High Dynamic Range (HDR) imaging inspires many applications such as image based lighting simulation, in-vehicle sensors, camera surveillance, and high contrast digital negative developments. Many researchers have proposed techniques for HDR acquisition, tone mapping, coding, etc. [1]. In the last decade many acquisition techniques have been developed based on a multiple-exposure principle [2], in which the HDR image is constructed by merging some photographs taken with multiple exposures. Furthermore the recent advances in CMOS sensor technologies make it possible to capture HDR video in real time [3], [4]. Many of the HDR image sensors have response functions that do not have a linear relationship to scene radiance [3]. Typically they have logarithmic or gamma-like responses that tends to suppress contrasts in highlight regions [3].

Since the HDR has a wide dynamic range, in order to display it on conventional output devices it is necessary to compress the range. This range compression procedure is generally called a Tone Mapping Operator (TMO). Most of the tone mapping fall into two types, local and global operators. In general the local operators preserve local contrasts better, while the global ones have lower computational complexity and many of them can be implemented by Look Up Tables (LUTs). Many TMOs have been proposed including local and global operators [1]. Most of the conventional methods are optimized for still images constructed from multiple exposures, in which pixel values are assumed to be calibrated to be linear to scene radiance. Although some tone mapping methods for video are proposed to address flicker effects of the video or to examine the HVS responses that tends to suppress contrasts in highlight regions [3].

2.1. Framework

Many of the conventional tone mapping operators are based on the Human Visual System, in which the effect of range compression varies depending on local contrasts. This type of the tone mapping works well for the HDR images captured by the multiple exposure principle, whose pixel values are almost linear to scene radiance and have high dynamic range. However it does not work well for typical HDR videos, since the level of contrast varies depending on its luminance due to the nonlinear relationship to actual radiance.

The simple gamma tone mapping operator with $\gamma < 1$ preserves the detail of low luminance region, while the one with $\gamma > 1$ has inverse property. Our tone mapping properly blends these two effects. Here we call the mapping with $\gamma < 1$ the gamma mapping, the one with $\gamma > 1$ the inverse gamma mapping. In the method, to preserve the detail of low and high luminance regions, the tones of these regions are mapped by using the gamma and the inverse gamma curves, respectively.

The procedure of our tone mapping is shown in Fig.1. First, we find the luminance $Y$ of the HDR, and then create an illumination map by blurring the luminance. Then a contrast component is extracted from it, and is enhanced depending on the pixel values (Section 2.2). Next the gamma blending is employed (Section 2.3). In this process, the tone of the contrast enhanced illumination map is transformed into a displayable range by the gamma and the inverse gamma curves. The degree of the gamma and inverse gamma mapping is controlled by the illumination map. The detail of the illumination map is shown in the next section. Finally, we obtain a LDR color image by using that LDR luma and the color component of the original HDR image.
2.2. Illumination Map

In our method, the illumination map is calculated and then its contrast is enhanced. The illumination map \( L \) is simply a blurred version of the intensity \( Y \). The low pass filtering is done using the multi-scale pyramid to reduce the computational complexity. Next the residual is calculated by

\[
R(i) = Y(i) - L(i),
\]

where \( i \) is a pixel index. This residual \( R \) is used for the contrast enhancement introduced below. Note that although the procedure is similar to the Retinex [7], in our case this is used as a pre-processing and we need only a lowpass filter with a few taps to obtain \( L \) that has much less computational complexity.

Since we assume that the pixel intensity is not linear to scene radiance, the contrast around some luminance of the image may be low, that is, for example if the sensor has a logarithmic response, high luminance regions become low contrast. To address the problem we enhance the contrast of \( L \) by

\[
Y_c(i) = R(i) \cdot (\alpha_0(i) + W_l(i) + W_m(i) + W_h(i)) + L(i),
\]

Here we control the contrast using the weights \( W_l(i) \), \( W_m(i) \), and \( W_h(i) \) that play roles of enhancing the contrast in low, middle and high luminance regions, respectively, and \( \alpha_0 \) is a parameter that balances the weighting effects. The weights are controlled by user defined parameters \( \alpha_l, \alpha_m, \alpha_h \) as

\[
W_l(i) = \alpha_l \cdot (1 - L'(i))
\]

\[
W_m(i) = \alpha_m \cdot \exp \left\{ -\frac{(L'(i) - \bar{L})^2}{0.04} \right\}
\]

\[
W_h(i) = \alpha_h \cdot L'(i)
\]

\[
L'(i) = \frac{L(i) - L_{\text{min}}}{L_{\text{max}} - L_{\text{min}}},
\]

where \( L_{\text{max}} \) and \( L_{\text{min}} \) are the maximum and minimum pixel values of \( L \), and \( \bar{\cdot} \) denotes the mean of \( \cdot \). As described above, since our method enhances the contrasts in several illumination regions, our method can adaptively enhance the contrast pixel by pixel.

