Fast Tone Mapping for High Dynamic Range Images

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Abstract

We present a fast, effective and flexible tone reproduction method that preserves visibility and contrast impression of high dynamic range scenes in low dynamic range reproduction devices. A single parameter controls the visibility and contrast in a simple and elegant manner and at interactive speed. The new method is simple to use and is computationally highly efficient. Experiments show that the technique produces good results on a variety of high dynamic range images. The method can also be used to enhance ordinary low dynamic range digital images.

1. Introduction

The real world scenes we experience in our daily life often have a very wide range of luminance values. Human visual system is capable of perceiving scenes over five orders of magnitude and can gradually adapt to scenes with dynamic ranges of over nine orders of magnitude. With the rapid advancement of digital imaging technology, there is increasing interest in taking digital photographs that capture the full dynamic range of the scene of view. Although it is conceivable that future digital cameras would be able to capture high dynamic range (HDR) photos by the click of a button, current technology often only enables part of the real world high dynamic scene visible in any one single shot. Figure 1 illustrates such a scenario. This is an indoor scene with the sunlight shining through the window and the camera was placed at the dark end. In order to make the features near the window visible, shorter exposure was used. However, this made the scene further away from the light source too dark. To make the features in the dark end visible, we increased the exposure interval. This time, on the other hand, the areas near the window became saturated. To human observers, however, all features in the darkest as well as the brightest areas are equally clearly visible simultaneously. How to make all these features with such a wide range of radiance simultaneously visible in a single digital photo is the problem we are addressing in this paper.

In fact, recent technologies have made it relatively easy to create numerical luminance maps that capture the full dynamic range of real world scene [1]. A HDR radiance map of a scene can be generated by using a sequence of low dynamic range (LDR) images of the same scene taken under different exposure intervals.

Figure 1, Digital photos of the same scene taken with different exposure interval.

Figure 2, Result of low dynamic range display mapped from a HDR radiance map with a dynamic range of 602,055 : 1, $\alpha = 0.5$

The radiance map records the full dynamic range of the scene in numerical format. However, most reproduction devices, such as CRT monitors or printers, can only reproduce images spanned no more than a few orders of magnitude, which is significantly lower than the dynamic range of the radiance map data. In order to reproduce HDR maps in LDR devices, mapping or tone reproduction techniques are used to map HDR values to LDR values.

In this paper, we present a novel algorithm for mapping HDR scenes to LDR reproduction devices in such a way that the visibility and the visual contrast of the original scenes are well preserved in the LDR display. The organization of the paper is as follows. In section 2, we briefly review previous work. Section 3 presents a novel fast algorithm for the mapping of high dynamic range data to low dynamic range display. Section 4 presents experimental results and section 5 concludes the paper.

2. Related Work

There has been increasing interest in high dynamic range image. In the past decade or so, a number of techniques have been developed for tone reproduction for high contrast images. There are two broad categories of technology, i.e., tone reproduction curve (TRC) based and tone reproduction operator (TRO) based [2].

TRC refers to techniques that manipulate the pixel distributions. Earlier pioneering work in this category include that of [3] which introduced a tone reproduction method that attempted to match display brightness with real world sensations. More recently, [4] presented a tone mapping method that modeled some aspects of human visual system. Perhaps the most comprehensive technique in this category is that of [5], which introduced a quite sophisticated tone reproduction curve technique that incorporated models of human contrast sensitivity, glare, spatial acuity and color sensitivity.

TRO techniques involve the spatial manipulation of local neighboring pixel values, often at multiple scales. The scientific principle of this type of technique is based on the image formation model: $I(x, y) = L(x, y)\ R(x, y)$, which states that image intensity function $I(x, y)$ is the product of the luminance function $L(x, y)$ and the scene reflectance function $R(x, y)$. Because real world reflectance $R(x, y)$ has low dynamic range (normally not exceeding 100:1), reducing the dynamic range of $I(x, y)$ can be achieved by reducing the dynamic range of $L(x, y)$ if one could separate $L(x, y)$ from $R(x, y)$. Methods based on this principle include [6], [7] and [8]. They mainly differ in the way in which they attempted to separate the luminance component from the reflectance component.

Recent development has also attempted to incorporate traditional photographic technology to the digital domain for the reproduction of high dynamic range images [9].

A very impressive latest development in high dynamic range compression is that of [10]. Based on the observation that human visual system is only sensitive to relative local contrast, the authors developed a multiresolution gradient domain technique.

TRC methods do not involve spatial processing, they are therefore computationally very fast. TRO methods involve multiresolution spatial processing and are therefore computationally more expensive. Because TRO methods can reverse local contrast, they can sometimes cause "halo" effects in the reproduction. Another difficulty of traditional techniques is that there were too many parameters the users have to set which made them quite difficult to use.

