High-Dynamic Range Imaging Techniques Based on Both Color-Separation Algorithms Used in Conventional Graphic Arts and the Human Visual Perception Modeling

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ABSTRACT

The aim of this research is to derive illuminant-independent type of HDR imaging modules which can optimally multi-spectrally reconstruct of every color concerned in high-dynamic-range of original images for preferable cross-media color reproduction applications. Each module, based on either of broadband and multispectral approach, would be incorporated models of perceptual HDR tone-mapping, device characterization. In this study, an xvYCC format of HDR digital camera was used to capture HDR scene images for test. A tone-mapping module was derived based on a multi-scale representation of the human visual system and used equations similar to a photoreceptor adaptation equation, proposed by Michaelis-Menten. Additionally, an adaptive bilateral type of gamut mapping algorithm, using approach of a multiple conversing-points (previously derived), was incorporated with or without adaptive Un-sharp Masking (USM) to carry out the optimization of HDR image rendering. An LCD with standard color space of Adobe RGB (D65) was used as a soft-proofing platform to display/represent HDR original RGB images, and also evaluate both rendition-quality and prediction-performance of modules derived. Also, another LCD with standard color space of sRGB was used to test gamut-mapping algorithms, used to be integrated with tone-mapping module derived.

Keywords: High-dynamic-range imaging, Gamut mapping algorithm, Photoreceptor adaptation equation, Tone reproduction operator, Cross-media color reproduction, Human vision system, Un-sharp masking, HDR tone mapping, Device Characterization, Adaptive bilateral filter.

1. INTRODUCTION

The dynamic range of light energy under daylights of sun, in natural scenes, can be very high. Usually, it’s on the order of 10,000 to 1 from highlights to shadows, or higher if light sources are directly visible. As new physically-based imaging rendering methods/techniques have been utilizing in digital cameras [1], the radiance maps on images produced can optimally represent the wide ranges of variations of light energy in scenes. Unfortunately, neither of these available methods can practically specify how to realistically display these images on existing electronic output media that only have moderate output radiance levels and typical dynamic ranges of 100 to 1, or less. This is either the HDR display output problem, or the HDR tone-mapping problem.

Recently the issues of developing tone-reproduction operators that can produce both visual matches and radiance maps between the high dynamic range scene and the displays images have started being addressed by graphics/imaging researchers. Therefore, toward implementing tone reproduction operator, the visual model should be made use to relate the perceptual responses of a scene to the responses of the display color image for the observer considered. Different tone-reproduction operators could be implemented using different visual models to establish what constitutes visual matches. Since the images produced using operators depend on the visual models incorporated, a fundamental solution to the problems of realistic tone reproduction requires a more comprehensive module that can faithfully simulate human visual perception.

In this study, a set of HDR imaging module was derived. It would be further, considered in the near future, integrated with illuminant-independent type of device characterization models, derived previously [2], to optimally multi-spectrally reconstruct every pixel concerned in high-dynamic-range of original images in question, for preferable cross-media color reproduction applications. A computational model of adaptation and spatial vision for realistic tone
reproduction was firstly developed in this study. It was derived based on the approach suggested by Pattanaik et al. [3, 4]. It carried out a multiscale representation of the human visual system; and then followed by using an equation similar to a photoreceptor adaptation equation, originally proposed by Michaelis-Menten [5, 6]. Moreover, with the incorporations of multiscale type adaptation-and-spatial vision model, HDR tone-mapping operator, device characterization and gamut mapping models, the module derived would mapped the vast ranges of radiances, found in real and synthetic scenes, into the small limited ranges available on conventional display devices of LCD’s and printers/presses.

2. COMPUTATIONAL FRAMEWORK OF MODEL

![Figure 1. The specific computational procedures used to implement each step of the model.]

