Real-Time Adaptive Radiometric Compensation

IEEE Transaction on Visualization and Computer Graphics,
vol. 13, no. 5, Sept.-Oct.2007
Anselm Grundhofer and Oliver Bimber

Presented by Soo-Jin Sung

School of Electrical Engineering and Computer Science
Kyungpook National Univ.
Abstract

- Radiometric compensation techniques
  - Making to project images onto colored and textured surfaces
  - Realization with projector-camera systems by scanning the projection surface
    - Calculation of a compensation image to neutralizes geometric distortions and color blending caused by the underlying surface
    - The reduction of the brightness and the contrast of the input image compared to a conventional projection onto a white canvas
  - The compensation image having the outside value of the dynamic range of the projector
    - Clipping errors and visible artifacts on the surface
Presented method
- A novel algorithm that dynamically adjusts the content of the input images before radiometric compensation is carried out
- The results
  - The reduction of the perceived visual artifacts
  - Preserving a maximum of luminance and contrast
- Implementation of the algorithm entirely on the GPU
Introduction

- Projector-camera systems
  - Use for projecting onto complex everyday surfaces, like papered walls or structured table tops
  - Only consideration the characteristics of the surface such as its reflectance or geometry for the compensation of visual artifacts
  - No taking the properties of the image to be displayed like its brightness and contrast
    - Leading clipping errors and remaining visual artifacts at dark surface
    - An adjustment of the image intensity to avoid this problem
    - Adaptation of the image content for minimizing these artifacts
    - Too complex image to support real-time applications
– Proposed algorithm
  • A novel algorithm that adjusts the image content to reduce visible artifacts in real-time
    – An analysis of the projection surface and the image content followed by a manipulation of the image’s local and global intensity values
  • The result
    – A significant reduction of clipping errors and visible artifacts
    – Preserving a high contrast ratio and brightness
    – Validation of the objective enhancement of the perceived visual quality for projected animated content by an informal user study

◆ Outline of the article
  – A discussion on relevant related work
  – An overview of our approach
  – The detail description of the algorithm
  – Examples and a performance analysis of algorithm
  – The results of an informal user study and conclusion
Related and Previous Work

Basic Radiometric Compensation Techniques

- Applying structured light projection and camera feedback for measuring surface and environment parameters
- Fujii et al.
  - Utilizing an co-axial alignment of projector and camera for dynamic compensation on non-static surfaces
  - A closed feedback loop used in this case to re-adjust the compensations over time
- Nayar et al.
  - Use a 3x3 matrix for each pixel to encode the mixing between the color channels of projector and camera
  - Measurement of the values of the matrices by projecting a series of uniform color patterns onto the surface and capturing the reflected images
– Bimber et al.
  • Supporting multiple projectors to increase the overall brightness and consequently reduces clipping artifacts on complex surfaces

– Wetzstein et al.
  • Present a generalized approach by inverting the full light transport captured between projector and camera
  • Compensation of projector and camera defocus in real-time with this approach

– Techniques to support and image compensation in real-time
– If the compensation image contains values above the maximal brightness or below the black level of the projector
  • Occurring clipping artifacts
Content Dependent Radiometric and Photometric Compensation

- Extended algorithms
- Wang et al.
  - Presenting the technique that scales the overall intensity of the input image until clipping errors that result are below a perceivable threshold
  - Applying to static monochrome images and surfaces
- Park et al.
  - Describing a technique for increasing the contrast in the compensation image by a histogram equalization to the colored input image
  - Non-preserving the contrast ratio of the original image
  - No considering occurred clipping errors by this method
– Ashdown et al.
  • Scanning the surface’s reflectance with a color calibrated HDR camera
  • Transforming the captured data and the image content into the device-independent CIE L\'u\'v\'color space
  • Fitting a chrominance values into the gamut of each projector pixel
  • Applying a luminance with a relaxation method based on differential equations
    • For static images only
– Reducing clipping artifacts and increasing an visual quality
– Inconsistence of a real time compensation
  • Due to computational complexity
Overview

◆ Algorithm performance
  – Content adaptation and radiometric compensation in real-time
  – Reduction of visual artifacts while preserving a maximum brightness and contrast
  – Implementation on the GPU in five steps

  Step1: an analysis of the input image and of the projection surface is performed to gain sufficient parameters for adapting the input image.

