

Design and Implementation of Exponential and Logarithmic Tone Mapping Operators for HDR Images

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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, an 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 images. 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.

Index Terms - HDR, LDR, Tone mapping, Gamma Correction.

I. INTRODUCTION

Tone mapping is a technique used in image processing and computer graphics to map one set of colors to another to approximate the appearance of high-dynamic-range images in a medium that has a more limited dynamic range. Print-outs, CRT or LCD monitors, and projectors all have a limited dynamic range that is inadequate to reproduce the full range of light intensities present in natural scenes. Tone mapping addresses the problem of strong contrast reduction from the scene radiance to the displayable range while preserving the image details and color appearance important to appreciate the original scene content.

The introduction of film-based photography created issues since capturing the enormous dynamic range of lighting from the real world on a chemically limited negative was very difficult. Early film developers attempted to remedy this issue by designing the film stocks and the print development systems that gave a desired S-shaped tone curve with slightly enhanced contrast (about 15%) in the middle range and gradually compressed highlights and shadows [1]-[3]. Photographers have also used dodging and burning to overcome the limitations of the print process [4]-[5].

The advent of digital photography gave hope for better solutions to this problem. One of the earliest algorithms employed by Land and McCann in 1971 was Retinex, inspired by theories of lightness perception [6]. This method is inspired by the eye's biological mechanisms of adaptation when lighting conditions are an issue. Gamut mapping algorithms were also extensively studied in the context of color printing. Computational models such as CIECAM02 or iCAM were used to predict color appearance. Despite this, if algorithms could not sufficiently map tones and colors, a skilled artist was still needed, as is the case with cinematographic movie post-processing [7]-[8]. Computer graphic techniques capable of rendering high-contrast scenes shifted the focus from color to luminance as the main limiting factor of display devices. Several tone mapping operators were developed to map high dynamic range (HDR) images to standard displays. More recently, this work has branched away from utilizing luminance to extend image contrast and towards other methods such as user-assisted image reproduction [9]. Currently, image reproduction has shifted towards display-driven solutions since displays now possess advanced image processing algorithms that help adapt rendering of the image to viewing conditions, save power, up-scale color gamut and dynamic range.

The goals of tone mapping can be differently stated depending on the particular application. In some cases producing just aesthetically pleasing images is the main goal, while other applications might emphasize reproducing as many image details as possible, or maximizing the image contrast. The goal in realistic rendering applications might be to obtain a perceptual match between a real scene and a displayed image even though the display device is not able to reproduce the full range of luminance values. Various tone mapping operators have been developed in the recent years [10][11]. They all can be divided in two main types:

- *global (or spatially uniform)* operators: they are non-linear functions based on the luminance and other global variables of the image. Once the optimal function has been estimated according to the particular image, every pixel in the image is mapped in the same way, independent of the value of surrounding pixels in the image. Those techniques are simple and fast [1] (since they can be implemented using look-up tables), but they can cause a loss of contrast. Examples of common global tone mapping methods are contrast reduction and color inversion.
- *local (or spatially varying)* operators: the parameters of the non-linear function change in each pixel, according to features extracted from the surrounding parameters. In other words, the effect of the algorithm changes in each pixel according to the local features of the image. Those algorithms are more complicated than the global ones; they can show artifacts (e.g. halo effect and ringing); and the output can look unrealistic, but they can (if used correctly) provide the best performance, since human vision is mainly sensitive to local contrast.

Only the 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. These issues were addressed in the next sections.

II. 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. The shape of the gamma curve is determined by a number ranging from 0.0 to 10.0 known as the "gamma value".

Fig. 1 shows several gamma curves demonstrating the effect that the gamma value has on the shape of the gamma curve.

