HDR Image Quality Assessment using Tone Mapping Operators

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Abstract— With the developments in Image acquisition techniques there is an increasing interest towards High Dynamic Range (HDR) images where the number of intensity levels ranges between 2 to 10,000. With these many intensity levels, the accurate representation of luminance variations is absolutely possible. But, because the standard display devices are devised to display Low Dynamic Range (LDR) images, there is a need to convert HDR image to LDR image without losing important image structures in HDR images. In the literature a number of techniques are proposed to get tone mapped image from HDR image. In this paper an attempt has been made to analyze four TMOs, i.e., Linear Mode, Gamma Correction, Reinhard and Reinhard with color correction. A subjective analysis tells us that the Reinhard with color correction has produced better results. In this paper two new tone mapping operators are proposed.***)***

Keywords*- HDR, LDR, Tone mapping, Gamma Correction*

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I. REINHARD TMO

The tone reproduction problem was first defined by photographers. Often their goal is to produce realistic "renderings" of captured scenes, and they have to produce such renderings while facing the limitations presented by slides or prints on photographic papers. Many common practices were developed over the 150 years of photographic practice [1]. At the same time there were a host of quantitative measurements of media response characteristics by developers [2]. However, there was usually a disconnect between the artistic and technical aspects of photographic practice, so it was very difficult to produce satisfactory images without a great deal of experience. Ansel Adams attempted to bridge this gap with an approach he called the Zone System [3] which was first developed in the 1940s and later popularized by Minor White [4]. It is a system of "practical sensitometry", where the photographer uses measured information in the field to improve the chances of producing a good final print. The Zone System is still widely used more than fifty years after its inception [5][6][7]. Therefore, we believe it is useful as a basis for addressing the tone reproduction problem. Before discussing how the Zone System is applied, we first summarize some relevant terminology.

Zone: A zone is defined as a Roman numeral associated with an approximate luminance range in a scene as well as an approximate reflectance of a print. There are eleven print zones, ranging from pure black (zone 0) to pure white (zone X), each doubling in intensity, and a potentially much larger number of scene zones (Figure 1).

Middle-grey: This is the subjective middle brightness region of the scene, which is typically mapped to print zone.

Dynamic range: In computer graphics the dynamic range of a scene is expressed as the ratio of the highest scene luminance to the lowest scene luminance. Photographers are more interested in the ratio of the highest and lowest luminance regions where *detail* is visible. This can be viewed as a subjective measure of dynamic range. Because zones relate logarithmically to scene luminances, dynamic range can be expressed as the difference between highest and lowest distinguishable scene zones (Figure 1).

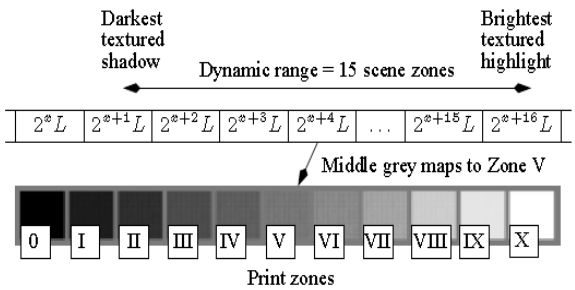

Figure 1: The mapping from scene zones to print zones. Scene zones at either extreme will map to pure black (zone 0) or white (zone X) if the dynamic range of the scene is eleven zones or more.

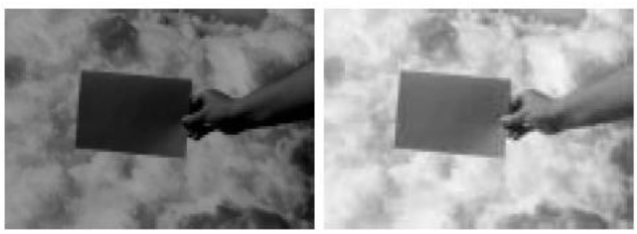
Figure 2: A normal-key map for a high-key scene (for example containing snow) results in an unsatisfactory image (left). A high-key map solves the problem (right).

Key: The key of a scene indicates whether it is subjectively light, normal, or dark. A white-painted room would be high-key, and a dim stable would be low-key.

Figure 3: A photographer uses the Zone System to anticipate potential print problems.