  Step2: The intensities of the input image are globally scaled depending on the parameters determined in step 1.

  Step3: The scaled image that results from step 2 is analyzed for clipping errors.

  Step4: The intensities of the image content is re-scaled globally and locally depending on the results of the error analysis in step 3.

  Step5: The re-scaled image from step 4 is radiometrically compensated and projected.
Surface Analysis

- Additional parameters for each pixel
  - The contribution of the (uncontrollable) environmental light which is reflected from the surface – **EM** (including the projector’s black-level)
  - The surface’s reflectance and the projector-to-surface form-factors – **FM** (the fall-off of projected intensity, depending on the projector-to-surface distance and the projection angle)
- The intensity range for which a radiometric compensation without clipping is possible
  - Computation from the two parameters FM and EM
  - Computation of the range of intensities for a conservative compensation
– Compensation of any input pixels $O(x,y)$ within this global range
  • For each point on the surface without causing clipping artifacts
    \[
    EM_{\text{max}} \leq O(x,y) \leq FM_{\text{min}}
    \]  

– The maximum range of displayable intensities
  • The color values of any input pixel within their local range
    \[
    EM(x,y) \leq O(x,y) \leq FM(x,y)
    \]  

**Fig. 1.** Three-dimensional view of the intensity range reflected by a striped wall paper. The area between both green planes depict the range of a conservative compensation without clipping errors. The area between the red planes represents the maximum range in which a compensation is possible (potentially with clipping errors).
Content Analysis

- Analyzing to support global and local luminance for outside pixels of the displayable range

- Average Image Luminance ($L_{avg}$)
  - Use as initial factor for an automatic scaling of the image content
  - Transform of the input image into its CIE XYZ representation
  - Storing the $Y$ values and rendering into a texture by using FBOs
  - Multiple rendering passes
    - Downscaling the luminance image by the factor 2
    - Averaging the four neighboring pixels in each step
  - Rendering the results into textures via FBOs
  - Forwarding to the next rendering pass
  - Repeat until the remaining luminance image contains the average value
- **Threshold Map**
  - Depending on the perception of luminance variations in images by factors
    - Such as the display brightness, the local image contrast and the spatial frequencies of the content
  - Containing the maximum luminance differences that can be varied in the original image without causing a visually perceivable difference
  - The threshold-versus-intensity (TVI) function
    - Describing the peak luminance sensitivity of the human visual system which is only correct for environments with uniform background luminance
    - Depending on the local image content in case of an image with non-uniform content
    - Computation of these spatially varying factors and storing in the elevation factor map
  - Computation by multiplying the corresponding entries of the TVI map and the elevation factor map
• TVI Map
  – Using the adaptation luminance \( L_{\text{adapt}} \) at each pixel
  – Calculation by averaging the luminance values over 1° of the visual angle centered at the according pixel
  – Using a photometer to measure the average minimum and maximum reflected physical luminance values of the surface by projection a complete white and black image.

**Fig. 2.** Flow chart of the GPU-based TVI map generation.
• Elevation Factor Map
  – Use for adjusting the TVI map depending on the spatial frequencies and contrast ratios of the input image content
  – Computing a Laplacian pyramid from the input images’ Gaussian pyramid
  – Converting the laplacian pyramid into a contrast pyramid
    » Use for calculating the elevation factor map
  – The Gaussian Pyramid
    » Computation from the luminance image by down sampling and applying a Gaussian blur fragment shader
  – Multiplying the corresponding values of the TVI map and the elevation factor map to compute the threshold map

*Fig. 3.* Flow chart of the GPU-based elevation factor map generation.
• High Spatial Frequencies
  – Approximation of the amount of high spatial frequencies by analyzing the Laplacian pyramid
  – A useful parameter for the local intensity variation
Adaptation and Compensation

◆ Three steps of adaptation

  Step 1: Global scaling of the image’s intensities.
  Step 2: Error analysis of the scaled images resulting from step 1.
  Step 3: Global and local intensity adjustments based on the errors determined in step 2.

