An Inverse Tone Mapping Operation without Any Parameters for Remapping HDR Images

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Abstract. A number of successful tone mapping operators (TMOs) for contrast compression have been proposed due to the need to visualize high dynamic range (HDR) images on low dynamic range devices. This paper proposes a novel inverse tone mapping (TM) operation and a new remapping framework with the operation. Existing inverse TM operations require either the store of some parameters calculated in forward TM, or data-depended operations. The proposed inverse TM operation enables to reconstruct HDR images from LDR ones mapped by the Reinhard's global operator, not only without keeping any parameters but also without any data-depended calculation. The proposed remapping framework with the inverse operation consists of two TM operations. The first TM operation is carried out by the Reinhard's global operator. The second is done by an arbitrary TMO which can provide an LDR image with desirable quality. It enables not only to visualize an HDR image on low dynamic range devices but also to temporarily store an HDR one as an LDR one at low computing cost. We demonstrate the effectiveness of the proposed scheme by a number of simulations.

Keywords: High Dynamic Range, HDR Image, Tone Mapping, Inverse Tone Mapping, Re-tone Mapping

1 Introduction

High dynamic range (HDR) images are diffusing in many fields: photography, computer graphics, on vehicle cameras, medical imaging, and more. They have wider dynamic range of pixel values than standard low dynamic range (LDR) images. In contrast, display devices which can express the pixel values of HDR images are not popular yet. Therefore, the importance of a tone mapping (TM) operation which generates an LDR image from an HDR image by compressing its dynamic range has been growing.

Various research works on TM have so far been done [1, 2]. Many of these have focused on forward TMOs [3–5] and their implementation techniques [6–10] to generate high quality LDR images with low computational cost. Unlike these research works, this paper focuses on inverse TM, which is to reconstruct HDR images from LDR ones. The inverse TM has various important applications such as estimating HDR images [11–14], remapping HDR ones and mulitilayer coding [15–17]. However, the existing inverse TM operations require data-depended calculations that have high computational cost, or the store of some parameters calculated in forward TM [11,12,18]. These constraints have been obstructive to the progress of HDR images such as real-time processing of HDR videos.

Because of such a situation, we propose a novel inverse TM operation that allows to be carried out not only without any parameters but also without any data-depended calculation, because it has a closed form without parameters calculated in forward TM. The proposed inverse TMO enables to reconstruct HDR images from LDR ones mapped by the Reinhard's global operator [3], without keeping any parameters.

Furthermore, we propose a new remapping framework that consists of two TM operations. The first TM operation is carried out by the Reinhard's global operator. The second is done by an arbitrary TMO which can provide an LDR image with desirable quality. Therefore, it enables not only to visualize an HDR image on low dynamic range devices but also to temporarily store an HDR one as an LDR one at low computing cost. We demonstrate the effectiveness of the proposed scheme by a number of simulations.

2 Preparation

A TM operation generates an LDR image I_L from an HDR image I_H. Typical TM operations are reviewed.

2.1 Reinhard's global operator

"Photographic Tone Reproduction" [3] which is a typical TM operation is summarized, here. This TM operation consists of the following six steps.

(a) The world luminance $L_w(p)$ of an HDR image I_H is calculated form RGB pixel values of p the HDR image as,

$$L_w(p) = 0.27R(p) + 0.67G(p) + 0.06B(p) \tag{1}$$

where $R(p)$, $G(p)$ and $B(p)$ are RGB pixel values of the HDR image with a pixel p, respectively.

(b) The geometric mean $\overline{L}_w$ of the world luminance $L_w(p)$ is calculated as follows:

$$\overline{L}_w = \exp\left(\frac{1}{N}\sum_{p=1}^{N}\log L_w(p)\right) \tag{2}$$

where N is the total number of pixels in the input HDR image I_H.

(c) The scaled luminance $L(p)$ is calculated as

$$L(p) = \frac{\alpha}{\bar{L}_w} L_w(p) \tag{3}$$

where $\alpha \in [0, 1]$ is the parameter called "key value".

