National Tsing Hua University
Department of Electrical Engineering
EE6620 Computational Photography, Spring 2022

Homework #1
High Dynamic Range Imaging

Assigned on March 11, 2022

Due by April 1, 2022

Homework Description

Modern cameras are unable to capture the full dynamic range of commonly encountered natural scenes. High-dynamic-range (HDR) photographs are generally achieved by capturing multiple standard-exposure images, often using exposure bracketing, and then merging them into a single HDR image. Also, to view the HDR image on an ordinary low-dynamic-range (LDR) display, tone mapping operation from HDR to LDR on images is required. In this assignment, you will implement the whole HDR photography flow, including **image bracketing**, **camera response calibration**, **white balance**, and finally, **tone mapping**, to visualize your results.


GlobalTM


LocalTM (Gaussian)

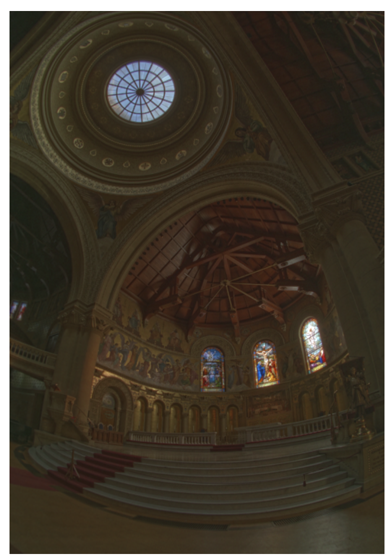
LocalTM (Bilateral)

Table 1: Scores

Items		Score
Implementation (50%)	Camera Response Calibration	20%
	White Balance	5%
	Global Tone Mapping	5%
	Local Tone Mapping (Gaussian)	10%
	Local Tone Mapping (Bilateral)	10%
Report (50%)	Exploration	20%
	Research Study	30%

1 Implementation

In this section, you will implement the algorithms for the whole HDR imaging flow. For each function you need to implement in HDR_functions.py, a corresponding test function is provided in test_HDR_functions.py to help you check the correctness. You can develop your functions step by step with these unit tests to complete the whole HDR flow. In test_HDR_functions.py, argument TEST_PAT_SIZE can be assigned to either small of large. small stands for small test pattern size and large stands for large test pattern size. It is recommended to set TEST_PAT_SIZE small for quick debugging during implementation. However, you have to **pass the unit test with TEST_PAT_SIZE** large **to get the full score in each part. And please do not modify original function IO. Otherwise, your implementation will be considered as incorrect.** Note that for large pattern size, the bilateral filtering process may take longer time to complete. Two test images are provided in folder /TestImage, one is memorial and the other is vinesunset. After passing all unit tests, you can execute HDR_flow.py to run the whole HDR imaging flow.

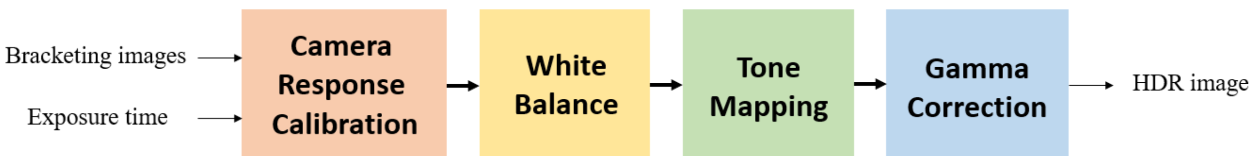

Figure 1: HDR imaging flow

1.1 Camera Response Calibration (20%)

Camera response calibration estimates the radiometric response of a camera. In this assignment, you will implement the debevec method [1] to recover a high dynamic range radiance map from a set of bracketing images.

