2014 IEEE International Conference on Systems, Man, and Cybernetics
October 5-8, 2014, San Diego, CA, USA

Affine Invariant Features-Based Tone Mapping Algorithm for High Dynamic Range Images

Qiaosong Chen, Hai Li, Yuanyuan Ding, Chang Liu, Jin Wang, Xin Deng
Chongqing Key Laboratory of Computational Intelligence
Chongqing University of Posts and Telecommunications
Chongqing 400065, PR China

***Abstract*—Conventional digital display devices, due to their hardware limitations, can't represent the whole range of luminance in High Dynamic Range (HDR) images. In order to solve this incompatible problem, many tone mapping techniques were introduced to reproduce HDR images. Unlike the traditional methods applied in standard scale space, this paper proposes a novel affine invariant features-based tone mapping algorithm in affine Gaussian scale space. The reason of using this scale space is due to the fact that it is able to extract anisotropic feature regions in addition to traditional isotropic feature regions. Firstly, the proposed method extracts the anisotropic features from HDR images and reforms them to be isotropic by Fitting & Affine transformation. Then, dodging-and-burning processing is utilized to obtain base layer of HDR images. Finally, two-scale edge-preserving decomposition is employed to generate detail layer of HDR images and combine two layers to produce output images. Experimental results show that the proposed algorithm outperforms previous methods for reproducing the real scene of HDR images, especially for large perspective and scale transformed images which contain considerable anisotropic feature regions.**

Keywords—tone mapping; affine Gaussian scale space; dodging-and-burning; two-scale image decomposition;

I. INTRODUCTION

The dynamic range of luminance is a ratio between the highest luminance and the lowest one in a real scene. The larger the dynamic range becomes, the better it can present a real scene. The dynamic range of luminance in real world is very vast [1]. For example, the luminance of direct sunlight is up to 10^5cd/m^2; while that of the shadows might be 10^{-3}cd/m^2. The dynamic range is close to 10^8:1. Unlike traditional digital images stored by limited dynamic range formats such as JPEG, BMP and etc., HDR images are introduced as a new type of image to present a real scene with much wider dynamic range of luminance. It typically applies floating-point data to store the information of real scene completely [2]. However, the maximum intensity radiation of commercial imaging devices is limited. As the maximum brightness of the common display monitor is 100cd/m^2, the actual dynamic range is only 100:1. Thus, HDR images can not be completely presented in conventional digital display devices without adaption. Moreover, poor visual effects, blurred details and loss of information might occur [3].

In order to solve this problem, tone mapping (also called tone reproduction) operators can be employed to realize a proper dynamic range representation. By these operators, output images can preserve the information provided by HDR images and match the original real scene as far as possible. Especially, these operators should preserve well edges, details and colors [4].

Recently, tone mapping operator has been an active research area and many techniques have been proposed. In 2002, Erik Reinhard et al. [5] utilized a local averaging logarithmic operator and applied an automated dodging-and-burning algorithm (Reinhard Local Tone Mapping Algorithm, RLTMA). It convolves a circular Gaussian filter with the entire image at scale space, which improves the bright and dark regions of the original HDR images. In 2005, Michael Elad [6] provided a non-iterative bilateral filter-based retinex tone mapping algorithm (BilateralRTMA). It can preserve edges well in bright areas, and suppress the noise in dark areas. In 2007, Garrett M. Johnson et al. [7] published a new image color appearance model (iCAM06). It incorporates the spatial processing models in human visual system for contrast enhancement, and enhances local details in highlights and shadows through photoreceptor light adaptation functions. In 2008, Zeev Farbman et al. [8] proposed a new edge-preserving tone mapping algorithm (EdgePTMA). The weighted least squares optimization frame work is used to coarsen images and extract multi-scale details. Then it constructs multi-scale decompositions and results in detail enhancement. In 2011, Sylvain Paris et al. [9] delivered a new edge-aware tone mapping algorithm based on local Laplacian filters (LaplacianFTMA). Standard Laplacian pyramids are utilized to differentiate large-scale edges from small-scale details and achieve edge-preserving smoothing and detail enhancement. LaplacianFTMA can produce high-quality results without blurring edges or introducing halos.