A HDR imaging module as mentioned earlier, based on a multiscale model of adaptation and spatial vision in human visual system, was developed and applied to the problems of realistic tone reproduction across imaging devices. Additionally, an adaptive gamut mapping algorithm, incorporated with device characterization models for both Adobe RGB and sRGB formats of LCD displays, was also plugged in the computation framework to carry out the optimization of HDR image rendering. The adaptive gamut mapping algorithm was implemented using both a bilateral filtering technique [7] and a multiple-conversing-points approach [8, 9]. The Adobe RGB format of LCD (EIZO Color Edge CG221) was characterized under D65 white point, and used as a soft-proofing platform to display/represent HDR RGB images, and also to evaluate rendition-quality of images produced. Moreover, an Un-Sharp Masking (USM), used for detail enhancement which was conventional and practically applied in color separation algorithm for graphic arts, was carried out in the optimization process of HDR image rendition quality when needed. The specific computational procedures that were used to implement each step of the model are described below. A pictorial representation of each stage of the model/algorithm applied is presented in Figure 1.

2.1. Tone Mapping Algorithm

The reproduction of the visual appearance of original scene is the ultimate goal in the tone mapping. Therefore the tone mapping algorithm developed here made use of adaptive and spatial visual model with multi-scale, to provide the solution to compress the dynamic range of the HDR image to fit into the display range while preserving details.
Figure 2 provides a flow chart of each major step of computation in tone-mapping (or tone-reproduction) module derived. The module has two domain parts: the Visual model and the Display model. The visual model processes an input image to encode the perceived contrasts for both the chromatic and achromatic channels in their band-pass mechanisms. The display model, then, takes this encoded information and reconstructs an output image. The module must also involve the reversed process in order to optimally produce equivalent appearances of images, considered under the viewing conditions of the display device that has limited dynamic range of radiance maps.

An xvYCC format of HDR digital camera (Sony HDR-SR12) was used to capture HDR scene images for test. The HDR image is firstly converted to XYZ tristimulus values via xvYCC color space, then spectrally sampled to represent the visual system’s initial photoreceptor responses. This is carried out by integrating the spectral radiance distribution for each pixel after the multiplication by spectral responsivities [10, 11] of the long-, middle- and short-wavelength sensitive cones (LMS) and the rods. Then the Laplacian pyramid (difference-of-Gaussian pyramid, DOG) approach [12] carries out the spatial decomposition of these 4 images, representing the calibrated photoreceptor responses. In total, seven levels of Gaussian pyramid were implemented here. Each level of the Gaussian pyramid is then up-sampled such that each image is returned to the size of the initial image. DoG images are then calculated by taking the image at each level and subtracting the image from the next lower level. This results in 6 levels of band-pass images which are considered as representations of the signals in six band-pass mechanisms in the human visual system. Also the lowest-level low pass image is retained to reconstruct the image for reproduction applications. As follows, the DoG images are then converted to adapted contrast signals using a luminance gain control, set using TVI-like functions to represent the increment thresholds of the rod and cone systems and the growth in response that compensates perceived contrast to increase with luminance level (sub-Weber’s law behavior). As performing the gain control, it allows the model to have the prediction performance in chromatic–adaptation effects. The next stage of the module is to transform the adapted contrast images for the cones (LMS) into opponent signals (AC1C2), using the transform matrix applied in CIECAM02 color appearance model [10]. At this stage, the rod images are retained separately since their spatial processing
attributes differ from the cones. The adapted contrast signals are then passed through contrast transducer functions. Different transducer functions are applied to each spatial frequency mechanism to approximate psychophysically derived human spatial contrast sensitivity functions. Two-part functions, consisting of two power functions, are chosen to replicate the two regions of distinct slope in the transducer functions. Again, the rods use a separate function. After the contrast transducers, the rod and cone signals can be combined to produce signals that represent the three-dimensional color appearances of the input image.

As this point, the output of the visual model consists of appearance signals in an achromatic and two chromatic channels, and six spatial band-pass mechanisms plus a low-pass image. These appearance signals can, then, be backward through the model to recreate cone signals (that replicate the full color appearance of the image on a photopic/trichromatic display device such as a LCD display), and ultimately device signals such as RGB or CMYK.

