NATURALNESS-PRESERVED TONE MAPPING IN IMAGES BASED ON PERCEPTUAL QUANTIZATION

Cheolkon Jung and Kaiqiang Xu

School of Electronic Engineering, Xidian University, Xian 710071, China
zhengzk@xidian.edu.cn

ABSTRACT

In this paper, we propose naturalness-preserved tone mapping in images based on perceptual quantization (PQ). PQ is a transfer function based on Barten's contrast sensitive function (CSF) which represents human visual perception on luminance, and we adopt it to generate a limit curve for perceptual contrast enhancement. First, we obtain a limit curve in an image based on PQ transfer function to adjust the degree of contrast enhancement. Second, we redistribute the histogram using the limit curve and achieve perceptual contrast enhancement. Experimental results demonstrate that the proposed method effectively enhances contrast in images while successfully preserving naturalness.

***Index Terms*—** Contrast enhancement, limit curve, histogram equalization, histogram redistribution, human visual perception, naturalness, perceptual quantization.

1. INTRODUCTION

Image contrast enhancement is the key technology to improve visual quality of digital images. It makes useful information be strengthened, and thus causes images to be more suitable for the analysis and processing by humans or machines. Histogram equalization (HE) is a representative image enhancement method. Its principle is simple, and HE achieves an obvious enhancement of global contrast in an image. However, it causes excessive contrast enhancement if the image has large smooth area, i.e. its histogram has a peak. To address this problem, Vickers [1] proposed plateau HE which updated the histogram in an image by selecting a proper threshold and appropriately constrained background and noise. Pizer et al. [2] proposed contrast limited adaptive histogram equalization (CLAHE) to prevent the over-enhancement of noise. Based on HVS characteristics, Land [3] presented a retinex method that decomposed an image into illumination and reflection layers and individually processed two layers for contrast enhancement. The core problem of retinex-based methods is how to reasonably obtain the illumination layer [4]. In the early 1980s, Barten [5] discovered the relationship between the actual luminance and the brightness by human eye perception through experiments. Jayant [6] proposed a just noticeable different (JND) model based on the relationship. If the difference between two luminances in an image is less the critical JND, the two luminances are merged into one luminance because human eyes cannot perceive their difference. Tone mapping is a mapping technique in image processing and computer graphics to approximate the appearance of high dynamic range images.

In this paper, we propose naturalness-preserved tone mapping based on PQ. We design a global tone reproduction operator for contrast enhancement based on histogram adjustment. The operator seeks to enhance details in an image while preserving naturalness. First, we obtain a limit curve based on Bartens CSF model [7] to avoid over-enhancement and provide a higher dynamic range in contrast enhancement. Then, we redistribute the histogram of images based on the limit curve by truncating a part of the histogram that exceeds the ceiling and sharing it with the other bins. Therefore, the proposed tone mapping enhances the contrast of images while preserving naturalness.

2. RELATED WORK

Larson et al. [8] proposed a histogram adjustment technique based on the population of local luminance adaptation in images. They combined models of the human contrast sensitivity to reflect a subjective viewing experience. Disadvantage of Naive HE is that it is indiscriminate. It may increase the contrast of background noise, while decreasing the usable signal. To solve this problem, Ward limited the slope of the mapping function to the ratio of contrast visibility thresholds for displays and observers by using

$$\frac{dL_d}{dL_w} \leq \frac{\Delta L(L_d)}{\Delta L(L_w)} \tag{1}$$

where $\Delta L(L_a)$ is the just noticeable difference (JND) for adaptation level L_a; L_w is world luminance (unit: $cd/m2$); L_d is display luminance. The function is used as a limit for

This work was supported by the National Natural Science Foundation of China (No. 61271298) and the International S&T Cooperation Program of China (No. 2014DFG12780).