Dodging-and-burning: This is a printing technique where some light is withheld from a portion of the print during development (dodging), or more light is added to that region (burning). This will lighten or darken that region in the final print relative to what it would be if the same development were used for all portions of the print. In traditional photography this technique is applied using a small wand or a piece of paper with a hole cut out. A crucial part of the Zone System is its methodology for predicting how scene luminance will map to a set of print zones. The photographer first takes a luminance reading of a surface he perceives as a middle-grey (Figure 3 top). In a typical situation this will be mapped to zone V, which corresponds to the 18% reflectance of the print. For high-key scenes the middle-grey will be one of the darker regions, whereas in low-key scenes this will be one of the lighter regions. This choice is an artistic one, although an 18% grey-card is often used to make this selection process more mechanical (Figure 2). Next the photographer takes luminance readings of both light and dark regions to determine the dynamic range of the scene (Figure 3 bottom).

If the dynamic range of the scene does not exceed nine zones, an appropriate choice of middle grey can ensure that all textured detail is captured in the final print. For a dynamic range of more than nine zones, some areas will be mapped to pure black or white with a standard development process. Sometimes such loss of detail is desirable, such as a very bright object being mapped to pure white [3]. For regions where loss of detail is objectionable, the photographer can resort to dodging-and burning which will locally change the development process. The above procedure indicates that the photographic process is difficult to automate. For example, determining that an adobe building is high-key would be very difficult without some knowledge about the adobe's true reflectance.

Only knowledge of the geometry and light inter-reflections would allow one to know the difference between luminance ratios of a dark-dyed adobe house and a normal adobe house. However, the Zone System provides the photographer with a small set of subjective controls. These controls form the basis for our tone reproduction algorithm described in the following. The challenges faced in tone reproduction for rendered or captured digital images are largely the same as those faced in conventional photography. The main difference is that digital images are in sense "perfect" negatives, so no luminance information has been lost due to the limitations of the film process. This is a blessing in that detail is available in all luminance regions. On the other hand, this call for a more extreme dynamic range reduction, which could in principle, is handled by an extension of the dodging-and-burning process. We address this issue in the next section.

Algorithm of Reinhard TMO

Input: HDR image – I
Output: LDR image – im.

Step 1:	L ← Luminance of I
Step 2:	Calculate pAlpha, pWhite, pPhi
Step 3:	Lwa← Logarithmic mean of L
Step 4:	Lscaled←(pAlpha*L)/Lwa
Step 5:	Ld←Lscaled*(1+Lscaled/pWhite^2)/(1+Lscaled)
Step 6:	im←ChangeLuminance (I, L, Ld)

The simulation results of Reinhard TMO are shown in the figures 4, 5 and 6 on different images.

Figure 4: Reinhard TMO on 'small bottles_HDR' image.

Figure 5: Reinhard TMO on 'cs-warwick_HDR' image

Figure 6: Reinhard TMO on 'oxford-church_HDR' image

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II. COLOR CORRECTION

While many tone mapping algorithms offer sophisticated methods for mapping a real-world luminance range to the luminance range of the output medium, they often cause changes in color appearance. The most common tone manipulation is luminance compression, which usually causes darker tones to appear brighter and distorts contrast relationships. Figure 7B shows an HDR image after compressing luminance contrast by a factor of 0.3 while preserving pixel chrominance values (in terms of the CIE xy chromatic coordinates). When compared to the non-compressed image (exposure adjustment + sRGB display model) in Figure 8A, the colors are strongly over-saturated. If, instead of compressing luminance, all three color channels (red, green and blue) are compressed, the resulting image is under-saturated, as shown in Figure 7C. To address this problem, tone mapping algorithms often employ an ad-hoc color desaturation step, which improves the results, but gives no guarantee that the color appearance is preserved and requires manual parameter adjustment for each tone-mapped image (Figure 7D).

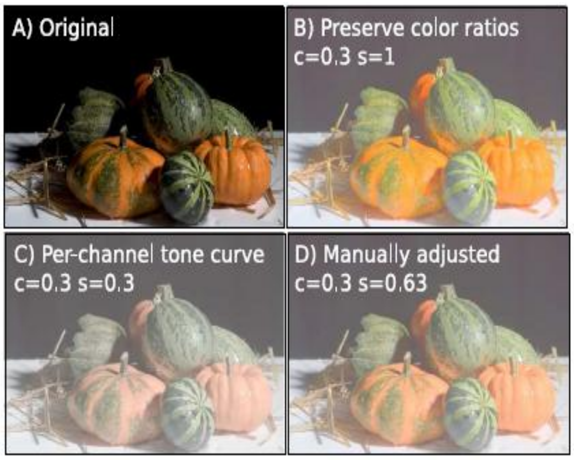

Figure 7: An original image A) compared with three images after contrast compression. Two common color correction methods B) and C) are compared with manual color adjustment D). Existing color correction methods cannot adjust colors for large contrast compression.

