HDR Image Rendering by Combining Single-Scale Local and Global Tone Mapping Operators

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Abstract

A Common task in computer graphics is the tone mapping of digital high dynamic range images to low dynamic range display devices such as monitors and printers. Various techniques have been proposed for compressing the dynamic range while retaining important visual information. The goal of those techniques has been to reproduce images that capture the visual appearance of scenes. In this paper, we emphasize that a really desirable image can not be obtained only by accurately reproducing the perceived scene in the image, and develop a new tone mapping technique for creating excellent images with combining local and global operators. Then we discuss the proposed technique theoretically and empirically by comparing with conventional tone mapping operators. The resulting algorithm is simple and produces good results for a wide variety of high dynamic range images.

Introduction

From sunlight to starlight, human visual system can see huge dynamic range scene intensity in real world. In recent years, there has been an explosion of interest in high dynamic range (HDR) imagery. As HDR images are available due to advances in camera technology and lighting simulation, there is a growing demand for being able to display those images on low dynamic range (LDR) devices. A variety of techniques using tone mapping operators has been developed for compressing the dynamic range of the image signal so that the original scene can be reproduced on the devices effectively.

The recent literature on HDR image compression has been extensively reviewed by others [1],[2]. The tone mapping operators are usually classified into *global* and *local* techniques. Most of the global techniques can reduce the dynamic range by a simple processing [3]-[6]. However, the contrast of details is compromised and the image can look washed out, because they apply the same mapping function to all pixels. In contrast, the local techniques use a mapping that varies spatially depending on the neighborhood of a pixel [7]-[18]. However, the overall contrast is compromised. Furthermore, the local methods unfortunately introduce haloing artifacts around large step edges. To reducing the halos, the local tone mapping technique often adopted the multi-scale decomposition of an image into different scales [13]-[16]. The contrast is reduced in each scale differently. However the computation cost of the multi-scale technique is too expensive. Furthermore, the technique can reduce the visibility of halos but cannot remove them. Recently, subband decomposition techniques including Laplacian pyramids, wavelets, and Gabor transforms were also proposed [17],[18]. Although these techniques may be effective, it introduces nonlinear distortions such as aliasing artifacts and still produces the halos.

The human visual system is considered as an ideal tone reproduction system. Adaptation process especially plays an important role in visual appearance of any viewed scene. Then the goal of most tone mapping techniques has been considered as reproducing images that capture the visual appearance of scenes. In this paper, we emphasize that a really desirable image can not be obtained only by accurately reproducing the perceived scene in the image, and develop a new tone mapping technique for creating excellent images with combining local and global operators.

In our algorithm, a global tone mapping operator determines overall impression of a reproduced LDR image, and then a local tone mapping operator is adopted for the purpose

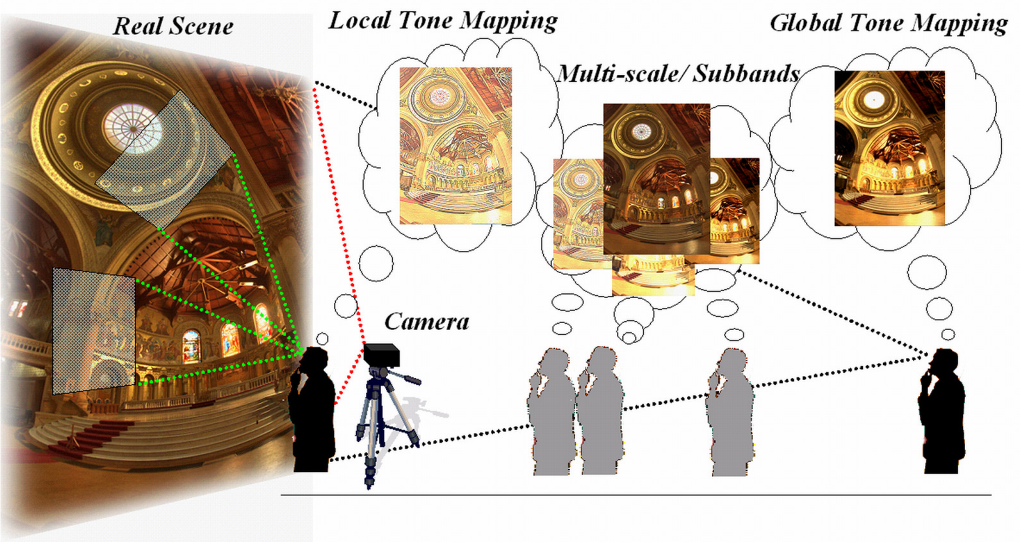


Figure 1*. The meaning of tone mapping operators.*

of preserving the image details. Our local operator is based on a single-scale processing. It does not require the complicated computation such as the multi-scale decomposition and the subband decomposition [17],[18].

