rTMO/EO – Enhancement of SDR contents for HDR Rendering Applications

Mekides Assefa Abebe

ICC Expert Day

March 15, 2022
Contents

Introduction

State of the art

Current trends

Limitations and Future research directions
Introduction

- Tone Mapping Operators (TMO): defined as a general operator $f$ over an HDR image $H$ as
  - $f(H) = \mathbb{R}_{in} \xrightarrow{x,y,c} \mathbb{R}_{out}$ where, $\mathbb{R}_{out} \subset \mathbb{R}_{in}$
  - $S(x, y, c) = f(H)$

- Reverse Tone Mapping Operators (rTMOs) / Expansion Operators (EO)
  - $f(S) = \mathbb{R}_{in} \xrightarrow{x,y,c} \mathbb{R}_{out}$ where, $\mathbb{R}_{in} \subset \mathbb{R}_{out}$
  - $H(x, y, c) = f(S)$
**Introduction**

**rTMOs**

- Ill-posed problem: details are lost in under- and over-exposed regions
- Mostly involves (as outlined by Banterle et al.) the following components.

- **Linearization**
- **Expansion of Pixel values**
- **Artifact reduction & Color correction**
- **Detail reconstruction**
Linearization

- RAW files sometimes are not linear
- Standard sRGB or sensor gamma $\gamma$
  \[ S_{Lin} = S^{1/\gamma} \]
- If radiometric calibration is not possible:
  - Real time estimation of CRF

**Camera Response Function $f(\cdot)$**

**Scene Radiance**

\[ I_1 = \int R(x, \lambda) g(\lambda) d\lambda d\xi \]

**Scene Irradiance**

\[ I_2 = \int I_1 \]

**Measured Color**

\[ M = f (I) \]

*Banterle et al., Advanced High Dynamic Range Imaging*

**argmin$_g$ $E(g, \Omega) = \{ g \mid E(g, \Omega) = \min_{g'} f (g', \Omega) \}$**

\[ E(g, \Omega) = \sum_{H \in \Omega} w_H N(g(H)) \]
State of the Art - rTMOs

Expansion of Pixel values

- Global approaches
- Classification and map based
- Perceptual based methods

\[ L_H(x) = a \left( \frac{L_S(x) - L_{S_{\text{min}}}}{L_{S_{\text{max}}} - L_{S_{\text{min}}}} \right)^\gamma \]

\[ k = \left( \frac{L_S(x) - \tau}{1 - \tau} \right)^\alpha \]

\[ L_H = \begin{cases} 
(1 - k)L_S(x) + kL_{H_{\text{max}}} & \text{if } L_S(x) \geq \tau \\
L_S(x) & \text{otherwise}
\end{cases} \]
State of the Art - rTMOs

Expansion of Pixel values

- Global approaches
- Classification and map based
- Perceptual based methods

Bilateral filter $\Rightarrow S_{Lin} = S^{1/\gamma}$

$L_{H_{temp}}(x) = L_S(x)(L_{H_{max}} - L_{H_{min}}) + L_{H_{max}}$

- Saturated region map detected $\tau = 0.92$
- Map is filtered with Gaussian filter
- Flood fill contrast enhancement algorithm used to enhance contrast around edges
- $L_H(x) = L_{H_{temp}}(x) * Map$
State of the Art - rTMOs

Expansion of Pixel values

- Global approaches
- Classification and map based
- Perceptual based methods

Expansion of Pixel values

\[
f_{pl}(Y, Y_n) = \begin{cases} 
1.226 \left( \frac{Y}{Y_n} \right)^{0.266} - 0.226 & \text{if } Y_n \leq 100 \text{ cd/m}^2 \\
1.127 \left( \frac{Y}{Y_n} \right)^{0.230} - 0.127 & \text{if } Y_n > 100 \text{ cd/m}^2 
\end{cases}
\]

\[
f_{mm}(Y, Y_n) = \begin{cases} 
1.448 \left( \frac{Y}{Y_n} \right)^{0.582} & \text{if } Y_n \leq 100 \text{ cd/m}^2 \\
0.813 \left( \frac{Y}{Y_n} \right)^{0.582} + 0.635 & \text{if } Y_n > 100 \text{ cd/m}^2 \\
1.680 \left( \frac{Y}{Y_n} \right)^{0.293} & \text{if } Y_n \leq 100 \text{ cd/m}^2 \\
0.096 \left( \frac{Y}{Y_n} \right)^{0.293} + 1.584 & \text{if } Y_n > 100 \text{ cd/m}^2 
\end{cases}
\]

PCS → CIE Lab color space – with replaced luminance function.

