeier</td>
<td>Mapping brightness value at suprathreshold level</td>
</tr>
<tr>
<td>1993</td>
<td>Chiu</td>
<td>First spatially varying operator</td>
</tr>
<tr>
<td>1994</td>
<td>Ward</td>
<td>Matches contrast sensitivity over photopic threshold</td>
</tr>
<tr>
<td>1996</td>
<td>Ferwerda</td>
<td>Matches contrast sensitivity at scotopic visibility</td>
</tr>
<tr>
<td>1997</td>
<td>Ward—Larson</td>
<td>Histogram mapping</td>
</tr>
<tr>
<td>1998</td>
<td>Pattanaik</td>
<td>Multi-scale for threshold and suprathreshold vision</td>
</tr>
<tr>
<td>2002</td>
<td>Reinhard</td>
<td>Photographic tone mapping</td>
</tr>
<tr>
<td>2002</td>
<td>Ashikhmin</td>
<td>Mapping by local contrast equivalence</td>
</tr>
<tr>
<td>2002</td>
<td>Durand—Dorsey</td>
<td>Fast bilateral filter</td>
</tr>
<tr>
<td>2002</td>
<td>Fattal</td>
<td>Attenuating large gradient for compression</td>
</tr>
<tr>
<td>2002</td>
<td>Kotera</td>
<td>Adaptive scale-gain MSR Retinex</td>
</tr>
<tr>
<td>2002</td>
<td>Fairchild</td>
<td>iCAM image appearance</td>
</tr>
<tr>
<td>2004</td>
<td>Rahman</td>
<td>Multi-scale Retinex with color restoration (MSRCR)</td>
</tr>
<tr>
<td>2005</td>
<td>Reinhard—Devlin</td>
<td>Photoreceptor model</td>
</tr>
<tr>
<td>2007</td>
<td>Meylan</td>
<td>Retinal local adaptation of color filter array images</td>
</tr>
<tr>
<td>2007</td>
<td>Wang</td>
<td>Integrated surround Retinex</td>
</tr>
<tr>
<td>2007</td>
<td>Kuang</td>
<td>iCAM06 image appearance</td>
</tr>
<tr>
<td>2009</td>
<td>Lu</td>
<td>Full range contrast perception model</td>
</tr>
<tr>
<td>2009</td>
<td>Shyu</td>
<td>Perceived visual contrast mapping locally</td>
</tr>
</tbody>
</table>
New color appearance model advent

- CIELAB and CIELUV
  - Experimental data from solid color patches
  - Attempt to human perceptual
  - Measuring perceptual color difference
- CIECAM97 and CIECAM02
  - Explaining human perception under different lighting condition
- S-CIELAB
  - Spatial filtering with CIELAB
- iCAM and iCAM06
  - Assuming human visual system to low-pass filter
  - HDR image reproduction with color appearance feature from CIE
- Developing tone mapping function
- Used to reproduce HDR image to LDR image
Contrast attribute

Various definition

- Tone reproduction
  - “The rate of change of relative luminance of image elements of a reproduction as a function of the relative luminance of the same image elements of the original image”

- Visual science
  - “The difference between minimum and maximum luminance in an image”

- General form of contrast measurement in math
  - Known as Michelson contrast
    \[
    C_m = \frac{(L_{\text{max}} - L_{\text{min}})}{(L_{\text{max}} + L_{\text{min}})}
    \]
    where $L_{\text{max}}$ is maximum luminance value, $L_{\text{min}}$ is minimum luminance value.
Research on contrast

- Calabria and Fairchild
  - Preferred perceived image contrast
    - Existence of certain relation between physical and perceived
- Stevens
  - Experiment on various luminance level
    - Perceived contrast increase with increasing luminance level
- Wandell
  - Defining image contrast
    - Ratio of local intensity and average image intensity
- Burhardt et al
  - Revealing relation between physical and perceived visual contrast
- Fechner
  - Proportional relation between perceived magnitude of stimulus and logarithm of physical stimulus intensity
− General form of physical contrast and perceived visual contrast model

\[ PVC = offset + scalar \times \log(PC) \]  
where PVC is Perceived visual contrast, 
PC is Physical contrast.

