Reinhard's Global Operator Based Inverse Tone Mapping with One Parameter

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Abstract This paper proposes a new inverse tone mapping operator (TMO) with only one parameter. The proposed inverse TMO is based on Reinhard's global operator which is a well-known TMO. Inverse TM operations have two applications: generating an HDR image from an existing LDR one, and reconstructing an original HDR image from the mapped LDR image. In this paper, we focus on the latter application and the proposed method can produce an HDR image that has high image quality. In the latter application, two parameters used in Reinhard's TMO, i.e. the key value α regarding brightness of a mapped LDR one and the geometric mean $\overline{L}_w$ of an original HDR one, are generally required for carrying out the Reinhard based inverse TMO. In this paper, we show that it is possible to estimate $\overline{L}_w$ from α under some conditions, so that a new inverse TMO with one parameter is proposed. Experimental results show that the proposed method outperforms conventional ones for the latter application, in terms of high image quality and low computing cost.

key words: *HDR Image, Tone Mapping, Inverse Tone Mapping*

1. Introduction

High dynamic range (HDR) imaging enables the capture of an extremely wide range of the illumination present in a scene and so produces images that more closely resemble what we see with our own eyes. Various research works on HDR imaging have so far been reported. Many of these have focused on tone mapping (TM) operations [1–6]. TM operations which generate LDR images from HDR ones is required to display HDR ones on conventional LDR devices. Meanwhile, with the availabilty of high quality display devices, the acquisitions of HDR images or videos become more and more important.

To produce HDR images, two main approaches have been proposed: capturing a stack of differently exposed LDR images that are merged into a final HDR result, and specialized HDR camera systems that measure a wide dynamic range. With conventional cameras, the most common approach for HDR imaging is to sequentially capture multiple images of the same scene using different exposures [7,8]. However, this kind of approaches is only suitable for static scenes. Recently, novel HDR-video cameras have been also provided by manufacturers such as the Spheron HDRv and Red HDRx technologies, to produce impressive videos [9, 10]. However, such techniques have a problem, that is the high cost of the overall system. In addition, these approaches are not suitable for reproducing real-world appearance images through legacy LDR images or videos.

Because of such a situation, this paper focuses on inverse TM operators (TMOs) that work on reproducing real-world appearance images through LDR images. Inverse TM operations have two applications: generating an HDR image from an existing LDR one, and reconstructing an original HDR image from the mapped LDR one. A lot of inverse TM operators for the former application have been proposed [11–15]. Huo et al. succeeded in expanding the local dynamic range in dark and bright area by using the dodging and burning algorithm with a S curve operator [14]. Wang et al. proposed an inverse TM operation which conflates pseudo-multiple-exposures HDR images generated from a single LDR image [15]. A high-performance inverse TM operation at low computational costs is required because HDR imaging techniques are expected to be applied to not only images but also videos. However, the existing inverse TM operations require complex processing for generating high quality HDR images, and moreover, they do not support the latter application.

The latter application is used to compression coding an HDR image such as for the JPEG-XT standard [16] and remapping operations [17, 18]. In [17], the Reinhard based inverse TMO without parameters has been proposed. The inverse TMO is designed for an remapping operation that enables to remap an LDR image to another LDR one. However, it cannot provide high quality HDR ones for the latter application.

To overcome these problems, we propose a novel inverse TMO which allows us to apply to the latter application at low computational costs. The proposed inverse TMO is based on a inverse transform of Reinhard's global operator [1]. Conventionally, two parameters used in Reinhard's TMO, i.e. the key value α regarding brightness of a mapped LDR one and the geometric mean $\overline{L}_w$ of an original HDR one, are generally required for carrying out the Reinhard based inverse TMO. In this paper, we show that $\overline{L}_w$ can be estimated from α under some conditions, so that a new inverse TMO with one parameter is proposed.

We evaluate the effectiveness of the proposed inverse TMO in terms of the quality of generated HDR images and the executing time by a number of simulations. Simulation results show that the proposed method is able to outperform conventional ones, maintaining the image quality with a low computational cost.

2. Preparation

A TM operation generates an LDR image I_L from an HDR image I_H. A typical TM operation is reviewed.

2.1 Photographic Tone Reproduction

"Photographic Tone Reproduction" [1] which is a typical TM operation is summarized, here. This TM operation consists of the following six steps (see Fig.1).