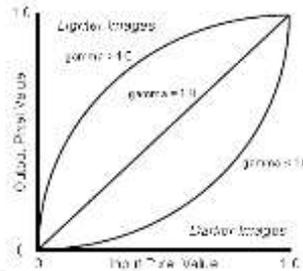


Fig. 1. Gamma Curves

In Fig. 1, the pixel values range from 0.0 representing pure black, to 1.0, which represents pure white. As the curve 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:

$$new\ val(x) = x^{\left(\frac{1}{gamma\ value}\right)} \quad (1)$$

where x is the original pixel value and 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: $ig \leftarrow 1/g$

Step 2: $I \leftarrow (img)^{ig}$

Step 3: $im \leftarrow \text{Clamp}(I)$

The simulation results of Gamma Correction are shown in the Fig. 2, 3 and 4 on different images.



Fig. 2. Gamma correction on small_bottles_hdr image



Fig. 3. Gamma correction on cs-warwick_hdr image



Fig. 4. Gamma correction on oxford church_hdr

III. REINHARD TMO

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. When compared to the non-compressed image (exposure adjustment + sRGB display model), 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. 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.

Algorithm of Reinhard TMO

Input: HDR image – I

Output: LDR image – im.

- Step 1: $L \leftarrow$ Luminance of I
- Step 2: Calculate pAlpha, pWhite, pPhi
- Step 3: $L_{wa} \leftarrow$ Logarithmic mean of L
- Step 4: $L_{scaled} \leftarrow (pAlpha * L) / L_{wa}$
- Step 5: $L_d \leftarrow L_{scaled} * (1 + L_{scaled} / pWhite^2) / (1 + L_{scaled})$
- Step 6: $im \leftarrow$ ChangeLuminance (I, L, L_d)

The simulation results of Reinhard TMO are shown in the Fig. 5, 6 and 7 on different images. The common approach to color treatment in tone mapping, introduced by Schlick [12], is preserving color ratios:

$$C_{out} = \frac{C_{in}}{L_{in}} L_{out} \quad (2)$$

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 [13]. 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, and suggested an *ad-hoc* formula [14]-[17]:

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

where s controls color saturation. The drawback of the above equation is that it alters the resulting luminance for $s \neq 1$ and for colors different from gray, that is $kRr_{out} + kGg_{out} + kBb_{out} \neq L_{out}$, 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.



Fig. 5. Reinhard TMO on 'small bottles_HDR' image



Fig. 6. Reinhard TMO on 'cs-warwick_HDR' image



Fig. 7. Reinhard TMO on 'oxford-church_HDR' image

Therefore, we introduce and examine in this paper another formula, which preserves luminance and involves only linear interpolation between chromatic and corresponding achromatic colors:

$$C_{out} = \left(\left(\frac{C_{in}}{L_{in}} - 1 \right) s + 1 \right) L_{out} \quad (4)$$

Algorithm for Color Correction

Input: LDR image – img

Output: Color corrected LDR image – imgOut.

Step 1: $L \leftarrow$ Luminance of img

Step 2: $imgOut \leftarrow L * (img)^{1/2}$

The simulation results of Reinhard TMO with color correction are shown in the Fig. 8, 9 and 10 on different images.

IV. PROPOSED TMOs

A perception-motivated tone mapping algorithm was presented for interactive display of high contrast scenes. In the proposed algorithm the scene luminance values are compressed using logarithmic functions and exponential functions.



Fig. 8. Reinhard color correction operation on small bottles_HDR image



Fig. 9. Reinhard color correction operation on cs-warwick_HDR image



Fig. 10. Reinhard color correction operation on oxford-church_HDR image

Algorithm for Logarithmic TMO

Input: HDR image – I

Output: LDR image – im.

- Step 1: $L \leftarrow$ Luminance of I
- Step 2: $L_{max} \leftarrow$ maximum luminance value
- Step 3: $L_d \leftarrow \log(2)/\log(1+L_{Max})$
- Step 4: $im \leftarrow$ ChangeLuminance (I, L, L_d)

The simulation results of Logarithmic TMO are shown in the Fig. 11, 12 and 13 on different images.



