Testing HDR Image Rendering Algorithms

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Abstract

Eight high-dynamic-range image rendering algorithms were tested using ten high-dynamic-range pictorial images. A large-scale paired comparison psychophysical experiment was developed containing two sections, comparing the overall rendering performances and grayscale tone mapping performance respectively. An interval scale of preference was created to evaluate the rendering results. The results showed the consistency of tone-mapping performance with the overall rendering results, and illustrated that Durand and Dorsey's bilateral fast filtering technique and Reinhard's photographic tone reproduction have the best rendering performance overall. The goal of this experiment was to establish a sound testing and evaluation methodology based on psychophysical experiment results for future research on accuracy of rendering algorithms.

Introduction

The difficulties for capturing and displaying High-Dynamic-Range (HDR) scenes have long been appreciated. Natural scenes contain a large amount of luminance variation, often spanning a range of 10,000:1. Human observers can readily perceive details in scenes that span the range of 4-5 orders of luminance magnitude through local adaptation, and can adapt to over 9 orders of luminance magnitude in minutes. Recent advances in color imaging techniques[1-3] have created imaging systems capable of capturing HDR images with low-dynamic-range image detectors. However, HDR images still cannot be easily displayed on current CRT or LCD monitors, which have dynamic range limitations of about 100:1. Printed images have an even narrower dynamic range. This dynamic range gap has become a bottleneck in accurate digital reproduction pipeline, and advanced research on tone mapping to display the appearance of high-dynamic-range images is of great importance in accurate image analysis and photography.

In the last decade a number of HDR image rendering algorithms have been developed to deliver the desired perceptual effect of HDR images on low-dynamic-range displays. Detailed review of many of these algorithms can be found in Devlin,[4] Matkovic,[5] Drago,[6] and Tumblin.[7,8] These rendering techniques can be broadly classified into two categories: spatially uniform and spatially varying. Spatially uniform mapping applies the same transformation to every pixel in the image based upon the global image content. The main advantage of spatially uniform mapping lies in the simplicity and computational efficiency, although there is a fundamental difficulty in keeping the appropriate local contrast in each region of the image. Spatially varying mapping is more flexible in controlling local contrast, since a specific mapping tactic is used for each pixel based on its local spatial content. It often takes more time for local comparisons; therefore, computational efficiency optimization is important in real applications for spatially varying mapping.

When a new rendering algorithm is proposed, the rendering performance may be compared with some of the previous HDR image rendering algorithms; however, a sound testing and evaluation methodology based on psychophysical experiment results has not yet been well established. Moroney[9] presented his initial attempt to test Retinex[10-12] and iCAM[13] using three HDR grayscale images. The experiment in this paper tested a wide range of algorithms and a larger set of images to compare the performance of many existing rendering algorithms so as to aid in the future development of HDR rendering algorithms.

Experimental Algorithms

For this research, eight rendering algorithms were selected from the literature, which represent different tone mapping and spatial processing techniques. Sigmoidal transformation[14] and Local color correction proposed by Moroney[15] were selected to examine the performance of using classic 8-bit image enhancement techniques for rendering higher-dynamic-range images. The histogram adjustment technique proposed by Ward Larson,[16] which incorporates a human perceptual model, is one of the best spatially-uniform mapping operators. Spatially varying mapping operators often have better rendering performance; for this reason, five recently developed rendering algorithms are included in our experiment: Retinex,[10-12,17] iCAM by Fairchild and Johnson,[13,18] bilateral fast filtering by Durand and Dorsey,[19] photographic tone reproduction by Reinhard et al.[20] and gradient compression by Fattal et al.[21]

Sigmoidal Transformation

Braun[14] presented image lightness rescaling techniques for gamut mapping of 8-bit images using a sigmoidal contrast enhancement function. The form of the sigmoidal functions was derived from a discrete cumulative normal function, given in Equation 1, where x_0 and σ are the mean and variance of the normal distribution respectively.

$$s_i = \sum_{n=0}^{n=i} \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x_n - x_0)^2}{2\sigma^2}} \quad (1)$$

Instead of lightness, the logarithm of luminance, normalized from 0 to 100, was used to compress the HDR images. Based on Braun's idea, the images were classified into three groups: high lightness-class, normal lightness-class and low lightness-class. The image classifications are based on the average luminance factor. A preliminary experiment was done to derive empirically based optimal x_0 and σ parameters for these three classes as listed in Table 1.