◆ Pre-Adaptation

  – Use to apply an approximate global scaling of the image’s intensity
  – Calculation of a compensation image from the scaled input image
  – Use for calculation the final global and local scaling parameters
The intensities of the input images

- Scaling depending on the average image luminance and the maximum and minimum color values of the projection surface
- Images with a low average luminance are up-scaled
- Too bright images are down-scaled in their intensity

\[
I_{\text{max}}(x, y) = scale(I(x, y), FM_{\text{max}}, EM_{\text{min}})
\]

\[
I_{\text{min}}(x, y) = scale(I(x, y), FM_{\text{min}}, EM_{\text{max}})
\]  

\[
scale(in, \text{max}, \text{min}) = \text{min} + (in \cdot (\text{max} - \text{min}))
\]

\[
I_{\text{scale}}(x, y) = interp(I_{\text{max}}(x, y), I_{\text{min}}(x, y), L_{\text{avg}})
\]

\[
interp(x, y, u) = x \cdot (1.0 - u) + y \cdot u
\]  

- The final image intensities
  - A linear interpolation between of \( I_{\text{min}}(x, y) \) and \( I_{\text{max}}(x, y) \) with the interpolation weights depend on the derived luminance average of the input image \( L_{\text{adapt}} \)
Analyzing for the maximum clipping error

- Each pixel of an initial compensation image $I_c$ in each color channel

$$Err_r = \begin{cases} 
1.0 - \max(I_{c,r}, I_{c,g}, I_{c,b}); & \left( I_{c,r} \lor I_{c,g} \lor I_{c,b} < 0 \right) \\
0; & \text{else}
\end{cases}$$

$$Err_g = \begin{cases} 
\left| \min(I_{c,r}, I_{c,g}, I_{c,b}) \right|; & \left( I_{c,r} \lor I_{c,g} \lor I_{c,b} < 0 \right) \\
0; & \text{else}
\end{cases}$$

$$Err_b = \begin{cases} 
1.0 - \max(I_{c,r}, I_{c,g}, I_{c,b}); & \left( I_{c,r} \lor I_{c,g} \lor I_{c,b} < 0 \right) \\
0; & \text{else}
\end{cases}$$

- Realization by a direct render-to-texture operation via frame buffer objects
◆ Error Analysis

– Clipping errors
  • Lead to abrupt alternations in luminance and chrominance within the displayed image

– A conservative global luminance reduction
  • Lead to a full elimination of clipping errors
  • A significant reduction in contrast and brightness

– Blurring the calculated clipping errors with a Gaussian smoothing kernel $G$

\[
Err_{FM} (x, y) = Err_r(x, y) \otimes G(\sigma) \tag{6}
\]
\[
Err_{EM} (x, y) = Err_g(x, y) \otimes G(\sigma)
\]
– A smooth local modification
  • Require for avoiding abrupt intensity variations
  • Adjusting the $\sigma$ parameter of the filter kernel inverse proportionally to the amount of high spatial frequencies of the input image
  • The new global scaling factor $S'$
    – More precise adjustment with respect to the largest detected clipping value within the image
      \[ S' = \min(1, L_{\text{avg}} + \max(\max(Err_r) - Err_{\text{max}})) \] (7)
  • If $Err_r$ stores values above a maximum tolerated clipping error $Err_{\text{max}}$
    – Decreasing $S'$ and leadings to a larger reduction in brightness
  • If there is no clipping at all within the entire image
    – Adjusting $S'$ with respect to the smallest value in $Err_b$
    – Leading to an increase in brightness
\[ S' = \max(0, L_{avg} - 1 + \max(Err_b)) \] (8)

- Figure 4.
  - Summarizing all calculation steps
  - The result of the pre-adaptation (a)
  - The computed clipping values in the color channels of an auxiliary texture (b)
  - The clipping errors for values above and below the displayable range (the red (b1) and green (b2)
  - Blurring depending on the amount of high spatial frequencies within the input images (c1 and c2)
◆ Final Adaptation and Compensation

