A JOINT GLOBAL AND LOCAL TONE MAPPING ALGORITHM FOR DISPLAYING WIDE DYNAMIC RANGE IMAGES

Alain Horé, Chika A. Ofili, and Orly Yadid-Pecht, Fellow, IEEE

***Abstract**: In this paper, we introduce an efficient improved tone mapping algorithm that can be used for displaying wide dynamic range (WDR) images on conventional display devices that are mainly of low dynamic range (LDR). That algorithm, which enhances the exponent-based tone mapping algorithm of Ofili et al., uses both local and global image information for improving the contrast and increasing the brightness of images. It also directly operates on the Bayer domain instead of the luminance/chrominance domain that is used by the vast majority of tone mapping algorithms. Experimental results performed on different WDR images show that we are able to get images that are more pleasant visually when compared to nine other tone mapping algorithms. These observations are also confirmed numerically through the use of the TMQI, an objective image quality measure.*

***Keywords**: Wide dynamic range images, tone mapping, color filter array, contrast enhancement.*

***ACM Classification Keywords**: A.0 General Literature - Conference Proceedings; I.4.3 Image Processing and Computer Vision – Enhancement*

Introduction

In imaging, the dynamic range describes the luminance ratio between the brightest part and the darkest part of a scene [1]. Natural sceneries often have a wide dynamic range (WDR) ratio that exceeds 100,000:1 [2]. Through the adaptation mechanism in human visual system (HVS), we are capable of simultaneously detecting different parts of a scene with high dynamic range. In fact, the HVS is capable of perceiving scenes over five orders of magnitude and can gradually adapt to scenes with dynamic range of over nine orders of magnitude. However, the conventional imaging display devices (such as LCD monitors, mobile phones) have a limited dynamic range (LDR), and they can reproduce dynamic ranges around two or three orders of magnitude. Due to recent technological improvements, modern image sensors can capture WDR images that accurately describe real world sceneries [3]. However, when these captured WDR images are displayed on standard display devices, they appear to be over-exposed in well-lit scenes or under-exposed in dark scenes. This leads to the loss of image details. A tone mapping algorithm is used to adapt the captured wide dynamic range scenes to the low dynamic range devices while maintaining the details from the original scenery. In Figure 1, it is shown how our proposed tone mapping algorithm can be used to enhance the quality and colors of an image.

There are two main classes of tone mapping algorithms: global techniques and local techniques. Global techniques are also called tone reproduction curves (TRC). They manipulate each individual pixel without considering its neighborhood [2, 4-8]. In fact, a single function is used for all the pixels, which outputs the same value for the same input intensity. Mathematically, a tone reproduction curve can be defined as follows:

$$y(p) = \psi(x(p)) \tag{1}$$

Figure 1. Effect of tone mapping on the quality of images.

where *x* is the original WDR image, *y* the final low dynamic range (LDR) tone mapped image, and *p* is a pixel. $\psi : \Gamma \to \Omega$ is a function that maps wide dynamic range intensities of the set Γ to the set of low dynamic range intensities Ω. The mapping function ψ can be for example a gamma function, a logarithmic function, a power function, or any continuous mathematical function. Common definitions for Γ and Ω are $\Gamma = [0, 2^{16} - 1]$ and $\Omega = [0, 2^{8} - 1]$. Although TRC-based techniques are computationally efficient since they are simple to carry out, they are prone to issues like halos which appear as false black structures around pixels at the border between bright and dark areas [2]. Also, they are generally not enough efficient to enhance contrast and to preserve details because they do not consider the contrast characteristics of the local region [2].

