Adaptive Contrast Adjustment for Postprocessing of Tone Mapped High Dynamic Range Images

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***Abstract*—Tone mapping operators (TMOs) employed to visualize high dynamic range (HDR) content on conventional low dynamic range (LDR) devices suffer from two major drawbacks. First, none of them can faithfully reproduce all the contrast present in HDR images. Second, most of them require one or more parameters which are mostly content specific and their optimal values can be set only via subjective testing. To address these issues, this paper proposes that 'quality driven' adaptive contrast enhancement is a practical solution. This is achieved by enhancing the contrast adaptively based on the loss of contrast between the HDR and tone mapped image. Experimental results confirm that the proposed adaptive solution always improves upon the contrast achieved from whatever given TMO parameter settings in the tested images. So it helps to achieve the results of a more optimal TMO parameter setting without the human input.**

I. INTRODUCTION

High Dynamic Range imaging (HDRI) has been steadily gaining popularity in both academia and industry [6]. The reason being that HDR faithfully depicts the dynamic range of the real world luminance (typically varying from 10^{-1} cd/m^2 to 10^5 cd/m^2) by storing them as floating point values. As a result, an HDR image can capture very high contrasts which in turn enables it to incorporate maximum details that the human eye can discern. However, the cost of HDR display technologies is currently quite high and yet to reach consumer levels. In such scenario, the only alternative is to display HDR contents directly on commonly available devices such as CRT, LCD monitors, printers etc. which have a significantly low dynamic range (LDR). It follows that these cannot provide the necessary luminance range (usually their range lies between 1 to 300 cd/m^2) for a true HDR experience. Therefore an important issue in HDRI is to reduce the dynamic range of the HDR content. This problem has been commonly addressed by employing tone mapping operators (TMOs). Tone mapping refers to the reduction in dynamic range so as to properly display the HDR content onto LDR devices.

Several TMOs have been developed over the past years [6]. Some are simple and based on operations such as linear scaling and clipping while the more sophisticated ones exploit several properties of the Human Visual System (HVS) [3] with the aim of preserving the important details. Even though several TMOs exist, there are two major issues with them. First, majority (if not all) of them cannot preserve all the contrast present in the HDR image. This can reduce the perceptual quality of the tone mapped contents due to the introduction of artifacts related to changes in contrast as well as loss of important details. Second, many TMOs involve one or more parameters which is usually left for the user to set. Unfortunately, there is no systematic and general method to determine the optimal TMO parameters. This issue is further complicated by the fact that a set of TMO parameters suitable for one image content may not be optimal for another. As a result, the best (and only) way to determine parameters values is through subjective tests which obviously are not suitable for real-time processing.

II. PROPOSED IDEA

To target the two aforementioned issues with existing TMOs, we propose that the use of contrast enhancement as a post processing step would be beneficial in improving the contrast of tone mapped images. This will particularly be effective in cases when the large amount of contrast has been damaged as a result of TMO design and/or the specified TMO parameters. Further it may also be mentioned that many TMOs operate locally as a result of which contrast loss occurs non-uniformly in different image regions (instead of a uniform contrast loss in the entire image). Therefore, it is less effective to enhance the contrast of tone mapped images uniformly since some regions may have lost more details as compared to others. That is, adaptive contrast enhancement based on the loss of contrast is expected to be a more effective solution in restoring the contrast lost during tone mapping. To this end, we first assess the loss of contrast between the HDR image and its corresponding tone mapped image. Next, we use this to determine the clip limit for the contrast enhancement algorithm. The idea is that when more contrast is lost in some region, the clip limit is set to a higher value leading to more

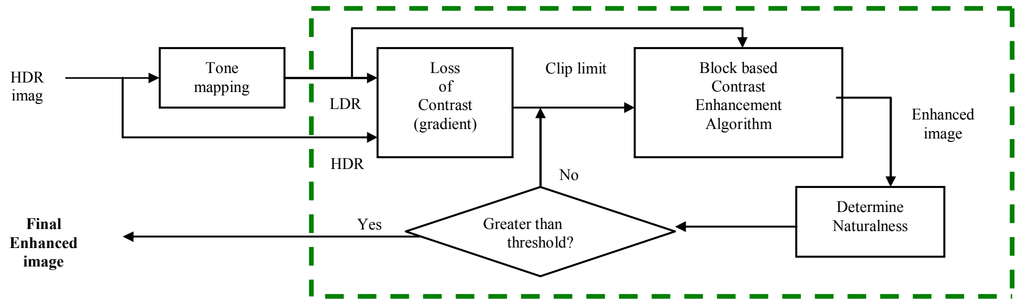


Figure 1. Block diagram of the proposed adaptive post processing contrast enhancement method

contrast enhancement. Likewise, for regions where tone mapping resulted in much smaller loss of contrast, the clip limit is automatically set to a lower value thereby limiting contrast enhancement in that region. The final result is that the contrast of the tone mapped image is enhanced adaptively and in a more 'quality aware' fashion rather than simply applying contrast enhancement to the whole image. The final step in our method is that of assessing the naturalness of the enhanced image. If the naturalness is grater than a threshold, then no further processing is required. If however, the naturalness is lower than the threshold, it implies that the image has probably been over enhanced making it appear unnatural. Then corrective action is necessary by re-adjusting the clip limit. A block diagram of the proposed method is shown in Figure 1.