Until now, most of tone mapping algorithms have already been proposed based on standard scale space. This scale space is regarded as somewhat inefficient capabilities in edge-preservation. This paper puts forward a new tone mapping method on affine Gaussian scale space, which is efficient in edge-aware processing. It consists of two steps. Firstly, anisotropic dodging-and-burning is applied to coarsen image and extract details at various spatial scales. Secondly, two-scale decomposition is implemented to split HDR image into a

This work was partially sponsored by the Huawei Innovation Research Program (No. YB2013120140), the National Natural Science Foundation of China (No. 61203308), and the Natural Science Foundation Project of CQ CSTC under Grant No. cstc2012jjA40034.

978-1-4799-3840-7/14/$31.00 ©2014 IEEE

base layer and a detail layer, and then combine the two layers to output edge-preserving images.

The remainder of this paper is organized as follows. Section 2 introduces the fundamental background of dodging-and-burning algorithm, affine Gaussian scale space method and affine feature extraction. Section 3 shows the proposed algorithm in detail. In section 4, performance evaluations are explained. Finally, section 5 concludes the paper.

II. Research Background

A. Dodging-and-burning

RLTMA consists of global operator and local operator. The former utilizes a log-average luminance function to compress the HDR images integrally; the latter employs automatic dodging-and-burning to process different regions of images, brightening selected dark regions and darkening selected light regions to avoid loss of details [10].

Dodging-and-burning is a method derived from printing technique that withholds some light from a bright region in an image (dodging), or adds more light to that region (burning). RLTMA typically applies dodging-and-burning to operate an entire region bounded by large contrast. The size of a local region is calculated based on the measure of local contrast, which is obtained by multiple spatial scales [11]. Dodging-and-burning is advised to adopt a center-surround function at each spatial scale, rooting in subtracting two Gaussian blurred images.

Here, a circular Gaussian filter [12] is introduced in (1):

$$R_i(x,y,s) = \frac{1}{\pi(\alpha_i s)^2}\exp\left(-\frac{x^2+y^2}{(\alpha_i s)^2}\right) \tag{1}$$

where x, y denote the horizontal and vertical coordinate of a pixel, respectively. s is a scale of Gaussian filter, α_i represents a scaling parameter. Then, an image convolution function is given by (2):

$$V_i(x,y,s) = L(x,y) \otimes R_i(x,y,s) \tag{2}$$

A center-surround function is defined by (3):

$$V(x,y,s) = \frac{V_1(x,y,s) - V_2(x,y,s)}{2^{\Phi} a/s^2 + V_1(x,y,s)} \tag{3}$$

where center V_1 and surround V_2 are calculated by (1) and (2). Equation (3) is directly applied to detect the largest local neighborhood where no drastic change of contrast occurs in isotropic regions.

To choose the largest neighborhood around a pixel where no large contrast changes occur, selection of proper scale $s_{\max}$ is needed, where

$$\left|V(x,y,s_{\max})\right| < \varepsilon \tag{4}$$

is true. Here, ε represents a small positive threshold. If no obvious change happens in a neighborhood bound by $s_{\max}$, it means that the values of surrounding pixels in the neighborhood are similar. For a given value $s_{\max}$, $V_1(x,y,s_{\max}(x,y))$ will serve as a local average for that given pixel. Dodging-and-burning can automatically select an appropriate neighborhood for each pixel and implement a pixel-by-pixel dodging and burning operator effectively, so as to create subjectively satisfactory and essentially artifact-free output images.

B. Affine Gaussian Scale Space Method

In 1994, Lindeberg [13] proposed standard scale space method to solve the isotropic scaling in images. It uses a set of Gaussian filters of different scales to convolute an image, as shown in (5):

$$\left|LoG(X,\sigma_n)\right| = \sigma_n^2 \left|L_{xx}(X,\sigma_n) + L_{yy}(X,\sigma_n)\right| \tag{5}$$

where σ_n represents the standard deviation of the Gaussian filter, $L(X,\sigma_n)$ is the Gaussian filtered image, $L_{xx}(X,\sigma_n)$ and $L_{yy}(X,\sigma_n)$ denote the second derivative in the x direction and y direction, respectively.