(a) The world luminance $L_w(p)$ of an HDR image I_H is calculated from RGB pixel values of 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. If eq.(2) has singularities at some pixels i.e. $L_w(p) = 0$, $\overline{L}_w$ is calculated as follows:

$$\overline{L}_w = \exp\left(\frac{1}{N}\left(\sum_{p\notin B}\log L_w(p) + \sum_{p\in B}\log\epsilon\right)\right) \tag{3}$$

where $B = \{p|L_w(p) = 0\}$ and ϵ is a small value.

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

$$L(p) = \frac{\alpha}{\overline{L}_w}L_w(p) \tag{4}$$

where $\alpha \in [0, 1]$ is the parameter called "key value", which indicates subjectively if the scene is light, normal, or dark [1]. α corresponds to the geometric mean of the scaled luminance.

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

$$L_d(p) = y(L(p)). \tag{5}$$

The Reinhard's global operator [1] which is a well-known TMO is given by

$$L_d(p) = \frac{L(p)}{1 + L(p)}. \tag{6}$$

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

$$C_f(p) = \frac{L_d(p)}{L_w(p)}C(p) \tag{7}$$

where $C(p) \in \{R(p), G(p), B(p)\}$ is the floating-point RGB value of the input HDR image I_H, 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 8-bit color RGB values $C_i(p)$ of the LDR image I_{Lg} is derived from

$$C_i(p) = \mathrm{round}(C_f(p) \cdot 255) \tag{8}$$

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

2.2 Scenario

This paper proposes a novel inverse TMO to reconstruct the original HDR image from an LDR image mapped by Reinhard's global operator. The inverse function of the Reinhard's global operator is given as, from eqs.(4) and (6)

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

To calculate this equation, the original HDR image I_H or two parameters (α and $\overline{L}_w$) are required to be stored. In particular, every image has a different $\overline{L}_w$ value. Therefore, when we map a number of HDR images or videos to LDR ones, all $\overline{L}_w$ values have to be stored to carry out eq.(9). On the other hand, α is commonly used for multiple images.

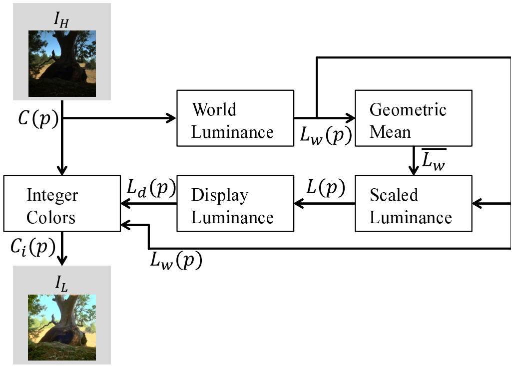

Fig. 1 Photographic Tone Reproduction

In this paper, a new inverse TMO with one parameter is proposed, where the other parameter is estimated.

3. Proposed inverse TM operation

Assuming the use of the Reinhard's global operator, a new inverse TM operation based on photographic tone reproduction is proposed.

3.1 Inverse TMO based on the Reinhard's TMO

The proposed inverse TMO is shown as

$$L'_w(p) = \frac{G}{A}\cdot L(p) = \frac{G \cdot L_d(p)}{A(1 - L_d(p))}. \tag{10}$$

As described later, the parameters A and G are given by using α as

$$\begin{cases} A = \alpha \\ G = \exp\left(\frac{N}{|B|}\log\overline{L} - \frac{|B^C|}{|B|}\log\alpha\right). \end{cases} \tag{11}$$

B^C is a complement of the set B i.e. $B^C = \{p|L_w(p) \neq 0\}$ and the geometric mean of the scaled luminance $L(p)$, $\overline{L}$ is given by, as well as in eq.(3)

$$\begin{aligned} \overline{L} &= \exp\left(\frac{1}{N}\left(\sum_{p\notin B}\log L(p) + \sum_{p\in B}\log\epsilon\right)\right) \\ &= \exp\left(\frac{1}{N}\left(\sum_{p\notin B}\log\frac{L_d(p)}{1 - L_d(p)} + \sum_{p\in B}\log\epsilon\right)\right). \end{aligned} \tag{12}$$

Compared eq.(10) with eq.(9), parameters α and $\overline{L}_w$ are replaced with A and G in eq.(9).

Note that $|B| \neq 0$ is assumed in eq.(11). Therefore, to calculate eq.(11), the minimum value in the world luminance $L_w(p)$ is replaced with zero value, if image I_H satisfies $|B| = 0$.

3.2 Proposed procedure

The procedure for generating an HDR image I'_H from an LDR image I_L is summarized as follows (see Fig.2).

Under the assumption shown in 3.1, i.e. $|B| \neq 0$, the following procedure is carried out.