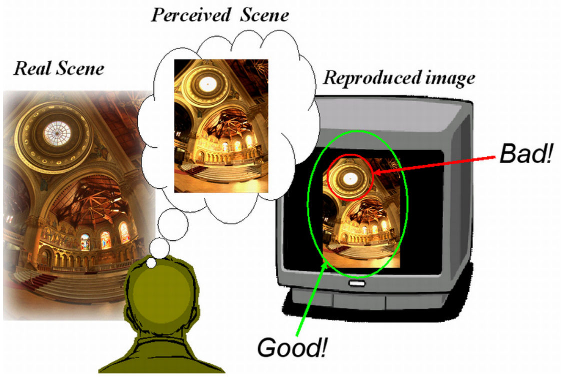
Previous Tone Mapping

We consider the meaning of previous tone mapping approaches by a new interpretation. The meaning of tone mapping operators can be summarized as shown in Fig.1. Tone mapping operators can be usually classified into global and local techniques.

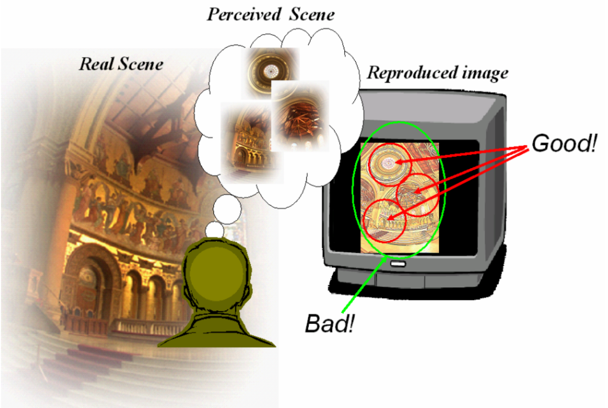
Global model mimics the steady state of human vision, which is simple and efficient. The image intensity I_s at pixel s captured by a camera is simply mapped to a modified image intensity, $I'_s = p(I_s)$, where p is a compressive function such as a power function, or a function that is adapted to the image histogram [3]-[6]. This operator may reproduce a perceived scene when we look at a real scene from long distance so that the scene comes within the viewing field. That is, this operator reproduces the scene that the person on the right side perceives as shown in Fig. 1. The reproduced image by the global operator is often pointed out that the local contrast decreases because of dealing with the whole image with a single mapping curve. However, the distortion is a fundamental problem, and even if an ideal global tone mapping operator will be developed, the problem is not solved.

Figure 2(a) shows the goal of the global tone mapping by using an ideal operator. As shown in the figure, the ideal reproduced image becomes equivalent to the perceived scene. Overall impression of the image may be the same as the perceived scene. However, it is necessary to note that the perceived scene won't become an ideal reproduced image we want. Most retinal cells vary their response only within a range of intensities that is very narrow if compared against the entire range of vision. Adaptation processes dynamically adjust these narrow response functions to conform better to the available light. So, it is correct reproduction that the contrast within the discernment region or the shade region decreases when the same size as the reproduced scene is looked at, and also we perceive the scene like that. However, we do not hope for the distortion in such a decrease in contrast to the reproduction image. That is, even if an ideal global operator will be developed, the reproduction image is not consequentially satisfied.