Table 1. Optimal x_0 and σ for three classes of images

	Average Lum. factor	x_0	σ
high lightness-class	0.00 – 0.30	35	60
normal lightness-class	0.31 – 0.60	30	55
low lightness-class	0.61 - 1.00	25	40

Local Color Correction

Moroney[15] proposed the local color correction technique, a spatially varying operator based on non-linear masking, for image enhancement for 8-bit RGB images. The mask is simply an inverted low-pass filtered monochrome version of the input image, which is blurred by a specific size of Gaussian filter. For HDR images, the logarithm of luminance is normalized from 0 to 255 and then is used to compute the mask instead. This algorithm is shown in Equation 2. The adjusted luminance is then rescaled into the displayable range.

$$Output = 255 * \left(\frac{Input}{255}\right)^{\left(2^{\left(\frac{128 - Mask}{128}\right)}\right)} \quad (2)$$

Histogram Adjustment

Ward Larson et al.[16] presented a spatially uniform mapping technique using histogram adjustment to reproduce perceptually accurate tones in HDR scenes. By discovering local luminance adaptation levels and modifying the luminance histogram, this technique can map the original image to display values to preserve local contrast visibility. The human visual models of glare, spatial acuity and color sensitivity effects are incorporated into this model to reproduce imperfections in human vision to mimic the subjective viewing experience.[22] Since the rendering preference was tested in this experiment, only the human contrast sensitivity function was used.

Retinex

Retinex[10] has 40 years of history since Land first described the idea in 1963, and many implementations have been published over the years. McCann[23] summarized that "A Retinex is all mechanisms from retina to cortex necessary to form images in terms of lightness". The application of dynamic range compression of real images was described in a patent by Frankle and McCann.[24] We test the McCann99 version of Retinex with the public Matlab code by Funt.[12] The number of Retinex iterations controls contrast and dynamic range compression of the resulting image; Funt[25] proposed an automatic method for setting this important free parameter, which is used in our experiment.

iCAM

iCAM was proposed as an image appearance model by Fairchild and Johnson,[18] which aims to combine traditional color appearance capabilities along with spatial vision and image quality metrics. As such, iCAM has the unique capability to predict accurate color appearance in high-dynamic-range scenes. Johnson[13] described the specific implementation of the iCAM framework for high dynamic range tone mapping. The device dependent RGB input image is transformed to IPT color space considering local chromatic adaptation and luminance adaptation transform using Gaussian blur filter. Next another low-passed version of the luminance channel image is used to calculate the local tone reproductions curves for each pixel. The mapped IPT image is then inverted back to a device dependent image for display. Matlab code from Johnson and Taplin[26] was modified and used in this experiment.

Bilateral Fast Filtering Technique

Durand and Dorsey[19] proposed a rendering technique to reduce the contrast while preserving details in the image. An edge-preserving spatial processing operator, so-called bilateral filter, can decompose the image into two layers: the base layer, encoding large-scale variations, and the detail layer. The contrast of the base layer is compressed and they are combined again with the detail layer to produce the final image. This filter is the further development from Tumblin and Turk's LCIS method, [27] and it is easier to control and faster, while it also address two problems mentioned by Tumblin about the halo artifacts and diffusion at discontinuities.

Photographic Tone Reproduction

Photographers traditionally used the zone-system and dodging-and-burning techniques to map scene luminance into a set of prints. Reinhard et al.[20] presented a photographic tone reproduction technique for scene rendering, which is analogous to this technique. The luminance and dynamic range of a scene can be divided into zones, and an appropriate choice for middle-gray and key of the scene ensures that the maximum possible detail is retained. A simple but effective global operator is used to compress the high intensities in the image, which avoids introducing artifacts other than some contrast reduction in the highlights; if a high dynamic range scene consists of over 11 zones, the dodging-and-burning technique is used. The method[28] of automatic selecting two user parameters, "key" and "white point", was used in this experiment.

Gradient Compression

Fattal et al.[21] proposed a tone mapping technique based on gradient domain high dynamic range compression. They observed that drastic luminance changes often cause large magnitude luminance gradients and fine details often correspond to smaller gradient magnitudes. An appropriate spatially variant mapping function was created to attenuate the large gradients at various scales, while preserving fine details. The gradient attenuation function is derived by combination of attenuation functions in different scales using a multi-resolution decompression technique. The gradient domain of the logarithm of luminances is compressed by the attenuation, and the new dynamic range image is then obtained by solving a set of Poisson equations on the modified gradient field. The goal of this algorithm is to offer a fast and easy-to-use tone mapping technique instead of perceptual accuracy.[21]

Experiment

An exploratory psychophysical experiment was designed to test HDR image rendering algorithms using ten pictorial HDR color images on LCD display. The observers were asked to scale preference, while considering the tone compression performance, color appearance and other image attributes.