Even though objective measurement of loss of contrast between HDR and tone mapped image and the naturalness are themselves challenging, we believe that our idea has potential and we have verified it on a sufficiently large set of HDR images processed by several well known TMOs. We found that with the proposed post processing the resultant images usually have better contrast and brightness.

III. Implementation Details

In this paper, we adopted a gradient based method to assess the loss of contrast between the HDR image and its corresponding tone mapped version. We employed the Sobel operator to compute the derivatives along the x (row) and y (column) directions. We denote these as $L_x(i, j)$ and $L_y(i, j)$ at location (i, j) for the tone mapped (LDR) image. Similarly for the HDR image, we have $H_x(i, j)$ and $H_y(i, j)$. We then measured the similarity between the derivatives of the HDR and LDR images to obtain the 'contrast similarity' map $SM(i, j)$ defined as

$$SM(i,j) = \frac{L_x(i,j).H_x(i,j) + L_y(i,j).H_y(i,j) + k}{\sqrt{L_x^2 + L_y^2}.\sqrt{H_x^2 + H_y^2} + k} \quad (1)$$

Here k is a small constant added to tackle the when denominator approaches 0. In the proposed method, we set $k = 0.01$. Note that since the range of values in HDR and LDR is not the same, we use only the gradient direction to compute SM. The main advantage of defining $SM(i, j)$ in this manner is that it remains bounded i.e. $SM(i, j)$ lies in the range [0, 1] with 1 indicating no 'contrast loss'. This completes the first step of the proposed method.

For the second step, we used the Contrast Limited Adaptive Histogram Equalization (CLAHE). Even though CLAHE operates in an adaptive manner i.e. it performs histogram equalization based on local image content, it does not directly take into account the loss of contrast more so in the context of tone mapped images. In that sense, we can refer to CLAHE as a no reference contrast enhancement method since it does not use any information regarding the loss of contrast due to a particular operation. Because the proposed method provides information about contrast loss, it can be considered as contrast enhancement with a reference which intuitively should also perform better than reference free enhancement. A brief and relevant description of CLAHE algorithm is now provided and the reader is referred to [1] for complete details.

For CLAHE algorithm, the input image of size R x H is divided into local regions and for each region histogram is computed. Next, based on a parameter known as clip limit CL, contrast enhancement is controlled by limiting the histogram values to the clip limit. Note that a higher clip limit implies more contrast. The resultant histogram is then normalized and used to estimate the cumulative probability density function (cdf) which is the mapping function from the original image patch to the contrast enhanced one. In this manner, the contrast of each local region is enhanced which are then combined using bilinear interpolation in order to eliminate artificially induced boundaries. Pertaining to the clip limit, CLAHE uses it limit the slope of the cdf which is particularly useful in flat regions of the image. However, the problem is that CLAHE uses the same clip limit (default value being 0.01) for all the image regions and this ignores the fact TMOs can lead to non-uniform loss of contrast. Hence there is a need for adaptive determination of the clip limit.

We achieve this by using 'contrast similarity' map SM defined in Eq. (1). Since the clip limit and SM follow opposite trend i.e. higher SM means smaller contrast loss while higher CL implies more contrast, we define the adaptive clip $CL_{adaptive}$ limit as

$$CL_{adaptive} = 1 - \lambda.SM \quad (2)$$

where $\lambda \in [0,1]$ is a parameter that we used to weight SM. A bigger value of λ would lead to a smaller $CL_{adaptive}$ which means lower contrast enhancement. To set a proper value for λ, we did a small pilot subjective study on the visual quality of several enhanced images. Importantly, we found that small changes in λ did not result in too large variations of the visual quality of the resultant images and even with λ = 1 acceptable results were achieved. So, unlike the clip limit, λ need not be adaptive and can be fixed. For the results reported in this paper we used λ = 0.97 which seemed to provide the best visual quality for the images used in the pilot study.