− Experiment data
  
  • Perceived contrast measurement

**Table 2.** Estimated data points (normalized to between 0 and 1) sampled from perceived contrast curves in Burkhardt at five levels of background luminance.
• Result from Table 2.

**Fig 1.** Fitting results from Burkhardt’s data points to reveal the estimated relationship between luminance (physical) contrast and perceived visual contrast.
Modeling offset and scalar based on Steves effort

Predicted offset = 0.6850 + 0.07879*Log(Luminance)  \hspace{1cm} (3)
Predicted scalar= 0.5476 + 0.08178*Log(Luminance)  \hspace{1cm} (4)

Table 3. Regression result between physical contrast and relative perceived visual contrast at different levels of background luminance in the form of Eq.(2).

<table>
<thead>
<tr>
<th>Background Luminance (cd/m²)</th>
<th>Offset</th>
<th>Scalar</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.017</td>
<td>0.5658</td>
<td>0.4234</td>
<td>0.994</td>
</tr>
<tr>
<td>0.17</td>
<td>0.6059</td>
<td>0.4657</td>
<td>0.998</td>
</tr>
<tr>
<td>1.55</td>
<td>0.6885</td>
<td>0.5521</td>
<td>0.983</td>
</tr>
<tr>
<td>17.00</td>
<td>0.7797</td>
<td>0.6460</td>
<td>0.960</td>
</tr>
<tr>
<td>200.00</td>
<td>0.8778</td>
<td>0.7472</td>
<td>0.931</td>
</tr>
</tbody>
</table>
Perceived visual contrast combined with two parameters

\[ \text{PVC} = (0.6850 + 0.07879 \times \text{Log}(L_B)) + (0.5476 + 0.08178 \times \text{Log}(L_B)) \times \text{Log}(\text{PC}), \]  

where PVC is magnitude of perceived visual contrast,

- PC is absolute value of physical contrast defined by Burkhardt,

- \( L_B \) is background luminance.

- Mathematical expression of PC defined by Burkhardt

\[ \text{PC} = \frac{(L_{\text{max}} - L_{\text{min}})}{(L_{\text{max}} + L_{\text{min}})} \]  

where \( L_{\text{max}} \) is maximum luminance value,

- \( L_{\text{min}} \) is minimum luminance value.

» Case of incremental bars Eq.(4) become

\[ \text{PC}(x, y) = \frac{(S_C(x, y) - S_B(x, y))}{(S_C(x, y) + S_B(x, y))} \]  

where \( S_C \) is center stimulus,

- \( S_B \) is background luminance.
Proposed method

- Relative perceived visual contrast (RPVC)
  - Tone mapping function extended from Burkhard’s dataset
  - Making PVC as closing to real-life situation

\[
\text{RPVC}(x, y) = (0.6850 + 0.07879 * \log(L_B(x, y)))
\]

\[
+ (0.5476 + 0.08178 * \log(L_B(x, y))) * \log\left(\frac{L_{\max}(x, y) - L_{\min}(x, y)}{L_{\max}(x, y) + L_{\min}(x, y)}\right)
\]

\[- 0.1577\]

where \(L_B\) is adapting background luminance,
\(L_{\max}\) is central luminance,
\(L_{\min}\) is background luminance,
RPVC function with various luminance

**Fig 2.** Estimated relative perceived visual contrast curves (versus physical contrast) for luminance levels range from 0.001 cd/m² (nits) to 1,000,000 cd/m².
HDR Image Reproduction with RPVC Mapping Function

- Reproducing HDR scene to LDR image
  - Research to preserve human’s visual experience
    - Hurlbert and Wolf
      - Constancy of cone Contrast
        » Approximately equal appearance achieved by equal cone contrast
        » Relation between target surface and its background area
    - Chichilnisky and wandell
      - Adjustment role
        » Equal appearance at different dissimilar background luminance level
        » Due to adapting background luminance level
  - Conclusion of research
    - Function existence that equivalence of perceived visual HDR and LDR
Function of RPVC