2.3. Gamma Blending

The gamma tone mapping operator with \( \gamma < 1 \) is apt to coarsely encode high luminance regions. The inverse gamma tone mapping operator has its opposite effect. To address this problem, our tone mapping operator blends the strength of these two gamma encodings.

Fig. 1. the flow of our tone mapping method

\[
Y_{GC}(i) = \max \left( \min \left( \frac{\alpha_{GC} Y_{GC}(i), 1}, 0 \right) \frac{2}{2 + \log_{10} (Y_{GC} + 1)} \right)
\]

\[
\alpha_{GC} = 1.03 - \frac{2}{2 + \log_{10} (Y_{GC} + 1)}
\]

\[
Y_{GC} = \exp \left( \frac{1}{N} \sum_{i=1}^{N} \log (Y_c(i) + \epsilon) \right)
\]

where \( N \) is the number of pixels, and \( \bar{\cdot} \) denotes the mean of \( \cdot \). This scaling is derived from [8]. Then, the scaled map \( Y_{GC} \) is tone mapped by the gamma curve.

\[
Y^{(LDR)}_{GC}(i) = Y_{GC}(i)\gamma
\]

For the inverse gamma mapping, we do not simply use \( Y_c^{1/\gamma} \), and introduce the following scheme,

\[
Y^{(LDR)}_{IGC}(i) = 1 - (1 - Y_{IGC}(i))^{\gamma},
\]

where \( Y_{IGC}(i) \) is derived by similarly scaling \( (1 - Y_c) \),

\[
Y_{IGC}(i) = \max \left( \min \left( \frac{1 - \alpha_{IGC} (1 - Y_c(i)), 1}, 0 \right) \frac{2}{2 + \log_{10} (Y_{IGC} + 1)} \right)
\]

\[
\alpha_{IGC} = 1.03 - \frac{2}{2 + \log_{10} (Y_{IGC} + 1)}
\]

\[
Y_{IGC} = \exp \left( \frac{1}{N} \sum_{i=1}^{N} \log (1 - Y_c(i) + \epsilon) \right)
\]

This mapping differs from the simple inverse gamma \( Y_c^{1/\gamma} \) in two ways: (1) while the inverse gamma (dotted line in Fig.6(c)) excessively evaluates highlights and suppresses low luminance regions,
our mapping (solid line in Fig.6(c)) has simply its inverse effect and compensate the disadvantage of the gamma mapping as is shown in Fig.3(a)-(c), and (II) the gamma and inverse gamma mapping in our method can be implemented by a single Look Up Tables (LUT) of \( x^\gamma \), which saves storage and computational cost.

Finally, \( Y_{GC} \) and \( Y_{IGC} \) are blended by using the illumination map

\[
Y^{(LDR)}(i) = (1 - L(i)) \cdot Y^{(LDR)}_{GC}(i) + L(i) \cdot Y^{(LDR)}_{IGC}(i),
\]

where \( L \) is scaled to \([0, 1]\). This tone mapping enhances the gamma effect for high luminance regions as well as the inverse gamma effect for shadows, and its detailed contrast is controlled by (2).

Here, \( \gamma \) in (5) and (6) adaptively varies scene by scene as in

\[
\gamma = \left(1 + \frac{3}{1 + \exp(-30 \cdot ((L_{\text{max}} - L_{\text{min}}) - 0.6))}\right)^{-1}. \tag{9}
\]

This controls the tone mapping effect depending on the dynamic range, that is, if the dynamic range is large, the effect also becomes higher, and if the range becomes lower, the mapping approaches a simple linear transform. Fig.3 (d) illustrates some examples of the blended curve.

![Gamma and Inverse Gamma mapping](image)

**Fig. 3.** Gamma and Inverse Gamma mapping: Our inverse gamma mapping (c) is derived by flipping the gamma in (a). Then the curves (a) and (b) are blended as in (d).