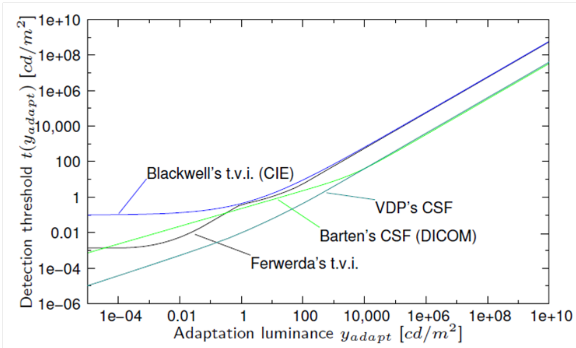

Fig. 1. HVS models based on different CSF and TVI [9].

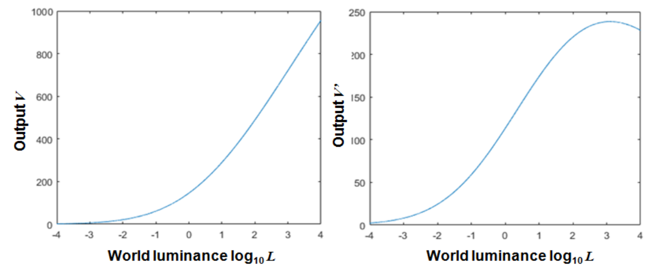

Fig. 2. Left: PQ curve, Right: Derivative V of PQ curve.

adjusting the histogram as follows:

$$f(b_i) \leq \frac{T}{N} \cdot \frac{log(L_{wmax}) - log(L_{wmin})}{log(L_{dmax}) - log(L_{dmin})} \cdot \frac{\Delta L(L_{di})/L_{di}}{\Delta L(L_{wi})/L_{wi}} \tag{2}$$

where L_{wi} is the world luminance for the histogram bin b_i; L_{di} is the display luminance for b_i; T is the sum of pixels; $f(b_i)$ is the frequency count for b_i; and N is the number of histogram bins. Larson et al. [9] used Eq. (2) to ensure no histogram bin that exceeded this limit, and then truncated a part of the histogram that exceeded the clip limit. There are many HVS models as shown in Fig. 1. These models estimate the smallest difference of luminance that is visible to the human eye, i.e. the detection threshold, in different test environments. The HVS models are classified into two main groups: threshold versus intensity (TVI) and contrast sensitivity function (CSF). TVI is measured for a fixed pattern, while CSF is measured for a sinusoidal patterns or Gabor patches of different spatial frequencies.

3. PROPOSED METHOD

3.1. Luminance-Based Histogram

Many tone mapping operators use HVS characteristics to process the input luminance and chrominance to approximate the appearance of high dynamic range images from low dynamic range contents. However, the images displayed in common displays are 8bit images whose range is 0∼255 and some modern displays such as HDR TV are 10bits. However, the Y component of 8- or 10-bits images is luma, not real-scene brightness. Thus, it is required to convert the gray values into scene luminance values as follows [10]:

$$L_d(L') = (L')^{\gamma} \cdot (L_{max} - L_{black}) + L_{black} + L_{refl} \tag{3}$$

where L_d is the displayed luminance or radiance, which is measured from the display surface; L' is the normalization of pixel value, i.e. [0, 1]; γ is the display gamma (usually set to be 2.2); L_{max} and L_{black} are the lowest and highest luminance of the display; L_{refl} is the ambient light reflected from a display surface. After converting pixel values into luminance, we get a histogram of the images.

3.2. Limit Curve Based on HVS

The SMPTE ST 2084 OETF, i.e. perceptual quantization transform function (PQTF) [11], is the most popular opto-electrical transfer function (OETF) in HDR video coding with HEVC main 10 profile. The PQ function for 10bit video coding is obtained as follows:

$$V(L) = v_{max} \cdot (\frac{c_1 + c_2(L/10000)^{m_1}}{1 + c_3(L/10000)^{m_1}})^{m_2} \tag{4}$$

where constants c_1, c_2, c_3, m_1, and m_2 are 0.8359375, 18.8515625, 18.6875, 0.15930176, and 78.08438, respectively; L is the luminance and other parameters are constant; V is the gray value and v_{max} is the maximum value. We obtain the derivative of the PQ curve as follows:

$$V' = 1/\Delta L \tag{5}$$

where ΔL is JND to generate 10bit images and V' is the derivative of the PQ curve.
In HDR10, the PQ curve is used to deal with three color channels (RGB), respectively. In this work, we use the PQ curve to process the luminance channel, and perform tone mapping from log10 luminance values to gray values as follows:

$$V(L) = v_{max} \cdot (\frac{c_1 + c_2(10^{L_1}/10000)^{m_1}}{1 + c_3(10^{L_1}/10000)^{m_1}})^{m_2} \tag{6}$$

where L_1 is the log10 luminance. The derivative of the PQ curve can be written as follows:

$$V'(L_1) = log(10) \cdot L/\Delta L \tag{7}$$

The relationship between tone mapping and HVS model is described as follows:

$$\frac{f(b_i)}{T} \leq k \cdot \frac{V'(L_{1i})}{\sum_{i=1}^{n} V'(L_{1i})} \tag{8}$$

where k is a constant to adjust tone mapping results; T is the number of samples.

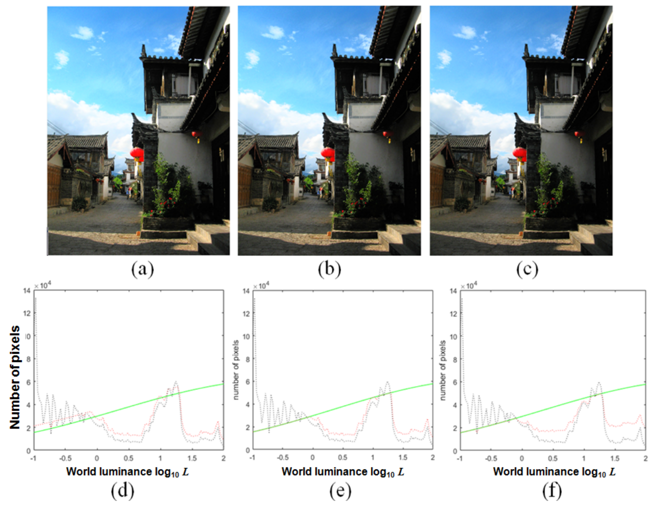

Fig. 3. Contrast enhancement results and their histograms. (a) CLAHE. (b) [12]. (c) Proposed method. (d), (e), and (f) Processed histograms and their limit curves of (a), (b), and (c). Black: Untreated histogram. Green: Limit curve. Red: Histogram after processing.

3.3. Histogram Redistribution

A part of the histogram bins that exceed the clip limit would not be abandoned, which should be redistributed to moderate its slope. Fig. 3 shows three redistribution methods of CLAHE, [12], and the proposed method. CLAHE redistributes the redundant histogram part, which exceeds the clip limit equally among all histogram bins, and there still exist some bins over the clip limit (see Fig. 3(d)). [12] is similar to CLAHE, but makes the number of every bin not exceed the ceiling (see Fig. 3(e)). The proposed method achieves redistribution (see Fig. 3 (f)) which provides a lower limit and avoids over-compression as follows:

$$Excess = \sum_i^n f(b_i) - Lim_i \quad if(f(b_i) > Lim_i) \tag{9}$$

$$Lack = \sum_i^n Lim_i - f(b_i) \quad if(f(b_i) < Lim_i) \tag{10}$$

where Lim_i is the ceiling of histogram bin b_i.
If $f(b_i)$ of histogram bin b_i is larger than the ceiling, then we truncate the part beyond it; if $f(b_i)$ smaller, then the number of bin b_i is recalculated as follows:

$$f(b_i)_{new} = f(b_i) + (Lim_i - f(b_i))\frac{Excess}{Lack} \tag{11}$$

The sky regions close to white clouds in Figs. 3(a), (b), and (c) are obviously different. In Figs. 3(a) and (b), the contrast of the two regions is enhanced more than the region in Fig. 3(c), which is more similar to the original image.