Local tone mapping algorithms, also called tone reproduction operators (TRO), are spatial location dependent, and varying transformations are applied to each pixel depending on its surrounding [3]. Thus, they use different tonal curves in different regions of an image [2, 9 - 15]. They improve the local contrast and details of an image. However, they are computationally expensive, and are subject to artifacts such as false colors and false contours. Mathematically, a tone reproduction curve can be defined as follows:

$$y(p) = \mathrm{Z}\left(x(p), \zeta_p\right) \tag{2}$$

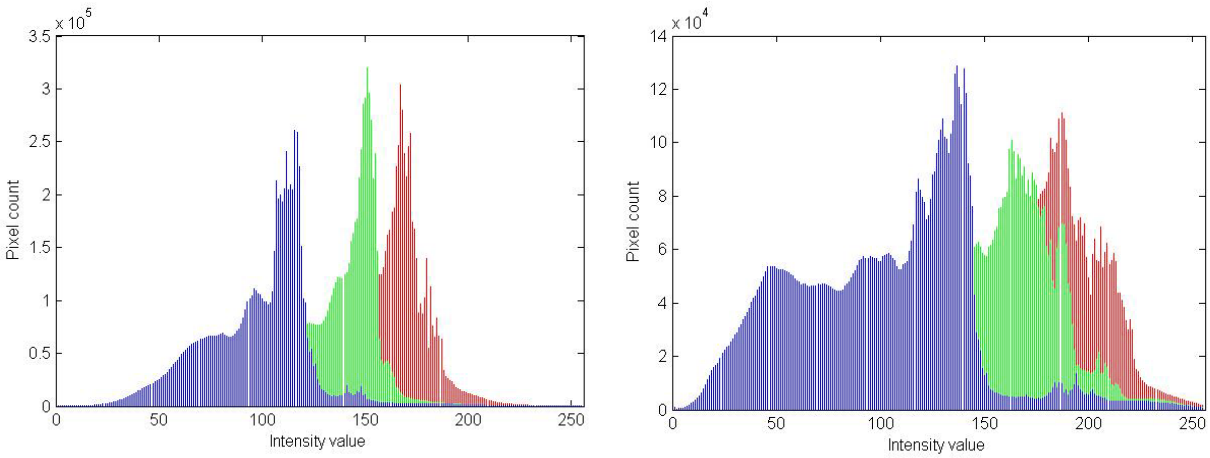
where *x* is the original WDR image, *y* the final low dynamic range (LDR) tone mapped image, *p* is a pixel, and ζ_p is a neighborhood of pixel *p*. $\mathrm{Z} : \Gamma \times \mathrm{N} \to \Omega$ is the mapping function that takes an input WDR intensity value from Γ and a neighborhood from N, and computes the final LDR intensity as an element of Ω. Neighborhoods can be expressed in the form of matrices as commonly found in image processing.

In [8], Ofili *et al.* have proposed a combined global and local tone mapping algorithm for displaying WDR images. In the rest of the paper, this algorithm which was developed in our lab, Integrated Sensors and Intelligent Systems lab (ISIS), will simply be referred to as our original tone mapping algorithm. It is based on an exponential function, and uses a low-pass Gaussian filter for getting the local information needed for performing tone mapping while preserving details. However, it is prone to false colors, and the local contrast is not always good as can be seen in Figure 2 where we show two images from our original exponent-based tone mapping algorithm and the modified algorithm presented further in this paper. As we can see in the figure, the image from the modified algorithm contains more details and contrast than the image obtained from our original exponent-based tone mapping algorithm. We can also notice blur and false colors (reddish appearance) in the image from our original tone mapping algorithm. The histograms of the red, green and blue bands of the images of Figure 2 are shown in Figure 3. As we can notice, the histogram is more spread with the modified tone mapping algorithm in comparison to our original exponent-based tone mapping algorithm, which means better contrast.

The rest of the paper is as follows: first, we describe our original exponent-based tone mapping algorithm, and then we introduce our modified tone mapping algorithm which enables to get images with better contrast and reduced false colors. After that, we present some experimental results, and we end the paper with the concluding remarks.

(a) (b)

Figure 2. Tone mapped images. (a) Our original exponent-based tone mapping algorithm. (b) The modified exponent-based tone mapping algorithm presented in this paper.



(a) (b)

Figure 3. Histograms of the red, green and blue bands for the images shown in of Figure 2. (a) Our original exponent-based tone mapping algorithm. (b) The modified tone mapping algorithm presented in this paper.