The common approach to color treatment in tone mapping, introduced by Schlick [8], is preserving color ratios:

$$C_{out} = \frac{C_{in}}{L_{in}} L_{out} \quad (1)$$

where C denotes one of the color channels (red, green, or blue), L is pixel luminance and *in*/*out* subscripts denote pixels before and after tone mapping. All values are given in linearized (not gamma-corrected) color space. Later papers on tone mapping, employing stronger contrast compression, observed that the resulting images are over-saturated, as shown in Figure 7B, and suggested an *ad-hoc* formula [9]:

$$C_{out} = \left(\frac{C_{in}}{L_{in}}\right)^{,2} L_{out} \quad (2)$$

where s controls color saturation. The drawback of the above equation is that it alters the resulting luminance for s6=1 and for colors different from gray, that is $kRRout + kGGout + kBBout \neq Lout$, where kR,G,B are the linear factors used to compute luminance for a given color space. This formula can alter the luminance by as much as factor of 3 for highly color saturated pixels, which is an undesirable side effect. Therefore, we introduce and examine in this paper another formula, which preserves luminance and involves only linear interpolation between chromatic and corresponding achromatic colors:

$$C_{out} = \left(\left(\frac{C_{in}}{L_{in}} - 1\right)s + 1\right)L_{out} \quad (3)$$

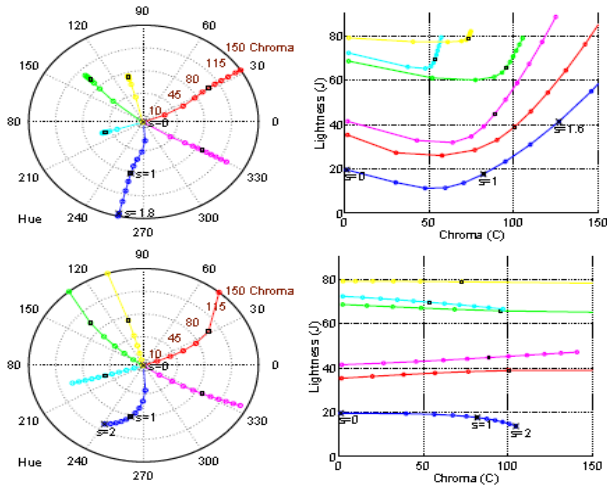

Figure 8: CIECAM02 prediction of hue, chroma and lightness for the non-linear (two plots at the top, Equation 2) and luminance preserving (two plots at the bottom, Equation 3) color correction formulas. The lines depict the change of perceptual attributes for six basic colors (red, magenta, blue, cyan, green and yellow) of different luminance when the saturation factor s varies from 0 to 2. The initial points (s = 1) are marked with black squares. The non-linear formula (Equation 2) strongly distorts lightness, but better preserves hues than the luminance preserving formula (Equation 3).

Algorithm for Color Correction

Input: LDR image – img
Output: Color corrected LDR image – imgOut.
Step 1: L← Luminance of img
Step 2: imgOut← L * (img)^{½}

The simulation results of Reinhard TMO are shown in the figures 9, 10 and 11 on different images.

Figure 9: Reinhard color correction operation on small bottles_HDR image.

Figure 10: Reinhard color correction operation on cs-warwick_HDR image.

Figure 11: Reinhard color correction operation on oxford-church_HDR image

III. GAMMA CORRECTION

Gamma correction is a built-in printer feature that allows users to adjust the lightness/darkness level of their prints. The amount of correction is specified by a single value ranging from 0.0 to 10.0. Gamma correction may be specified on both a printer default and user-specific basis across the network and on a printer default basis through the printer's front panel. Gamma correction allows users to better match the intensity of their prints to what they see on their computer screen (CRT). For instance, an image that appears just fine on the CRT might print out darker on the printer. This is because the printer "gamma" (the characteristic traversal from dark to light) is different from that of the monitor. To fix this problem, the user can select a "gamma curve" to be applied to the image before printing that will lighten or darken the overall tone of the image without affecting the dynamic range.

