Model of Retinal Local Adaptation for Tone Mapping of Color Filter Array Images

*Journal of Optical Society of America A*
vol. 24, no. 9, 2007
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Abstract

◆ Tone mapping algorithm
  – Use of the model of retinal processing
  – Two major improvements
    • Applying the mosaic image captured by the sensor
      – Applying a nonlinearity to the chromatic responses captured by the cone mosaic
    • Variation of the center/surround class of local tone mapping algorithms
      – Avoiding halos and maintaining good global appearance
      – The weighted average serves as a variable in the Naka-Rushton equation
Introduction

◆ Proposed workflow
  – Performance of color rendering operations on the CFA image
    • Consideration of the tone mapping operation of color rendering
    • Demosaicing is the last step of the color processing workflow
  – Motivations
    • Similarity of the retinal processing of the human visual system (HVS)
      – No loss of information prior to rendering
– Comparison of workflows between traditional image processing workflow and proposed workflow

Fig. 2. (a) Traditional image processing workflow. (b) Our proposed workflow.
Inspiration from the nonlinear adaptation

- Occurrence in the retina
  - Efficient improvement of local contrasts while conserving good global appearance

- Example of applying proposed method
  - Containing high contrast and important image details in dark and bright areas

Fig. 2. (c) Image rendered with a global tone mapping operator (gamma). (d) Image rendered according to our method.
◆ Application of proposed algorithm
  – Various kinds of captured scenes having different dynamic ranges and different keys
    • Definition of dynamic range
      – Luminance ratio of the brightest and darkest object in the scene
    • Definition of high and low keys
      – Higher-than-average and lower-than-average intensity in images
  – Results
    • Improvement image appearance in all cases without creating artifacts
Background

◆ The purpose
  – Correspondence of proposed tone mapping algorithm with simplified model of retinal processing
    • Consideration of the sampling of chromatic information by the cone mosaic and the nonlinearity
    • Concentration of one specific nonlinear processing model proposed by Naka and Rushton
  – Properties of the CFA images
  – Review of general tone mapping operation
    • Center/surround family of local tone mapping algorithms
Model of retinal processing

- Correspondence between the HVS and a color image
  - Trichromacy and the three color channels
  - Spatiochromatic sampling of the cone mosaic and the sampling of color in the Bayer CFA

Fig. 1. (Color online) Bayer CFA (left) and the spatiochromatic sampling of the cone mosaic (right) (Inspired from Roorda et al.).
– Another analogy with HVS

• Tone mapping operations in the image processing workflow and the **nonlinear adaptation** taking place in the retina

**Fig. 3.** Simplified model of the retina.
– Proposed tone mapping algorithm
  
  • Application of two nonlinear processings on the CFA image in imitation of the IPL and OPL functionalities
    – Nonlinear operations by Naka and Rushton
      » Model for the photoreceptor nonlinearities and adaptation to incoming light
  
  • Nonlinear mosaic image
    – Demosaicing to reconstruct the RGB tone mapped image
Adaptive nonlinearity

- Model of the OPL and IPL nonlinearities from Naka-Rushton equation

\[ Y = \frac{X}{X + X_0} \]  \hspace{1cm} (1)

where \( X \) is the input light intensity,
\( X_0 \) is the adaptation factor, and
\( Y \) is the adapted signal.

- Determination of the adaptive factor \( X_0 \) for each pixel
  - Average light intensity in the neighborhood of one pixel
• Naka-Rushton function for different values of $X_0$
  – If $X_0$ is small, the cell output has increased sensitivity
  – If $X_0$ is large, there is not much change in sensitivity
• Using the Naka-Rushton equation in proposed model
  – Calculation of the nonlinearities of both the OPL and IPL
    » $X_0$ is given by the output of the horizontal cells or amacrine cells

![Naka–Rushton function with different adaptation factors $X_0$.](image)

Fig. 4. Naka–Rushton function with different adaptation factors $X_0$. 
◆ Properties of a CFA image

– Application of the two nonlinearities to the CFA image
  • Use of the separated CFA image
    – The luminance and the chrominance of the image
    – Using only the luminance for the nonlinearities

– Amplitude Fourier spectrum of a Bayer CFA image
  • Luminance is located in the center of the spectrum
  • Chrominance is located at the borders