Original exponent-based tone mapping algorithm

The tone mapping algorithm of Ofili *et al*. [8] is defined by:

$$\begin{cases} y(p) = x_{\max} \times \dfrac{1 - e^{-\frac{x(p)}{x_0(p)}}}{1 - e^{-\frac{x_{\max}}{x_0(p)}}} \\ x_0(p) = \kappa \times \mu_x + (x * h)(p) \end{cases} \tag{3}$$

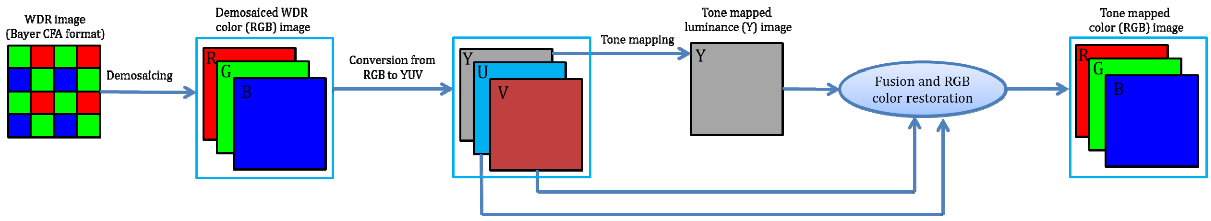
where x is the original WDR image, y the final LDR image, p a pixel, x_{max} the maximum value for the display device (for example, for an 8-bit display device, $x_{max}=2^8-1=255$). x_0 is the adaptation factor and it is computed as the sum of a global component, $\kappa \times \mu_x$, and a local component $x * h$. In the global component part, κ is a parameter that plays a major role in brightening an image. When it increases, the tone mapped image becomes darker, while it becomes brighter when κ decreases. μ_x is the average intensity of WDR image x. Regarding the local component that is used to extract the local information, * denotes the convolution operation, and h is a low-pass filter. In this paper, a 2D Gaussian filter is used for h.

Modified tone mapping algorithm

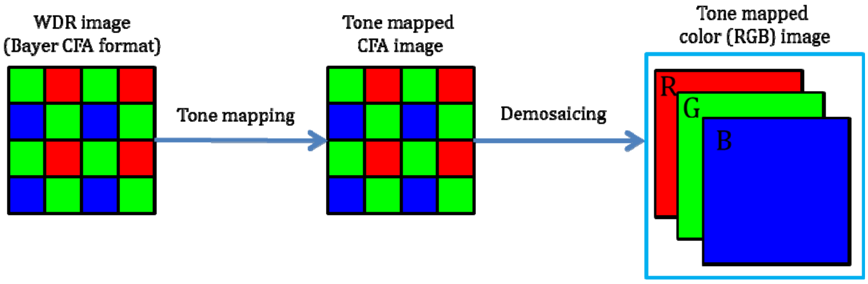
As reported in the introduction, our original exponent-based tone mapping algorithm does not perform well regarding the contrast of an image. In fact, this is due to the local component term $x * h$ in the adaptation factor x_0. For getting more contrast, we propose to add a multiplicative constant 0.5 to that local component, and thus the modified tone mapping equation is given by:

$$\begin{cases} y(p) = x_{\max} \times \dfrac{1 - e^{-\frac{x(p)}{x_0(p)}}}{1 - e^{-\frac{x_{\max}}{x_0(p)}}} \\ x_0(p) = \kappa \times \mu_x + \dfrac{(x * h)(p)}{2} \end{cases} \tag{4}$$

Like in the case of our original tone mapping algorithm, the modified tone mapping equation is applied to images extracted from a Bayer color filter array, an idea originally developed by Meylan *et al*. [16]. Thus, we do not perform tone mapping on a luminance band and then combine the result with chrominance information as is done by different authors. In Figure 4, we show the traditional tone mapping workflow, and we also show the model developed by Meylan *et al*. and used in this paper.