(d) The display luminance $L_d(p)$ is calculated by using a tone mapping function $y(\cdot)$ as follows:

$$L_d(p) = y(L(p)). \tag{4}$$

The Reinhard's global operator [3] which is a well-known tone mapping function is given by

$$L_d(p) = \frac{L(p)}{1 + L(p)}. \tag{5}$$

(e) The floating-point pixel values $C_f(p)$ of the LDR image is calculated as follows:

$$C_f(p) = \frac{L_d(p)}{L_w(p)} C(p) \tag{6}$$

where $C(p) \in \{R(p), G(p), B(p)\}$ is the floating-point RGB value of the input HDR image, and $C_f(p) \in \{R_f(p), G_f(p), B_f(p)\}$. Besides, the gamma correction is performed for $C_f(p)$ as needed.

(f) The 24-bit color RGB values $C_i(p)$ of the LDR image I_L is derived from

$$C_i(p) = \text{round}(C_f(p) \cdot 255) \tag{7}$$

where $\text{round}(x)$ rounds x to its nearest integer value, and $C_i(p) \in \{R_i(p), G_i(p), B_i(p)\}$.

2.2 Local operator

Local tone mapping generally produces LDR images with better image quality than global tone mapping, although a large amount of calculation is needed. The difference in the calculation procedure is only in step (d).

Replacing eq.(5) with a local function, a local TMO is carried out. For example, under the assumption of the use of the Reinhard's local operator, it is given as,

$$L_d(p) = \frac{L(p)}{1 + V(p, s_m(p))} \tag{8}$$

where $V(p, s_m(p))$ provides a local average of the luminance around p in a disc of radius $s_m(p)$, and $s_m(p)$ is the largest area around a given pixel p where no large contrast changes occur [3].

2.3 Scenario

An inverse TM operation, which is to estimate an HDR image from a mapped LDR one, is usually needed for remapping HDR images or implementing multi-layer coding of HDR ones [15–17]. In this paper, a novel inverse TM operation is proposed to reconstruct an HDR image from an LDR one mapped by the Reinhard's global operator. The framework of this study is illustrated in Fig. 1. The first TM operation is carried out by using the Reinhard's global operator that is a well-known typical TMO. The second is done by an arbitrary TMO such as a local TMO, which can provide an LDR image with desirable quality. Before the second TM operation, an inverse TM operation is required. Conventionally, two parameters i.e. α and $\overline{L}_w$ have to be stored to conduct it. We propose a novel method in which the parameters are not required to be stored (see Fig.2(b)). As a result, The proposed scheme enables to reconstruct a HDR image from the mapped LDR one not only without any parameters but also without any data-depended calculations.

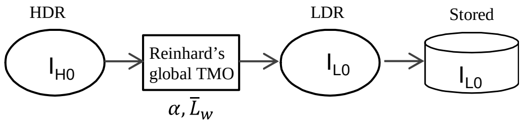
A lot of succesful TMOs have been proposed so far, and the quality of mapped LDR images and the computing cost of TM operations depend on the type of TMOs. High computing cost is generally required to generate well-detailed LDR images. On the other hand, in HDR image and video processing, it is required to reduce the amount of calculation and the volume of data. By applying the proposed framework, the first TM operation is simply carried out on a terminal having low computational capability, then the mapped images can be efficiently compressed as simple LDR images without storing the parameters, and the second one is done to generate a well-detailed LDR image with time and care, on a terminal having high computational capability as a computer. Therefore, the proposed framework enables not only to simply visualize an HDR image on low dynamic range devices but also to temporarily store an HDR one as an LDR one at low computing cost.

3 Proposed Method

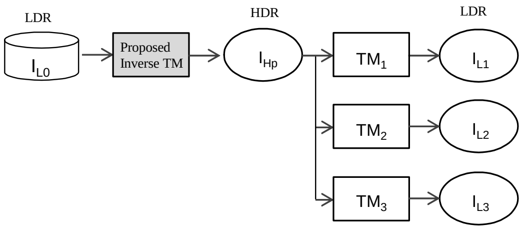
Assuming the use of the Reinhard's global operator, a new inverse TM operation is proposed. The inverse function is given as, from eqs.(3) and (5).

$$L_w(p) = \frac{\overline{L}_w}{\alpha} \cdot L(p) = \frac{\overline{L}_w \cdot L_d(p)}{\alpha(1 - L_d(p))}. \tag{9}$$

It is confirmed that the key value α and the geometric mean $\overline{L}_w$ are necessary to calculate eq.(9), although $L_d(p)$ can be done from the LDR image. It will be shown that there are no parameters in the proposed function.



