

Regularized Tone Mapping Using Edge Preserving Filters

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Abstract—Tone mapping is the process of compressing the dynamic range of a scene to make it compatible with displays with limited dynamic range. In this paper, we present a new approach for tone mapping of high dynamic range (HDR) images using edge-preserving filter. We pose it as a variational problem and derive an optimal solution. We compare the results with some of the existing tone mapping algorithms and show that our algorithm compresses the high dynamic range better while preserving the details and avoiding common artefacts. We use an online dynamic range independent metric for analysing the results by the proposed and existing operators and to detect the deviation from the reference HDR image.

I. INTRODUCTION

Human Visual System (HVS) [1] can see details that vary by more than four orders of magnitude. High dynamic range (HDR) imaging refers to the technique that tries to capture this entire dynamic range using a single digital image [2]. For generation of HDR content, several images of the scene with different exposure times are generally captured and fused together [2], [3]. Recently, there has been an ever-increasing demand of displaying more and more realistic and natural images in computer graphics, video games, virtual reality, photography, etc. Traditional displays still can not handle the entire dynamic range and works only with low dynamic range (LDR) images. This shows the importance and requirement of a quick and adaptive tone mapping operator which along with properly compressing the dynamic range, produces results closest to the natural scene.

The motivation behind the present work is to design a tone mapping algorithm which aids us in the generation of a high contrast LDR image and can capture all the brightness and contrast levels present in the original HDR image. We would like to approach this problem with an emphasis on the understanding of the fundamental principles of local tone mapping operators (TMOs). The understanding of how the contrast can locally be processed to generate high quality LDR image has enabled us to design a novel local TMO.

We would like to pose the problem of tone mapping as an optimization problem and solve it using the variational methods. We propose a novel approach using edge-preserving filter which preserves the details in the both the higher and the lower intensity regions of the scene. We use an edge-preserving filter and iteratively solve the minimization problem. We show that the algorithm converges to the optimal LDR image.

The major contributions of this paper are:

- We intrinsically attenuate the higher contrast information present in the input HDR image with each iteration making it more effective.
- The proposed solution iteratively calculates the base layer and uses that to find the solution making the convergence faster [4].
- The proposed solution processes both high and low intensity regions appropriately independent of the global contrast of the scene.

In this paper we discuss about the existing tone mapping algorithms in section II. In section III, we will discuss about the formulation and the iterative solution. The implementation part of the algorithm will be explained in section IV. We will present our results and their comparison with the existing operators in section V using the online dynamic range (in)dependent metric [5]. Finally, the paper ends with conclusions and scope for future work, in section VI.

II. RELATED WORK

The simplest and very basic way of range compression is linear TMO which just multiplies the input luminance with some scaling factor. This factor can be chosen based on the outputs that are suitable to perceive visually. One very simple option is to take the ratio of luminance channel with the maximum pixel value, but it results in dark patches in various regions of the output image. Other such scaling factors are suggested in [6]. Similarly the logarithmic mappers calculate the logarithmic ratio of pixel luminance to the maximum luminance, to compress the entire dynamic range.

One of the very first TMOs which worked on the global features of a given HDR image, was proposed by Tumblin and Rushmeier [7] and it was further revised by Tumblin *et al* [8]. In this, gamma correction was applied on given HDR image to preserve its brightness but it was prone to produce dark images on the application of wrong gamma values. Along with proper gamma values, it required calibrated luminance values of the display to produce good results. Larson *et al* [9] utilised the techniques of histogram equalization [10], modified it and proposed a new operator. It provides modified histogram equalization for HDR images and achieves good results by compressing the high dynamic range and overall contrast to some extent.

Schlick [11] proposed another very basic and intuitive technique of quantization. It can be used as a global uniform

quantization or non-uniform quantization by spatially varying one of the parameters. This is a simple and fast TMO but the user interaction required to specify the parameters values is one of its major drawbacks. Another time-dependent TMO was proposed by Pattanaik et al. [12] based on the fact that the time taken by HVS to adapt to the scene luminance is proportional to the varying luminance levels. It is a global and time-dependent TMO and being fully automatic, it addresses the problem of previously mentioned TMOs but the fact that it lacks in producing other effects like glare of HVS, makes it less effective. A completely different approach of adaptive logarithmic mapping was proposed by Drago *et al* [13]. It is computationally fast and works pretty fine in many cases but fails in preserving the finer details like other global TMOs.