(a)



(b)

Figure 4. Image processing workflow. (a) Traditional model. (b) Model used in our tone mapping system and originally proposed by Meylan *et al*. [16]

Experimental results

For evaluation purposes, the modified exponential-based tone mapping algorithm is applied to three WDR images. The resulting tone mapped images are compared with nine other tone mapping operators: our original exponent-based tone mapping algorithm [8], bilateral filtering algorithm of Durand *et al*. [17], logarithmic mapping of Drago *et al*. [18], gradient tone mapping algorithm of Fattal *et al*. [11], display adaptive tone mapping algorithm of Mantiuk *et al*. [19], retinal display algorithm of Meylan *et al*. [16], Ashikmin's spatially varying operator [20], tone reproduction algorithm of Reinhard *et al*. [21], and Pattanaik *et al*.'s multiscale observer model [22]. Figures 5 to 22 show three WDR images tested as well as the resulting tone mapped images obtained from the different tone mapping algorithms. All image results were obtained from software implementations of the different tone mapping algorithms. As can be noticed in the figures, the modified exponent-based tone mapping algorithm gives images with good contrast and brightness as well as enhanced details. This confirms the good effect of modifying the local contrast component in the adaptation factor. For objective comparison, a tone mapping quality index proposed by Yeganeh *et al*. [23] is used, which assesses the effectiveness of the different tone mapping operators. The objective assessment algorithm produces three image quality scores that are used in evaluating the image quality of a tone mapped image: the structural similarity (S) between the tone mapped image and the original WDR image, the naturalness (N) of the tone mapped image, and the overall image quality measure which the authors call "tone mapping quality index" (TMQI). TMQI is computed as a non-linear combination of both the structural similarity score (S) and the naturalness score (N). It generally ranges from 0 to 1, where 1 is the highest in terms of image quality. The objective test results (TMQI) for the different tone mapping operators implemented are shown in Table 1. As can be seen, the TMQI values from the modified exponent-based tone mapping system are in the high score range that can be attained using this objective test. We have obtained the highest values for the images tested in comparison to the nine other tone mapping algorithms, which highlights the good performance of our algorithm. Moreover, we should note that although the tone mapping system by Meylan *et al*. [16] is also applied on the Bayer format of the colored WDR image, lower TMQI scores were obtained for all the images in comparison to our tone mapping system.

Table 1 TMQI scores for the various tone mapping operators.

Tone mapping operators	Image 1	Image 2	Image 3
Modified exponent-based tone mapping algorithm (this work)	**0.9626**	**0.8582**	**0.8463**
Original exponent-based tone mapping algorithm [4]	0.9411	0.8057	0.7730
Fattal *et al.* [5]	0.8675	0.7272	0.7371
Durand *et al.* [6]	0.9414	0.7474	0.7578
Drago *et al.* [7]	0.8932	0.8049	0.7888
Meylan *et al.* [3]	0.8628	0.8344	0.7793
Mantiuk *et al.* [8]	0.9159	0.7983	0.8200
Pattanaik *et al.* [9]	0.8295	0.7425	0.6903
Reinhard *et al.* [10]	0.9552	0.8228	0.8030
Ashikhmin [4]	0.7934	0.5357	0.7039