– The result of the global re-adjustment with the scaling factor $S'$
  
  • Locally adapted $I'_{\text{scale}}$ depending on the blurred clipping errors
  
  • Up-scaled $Err_{FM}$ and $Err_{EM}$ to projector resolution

– The local adaptation in areas with clipping values above 1.0

$$l = L(x, y) \cdot Err_{FM}(x, y) \cdot f_1$$

$$I'_{\text{scale}}(x, y) = \begin{cases} 
I'_{\text{scale}}(x, y) - l, & l < TM(x, y) \cdot f_2 \\
I'_{\text{scale}}(x, y) - TM(x, y) \cdot f_2, & \text{else}
\end{cases} \quad (9)$$

• Decreasing local intensities in the globally scaled image content
– Occurred clipping errors in the reverse case
  • Due to values below the black-level of the projector
– Increasing the local image intensities

\[
l = (1.0 - L(x, y)) \cdot Err_{EM}(x, y) \cdot f_1
\]

\[
I''_{scale}(x, y) = \begin{cases} 
I'_{scale}(x, y) + l, & l < TM(x, y) \cdot f_2 \\
I'_{scale}(x, y) + TM(x, y) \cdot f_2, & \text{else}
\end{cases}
\]

• Storing the results \( I''_{scale}(x, y) \) of the final adaptation stage
• Use of the scaling factor \( f_1 \) for varying the local adaptation manually
  – Empirical founding an optimal value of \( f_1 = 1.5 \)
• Adapting the amount of modification to the actual brightness of a pixel
  – Weighted clipping errors \( Err_{FM} \) and \( Err_{EM} \) by the corresponding luminance values \( L(x, y) \)
• Adjusting manually with a second scaling factor \( f_2 = 2.0 \)
- Radiometrically compensation
  - The presented compensation equation for a one projector setup
    \[ I'_c = \frac{I''_{\text{scale}} - E M}{F M} \]  
    \[ (11) \]
  - Use of \( n \) overlaying projectors to produce a brighter image at the surface
    \[ I'_{c,p} = \frac{I''_{\text{scale}} - \sum_{p=1}^{n} E_p M}{\sum_{p=1}^{n} F_p M} \]  
    \[ (12) \]
– Figure 5

- The adjusted scaling factor $S'$
  - Use for re-scaling the input image globally

- Applying the smoothened error textures with the threshold map (e) and the local luminance information (d)
  - Performing local intensity adjustments in the input image (i)

- Computing the adapted compensation image (h)

**Fig. 5.** Flow chart of the final image adaptation and radiometric compensation steps.
◆ Temporal Adaptation
- Leading to abrupt changes in brightness and contrast and to visible flickering in case of animated content
- A temporal adaptation model

\[ S_i'' = S_{i-1}' + (S_i' - S_{i-1}'') \cdot \left(1 - e^{-\frac{T}{\tau}}\right) \]

• The temporally adapted scaling factor \( S_i'' \)
  - Depending on the factor \( S_i' \) computed for the current frame
  - Depending on the factor \( S_{i-1}'' \) used for the previous frame
• An exponential attenuation function
  - Determining based on the actual frame rate \( T \)
  - A constant \( \tau \) described for the rate of human luminance adaptation
    » Using a value of \( \tau = 0.1 \) for rods
– Converting from abrupt global luminance variations to smooth intensity changes over time
– The blurred clipping errors ($Err_{FM}$ and $Err_{EM}$)
  • Smoothing over time to decrease the visibility of the local intensity adjustments
  • Using the averaged values with the error values for the previous image $Err'_{i-1}$ instead of using the computed error textures $Err_i$ at time instance $i$

$$Err'_i(x, y) = \frac{Err'_{i-1}(x, y) + Err_i(x, y)}{2}$$ (14)

• Less expensive computation than applying equation (13) to each individual error pixel
Several visual examples of this algorithm’s outcome

- Figure 6
  - Reduction of the visible clipping errors without decreasing the image’s overall contrast and brightness much
  - (a) is a striped wall paper
  - (b) is an uncompensated projection of the underlying surface
  - (c) is an result of our adaptive algorithm without local reductions
    - Visible clipping artifact in the bright area of the upper left corner
  - (d) is the final result
    - Including automatic global and local adaptations

**Fig. 6.** Adaptive radiometric compensated projection with global (c) and additional local luminance adjustments (d).
– Figure 7
  • Detection of the slight color mismatches compared to the original image
  • Producing an acceptable result when comparing it with an uncompensated projection (c)

**Fig. 7.** Projection onto a striped wallpaper with saturated colors, without (c) and with (d) adaptive radiometric compensation.