1. Calculate a display luminance $L_d(p)$ from RGB values

of an LDR image as

$$L_d(p) = \frac{0.27R_i(p) + 0.67G_i(p) + 0.06B_i(p)}{255}. \quad (13)$$

2. Let B be a set of pixels p such that $L_d(p) = 0$.
3. Calculate $\overline{L}$ by eq.(12)
4. Calculate parameters A and G by eq.(11) with α.
5. Calculate a world luminance $L'_w(p)$ according to eq.(10) using A and G.
6. Obtain an HDR image I'_H with color components $C'(p) \in \{R'(p), G'(p), B'(p)\}$ as follows:

$$C'(p) = \frac{L'_w(p)}{L_d(p)} \cdot C_f(p) = \frac{L'_w(p)}{L_d(p)} \cdot \frac{C_i(p)}{255}. \quad (14)$$

3.3 Deriving the proposed inverse TMO

The calculating formulas of parameters A and G shown in eq.(10) is derived here.

First, we consider the geometric mean $\overline{L}$ of the scaled luminance $L(p)$. The geometric mean $\overline{L}$ is calculated by substituting eq. (4) into eq. (12),

$$\begin{aligned} \overline{L} &= \exp\left(\frac{1}{N}\left(\sum_{p \notin B} \log \frac{\alpha}{\overline{L}_w} L_w(p) + \sum_{p \in B} \log \epsilon\right)\right) \\ &= \exp\left(\frac{1}{N}\sum_{p \notin B} \log \alpha - \frac{1}{N}\sum_{p \notin B} \log \overline{L}_w\right) \\ &\quad \cdot \exp\left(\frac{1}{N}\sum_{p \notin B} \log L_w(p) + \frac{1}{N}\sum_{p \in B} \log \epsilon\right) \\ &= \exp\left(\frac{|B^C|}{N} \log \alpha + \frac{|B|}{N} \log \overline{L}_w\right). \quad (15) \end{aligned}$$

From eq.(15), we achieve relational expressions as follows:

$$\alpha = \exp\left(\frac{N}{|B^C|} \log \overline{L} - \frac{|B|}{|B^C|} \log \overline{L}_w\right) \quad (16)$$

$$\overline{L}_w = \exp\left(\frac{N}{|B|} \log \overline{L} - \frac{|B^C|}{|B|} \log \alpha\right). \quad (17)$$

Therefore, replacing α and $\overline{L}_w$ with A and G respectively, we arrive at eq.(11). As a result, one parameter α or $\overline{L}_w$ is calculable by eq.(16) or eq.(17), under the condition that α or $\overline{L}_w$ is known, since $\overline{L}$ is calculated from the mapped LDR image.

3.4 Evaluating the proposed method

To evaluate the quality of HDR images generated by the proposed inverse TMO, objective quality assessments and reference HDR images are needed. HDR images generally have a much wider dynamic range than that of LDR ones. For this reason, conventional quality assessments such as PSNR or SSIM are not suited to evaluate the quality of HDR images. Therefore, various research works on evaluating HDR images have so far been done [19]. In this paper, we will use HDR-VDP-2.2 [20] and PU encoding [21] + MS-SSIM [22] as typical quality metrics to evaluate the quality of HDR images.

4. Simulation

We evaluated the proposed inverse TMO in terms of the quality of a generated HDR image I'_H and the executing time by a number of simulations with HDR images.

Table 1 Machine spec used in the simulation

Processor	Intel Core i7-3770 3.40GHz
Memory	16GB
OS	ubuntu 14.04 LTS
Software	MATLAB R2014b

4.1 Simulation conditions

We used 60 HDR images selected from the databases [23,24] for the evaluation (see Fig. 3). The proposed method was compared with four inverse TMOs, i.e. the conventional inverse operation using eq.(9) with the true parameters, PMET [15], Kuo's method [13] and Huo's method [14]. The proposed method and the conventional one in eq.(9) are called inverse photographic tone reproduction (IPTR) in the following section. The simulation was run on a PC, with a 3.4GHz processor and a main memory of 16Gbytes (see Table 1).

The following procedure was carried out to evaluate the effectiveness.

1. Map an HDR image I_H to an LDR image I_L by Reinhard's global operator.
2. Carry out an inverse TMO for I_L to obtain I'_H.
3. Evaluate the similarity between images I'_H and I_H, in accordance with the criterions i.e. HDR-VDP-2.2 MOS value [20] and PU encoding [21]+ MS-SSIM [22].

4.2 Simulation results

Figure 4 illustrates the average executing time when each inverse TMOs are carried out 100 times for 60 images. From the figure, the proposed inverse TMO has much lower computational cost than the others while the proposed one takes a little more time than IPTR with two parameters. On the other hand, PMET has the largest computational cost.