Scene Selection

The selection of test scenes is an important consideration for comparing HDR image rendering algorithms. Dynamic ranges and average luminances of the scenes are the two most salient factors that determine the rendering performance of the algorithms. A quantitative evaluation system was developed to describe these two factors from the zone system,[28] which is widely used in photography. The dynamic range of an image is defined in Equation 3.

$$Dynamic\ Range = log_2 L_{Max} - log_2 L_{Min} \tag{3}$$

L_{Max} and L_{Min} are the maximum and minimum luminance of the scene respectively. The average luminance factor can indicate whether a scene is subjectively light, normal, or dark, which can be calculated from Equation 4 to 6.

$$\bar{L}_w = \exp\left(\frac{1}{N}\sum_{x,y}\log\left(\delta + L_w(x,y)\right)\right) \tag{4}$$

$$Average\ Luminance = log_2 \bar{L}_w - log_2 L_{Min} \tag{5}$$

$$Average\ Lum.\ Factor = \frac{Average\ Luminance}{Dynamic\ Range} \tag{6}$$

Equation 4 is from Reinhard's[28] photographic tone reproduction technique, where L_w is the world luminance for pixel (x, y), N is the total number of pixels in the image, δ is a small value to avoid singularity and $\bar{L}_w$ describes the average of luminance of the image. The normalized average luminance by dynamic range can be used to quantitatively express the general subjective luminance of an image.

Since the rendering performances may be dependent on a specific capture process or content, ten scenes were selected to test the experimental algorithms from a variety HDR image sources. These experimental images mapped into our evaluation system are shown in Figure 1. Ten experimental scenes are close to evenly distributed in this map, covering different dynamic ranges and three luminance groups: dark, normal and light. Image "memorial" is a classic benchmark HDR image from Debevec;[29] "bristolb", "tahoe1", "clockbui" are courtesy of Greg Ward;[30] Scene "lamp_up" was taken by Pattanaik et al. ,[31] and "Belgium" is publicly available from Hebrew University of Jerusalem.[32] Three images, "colorcube", "split_cube2" and "garage" are from the RIT High Dynamic Range Image Database.[33] Finally, a computer-generated scene, "lamp_pete", rendered by Shirley,[30] was selected.

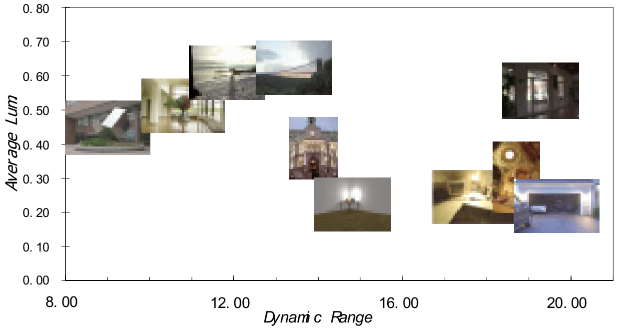

Figure 1. Experimental Images Map. Left to right: split_cube2, colorcube, tahoe1, bristolb, clockbui, lamp_pete, lamp_up, memorial, Belgium and garage.

Algorithm Implementation

The implementation source code for Retinex, iCAM, histogram adjustment and photographic tone reproduction algorithms are publicly available, and the other four algorithms were implemented in Matlab for this experiment. The input HDR images are all in Radiance rgbe format. As the original color primaries of most of these RGB images are unknown, the image values are supposed to be linear in absolute luminance. The relative luminance values are approximated from the input R, G, and B triplets with $L = 0.27R + 0.67G + 0.06B$. Parameter selections have significant influence in rendering performance, so default parameters are used in each algorithm according to the original publications. As we developed the implementation of HDR image rendering application for sigmoidal transform and local color correction, the parameters for these two algorithms were empirically determined from preliminary experiments. A consistent color image output to minimize color shift is another important issue for color image rendering. iCAM was developed in a specific device independent color space, while other algorithms are mainly design only for tone mapping without color processing. For these algorithms, the color processing method proposed by Schlick[34] was used.