(a) is the original image
(b) is a surface with saturated colors
(c) is an uncompensated projection
(d) is the final result
– Figure 8
  • Producing a brighter result compared to a (c)
    – With the local intensity adjustments

Fig. 8. Projection onto a wooden surface, without (b), with manually adjusted (c) and with adaptive radiometric compensation (d).

(a) is a wooden surface
(b) is an uncompensated projection
(c) is a manually adjusted compensation
(d) is a compensation with this algorithm
– Figure 9
  • Illustration of two different frames from the movie Shrek 2
    – Bright scene (b) and dark scene (e)
  • A basic compensation algorithm (c, d)
    – Occurrence of the visible clipping errors in areas with bright intensities
  • Reducing the visibility of the underlying surface while widely preserving brightness and contrast of the original video

Fig. 9. Two frames of an animation (b, e) projected onto a natural stone wall with a static radiometric compensation (c, f) and with our adaptive algorithm (d, g).
Performance Analysis

- Test platform
  - Intel Pentium 4, 2.8GHz, 1GB RAM, NVidia GeForce 7900 GTX, XGA projector resolution
  - A PAL resolution video
    - Compensation with approximately 35 frames per second
    - Choosing 128 x 128 pixels
  - Speed-up factors of 1.7 to 38.7

**TABLE 1**
Comparison between CPU and GPU implementations of four necessary image processing tasks (in FPS)

<table>
<thead>
<tr>
<th>Task</th>
<th>CPU</th>
<th>GPU</th>
<th>Gain factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian pyramid</td>
<td>38</td>
<td>166</td>
<td>4.3</td>
</tr>
<tr>
<td>Gaussian blur (Kernel: 77² pixels)</td>
<td>4</td>
<td>115</td>
<td>38.7</td>
</tr>
<tr>
<td>Average luminance</td>
<td>175</td>
<td>303</td>
<td>1.7</td>
</tr>
<tr>
<td>High frequency analysis</td>
<td>41</td>
<td>397</td>
<td>9.6</td>
</tr>
</tbody>
</table>

**Fig. 10.** Measured performance for different pre-adaptation resolutions.
Informal User Study

◆ An object
  – Validating the increase of perceived visual improvement that can be gained by an adaptive approach compared to a basic radiometric compensation

◆ Performed environment
  – A dark room without environment light
  – Adaptation to the lighting conditions for five minutes before the test sequences were presented to them
  – Using two LCD-projectors
    • Color calibration with a photometer for fitting the gamuts of both devices
    • The first projector for compensated images onto a natural stone wall
    • The second one to projection the original image onto a white canvas
◆ The first part
  – The projected still images onto the stone wall with a duration of 15 seconds
  – Showing nest to each other at the same time
  – Compensation between the adaptive algorithm and a constant basic method

◆ The second part
  – Projection for four video sequences one after another
  – Use of two different scaling factors for the static compensation method
    • Factor to avoid visible clipping errors completely
      – Dim, but clipping-free projections (videos number 1 and 2)
    • Selected factor to be equal the average scaling factor
      – (Videos number 3 and 4)
The third part
- Presentation of the adaptive and static compensations compared with a conventional projection onto a white planar canvas

Evaluation
- Rating participants preferences within five scales
  - “left image much more convenient”, “no difference” and “right image much more convenient”
- Participation for 32 subjects

The results
- Favor for dynamic content for the adaptive algorithm
- Perceived enhance for videos with varying contrast and brightness levels

Fig. 11. Comparison of four compensated (static and adapted) videos projected onto a natural stone wall were compared.
Conclusions and Future Work

◆ Presented algorithm
  – A real-time capable adaptive radiometric compensation algorithm
    • Consideration of the surface’s reflectance and geometry, the image
      content and the capabilities of the human visual system
  – Analysis of the projection surface and the image content
  – Adaptation of the input images globally and locally in two steps
  – A minimization of clipping errors and corresponding chrominance
    shifts
  – Implementation of GPU to enables real-time frame rates