### 2.4. Flicker suppression

When the width of a scene changes, the range of range compression also changes. This results in flicker artifacts, since Eq.(9) depends on the range \( L_{\text{max}} - L_{\text{min}} \). The artifacts can be reduced by preventing from sudden change of the range. In our method, \( L_{\text{max}} \) and \( L_{\text{min}} \) are controlled by the following approach. First we calculate the difference of the luminance range:

\[
r_d = |L^{(k)}_{\text{max}} - L^{(k-1)}_{\text{max}}| + |L^{(k)}_{\text{min}} - L^{(k-1)}_{\text{min}}|/L^{(k)}_{\text{max}} \tag{10}
\]

Depending on \( r_d \), we set:

\[
\tilde{L}^{(k)}_{\text{max}, \text{min}} = (1 - \delta)L^{(k)}_{\text{max}, \text{min}} + \delta L^{(k-1)}_{\text{max}, \text{min}}, \tag{11}
\]

where \( \delta = \max\{a - e^x, b\} \).

Here \( a \) and \( b \) are user-defined parameters. The larger the values are, the more the flicker artifacts are suppressed. However when the dynamic range becomes suddenly large, large values cause the loss of the dynamic range after tone mapping. In our method, we determine them as 0.9 and 0.7, respectively by trial and error.

### 3. NUMERICAL RESULTS

In this section, we show the experimental results and compare our method with the Reinhard’s local operator [8], which is one of the most well-known TMOs.

#### 3.1. Quantitative evaluation method

In order to evaluate the result of tone mapping quantitatively, we introduce three criteria.

(a) Contrast Evaluation in SSIM

This is a contrast evaluation criterion used in the SSIM [9], which is the global variance of pixel values.

(b) Local Variance

This method calculates the local variance of the LDR, which is simply defined by the mean of variances in locations.

(c) Detailed Variance / Background Variance

This is the evaluation method in [10]. This criterion separately calculates a DV (Detailed Variance) region and the BV (Background Variance) region from the LDR, and then the ratio \( DV/BV \) is found. The DV is the mean local variances in the region with important edges (i.e. In the DV region). The BV is the mean variances in the region with nonessential edges. We use the ratio \( DV/BV \) for the criterion.

Note that all the three criteria give larger values for better quality.

#### 3.2. Results

Sample HDR sequences are captured by the image sensor, RIROI series of ENG Co., Ltd. Some frames are shown in Fig.4. The resolution of the sequences is 640 \( \times \) 480. The bit depth of the sensor output is 12 bits and its dynamic range is approximately 120dB.

Fig.5 shows the tone mapping results. Since directly applying Reinhard’s TMO in Fig. 5(a) yields very low contrast even with optimized parameter settings, we also show the enhanced Reinhard operation in Fig. 5(b) in which the histogram adjustment and equalization are performed as well as the Reinhard’s TMO. Fig. 5(c) is the results of our method. One can see that our method preserves more details than the improved Reinhard’s TMO from the low to high luminance regions. Fig.6 shows the three quantitative evaluation results for the HDR sequence of Fig.4, and Table 1 denotes the means of the criteria over all frames. Note that the conventional method, (II) of Fig.6 is also the improved version of Reinhard’s TMO that performs better than the original one. One can see that our method outperforms the conventional method in all the criteria.

Our algorithm is implemented in C++ on a PC (CPU:Core.i7 2.67GHz, memory: 9GB) and it takes 0.045 sec in average for a 640 \( \times \) 480 frame. In our algorithm, most of the parts can be implemented by LUT. Among the main components, only the lowpass filtering (we use a 5 \( \times \) 5 filter) employed to obtain \( \tilde{L} \) is a process that one cannot apply the LUT, while Reinhard’s operator needs more than two convolutions of a longer order lowpass filter. Moreover in our method, the most of the time-consuming parts such as exponential
calculations in (3), (4) and (7) allow coarsely quantized LUTs, except for the gamma encoding in (5) and (6). In the end our method is about five times faster than the Reinhard’s local TMO.

Fig. 4. Sample frames of “tunnel”: 100th, 300th and 400th frames

Fig. 5. the Results of tone mapping: (a) Reinhard, (b) Reinhard with histogram adjustment, (c) Our method

Table 1. Means of the error

<table>
<thead>
<tr>
<th>Criterion</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinhard [8]</td>
<td>0.1709</td>
<td>0.0311</td>
<td>2.7079</td>
</tr>
<tr>
<td>Our method</td>
<td>0.1756</td>
<td>0.0346</td>
<td>3.0130</td>
</tr>
</tbody>
</table>

4. CONCLUSION

We proposed a new tone mapping method for the HDR video based on the gamma blending. Our method achieves a high quality tone mapping especially for HDR video that has nonlinear response to scene radiance. Some experimental results show that our method preserves local contrasts more than the well-known conventional approach.

5. REFERENCES