Unlike global TMOs, local TMOs successfully compress the dynamic range along with preserving the minute details as they work differently on local and global contrasts. Chiu *et al* [14] proposed one of the earliest local TMO. It derives inspiration from the global scaling TMOs and utilises the same in local domain (average of neighbouring pixels which is used to scale the original luminance). But the final results still suffered from halos at the edges between very bright and dark areas. To remove the halos, scaling function was iteratively smoothed with a Gaussian filter. But this resulted in the approach being computationally expensive and tone mapped image still contained halos. A different approach was proposed by Reinhard *et al* [15] based on photographic principles. It uses differently sized Gaussian kernels to find the regions without edges and avoid halos.

Ashikhmin [16] proposed two approaches to preserve local contrast or visual contrast based on the final goal. Local contrast is calculated by taking ratio of the difference of the two Gaussian filtered images in both the approaches. Durand and Dorsey in [17] exploited the properties of bilateral filter. It is an edge-preserving filter and separates the image into base layer (containing the edges present in input image) and detail layer. All the mapping and computations are performed on the base layer and the results are recombined with the detail later and the chromaticity to get the final tone mapped image. But the problem of halos still persisted in [17]. A further improvement was given by Choudhary and Tumblin where they utilised trilateral filter instead of bilateral filter [18].

Fattal *et al* attenuated the large gradients of the images (while preserving the small ones) to achieve range compression based on the fact that changes in luminance in a HDR image is due to large changes in gradients [19]. Yee and Pattanaik proposed segmentation based operator, dividing the HDR image into regions and calculating an adaptive luminance for each region [20]. The HDR compression can also be achieved by adjusting the operator based on the display device attributes as proposed by Mantiuk *et al* [21]. The course presented in SIGGRAPH provides a review of common TMOs [22].

III. PROPOSED APPROACH

Our solution follows a similar idea to that of Durand and Dorsey [17] where they extrinsically derived the base layer from bilateral filter, attenuated it and then fused it with the detail layer to get the final tone mapped image. But in our approach we intrinsically attenuate the base layer using an iterative method which leads to better results.

A. Formulation

We formulate the tone mapping as a minimization problem and find a solution for that. Consider the regularized minimization problem as given in the Equation 1.

$$\hat{z}(x, y) = \arg \min_{z(x, y)} \iint_{x, y} [(z(x, y) - \tilde{a}(x, y))^2 + \lambda \{(z_x)^2 + (z_y)^2\}] dx dy \quad (1)$$

where $z(x, y)$ is the luminance channel of LDR that we would like to estimate and $\tilde{a}(x, y)$ is a function of the luminance channel $a(x, y)$ of the HDR image. The other term is the smoothness term which is calculated by taking the partial derivatives of $z(x, y)$ to make the problem well posed. The Lagrange multiplier λ acts as a trade-off between the two terms. In our implementation we chose λ to be small (around 1 to 2) as on increasing the value of λ computation time for convergence increases and results also get degraded. The solution is given by Euler-Lagrange equation (a second order partial differential equation). We want to minimize the functional given in Equation 1. Consider Equation 2 below for the functional under consideration.

$$F(x, y, z, z_x, z_y) = (z(x, y) - \tilde{a}(x, y))^2 + \lambda(z_x)^2 + (z_y)^2 \quad (2)$$

The Euler-Lagrange equation for minimizing Equation 1 is given by Equation 3.

$$F_z - \frac{\partial F_{z_x}}{\partial x} - \frac{\partial F_{z_y}}{\partial y} = 0 \quad (3)$$

where F_z, F_{z_x}, F_{z_y} represent the partial derivatives of F with respect to z, z_x, z_y respectively. We shall solve this equation iteratively to get the desired solution.

B. Iterative Solution

To solve the Equation 3 iteratively, we use the approach given in [23, Chapter 12]. In discrete domain Equation 1 will be given by Equation 4.

$$e = \sum_i \sum_j [(z_{i,j} - \tilde{a}_{i,j})^2 + \frac{1}{4} \lambda \{(z_{i+1,j} - z_{i,j})^2 + (z_{i,j+1} - z_{i,j})^2\}] \quad (4)$$

We estimate $\tilde{a}_{i,j}$ to be $\tilde{a}_{i,j} = \frac{a_{i,j}}{b_{i,j} \times \max(b_{i,j})}$, where (i, j) refers to the discrete pixel location and $b(i, j)$ is the base layer on a discrete grid estimated using an edge preserving filter. Here we are dividing by the maximum of $b_{i,j}$ to normalize the values across all the pixels. The idea behind using an edge preserving filter is to find large variations in the image and attenuate them iteratively. This attenuation process enables us to reduce the dynamic range of the image along strong edges and encode the information present in lesser number of bits.