The debevec method consists of 3 steps:

a. Describe the objection function in matrix form.

$$O = \sum_i \sum_j w(Z_{ij})[g(Z_{ij}) - \ln E_i - \ln \Delta t_j)]^2 + \lambda \sum_{z=Z_{min}+1}^{Z_{max}-1} [w(z)g''(z)]^2 \tag{1}$$

In the objection function, Z_{ij} is the intensity measurement for pixel i on image j. Δt_j is the exposure time of the image j, and E_i is our target radiance of location i. $g(z)$ is the camera response which maps the measured intensity Z_{ij} to exposure $E_i \Delta t_j$. The objection function connects data term and smoothness term with a Lagrange multiplier λ. A curve shape prior $w(z)$ is applied in debevec method to fit the curve assumption:

$$w(z) = \begin{cases} z - Z_{min} & z \leq \frac{1}{2}(Z_{min} + Z_{max}) \\ Z_{max} - z & z > \frac{1}{2}(Z_{min} + Z_{max}) \end{cases} \tag{2}$$

Besides, we should also apply an unit exposure assumption by letting $g(127) = 0$. We will describe the equation and prior in the matrix form $Ax = b$. The relation between the objection function and the matrix is shown in Figure 2.

For data term, we would like to fill the matrix with

$$[w(Z_{ij}),\ -w(Z_{ij})] \cdot [g(Z_{ij}),\ \ln E_i] = w(Z_{ij}) \ln \Delta t_j \tag{3}$$

for measurement $(Z_{ij}, \Delta t_j)$.

And for smoothness term with Lagrange multiplier, we would like to fill the matrix with

$$\lambda[w(z),\ -2w(z),\ w(z)] \cdot [g(z-1),\ g(z),\ g(z+1)] = 0 \tag{4}$$

for intensity z.

b. Solve the least square problem with function numpy.linalg.lstsq().

c. Estimate the radiance map from response curve. The final radiance for each pixel i can be estimated by averaging measurements from all images j:

$$\ln E_i = \frac{\sum_j w(Z_{ij})(g(Z_{ij}) - \ln \Delta t_j)}{\sum_j w(Z_{ij})} \tag{5}$$

Complete functions EstimateResponse() (steps a, b) and ConstructRadiance() (step c) in HDR_functions.py.

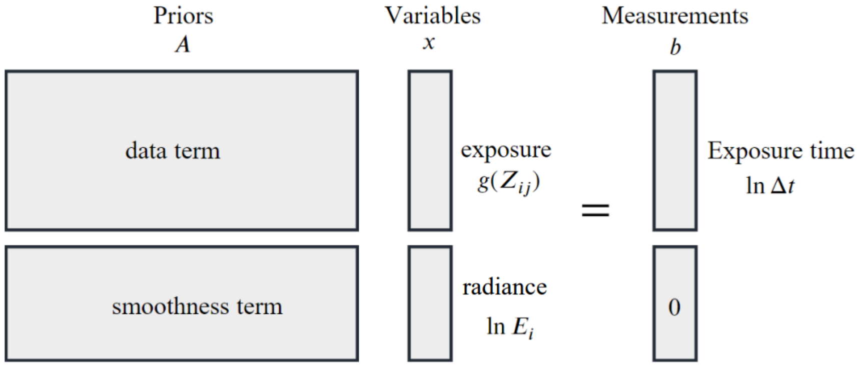

Figure 2: Matrix Form

1.2 White balance (5%)

White balance is the process of removing unrealistic color casts, so that the objects which appear white in person are rendered white in your photo/display. In this part, we scale the color ratios such that the "known to be white" region has equal average intensity in three color channels. To achieve this, color channels G and B are scaled with R_{avg}/G_{avg} and R_{avg}/B_{avg} respectively based on the average value measured in the "known to be white" region:

$$X_{avg} = \text{avg}_{(i,j)\in\Omega_{ktbw}} X \tag{6}$$

$$X' = X * (R_{avg}/X_{avg}),\ for\ X \in \{G, B\} \tag{7}$$

G, B, and G', B' here stand for the radiance before and after the white balance.
Complete function WhiteBalance() in HDR_functions.py.

1.3 Global tone mapping (5%)

Global tone mapping compresses the contrast of intensity by scaling in log domain as shown in Eq. (8)

$$\log_2 \hat{X} = s(\log_2 X - \log_2 X_{max}) + \log_2 X_{max}, \tag{8}$$

$$X_{max} = \max_{i,j}(X(i,j))$$

where X is the radiance, and $\hat{X}$ is the compressed result. Note that this operation should be performed on each of the color channels. Besides the tone mapping operation, we should also perform gamma correction to convert linear RGB to nonlinear color space and transform range to 0-255 before saving.

$$X' = \hat{X}^{1/\gamma} \tag{9}$$

In tone mapping, the contrast is reduced in log domain and s here is a parameter to adjust the contrast. On the other hand, γ in nonlinear correction is fixed to commonly used 2.2.
Complete function GlobalTM() in HDR_functions.py.