Since standard scale space method can solve the isotropic scaling only, Lindeberg published affine Gaussian scale space method [14] under anisotropic case. Thus, an anisotropic Gaussian filter is introduced in (6):

$$g(x,\Sigma) = \frac{1}{2\pi\sqrt{\det\Sigma}}\exp(-x^T\Sigma^{-1}x/2) \tag{6}$$

And image convolution function is given by (7):

$$L(x,\Sigma) = g(x,\Sigma) \otimes f(x) \tag{7}$$

This operation is equivalent to convolute an image with a rotating elliptical Gaussian filter. Unlike the standard scale space method applied on Gaussian filter, the affine Gaussian scale space method can be utilized on elliptical Gaussian filter. Compared with Gaussian filter, elliptical Gaussian filter is suitable for edge-aware operations, such as edge-preserving smooth, detail enhancement and tone mapping.

C. Extraction Of MSERs

In 2004, J Matas et al. [15] suggested a maximally stable extremal regions (MSERs) based on watershed method. It is an effective operator to extract affine feature regions. The extraction of MSERs is determined by (8):

$$q(i) = \frac{\left|Q_{i+\Delta}\right| - \left|Q_{i-\Delta}\right|}{\left|Q_i\right|} \tag{8}$$

where $Q_1,\ldots,Q_{i-1},Q_i\ldots$ are a series of nested extreme regions, and $Q_i \subset Q_{i+1}$. If $q(i)$ can get local minimum value by i^*, this corresponding region Q_{i^*} is MSERs.

Haja Andreas [16] points out that MSERs operator is one of the most stable and effective methods detecting the affine invariant feature regions. In practice, MSERs operator has been demonstrated to have better performance than other affine invariant extractor.

III. PROPOSED TONE MAPPING ALGORITHM

Since rotation, scaling and translation might occur in image acquisition, original HDR images usually contain a lot of anisotropic regions. For example, isotropic circular area might be recorded as anisotropic elliptical area in photography due to non-vertical shooting angles. However, (1) and (2) imply that dodging-and-burning is unable to be applied in anisotropic regions because they are based on standard scale space. In order to solve this problem, this paper proposes Affine Invariant Features-based Tone Mapping algorithm (AIFTMA) in affine Gaussian scale space. The flowchart of proposed AIFTMA is shown in Fig. 1. It applies a new anisotropic dodging-and-burning method including three steps, and then adopts two-scale decomposition to output the final results.

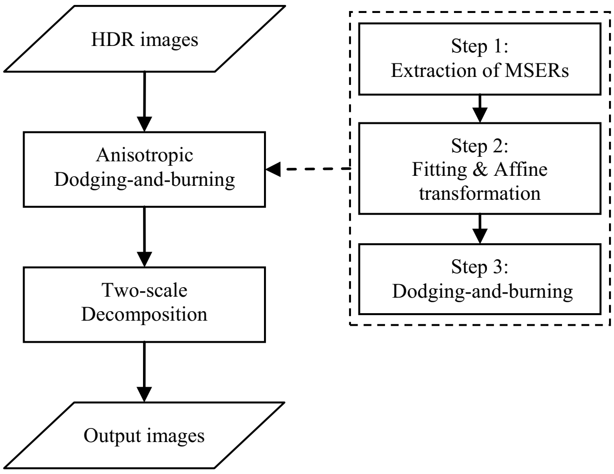


Fig. 1 The flowchart of proposed AIFTMA

A. *Anisotropic Dodging-and-burning*

The background of affine Gaussian scale space method shows that elliptical Gaussian filter is suitable for anisotropic feature regions. However, selection of three parameters in elliptical region makes it difficult to construct different elliptical Gaussian filters. Thus, traditional approaches usually simplify anisotropic feature regions to be isotropic feature regions and impose Gaussian filter directly. Unlike the traditional methods abandoning to use elliptical Gaussian filter, inspiration of this paper is to find an equivalent in affine Gaussian scale space to imitate the effect of using elliptical Gaussian filter for tone mapping algorithm. Equation (9) indicates that the elliptical Gaussian filtered image can be calculated as not only the inner product between elliptical Gaussian filter and elliptical feature regions but also that between Gaussian filter and circular-reformed feature regions [17].