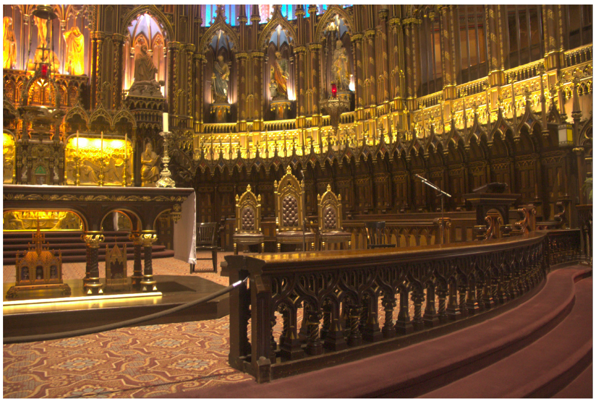


Figure 5 : Original WDR image

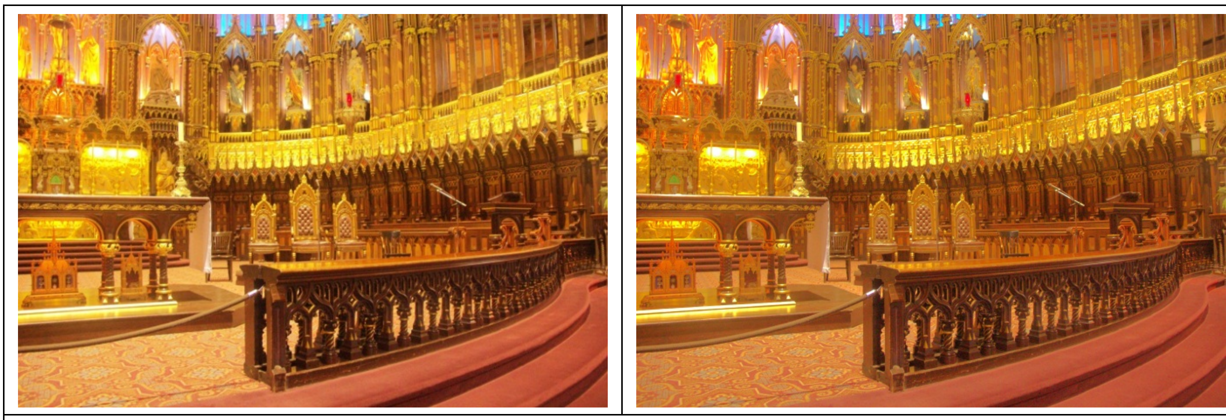


Figure 6 . Tone mapped images. (Left) Our modified tone mapping algorithm. (Right) Our original algorithm.

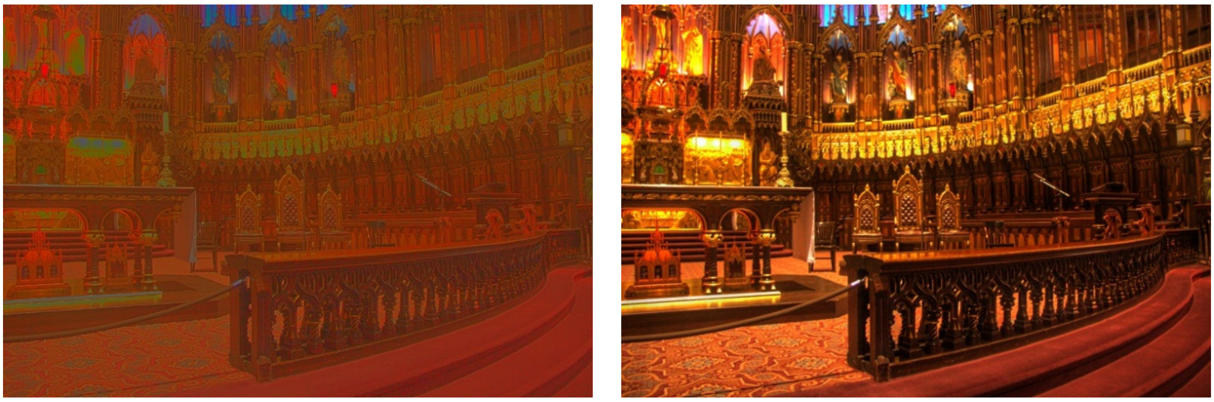


Figure 7. Tone mapped images. (Left) Ashikhmin's algorithm. (Right) Fattal et al.'s algorithm.