– For efficient demosaicing algorithm
  • Choosing the appropriate filters
    – Wide-band low-pass filter to recover the luminance
    – High-pass or bandpass filter to recover the downsampled chrominance
◆ Tone mapping
  – Matching scene to display luminance
    • Depending on the dynamic range of the display
  – Classification of tone mapping algorithms
    • Global (spatially invariant) tone mapping
      – Mapping the input pixel value to a display value
      – Logarithm, gamma, and sigmoid
    • Local (spatially variant) tone mapping
      – Lead of one input pixel value to different output values depending on the pixel’s surround
      – Increasing the local contrast to improve detail visibility
      – Center/surround, using gradient values, frequency-based methods
Center/surround methods

- Traditional center/surround algorithms
  
  • Difference in the log domain between each pixel value and a weighted average of the pixel values in its surround

\[
I'(p) = \log(I(p)) - \log(I(p) * G)
\]  

where \( p \) is a pixel in the image, 
\( I \) is the treated image, 
\( * \) is convolution operation, and 
\( G \) is a low-pass filter (often a Gaussian).

• A common drawback
  
  - Increase in local contrast depends on the size of the filter
    
    » Use of small filter: Appearing the halo artifacts on shadows along high-contrast edge
    
    » Use of large filter: Increase in local contrast is not sufficient to retrieve detail visibility in dark or bright areas
– Tendency to gray out low-contrast areas
  • Multi-scale method
    – Overcoming the drawback on the traditional center/surround method

– Advantage of the proposed algorithm
  • Providing the artifact-free reproduction for all kinds of scenes
Local tone mapping algorithm for CFA Images

◆ Tone mapping method
  – Process of images according to the retinal model
    • Application to the CFA image
    • Demosaicing is applied last in order to obtain a color image

◆ First nonlinearity
  – Adaptive nonlinearity of the OPL
    • Correspondence to the horizontal cell responses
    • Computation for each pixel by performing a low-pass filter on the input CFA image
– Calculation of the adaptation factor

\[ H(p) = I_{CFA}(p) \ast G_H + \frac{I_{CFA}}{2} \]  \hspace{1cm} (3)

where \( p \) is a pixel in the image,
\( H(p) \) is the adaptation factor at pixel \( p \),
\( I_{CFA} \) is the intensity of the mosaic input image, normalized between \([0,1]\)
* is convolution operation, and
\( G_H \) is a low-pass filter

\( G_H \)

– Model of the transfer function of the horizontal cells

\[ G_H(x, y) = e^{-[(x^2+y^2)/2\sigma_H^2]} \]  \hspace{1cm} (4)

where \( x \in [-4\sigma_H, 4\sigma_H] \) and \( y \in [-4\sigma_H, 4\sigma_H] \)
– Calculation of the responses of the bipolar cells network

• Use of the adaptation factors given by $H$

$$I_{bip}(p) = (I_{CFA}(\text{max}) + H(p)) + \frac{I_{CFA}(P)}{I_{CFA}(p) + H(p)}$$  \hspace{1cm} (5)

Fig. 5. Simulation of the OPL adaptive nonlinear processing. The input signal is processed by the Naka–Rushton equation, whose adaptation factors are given by filtering the CFA image with a low-pass filter.
◆ Second nonlinearity

– Application of the model of the behavior of the IPL
  • Calculation of the tone mapped image $I_{ga}$
    \[
    I_{ga}(p) = (I_{bip}(\text{max}) + A(p)) + \frac{I_{bip}(P)}{I_{bip}(p) + A(p)}
    \] (6)
  • $A(p)$
    – Output of the amacrine cells
    – Low-pass version of the image intensities at the bipolar cells level
    \[
    A(p) = I_{bip}(p) \ast G_A + \frac{I_{bip}}{2}
    \] (7)
    \[
    G_A(x, y) = e^{-[(x^2+y^2)/2\sigma_A^2]}
    \] (8)

where $x \in [-4\sigma_H, 4\sigma_H]$ and $y \in [-4\sigma_H, 4\sigma_H]$
Demosaicing