$$\left\langle \overline{g}(\tau_1,\cdots,\tau_k)\phi, s(x,y)\right\rangle \Leftrightarrow \left\langle \phi, g(\tau_1,\cdots,\tau_k)s(x,y)\right\rangle \quad (9)$$

where $s(x,y)$ represents MSERs-detected elliptical feature region, $g(\tau_1,\ldots,\tau_k)$ represents the transformation operator to reform elliptical feature regions into circular feature regions, $\overline{g}(\tau_1,\ldots,\tau_k)$ represents conjugate complex number of $g(\tau_1,\ldots,\tau_k)$ and serves as an inverse transformation operator to reform circular feature regions into elliptical feature regions. Φ represents Gaussian filter in this paper. Equation (9) shows that convolution between elliptical-reformed Φ and $s(x,y)$ is equivalent to that between Φ and circular-reformed $s(x,y)$. Thus, the elliptical Gaussian filtered image can be obtained by calculating the inner production between Gaussian filter and circular-reformed feature regions.

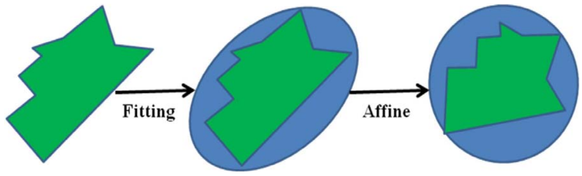


Fig. 2 An example of Fitting and Affine transformation

Based on the theoretical deduction in above, the proposed anisotropic dodging-and-burning is executed in three steps. In the step 1, MSERs operator is applied to extract anisotropic affine feature regions. Fig. 2 shows the processing of Step 2. The irregular green region represents the MSERs-detected affine feature region. Since the extracted affine areas are irregular shape, ellipse fitting operator is utilized to encircle the irregular shape by blue elliptical outline in step 2. Then, affine transformation is employed to reform elliptical outline into circular shape by second-moment matrix.

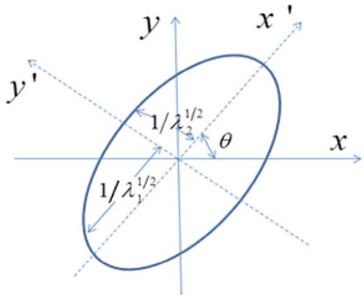


Fig. 3 The ellipse representation of the second moment matrix

Details of affine transformation are shown in Fig. 3. The center of the ellipse is set as the center of MSERs-detected feature region, and the semi-axes of this ellipse are $1/\lambda_1^{1/2}$ and $1/\lambda_2^{1/2}$, respectively. Here, λ_1 and λ_2 are eigen values of the second moment matrix [18]. Then affine transformation is employed to reform blue ellipse outline into circle shape by rotation and scaling. In this way, the irregular affine feature region inside can be compressed as well.

Here, elliptical feature regions have been reformed into circular feature regions, which obey the theoretical deduction in (9). In Step 3, dodging-and-burning operator [5] is applied to detect the biggest local neighborhood for each pixel in the image. It leads to the elliptical Gaussian filtered image by calculating the convolution between Gaussian filter and circular-reformed feature regions.

B. *Two-scale Edge-preserving Decompostion*

In [19], Tumblin and Turk built on anisotropic diffusion to decompose an image using a low-curvature image simplifier. Inspired by this decomposition idea, this paper employs two-scale decomposition based on the anisotropic dodging-and-burning.

Firstly, the elliptical Gaussian filtered image from anisotropic dodging-and-burning is regarded as the base layer (large-scale features) of HDR image. Then, detail layer (small-scale features) can be calculated as (10):

$$Detail = L - Base \tag{10}$$

where L represents the original luminance in HDR image, *Detail* and *Base* represent a detail layer and a base layer, respectively. Secondly, the base and detail layers are added with different weighting factors to get combined luminance as (11):

$$L' = \alpha * Base + \beta * Detail \tag{11}$$

where L' represents the combined luminance, α and β represent weighting factors ($0<\alpha<1$, $\beta\geq1$). Finally, output image can be yielded by (12):

$$\begin{cases} I_r' = (\frac{I_r}{L})^s * L' \\ I_g' = (\frac{I_g}{L})^s * L' \\ I_b' = (\frac{I_b}{L})^s * L' \end{cases} \tag{12}$$

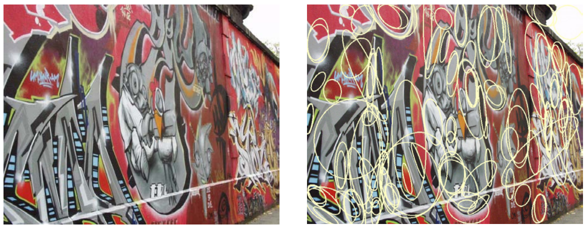
where I_r, I_g, I_b are the RGB values of original HDR image, respectively. I_r', I_g', I_b' represent the RGB values of output image, respectively. s represents a parameter derived from color saturation.