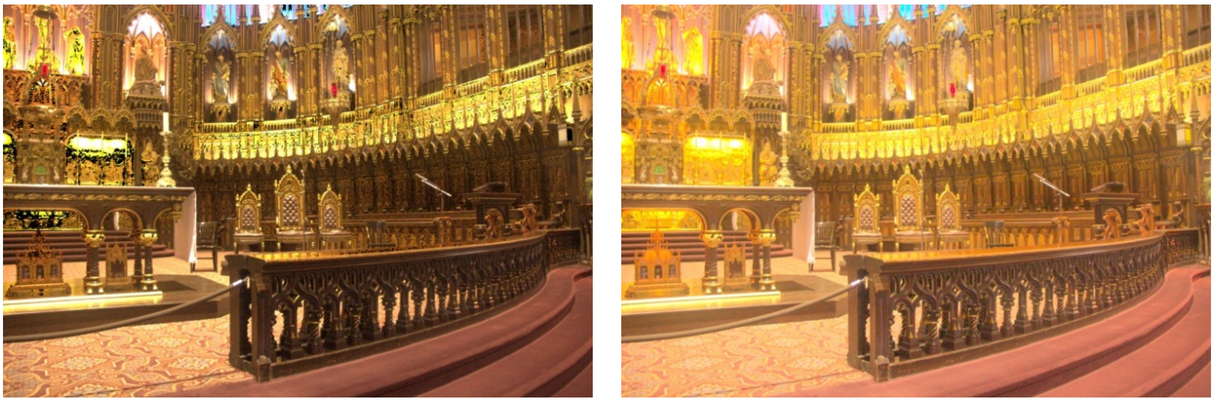


Figure 8. Tone mapped images. (Left) Durand et al.'s algorithm. (Right) Drago et al.'s algorithm.

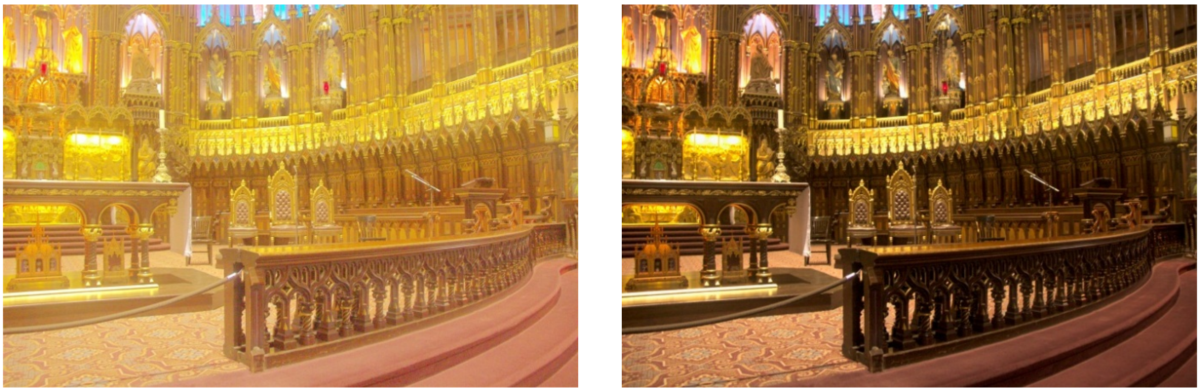


Figure 9. Tone mapped images. (Left) Meylan et al.'s algorithm. (Right) Mantiuk et al.'s algorithm