- Assumption

\[
\text{RPVC}_{\text{HDR}}(L_B(x, y), S_B(x, y), S_C(x, y)) = \text{RPVC}_{\text{LDR}}(L'_B(x, y), S'_B(x, y), S'_C(x, y))
\]

where \( S_C(x, y) \) is central stimulus of HDR original,
\( S_B(x, y) \) is background stimulus of HDR original,
\( L_B \) is adapting local background luminance of HDR original,
\( S'_B(x, y) \) is background stimulus of LDR original,
\( L'_B(x, y) \) is adapting local background luminance of LDR original,
\( S'_C(x, y) \) is reproduced image on LDR medium.
– Flow chart of proposed method

**Fig 3.** Flowchart of the proposed RPVC HDR processing method
All processing of RPVC

- Reading image
  - Input and convert HDR file to XYZ
- Estimate input range
  - Applying logarithmic to establish reference scene image
  - Histogram analysis to locate maximum and minimum bound
- Computing local contrast parameters for HDR
  - Transforming image into LMS space to generate central stimulus ($S_C$)
    \[
    \begin{bmatrix}
    L \\
    M \\
    S
    \end{bmatrix}
    =
    \begin{bmatrix}
    0.4002 & 0.7076 & -0.0808 \\
    -0.2280 & 1.1500 & 0.0612 \\
    0.0000 & 0.0000 & 0.9184
    \end{bmatrix}
    \begin{bmatrix}
    X \\
    Y \\
    Z
    \end{bmatrix}
    \]
  - Using bilateral-type filter to generate local background stimulus ($S_B$)
– Computing HDR adaptation level
  • Using $S_B$ to calculate adapting background luminance ($L_B$)
– Performing global tone mapping
  • Linear mapping method to calculate scaling factor

$$sf = \frac{\log_{10}(Y_{D_{\text{max}}}) - \log_{10}(Y_{D_{\text{min}}})}{\log_{10}(Y_{S_{\text{max}}}) - \log_{10}(Y_{S_{\text{min}}})}$$

where $sf$ is scaling factor,
$Y_S$ is luminance range of scene,
$Y_D$ is luminance range of display medium.

• Global tone compression to generate projected medium value

$$\log_{10}(XYZ_{d}) = (\log_{10}(XYZ_{s}) - \log_{10}(XYZ_{s_{\text{max}}})) \times sf$$
$$+ \log_{10}(XYZ_{d_{\text{max}}})$$
– Computing LDR parameters
  • Transform projected medium value back to 10 base value to generate projected adapting background luminance value($L'_B$)
  • Transforming projected medium value from XYZ back to LMS
  • Using bilateral-type filter to generate background stimulus value($S'_B$)
– Performing RPVC mapping
  • Using RPVC equation to calculate central stimulus($S'_C$) of reproduced LDR image
    - Using pre-calculated value
      » Background stimulus of scene ($S_B$)
      » Central stimulus of scene($S_C$)
      » Adapting background luminance of scene($L_B$)
      » Projected adapting background luminance on reproduction medium($L'_B$)
      » Projected background stimulus on the reproduction medium($S'_B$)
  • Calculating ($S'_C$) of LDR image in LMS space for every pixel
− Adjusting for environment factors
  • Compensation surround luminance by averaged luminance of whole image in IPT space
    − Using Gamma value
      » 1.2 for dark condition
      » 1.1 for dim condition
      » 1.0 for lighting condition

− Output image
  • Converting IPT to LMS and to XYZ space
  • LDR image reproduced to device dependent output medium
Experiment Design

- Performance of RPVC verification
  - Setting room for experiment

Fig 4. The lighting configuration used in the first experiment. The cool-white fluorescent light set on the left provides much higher illumination than the one the far right (not seen) to generate HDR condition.
- Making source image

(a) Over-exposure (1.3s f8.0)  (b) Normal exposure (1/3s f8.0)  (c) Under exposure (1/12s f8.0)

**Fig 5.** The original image: (1) over-exposure, (2) normal exposure, (3) under-exposure
– Setting room for HDR environment

Fig 6. The viewing environment for the paired comparison between the real HDR scene and the reproduced LDR images. (The room light was turned on here for illustration.) The observer can turn 90° to view each side back and forth.
– Other HDR model use to confirm RPVC performance

Table 4. List of the HDR models used in the first experiment.

