

FUSION OF TONE-MAPPED HIGH DYNAMIC RANGE IMAGES BASED ON OBJECTIVE RANGE-INDEPENDENT QUALITY MAPS

Charles Yaacoub, Cendrella Yaghi, Christine Bou-Rizk

Faculty of Engineering, Holy Spirit University of Kaslik (USEK), P.O.Box 446 Jounieh, Lebanon

ABSTRACT

Tone mapping operators for converting high dynamic range images to low dynamic range versions usually incur a loss of details compared to the original scene. As each operator performs differently in different image regions, this paper introduces a fusion technique that combines the output of several operators in a single image, based on objective quality maps that do not depend on the dynamic range of neither the input nor the output images, thus offering a better detail preservation capability compared to the case where each operator is independently applied. Results show significant improvement in the output quality obtained with the proposed technique compared to traditional tone mapping operators.

Index Terms— High dynamic range, image fusion, image quality metrics, tone mapping, visual perception.

1. INTRODUCTION

High Dynamic Range (HDR) imaging was first introduced in order to obtain an image that correlates as much as possible with real world scenes, as there is no human-made electronic device that can capture a scene as the eye can observe it. The aim of HDR imaging is to cover the entire range of light and present the full information in a scene. However, a fundamental problem is encountered by the limitations of standard display that cannot reproduce an image with a high ratio between light and dark areas, and therefore not allowing for a correct visualization of HDR images. Tone mapping operators (TMOs) are used to overcome this problem by reducing the dynamic range of the HDR image in a way suitable for the display, while maintaining, to some extent, the visual appearance of the scene.

There are mainly two broad categories of TMOs: global operators and local ones. A global TMO [1-4] is an algorithm that uniformly applies the same operation on all pixels within a HDR image, regardless of their spatial location. Global operators are relatively simple, fast, and computationally efficient. However, if the dynamic range of a scene exceeds by far the range that can be produced by a display, global TMOs may result into significant loss of contrast and destruction of important details in the resulting

LDR image. On the other hand, local TMOs [5-8] adapt locally to scene variations as they take into account each pixel's neighborhood while mapping the pixel from the HDR space to the LDR's. Local operators often produce more pleasing results as they better conserve details in high-light and shadow regions, since the human eye locally reacts to contrast, at the expense of a higher computational load compared to global TMOs. A main disadvantage of local TMOs is the appearance of halo effect in the resulting LDR image.

Quality assessment is an important issue in tone mapping algorithms. While comparing HDR-to-HDR or LDR-to-LDR images, both have the same dynamic range, thus traditional quality assessment measures can be used, such as the Mean Square Error (MSE), Mean Absolute Difference (MAD), Peak Signal-to-Noise Ratio (PSNR), etc... However, when mapping a HDR image to a LDR, these quality measures become inadequate in representing similarities or differences in both versions of the image. A TMO performance is usually discussed subjectively by analyzing the visual appearance of the mapped output. Recently, several attempts have been made to derive an objective measure for the assessment of tone mapping operators. Aydin *et al.* proposed in [9] a method that compares the tone-mapped LDR image to its initial HDR version, and results in three quality maps measuring different aspects in the mapped output at each pixel position: the loss of visible features, the amplification of invisible features, and the reversal of visible contrast. Yeganeh and Wang proposed in [10] a metric with a single score that represents the quality of the mapped LDR image, as opposed to the pixel-by-pixel quality maps in [9].

The perceptual quality of a tone-mapped image depends not only on its dynamic range and the TMO used, but also on the captured scene itself. In other word, there is no *best* operator that can be used to always obtain the best results. Additionally, a TMO could perform well in some regions of an image, while another TMO could perform better in other regions. Therefore, fusing several tone-mapped images obtained by applying different TMOs on the same HDR image could be beneficial for improving the LDR output. This can be seen as similar to exposure fusion [11] where several LDR images are fused. However, in exposure fusion, the original LDR versions of a scene, captured at different exposures, are available for processing without

constructing an HDR image. In this paper, we consider the case where only an HDR image is available, and thus it is the only reference that can originally describe the captured scene. Several TMOs are applied and the original HDR image is used for evaluating the performance of each TMO at each pixel coordinates, based on the objective quality maps derived in [9]. Finally, several approaches for fusing the different LDR images in a unique output are proposed. To the best of the authors' knowledge, there is no previous study on fusing several tone-mapped images for improving the final LDR output given only an HDR input image.

The remainder of this paper is organized as follows. In Section 2, the objective quality assessment technique of [9] is briefly reviewed. Section 3 presents the proposed fusion algorithms for improving the quality of the LDR output image. Practical results are discussed in Section 4, and conclusions are finally drawn in Section 5.