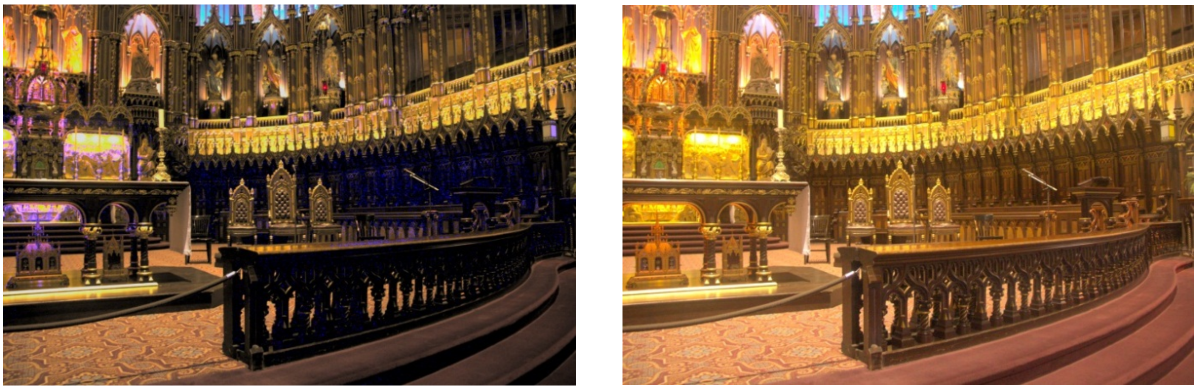


Figure 10. Tone mapped images. (Left) Pattanaik et al.'s algorithm. (Right) Reinhard et al.'s algorithm.

Figure 11 : Original WDR image.

Figure 12 : Tone mapped images. (Left) Our modified tone mapping algorithm. (Right) Our original algorithm.

Figure 13. Tone mapped images. (Left) Ashikhmin's algorithm. (Right) Fattal et al.'s algorithm.

Figure 14. Tone mapped images. (Left) Durand et al.'s algorithm. (Right) Drago et al.'s algorithm.

Figure 15. Tone mapped images. (Left) Meylan et al.'s algorithm. (Right) Mantiuk et al.'s algorithm.

Figure 16. Tone mapped images. (Left) Pattanaik et al.'s algorithm. (Right) Reinhard et al.'s algorithm.

Figure 17. Original WDR image

Figure 18. Tone mapped images. (Left) Our modified tone mapping algorithm. (Right) Our original algorithm.

Figure 19. Tone mapped images. (Left) Ashikhmin's algorithm. (Right) Fattal et al.'s algorithm.

Figure 20. Tone mapped images. (Left) Durand et al.'s algorithm. (Right) Drago et al.'s algorithm.

Figure 21. Tone mapped images. (Left) Meylan et al.'s algorithm. (Right) Mantiuk et al.'s algorithm.

Figure 22. Tone mapped images. (Left) Pattanaik et al.'s algorithm. (Right) Reinhard et al.'s algorithm.

Conclusion

In this paper, we have presented a modified and enhanced exponent-based tone mapping algorithm that exploits both global and local image information for producing low dynamic range images with high brightness and good contrast. Experimental tests performing with different WDR images have shown that high objective quality measure values are attainable using our algorithm, and it is also able to produce visually pleasant images. Due to its simplified mathematical model, our algorithm can be a good candidate for implementation on system-on-a-chip.

Bibliography

[1] O. Yadid-Pecht and R. Etienne-Cummings, “CMOS imagers: from phototransduction to image processing”, Kluwer Academic Publisher, 2004.

[2] J. Duan, W. Dong, R. Mu, G. Qiu, and M. Chen, “Local contrast stretch based tone mapping for high dynamic range images”, IEEE Symposium on Computational Intelligence for Multimedia, Signal and Vision, pp. 26-32, 2011.

[3] Y. Dattner and O. Yadid-Pecht, “High and low light CMOS imager employing wide dynamic range expansion and low noise readout”, IEEE Sensors Journal, vol. 12, no. 6, pp. 2172-2179, 2012.

[4] J. Tumblin and H. Rushmeier, “Tone reproduction for realistic images”, IEEE Computer Graphics and Applications, vol. 13, no. 6, pp. 42-48, 1993.

[5] G. W. Larson, H. Rushmeier, and C. Piatko, “A visibility matching tone reproduction operator for high dynamic range scenes”, IEEE Transactions on Visualization and Computer Graphics, vol. 3, no. 4, pp. 291 – 306, 1997.

[6] J. A. Ferwerda, S. N. Pattanaik, P. Shirley, and D. P. Greenberg. “A model of visual adaptation for realistic image synthesis”, ACM SIGGRAPH, pp. 249-258, 1996.

[7] J. Duan, G. Qiu, and G.m D. Finlayson. “Learning to display high dynamic range images”, Pattern Recognition, vol. 40, no. 10, pp. 2641-2655, 2007.