– Use of the demosaicing algorithm by Alleysson

• Estimation of the luminance image using a wide-band low-pass filter

\[
F_{\text{dem}} = \frac{1}{256} \begin{bmatrix}
1 & 4 & 6 & 4 & 1 \\
4 & 16 & 24 & 16 & 4 \\
6 & 24 & 36 & 24 & 6 \\
4 & 16 & 24 & 16 & 4 \\
1 & 4 & 6 & 4 & 1
\end{bmatrix}
\] (9)

Then

\[
L(p) = I_{ga}(p) * F_{\text{dem}}
\] (10)

where \(L\) is the nonlinearly encoded luminance (called “lightness”).
• Estimation of the chrominance by subtracting $L$ from the mosaiced image $I_{ga}$

$$C(p) = I_{ga}(p) - L(p)$$

(11)

where $C(p)$ is a mosaic and contains the down sampled chrominance.

– Separation of three downsampled chrominance channels

Fig. 6. Chrominance channels are separated before interpolation.
» Use of the modulation functions

\[ m_R(x, y) = \frac{(1 + \cos(\pi x))(1 + \cos(\pi y))}{4}, \]

\[ m_G(x, y) = \frac{(1 - \cos(\pi x)\cos(\pi y))}{2}, \]

\[ m_B(x, y) = \frac{(1 - \cos(\pi x))(1 - \cos(\pi y))}{4} \] (12)

where \( x, y \) is the coordinate of a pixel \( p \) in the image.

» Chrominance channels

\[ C_1(x, y) = C(x, y) \cdot m_R(x, y), \]

\[ C_2(x, y) = C(x, y) \cdot m_G(x, y), \]

\[ C_3(x, y) = C(x, y) \cdot m_B(x, y) \] (13)

– Reconstruction of the missing pixels

» Use of a simple bilinear interpolation
• Calculation of the RGB image
  – Adding the lightness and the chrominance channels

\[
R(p) = L(p) + C'_1(p),
\]
\[
G(p) = L(p) + C'_2(p),
\]
\[
B(p) = L(p) + C'_3(p)
\]

(14)

where \( C'_1, C'_2, C'_3 \) are the interpolated chrominance channels.
Results

◆ Experimental environment
  – Capturing the CFA image
    • Canon camera (Canon EOS 300D)
    • Retrieval of RAW data
      – Use of the free program DCRAW
    • Application of inversing the original nonlinearity assuming a power function (gamma) of 2.4
    • Recreation of mosaic according to the Bayer pattern
Comparison of resulting images

Fig. 7. Comparison of our algorithm with other tone mapping operators.
– Two advantage of proposed method
  • Providing good-looking images regardless of the characteristics of the input image
    – Other methods are often restricted to a set of images having common features
  • Proposed algorithm is quite fast compared with other existing local tone mapping algorithms
    – Performance of algorithm on the CFA image
    – Use of relatively small filters
Discussion

◆ Tone mapping algorithm
  – Application to the CFA image
    • Inspiration by a simple model of retinal processing
      – Application of the two nonlinearities by a Naka-Rushton function
  – Two nonlinearities
    • Occurrence in postreceptor
    • Horizontal cells
      – Formation of the center/surround
Use of the Naka-Rushton equation

- Representation of different scenes equally well
- Invisibleness the halos or graying out
- Use of an average of the surrounding pixel values
  
  - Application of the H or A (the adaptation factor)
    - Dark area: Adaptation factor is small
    - Bright area: Adaptation factor is large
  
  - Increase of local contrast in dark areas while still conserving local contrast in bright areas
Influence of different filter size
- Robustness to varying parameters
- Example of proposed method with different filter size

Fig. 8. Example of our method applied with different filter sizes. Left: Small filters ($\sigma_H = 1$ and $\sigma_A = 1$). Right: Large filter ($\sigma_H = 3$ and $\sigma_A = 5$).
Aim of proposed algorithm

- Achieving pleasing reproductions of images
  - This cannot be measured objectively.
  - Pleasing
    - Different things to different people
    - Dependence not only on scene dynamic range and key but also on scene content
    - Evaluation using psychovisual experiments and human subjects
Conclusion

◆ Proposed the tone mapping algorithm based on a model of retinal processing
  – Performance of the algorithm on the CFA image
    • Similarity to the HVS
  – Fastness compared with existing tone mapping methods
    • Providing good results for all tested images

◆ Future work
  – Integration of other rendering operations
    • White balancing and color matricing