A visibility matching tone reproduction operator for high dynamic range scenes

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Flow chart

Histogram of brightness, Cumulative distribution function

Histogram equalization

Linear ceiling on the contrast

Human contrast sensitivity

Glare, Color sensitivity, Spatial acuity
Abstract

◆ Presenting tone reproduction operator
  – Using a histogram adjustment technique
  – Based on the population of local adaptation luminance in the scene
  – Incorporating several models
    • Human contrast sensitivity
    • Glare
    • Spatial acuity
    • Color sensitivity
Introduction

◆ Tone mapping
  – The conversion from real-world to display luminance
◆ Important criteria for reliable tone mapping
  – Reproduction of visibility
  – Reproduction of impression for brightness, contrast, and color
false color image (window office)

Fig. 1. A false color image showing the world luminance values for a window office in candelas per meter squared.
Overexposed and underexposed image

Fig. 2. A linear mapping of the luminances in Fig. 1 that overexposes the view through the window.

Fig. 3. A linear mapping of the luminances in Fig. 1 that underexposes the view of the interior.
Using new tone mapping technique

Fig. 4. The luminances in Fig. 1 mapped to preserve the visibility of both indoor and outdoor features using the new tone-mapping techniques described in this paper.
Bright source with a dark halo

![Dynamic range compression based on a spatially varying scale factor.](image)

Fig. 5. Dynamic range compression based on a spatially varying scale factor.
Overview of the new method

◆ Starting point
  – Using histogram and cumulative distribution function
    • Closing the gaps of sparsely populated luminance values
    • Avoiding the clipping problems
- Brightness histogram of window office

**Fig. 6.** A histogram of adaptation values form Fig. 1.
Maintaining subjective visibility

- Simulation of glare, spatial acuity, and color sensitivity
Fig. 7. A plot comparing the global brightness mapping functions for Figs. 2, 3, and 4, respectively.
Histogram adjustment

Symbol and definitions

\[ L_w = \text{world luminance (in cd/m}^2\text{)} \]
\[ B_w = \text{world brightness, } \log(L_w) \]
\[ L_{\text{wmin}} = \text{minimum world luminance for scene} \]
\[ L_{\text{wmax}} = \text{maximum world luminance for scene} \]
\[ L_d = \text{display luminance (in cd/m}^2\text{)} \]
\[ L_{\text{dmin}} = \text{minimum display luminance (black level)} \]
\[ L_{\text{dmax}} = \text{maximum display luminance (white level)} \]
\[ B_{de} = \text{computed display brightness, } \log(L_d) \]
\[ N = \text{the number of histogram bins} \]
\[ T = \text{the total number of adaptation samples} \]
\[ f(b_i) = \text{frequency count for the histogram bin at } b_i \]
\[ \Delta b = \text{the bin step size in } \log(\text{cd/m}^2) \]
\[ P(b) = \text{the cumulative distribution function} \]
\[ \log(x) = \text{natural logarithm of } x \]
\[ \log10(x) = \text{decimal logarithm of } x \]
Histogram calculation

- Correcting resolution for 1° diameter pixels

\[ S = \frac{2 \tan(\theta/2)}{0.01745} \]

\[ S = \text{width or height in pixels} \]
\[ \theta = \text{horizontal or vertical full view angle} \]
\[ 0.01745 = \text{number of radians in 1°} \]
• Cumulative distribution
  – Cumulative frequency distribution

\[
P(b) = \frac{\sum_{b_i \leq b} f(b_i)}{T}, \quad T = \sum_{b_i} f(b_i)
\]  

(2)

– Derivative of the function

\[
\frac{dP(b)}{db} = \frac{f(b)}{T \Delta b}, \quad \Delta b = \frac{[\log(L_{\text{wmax}}) - \log(L_{\text{wmin}})]}{N}
\]  

(3)
Navie histogram equalization

- Equalization formula in terms of brightness

\[ B_{de} = \log(L_{dmin}) + [\log(L_{dmax}) - \log(L_{dmin})] \cdot P(B_w) \quad (4) \]
– Applying the naive histogram equalization