3. A New TRC-based Tone Mapping Method

For high dynamic range mapping, there are at least two requirements. Firstly, it has to ensure that all features, from the darkest to the brightest, to be visible simultaneously. Secondly, it has to preserve the original scene's visual contrast to produce a visual sensation matching that of the original scene. In a sense, these two are conflicting requirements. With a reduction in dynamic range, the available values for displaying the scene are limited. If one makes all features visible, we may loose contrast. On the other hand, if one makes the display well contrast, then some features may not be visible. A good tone reproduction method has to strike a good balance between these two conflicting requirements under the constraint of limited available display dynamic range.

To preserve the original scene's visual contrast, the best one can do is to linearly map the pixels from a high dynamic range to a low dynamic range. However, since the dynamic range in the display devices is much narrower than that of the original scene, visibility will be lost due to compression. Also, linear mapping maps all values in the same way, some values in the low dynamic range may be empty thus resulting in an under utilization of all displayable values. On the other extreme, one can render the low dynamic range image that fully exploits all displayable values and has a maximum contrast, i.e., histogram equalized. However, this will alter the original scene's visual impression, because it exaggerates contrast in densely populated pixel value intervals while compress too aggressively sparsely populated intervals. A good tone reproduction algorithm will have to strike a balance between linear mapping and good visual contrast.

For any high dynamic range compression technique, whether TRC based or TRO based, some values in the high dynamic range image will have to be merged and displayed as one single value in the low dynamic range devices. The key is to decide which values in the high dynamic scene to be merged together. In TRO based techniques, the spatial context of the pixels plays a role in the decision, whilst in TRC based techniques, spatial context is not part of the consideration. Whilst TRO based techniques will explicitly preserve, sometimes even enhance, local contrast, they are often more computationally demanding and require more manually adjusted parameters, hence are less easy to use. We present a computationally simple, effective and easy to use TRC based high dynamic range compression technique.

Similar to other techniques, we only work on the luminance channel and all operations are performed in log space. To illustrate the principle, Figure 3 shows the histogram of the HDR radiance map of Figure 2. Our method is based on a rather simple observation that in any given image, there are densely populated areas and also sparsely populated areas. A tone-mapping algorithm should assign relatively more display values to the densely populated area and relatively fewer values to the sparsely populated areas while maintaining the relative contrast of the original scene. Such an operation will compress sparse regions of the histogram more while compress dense regions less (or maybe even expand slightly). While there may be many possible ways to implement this idea, we present a hierarchical, computationally simple and flexible implementation.

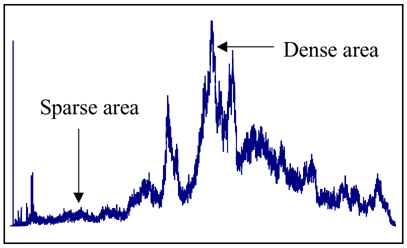

Figure 3, Log histogram of the radiance map of Figure 2.

3.1. An Implementation

Let $I(x, y)$ be the high dynamic input image. We first calculate the log value image $LI(x, y) = \log(I(x, y))$. Let L_{min} = MIN $\{LI(x, y)\}$, L_{max} = MAX $\{LI(x, y)\}$. A histogram, $\{H[k] = \textbf{\textit{Prob}}[LI(x, y) = k]\}$, is first constructed. The algorithm then divides the dynamic range $[L_{min}, L_{max}]$ into N intervals using a hierarchical division procedure.

First, a control parameter α, $0 \le \alpha \le 1$, is defined (this is the only user defined parameter in the algorithm, and its meaning will be explained shortly). We then find a value β_0, $L_{min} \le \beta_0 \le L_{min}$, such that pixel populations on both sides of the value are equal:

$$\sum_{k=L_{\min}}^{\beta_0} H[k] = \sum_{k=\beta_0}^{L_{\max}} H[k] \tag{1}$$

We then divide the dynamic range into 2 segments by finding a cutting value, C_0:

$$C_0 = \frac{L_{\max} + L_{\min}}{2} + \alpha\left(\beta_0 - \frac{L_{\max} + L_{\min}}{2}\right) \tag{2}$$

The dynamic range is now divided into two intervals: $[L_{min}, C_0]$ and $[C_0, L_{max}]$. These two intervals are then again each divided into two subsequent intervals following a similar rule.