On solving Equation 4 using the approach mentioned in [23] we get the solution as given by the equation below.

$$\hat{z}_{i,j}^{(n+1)} = \frac{\tilde{a}_{i,j} + \lambda \hat{z}_{i,j}^{(n)}}{1 + \lambda} \quad (5)$$

which is clearly an iterative solution we intend to achieve.

This may look straightforward but the way we utilize the value of $a(i, j)$ makes it different. We use an edge preserving filter to calculate the base layer and feed it to the next iteration to calculate the value of $\tilde{a}(i, j)$. Now the result of our iteration goes to input of the edge preserving filter. So this is a sort of closed form solution and this continues till the solution converges to some error bound. Thus changing the value of the base layer ($b(i, j)$) for each iteration based on the output of the previous iteration, we intrinsically attenuate the higher contrast present in the given HDR image. Also this doesn't effect the detail layer. Finally converged luminance channel is fused with the initially calculated detail layer and this way we get the desired tone mapped image.

IV. IMPLEMENTATION

In this section, we shall discuss the implementation aspects of the proposed algorithm for tone mapping.

A. Extraction of luminance channel

Most of the HDR images are colour images. But for the tone mapping purposes, we only work with the luminance channel. To start with, we extract the luminance from the given HDR image (generally RGB) by the following relation given in [?].

$$L = 0.2126I_R + 0.7152I_G + 0.0722I_B$$

The weights given the red, green and blue channel match the intensity values as perceived by human eye.

B. Edge Preserving Filter

We use the weighted least square based filter or simply WLS filter to calculate the base layer and the detail layer [4]. We then initialise our LDR image with gamma corrected HDR image and the output of WLS filter (base layer), which is updated as \tilde{a} during each iteration. The results of the first iteration is then fed to WLS filter to again calculate the base layer. The new base layer and the result after first iteration is given as an input to the next iteration. This process is continued till a very small error bound is reached. In this manner, we could iteratively calculate the output luminance of the desired LDR image. In the next section we will show that the iteration eventually converges to a proper solution. The LDR luminance is fused with the detail layer and the colour is restored to get the final LDR image. We employ scaling and gamma-correction on the intensity values to keep them in the desired range of 8-bits per channel.

C. Convergence

The iterative solution that we previously mentioned converges to the desired solution. We ran our algorithm for many HDR images and each time it converged to a very small error bound (0.1-0.3). For calculation of error, root mean square (RMS) value was calculated and checked after each iteration if the error is less than this error bound. This convergence process is shown in the Figure 1 for 4 different images. It can be observed that the error decreases and reaches a small value in finite number of iterations.

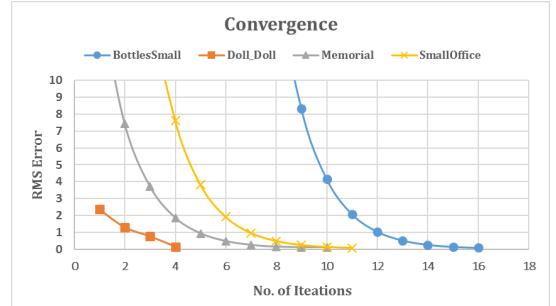


Fig. 1: Convergence of RMS error for various HDR images

V. RESULTS AND DISCUSSIONS

For obtaining the desired LDR image, various values of λ were used. We now present the results and show how they vary with different values of the Lagrangian multiplier λ which weighs the smoothness term.