The final step of the proposed method is to check for the naturalness of the enhanced image. This step is required partly due to the fact that TMOs themselves can result in unnatural images. Objective measurement of naturalness of an image is difficult given that it is highly subjective and involves several aspects that contribute to the overall appearance of the image to the viewer. Nonetheless, in this paper, we employed the statistical naturalness measure recently proposed in [7]. It is based on contrast and luminance (brightness) computed using mean and standard deviation respectively. For this, histograms of means and standard deviations of almost 3000 good quality natural LDR images were plotted. It was found that these histograms could be well fitted using a Gaussian and a Beta probability density functions respectively where the model parameters were determined via regression. The density functions are given by

$$P_m(m) = \frac{1}{\sqrt{2\pi}\sigma_m} \exp\left[-\frac{m-\mu_m}{2\sigma_m^2} \right] \tag{3}$$

and

$$P_d(d) = \frac{(1-d)^{\beta_{d-1}} d^{\alpha_{d-1}}}{B(\alpha_d, \beta_d)} \tag{4}$$

where $B(.,.)$ is the Beta function. The model parameters as estimated by regression were $\mu_m = 115.94$, $\sigma_m = 27.99$, $\alpha_d = 4.4$ and $\beta_d = 10.1$.

Finally, assuming that luminance and contrast are independent, their joint probability density function will be a product of the two. So naturalness was defined as

$$N = \frac{1}{T} P_m P_d \tag{5}$$

where $T = \max\{P_m, P_d\}$ is the normalization factor. So N lies between 0 and 1 with higher value indicating higher statistical naturalness.

Since our aim is to compare the naturalness of enhanced images, we define the ratio of naturalness as

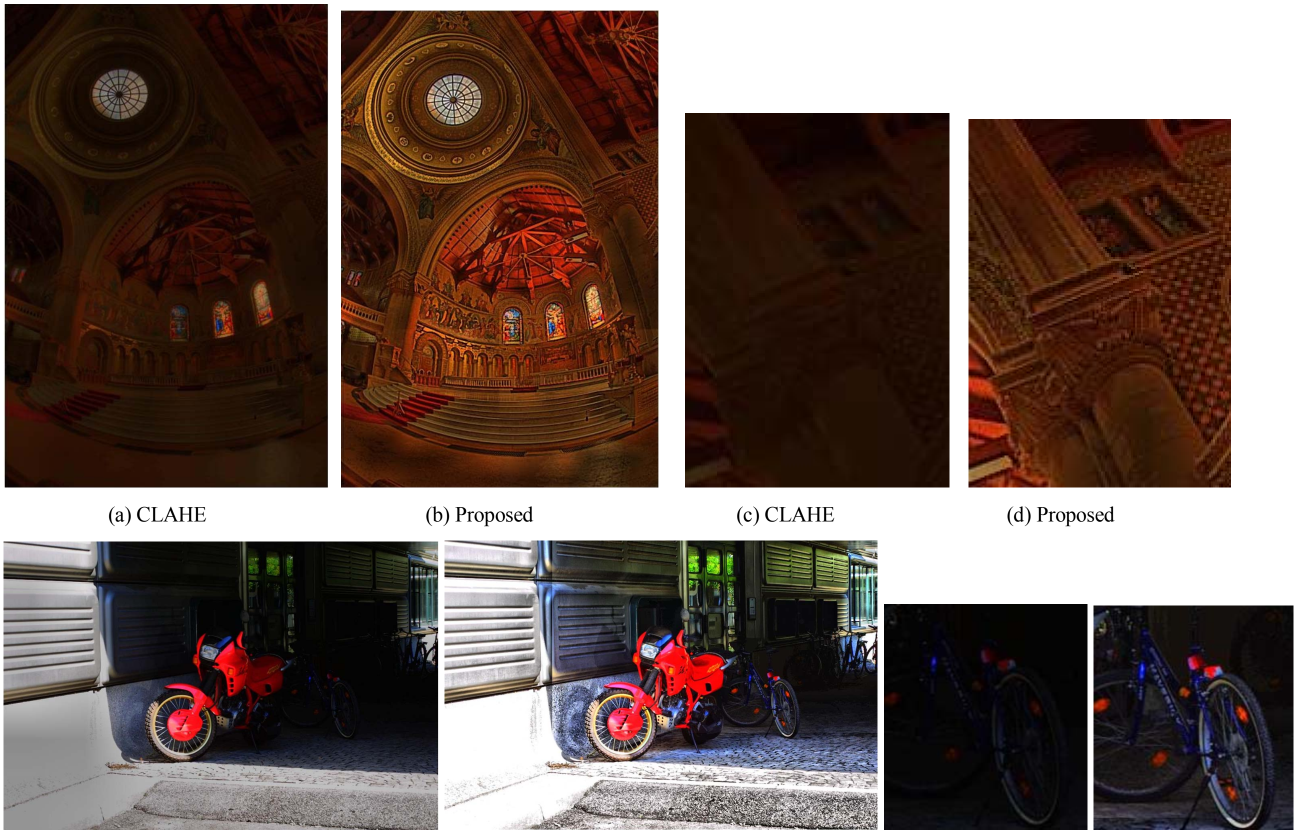
$$N_{ratio} = N_{proposed} / N_{clahe} \tag{6}$$

