Camera Response Function Assessment in Multispectral HDR Imaging

Abstract
Multispectral imaging techniques improve the accuracy of spectral reconstruction as well as color measurement in image-based data capture systems compared to the conventional RGB cameras. On the other hand, high dynamic range imaging provides recording a higher range of scene radiance values when the dynamic range of the camera does not cover values between the minimum and maximum radiance of the scene. In high dynamic range imaging, camera response function plays a crucial role in the irradiance map reconstruction. It could be either absolutely measured by laboratory equipment or relatively estimated through a set of images with different exposure times. In this work, camera response function assessment has been addressed for a filter wheel multispectral camera. Both measurement and estimation methods are investigated through experiments and results are compared to the ground truth data. The results showed high dynamic range imaging with measured absolute camera response function has two benefits: it measures radiance in the same scale and physical units, and outperformed in terms of the precision of reflectance measurement.

Introduction

In BRDF, reflectance is defined as spatially varying BRDF (svBRDF). Although svBRDF reflects a material's appearance, it is an accepted model of such materials. To this aim, bidirectional reflectance distribution function (BRDF) measurement is an essential tool in various industries such as computer vision, graphics, packaging, and print. In metrological and specifically BRDF measurement setups, a set of images with different exposure times are measured by laboratory equipment or relatively estimated through HDRI software. On the other hand, high dynamic range imaging (HDRI) enriches spectral reflectance measurement.

Multispectral HDRI

In general, CRF measurement methods can be divided into two main groups: CRF measurement and CRF estimation. From measurement and estimation methods, CRF could be either absolutely measured by laboratory equipment or relatively estimated through a set of images with different exposure times. In this work, camera response function assessment has been addressed for a filter wheel multispectral camera. Both measurement and estimation methods are investigated through experiments and results are compared to the ground truth data. The results showed high dynamic range imaging with measured absolute camera response function has two benefits: it measures radiance in the same scale and physical units, and outperformed in terms of the precision of reflectance measurement.

Related Works

There are three main elements in the ground truth data. In BRDF, reflectance is defined as spatially varying BRDF (svBRDF). Although svBRDF reflects a material's appearance, it is an accepted model of such materials. To this aim, bidirectional reflectance distribution function (BRDF) measurement is an essential tool in various industries such as computer vision, graphics, packaging, and print. In metrological and specifically BRDF measurement setups, a set of images with different exposure times are measured by laboratory equipment or relatively estimated through HDRI software. On the other hand, high dynamic range imaging (HDRI) enriches spectral reflectance measurement.

In the literature, some works have addressed HDRI for multispectral HDR imaging. Norberg et al. [1] proposed HDRI for spectral filter array and estimated relative CRF. They have evaluated different exposure times from digital counts (camera response function) and therefore considered relative CRFs. In another work, Martinez et al. [2] investigated HDRI with multispectral cameras. Brauers et al. [3] used a method to measure relative CRF and therefore compared to the ground truth data captured by standard equipment. Additionally, Nayar et al. [4] have introduced a system where a filter wheel camera and a filter wheel are used to measure relative CRF. They have evaluated different exposure times and reflectance from HDR multispectral cameras. They have proposed an algorithm to measure absolute CRF. In another work, Brauers et al. [5] have used an integrating sphere to measure relative CRF. They have evaluated different exposure times from digital counts (camera response function) and therefore considered relative CRFs. In another work, Mall et al. [6] have introduced an electronic camera for multispectral HDR imaging. In contrast to their method, their method improved reflectance from HDR multispectral cameras. They have proposed HDRI for spectral filter array and estimated relative CRFs. They have proposed an algorithm to measure absolute CRF. In another work, Guarnera et al. [7] have introduced a system where a filter wheel camera and a filter wheel are used to measure relative CRF. They have evaluated different exposure times and reflectance from HDR multispectral cameras. They have proposed an algorithm to measure absolute CRF. In another work, Mitmeyer et al. [8] have introduced a system where a filter wheel camera and a filter wheel are used to measure relative CRF. They have evaluated different exposure times and reflectance from HDR multispectral cameras. They have proposed an algorithm to measure absolute CRF. In another work, Marti et al. [9] have introduced a system where a filter wheel camera and a filter wheel are used to measure relative CRF. They have evaluated different exposure times and reflectance from HDR multispectral cameras. They have proposed an algorithm to measure absolute CRF. In another work, Brauers et al. [10] have introduced a system where a filter wheel camera and a filter wheel are used to measure relative CRF. They have evaluated different exposure times and reflectance from HDR multispectral cameras. They have proposed an algorithm to measure absolute CRF. In another work, Mitmeyer et al. [11] have introduced a system where a filter wheel camera and a filter wheel are used to measure relative CRF. They have evaluated different exposure times and reflectance from HDR multispectral cameras. They have proposed an algorithm to measure absolute CRF.
The corresponding to the same area software extracted curve and considered as the response function and reference with turned off light source), and the image from very dark to very light. In this work HDRI has been proposed and addressed in a lot of works in the literature. However, HDRI software methods are limited in capturing scenes that contain contents with various amounts of radiances of orders of magnitude while the dynamic range of the camera. Most of the HDRI methods and hardware methods. In this work keen reader is referred to [12].