Mekides Assefa et al. Perceptual lightness modeling for high-dynamic-range imaging
State of the Art - rTMOs

Expansion of Pixel values

- Global approaches
- Classification and map based
- Perceptual based methods

ANOVA multiple comparison: subjective evaluation results

<table>
<thead>
<tr>
<th>Method</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akyuz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Banterle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HDR ground truth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIELab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hdr-CIELab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michaelis-Menten</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power law</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mekides Assefa et al. Perceptual lightness modeling for high-dynamic-range imaging

Perceptual Quality:

- Pleasantness
- Color appearance fidelity
State of the Art - rTMOs

Artifact reduction & Color correction

✧ Quantization artifacts
  ◦ 8-bit per channel creates banding artifacts for expanded luminance ranges on HDR screens
  ◦ With ground truth – Dithering, and companding
  ◦ With no ground truth – Decontouring (Such as adaptive filtering and predictive cancellation)

✧ Color correction
  ◦ Correction of color desaturation

\[ C_H = r \frac{S}{H} C_S, \quad r = \frac{f(C_S, H)}{f(C_S, S)}, \quad f(C, I) = \frac{C}{\sqrt{C^2 + I^2}} \]

Tania Pouli et al. Color Correction for Tone Reproduction
State of the Art - rTMOs

Detail reconstruction

Majority of currently available image and video content have exposure problems.

- Detail recovery
- Artistic intent
- Appearance and quality
- Enhancing computer vision and imaging applications
State of the Art - rTMOs

Detail reconstruction

Color clipping correction

Over-exposure correction

RGB channel correlation and RGB channel saturation at different spatial position

Abebe, M. A et al. “Color Clipping and Over-exposure Correction”

Bright Region Enhancement

State of the Art - rTMOs

Detail reconstruction

Works well for color clipping and specular highlights

Fails in the presence of severely over-exposed regions
Current trends - rTMOs

- HDR standards
  - Various ITU standards on PQ and HLG encoding and interoperability

- Volumetric mapping
- Color management solutions

https://www.w3.org/Graphics/Color/Workshop/slides/talk/kunkel

ACES Block diagram
More data set and DL methods are available for under-exposed/low light image enhancement application.
Current trends - rTMOs

Deep Learning Methods

Slightly tone mapped HDR - LDR data set: created from RIT Photographic Survey database and data set.
- 402 paired images and 804 unpaired images

(a) Reference HDR  (b) Input LDR  (c) Slightly tone mapped HDR
Loss function

\[ L_{\text{final}} = \sum_{i=1}^{n} 2^{l-2} L_{\text{norm}_1}(T_i, Y_i) + L_{\text{norm}_1}(T, Y) - \log(D(T, Y)) \]
Current trends - rTMOs

Deep Learning Methods

GAN based image-to-image translation models were adapted for exposure correction application.

ReExposeNet and UCan

GAN based image-to-image translation models were adapted for exposure correction application.

Pix2Pix GAN

CycleGAN

ReLU

Atrous convolution ELU

nearest neighbor interpolation

Covolution Pooling

skip connections upsampling

UNet

Discriminator

Generator A

Cycle consistency loss

L1 norm

Generator B

\[
L_{GAN}(G, D) = E_{x,y}[\log D(x, y)] + E_{z|x}[\log(1 - D(x, G(z, z)))]
\]

\[
G_{L1}^* = \arg \min_G \max_D L_{GAN}(G(D)) + \lambda L_{L1}(G)
\]

Mekides Assefa et al., Content Fidelity of Deep Learning Methods for Clipping and Over-exposure Correction
Current trends - rTMOs

Deep Learning Methods

Results and Color fidelity issues
Color and content fidelity issues.
Semantically incoherent corrections.
Poor generalization.
Problems get worse for severely over-exposed contents.
Limitations and Future Research Directions

✧ **Color fidelity**
  ✧ Perceptually uniform color spaces
  ✧ Quality intent: pleasantess, reproduction quality

✧ **Interoperability**
  ✧ Display screens calibration:
    ✧ displays with multiple HDR standard modes are available
  ✧ Radiometric calibration
  ✧ Videos: dynamically changing scenes
  ✧ **HDR + wide color gamut** devices: volumetric mapping

✧ **Content recovery**
  ✧ Better data set
  ✧ Semantically coherent and cross-class attention models
  ✧ Image/video quality aware loss functions
rTMO/EO – Enhancement of SDR contents for HDR Rendering Applications

Mekides Assefa Abebe

ICC Expert Day
March 15, 2022