To sum up, proposed AIFTMA is summarized as follow:

1. Compute original luminance image L:
$$L = 0.299 * I_r + 0.587 * I_g + 0.114 * I_b \tag{13}$$
2. Apply MSERs operator to extract anisotropic regions in L.
3. Outline each of anisotropic regions by ellipse fitting.
4. Rotate each of ellipse regions to make their semi-major axis in horizontal.
5. Reform each of rotated ellipse regions into circular regions by affine transformation. Their scaling factors are given by:
$$scale\_a = \frac{\sqrt{a*b}}{a} \qquad scale\_b = \frac{\sqrt{a*b}}{b} \tag{14}$$
where the length of the semi-major axis is set as a, that of the semi-minor axis is set as b.
6. Apply dodging-and-burning to detect the biggest local neighborhood for each pixel in each circular region.
7. Those pixels excluded by MSERs operator will be calculated by (1)~(4) directly.
8. Use two-scale edge-preserving decomposition as (10)~(12) to yield output image.

IV. EXPERIMENTAL RESULTS

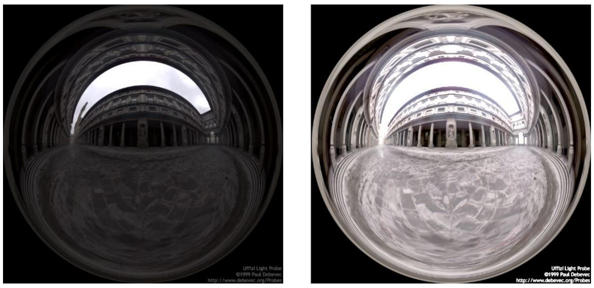
Since MSERs operator has a good performance of affine invariance, proposed AIFTMA applies it to extract anisotropic affine feature regions in HDR images directly. Fig. 4 gives an example to show the comparison between original image and feature detected images by MSERs operator. White elliptical areas are MSERs-detected regions after ellipse fitting procedure. They will be reformed into isotropic regions by affine transformation later.



(a) Original image (b) Feature detected image
Fig. 4 An example of comparison between original image and feature detected image by MSERs operator

This paper utilizes a series of experimental HDR images to verify the performance of proposed AIFTMA. These images come from Radiance map courtesy of Paul Debevec [20]. Images "memorial" and "uffizi_probe" are selected as the demo in this paper because the former is famous in tone mapping research and the latter typically contains large perspective and scale transformed contents. In order to compare the performance of the proposed method, five different previous algorithms are utilized. They include RLTMA [5], BilateralRTMA [6], iCAM06 [7], EdgePTMA [8] and LaplacianFTMA [9]. Here, these algorithms have been used with their default parameters. Fig. 5 and Fig. 6 show images "memorial" and "uffizi_probe" under different exposure parameters of HDR images, respectively. They are used to exhibit the dark and bright details in HDR image as many as possible.

(a) Low exposure (b) High exposure
Fig. 5 Different exposure parameters of HDR image "memorial"



(a) Low exposure (b) High exposure

Fig. 6 Different exposure parameters of HDR image “uffizi_probe”

Fig. 7 and Fig. 8 show the comparison of the proposed method with five different previous algorithms, respectively. In Fig. 7, proposed AIFTMA is efficient to extract the features in anisotropic regions and preserve the edges and details in image “memorial”. Among the five previous works employed in the experiments, EdgePTMA and LaplacianFTMA have best results. However, selected parts of image show that details lost in dark area between windows are noticeable for EdgePTMA, and LaplacianFTMA results in over-enhancement for the paintings on the windows.

