Adaptive Local Tone Mapping Based on Retinex for High Dynamic Range Images

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***Abstract*--In this paper, we present a new tone mapping technique for high dynamic range images based on the retinex theory. Our algorithm consists of two steps, global adaptation and local adaptation of the human visual system. In the local adaptation process, the Gaussian filter of the retinex algorithms is substituted with a guided filter to reduce halo artifacts. To guarantee good rendition and dynamic range compression, we propose a contrast enhancement factor based on the luminance values of the scene. In addition, an adaptive nonlinearity offset is introduced to deal with the strength of the logarithm function's nonlinearity. Experiments show that our algorithm provides satisfactory results while preserving details and reducing halo artifacts.**

I. INTRODUCTION

The dynamic range of real world scenes is extensively large spanning over four orders from shadows to highlights [1]. Due to its adaptation mechanisms, the human visual system can cope with the real scenes. However, photographs are different from the real scenes, such as daylight outdoor scenes whose dynamic range is vast. The dynamic range of a scene cannot be captured by a conventional camera or a digital camera because of their imperfectness [2]. Although high dynamic range (HDR) images containing the full dynamic range of the real scene can be obtained from differently exposed photographs [3], low dynamic range (LDR) display devices such as ordinary monitors cannot handle the full dynamic range of the scene. The devices can display only two orders of magnitude [1], [4]. Once the HDR images are linearly mapped to the display devices, much information is lost. Thus, the HDR images must be compressed before being mapped to the devices. The mapping techniques from the HDR images to the LDR display devices are called tone mapping or tone reproduction which is related with our work.

There are two categories separating the techniques: first one is the global operator, and the other one is the local operator [2]. The global tone mapping operators apply a single function to all pixels. Drago *et al.* [5] presented logarithmic compression of scene's luminance values with an adaptive logarithm base. In the darkest area, they used 2 as a logarithm base, whereas they used 10 as a logarithm base to compress contrast more in the highest area. Later, Cvetković *et al.* [6] introduced an improved tone mapping function based on splines which enhances the visibility in dark regions while preserving the visibility in bright regions. Furthermore, they combined their algorithm with a multiple-exposure technique to improve SNR in dark regions. These global methods usually require low computational complexity but cannot preserve the details of the scene.

The local tone mapping operators apply different functions to each pixel based on its neighborhood pixels. Reinhard *et al*. [1] developed a new tone mapping operator which uses a photographic experience called Zone System. They introduced an automatic dodging and burning technique to avoid loss of details. Durand and Dorsey [7] introduced a fast bilateral filter to decompose the image into a base layer and a detail layer. They reduced contrast of the base layer, while preserving the detail layer. Fattal *et al*. [8] presented a new method based on gradients. They attenuated magnitudes of the large gradients in a logarithm domain using a gradient attenuation function. After solving a Poisson equation, the tone mapped image was obtained. Later Meylan and Susstrunk [4] proposed a retinex based method to render HDR images. They introduced an adaptive filter and a sigmoid function to solve the drawbacks of the surround-based retinex. These local methods usually perform better than global methods, but there are several drawbacks. One is that the local methods are more complex than global methods. The other is that halo artifacts arise from utilizing neighborhood pixels. Accordingly, along with preserving visual contents and the overall appearance of the original scene, reducing halo artifacts must be considered when designing a tone mapping operator. Especially, it is important to preserve much information from scenes for video surveillance systems.

In this paper, we propose a new local tone mapping method that preserve details and prevent halo artifacts based on the center /surround retinex [9-11].

This paper is organized as follows. Section 2 reviews the center/surround retinex which is the basis for our work. We investigate the characteristics of the center/surround retinex and describe its drawbacks. Our new tone mapping operator is proposed in Section 3, and Section 4 provides experimental results. Finally, Section 5 concludes our work.