1.4 Local tone mapping with Gaussian filter (10%)

Local tone mapping performs contrast compression only on the base layer to preserve details while balancing the luminance of different regions. A reference flow to achieve this goal is listed as below. Note that you should use **symmetric padding** in the filtering.

Local Tone Mapping Flow:

a. Separate Intensity map(I) and Color Ratio(C_r, C_g, C_b) for radiance (R, G, B).

$$I = \text{avg}(R, G, B) \tag{10}$$

$$C_x = X/I,\ for\ X \in \{R, G, B\} \tag{11}$$

b. Take log of intensity

$$L = \log_2 I \tag{12}$$

c. Separate the detail layer (L_D) and base layer (L_B) of L with Gaussian filter,

$$L_B(i,j) = \frac{\sum_{k,l} L(i+k, j+l)w(k,l)}{\sum_{k,l} w(k,l)}, \tag{13}$$

$$w_{Gaussian}(k,l) = \exp\left(-\frac{||(0,0)-(k,l)||^2}{2\sigma_s^2}\right),\ k,l \in [-N/2, N/2] \tag{14}$$

$$L_D = L - L_B \tag{15}$$

Eq. (13) express the convolution between an image L and symmetric filter w. Indices i, j indexes the pixel of an image on location (i, j). Indices k, l span a filter with $N \times N$ window size. σ_s^2 in Eq. (14) is the variance of the Gaussian filter.

d. Compress the contrast

$$L'_B = (L_B - L_{max}) * \frac{scale}{L_{max} - L_{min}}, \tag{16}$$

$$L_{min} = \min_{i,j} L_B(i,j),$$

$$L_{max} = \max_{i,j} L_B(i,j)$$

where $scale$ is a parameter for contrast adjustment, different scenes may have different settings. The value around 2~15 would look good for most of scenes.

e. Reconstruct intensity map with adjusted base layer and detail layer,

$$I' = 2^{L'_B + L_D} \tag{17}$$

f. Reconstruct color map with adjusted intensity and color ratio,

$$C = C_x * I',\ for\ X \in \{R, G, B\} \tag{18}$$

Besides the tone mapping operation, we should also perform gamma correction Eq. (9) to convert linear RGB to nonlinear color space and transform range to 0-255 before saving.

Complete functions LocalTM() and GaussianFilter() in HDR_functions.py.

1.5 Local tone mapping with Bilateral filter (10%)

Replace Gaussian filter in local tone mapping (sec 1.4 step c) with bilateral filter.

Bilateral filter on image L can be expressed as

$$w_{bilateral}(L, i, j, k, l) = \exp\left(-\frac{||(0,0)-(k,l)||^2}{2\sigma_s^2} - \frac{||L(i,j)-L(i+k,j+l)||^2}{2\sigma_r^2}\right) \tag{19}$$

where σ_s^2 and σ_r^2 represent the spatial and range variances of the bilateral filter. Again, indices k, l are bounded in $[-N/2, N/2]$ window.

Complete function BilateralFilter() in HDR_functions.py.

2 Report (50%)

In this section, we will go into detail over the HDR imaging flow. There are two parts of problems: Exploration and Research Study. Answer the problems clearly and integrally in a report.

2.1 Exploration (20%)

a. A conceptual figure Figure 3 shows how bracketing images can recover the radiance of a scene. What is the meaning of this figure? Try to plot the same figure for memorial image set and describe how you plot the figure. **(5%)**