On the other hand, local operators use a mapping that varies spatially depending on the neighborhood of a pixel [7]-[18]. Simply, an image intensity I_s at pixel s is considered as the product of reflectance R_s and illuminant L_s. When inferring the illuminant L_s, we can restore the reflectance with $R_s \cong I_s/L_s$ from the captured image I_s. To estimate the local distribution of illumination L_s, the arithmetic average, the geometric average, and a Gaussian blurred version within a local region of the image is mainly used. This operator generates the reproduction image by spatially connecting the scenes perceived locally. That is, this operator reproduces the scene that the person on the left side perceives as shown in Fig. 1. Reproduced images by the local operator are often pointed out that haloing artifacts around large step edges occur. The size of the halo depends on the size of the local region. In the case of the size is small, the halo can be reduced but overall contrast reduction occurs. However, this is a fundamental problem, and even if an ideal local tone mapping operator will be developed, the problem is not solved. Figure 2(b) shows the goal of the local tone mapping by using an ideal operator. As shown in the figure, the ideal reproduced image becomes equivalent to the perceived scene between both corresponding local regions. However, overall impression of the reproduction image by spatially connecting the scene perceived locally won't become an ideal reproduced image we want. Of course, it is correct reproduction for each local region, and we also perceive the scene like that. However, we have to look at the entire image at the same time. That is, even if an ideal local operator will be developed, the reproduction image is not consequentially satisfied.



(a) Ideal image reproduction by global tone mapping



(b) Ideal image reproduction by local tone mapping

Figure 2. *Goal of global and local tone mappings.*

As mentioned above, it is fundamentally impossible to reproduce an image that we are satisfied from either of global or local tone mapping operators. Recently, local tone mapping techniques use a decomposition of the image into different layer, subbands or scales [13]-[18]. The contrast is reduced differently for each scale, and the final image is a recomposition of the various scales after contrast reduction. As shown in Fig.1, this approach can be considered to have tried to generate an artistic reproduction image that appropriately synthesizes the scenes perceived by two or more distances to the real scene. This approach, which does not *reproduce* the perceived scene but *create* the tone mapped image, may show a correct route where we should walk. However, there are a lot of arbitrary steps for synthesizing images and determining optimum parameters. So, this approach is technologically a trial and error stage still.

Proposal of Tone Mapping Operator

We propose a general idea of new tone mapping approach. In our algorithm, overall impression of an entire image is reproduced by a global adaptation mechanism and local visibility can be improved by moving adaptation levels according to local surround intensities.

Global Operator

When we look at a reproduced image, we put the entire image in view. Therefore, the global tone mapping to the entire scene is a basic reproduction process. By considering the global tone mapping, human visual system (HVS) should not be disregarded. Various mechanisms in the HVS mediate adaptation to lightning conditions. We specifically employ a model of photoreceptor adaptation, which can be described as a receptors' automatic adjustment to the general level of illumination. Compared to the broad range of background light intensities over which the visual system performs, photoreceptors respond linearly to a rather narrow range of intensities. This range is only about 3 log units. The log-linear plot in this figure of the intensity-response function is derived from measurements of the response of dark-adapted vertebrate rod cells on brief exposures to various intensities of light [19]. The adaptation processes dynamically adjust these narrow response functions to conform better to the available light.

The model is first proposed by Naka and Rushton [20] in 1966 to describe fish S-potentials. In Ref.[19], direct cellular measurements of response functions for cone, rod, and bipolar cells and firing rates for sustained ON-center retinal ganglia closely follow:

$$\frac{Res(I)}{Res_{\max}} = \frac{I^n}{I^n + \sigma^n} \quad . \tag{1}$$

Here, Res is the photoreceptor response $(0 < Res < Res_{\max})$, $Res_{\max}$ is the maximum response, I is light intensity, and σ is the semi-saturation constant that makes $Res = (1/2)Res_{\max}$. Parameter n is a sensitivity control exponent that has a value generally between 0.7 and 1.0 [19].

Figure 3 shows the responses of retina to the luminance intensities with different adaptation levels, which helps us to understand the adaptation process well. From left to right, Fig. 3 shows the responses of retina at adaptation level 0.001, 0.01, 0.1, 1, 10, 100 and 1000 respectively. From Fig. 3, we can also see that the retinal response is an S-shape curve when the luminance intensities are drawn in logarithmic domain. This confirms that the HVS compresses the very bright and very dark shadow dramatically while keeping the middle range invariant to preserve well contrast.