II. CENTER/SURROUND RETINEX

The retinex theory was initially defined by Land [12]. It explains how the reliable color information from the world is extracted by the human visual system [4]. Based on the center/surround retinex [9], Jobson *et al.* introduced the single-scale retinex (SSR) [10] and the multiscale retinex (MSR) [11]. In this paper, these are called retinex algorithms. SSR is given by

$$R_i(x,y) = \log I_i(x,y) - \log(F(x,y) * I_i(x,y)), \tag{1}$$

where x, y are the pixel coordinates in the image, $R_i(x,y)$ is the retinex output, $I_i(x,y)$ is the image distribution in the i-th spectral band, * denotes the convolution operation, and $F(x,y)$ is the Gaussian surround function,

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$$F(x,y) = Ke^{-(x^2+y^2)/c^2}, \quad (2)$$

where c is the Gaussian surround space constant. K is the normalization factor.

A small space constant produces good dynamic range compression but bad color rendition. Conversely, a large constant produces good color rendition but bad dynamic range compression [10], [11]. MSR is described in (3),

$$R_{MSR_i}(x,y) = \sum_{n=1}^{N} \omega_n R_{n_i}(x,y), \quad (3)$$

where N is the number of scales, $R_{n_i}(x,y)$ is the i-th component of the n-th scale, $R_{MSR_i}(x,y)$ is the i-th spectral component of the MSR output, and ω_n is the weight associated with the n-th scale.

The purpose of MSR is to reduce halo artifacts around high contrast edges and to keep balance with the dynamic range compression and the color rendition. MSR produces good dynamic range compression, but still suffer from halo artifacts. In addition, SSR with small space constant makes large uniform regions graying out and flat-looking in images. These drawbacks are shown in Fig. 1 and also investigated in previous studies, such as [10], [11], [4].

(a) (b)

Fig. 1. Results of the retinex algorithms with drawbacks. (a) MSR output. (b) SSR output with small space constant.

III. PROPOSED TONE MAPPING BASED ON RETINEX

In Section 2, we described the characteristics and drawbacks of the retinex algorithms. These drawbacks are overcome by introducing a new method. In our algorithm, luminance values are obtained from input HDR images and processed. First, we apply a global tone mapping as a preprocessing. After that, a local tone mapping is applied based on the retinex algorithms. Finally, after normalization, an output image is obtained from the processed luminance values and the input chrominance values.

A. Global Adaptation

Global adaptation takes place like an early stage of the human visual system [4]. The human visual system senses brightness as an approximate logarithmic function according to the Weber-Fechner law [5]. To globally compress the dynamic range of a HDR scene, we use the following function in (4) presented in [5].

$$L_g(x,y) = \frac{\log(L_w(x,y)/\overline{L}_w + 1)}{\log(L_{w\max}/\overline{L}_w + 1)}, \quad (4)$$

where $L_g(x,y)$ is the global adaptation output, $L_w(x,y)$ is the input world luminance values, $L_{w\max}$ denotes the maximum luminance value of the input world luminance values, $\overline{L}_w$ and is the log-average luminance [1] and given as

$$\overline{L}_w = \exp\left(\frac{1}{N}\sum_{x,y}\log(\delta + L_w(x,y))\right), \quad (5)$$

where N is the total number of pixels in the image and δ is the small value to avoid the singularity that occurs if black pixels are present in the images.

The input world luminance values and the maximum luminance values are divided by the log-average luminance of the scene. This enables (4) to adapt to each scene. As the log-average luminance converges to the high value, the function converges from the shape of the logarithm function to the linear function. Thus, scenes of the low log-average luminance are boosted more than scenes with high values. As a result, the overall scene luminance values are adequately compressed in accordance with the log-average luminance of the scene.

B. Local Adaptation

Local adaptation based on the retinex theory is applied after the global adaptation process. In (1), the output $R_i(x,y)$ of the input $I_i(x,y)$ which lies near the much brighter pixel values become very dark, and this causes the halo artifacts which make the result looks unnatural. The artifacts can be reduced by introducing an edge-preserving filter. We substitute the guided filter [13] for the Gaussian filter of the retinex algorithms. The guided filter is an edge-preserving filter like the bilateral filter [14] whose weights depend not only on the Euclidean distances but also on the luminance differences. These filters behave similar, but the guided filter has better performance near the edges [13]. Also, its computational complexity is linear-time without approximation and independent of the kernel size [13]. The local adaptation equation can be written as