Fig. 11. Logarithmic tone mapped operation on small bottles_HDR image



Fig. 12. Logarithmic tone mapped operation on cs-warwick_HDR image



Fig. 13. Logarithmic tone mapped operation on oxford-church_HDR image

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: $L \leftarrow$ Luminance of I

Step 2: $L_{wa} \leftarrow$ logarithmic mean value

Step 3: $L_d \leftarrow 1 - e^{-L/L_{wa}}$

Step 4: $im \leftarrow$ ChangeLuminance (I, L, L_d)

ChangeLuminance Function:

Input: HDR image – I, Old Luminance – L_{old} , New Luminance – L_{new}

Output: LDR image – im.

Step 1: Remove the old Luminance

Step 2: $im \leftarrow (I * L_{new}) / L_{old}$

The simulation results of exponential TMO are shown in the Fig. 14, 15 and 16 on different images.



Fig. 14. Exponential tone mapped operation on 'small_bottles_HDR' image



Fig. 15. Exponential tone mapped operation on 'cs-warwick_HDR' image

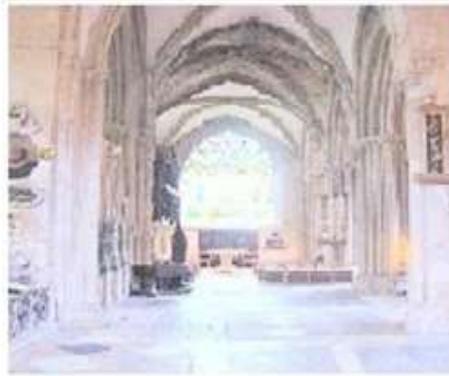


Fig. 16. Exponential tone mapped operation on 'oxford-church_HDR' image

The comparison between different TMOs on different images is done based on Naturalness and structural fidelity. 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.

Table 1. Naturalness of different TMOs with different HDR Images

| TMO | Im1 | Im2 | Im3 | Im4 | Im5 | Im6 |
|-----------------------------------|---------|-------|---------|---------|---------|-------|
| Linear Mode | 1E-12 | 2E-12 | 3E-13 | 1.3E-12 | 1.5E-13 | 4E-12 |
| Gamma Correction | 2E-12 | 2E-12 | 8.9E-13 | 3.9E-13 | 6.7E-13 | 5E-12 |
| Reinhard TMO | 1.8E-12 | 2E-12 | 7.4E-13 | 1.5E-11 | 2.7E-12 | 7E-12 |
| Reinhard Colour Correction | 1.8E-12 | 2E-12 | 7.4E-13 | 1.5E-11 | 2.7E-12 | 7E-12 |
| Logarithmic TMO | 8.1E-14 | 1E-12 | 4E-14 | 5.5E-13 | 6.5E-14 | 1E-12 |
| Exponential TMO | 7.1E-12 | 3E-12 | 1.4E-11 | 3.2E-11 | 1E-11 | 9E-12 |

Table 2. Structural Fidelity of different TMOs with different HDR Images

| TMO | Im1 | Im2 | Im3 | Im4 | Im5 | Im6 |
|----------------------------------|--------|--------|-------|--------|-------|-------|
| Linear Mode | 0.0136 | 0.0264 | 0.014 | 0.0424 | 0.038 | 0.04 |
| Gamma Correction | 0.0133 | 0.0257 | 0.013 | 0.0423 | 0.038 | 0.04 |
| Reinhard TMO | 0.0136 | 0.0258 | 0.013 | 0.0424 | 0.038 | 0.039 |
| Reinhard Color Correction | 0.0133 | 0.0258 | 0.013 | 0.0424 | 0.038 | 0.039 |
| Logarithmic TMO | 0.0131 | 0.0257 | 0.013 | 0.042 | 0.038 | 0.04 |
| Exponential TMO | 0.0126 | 0.023 | 0.014 | 0.0403 | 0.036 | 0.037 |

V. 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 existing TMOs.

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