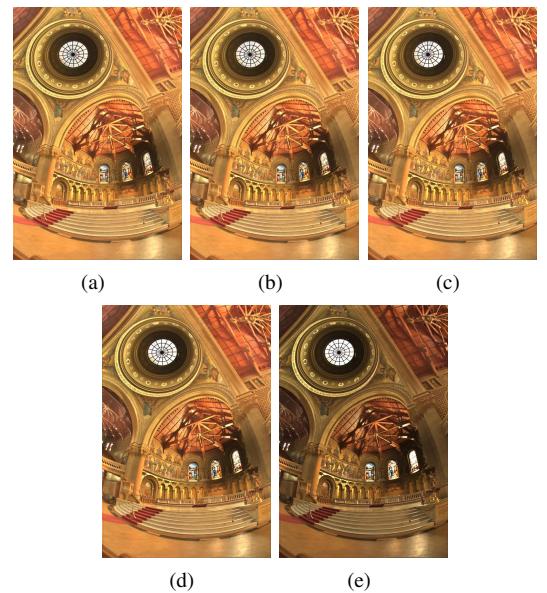


Fig. 2: The input HDR image is memorial [24]. The LDR images generated by the proposed approach for (a) $\lambda = 1$, (b) $\lambda = 1.5$, (c) $\lambda = 2$, (d) $\lambda = 5$, (e) $\lambda = 10$.

We show the LDR images for five different values of λ in Figure 2. It can be observed that on increasing the values of λ , the darkness level in the image increases (Figure 2 (d), (e)) and for even larger values (100-200), LDR images lost more contrast and brightness. For negative values of lambda the results were not converging. Also for small values of lambda (1-2), results obtained were comparatively better.

As we are using WLS filter as an edge-preserving filter for calculating the base layer for each iteration, the final output will depend on it. WLS filter itself depends on the input parameters (λ_{wls}) that we supply to the algorithm. We now present another set of results and show how they vary with varying input to the WLS filter.

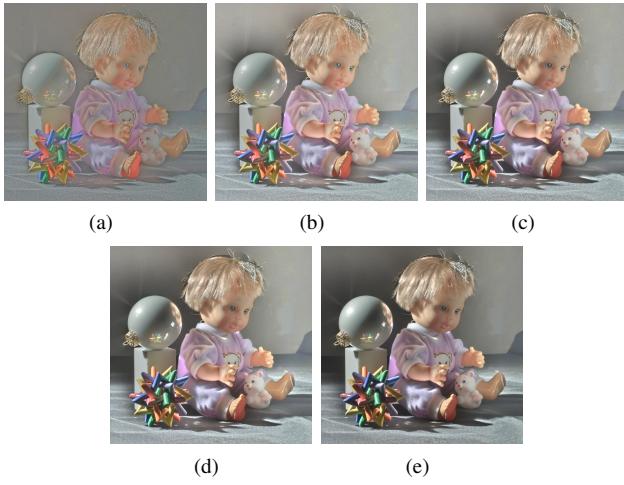


Fig. 3: The input HDR image is doll_doll [25]. The LDR images generated by the proposed approach using WLS filter for the values $\alpha = 1.2$ and (a) $\lambda_{wls} = 1$, (b) $\lambda_{wls} = 5$, (c) $\lambda_{wls} = 10$, (d) $\lambda_{wls} = 15$, (e) $\lambda_{wls} = 20$.

As mentioned in [4], on increasing the value of λ_{wls} , we get smoother images. As it can be seen in Figure 3 (a), image produced is sharp but the colors are lost for $\lambda_{wls} = 1$. On increasing the value to 5 in Figure 3 (b), colors are restored to some extent. But the image is still faded and sharp. In Figure 3 (c), (d) the results are quite good and colors are also properly restored. On increasing λ_{wls} to much higher values, image becomes really dark and some other distortions also start creeping in. It can be seen in Figure 3 (e), where a separate layer can be seen in the sphere (used for decoration purpose). So in our approach 10-15 seems to be a suitable range for λ_{wls} .

We now present two sets (BottleSmall, smallOffice) of tone mapped images, calculated using our TMO and compare them with reference TMOs. For each of the reference TMOs, the values of the parameters have been set to their default values considering that the default values set by their authors will good results, unless otherwise stated (In case of TumblinRushmeierTMO [7] image was totally blacked out for default value of CMax).

After calculating the results using the reference TMOs and doing the each and every step mentioned in them (Gamma correction of DragoTMO using GammaDrago), the results of some of the TMOs were still in negative to positive range, which doesn't work with 8-bit display. So either we could rescale them or clamp them. So we chose to clamp the results as the output of these TMOs was supposed to be the output LDR image as mentioned in the HDR Toolbox [26].

Also for each of the tone mapped images, we compare the results with the corresponding HDR image using the online Dynamic Range (In)Dependent Metrics (DRIM) [5]. It compares the images with the reference image on the basis of three parameters: loss of visible contrast, amplification of invisible contrast, and reversal of visible contrast. The colour code for these three parameters are given in Figure 4.

