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Tone mapped HDR images contrast enhancement using piecewise linear perceptual transformation

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***Abstract*—This paper addresses the conversion problem of High Dynamic Range (HDR) images into Low Dynamic Range (LDR) images. The aim of this conversion is to ensure a good visual rendering of the displayed Tone Mapped (TM) HDR images in accordance with the observers' assessment. To do so, the proposed algorithm adjusts a piecewise linear function to the logarithm luminance distribution of the HDR image to adapt this transformation to the perceptual quantizer in accordance with the Human Visual System (HVS). The computation of the slope value of the piecewise linear transformation is simplified. Indeed, it is given by the ratio between the probability and the logarithm luminance distance in the sampling bin. This leads to histograms which tend to be flat, thus inducing a contrast enhancement of the tone mapped HDR images in both under-exposed and over-exposed areas. Simulation results provide good results, both in terms of visual quality and TMQI metric, compared to existing competitive TM approaches.**

***Index Terms*—High Dynamic Range image, Low Dynamic Range image, Tone mapping, Histogram, Contrast enhancement.**

I. Introduction

Acquiring visual information (e.g. images, videos) of real scenes representing the full range of luminance values of real world (i.e. including both under- and over-exposed areas) is possible through High Dynamic Range (HDR) capture devices. However, the cost of these devices remain too expensive. Therefore to continue viewing HDR content on conventional Low Dynamic Range (LDR) display devices, requires the reduction of the Dynamic Range (DR) of the HDR content using specific tone mapping algorithms. Indeed the main purpose of HDR image Tone Mapping (TM) approach is to find a trade-off between the relevant information (e.g. details, contrast, brightness...) to be preserved or discarded in the image so as to ensure a good visual quality of the displayed image on LDR devices that would be appreciated by observers.

A state of the art on HDR image TM approaches is fairly complete in [1], [2] and [3]. Among the developed TM strategies, this paper quickly reviews those that caught our attention because of their performance. Some approaches aim only at preserving detail or enhancing contrast, while others prefer to improve both. In what follows, the described approaches aimed to highlight mainly the details. A second generation of wavelets based on the edge content of the image avoiding having pixels from both sides of an edge has been proposed in In [4]. In [5], a separable non-linear multiresolution approach based on essentially non-oscillatory interpolation strategy has been developed. These approaches take into account the singularities (e.g. edge points) in their mathematical models preserving then the structural information of the HDR images. A non-separable version has been investigated and proposed in [6]. The results provided in [4], [5] and [6] show that the decomposition of the HDR image on different resolution levels would seem to be a good strategy. However, the choice of the decomposition filters is extremely important and decisive in the extractive power of the approximation and detail information.

However other TM strategies aimed both to preserve detail and enhance contrast. Indeed in [9], an edge-preserving bilateral filter is introduced to decompose the HDR image into two layers: a base layer encoding large-scale variations and a detail one. Contrast is then reduced only in the first layer while the details are kept unchanged. In [10], an adaptive logarithmic mapping method of luminance values is presented. It concerns the adjustment of the logarithmic basis depending on the radiance of the pixels. In [11], a subband architecture related on an oversampled Haar pyramid representation is proposed. Subband coefficients are re-scaled according to a gain control function reducing the high frequency magnitudes and boosting low ones.

Below are described methods that enhance contrast using in most cases histograms. In [12], a TM optimization approach using a histogram adjustment between linear mapping and the equalized histogram mapping is developed. A modification of this approach is made in [13]. The latter considers both histogram equalization and human sensitivity to the light function. A piecewise linear perceptual quantizer modeling the "s-shaped" curve of the Human Visual Adaptation with getting more optional contrast by changing the norm space is proposed in [7]. Later, in [8], authors proposed a combination of a near optimal lifting scheme and perceptual quantizer to enhance the contrast and preserve more details in the tone mapped HDR images.

This paper is organized as follows. Section II presents the the proposed TM HDR image approach. The later is based on the adjustment of the contrast according to a perceptual piecewise linear quantizer. Section III discusses the simulation results. Section IV concludes the paper.

II. Proposed tone mapping HDR image approach

The purpose of this section is to find the TM HDR values. For this, the proposed approach adjusts locally the distribution of the HDR image logarithm luminance values according to the HVS to enhance the contrast using a simplified piecewise linear function compared to [7].

The original HDR image is assumed to be of size $N \times M$. Denote $\widetilde{l}_{HDR}$ the HDR image luminance. It is considered in the logarithm domain since the latter is well adapted to the HVS. It is denoted $\mathbf{I}_{HDR}$ and defined as follows:

$$\mathbf{I}_{HDR} := \{\mathbf{I}_{HDR}(x_n, y_m) = \log_{10}(\widetilde{l}_{HDR}(x_n, y_m)) \quad (1)$$
$$\text{for } 1 \leq n \leq N \text{ and } 1 \leq m \leq M\}, \quad (2)$$

where $\mathbf{I}_{HDR}(x_n, y_m)$ is the HDR logarithm luminance value of the pixel located at position (x_n, y_m) on the image.