Of all nonlinear mappings, logarithmic and exponential mappings are among the most straightforward. For medium dynamic range images, accommodated by current LDR display devices, these very simple solutions may still be competitively with more complex operators. Therefore, in this study, both logarithmic and exponential mapping operators were implemented to process luminance mapping using Eqns. 1 and 2 respectively.

\[
L_d(x, y) = \frac{\log_{10}(1 + L_w(x, y))}{\log_{10}(1 + L_{\text{max}})} \quad (1)
\]

\[
L_d(x, y) = 1 - \exp\left(\frac{L_w(x, y)}{L_{\text{av}}^n}\right) \quad (2)
\]

Here, \(L_d(x, y)\) is the display luminance that is the quantity we wish to display; \(L_{\text{av}}\), average luminance; \(L_{\text{max}}\), the maximum luminance on image; and \(L_w(x, y)\), image luminance. The logarithm is a compressive function for values larger than 1; whereas the exponential mapping operators transforms world luminances to display luminances using the exponential function, bound between 0 for black pixels and 1 for infinitely bright pixels.

2.2. Device Characterization and Gamut Mapping

Two LCD with standard color space of Adobe RGB and sRGB 9 (both under D65 white point calibration) were used as displays of images. The Adobe RGB format of display was used as a soft-proofing platform to display/represent HDR RGB images, and also to evaluate both rendition-quality and prediction-performance of modules derived. Moreover, the sRGB LCD (EIZO ColorEdge CE240W) was used as LDR display, representing the common available LCD with intermediate limit of dynamic range. Therefore, an adaptive gamut mapping algorithm, introduced by Nicolas Bonnier et al. [7] mentioned earlier were also implemented in this study. By plugging bilateral filtering with a multiple conversing-points approach (Fig. 3), it maps the Adobe RGB image to sRGB images. Additionally, the adaptive GMA could also be incorporated with or without an adaptive Un-sharp Masking (USM), to carry out the optimization of HDR image rendition.

This adaptive gamut mapping algorithm decomposes the image tested into two bands (see Fig. 4), and can provide several available options: 1) re-render \(I_{\text{low}}\); 2) rescale and remap its lightness range; and 3) adjust \(I_{\text{high}}\) using a scaling factor; 4) spatially filter or modify image considered using a more complex function [13]; 5) adjust the merging function of the two adjusted bands. Fig. 4 shows the adaptive algorithms derived in this study by the following process:

- Conversion of the original Adobe RGB image to the CIELAB color space: \(I_{\text{in}}\).
- Decomposition of the CIELAB image into two bands using bilateral filtering (BF): \(I_{\text{low}}\) and \(I_{\text{high}}\).
- Hue-Preserving Minimum \(\Delta E\) clipping \([14] (\text{HPMin } \Delta E\text{ clipping})\) (3) of the low-pass band \(I_{\text{low}}\): \(I_{\text{low}}\).
- \(I_{\text{out}} = \text{HPMin } \Delta E\ (I_{\text{in}})\), with \(I_{\text{in}}\) the original image and \(I_{\text{out}}\) the gamut mapped image.
- Adaptive merging of \(I_{\text{low}}\) (4) and \(I_{\text{high}}\) (5): \(I_{\text{out}}\).
- Conversion to the sRGB encoding of the output LCD.
3. APPLYING THE MODEL AND EVALUATIONS

3.1. HDR Tone Mapping Algorithm
The series of images in Fig. 5 illustrate application of the model using tone mapping operators shown in Eqns. (1) and (2) and also linear approach. The linear method gives the similar impression as original captured image shown in Adobe RGB type of LCD. However, the exponential mapping produces different appearances of images, depending on the chosen $L_{av}$ (average luminances) value. And, the logarithmic mapping produces an image that is overall much brighter. Actually, the original scene appears to sit somewhere among those renditions, and thus either algorithm produced a displayable image that was simulated to the original scene under various illumination conditions. Therefore, the
function form, as well as the choice of anchor value, has a significant impact on the resulted appearance of images produced. Although more experimentations would be needed to obtain definite conclusions, it seems that the value, $L_{av}$ or $L_w$, chosen to anchor the mapping, has the more profound effect on the overall image appearance results.