From Figure 5 it can be observed that, in case of Ward-

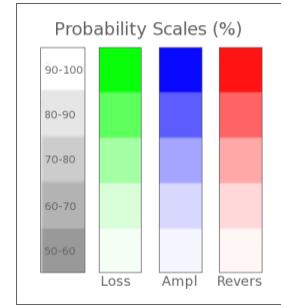


Fig. 4: DRIM Index

HistTMO (Figure 5 (b)) and ReinhardTMO (Figure 5 (e)), the portion in front of the table has become really dark. Also in TumblinRushmeierTMO Figure 5 (a) and WardHistTMO (Figure 5 (b)), background has become comparatively darker. The results of ChiuTMO (Figure 5 (d)), FattalTMO (Figure 5 (h)) are really bad. There is a lot of darkness in many portion in both of them. Along with that, ChiuTMO (Figure 5 (d)) is also full of halos (We already mentioned the process how we calculated these results). AshikminTMO (Figure 5 (f)) kind of fades the image making it visibly poor, the reason being the amplification of contrast. But our TMO (Figure 5 (j)) is able to preserve contrast in both dark and bright regions, without producing any halo effects.

In DurandTMO, there is loss of contrast near the bottle area that can be observed from (Figure 6 (g)). In YeeTMO (Figure 6 (i)), there is a huge amount of loss of contrast on the bottle region along with contrast reversal in patches. Also from Figure 6 it can be observed that in all the mentioned TMOs there is lot of loss in contrast as well as the reversal of contrast in the output images along with amplification problem in some of them. But in our TMO (Figure 6 (j)) these effects are negligible.

From Figure 7 it can be observed that there are again some darkening effects in WardHistAdjTMO (Figure 7 (b)), ChiuTMO (Figure 7 (d)), ReinhardTMO (Figure 7 (e)) and FattalTMO (Figure 7 (h)). In TumblinRushmeierTMO (Figure 7 (a)) area near the window has been totally washed out and the background is not visible. In Figure 8 (c), it can be seen that DragoTMO results in a loss of contrast and same is the case with DurandTMO (Figure 8 (g)). In YeeTMO area near the window has become very sharp and it can be seen from Figure 8 (i) that there is a lot of contrast reversal and loss. Again there is fading effects in AshikminTMO (Figure 7 (f)) making it visually unpleasant. Our TMO successfully overcomes these problems. From Figure 8 (j) it can be seen that there is not much problem with contrast reversal or loss. We are able to compress the dynamic range and the LDR image is visually pleasing.

The results were calculated using MATLAB environment (R2014a) using a machine with Intel Core i5 (2.5GHz, 64 bit) processor and 4GB RAM. The proposed algorithm is computationally faster and it took around 30-50 seconds on an average to calculate results which is comparable to the reference TMOs. In case of YeeTMO it took around 170-200 seconds to find the results on the same images.