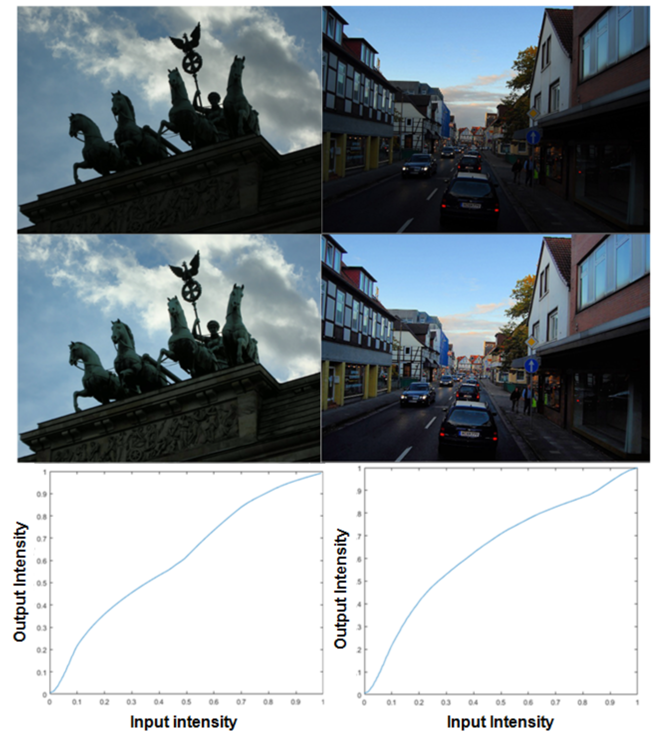

Fig. 4. Top: Original images of *DSCN* and *Town*. Middle: Results by the proposed method. Bottom: Mapping curves.

4. EXPERIMENTAL RESULTS

We perform experiments on a PC with Core Duo 2.33 GHz CPU and 4G RAM using Matlab R2015b and Windows 7 operation system. In (3), we set L_{max} and L_{black} to 0.1 and 100 cd/m^2, respectively. In (8), we set k to 1.5. We compare the performance of the proposed method with those of variational contrast enhancement algorithm (CVC) [13], weight threshold histogram equalization (WTHE) [14], channel division (ChDiv) [15], and adaptive gamma correction with weighting distribution (AGCWD) [16]. Fig. 4 shows tone mapping results and mapping curves in *DSCN* and *Town*. The proposed method successfully enhances the dark regions with clear details, and the highlight regions (sky regions) are not over-compressed. From the slope of the first mapping curve, it can be observed that no any slope is very small because the proposed method prevents the result from over-compression due to fewer pixels in some dynamic range as shown in Figs. 3, 5, and 6. As shown in Figs. 5 and 6, the sky regions produced are over-enhanced by CVC and WTHE so that the noise is amplified. The contrast in the white clouds is enhanced by ChDiv, but the result is not natural-looking. AGCWD compresses the highlight regions, which make the results look brighter.

Moreover, we perform quantitative measurements on the results in terms of discrete entropy (DE), feature similarity (F-

TABLE I
Objective Evaluation Results in terms of DE and FSIM

Method	Input	CVC[13]	WTHE[14]	ChDiv[15]	AGCWD[16]	Proposed
DE	6.9825	7.0162	7.0064	7.1996	7.270	7.2981
FSIM	1.0000	0.8956	0.8611	0.8882	0.9325	0.9375

Fig. 5. Tone mapping results by different methods. Top left to bottom right: Input image, enhanced results by CVC, WTHE, ChDiv, AGCWD and the proposed method.

Fig. 6. Tone mapping results by different methods. Top left to bottom right: Input image, enhanced results by CVC, WTHE, ChDiv, AGCWD and the proposed method.

SIM) as follows:
(1) DE [17] estimates image details according to the probability histogram distribution, which measures the degree of randomness by the average amount of information. The enhanced result with high contrast or uniform histogram distribution has a high entropy value.
(2) FSIM [18] measures the overall feature similarity between the enhanced and reference images.
TABLE I lists the average performance on the 100 test images. DE indicates the degree of details, and TABLE I indicates that the proposed method performs better than CVC, WTHE, and ChDiv. In terms of FSIM which shows the feature similarity between the result image and original image, the average performance in the proposed method is better than CVC, WTHE, and ChDiv. This is because the proposed method is designed based on an HVS model, and thus produces natural-looking results close to the original image tone and human visual perception. AGCWD and the proposed method achieve similar performance in terms of DE and F-SIM. AGCWD is a good image enhancement method based on histogram, but it loses many details in very bright regions.