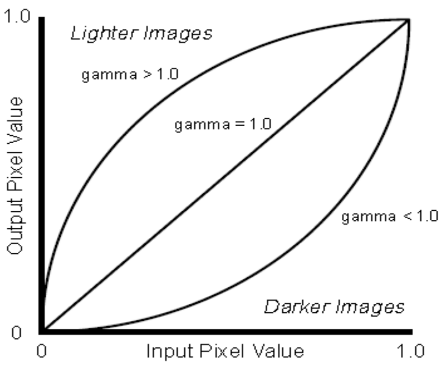

Figure 12: Gamma Curves

The shape of the gamma curve is determined by a number ranging from 0.0 to 10.0 known as the "gamma value". Figure 12 shows several gamma curves demonstrating the effect that the gamma value has on the shape of the gamma curve. In Figure 12, the pixel values range from 0.0 representing pure black, to 1.0, which represents pure white. As the figure shows, gamma values of less than 1.0 darken an image. Gamma values greater than 1.0 lighten an image and a gamma equal to 1.0 produces no effect on an image. The actual gamma function used within the printer is given as follows:

$$newval(x) = x^{\left(\frac{1}{gammaval}\right)} \quad (4)$$

where x is the original pixel value and gammaval is the gamma value ranging from 0.0 to 10.0. This curve is valuable in keeping the pure black parts of the image black and the white parts white, while adjusting the values in-between in a smooth manner. Thus, the overall tone of an image can be lightened or darkened depending on the gamma value used, while maintaining the dynamic range of the image.

Algorithm for Gamma Correction

Inputs: HDR image – img, Gamma Value – g

Output: LDR image – im.

Step 1: ig← 1/g

Step 2: I ← $(img)^{ig}$

Step 3: im←Clamp(I)

The simulation results of Gamma Correction are shown in the figures 13, 14 and 15 on different images.

Figure 13: Gamma correction on small bottles_hdr image

Figure 14: Gamma correction on cs-warwick_hdr image

Figure 15: Gamma correction on oxford church_hdr image

IV. LOGARITHMIC TMO

We presented a perception-motivated tone mapping algorithm for interactive display of high contrast scenes. In our algorithm the scene luminance values are compressed using logarithmic functions, which are computed using different.

Algorithm for Logarithmic TMO

Input: HDR image – I
Output: LDR image – im.
Step 1: L←Luminance of I
Step 2: Lmax← maximum luminance value
Step 3: Ld← log(2)/log(1+Lmax)
Step 4: im←ChangeLuminance (I, L, Ld)

The simulation results of Logarithmic TMO are shown in the figures 16, 17 and 18 on different images.

Figure 16: Logarithmic tone mapped operation on small bottles_HDR image.

Figure 17: Logarithmic tone mapped operation on cs-warwick_HDR image.

Figure 18: Logarithmic tone mapped operation on oxford-church_HDR image

V. EXPOENETIAL TMO

In terms of color reproduction, some operators produced results consistently too bright (Retina model TMO, Visual adaptation TMO, Time-adaptation TMO, Camera TMO), or too dark (Virtual exposures TMO, Color appearance TMO, Temporal coherence TMO). That, however, was not as disturbing as the excessive color saturation in Cone model TMO and Local adaptation TMO.

Algorithm for Exponential TMO

Input: HDR image – I
Output: LDR image – im.
Step 1: L←Luminance of I
Step 2: Lwa←logarithmic mean value
Step 3: Ld← 1 –$e^{L/Lwa}$
Step 4: im←ChangeLuminance (I, L, Ld)

ChangeLuminance Function:
Input: HDR image – I, Old Luminance – Lold, New Luminance – Lnew
Output: LDR image – im.
Step 1: Remove the old Luminance
Step 2: im← (I*Lnew)/Lold

The simulation results of exponential TMO are shown in the figures 19, 20 and 21 on different images.

Figure 19: Exponential tone mapped operation on small bottles_HDR image (Im-1).

Figure 20: Exponential tone mapped operation on cs-warwick_HDR image (Im-2).

Figure 21: Exponential tone mapped operation on oxford-church_HDR image (Im-3)

The comparison between different TMOs on different images is done based on Naturalness and structural similarity. These values are given in the tables 1 and 2. The simulation results of the above techniques on different images are given in figures 22, 23 and 24.