Psychophysics Experiment

The rendering results are displayed on an Apple Cinema HD LCD Display with the maximum luminance of 180 cd/m^2. The 23-inch diagonal display has a 1920 by 1200 pixels resolution, allowing two 787 by 704 pixels images to be displayed simultaneously. The LCD display was characterized with the colorimetric characterization model presented by Day.[35] The images were presented on a 20% gray background in a dark surround. Two paired comparison psychophysical experiments were implemented. The general rendering performance, including tone compressing, natural appearance, color saturation, image contrast and image sharpness, etc. were compared in the first session, while tone mapping performances of grayscale images were compared in the second section. The grayscale images used in the second section were converted from the luminance channel of the color images, discounting by the white point of LCD display to minimize the color shift in the images. In total 280 comparisons were then randomized and were presented to the observer with random selection between left and right side of the display. The display was placed at a distance of about 60 cm. Observers were presented with the task of choosing which of the two images they preferred, then clicking the image directly. On average, an observer was able to finish a section in 30 minutes.

Results and Discussion

Thirty-three and twenty-three color-normal observers with varying imaging experience took part in this experiment for the two sections respectively. Thurston's Law of Comparative Judgments, Case V, was used to analyze the paired-comparison results, and observer data were converted into an interval scale of preference. Due to the vast performance difference between some of the image pairs, there are some zero-one proportion matrix problems, where the normal deviates are undefined. Morrisey's incomplete matrix solution,[36] which uses a linear regression technique to fill in the missing z-value, was used to solve this unanimous judgment problem.

For color rendering in section 1, the interval scale along with 95% confidence limits for each scene is shown in Figure 2, and average interval scales of ten scenes are shown in Figure 3. Each model is shown along the ordinate in the order of the combined scale value, from the worst to the best. A test of Average Absolute Deviation on the interval scores results in the error of 0.042, indicating that Case V model fits the data well. From the results, Durand & Dorsey's bilateral fast filtering technique and Reinhard's photographic tone reproduction have the best overall rendering performance among the algorithms. Bilateral fast filtering technique has good results in almost all ten experimental scenes rendering except the scene "lamp_pete". Photographic tone reproduction has consistent good rendering performance in all ten scenes with slightly lower average interval score than bilateral fast filtering, but it is not statistically significant. Ward Larson's histogram adjustment and iCAM are comparable to each other, and significantly better than other four algorithms. Retinex has largest preference variance, containing the best rendering performance in scene "lamp_up" and the worst in scene "garage". The fact that Moroney's local color control technique and Sigmoidal rendering technique have low average preference indicates that traditional 8-bit image enhancement technique may have limited application in HDR image rendering. Fattal's gradient domain compression technique has the lowest preference level, perhaps because original source code is unavailable and the implementation might differ from that in the original publication.

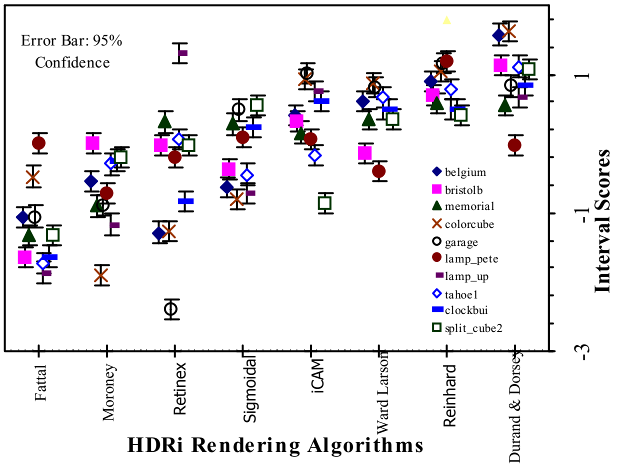

Figure 2. Interval Scores of HDR image rendering for ten scenes (color images)

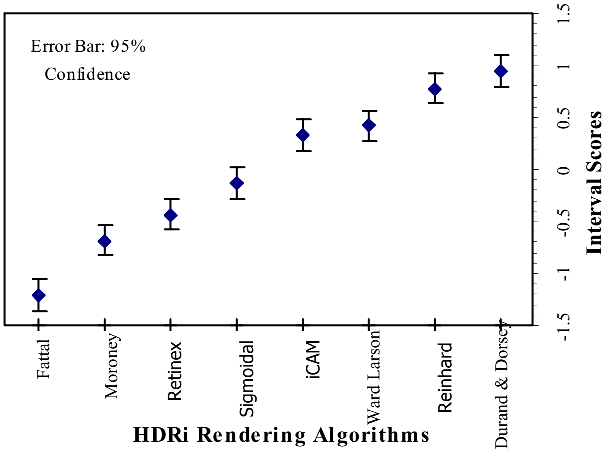

Figure 3. Average Interval Scores of HDR image rendering for ten scenes (color images)