A. Non-uniform distribution of the HDR logarithm luminance

The $\mathbf{I}_{HDR}$ values are first sorted and classified into equal B bins defined by cutting points denoted c^i_{uHDR} (with $1 \leq i \leq B$). The index i refers to the bin number. A non-uniform histogram equalization is also performed. c^i_{nuHDR} (with $1 \leq i \leq B$) cutting points, defining the bounds of the non-uniform consecutive B bins, are deduced. From uniform and non-uniform cutting points, new cutting points locally adapted to the logarithm luminance values are deduced as described below.

The new lower bound (i.e. new cutting point) of each bin, denoted $l^i_{HDR}(1)$, is then adjusted by the introduction of the parameter β^i as follows:

$$l^i_{HDR}(1) = c^i_{uHDR} + \beta_i(c^i_{nuHDR} - c^i_{uHDR}), \quad (3)$$

where β_i is a positive parameter smaller than 1 depending on the sub-interval $[c^i_{uHDR},\ c^i_{nuHDR}]$. Since the lower cutting point $l^i_{HDR}(1)$ is deduced as the average of the logarithm luminance values on each sub-interval $[c^i_{uHDR},\ c^i_{nuHDR}]$ as in [13], the parameter β_i is then given by:

$$\beta_i = \frac{mean(\mathbf{I}_{HDR}[c^i_{uHDR},\ c^i_{nuHDR}]) - c^i_{uHDR}}{c^i_{nuHDR} - c^i_{uHDR}}. \quad (4)$$

Note that this strategy avoids to get empty bins. The $\mathbf{I}_{HDR}$ values are then classified into non-uniform B bins as follows:

$$\begin{aligned}\mathbf{I}_{HDR} = \{l_{HDR}(k) \ \text{ for } k = 1, ..., N \times M\} = \\ \{[l^1_{HDR}(1), ..., l^1_{HDR}(K_1)], ...,\ [l^i_{HDR}(1), ..., l^i_{HDR}(K_i)], \\ ...,\ [l^B_{HDR}(1), ..., l^B_{HDR}(K_B)]\},\end{aligned} \quad (5)$$

depending on the quantization level set, where K_i is the number of values in the i-th bin (i.e. $1 \leq i \leq B$; $K_i > 0$) and satisfying the following relation $\sum_{i=1}^{B} K_i = N \times M$.

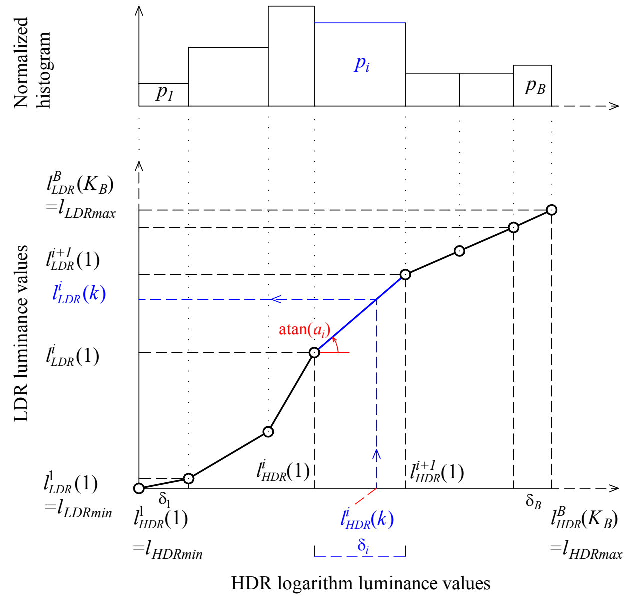

Fig. 1: TM approach using piecewise linear curve.

B. Piecewise linear perceptual quantizer

The "s-shaped" TM perceptual curve, as discussed in [15] and [16], is modelled by a piecewise linear curve on each bin (see Fig. 1). Consider the i-th bin, defined by $[l^i_{HDR}(1), ..., l^i_{HDR}(K_i)]$, the TM values are then modeled as follows:

$$l^i_{LDR}(k) = a_i l^i_{HDR}(k) + b_i \text{ with } k \in [1, K_i], \quad (6)$$

where a_i (with $a_i \neq 0$) and b_i are two unknown parameters depending on the i-th bin.