Local Operator

As shown in Fig.1, even if we look at the scene standing at the camera position, we can see only a local scene in the captured image. Therefore, a mechanism for reproducing the local scene is necessary to generate excellent image. The local tone mapping problem is intimately related to the problem of recovering reflectance from an image. As mentioned above, an image I_s is regarded as a product

$$I_s = R_s L_s \ , \tag{2}$$

where R_s is the reflectance and L_s is the illuminance at each point s. The function R_s is commonly referred to as the intrinsic image of a scene. The largest luminance variations in an HDR image come form the illuminance function L_s, since real-world reflectance is unlikely to create contrasts greater than 100:1. Thus, dynamic range compression can, in principle, be achieved the L_s component to obtain a new illuminance function $\tilde{L}_s$, and remultiplying:

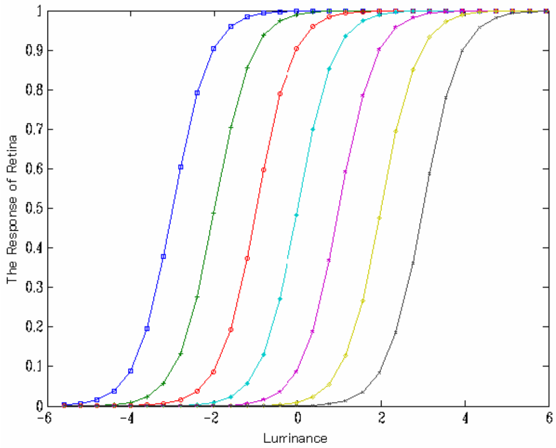


Figure 3. *The response of retina at adaptation level: 10^{-3}, 10^{-2}, 10^{-1}, 1, 10, 10^2, 10^3 over the luminance intensities*

$$\tilde{I}_s = R_s \tilde{L}_s \ . \tag{3}$$

Intuitively, this reduces the contrast between brightly illuminated areas and those in deep shadow, while leaving the contrasts due to texture and reflectance undistorted. Tumblin et al. use this approach for displaying high-contrast synthetic images [3], where the material properties of the surfaces and the illuminance are known at each point in the image, making it possible to compute a perfect separation of an image to various layers of lightning and surface properties.

Recently, Rahman et al. presented a dynamic range compression method [8] based on a multiscale version of retinex theory of color vision. Retinex estimates the reflectance R_s as the ratio of I_s to its low-pass filtered version. A similar operator was explored by Chiu et al. [7], and was also found to suffer from halo artifacts and compute the logarithm of the Retinex responses for several low-pass filters of different sizes, and linearly combine the results. The linear combination helps reduce halos, but does not eliminate them entirely. Durand and Dorsey introduced the bilateral filter for estimating the illuminance distribution $\tilde{L}_s$ [10]. Bilateral filtering is an edge-preserving smoothing operator that effectively blurs an image but keeps sharp edges intact by using the following equation:

$$\tilde{L}_s(\sigma_m, \sigma_d) = \frac{1}{k_s} \sum_{p \subset \Omega} f_{\sigma_m}(p - s) g_{\sigma_d}(I_p - I_s) I_p, \tag{4}$$

$$k_s = \sum_{p \subset \Omega} f_{\sigma_m}(p - s) g_{\sigma_d}(I_p - I_s) \ , \tag{5}$$

where σ_m is the standard deviation for a Gaussian f in the spatial domain such as

$$f_{\sigma_m}(s \mid s = (a,b)) = K_m \exp\{-(a^2 + b^2)/\sigma_m{}^2\} \ , \tag{6}$$

and σ_d is the standard deviation for a Gaussian g in the luminance domain. Here, K_m is a normalization factor. Ω is the whole image.

Proposed Hybrid Operator

The proposed tone mapping operator is defined by combining the global operator in Eq.(1) and the local operator in Eqs.(3) and (4) as follows

$$R_s{}^{(i)}(\sigma_m, \sigma_{\mathrm{d}}) = R_{\max} \frac{I_s{}^{(i)^n}}{L_s(\sigma_m, \sigma_{\mathrm{d}})^n + \sigma^n} \quad ; i = R, G, B \ , \tag{7}$$