Figure 22: TMOs on Im-4

Figure 23: TMOs on Im-5

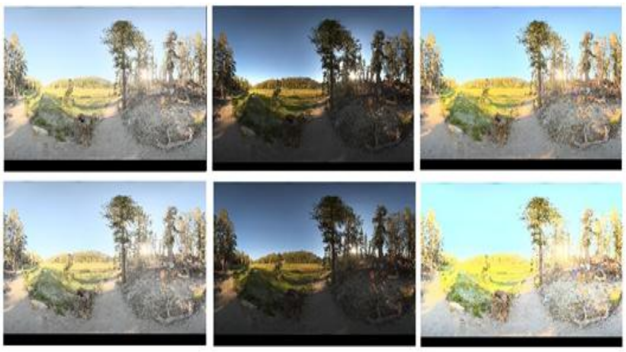

Figure 24: TMOs on Im-6

Table 1: Naturalness of different TMOs with different HDR Images

		Im1	Im2	Im3	im4	im5	im6
1	Linear Mode	1E-12	2E-12	3E-13	1.3E-12	1.5E-13	4E-12
2	Gamma Correction	2E-12	2E-12	8.9E-13	3.9E-13	6.7E-13	5E-12
3	Reinhard TMO	1.8E-12	2E-12	7.4E-13	1.5E-11	2.7E-12	7E-12
4	Reinhard Colour Correction	1.8E-12	2E-12	7.4E-13	1.5E-11	2.7E-12	7E-12
5	Logirithamic TMO	8.1E-14	1E-12	4E-14	5.5E-13	6.5E-14	1E-12
6	Exponential TMO	7.1E-12	3E-12	1.4E-11	3.2E-11	1E-11	9E-12

Table 2: Structural Similarity of different TMOs with different HDR images

	TMO	Im1	Im2	Im3	Im4	Im5	Im6
1	Linear Mode	0.0136	0.0264	0.014	0.0424	0.038	0.04
2	Gamma Correction	0.0133	0.0257	0.013	0.0423	0.038	0.04
3	Reinhard TMO	0.0136	0.0258	0.013	0.0424	0.038	0.039
4	Reinhard Color Correction	0.0133	0.0258	0.013	0.0424	0.038	0.039
5	Logirithamic TMO	0.0131	0.0257	0.013	0.042	0.038	0.04
6	Exponential TMO	0.0126	0.023	0.014	0.0403	0.036	0.037

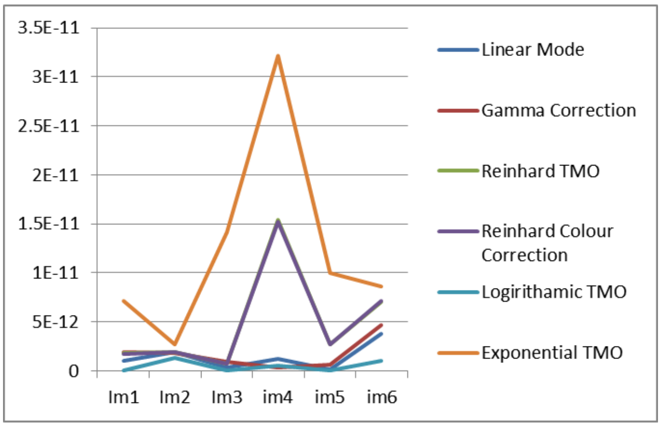

Figure 25: Naturalness of different TMOs with different HDR Images

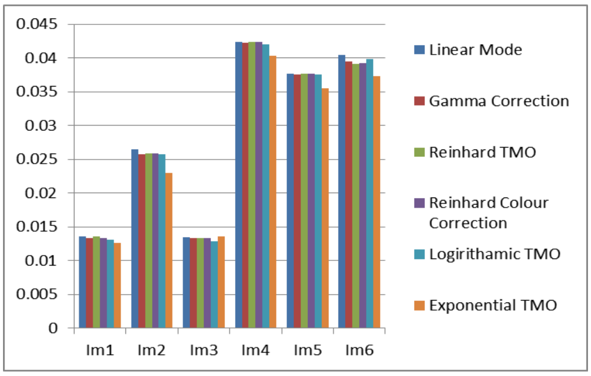

FIGURE 26: STRUCTURAL SIMILARITY OF DIFFERENT TMOS WITH DIFFERENT HDR IMAGES ACKNOWLEDGMENT

VI. CONCLUSIONS

In this paper an attempt has been made to understand and analyze different tone mapping operators. A classic photographic task is the mapping of the potentially high dynamic range of real world luminance to the low dynamic range of the photographic print. This tone reproduction problem is also faced by computer graphics practitioners who map digital images to a low dynamic range print or screen. The work presented in this paper leverages the time-tested techniques of photographic practice to develop a new tone reproduction operator. Tone mapping inevitably results in an image distortion which affects both tone and color reproduction. While many tone mapping algorithms offer sophisticated methods for mapping a real-world luminance range to the luminance range of the output medium, they often cause changes in color appearance. The most common tone manipulation is luminance compression, which usually causes darker tones to appear brighter and distorts contrast relationships. Along with TMOs, in this paper color correction techniques are presented. Two new TMOs are proposed which mapped the tone of HDR images as comparable with the existingTMOs. .

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