Tables 2 and 3 denote the scores of similarities between HDR images I'_H and I_H which were evaluated by HDR-VDP-2.2 $\in [0, 100]$ and PU encoding + MS-SSIM $\in [0, 1]$, whose lager score indicates a higher similarity between two images.

Tables 2 and 3 show that the proposed method can reconstruct HDR images with high quality, and the quality is almost the same as that of IPTR with two parameters. A slightly difference between them are caused due to quantization error at eq.(8). In addition, the effectiveness of calculating the parameter G is confirmed since the proposed method outperforms IPTR without parameters.

For these results, it is verified that the proposed inverse TMO is effective to reconstruct original HDR images from mapped LDR ones, and it is carried out at a low computational cost.

5. Conclusion

This paper has proposed a novel inverse TMO with only one parameter, which is based on Reinhard's global operator. The proposed inverse TMO allows us to reconstruct an original HDR image from the mapped LDR image, while keeping high qualities. We also showed that it is possible to

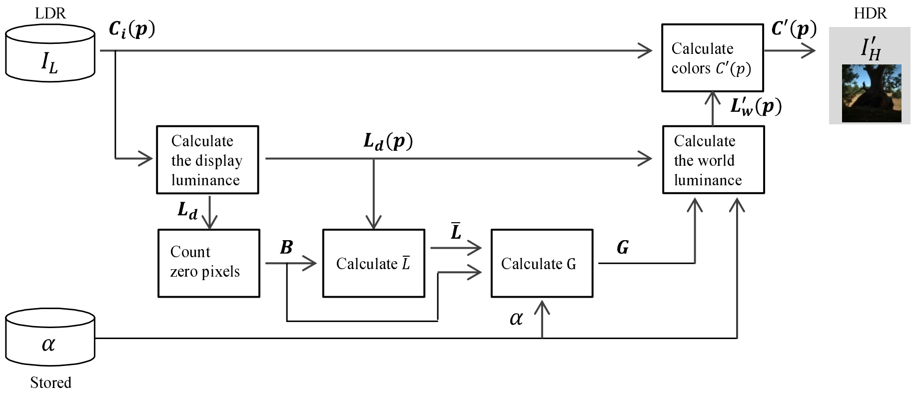

Fig. 2 Proposed inverse tone mapping operation

(a) adjuster (b) tree (c) memorial (d) mirror pattern

Fig. 3 Examples of tone mapped images

Table 2 Experimental results (HDR-VDP-2.2)

inverse TMO	IPTR (proposed, with α)	IPTR (with two parameters)	IPTR [17] (without parameters)	PMET [15]	Kuo's ITMO [13]	Huo's ITMO [14]
Adjuster	58.25	58.17	57.81	57.41	42.65	53.13
Cannon	95.00	95.53	70.69	55.17	49.92	56.58
Flowers	83.22	83.22	63.92	54.70	58.20	55.39
Kapaa	90.55	90.88	64.21	54.47	44.54	55.46
memorial	49.60	49.61	51.61	45.33	39.60	44.65
Average (60 images)	62.72	63.22	57.34	53.38	43.38	52.76

Table 3 Experimental results (PU encoding + MS-SSIM)

inverse TMO	IPTR (proposed, with α)	IPTR (with two parameters)	IPTR [17] (without parameters)	PMET [15]	Kuo's ITMO [13]	Huo's ITMO [14]
Adjuster	0.991	0.991	0.931	0.944	0.534	0.909
Cannon	1.000	1.000	0.990	0.773	0.744	0.747
Flowers	1.000	1.000	0.947	0.706	0.871	0.675
Kapaa	1.000	1.000	0.950	0.702	0.524	0.670
memorial	0.981	0.981	0.961	0.879	0.581	0.856
Average (60 images)	0.977	0.977	0.920	0.860	0.597	0.831

calculate $\overline{L}_w$ by using α under some conditions. The simulation results showed that the proposed method outperforms conventional ones at a low computational cost.

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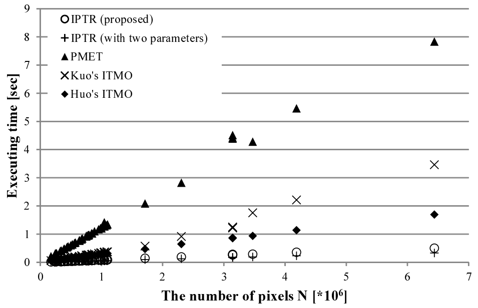

Fig. 4 Executing time of iTMOs

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