(a) 1st TM



(b) 2nd TM

Fig. 1. The proposed framework

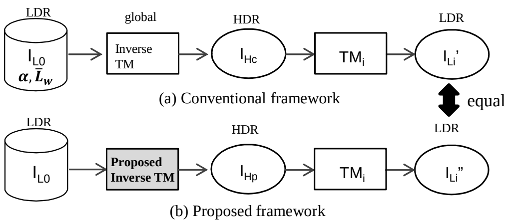


Fig. 2. Re-tone mapping operation

3.1 Estimation of Key Value α

First, it is shown that it is possible to estimate α from an LDR image. By substituting eq.(9) into eq.(2),

$$\overline{L}_w = \exp\left(\frac{1}{N}\sum_{p=1}^{N}\log\frac{\overline{L}_w \cdot L_d(p)}{\alpha(1-L_d(p)}\right). \tag{10}$$

Then, arranging the above equation,

$$\begin{aligned}\overline{L}_w &= \exp\left(\frac{1}{N}\sum_{p=1}^{N}\left(\log\frac{\overline{L}_w}{\alpha}+\log\frac{L_d(p)}{1-L_d(p)}\right)\right)\\ &= \exp\left(\log\frac{\overline{L}_w}{\alpha}+\frac{1}{N}\sum_{p=1}^{N}\log\frac{L_d(p)}{1-L_d(p)}\right)\\ &= \frac{\overline{L}_w}{\alpha}\cdot\exp\left(\frac{1}{N}\sum_{p=1}^{N}\log\frac{L_d(p)}{1-L_d(p)}\right). \end{aligned} \tag{11}$$

As a result, we obtain the relation:

$$\alpha = \exp\left(\frac{1}{N}\sum_{p=1}^{N}\log\frac{L_d(p)}{1-L_d(p)}\right). \tag{12}$$

Note that there is no $\overline{L}_w$ in eq.(12). Therefore, α can be obtained from eq.(12) without the parameter $\overline{L}_w$. This result leads to a new inverse TM operation without both parameters α and $\overline{L}_w$ (see Fig.2).

3.2 Re-tone mapping and parameters $\alpha, \overline{L}_w$

The geometric mean of an HDR image can not be derived from the tone mapped LDR image I_{L0}. Thus, a new inverse TM operation without α and $\overline{L}_w$ is proposed to produce a tentative HDR image I_{Hp}.

Let A and G be constant values. Substituting $\alpha = A$ and $\overline{L}_w = G$ in eq.(9) respectively, a tentative world luminance $L''_w(p)$ is given by

$$L''_w(p) = \frac{G \cdot L_d(p)}{A(1-L_d(p))}. \tag{13}$$

Then, the scaled luminance $L''(p)$ for the second TM operation is represented as, from eqs.(3) and (13).

$$\begin{aligned} L''(p) &= \frac{\alpha'}{\overline{L}''_w} \cdot L''_w(p) = \frac{\alpha'}{\overline{L}''_w} \cdot \frac{G \cdot L_d(p)}{A(1-L_d(p))} \\ &= \frac{\alpha'}{\alpha} \cdot \frac{L_d(p)}{1-L_d(p)} \end{aligned} \tag{14}$$

where from eqs.(2) and (12)

$$\begin{aligned} \overline{L}''_w &= \exp\left(\frac{1}{N}\sum_{p=1}^{N}\log\frac{G \cdot L_d(p)}{A(1-L_d(p)}\right) \\ &= \frac{G}{A}\exp\left(\frac{1}{N}\sum_{p=1}^{N}\log\frac{L_d(p)}{1-L_d(p)}\right) \\ &= \frac{G}{A} \cdot \alpha. \end{aligned} \tag{15}$$

and α' is a key value for the second TM operation.