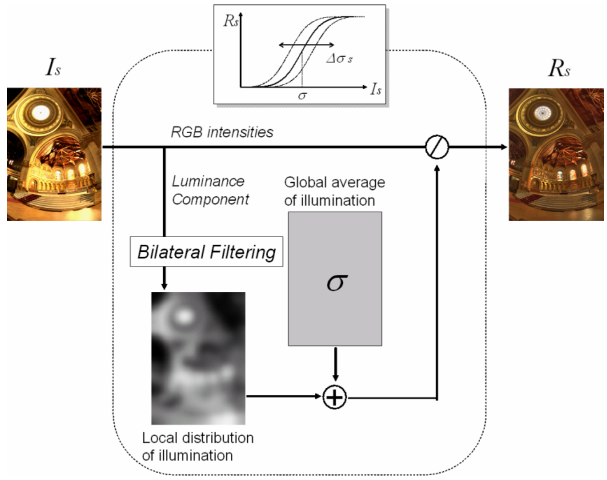


Figure 4. *The proposed tone mapping diagram.*

$$L_s(\sigma_m,\sigma_d)=\frac{1}{k_s}\sum_{p\subset\Omega} f_{\sigma_m}(p-s)g_{\sigma_d}(I_p-I_s)I_p, \tag{8}$$

$$k_s=\sum_{p\subset\Omega} f_{\sigma_m}(p-s)g_{\sigma_d}(I_p-I_s), \tag{9}$$

where $R_{\max}=255$ for 8 bits output device. $I_s^{(i)}$ is HDR input intensity [cd/m^2] of *i*-channel for a pixel *s*. Then the LDR output $R_s^{(i)}(\sigma_m,\sigma_d)$ can be derived. As shown in Eq.(8), $L_s(\sigma_m,\sigma_d)$ can be derived by the bilateral filtering of I_s. In order to make clear the physical meanings of Eq.(7), we rewrite Eq.(7) by $L_s(\sigma_m,\sigma_d)^n=I_s^{(i)^n}+\Delta I_s(\sigma_m,\sigma_d)$ as follows:

$$\begin{aligned} R_s^{(i)}(\sigma_m,\sigma_d) &= \frac{I_s^{(i)^n}}{I_s^{(i)^n}+\Delta I_s(\sigma_m,\sigma_d)+\sigma^n} \\ &= \frac{I_s^{(i)^n}}{I_s^{(i)^n}+(\sigma+\Delta\sigma_s(\sigma_m,\sigma_d))^n} \end{aligned}. \tag{10}$$

By comparing with Eq.(10) as Eq.(1), the semi-saturation constant σ in Eq.(1) is variable in the proposed operator depending on the spatial position. In a word, the S-shaped response in Fig.3 is decided as a basic mapping function by obtaining the semi-saturation constant σ from the entire image. However, in our operator, the S-shaped curve shifts right and left depending on the place. The amount of the movement $\Delta\sigma_s$ is decided depending on the difference between center luminance and the local distribution of illumination calculated by the bilateral filtering.

In the case $\Delta I_s>0$, that is the local distribution of illumination is lighter than the center luminance, the S-shaped curve decided by the global tone-mapping will slightly move to the right in Fig.3 for making the contrast in the bright part. In the case $\Delta I_s<0$, that is the local distribution of illumination is darker than the center luminance, the S-shaped curve decided by the global tone-mapping will slightly move to the left in Fig.3 for making the contrast in the dark part.

We consider the proposed hybrid operator from the viewpoint of the local tone mapping. The denominator of Eq. (6) shows the illumination estimated by adding the offset σ to local distribution of illumination $\tilde{L}_s$. This means a histogram rescaling of the estimated illuminant distribution in the framework of the conventional local tone mapping algorithms as shown in Eq.(3) [7],[8],[10].

The overview of the proposed framework is shown in Fig. 4. The proposed algorithm can be considered as a local tone mapping in Eq.(3) with a global offset, but also considered as an adaptive global tone mapping with a slight change depending on the position.

User Parameters

For certain applications it may be important to have a tone reproduction operator without any user parameters. Other applications may benefit from a small amount of user intervention, provided that the parameters are intuitive and that the number of parameters is small.

Four of the user parameters were introduced in our algorithm. These are n, σ, σ_m and σ_d, which control contrast, luminance, and halos by two bilateral filter's parameters, respectively. The sensitivity parameter n was discussed in the literature [19]. In the literature, n=0.7 for long test flashes (seconds) and 1.0 for short test flashes (10 ms). In our operator, n=1.0 was better for most of HDR images by experiments. The semi-saturation parameter σ means the level of half-intensity of the restored image. In generally, the arithmetic average, the geometric average, or a Gaussian blurred version within a local region of the image is mainly used. We experimented to various HDR images, the arithmetic average was better.