2. LDR IMAGE QUALITY ASSESSMENT

Aydin *et al.* proposed in [9] an approach that has the ability to compare a pair of images with significantly different dynamic ranges, thus suitable for HDR-to-LDR comparison. The derived metric classifies the distortion at each pixel position in the tone-mapped output as Loss of Visible Features (LVF), Amplification of Invisible Features (AIF), and Reversal of Visible Contrast (RVC).

First, the luminance from the HDR reference and the LDR test images are retrieved. A contrast detection predictor [12] is then applied and the output split into several bands of different orientations and spatial bandwidths. Three types of distortion are separately predicted afterwards, for each spatial band (b) and orientation (o), by computing the conditional probabilities of LVF, AIF and RVC in equations (1), (2) and (3), respectively, where the subscript $/v$ denotes *visible contrast* and $/i$ denotes *invisible contrast*.

$$P_{LVF}^{b,o} = P_{HDR/v}^{b,o} \cdot P_{LDR/i}^{b,o}, \quad (1)$$

$$P_{AIF}^{b,o} = P_{HDR/i}^{b,o} \cdot P_{LDR/v}^{b,o}, \quad (2)$$

$$P_{RVC}^{b,o} = \begin{cases} P_{HDR/v}^{b,o} \cdot P_{LDR/v}^{b,o} & \text{if the polarities of contrast} \\ & \text{in HDR and LDR images differ,} \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

The details for deriving the different probabilities $P_{t/c}^{b,o}$, $t \in \{LDR, HDR\}$ and $c \in \{v, i\}$, can be found in [9].

The probability map for any type of distortion $d \in \{LVF, AIF, RVC\}$ is then obtained by:

$$\hat{P}_d^{b,o} = F^{-1} \left\{ F \left\{ P_d^{b,o} \right\} \cdot B^{b,o} \right\}, \quad (4)$$

where F represents the Fourier transform, F^{-1} its inverse, and $B^{b,o}$ the cortex filter [13] for the band (b) and orientation (o) as defined in [9]. Finally, since the probability maps (eq.4) are calculated independently at each band, the quality maps P_d are computed as:

$$P_d = 1 - \prod_b \prod_o \left(1 - \hat{P}_d^{b,o} \right). \quad (5)$$

3. PROPOSED FUSION TECHNIQUES

As mentioned earlier, a TMO might better preserve details than other TMOs in some image regions, while others could be better detail-preserving operators in other regions of the same image. Therefore, combining the output of different tone-mapping operators in a single image could be beneficial for improving the final result.

Our proposed algorithms for fusing the LDR outputs obtained by applying different TMOs on the same HDR input image are based on an intuitive approach of weight-averaging the LDR versions, with the weights depending on the distortion maps defined in Section 2.

The output image can be obtained by considering only one type of distortion $d \in \{LVF, AIF, RVC\}$ as:

$$LDR^{(d)} = \frac{\sum_{n=1}^N \left(\overline{P_{d,n}} \cdot LDR_n \right)}{\sum_{n=1}^N \overline{P_{d,n}}}, \quad (6)$$

where N represents the number of used operators, LDR_n the LDR luminance image obtained with the n^{th} operator, and $\overline{P_{d,n}}$ the weights defined as:

$$\overline{P_{d,n}} = \begin{cases} P_{d,n} & \text{if } d = AIF \\ 1 - P_{d,n}, & \text{otherwise} \end{cases}, \quad (7)$$

with $P_{d,n}$ being the quality map P_d computed for the image LDR_n as defined in equation (5). Obviously, the weight increases when the distortion decreases, for the case of LVF and RVC. However, in case of AIF, we consider that the amplification of invisible features may reveal details in the scene that were not initially perceived, and thus this type of distortion may constructively contribute in the final output. Fusion can also be performed by jointly considering all types of distortions. The output can thus be expressed as:

$$LDR^{(all)} = \frac{\sum_{d \in \{LVF, AIF, RVC\}} \sum_{n=1}^N \left(\overline{P_{d,n}} \cdot LDR_n \right)}{\sum_{d \in \{LVF, AIF, RVC\}} \sum_{n=1}^N \overline{P_{d,n}}}. \quad (8)$$