Introduce δ_i as the difference between HDR luminance in two consecutive bins (see Fig.1):

$$\delta_i = l^{i+1}_{HDR}(1) - l^i_{HDR}(1). \quad (7)$$

Denote l_{LDRmax} (respectively l_{LDRmin}) the maximum (respectively minimum) LDR luminance value. The LDR dynamic range (i.e. $l_{LDRmax} - l_{LDRmin}$) must satisfy the following relation:

$$l_{LDRmax} - l_{LDRmin} = \textstyle\sum_{i=1}^{B} a_i \cdot \delta_i. \quad (8)$$

The unknown slope a_i has been computed in a sophisticated way in [7]. In this paper, a simplified solution is proposed. Remember that the slope a_i is proportional to $(l^i_{LDR}(k) - l^i_{LDR}(1))$ which is also unknown. The latter can be linked to the probability p_i of the $l^i_{HDR}(k)$ value in the i-th bin and is given by $p_i = \frac{K_i}{\sum_{i=1}^{B} K_i}$. The probability associated to the LDR dynamic range (i.e. $l_{LDRmax} - l_{LDRmin}$) is assumed to be equal to one. Therefore one can deduce that $l^i_{LDR}(k) - l^i_{LDR}(1) = p_i \times (l_{LDRmax} - l_{LDRmin})$. The slope a_i is then computed as follows:

$$a^i = \frac{l_{LDRmax} - l_{LDRmin}}{\delta_i} \cdot p_i. \quad (9)$$

The more probability p_i, the more value a_i, and vice versa. The set of slopes satisfy the constraint condition given by (8).

The unknown parameter b_i is computed by the following formula: $b_i = l^i_{LDR}(1) - a_i \times l^i_{HDR}(1)$. The HDR mapped values are deduced according to equation (6). The global piecewise linear curve is continuous and strictly monotonic increasing according to the positive slopes (i.e $a_i > 0$, or angles $0° < \text{atan}(a_i) < 90°$).

III. Simulation results

This section discusses the performance of the proposed TM HDR image approach. The TM image objective quality is measured with the "Tone-Mapped image Quality Index" (TMQI) metric [21]. Simulations have been conducted under Matlab environnement using the HDR Toolbox ([1]) with 274 test HDR images. For lack of space, we only present the results obtained with 8 HDR images ("Bottle Small", "Office", "Oxford Church", "Memorial", "Light", "ClarkCenter", "DollDoll", "ClockBuilding", "AtriumNight" and "PeaceRocks") having different dynamic range (or contrast ratio) from 8 f-stops to 29 f-stops.

The results are compared to: (i) CEDP [8] with norm 1 and level 1; (ii) NUHA [7] with norm 1; (iii) NONSEP ENO-CA [6]; (iv) SEP ENO-CA [5] with parameters $\alpha_1 = 0.3$, $\alpha_2 = 0.7$; (v) Li TMO [11] with Haar multiscale; (vi) Fattal [4] using RBW method with parameters $\alpha = 0.8$, $\beta = 0.3$, $\gamma = 0.8$; (vii) Duan [12] using $\beta = 0.5$; (viii) TMOs in HDR Toolbox: Drago [10], Reinhard [17], Ward [18], Durand [9], Schlick [20] using default parameters as given in the HDR Toolbox. The parameters are chosen so as to give the best results in terms of TMQI metric in all methods.

Table I provides the TMQI metrics. The proposed TM approach namely "Proposed" is deployed with $B = 256$, $l_{LDRmax} = 255$ and $l_{LDRmin} = 0$. The results show that our TM approach is competitive to those developed in the literature. Fig. 2 provides :(i) the TM "ClarkCenter" image of good visual quality in adequacy with the TMQI metric; (ii) normalized histogram with flatness; and (iii) tone mapping curve closest to the "s-shaped" curve.

TABLE I: Tone Mapped Image Quality Index (TMQI)

TMOs	Anturium	Bottle	Office	Church	Memorial	Light
DR f-stops	8.73	16.03	16.29	15.46	18.38	17.46
Drago [10]	0.874	0.801	0.800	0.814	0.800	0.800
Reinhard [17]	0.778	0.807	0.826	0.789	0.791	0.794
Ward [18]	0.806	0.783	0.775	0.817	0.795	0.789
Durand [9]	0.811	0.892	0.825	0.929	0.814	0.800
Tumblin [19]	0.715	0.713	0.735	0.675	0.759	0.750
Schlick [20]	0.770	0.835	0.926	0.970	0.787	0.780
Duan [12]	**0.964**	0.916	**0.955**	**0.986**	0.935	0.916
Fattal [4]	0.889	0.928	0.943	0.889	0.927	**0.971**
Li [11]	**0.964**	**0.954**	0.854	0.877	0.834	0.888
Anas [13]	0.900	0.837	0.896	0.850	0.823	0.832
SEPENO [5]	0.896	0.934	0.943	0.895	0.932	0.970
NONSEP [6]	0.938	0.873	0.935	0.820	0.832	0.932
NUHA [7]	0.929	0.850	0.927	0.897	0.922	0.916
CEDP [8]	0.957	0.878	0.943	0.980	**0.960**	**0.971**
Proposed	**0.975**	**0.959**	**0.960**	**0.987**	**0.961**	**0.985**

Fig. 3 compares the visual quality of the TM "AtriumNight" images using "Li" and our approach. Although "Li" approach added some post-processing to improve the visual rendering such as cutting off the brightest and darkest parts as well as adding 15% of a histogram equalized layer to the result, our approach is of better visual quality and higher TMQI. Fig. 4 concerns the TM "DollDoll" images using "Fattal" and our approach. These images confirm the performance of our proposal.