Parameters σ_m and σ_d are standard deviations of the bilateral filter. Bilateral filtering was developed by Tomasi and Manduchi as an alternative to anisotropic diffusion [21]. It is non-linear filter where the output is a weighted average of the input. They use a Gaussian for *f* in the spatial domain, and a Gaussian for *g* in the intensity domain, Therefore, the value at a pixel *s* is influenced mainly by pixel that are close spatially and that have a similar intensity. The appropriate standard deviation σ_m of the Gaussian for the spatial domain may depend on the visual angle, because the parameter is used to remove the influence of the local illumination.

As shown in Fig.1, when the real scene was watched at the camera position, the scene projected to the retina is local and the region where it influences perception is limited. In our experiment, σ_m= 1/4 pixels within 2 degree viewing angle was appropriate for test images, because the amount of Gaussian distribution within $\pm 2\sigma_m$ is 95%. Though, it is necessary to try and error in an uncertain image at the camera position, a very small σ_m was experimentally suitable. The standard deviation σ_d of the Gaussian for intensity domain may depend on the dynamic range of the HDR image. However, this parameter is not sensitive for the reproduced image. We use σ_d =0.01 for most of standard HDR images in the next section.

Experiments

First, we apply our model to standard HDR images and compare our result with the conventional approaches. Second, we construct an imaging system for acquiring HDR images and render LDR images by the proposed algorithm on a display for verifying the performance. Parameters were set based on the consideration in the previous section.

Evaluation by using standard HDR images

In the first experiment, we used various HDR images from Mark's HDR photographic survey [22] and HDR DVD in the literature [2]. In this section, we show the result using the HDR image "UR Chapel(1)" as an example. The image size is 2411x4286 and the luminance range is over 1:10^6. Shown in Fig.5 are range compressed results on the image. Fig.5(a) shows the result by linear tone mapping. We can only see the bright stained glass. We get Fig.5(b) using the global tone mapping operator by Eq.(1), Fig.5(c) using local tone mapping operator by Eqs.(3) and (4). As shown in Fig.5(b), overall impression is realistic, but the brightness is saturated and colors are washed out as shown in the close-up image in Fig.5(f). So, the contrast of details is compromised. In contrast, as shown in Fig.5(c), local region is reproduced clearly by using the local operator. However, the overall impression is unnatural and artifact appears in the place where the difference of light and shade is violent as shown in Fig.5(g). Figure 5(d) and its close-up image in Fig.5(h) are reproduced by our hybrid operator. The reproduced result has both advantages of global and local operators.

Evaluation by our imaging system

We construct an imaging system for evaluating the tone mapped image with real world scene. For capturing the real scene, Canon EOS-1 was used which can output 12bit image. In order to obtain the linear camera output, the camera calibration was made using Macbeth Color Chart. In order to obtain 16bit HDR image, five camera images with different exposure time were captured, in our experiment, the exposure times were set to 1/8[sec], 1/15[sec], 1/30[sec], 1/60[sec] and 1/125[sec] respectively. Then the HDR image was constructed from five images by the method in Ref.[23].

In order to show the effectiveness of our algorithm, we compare our results with the results using typical tone mapping techniques. The high dynamic range scene was captured in an indoor meeting room at Chiba University. There are three kinds of light sources, which are outside light, fluorescent lamps at the ceiling in the room and fluorescent lamps of the passage. In order to evaluate the color reproduction, the Macbeth Color Chart was put on the chair. Figure 6 shows the reproduced results. Since the visual field of the real scene was considerably beyond the 2 degree visual field, the observer could not observe the whole scene simultaneously. The reproduced image in Fig.6(d) is one of the typical local operator. Comparing with our result, detailed reproduction of Fig.6(d) is better, but the overall contrast decreases. Our methods give visually pleasing results, and are successful in making detail visible in both the bright and dark regions without artifacts.