4. PRACTICAL RESULTS

In this paper, we consider the application of the

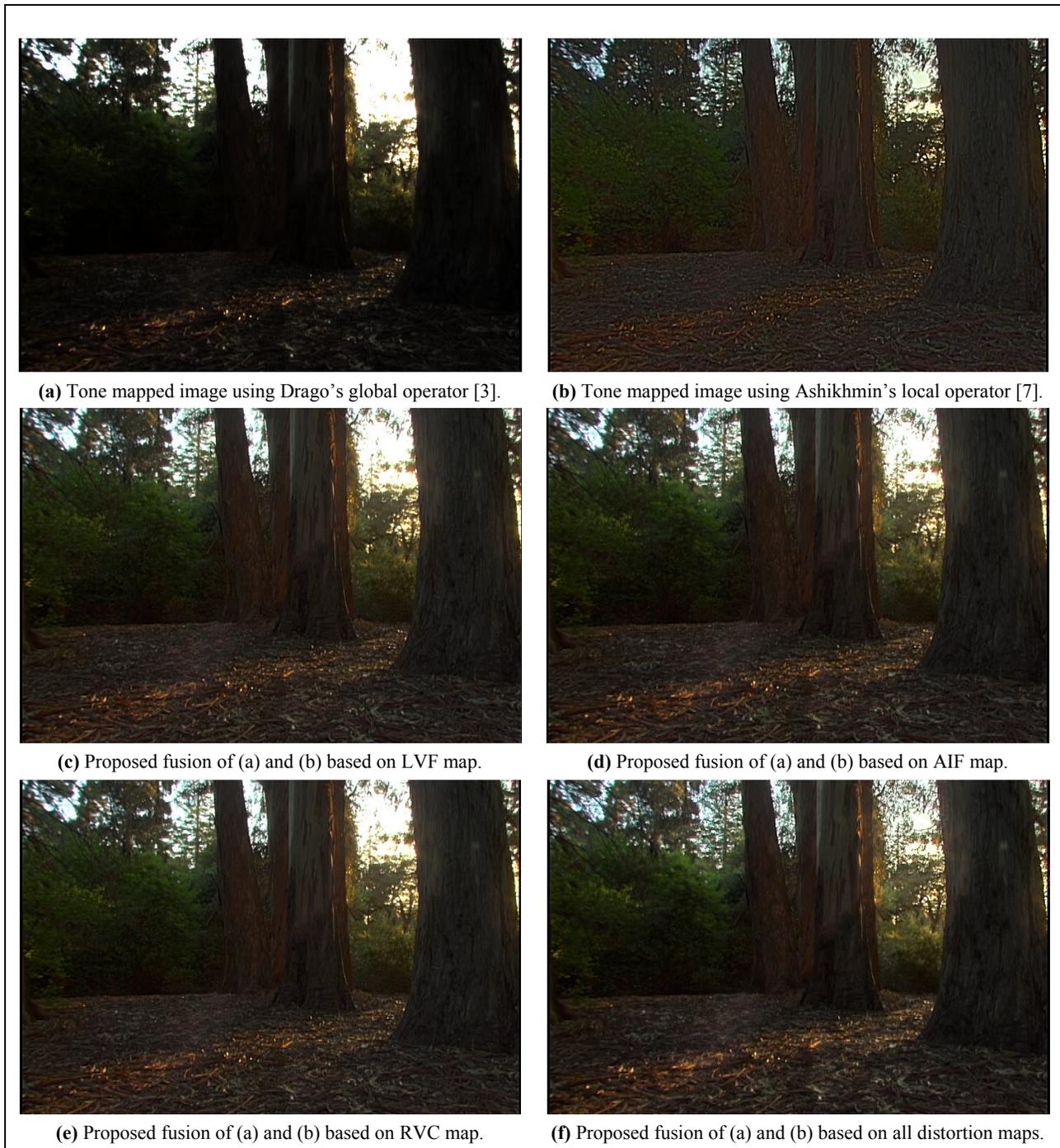


Figure 1- Sample results obtained by applying a global TMO (a), a local TMO (b), and the proposed fusion algorithms (c-f).

proposed fusion technique using $N=2$ tone mapping operators. The operators are chosen such that one is global (arbitrarily chosen from [1-4]) and the other is local (arbitrarily chosen from [5-8]), such that the fusion algorithm can benefit from the better detail preservation capability of local operators, while global operators allow avoiding the halo effect that local TMOs usually produce. Results are visually analyzed as well as objectively

evaluated based on the structural similarity index (SSIM) adapted in [10] for comparing a tone-mapped LDR image to its original HDR version. SSIM scores are normalized such that a value of 0 indicates worst quality and a value of 1 indicates best quality.

Figure 1 shows several results obtained by applying global and local tone mapping operators on the same input HDR image, as well as the proposed fusion technique. In

Figure 1(a), Drago’s global operator [3] is applied while in Figure 1(b), Ashikhmin’s local operator [7] is applied. It can be clearly observed that the local operator better preserves the details in most areas of the original scene, but the resulting image does not look as natural as the one obtained with the global TMO, which explains the low quality score shown in Table 1 for the local TMO. Images (c) to (e) in Figure 1 are obtained by applying the proposed fusion based on LVF, AIF, and RVC quality maps, respectively, while image (f) is obtained by jointly considering all quality maps. Visually, it can be noticed that all four results obtained by fusion have more pleasant appearance compared to the results obtained without fusion; details are more apparent without losing the naturalness of the original scene. This can also be noticed from the quality scores in Table 1, where the SSIM scores significantly increase with the fusion-based method compared to both the global and local TMOs. On the other hand, comparing the results (c) to (f), it can be observed that the quality scores are almost similar, and the best score is obtained when all the distortion maps are jointly considered. Even though a slight improvement in the SSIM score was obtained in (f) compared to (c), (d), and (e), the improved appearance in (f) can also be visually perceived, by looking for example to the bright areas between the trunks of the trees. It is important to mention that the SSIM in (f) reached a value very close to unity, which shows that a significant improvement in the LDR image and a visually appealing result can be obtained using only two operators, and the additional improvement that could have been obtained by applying the fusion algorithm using more candidate TMOs would have been marginal.