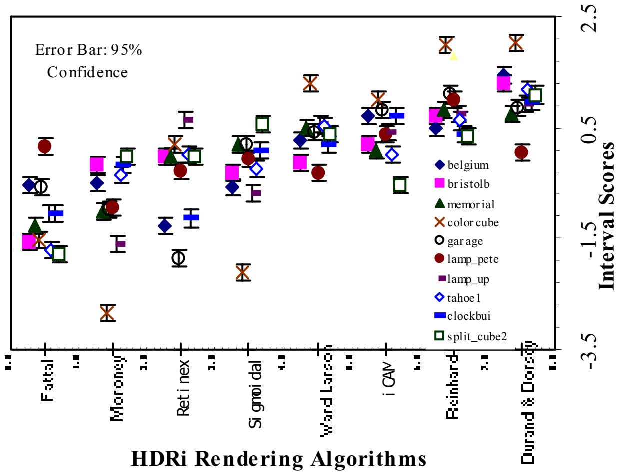

Figure 4. Interval Scores of tone mapping for ten scenes (grayscale images)

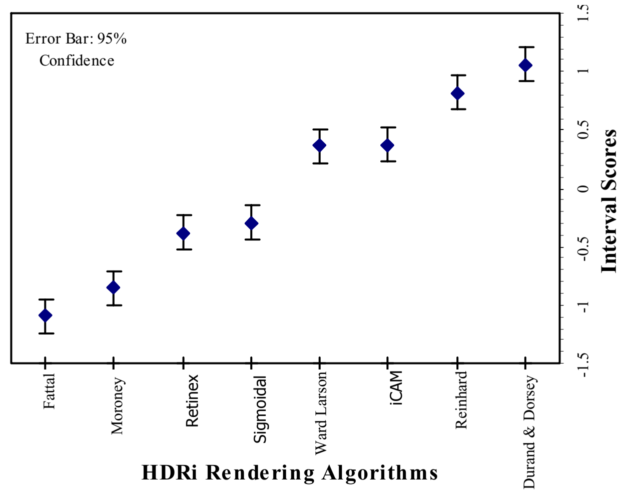

Figure 5. Average Interval Scores of tone mapping for ten scenes (grayscale images)

Figure 4 presents a graph of interval scale obtained from the grayscale tone mapping performance in ten scenes from the second section. The average interval scales for ten scenes are shown in Figure 5. Again, each model is shown along the ordinate in the order of average scale value. The Average Absolute Deviation calculated is 0.046, indicating that the model used was a good fit for the data. To determine the relationship between tone mapping and overall rendering performance, the interval scales from section one were plotted against those from section two in Figure 6. Tone mapping performance correlates with the overall rendering quite well with a correlation coefficient of 0.98. The grayscale tone mapping performances are consistent with those in the overall rendering results, if not the same. The grayscale tone mapping performances are consistent with those in the overall rendering results, if not the same. This suggests that tone-mapping performance may be a dominant factor at evaluating the overall rendering performance.

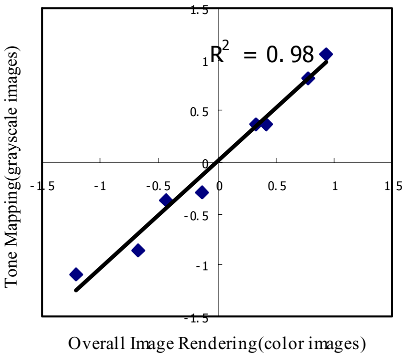

Figure 6. Tone mapping interval scores vs. overall image rendering interval scores

Conclusions

A large-scale paired comparison psychophysical experiment was developed to test the performance of eight HDR image rendering algorithms using ten pictorial scenes. In all, about 30 observers performed two experiments testing overall rendering performance and grayscale tone mapping performance respectively. Psychophysical analysis was used to created interval scales of preference. The results for these two experimental sections are consistently to each other and indicate that bilateral fast filtering technique and photographic tone reproduction have the best rendering results. Histogram adjustment and iCAM also have good rendering performance. Grayscale tone mapping performance correlates with the overall rendering rather well indicating that tone mapping is a very important factor in the overall HDR image rendering performance.

The future goal of this research is to take a close look at those HDR image-rendering algorithms with good performance, and relate the rendering attributes with specific rendering techniques. This might help to incorporate different kinds of rendering techniques into a robust model for high-dynamic-range image rendering. Instead of preference, high dynamic range scenes will be built to test reproduction accuracy.

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Biography

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