On the other hand, if α and $\overline{L}_w$ are known, the scaled luminance $L'(p)$ for the second is provided by

$$\begin{aligned} L'(p) &= \frac{\alpha'}{\overline{L}'_w} \cdot L'_w(p) = \frac{\alpha'}{\overline{L}'_w} \cdot \frac{\overline{L}_w \cdot L_d(p)}{\alpha(1-L_d(p))} \\ &= \frac{\alpha'}{\alpha} \cdot \frac{L_d(p)}{1-L_d(p)} \end{aligned} \tag{16}$$

where

$$\overline{L}'_w = \exp\left(\frac{1}{N}\sum_{p=1}^{N}\log\frac{\overline{L}_w \cdot L_d(p)}{\alpha(1-L_d(p))}\right)$$
$$= \frac{\overline{L}_w}{\alpha}\cdot\alpha = \overline{L}_w. \quad (17)$$

By comparing eq.(14) with eq.(16), we arrive at the relation:

$$L''(p) = L'(p). \quad (18)$$

Therefore, it is certified that $L'(p)$ can be calculated without α and $\overline{L}_w$, even when $L''_w(p) \neq L'_w(p)$.

3.3 Proposed Procedure

The proposed procedure for generating a remapped image I_{Li} from an LDR one I_{L0} under the use of an arbitrary TMO ($y(\cdot)$) is summarized as follows (see Fig.2(b)):

1. Calculate a tentative world luminance $L''_w(p)$ by eq.(13).
2. Calculate a tentative HDR image I_{Hp} with color components $C''(p) \in \{R''(p), G''(p), B''(p)\}$ as
$$C''(p) = \frac{L''_w(p)}{L_d(p)}\cdot C_f(p) = \frac{L''_w(p)}{L_d(p)}\cdot\frac{C_i(p)}{255}. \quad (19)$$
3. Caluculate a re-tone mapped display luminance $L''_d(p)$ by using an arbitrary TMO $y(\cdot)$, according to the equations: from eq.(2) to eq.(4).
4. Obtain a re-tone mapped LDR image I_{Li} by eqs.(6) and (7).

The effectiveness of the above procedure will be also experimentally confirmed in the next section.

4 Simulation

We evaluate the effectiveness of the proposed scheme by a number of simulations.

4.1 Simulation conditions

We used 60 HDR images selected from the databases [19, 20] for the evaluation. The following procedure was carried out to evaluate the effectiveness:

1. Map an HDR image to an LDR image by using the Reinhard's global operator.
2. Carry out the inverse TMO with parameters (and without parameters), to obtain I_{Hc} (and I_{Hp}) (see Fig.2).

3. Map I_{Hc} (and I_{Hp}) to LDR images by using two TMOs, which are the Reinhard's local operator and the Exponential TMO [2], to obtain I'_{Li} (and I''_{Li}).
4. Evaluate the similarity between images I'_{Li} and I''_{Li}, in accordance with the criterions i.e. PSNR, SSIM [21], and CIEDE2000 [22].

In this simulation, $\alpha = \alpha' = 0.5$ was used as a key value.

PSNR (Peak Signal-to-Noise Ratio), SSIM (the structural similarity index), and CIEDE2000 (the CIEDE2000 color difference formula), which are used for measuring the similarity between two images, are well-known image quality assessment indexes. The simulation was run on MATLAB R2014b, with a 3.4GHz processor and a main memory of 16Gbytes.

4.2 Simulation results

Figure 3 shows examples of LDR images mapped directly from an original HDR one (Adjuster) to illustrate the difference between the operators, where (c) and (d) are the magnified images of the square regions shown in (a) and (b) respectively. From the figures, it is confirmed that the quality of each LDR image depends on the type of TMO. In particular, the local TMO provides LDR images with more detailed information than global ones, but the computational cost is large as shown in table 1. Table 1 illustrates the relationship between the local operator and the global one.