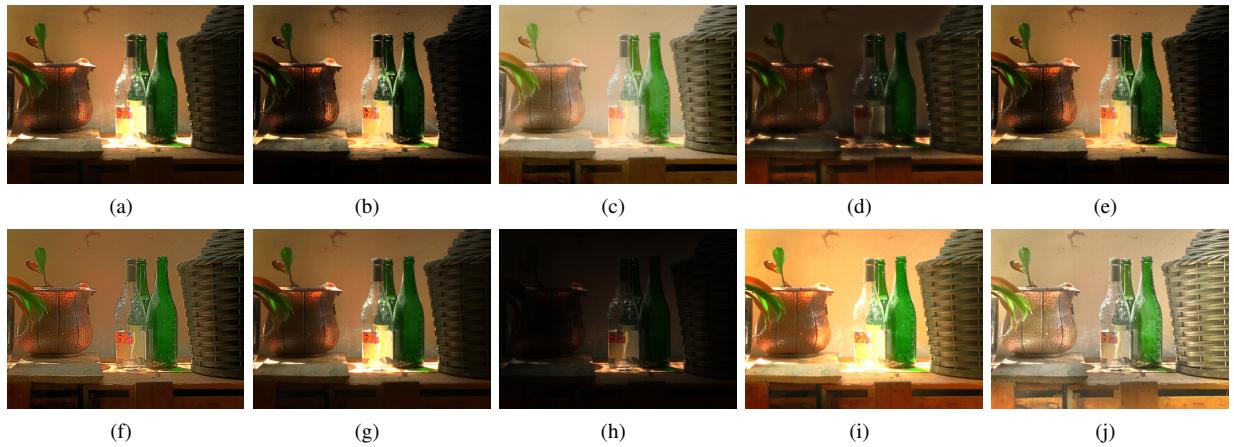


Fig. 5: Input HDR image BottlesSmall [24] (a) TumblinRushmeierTMO (CMax = 1), (b) WardHistAdjTMO, (c) DragoTMO, (d) ChiuTMO, (e) ReinhardTMO, (f) AshikhminTMO, (g) DuarandTMO, (h) FattalTMO, (i) YeeTMO, (j) Proposed Approach ($\lambda = 1.5$).

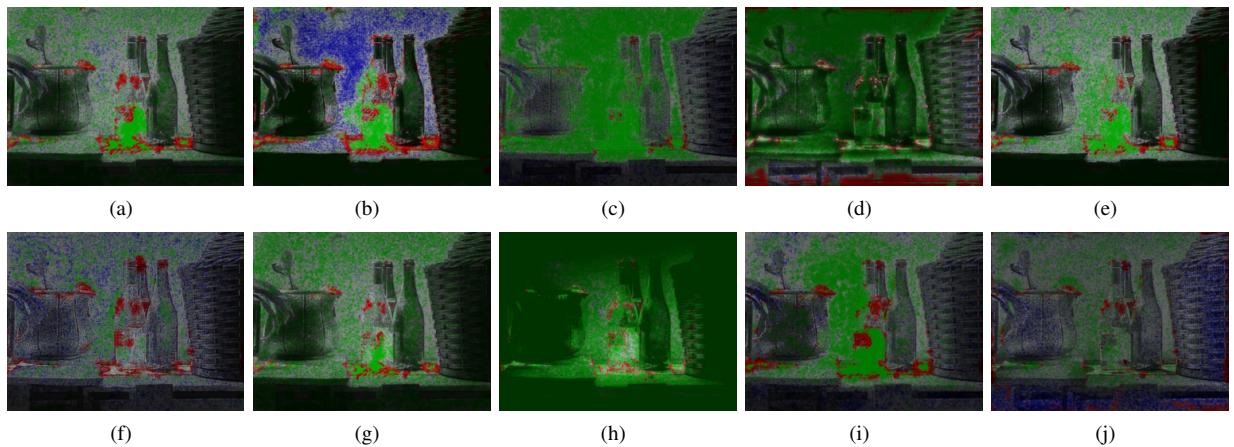


Fig. 6: Dynamic Range (In)dependent Metrics comparison results for corresponding TMOs in Figure 5.

VI. CONCLUSIONS AND FUTURE WORK

As we discussed in the previous section, our algorithm provides good results in comparison to the existing state-of-the-art TMOs. The proposed TMO has been able to compress the input contrast in both dark and bright regions without much loss, amplification, and reversal of contrast along with preserving the minute details present in the HDR image. The proposed algorithm has computational complexity comparable with the existing TMOs. We used the WLS filter in our algorithm for calculating the base layer because it is computationally faster than the bilateral filter. As we calculate base layer in each iteration, the edge preserving filter consumes most of the computation time in the algorithm. Hence, we would like to work on some generic edge-preserving filters that could extract base layer efficiently and are computationally faster.