In Fig. 8, image “uffizi_probe” contains large-scale perspective distortion. RLTMA, which uses dodging-and-burning directly, is unable to reproduce satisfying output image. BilateralRTMA, iCAM06 and EdgePTMA fail to preserve the details in the sky and the rooftop. Both LaplacianFTMA and AIFTMA can preserve the details. However, the author in [9] implies that one typical difficulty LaplacianFTMA encounters is that the sky above the rooftop interacts with the rooftop to form high-frequency textures that undesirably get amplified. In this sense, proposed AIFTMA outperforms LaplacianFTMA with no artifacts in the sky.

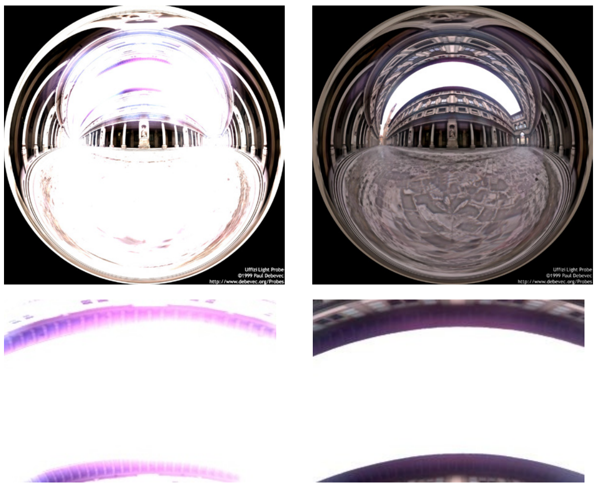
Moreover, LaplacianFTMA has a $O(N\log N)$ complexity for an image with N pixels [9], the complexity of AIFTMA is $O(N)$. So, the proposed algorithm strikes a balance between performance and efficiency.

(a) RLTMA (b) BilateralRTMA

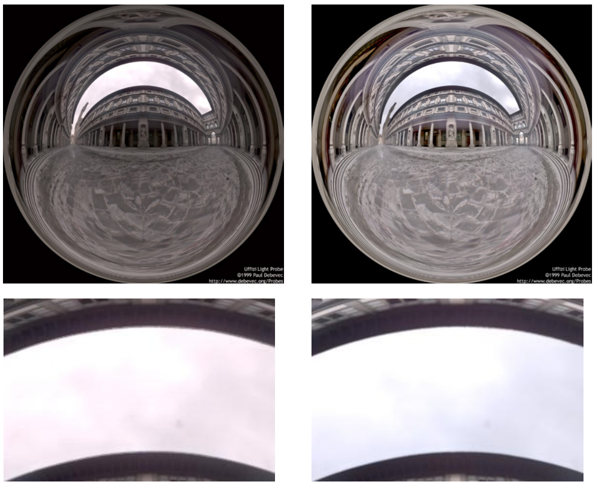
(c) iCAM06 (d) EdgePTMA

(e) LaplacianFTMA (f) Proposed AIFTMA

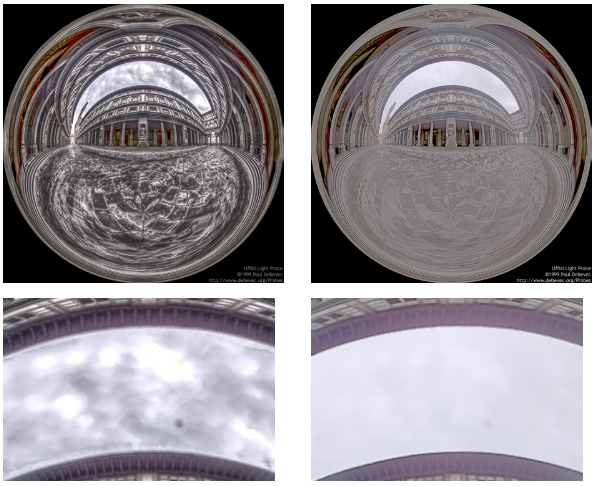
Fig. 7 Comparison of different tone mapping algorithms



(a) RLTMA (b) BilateralRTMA



(c) iCAM06 (d) EdgePTMA



(e) LaplacianFTMA (f) Proposed AIFTMA

Fig. 8 Comparison of different tone mapping algorithms

V. CONCLUSION

In the paper, a new affine invariant features-based tone mapping algorithm is proposed based on affine Gaussian scale space. The proposed algorithm can extract anisotropic feature regions in HDR images and transform them into isotropic regions effectively. Then, dodging-and-burning and two-scale edge-preserving decomposition are applied to generate output images. Results of the experiments demonstrate that the proposed method outperforms previous works, especially for large distortion and perspective changes in HDR images.