$$L_l(x,y) = \log L_g(x,y) - \log H_g(x,y), \quad (6)$$

where $L_l(x,y)$ denotes the local adaptation output, and $H_g(x,y)$ is the output of the guided filter applied to $L_g(x,y)$,

$$H_g(x,y) = \frac{1}{|\omega|}\sum_{(\xi_x,\xi_y)\in\omega(x,y)} (a(\xi_x,\xi_y)L_g(x,y) + b(\xi_x,\xi_y)), \quad (7)$$

where ξ_x, ξ_y are the neighborhood pixel coordinates, $\omega(x,y)$ is a local square window of a radius r centered at the pixel (x,y),

| ω | is the number of pixels in $\omega(x,y)$, $a(\xi_x, \xi_y)$ and $b(\xi_x, \xi_y)$ are some linear coefficients,

$$a(\xi_x,\xi_y)=\frac{\mu_2(\xi_x,\xi_y)-\mu^2(\xi_x,\xi_y)}{\sigma^2(\xi_x,\xi_y)+\varepsilon}, \tag{9}$$

$$b(\xi_x,\xi_y)=\mu(\xi_x,\xi_y)-a(\xi_x,\xi_y)\mu(\xi_x,\xi_y), \tag{10}$$

where $\mu(\xi_x, \xi_y)$ and $\sigma_2(\xi_x, \xi_y)$ are the mean and variance of L_g in $\omega(\xi_x, \xi_y)$, $\mu_2(\xi_x, \xi_y)$ is the mean of L^2_g in $\omega(\xi_x, \xi_y)$, and ε is a regularization parameter. The guidance and input image of the guided filter are identical in our algorithm.

After applying the filter, the halo artifacts are significantly reduced, but the output gives unsatisfactory overall appearance due to its low global contrast. Because of the characteristics of the edge-preserving filter, the filter assigns very low weights to the neighborhood pixels which have large differences between their luminance values and the value of the center pixel. As a result, $L_g(x,y)$ and $H_g(x,y)$ values of (6) tend to be analogous, which make no large differences among pixels of the local adaptation output. The result of (6) gives flat-looking appearance and loses its original luminance distribution of the input image. This analysis leads us to introduce new methods.

To prevent the flat-looking appearance caused by the filter and improve the performance of our method, we introduce two important factors. One, the contrast enhancement factor is given by

$$\alpha(x,y)=1+\eta\frac{L_g(x,y)}{L_{g\max}}, \tag{11}$$

where η denotes the contrast control parameter, and $L_{g\max}$ is the maximum luminance value of the global adaptation output.

The other, the adaptive nonlinearity offset which varies in accordance with the scene contents can be written as

$$\beta=\lambda\overline{L}_g, \tag{12}$$

where λ is the nonlinearity control parameter, and $\overline{L}_g$ is the log-average luminance of the global adaptation output.

By integrating these factors into (6), the final local adaptation equation is established as follows:

$$L_{out}(x,y)=\alpha(x,y)\log\left(\frac{L_g(x,y)}{H_g(x,y)}+\beta\right), \tag{13}$$

where $L_{out}(x,y)$ is the final local adaptation output.

We introduce the contrast enhancement factor $\alpha(x,y)$ to achieve satisfactory overall appearance of the rendered image. As mentioned above, using the guided filter causes the flat-looking appearance. The global adaptation output $L_g(x,y)$ controls the contrast enhancement factor of each pixel. Originally dark pixels make the contrast enhancement factor low and bright pixels make the factor high. Therefore, the local adaptation output has more natural appearance than before by considering the globally compressed scene's luminance values.

TABLE Ⅰ
The parameters used for our experiments.