REFERENCES

- [1] George Mather, *Foundations of perception*, Taylor & Francis, 2006.
- [2] Paul E Debevec and Jitendra Malik, “Recovering high dynamic range radiance maps from photographs,” in *ACM SIGGRAPH 2008 classes*. ACM, 2008, p. 31.
- [3] S Mann and R Picard, *Beingundigitalwith digital cameras*, MIT Media Lab Perceptual, 1994.
- [4] Zeev Farbman, Raanan Fattal, Dani Lischinski, and Richard Szeliski, “Edge-preserving decompositions for multi-scale tone and detail manipulation,” in *ACM Transactions on Graphics (TOG)*. ACM, 2008, vol. 27, p. 67.
- [5] Tunç Ozan Aydin, Rafal Mantiuk, Karol Myszkowski, and Hans-Peter Seidel, “Dynamic range independent image quality assessment,” in *ACM Transactions on Graphics (TOG)*. ACM, 2008, vol. 27, p. 69.
- [6] Greg Ward, “A contrast-based scalefactor for luminance display,” *Graphics gems IV*, pp. 415–421, 1994.
- [7] Jack Tumblin and Holly Rushmeier, “Tone reproduction for realistic images,” *Computer Graphics and Applications, IEEE*, vol. 13, no. 6, pp. 42–48, 1993.
- [8] Jack Tumblin, Jessica K Hodges, and Brian K Guenter, “Two methods for display of high contrast images,” *ACM Transactions on Graphics (TOG)*, vol. 18, no. 1, pp. 56–94, 1999.
- [9] Gregory Ward Larson, Holly Rushmeier, and Christine Piatko, “A visibility matching tone reproduction operator for high dynamic range scenes,” *Visualization and Computer Graphics, IEEE Transactions on*, vol. 3, no. 4, pp. 291–306, 1997.
- [10] Rafael C Gonzalez, Richard E Woods, and Steven L Eddins, “Digital image processing using matlab,” *Upper Saddle River, N. J: Pearson Prentice Hall*, 2004.

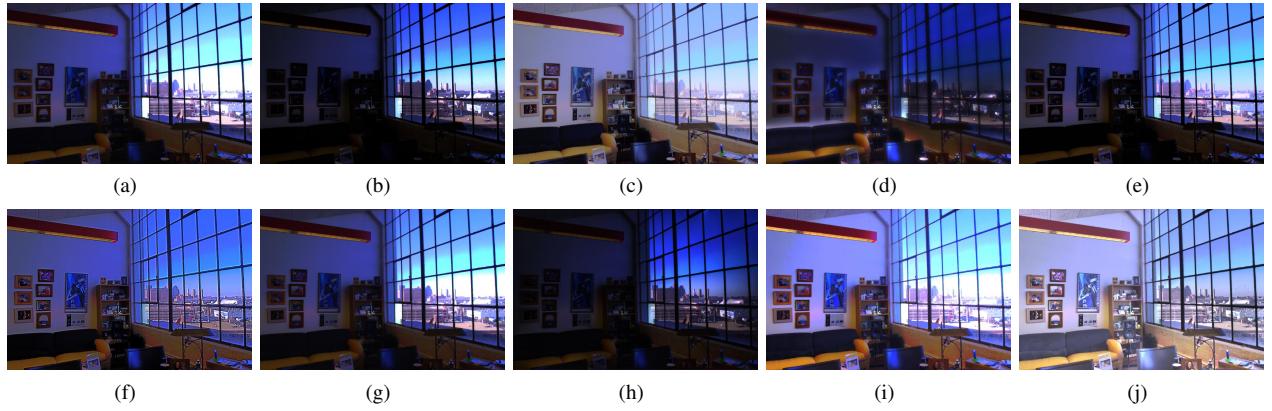


Fig. 7: The input HDR image is smallOffice [24] (a) TumblinRushmeierTMO, (b) WardHistAdjTMO, (c) DragoTMO, (d) ChiuTMO, (e) ReinhardTMO, (f) AshikhminTMO, (g) DuarandTMO, (h) FattalTMO, (i) YeeTMO, (j) Proposed Approach ($\lambda = 1.5$).

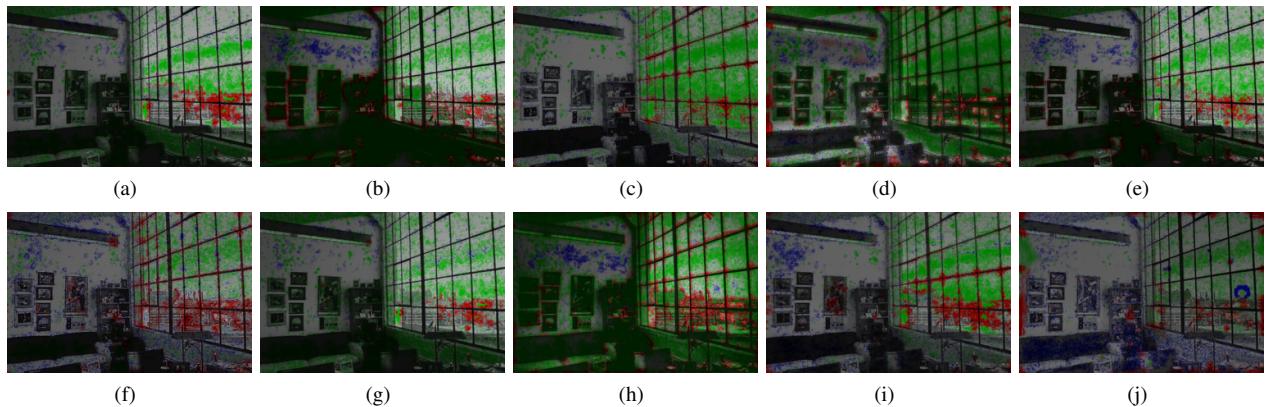


Fig. 8: Dynamic Range (In)dependent Metrics comparison results for corresponding TMOs in Figure 7.