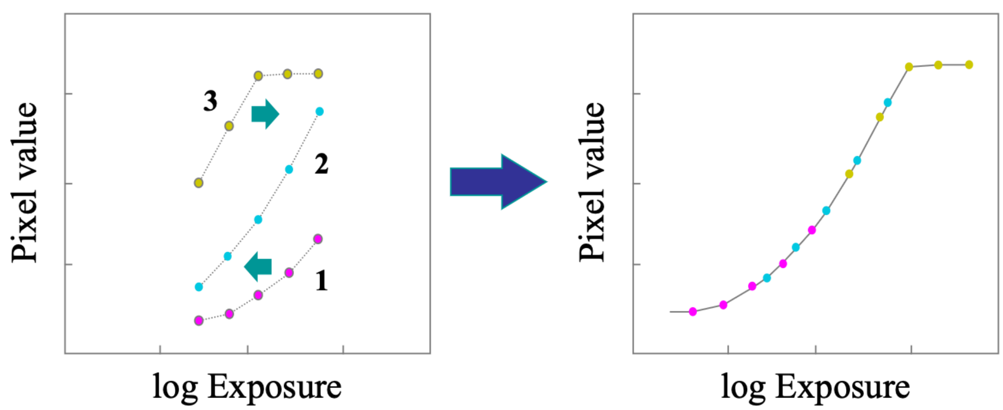

Figure 3: Radiometric Calibration

b. At the step of local tone mapping, why bilateral filter can eliminate halo effect, but gaussian filter cannot? **(5%)**

c. Create your own HDR image. Photograph a bracketing set of exposures for a designed scene and perform the HDR imaging flow. Generate at least three HDR images using differnet tone mapping methodology in the flow. i.e. Run the flow with global tone mapping, local tone mapping with gaussian filter, and local tone mapping with bilateral filter. Provide at least the following information in your report. **(10%)**

i. Your bracketing images and result HDR images
ii. How do you choose the scene?
Note that not every scene needs to perform HDR imaging flow
iii. What are your settings of camera when photographing?
e.g. exposure time, shutter speed, f-stop, …
iv. How do you decide the parameters in the HDR imaging flow?

If you apply any additional steps, also give some description in the report.

2.2 Research Study (30%)

In this part, you should answer the problems by the two-step research flow: **<u>Assumption</u>** and **<u>Justification</u>**. Based on your observation, propose an assumption to the question, and justify your ideas by experiments. The research process may be a loop:
observation -> propose assumption -> justification -> modify assumption -> justification -> ...
After you reach a satisfying result, clearly describe your assumption and how you justify it by experiments in the report. For assumption part, you have to provide the reason to explain why you think so. For justification part, clearly describe how you design the experiment, whether the experiment result match your idea or not, and why the experiment result can justify your ideas. Grading criteria for this part are based on clarity of the report and rigorousness of the justification.

For the first problem in this part, we will provide some guidance to help you understand this problem format. If you have no idea how to start, you can refer to the guidance. It may give you some ideas about the problem. Note that it is not mandatory to follow the guidance. You can do the research and describe it in your way.

a. In the objective function Eq. (1), the author apply a response curve assumption: the **smoothness term** which constrains the curve shape. Propose your idea to explain why this assumption reasonable and what will happen if we ignore the assumption. Then justify your ideas by experiments. **(10%)**
Guidance:
<u>Assumption</u>
During camera response calibration, we will try to minimize the objective function. And in the objective function, the smoothness term contains $g''(z)$. By the definition or the meaning of the second order differential, ... Considering the relation between exposure and pixel value, ...
<u>Justification</u>
Plot and compare the conceptual figure with and without the smoothness term. See if the difference match the assumption.

b. What is the meaning of the scaling factor in global tone mapping Eq. (8) and local tone mapping Eq. (16)? How do different settings of scaling factor affect the transformation and the result HDR image? Propose your assumption and reasons. Then justify your ideas by experiments. **(10%)**

c. At the step of white balance in sec 1.2, we fix the R channel value and modify G, B channel value. Can we fix G or B channel value and modify the other two channels instead? How dose differnet reference channel(fixed channel) affect the result HDR image? Propose your assumption and reasons. Then justify your ideas by experiments. **(10%)**

3 Deliverable

Put required files listed below in folder HW1_{studentID}

1. Your HDR_functions.py in folder /code
2. Your result HDR images of problem 2.1 c in folder /MyHDR_result
3. Your Report with filename {studentID}_report.pdf

Compress your whole folder HW1_{studentID} in HW1_{studentID}.zip and submit to eeclass.

Note that wrong file delivery or arrangement will get 5% punishment.

References

[1] P. E. Debevec and J. Malik, "Recovering high dynamic range radiance maps from photographs," in *ACM SIGGRAPH 2008 classes*, pp. 1–10, ACM, 2008.