3.2. Device Characterization and Gamut Mapping

Eight images in Adobe RGB type (Fig. 6) were used to test the adaptive gamut mapping algorithms (GMAs) derived. Three mapping methods, including linear compression, S-shape compression and clipping were considered. Additionally, the GMAs were also tested, a) with or without plug-in of the USM filter; b) using or not using adjusted approach (i.e. spatial-and-color adaptive clipping/compression), to evaluate the filter rendition performance. The USM considered was used in the adjusted type of gamut mapping to compensate the smoothing effect of bilateral filter. In total, 7 GMA models were investigated. They are listed in Table 1.

Finally, A set of forced-choice paired comparison psychophysical experiment were carried out, to make comparisons of colour appearance matching between the original images (displayed on the Adobe RGB LCD) and the reproduction images (displayed on the sRGB LCD). It was used to cross verify the prediction performances of those GMAs derived DCMs in question. A panel of 10 observers viewed a paired of reproductions randomly presented, and judged which of the two gave a better match (i.e. color fidelity) to an original image in question. The paired comparison results in terms of the z-score with 95% confidence limit (CL), for the combined 8 images, were summarized and plotted in Fig. 7. The results apparently showed that adjusted linear compression, using with and also without the adapted USM, outperformed the others. It implies that the use of both bilateral and USM filters significantly enhances the GMA rendering performance in cross-media color reproduction.

![Figure 5. Application of the model using a linear (a), an exponential (b and c) and a logarithmic mapping (d).](image-url)
Table 1. Seven gamut mapping (GM) algorithms tested.

<table>
<thead>
<tr>
<th>Model</th>
<th>GM 1</th>
<th>GM 2</th>
<th>GM 3</th>
<th>GM 4</th>
<th>GM 5</th>
<th>GM 6</th>
<th>GM 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM method</td>
<td>Clipping</td>
<td>Linear Compression</td>
<td>S-Shape</td>
<td>Adjusted Clipping</td>
<td>Adjusted Linear Compression</td>
<td>Adjusted Clipping</td>
<td>Adjusted Linear Compression</td>
</tr>
<tr>
<td>USM</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
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</table>

Note: USM was used in the adjusted type of gamut mapping to compensate the smoothing effect of bilateral filter.

Figure 7. GMAs performance evaluated using the paired comparison method.

6. CONCLUSIONS AND FUTURE WORK

An HDR imaging module, applied the visual model has been introduced to optimally reconstruct of every color concerned in high-dynamic-range of original scene images for preferable cross-media color reproduction applications. A multiscale tone reproduction module, based on the visual model, has applied to the problem of realistic tone reproduction. Additionally, by plugging an adaptive GMA with bilateral filter, and USM, this work should have major
There is still much work to be done in this area. Future models should integrate multispectral type of device characterization models to reduce metamerism problems. A well-performed CIEXYZ type of multi-spectral Standard Observer model was derived previously [2] to optimally reconstruct spectra of HDR scene. The Observer model, simulating responses of CIE 1931 color matching functions, was plugged-in a Winner algorithm with basis vectors. Those basic vectors used in the Winner algorithm were obtained using singular value decomposition method (SVD) which is based on a reflectance dataset of Glossy Munsell Book. A mean ΔE*00 value of 0.22 was found for reconstruct performances of the CIEXYZ multispectral Standard Observer model derived, under D65 white-point/illuminant. Therefore, via the multi-spectral Observer model, the broadband RGB type of Adobe RGB HDR images can be further satisfactorily transformed into the illuminant-independently multi-spectral images. The Adobe RGB type of both broadband (i.e. RGB format) and multi-spectral images can be, hence, preferably chosen as broadband and multi-spectral originals (of HDR scene) respectively for high-rendition imaging applications across media of digital HDR cameras, displays and printers/presses considered. Therefore the goal of deriving an illuminant-independent type of HDR imaging module can be satisfactorily achieved; and it can be applied to optimally multi-spectrally reconstruct every color concerned in high-dynamic-range of original images for preferable cross-media color reproduction applications.

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