**Fig. 8.** Rendering of a bathroom model mapped with a linear operator.

**Fig. 9.** Naive histogram equalization allows us to see the area around the light source, but contrast is exaggerated in other areas, such as the shower tiles.
Histogram adjustment with a linear ceiling

- Linear ceiling on the contrast produced by tone mapping operator

\[
\frac{dL_d}{dL_w} \leq \frac{L_d}{L_w} \quad (5a)
\]

\[
\exp(b_{de}) \cdot \frac{f(B_w)}{T\Delta b} \cdot \log(L_{dmax}) - \log(L_{dmin}) \leq \frac{L_d}{L_w} \quad (5b)
\]

\[
f(b) \leq \frac{T\Delta b}{\log(L_{dmax}) - \log(L_{dmin})} \quad , \quad L_d = \exp(b_{de}) \quad (5c)
\]

\[
f(b_i) \leq \frac{T}{N} \cdot \frac{[\log(L_{wmax}) - \log(L_{wmin})]}{[\log(L_{dmax}) - \log(L_{dmin})]} \quad (5d)
\]
– Result of our histogram adjustment algorithm with linear ceiling

Fig. 10. Histogram adjustment with a linear ceiling on contrast preserves both lamp visibility and tile appearance.
– Comparison of brightness mapping functions

Fig. 11. A comparison of naive histogram equalization with histogram adjustment. The linear mapping of brightness is also shown.
Histogram adjustment based on human contrast sensitivity

- Contrast sensitivity

\[ \Delta L_t(L_a) = \text{"just noticeable difference"} \]

for adaptation level \( L_a \)

(6)

Table 1. Piecewise approximation for \( \Delta L_t(L_a) \)

<table>
<thead>
<tr>
<th>log10 of just noticeable difference</th>
<th>applicable luminance range</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.86</td>
<td>( \log10(L_a) &lt; -3.94 )</td>
</tr>
<tr>
<td>((0.405 \log10(L_a) + 1.6)^{2.18} - 2.86 )</td>
<td>(-3.94 \leq \log10(L_a) &lt; -1.44 )</td>
</tr>
<tr>
<td>( \log10(L_a) - 0.395 )</td>
<td>(-1.44 \leq \log10(L_a) &lt; -0.0184 )</td>
</tr>
<tr>
<td>((0.249 \log10(L_a) + 0.65)^{2.7} - 0.72 )</td>
<td>(-0.0184 \leq \log10(L_a) &lt; 1.9 )</td>
</tr>
<tr>
<td>( \log10(L_a) - 1.255 )</td>
<td>( \log10(L_a) \geq 1.9 )</td>
</tr>
</tbody>
</table>
– New ceiling

\[ \frac{dL_d}{dL_w} \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)} \]  \hspace{1cm} (7a)

\[ \exp(B_{dc}) \cdot f(B_w) \cdot \frac{\log(L_{dmax}) - \log(L_{dmin})}{L_w} \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)} \]  \hspace{1cm} (7b)

\[ f(B_w) \leq \frac{\Delta L_t(L_d)}{\Delta L_t(L_w)} \cdot \frac{T \Delta b L_w}{[\log(L_{dmax}) - \log(L_{dmin})] L_d} \]  \hspace{1cm} (7c)

\[ L_d = \exp(B_{dc}), \ B_{dc} \ \text{given in (4)} \]
– Comparison of brightness mapping functions

**Fig. 12.** Our tone-mapping operator based on human contrast sensitivity, compared to the histogram adjustment with linear ceiling used in Fig. 10. Human contrast sensitivity makes little difference at these light level. The simple linear mapping is also shown here.
– Brightness mapping functions of dimmed bathroom scene

Fig. 13. The brightness map for the bathroom scene with lights dimmed to 1/100\textsuperscript{th} of their original intensity, where human contrast sensitivity makes a difference. This difference is evident in the comparison of the linear map and the human contrast sensitivity map. Again, the simple linear mapping is shown as a solid line for reference.
– Dimmed bathroom scene