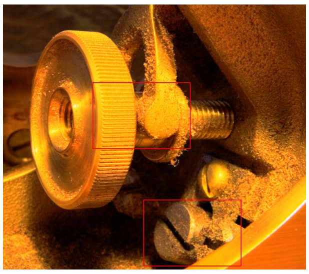
In Fig.4, re-tone mapped images from I_{L0} are illustrated, where I'_{Li} is an LDR image generated with α and $\overline{L}_w$, and I''_{Li} is without the parameters (i.e. $A = G = 1$). Both images in Fig.4 are similar, and furthermore have detailed information as well as in Fig. 3(d).

Table 2 summarizes the similarity between I'_{Li} and I''_{Li} in accordance with well-known three criterions. In case of PSNR $\in (0, \infty)$ and SSIM $\in [0, 1]$, a larger value means a higher similarity between two images. By contrast, a smaller value intends a higher similarity for CIEDE $\in [0, \infty)$. From the tables, we see that the proposed inverse TMO provided approximately the same results as the scheme with parameters. In other words, the proposed framework resulted in successful TMOs in the simulations.

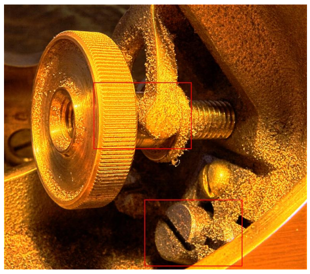
Table 1 also shows that the proposed inverse TM has much lower computational cost than Pseudo-Multiple-Exposure Tone Fusion (PMET) [12] which is a conventional inverse TM one.

5 Conclusion

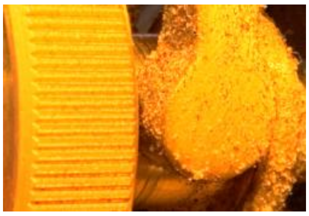
This paper has proposed a novel inverse TM opeartion, in which any parameters are not required to be stored. In addition, the proposed operation has a closed form without any data-depended calculations, which provides low computational



(a) I_{L0} (Reinhard's global)



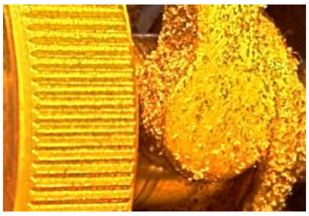
(b) I_{L1} (Reinhard's local)



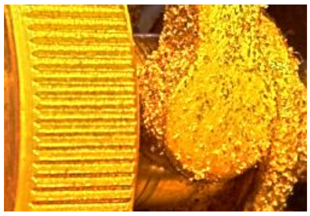
(c) I_{L0}

(d) I_{L1}

Fig. 3. Examples of tone mapped images (Adjuster)



(a) I'_{L1} (Conventional)



(b) I''_{L1} (Proposed)

Fig. 4. Examples of re-tone mapped images (Adjuster)

Table 1. Executing time of TM and ITM [sec]

	Image name	Ocean	Spheron	Napa
	Total pixels [$\times 10^3$]	1099	2308	6440
Forward TM	Reinhard's global	0.0093	0.2047	0.5509
	Reinhard's local	2.2164	4.5656	16.6398
Inverse TM	Proposed	0.0552	0.1195	0.3269
	PMET [12]	1.3981	2.9530	8.2201

Table 2. Similarity between I'_{L1} and I''_{L1}

	Reference: I'_{L1} Proposed framework		
	PSNR [dB]	SSIM	CIEDE
Adjuster	infinity	1	0
Cannon	infinity	1	0
Flowers	65.8505	1.0000	0.0096
SpheronPrice	infinity	1	0
Memorial	infinity	1	0
Average (60 images)		0.9993	0.1355

cost. As a result, it allows not only to simply visualize an HDR image on LDR devices but also to remap it to a well-detailed LDR image. The simulation results showed that the proposed inverse TM operation provides the same images as those reconstructed by the conventional one with two parameters. In addition, it was confirmed that the proposed one has low computatinal cost, compared to the conventional inverse TM operations.

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