Figure 2 shows another example where the result of fusion (bottom) is significantly better than both results obtained with the global (top) and local (middle) operators. Similar results were observed with different combinations of global and local operators, and using different HDR images.

Table 1- SSIM quality score for the results of Figure 1.

Figure 1	(a)	(b)	(c)	(d)	(e)	(f)
SSIM	0.894	0.432	0.940	0.939	0.931	0.950

5. CONCLUSION

In this paper, a fusion technique for tone-mapped high dynamic range images was proposed. Fusion was performed based on objective quality maps, representing three different types of distortions, computed at each pixel position. Practical results were visually analyzed comparing the different low dynamic range outputs, and objectively evaluated based on an objective quality metric that compares the LDR output to the reference HDR input. Results showed that a significantly improved output, in terms of detail preservation and visual appearance as well as

in terms of objective evaluation, can be obtained with the proposed fusion compared to the results obtained with the individual operators when applied independently. As for future work extensions, we propose studying the performance of the proposed technique depending on a larger number of operators. Complexity analysis would also be an important issue for investigation.

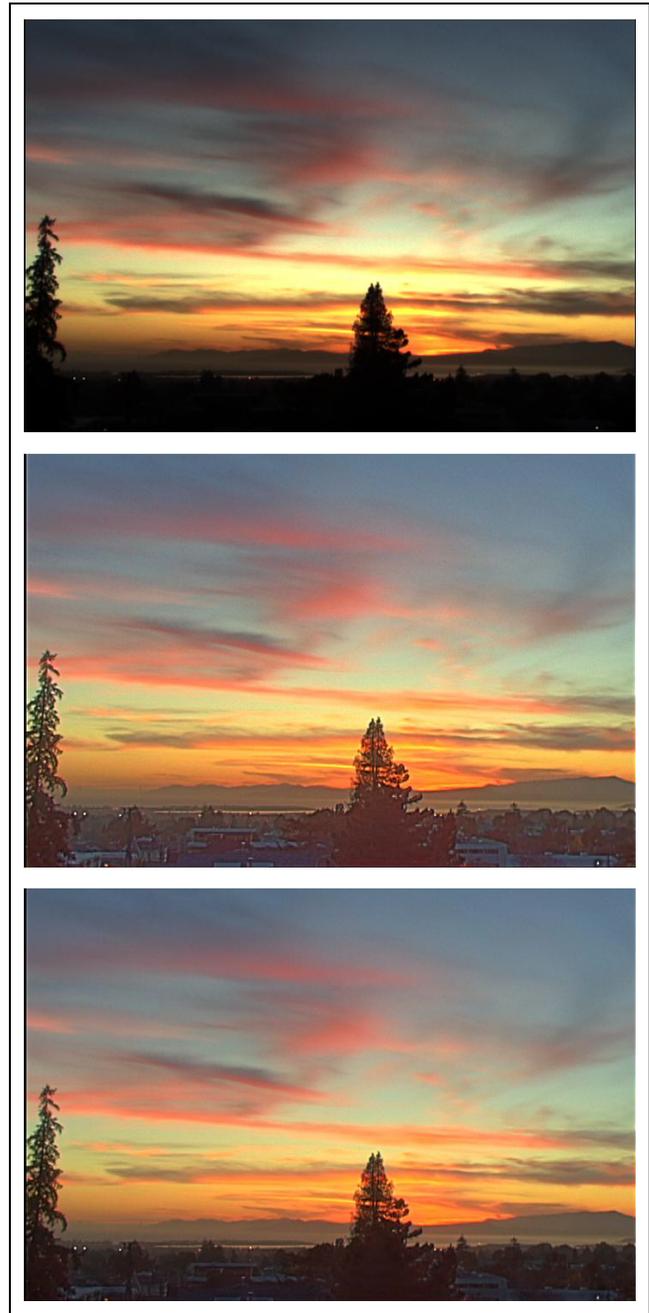


Figure 2- Sample results obtained by applying (top) Ward’s global TMO [2], (middle) Ashikhmin’s local TMO [7], and (bottom) the proposed fusion algorithm based on all distortion maps.

6. REFERENCES

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