Fig. 14. The dimmed bathroom scene mapped with the function shown in Fig. 13.
Human visual limitations

- Veiling luminance
  - Glare formula

\[
L_a = 0.913L_f + \frac{k}{\pi} \int_{\theta > \theta_f} \int \frac{L(\theta, \phi)}{\theta^2} \cos(\theta) \sin(\theta) d\theta d\phi
\]

- \(L_a\) = corrected adaptation luminance (in \(\text{cd/m}^2\))
- \(L_f\) = the average foveal luminance (in \(\text{cd/m}^2\))
- \(L(\theta, \phi)\) = the luminance in the direction \((\theta, \phi)\)
- \(\theta_f\) = foveal half angle, approx. 0.00873 radians (0.5°)
- \(K\) = constant measured by Holladay, 0.0096
– To compute the veiling luminance

\[
L_{vi} = 0.087 \cdot \frac{\sum_{j \neq i} L_j \cos(\theta_{i,j})}{\sum_{j \neq i} \cos(\theta_{i,j})} \cdot \frac{\theta_{i,j}^2}{\theta_{i,j}^2}
\]

(9)

\[
L_{vi} = \text{veiling luminance for fixation point } i
\]
\[
L_j = \text{foveal luminance for fixation point } j
\]
\[
\theta_{i,j} = \text{angle between sample } i \text{ and } j \text{ (in radian)}
\]

\[
\frac{\cos \theta}{\theta^2} \approx \frac{\cos \theta}{2 - 2 \cos \theta}
\]

(10)
– Adding the computed veil map to the original image

\[ L_{pvk} = 0.913L_{pk} + L_v(k) \]

\( L_{pvk} \) = veiled pixel at image position \( k \)
\( L_{pk} \) = original pixel at image position \( k \)
\( L_v(k) \) = interpolated veiling luminance at \( k \)
– Result of adding the computed veiling luminance

Fig. 15. Our tone reproduction operator for the original bathroom scene with veiling luminance added.
– Applying it before the histogram generation and adjustment

\[ L_{ai} = 0.913L_i + L_{vi} \]

\[ L_{ai} = \text{adjusted adaptation luminance at fixation point } i \]

\[ L_i = \text{foveal luminance for fixation point } i \]
Color sensitivity

- Scotopic luminance at each pixel

\[ Y_{s\cot} \approx Y \cdot \left[ 1.33 \cdot \left( 1 + \frac{Y+Z}{X} \right) - 1.68 \right] \]

\[ Y_{s\cot} = \text{scotopic luminance} \]
\[ X, Y, Z = \text{photopic color, CIE 2° observer} \]

- Obtaining mesopic color response
  - Using simple interpolation

![Luminance Range Diagram](Image)
– Result of adding the color sensitivity

Fig. 16. Our dimmed bathroom scene with tone mapping using human contrast sensitivity, veiling luminance, and mesopic color response.
Visual acuity

– Human visual acuity function

\[ R(L_a) \approx 17.25 \arctan(1.4 \log_{10}(L_a) + 0.35) + 25.72 \]

\[ R(L_a) = \text{visual acuity in cycles/degree} \]

\[ L_a = \text{local adaptation luminance (in cd/m}^2) \quad (14) \]

![Human Visual Acuity Function (Foveal) due to Shaler](image)

Fig. 17. Shaler’s visual acuity data and our functional fit to it.
– Dimmed bathroom scene with variable acuity adjustment

**Fig. 18.** The dim bathroom scene with variable acuity adjustment. The insets show two areas, one light and one dark, and the relative blurring of the two.
Results

◆ Lighting simulation

Fig. 19. A simulation of a shipboard control panel under emergency lighting.
Fig. 20. A simulation of an air traffic control console.
Fig. 21. A Christmas tree with very small light sources.
Electronic photography

Fig. 22. A scanned photograph of Memorial Church.

Fig. 23. Histogram adjusted radiance map of Memorial Church.
Conclusions

◆ To match human visibility
  – Using histogram adjustment technique based on contrast sensitivity
  – Considering human visual models
    • Glare
    • Color sensitivity
    • Spatial acuity