where $N_{proposed}$ and N_{clahe} respectively denote the statistical naturalness of the image processed by the proposed method (i.e. with adaptive clip limit) and the one processed by CLAHE (fixed clip limit). Obviously, N_{ratio} greater than 1 means that the proposed method results in images with more naturalness at least in the statistical sense. We found that N_{ratio} was always greater than 1 for all the images that we tested and this works quite well for low contrast tone mapped images. However taking into account the possible limitations of the statistical naturalness measure (which is only an approximate model), we empirically defined a stronger (i.e. bigger) threshold for acceptable quality images as 3.5 (and not 1) i.e. when $N_{ratio} > 3.5$, then no further processing is required. If however, $N_{ratio} < 3.5$, then the resultant image was usually over enhanced which tended to look unnatural. So in this case, we employed the original CLAHE for enhancement i.e. instead of using $CL_{adaptive}$ we used a small default constant clip limit ($CL = 0.01$) in order to limit contrast enhancement. In this way, the proposed method is made more generic and capable of handling larger contrast ranges and not just low contrast images.

IV. EXPERIMENTAL RESULTS

For the experimental validation of the proposed method, we selected 5 HDR images which were processed by linear TMO (simple linear mapping), Ashikimin TMO [2], Ward TMO [3], Tumblin TMO [4], Reinhard TMO [5] and the logarithmic TMO. We used the HDR toolbox [6] which provides Matlab implementations of these TMOs. The selected images are representative of a wide range of content such as indoor and outdoor scenes with varying illumination conditions. Although several other TMOs exist, these were chosen because they are popular and cover a wide range in terms of the approach taken to process HDR (some are simple ones while others employ more sophisticated HVS based processing). For example the linear TMO is the simplest of them all which performs a simple linear mapping from the floating point HDR value to [0,255] while the TMO proposed by Ward uses a scaling factor derived from a psychophysical contrast sensitivity model to reduce the range. Thus, each of the TMO employed uses different approaches to dynamic range reduction and thus leading to different extents and manner in which contrast loss occurs. Additionally, linear, logarithmic and Ward TMOs are global (these use a global mapping on the entire image) while the remaining ones are local TMOs (their mapping function is based on local image characteristics). All the TMOs employ one or more user defined parameters and we used the default values as provided by the respective authors for all but Ashikimin TMO. For this TMO, we found that the use of default value resulted in a saturated and very poor quality image and so this value was set to 0.3 for all the images tested. We obtained a total 60 enhanced images (5 HDR scenes x 6 TMOs x 2 contrast enhancement methods). We have shown 2 of these images in Fig. 2 (tone mapped by Ashikimin and logarithmic TMOs) and zoomed in views of some regions to demonstrate the usefulness of proposed scheme.

The first observation is that the proposed method results in much better contrast leading to overall visually more appealing images as shown in Fig. 2 (b), (f). This happens due to the supervised nature of the proposed method which enables it to adjust the level of contrast enhancement via the use of $CL_{adaptive}$. One major problem with many TMOs is that they cannot balance the contrast in dark and bright image areas. With CLAHE this problem cannot be remedied due to it being non-adaptive. This can be seen from Fig. 2 (e) where CLAHE improves contrast in bright areas (mainly foreground) but unable to do so in the darker areas (mainly the background). The proposed scheme on the other hand provides better contrast restoration in different regions (dark, bright, textured etc.) since it differentiates and takes into account the actual



(a) CLAHE (b) Proposed (c) CLAHE (d) Proposed

(e) CLAHE (f) Proposed (g) CLAHE (h) Proposed

Figure 2. Comparison of images processed by the proposed method and CLAHE. Zoomed in views for highlighted regions are also shown.

contrast loss for enhancement. For better comprehension and a closer look, we have also shown in Fig. 2 (c), (d), (g) and (h) the zoomed in views of image portions. Observe that the proposed method renders better visibility of the contents as compared to CLAHE. Because in general the contrast was improved for each image content and all the TMOs used, the proposed idea is general and effective strategy for post processing of tone mapped images for better visual quality. In Fig. 2, we provided only two examples due to lack of space. However, the reader is encouraged to download other images from the website http://dl.perreira.net/more_examples.rar for more visual examples that demonstrate the effectiveness of the proposed scheme in comparison to CLAHE.

V. CONCLUSIONS

None of the existing TMOs can preserve all the contrast and most of them require used defined parameters which are usually content specific. So they may result in images with poor contrast and it is not practical to obtain optimal parameters via subjective testing. To tackle this, we proposed an adaptive contrast enhancement strategy based on the loss of contrast between HDR and tone mapped images. Experimental results demonstrate the effectiveness of the proposed idea in enhancing contrast without human input thereby making it useful for real time applications.

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