The camera is able to cover HDRI comprehensively. Relative CRF estimation:

For further details the inverse of camera response function (CRF)

\[ P_{x,\lambda} = \frac{I_{x,\lambda}}{E_{x,\lambda}} = \frac{g_y^{-1}(I_{x,\lambda}-B_{x,\lambda})}{g_y^{-1}(W_{x,\lambda}-D_{x,\lambda})} \]

\[ E_{x,\lambda} = \frac{W_{x,\lambda}}{g_y^{-1}} \]

\[ W_{x,\lambda} = g_y^{-1}(W_{x,\lambda}) \]

Absolude CRF measurement:

\[ E_{x,\lambda}(x, y) = \frac{\sum_{n=1}^{N} \omega(\nu_{x,y}(x, y)) \frac{\partial^2 \rho_{x,y}(x, y)}{\partial y^2}}{\sum_{n=1}^{N} \omega(\nu_{x,y}(x, y))} \]

Methodology
As pixel values closer to the image border have to be renormalized to guarantee the smoothness of the CRF, a weighting function is used in the next stages as results were almost the same for both simple and broad hat functions. In this method, CRF is estimated with 

\[ f = \sum_{i=1}^{N} \sum_{j=1}^{M} \{ g(Z_{ij}) - \ln E_i - \ln \Delta t_j \}^2 + \gamma \sum_{z=Z_{\text{min}}}^{Z_{\text{max}}-1} \{ \omega(z) g''(z) \}^2 \]

where \( Z_{ij} \) is the pixel value in location \( i,j \), \( E_i \) is irradiance in pixel location \( i \), \( \Delta t_j \) is a weighting function, \( g(z) \) is the spectral transmittance of the filter, \( g''(z) \) is the second derivative of the filter transmittance, and \( \omega(z) \) is the weighting function for the spectral sensor responsivity.

**Experiments**

In the measured CRFs, the spectral response of the sensor has been fitted and expanding to the whole digital counts range, are almost the same for both simple and broad hat functions. In Malik method needs a scene with high dynamic range content to be captured. The scenes that are used in this work both simple and broad hat functions are used in the original work, in this manner too much. It has 8 different spectral bands. Six of them are used in this work. The Pixelteq SpectroCam filter wheel multispectral camera is used in this work. The 32 photos each channel is chosen for each filter. Some of them are shown in Figure 6. The mean of the absolute differences between measured/estimated CRF and camera responses after averaging and normalizing is pixel value in location \( i,j \).

**Data capture for CRF estimation using**

A Konika Minolta CS2000 a Colorchecker a 24 patches of which includes 24 filters. The 32 photos each channel is chosen as inputs for this method. The 32 photos each channel is chosen as inputs for this method. The 32 photos each channel is chosen as inputs for this method.

**Debevec and Malik’s method**

Debevec and Malik’s method needs a scene with high dynamic range content to be captured. The scenes that are used in this work both simple and broad hat functions are used in the original work, in this manner too much. It has 8 different spectral bands. Six of them are used in this work. The Pixelteq SpectroCam filter wheel multispectral camera is used in this work. The 32 photos each channel is chosen as inputs for this method. The 32 photos each channel is chosen as inputs for this method. The 32 photos each channel is chosen as inputs for this method.
Radiance map reconstruction and reflectance calculation

A subset of images taken for absolute CRF measurement consists of six exposure times: 1, 5, 10, 50, 100, 500 ms are selected for radiance map reconstruction and reflectance calculation which are reasonable exposures avoiding too much under and overexposures.