Parameters	Value
r	10
ε	0.01
η	36
λ	10

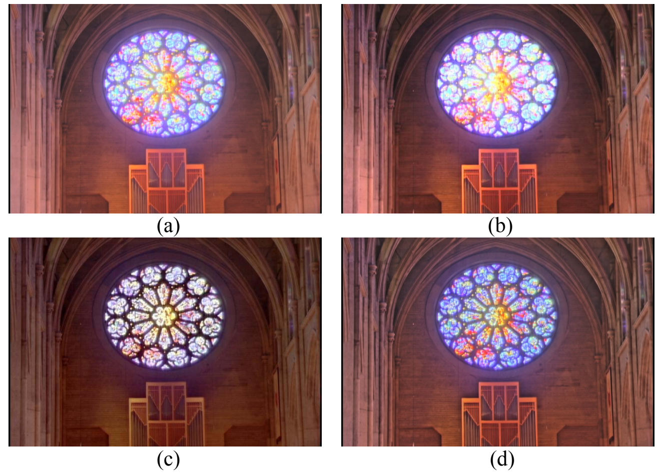

Fig. 3. Tone mapping results of Rosette. (a) Adaptive Logarithmic. (b) Photographic. (c) Retinex based adaptive filter. (d) Proposed.

In order to control the nonlinearity of the logarithm function according to the scene, we propose the adaptive nonlinearity offset β. The logarithm function is a nonlinear function whose gradient is gradually decreasing. The log-average luminance of the global adaptation output controls the strength of the nonlinearity by changing the starting point of the logarithm in (13). The low log-average luminance of the global adaptation output makes the logarithm function start from a large gradient. Then, the logarithm curve increases the overall luminance values more than the high log-average luminance case. This ensures proper mapping of the local adaptation output based on the scene contents.

After the local adaptation, the processed luminance values are rescaled from 0 to 1. Finally, the tone mapped image is obtained from the luminance values of the local adaptation output and the input HDR image.

IV. EXPERIMENTAL RESULTS

A variety of HDR images are tested in our experiments and the following luminance value is used: $L = 0.299R + 0.587G + 0.114B$. The parameters used for our experiments are shown in Table Ⅰ and the default parameters work well for various HDR images. The values of the radius r and regularization parameter ε of the guided filter keep balance with reducing halo artifacts and preserving the local contrast, the value of the nonlinearity control parameter λ ensures appropriate consideration to the contents of the scene, and the value of the contrast control parameter η provides proper overall contrast. As λ and η become larger, the overall luminance values of the output become darker and the global contrast of the output increases respectively.

The comparison with other tone mapping operators which are the adaptive logarithmic method [5], the photographic

(a) (b) (c) (d)

Fig. 4. Tone mapping results of Stanford Memorial Church. (a) Adaptive Logarithmic. (b) Photographic. (c) Retinex based adaptive filter. (d) Proposed.

method [1], the retinex based adaptive method [4], and the proposed method is presented in Fig. 3 and Fig. 4. All the methods are tested with default parameters. Since it is difficult to evaluate the objective performance of the methods, we choose psychophysical experimentation to evaluate the results. First three methods cannot preserve details well in bright region, but our method not only preserves a lot of visual contents but also shows good overall appearance which is competitive or better than other methods. The enlarged images in Fig. 4 show that our method displays the clearest details of all the available methods. Besides, it is another advantageous of our method that users can control the global contrast depending on its application.

Excluding the guided filtering process, our method takes 26ms for 512*768 pixels on 2.40 GHz Core 2 Quad with un-optimized code. The running time of the guided filtering which is faster than bilateral filtering is reported in [13].

V. CONCLUSIONS

With the increasing use of HDR images, the tone mapping techniques have been widely studied. We propose a local tone mapping algorithm based on the retinex theory to process the HDR images. Instead of using the Gaussian filter of the retinex algorithms, we adopt a guided filter to reduce the halo artifacts. We found that the guided filter does not take full advantage of neighborhood pixels, which causes the flat-looking appearance. To prevent this drawback, we introduce the contrast enhancement factor. Furthermore, we handle the logarithm function's nonlinearity by adding the adaptive nonlinearity offset. With these factors, we simultaneously achieve a good dynamic range compression and good overall appearance. The experimental results demonstrate that our method yields satisfactory rendering of HDR images and preserves much details, which will be beneficial for future video surveillance systems and consumer digital cameras.

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