For the segment $[L_{min}, C_0]$, we find a value $\beta_{1,0}$, $L_{min} \le \beta_{1,0} \le C_0$, such that pixel populations on both sides of the value are equal:

$$\sum_{k=L_{\min}}^{\beta_{1,0}} H[k] = \sum_{k=\beta_{1,0}}^{C_0} H[k] \tag{3}$$

We then divide the interval into 2 segments by finding a cutting value, $C_{1,0}$:

$$C_{1,0} = \frac{C_0 + L_{\min}}{2} + \alpha\left(\beta_{1,0} - \frac{C_0 + L_{\min}}{2}\right) \tag{4}$$

Similarly, for the segment $[C_0, L_{max}]$ we find a value $\beta_{1,1}$, $C_0 \le \beta_{1,1} \le L_{max}$, such that

$$\sum_{k=C_0}^{\beta_{1,1}} H[k] = \sum_{k=\beta_{1,1}}^{L_{\max}} H[k] \tag{5}$$

We then divide the interval into 2 segments by finding a cutting value, $C_{1,1}$:

$$C_{1,1} = \frac{L_{\max} + C_0}{2} + \alpha\left(\beta_{1,1} - \frac{L_{\max} + C_0}{2}\right) \tag{6}$$

As a result, the dynamic range will be divided into 4 intervals: $[L_{min}, C_{1,0}]$, $[C_{1,0}, C_0]$, $[C_0, C_{1,1}]$ and $[C_{1,1}, L_{max}]$.

We then perform the procedure recursively for each of the intervals and divide each into two segments. After n iterations, the dynamic range would have been divided into $N = \mathbf{2^n}$ segments. Pixels that fall into the same segments are then mapped to the same display value in the low dynamic range devices.

The only control parameter the user has to set in the algorithm is α. If $\alpha = 0$, the mapping is linear, if $\alpha = 1$, the mapping is histogram equalized. Setting $0 \le \alpha \le 1$, we control the mapping between linear and histogram equalized in a very simple and elegant way. For most images, setting $\alpha = 0$ will result in low visibility whilst setting $\alpha = 1$ will result in artificial contrast. By setting a single parameter $0 \le \alpha \le 1$ we can strike a balance between good visibility and well-preserved visual contrast. In fact our experiences showed that by setting $\alpha = 0.5$ as default worked very well for a variety of images. The method is computationally very simple. The parameter can be controlled at an interactive speed even for very large size images thus making the effects of changing the parameter instantly visible. To map an image of 768 x 512 pixels on a Pentium 4 with 1800MHz CPU using non-optimized code, the process takes about 0.47s.

4. Experimental Results

The technique has been tested on a variety of high dynamic range images. The luminance signal is calculated as: $L = 0.299{*}R{+}0.587{*}G{+}0.114{*}B$. $\text{Log}(L)$ is computed to compile a histogram (we used 1,000,000 bins in all our results). The dynamic range was divided into 256 intervals thus compressing the original high dynamic range to 256 values for display. We use following formula to compute the output LDR pixels

$$R_{out} = \left(\frac{R_{in}}{L_{in}}\right)^{\gamma} L_{out}, G_{out} = \left(\frac{G_{in}}{L_{in}}\right)^{\gamma} L_{out}, B_{out} = \left(\frac{B_{in}}{L_{in}}\right)^{\gamma} L_{out} \tag{7}$$

where L_{in} and L_{out} are luminance values before and after compression, γ controls display color (setting it between 0.4 and 0.6 worked well). How to compute the mapped luminance for display devices is a well-studied problem [11]. In our implementation, we simply gave all pixels mapped to the first interval a luminance value of 0 and those to the last interval a luminance value of 255. Because compression will inevitably loose some fine details, we found that sharpening the results a little improved the visual sharpness somewhat.

Figure 2 shows the result of displaying a HDR image with a dynamic range of 602,055 : 1. Figures 4 shows more examples of mapped HDR images. Subjective comparisons indicated that our results are comparable to those of other techniques in public literature, e.g., [4, 5, 7, 8, 9, 10].

Figure 4, Outputs from the new high dynamic range mapping technique. **Memorial Church**: Radiance map courtesy of Paul Debevec, L_{max} = 224.8, L_{min} = 0.00066, dynamic range: 340,016:1, α = 0.55. **Bathroom**: Radiance map courtesy of Gregory Ward Larson, L_{max} = 990.00, L_{min} = 0.01745, dynamic rang: 56,731:1. α = 0.5. **Car Park**: Radiance map courtesy of Sumant Pattanaik. L_{max} = 281.256, L_{min} = 0.1968, dynamic range: 1,429:1. α=0.6. **Nave**: Radiance map courtesy of Paul Debevec. L_{max} = 4178.047852, L_{min} =0.0, α = 0.55.

Figure 5, Result of enhancing ordinary LDR image. Left: original (24-bit RGB true color image), Right: enhanced, α = 0.5

The method is equally applicable to the enhancement of LDR images, an example is shown in Figure 5.

5. Conclusions

In this paper, we have presented a computationally efficient and very simple to use high dynamic range compression technique. Results have demonstrated the effectiveness of the new technique.

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