5. CONCLUSIONS

In this paper, we have proposed naturalness-preserved tone mapping in images based on PQ. We have obtained a limit curve based on PQ to avoid both over-enhancement and over-compression. Based on the limit curve, we have produced a tone mapping curve for contrast enhancement which are more suitable for human visual perception. Experimental results demonstrate that the proposed method effectively enhances contrast in images while successfully preserving naturalness.

6. REFERENCES

[1] V. E. Vickers. Plateau equalization algorithm for real-time display of high-quality infrared imagery. *Optical Engineering*, 35(7):1921–1926, 1996.

[2] S. M. Pizer, R. E. Johnston, J. P. Ericksen, B. C. Yankaskas, and K. E. Muller. Contrast-limited adaptive histogram equalization: speed and effectiveness. In *Proceedings of the First Conference on Visualization in Biomedical Computing*, pages 337–345. IEEE, 1990.

[3] E. H. Land. Recent advances in retinex theory and some implications for cortical computations: color vision and the natural image. *Proceedings of the National Academy of Sciences*, 80(16):5163–5169, 1983.

[4] Z.-U. Rahman, D. J. Jobson, and G. A. Woodell. Multi-scale retinex for color image enhancement. In *Proceedings of International Conference on Image Processing*, volume 3, pages 1003–1006. IEEE, 1996.

[5] P. G. J. Barten. *Contrast sensitivity of the human eye and its effects on image quality*, volume 72. SPIE Press, 1999.

[6] N. Jayant. Signal compression: Technology targets and research directions. *IEEE Journal on Selected Areas in Communications*, 10(5):796–818, 1992.

[7] T. Borer. Non-linear opto-electrical transfer functions for high dynamic range television. *BBC White Paper*, 2014.

[8] 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*, 3(4):291–306, 1997.

[9] R. Mantiuk, K. Myszkowski, and H.-P. Seidel. Lossy compression of high dynamic range images and video. In *Proceeding of Electronic Imaging*, pages 60570V–60570V. International Society for Optics and Photonics, 2006.

[10] R. Mantiuk, S. Daly, and L. Kerofsky. Display adaptive tone mapping. In *ACM Transactions on Graphics (TOG)*, volume 27, page 68. ACM, 2008.

[11] S. Miller, M. Nezamabadi, and S. Daly. Perceptual signal coding for more efficient usage of bit codes. *SMPTE Motion Imaging Journal*, 122(4):52–59, 2013.

[12] P. Irawan, J. A. Ferwerda, and S. R. Marschner. Perceptually based tone mapping of high dynamic range rmage streams. In *Rendering Techniques*, pages 231–242, 2005.

[13] T. Celik and T. Tjahjadi. Contextual and variational contrast enhancement. *IEEE Transactions on Image Processing*, 20(12):3431–3441, 2011.

[14] Q. Wang and R. K. Ward. Fast image/video contrast enhancement based on weighted thresholded histogram equalization. *IEEE Transactions on Consumer Electronics*, 53(2):757–764, 2007.

[15] A. R. Rivera, B. Ryu, and O. Chae. Content-aware dark image enhancement through channel division. *IEEE Transactions on Image Processing*, 21(9):3967–3980, 2012.

[16] S.-C. Huang, F.-C. Cheng, and Y.-S. Chiu. Efficient contrast enhancement using adaptive gamma correction with weighting distribution. *IEEE Transactions on Image Processing*, 22(3):1032–1041, 2013.

[17] C. Thum. Measurement of the entropy of an image with application to image focusing. *Journal of Modern Optics*, 31(2):203–211, 1984.

[18] L. Zhang, L. Zhang, X. Mou, and D. Zhang. Fsim: a feature similarity index for image quality assessment. *IEEE Transactions on Image Processing*, 20(8):2378–2386, 2011.