- [11] Christophe Schlick, “Quantization techniques for visualization of high dynamic range pictures,” in *Photorealistic Rendering Techniques*, pp. 7–20. Springer, 1995.
- [12] Sumantha N Pattanaik, Jack Tumblin, Hector Yee, and Donald P Greenberg, “Time-dependent visual adaptation for fast realistic image display,” in *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*. ACM Press/Addison-Wesley Publishing Co., 2000, pp. 47–54.
- [13] Frédéric Drago, Karol Myszkowski, Thomas Annen, and Norishige Chiba, “Adaptive logarithmic mapping for displaying high contrast scenes,” in *Computer Graphics Forum*. Wiley Online Library, 2003, vol. 22, pp. 419–426.
- [14] Ken Chiu, Michael Herf, Peter Shirley, S Swamy, Changyaw Wang, Kurt Zimmerman, et al., “Spatially nonuniform scaling functions for high contrast images,” in *Graphics Interface*. CANADIAN INFORMATION PROCESSING SOCIETY, 1993, pp. 245–245.
- [15] Erik Reinhard, Michael Stark, Peter Shirley, and James Ferwerda, “Photographic tone reproduction for digital images,” in *ACM Transactions on Graphics (TOG)*. ACM, 2002, vol. 21, pp. 267–276.
- [16] Michael Ashikhmin, “A tone mapping algorithm for high contrast images,” in *Proceedings of the 13th Eurographics workshop on Rendering*. Eurographics Association, 2002, pp. 145–156.
- [17] Frédéric Durand and Julie Dorsey, “Fast bilateral filtering for the display of high-dynamic-range images,” in *ACM Transactions on Graphics (TOG)*. ACM, 2002, vol. 21, pp. 257–266.
- [18] Prasun Choudhury and Jack Tumblin, “The trilateral filter for high contrast images and meshes,” in *ACM SIGGRAPH 2005 Courses*. ACM,
- 2005, p. 5.
- [19] Raanan Fattal, Dani Lischinski, and Michael Werman, “Gradient domain high dynamic range compression,” in *ACM Transactions on Graphics (TOG)*. ACM, 2002, vol. 21, pp. 249–256.
- [20] Yangli Hector Yee and Sumantha Pattanaik, “Segmentation and adaptive assimilation for detail-preserving display of high-dynamic range images.” *The Visual Computer*, vol. 19, no. 7-8, pp. 457–466, 2003.
- [21] Rafał Mantiuk, Scott Daly, and Louis Kerofsky, “Display adaptive tone mapping,” in *ACM Transactions on Graphics (TOG)*. ACM, 2008, vol. 27, p. 68.
- [22] Francesco Banterle, Alessandro Artusi, Tunç O Aydin, Piotr Didyk, Elmar Eisemann, Diego Gutierrez, Rafał Mantiuk, and Karol Myszkowski, “Multidimensional image retargeting,” in *SIGGRAPH Asia 2011 Courses*. ACM, 2011, p. 15.
- [23] Berthold Horn, *Robot vision*, MIT press, 1986.
- [24] Erik Reinhard, Wolfgang Heidrich, Paul Debevec, Sumantha Pattanaik, Greg Ward, and Karol Myszkowski, *High dynamic range imaging: acquisition, display, and image-based lighting*, Morgan Kaufmann, 2010.
- [25] Yuanzhen Li, Lavanya Sharan, and Edward H Adelson, “Compressing and companding high dynamic range images with subband architectures,” in *ACM Transactions on Graphics (TOG)*. ACM, 2005, vol. 24, pp. 836–844.
- [26] Francesco Banterle, Alessandro Artusi, Kurt Debattista, and Alan Chalmers, *Advanced high dynamic range imaging: theory and practice*, CRC Press, 2011.