The visual quality of the TM "ClockBuilding" images, given by Fig. 5, using "SEPENO" and our approach show that some details are lost on "SEPENO" TM mapped image compared to our approach. Moreover, our TM image is of better contrast. A similar result is provided by Fig. 6 where the "PeaceRock" HDR image has been mapped using "NUHA" and our method. One can observe that the brightness of our TM image is better.

For TM "church" images in Fig. 7, although TMQI metric is slightly different for "Duan" method (0.986) and our approach (0.987), the visual rendering of our TM image is better.

The performance of our approach is confirmed on more than 274 test HDR images where the details and contrast are better represented than other competitive methods for a wide range of f-stops.

IV. Conclusion

This paper proposed a simplified piecewise linear perceptual quantizer for tone mapped HDR images contrast enhancement. The HDR logarithm luminance values distribution are adjusted to fit the perceptual "s-shape" curve. Simulation results confirm the relevance of the proposed approach both in terms of the TMQI objective metric and the visual quality of the displayed image.

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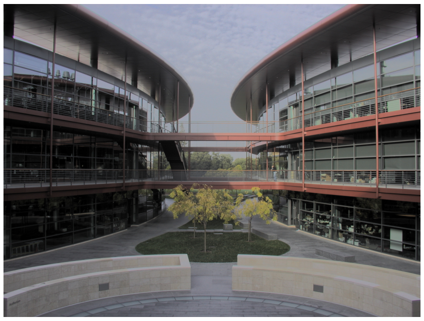
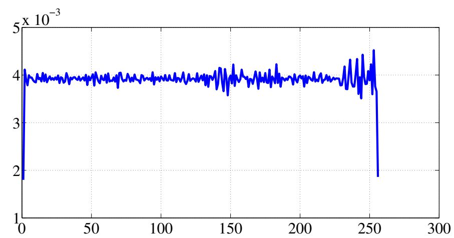
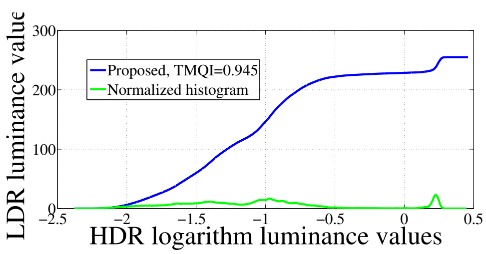


(a) Tone mapped image (TMQI=0.945)



(b) Normalized histogram



(c) Tone mapping curve

Fig. 2: TM ”ClarkCenter” image (19.42 f-stops).

(a) Proposed (TMQI=0.888)

(b) Fattal RBW (TMQI=0.733)

Fig. 4: TM ”DollDoll” image (13.89 f-stops).

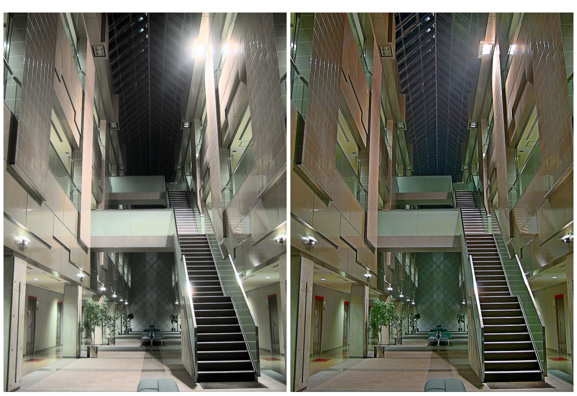


Fig. 3: TM ”AtriumNight” image (28.68 f-stops): (Left) Proposed (TMQI=0.958), (Right) Li (TMQI=0.888).

Fig. 5: TM ”ClockBuilding” image (14.19 f-stops): (Left) Proposed (TMQI=0.962), (Right) SEPENO (TMQI=0.753).

(a) Proposed (TMQI=0.893)

(b) NUHA Norm 1 (TMQI=0.865)

(c) NUHA Norm 2 (TMQI=0.771)

Fig. 6: TM ”PeaceRocks” image (24.14 f-stops).

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(a) Proposed (TMQI=0.987)

(b) Duan (TMQI=0.986)

Fig. 7: TM ”Church” image (15.46 f-stops).

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