Conclusions

We presented a novel tone mapping approach to the issue of reproduction of high dynamic range images on devices with limited dynamic range images on devices with limited dynamic range of intensity. In our approach, we combine global and local tone mapping operators. Recent perceptual studies concerning the reproduction of HDR images have shown high importance of overall image attributes. Motivated by these studies, we apply the global method first to reproduce overall image attributes correctly. At the same time, we construct the local distribution of illumination by bilateral filtering. Our experiments indicated that the proposed hybrid tone mapping approach typically produces reasonable results.

The perception of image attributes depends on partially on the semantics of the input image or scene. In the future, we will conduct subjective perceptual experiments to uncover and to quantify the effect of particular local enhancement method on the quality of reproduction of image attributes.

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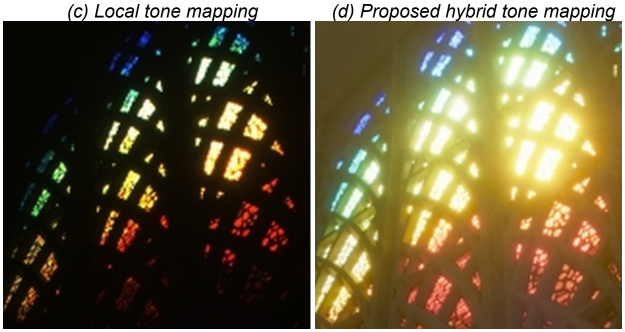
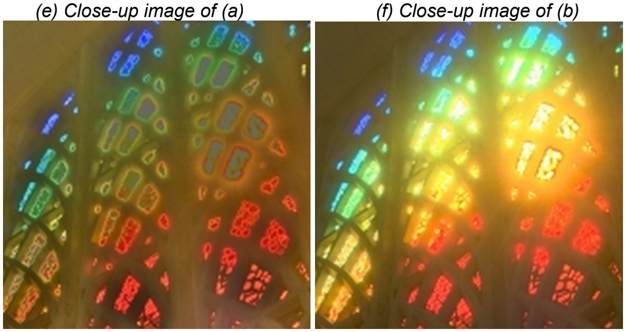
(a) Linear tone mapping *(b) Global tone mapping*

(c) Local tone mapping *(d) Proposed hybrid tone mapping*



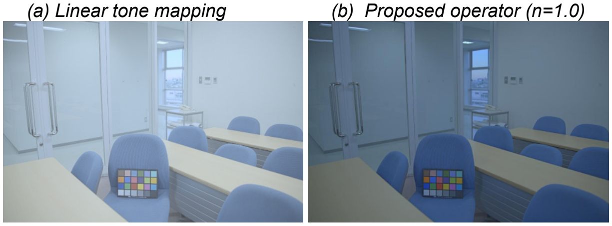
(e) Close-up image of (a) *(f) Close-up image of (b)*



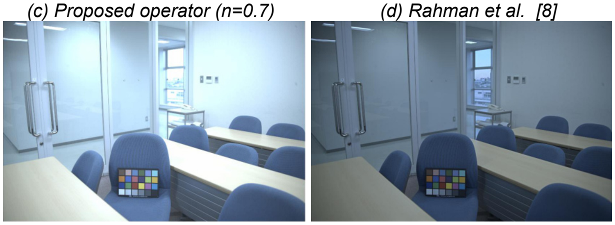
(g) Close-up image of (c) *(h) Close-up image of (d)*

Figure 5. *The reproduced images from the HDR image "UR Chapel(1)".*

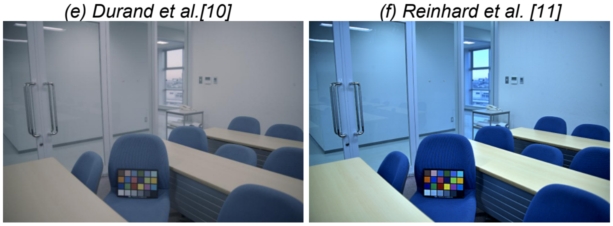
(a) Linear tone mapping (b) Proposed operator (n=1.0)



(c) Proposed operator (n=0.7) (d) Rahman et al. [8]



(e) Durand et al.[10] (f) Reinhard et al. [11]



(g) Pattanaik et al. [14] (h) Li et al. [18]

Figure 6. *Reproduced images from "Meeting room".*

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