The same images are used as input data for both HDRI with relative CRF estimation and absolute CRF measurement methods. The reconstruction error analysis, error between HDRI output and ground truth, has been done using root mean square error (RMSE) metric defined as:

\[ RMSE = \sqrt{\frac{\sum_{k=1}^{N} (P_k - \hat{P}_k)^2}{N}} \]

where \( P_k \) indicates measured radiance or reflectance in the \( k \)th channel, \( N \) represents the number of channels, and \( \hat{P}_k \) is the corresponding ground truth data.

Results and Discussion

Radiance map reconstruction

The radiance maps are reconstructed after CRF measurement and estimation. Since ground truth data is a spot measurement, the same area seen by the TSR are averaged from radiance map images corresponding to 24 patches of \( C_{24} \) and used for data analysis. The spectral radiances, with six spectral channels, calculated from HDR images reconstructed using CRF measurement method are compared to ground truth data. Figure 8 shows the spectral radiance of the first 6 patches, and RMSEs are represented in Figure 9 for all the 24 patches. The average of RMSE is 0.0071 \( W m^{-2} Sr^{-1} \) with a standard deviation of 0.0054. Figure 9 shows that the measurement error for patches with higher luminance is greater than darker patches and the 19th patch with the highest luminance has the largest error value among others. This analysis implies that the performance of HDRI with the CRF measurement method is acceptable with regards to radiance measurement and the outputs are in the same scale and physical units as standard measurement systems while HDRI with estimation method outputs relative radiances, and it does not have meaning to compare its results with the ground truth.
In a further step, the white patch of the C24, patch number 19, is considered as the reference white and reflectances are computed by the ratio of patch radiances to the radiance of this patch. As an example, Figure 10 illustrates reflectance of the first patch measured by two methods as well as TSR. The RMSEs are calculated with two approaches: in the first approach, the spectral reflectances, 6 channels, are obtained for the 24 patches and compared to the ground truth data. Table 1 summarizes the accuracy of reflectance measurement by two methods. The error is reported 0.0185 and 0.0313 as average error and 0.0080 and 0.0130 as standard deviation for CRF measurement and CRF estimation methods respectively, and obviously the measurement outperformed the estimation method as its average error is almost half of the other method.

In the second approach, the RMSE error of each spectral band is analyzed separately to evaluate the efficiency of different methods in reflectance measurement in different spectral channels. Table 1 indicates that as expected, measurement method has a better performance in channel-wise analysis as well since it has half average RMSE of the other method.

Figure 11 presents bar plot of reflectance measurement errors. It is obvious that the HDRI with measured absolute CRF has outperformed the other method in all the spectral channels and all the C24 patches. In Figure 11-(a), the error for patch number 19 equals to zero because it had been used as the reference white in the experiment. Figure 12 represents the errors in boxplot to provide a better visualization of the distribution of reflectance measurement errors.

Conclusions and Future Works

In this paper, the evaluation of multispectral HDRI is addressed with regard to different CRF assessment methods. Two different methods of CRF assessment have been implemented: in the first method absolute CRF is measured by means of reflective color charts and in the second method relative CRF is estimated through a well-known estimation method. HDRI is exploited to construct radiance map utilizing both CRFs and results are evaluated by comparing to the TSR measurements as ground truth. Radiances measured by camera using HDRI and measured absolute CRF matches with ground truth, but a significant mismatch is reported for HDRI using estimated relative CRF due to its relative behavior. However, reflectances are also calculated and results showed the reflectance measurement accuracy outperformed by the absolute CRF measurement method. This work is relevant since precision of HDRI is crucial in metrological measurements such as svBRDF devices. Although specularities in material are of higher dynamic range than the tested scene but there is little risk that the conclusion would differ. In addition, this comparison helps industries to opt a proper method between CRF estimation and cumbersome measurement methods in their products.

As for directions for further work, experiments with larger data capture, and including spectral reconstruction are suggested. Using HDR scenes in the final evaluation and cameras with different filter transmittances would show the importance of this investigation better than LDR scenes.
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References


Figure 1: The distribution of RMSE reflectance errors.