[8] C. A. Ofili, S. Glozman, and O. Yadid-Pecht, “An in-depth analysis and image quality assessment of exponent-based tone mapping algorithm”, International Journal Information Models and Analysis, vol. 1, no. 3, pp. 236-250, 2012.

[9] D. Lischinski, Z. Farbman, M. Uyttendaele, R. Szeliski. “Interactive local adjustment of tonal values”. ACM Transactions on Graphics. vol. 22, no. 3, pp.646–653, 2006.

[10] E. Reinhard, M. Stark, P. Shirley, and J. Ferwerda, “Photographic tone reproduction for digital images”, ACM SIGGRAPH, pp. 267-276, 2002.

[11] R. Fattal, M. Werman, and D. Lischinski, “Gradient domain high dynamic range compression”, ACM Transactions on Graphics, vol. 21, no. 3, pp. 249-256, 2002.

[12] J. Tumblin and G. Turk, “LCIS: A boundary hierarchy for detail preserving contrast reduction”, ACM SIGGRAPH, pp. 83-90, 1999.

[13] J. Duan, M. Bressan, C. Dance, and G. Qiu, “Tone-mapping high dynamic range images by novel histogram adjustment”, Pattern Recognition, vol. 43, no. 5, pp. 1847-1862, 2010.

[14] D. J. Jobson, Z. Rahman, and G. A. Woodell, “A multiscale retinex for dridging the gap between color images and the human observation of scenes”, IEEE Transactions on Image processing, vol. 6, no. 7, pp. 965-976, 1997.

[15] J. W. Lee, R. H. Park, and S. Chang, “Tone mapping using color correction function and image decomposition in high dynamic range imaging”, IEEE Transactions on Consumer Electronics, vol. 56, no. 4, pp. 2772-2780, 2010.

[16] L. Meylan, D. Alleysson, and S. Süsstrunk, "A Model of retinal local adaptation for the tone mapping of color filter array

images", Journal of the Optical Society of America A, vol. 24, no. 9, pp. 2807-2816, 2007.

[17] F. Durand and J. Dorsey, "Fast bilateral filtering for the display of high-dynamic-range images", ACM Transactions on Graphics, vol. 21, no. 3, pp. 257-266, 2002.

[18] F. Drago, K. Myszkowski, N. Chiba, and T. Annen, "Adaptive logarithmic mapping for displaying high contrast scenes", Computer Graphics Forum, vol. 22, no. 3, pp. 419-426, 2003.

[19] R. Mantiuk, L. Kerofsky, and S. Daly, "Display adaptive tone mapping", ACM Transactions on Graphics, vol. 27, no. 3, pp. 193-202, 2008.

[20] M. Ashikhmin, "A Tone mapping algorithm for high constrast images", Eurographics Workshop on Rendering, pp. 145-155, 2002.

[21] E. Reinhard, M. Stark, P. Shirley, and J. Ferwerda, "Display adaptive tone mapping", ACM Transactions on Graphics, vol. 21, no. 3, pp. 267-276, 2002.

[22] S. N. Pattanaik, J. Tumblin, H. Yee, and D. P. Greenberg, "Time-dependent visual adaptation for fast realistic image display", ACM SIGGRAPH Conference on Computer Graphics and Interactive Techniques, pp. 47–54, 2000.

[23] H. Yeganeh and Z. Wang, "Objective quality assessment of tone-mapped images", IEEE Transactions on Image Processing, vol. 22, no. 2, pp. 657-667, 2013.

Authors' Information

Alain Horé *is with the Department of Electrical and Computer Engineering, University of Calgary, Calgary, Alberta, T2N 1N4, Canada; e-mail: ahore@ucalgary.ca.*

Chika Antoinette Ofili *is with the Department of Electrical and Computer Engineering, University of Calgary, Calgary, Alberta, T2N 1N4, Canada; e-mail: cofili@ucalgary.ca.*

Orly Yadid-Pecht *is with the Department of Electrical and Computer Engineering, University of Calgary, Calgary, Alberta, T2N 1N4, Canada; e-mail: orly.yadid.pecht@ucalgary.ca.*