<table>
<thead>
<tr>
<th>Model no.</th>
<th>HDR model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Local contrast</td>
<td>Ashikhmin\textsuperscript{25}</td>
</tr>
<tr>
<td>2</td>
<td>Bilateral filtering</td>
<td>Durand–Dorsey\textsuperscript{26}</td>
</tr>
<tr>
<td>3</td>
<td>Photographic operator</td>
<td>Reinhard\textsuperscript{24}</td>
</tr>
<tr>
<td>4</td>
<td>Photoreceptor</td>
<td>Reinhard–Devlin\textsuperscript{28}</td>
</tr>
<tr>
<td>5</td>
<td>Retinex (Rahman)</td>
<td>Rahman\textsuperscript{8}</td>
</tr>
<tr>
<td>6</td>
<td>iCAM06</td>
<td>Fairchild,\textsuperscript{12,13} Kuang\textsuperscript{14}</td>
</tr>
<tr>
<td>7</td>
<td>RPVC</td>
<td>This article</td>
</tr>
</tbody>
</table>
– HDR image reproducing

Fig 7. The Seven HDR images reproduced in the first experiment.
Result and Analysis

- Result on first experiment
  - Z-score with real-scene

Table 5. List of Z-scores for all three rounds of real-scene tests.

<table>
<thead>
<tr>
<th>No.</th>
<th>HDR model</th>
<th>Overall</th>
<th>Bright area</th>
<th>Dark area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Local contrast</td>
<td>0.63</td>
<td>0.76</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>Bilateral filtering</td>
<td>-1.37</td>
<td>-1.31</td>
<td>-0.7</td>
</tr>
<tr>
<td>3</td>
<td>Photographic operator</td>
<td>-1.97</td>
<td>-1.85</td>
<td>-1.31</td>
</tr>
<tr>
<td>4</td>
<td>Photoreceptor</td>
<td>-0.59</td>
<td>-0.75</td>
<td>-0.06</td>
</tr>
<tr>
<td>5</td>
<td>Retinex (Rahman)</td>
<td>-0.07</td>
<td>0.03</td>
<td>-0.47</td>
</tr>
<tr>
<td>6</td>
<td>iCAM06</td>
<td>1.85</td>
<td>1.86</td>
<td>1.01</td>
</tr>
<tr>
<td>7</td>
<td>RPVC</td>
<td>1.52</td>
<td>1.25</td>
<td>1.23</td>
</tr>
</tbody>
</table>
Result of overall scene reproduction comparison

**Fig 8.** Result of the comparison for the overall reproduction in Z-score: 1. local contrast, 2. bilateral filtering, 3. photographic operator, 4. photoreceptor, 5. Rahman Retinex, 6. iCAM06, 7. RPVC
Result of bright region reproduction comparison

Fig 9. Result of the comparison for bright region reproduction in Z-score: 1. local contrast, 2. bilateral filtering, 3. photographic operator, 4. photoreceptor, 5. Rahman Retinex, 6. iCAM06, 7. RPVC
Result of dark region reproduction comparison

**Fig 10.** Result of the comparison for the dark region reproduction in Z-score: 1. local contrast, 2. bilateral filtering, 3. photographic operator, 4. photoreceptor, 5. Rahman Retinex, 6. iCAM06, 7. RPVC
Experiment compared with iCAM06 in various HDR scene
- Foggy-night HDR scene

Fig 11. A foggy-night HDR scene processed by (a) iCAM06 and (b) the RPVC model. It is important to see that there is no halo problem on the brightest spot. (Radiance data courtesy Jack Tumblin, Northwestern University)
Night HDR scene

(a) iCAM06 (gamma 1.2)  (b) RPVC

**Fig 12.** A typical night street HDR scene (Frontier) processed by (a) iCAM06 and (b) the RPVC model. It is important to note the similar hue on the neon signs for both outputs. (Original image from Mark Fairchild’s HDR Photographic Survey.)
– Dawn HDR scene

Fig 13. A typical dawn HDR scene processed by (a) iCAM06 and (b) the RPVC model. The main point is the distribution of the tone has to be realistic.
Morning HDR scene

Fig 14. An early morning HDR scene processed by (a) iCAM06 and (b) the RPVC model. It is before sunrise; therefore the contrast is low.
– Sunrise HDR scene

(a) iCAM06 (gamma 1.1) (b) RPVC

**Fig 15.** A typically sunrise HDR scene processed by (a) iCAM06 and (b) the RPVC model. If the contrast were too high, it would appear too shape as well.
Daylight HDR scene