REFERENCES

[1] F. Banterle, P. Ledda, K. Debattista, A. Chalmers, and M. Bloj, “A framework for inverse tone mapping,” The Visual Computer, 2007, 23(7): 467-478.

[2] T. Pouli and E. Reinhard, “Progressive color transfer for images of arbitrary dynamic range,” Computers & Graphics, 2011, 35(1): 67-80.

[3] S. H. Park and E. D. Montag, “Evaluating tone mapping algorithms for rendering non-pictorial (scientific) high-dynamic-range images,” Journal of Visual Communication and Image Representation, 2007, 18(5): 415-428.

[4] Y. S. Xie and J. Y. Fang, “Development and Prospect of Tone Mapping Techniques for HDRI,” China Illuminating Engineering Journal, 2011, 22(5): 11-17.

[5] E. Reinhard, M. Stark, P. Shirley, and J. Ferwerda, “Photographic tone reproduction for digital images,” ACM Transactions on Graphics (TOG), 2002, 21(3): 267-276.

[6] M. Elad, “Retinex by two bilateral filters,” Scale Space and PDE Methods in Computer Vision, Springer Berlin Heidelberg, pp. 217-229, 2005.

[7] J. Kuang, G. M. Johnson, and M. D. Fairchild, “iCAM06: A refined image appearance model for HDR image rendering,” Journal of Visual Communication and Image Representation, 2007, 18(5): 406-414.

[8] Z. Farbman, R. Fattal, D. Lischinski, and R. Szeliski, “Edge-preserving decompositions for multi-scale tone and detail manipulation,” ACM Transactions on Graphics (TOG), 2008, 27(3), 67: 1-10.

[9] S. Paris, S. W. Hasinoff, and J. Kautz, “Local Laplacian filters: edge-aware image processing with a Laplacian pyramid,” ACM Trans. Graph, 2011, 30(4), 68: 1-12.

[10] K. H. Yang, J. Ji, J. J. Guo, and W. S. Yu, “High Dynamic Range Images and Tone Mapping Operator,” Acta Automatica Sinica, 2009, 35(2): 113-122.

[11] E. Peli, “Contrast in complex images,” JOSA A, 1990, 7(10): 2032-2040.

[12] F. J. Blommaert and J. B. Martens, “An object-oriented model for brightness perception,” Spatial Vision, 1990, 5(1): 15-41.

[13] T. Lindeberg, “Scale-space theory: A basic tool for analyzing structures at different scales,” Journal of applied statistics, 1994, 21(1-2): 225-270.

[14] T. Lindeberg, “Edge detection and ridge detection with automatic scale selection,” International Journal of Computer Vision, 1998, 30(2): 117-156.

[15] J. Matas, O. Chum, M. Urban, and T. Pajdla, “Robust wide-baseline stereo from maximally stable extremal regions,” Image and vision computing, 2004, 22(10): 761-767.

[16] A. Haja, B. Jahne, and S. Abraham, “Localization accuracy of region detectors,” Computer Vision and Pattern Recognition, 2008. CVPR 2008. IEEE Conference on, pp. 1-8. IEEE, 2008.

[17] Y. Hel-Or and P. C. Teo, “A common framework for steerability, motion estimation, and invariant feature detection,” Circuits and Systems, 1998. ISCAS'98. Proceedings of the 1998 IEEE International Symposium on, vol. 5, pp. 337-340.IEEE, 1998.

[18] J. Gårding and T. Lindeberg, “Direct computation of shape cues using scale-adapted spatial derivative operators,” International Journal of Computer Vision, 1996, 17(2): 163-191.

[19] J. Tumblin and G. Turk, “LCIS: A boundary hierarchy for detail-preserving contrast reduction,” Proceedings of the 26th annual conference on Computer graphics and interactive techniques, pp. 83-90. ACM Press/Addison-Wesley Publishing Co., 1999.

[20] http://www.pauldebevec.com/Research/HDR/