Fig 16. A daylight HDR scene processed by (a) iCAM06 and (b) the RPVC model. The white balance shall be kept on the white wall.
Outdoor HDR scene

Fig 17. A typically outdoor HDR scene (Peak Lake) processed by (a) iCAM06 and (b) the RPVC model. It is important to see a sooth gradient on the white clouds. (Original image from Mark Fairchild’s HDR Photographic survey).
– Panoramic HDR scene

Fig 18. A panoramic view taken at noon. HDR scene processed by (a) iCAM06 and (b) the RPVC model. The lighting in this scene is very extreme. (Original photos courtesy Wen-Pin Chang, Splendid Studio Co., Ltd.)
Afternoon indoor HDR scene

(a) iCAM06 (gamma 1.0)  (b) RPVC

**Fig 19.** A typical afternoon indoor HDR scene processed by (a) iCAM06 and (b) the RPVC model. The main difference is that the sky should be kept white.
– Sunshine after rain HDR scene

Fig 20. Sunshine after rain. HDR scene processed by (a) iCAM06 and (b) the RPVC model. This is a very difficult lighting situation for regular photography. However, both models perform very well.
Sunset HDR scene

(a) iCAM06 (gamma 1.1)
(b) RPVC

**Fig 21.** A sunset HDR scene processed by (a) iCAM06 and (b) the RPVC model. The gradation of sky is well kept.
Indoor HDR scene

Fig 22. A indoor scene processed by (a) iCAM06 and (b) the RPVC model. This image (memorial_hires) is the most essential test image to show the general characteristics.
- Summery of test

**Table 6.** List of process times (in seconds) by iCAM06 and by the RPVC model, as well as by the RPVC model with iCAM06’s optimized bilateral filter, and by the RPVC model in optimized C code with parallel processing in experiment 2.

<table>
<thead>
<tr>
<th>Test image</th>
<th>Image size (Pixels)</th>
<th>By iCAM06’s MATLAB code</th>
<th>By the RPVC with a regular bilateral filter in MATLAB</th>
<th>By the RPVC with iCAM06’s optimized bilateral filter in MATLAB</th>
<th>By the RPVC in optimized Visual C code with parallel processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 11</td>
<td>376 × 556</td>
<td>4.1</td>
<td>27.0</td>
<td>4.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Fig. 12</td>
<td>1510 × 1003</td>
<td>30.6</td>
<td>185.4</td>
<td>39.2</td>
<td>10.3</td>
</tr>
<tr>
<td>Fig. 13</td>
<td>531 × 799</td>
<td>7.0</td>
<td>52.7</td>
<td>8.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Fig. 14</td>
<td>1510 × 1005</td>
<td>23.4</td>
<td>186.6</td>
<td>30.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Fig. 15</td>
<td>1511 × 1007</td>
<td>21.4</td>
<td>186.0</td>
<td>26.8</td>
<td>10.2</td>
</tr>
<tr>
<td>Fig. 16</td>
<td>530 × 797</td>
<td>7.1</td>
<td>53.5</td>
<td>9.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Fig. 17</td>
<td>697 × 443</td>
<td>14.3</td>
<td>45.4</td>
<td>15.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Fig. 18</td>
<td>1510 × 306</td>
<td>7.3</td>
<td>62.4</td>
<td>8.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Fig. 19</td>
<td>1510 × 1005</td>
<td>24.5</td>
<td>183.8</td>
<td>30.7</td>
<td>10.1</td>
</tr>
<tr>
<td>Fig. 20</td>
<td>1510 × 1006</td>
<td>24.2</td>
<td>185.8</td>
<td>31.8</td>
<td>10.2</td>
</tr>
<tr>
<td>Fig. 21</td>
<td>1510 × 1007</td>
<td>21.4</td>
<td>185.2</td>
<td>29.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Fig. 22</td>
<td>512 × 768</td>
<td>6.3</td>
<td>49.3</td>
<td>7.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Conclusion

- Proposed method
  - Based on perceived visual contrast increasing while adapting background luminance increased.
  - Bilateral filter and density domain linear mapping incorporated.
  - Competitive result with iCAM06
  - Feasible and as effective as iCAM06 in handling HDR image