Robust and convenient characterization for a multispectral imaging system

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Abstract: Multispectral imaging has been widely used for high-fidelity color reproduction. For accurate color reproduction, a robust characterization process is essential. In this paper, we present a robust and convenient characterization method for a multispectral imaging system using the irradiance of the illuminant. We measure the irradiance of the illuminant instead of the reference of the color chart, thereby reduces tedious measuring tasks. Furthermore, our method can obtain the spectral reflectance of a scene, which enables realistic relighting and image composition under different illumination conditions. The experiment results demonstrate that our method outperforms the previous method by giving smaller errors in terms of the estimated spectral reflectance, and showing more realistic image composition.

Keywords: multispectral imaging, characterization, spectral reflectance

Classification: Science and engineering for electronics

References

1 Introduction

Multispectral imaging refers to an advanced imaging technique that captures several images of the same scene using different spectral bands which usually is greater than 3. Since multispectral imaging allows a better color reproduction and relighting under various illumination conditions than by the conventional RGB-based images, many researchers have worked on this topic [1, 2, 3, 4].

For accurate color reproduction, a robust characterization process is essential. In most color device characterization methods, which are based on a RGB color system, the transformation model is determined between the known reference color of a color chart in the CIEXYZ color space and the captured color of the chart under the same illumination environment [5]. The reference XYZ color is provided by the chart manufacturer that uses the standard illumination condition or can be acquired by capturing the chart using the spectroradiometer. The multispectral imaging system can also be characterized by using a spectroradiometer. Hardeberg et. al [3] characterized a multispectral imaging system using a principal eigenvector method. They measured the spectral properties of the chart by using the spectroradiometer under their illumination environment.

Although previous approaches that use a spectroradiometer to measure the reference of a color chart have achieved high-accuracy to characterize a system, they are usually tedious since the spectroradiometer can measure only a very small region, one pixel at a time, and the reference of the chart must be measured every time the illumination condition is changed.

In this paper, we present a robust and convenient characterization method

![Fig. 1. Overall procedure of the proposed method](image-url)
for a multispectral imaging system using the irradiance of an illuminant. Fig. 1 illustrates the overall procedure of the proposed method. We first measure the irradiance of the illuminant to calculate the reference of the chart. Then, we construct the transformation matrix between the reference and the image captured by our multispectral imaging device. Since capturing the irradiance is much more convenient than using a spectroradiometer, our method can reduce tedious measuring tasks. After the transformation matrix $M$ is obtained, we can reproduce high-accuracy multispectral properties by applying $M$ to a raw image. The proposed method can also identify the spectral reflectance of an object by removing the illuminant effects. Using this information, a realistic relighting and composition are possible. Finally, the color matching function is applied to show the results on the display.

2 The proposed spectral response model

2.1 The camera response model

In the colorimetry, a pixel of the camera output can be modeled as:

$$ p_k = \int s(\lambda)r(\lambda)c_k(\lambda)d\lambda, \quad (1) $$

where $s(\lambda)$ is the spectral reflectance of the object at the pixel position, $r(\lambda)$ is the spectral power distribution of the illuminant and $c_k(\lambda)$ is the spectral response of the camera with $k^{th}$ filter. Eq. (1) is valid under the assumption that the spectral radiant exitant of the illuminant is the same as the irradiance at the object position.

For conventional characterization based on Eq. (1), the spectroradiometer should be placed at the camera position to measure all patches of the chart for the reference.

The standard illumination, such as D65 or D50, can also be used to calculate the reference without measuring by the spectroradiometer. However, the illumination environment should be well constructed to ensure the closeness between the radiant exitance of the illuminant and the irradiance at the object. This condition makes the characterization difficult and unpractical. In addition, the transformation model from the above reference is valid only under the same circumstance.

To overcome these limitations, we modify the response model of a pixel as below:

$$ p_k = \int s(\lambda)l(\lambda)c_k(\lambda)d\lambda, \quad (2) $$

where $l(\lambda)$ is the irradiance of the illuminant at the pixel position.

Eq. (2) can be rewritten as a discrete form,

$$ P_k = \sum_\lambda s^\lambda l^\lambda c_k^\lambda. \quad (3) $$

The spectral reference of the chart is,

$$ ref^\lambda = s^\lambda l^\lambda. \quad (4) $$
The irradiance, $l^\lambda$, can be obtained by i1 color management solution (hereafter i1) from X-Rite [6]. By using the irradiance instead of the radiant exitance, accurate reference can be acquired conveniently.

### 2.2 The transformation model

We can represent a pixel using a product in matrix notation,

$$ P = A \cdot B, \quad (5) $$

where $P$ is a pixel from $K$ channel multispectral images, expressed as $P = [p_1 p_2 \cdots p_K]^T$. $B$ is a scalar product of the spectral reflectance of the object (chart) and the spectral irradiance of the illuminant, $B = [b^\lambda_{\text{min}} \cdots b^\lambda_{\text{max}}]^T$, $b^\lambda = s^\lambda \cdot l^\lambda$. $A$ is an unknown value which contains the characteristic of the camera and the color filters, $A = [a_1 a_2 \cdots a_K]^T$, $a_k = [l_k^\lambda_{\text{min}} \cdots l_k^\lambda_{\text{max}}]$.

We measure 33 filter images at 10 nm interval in the range of 400 nm to 720 nm. Therefore, in order to robustly estimate the matrix $A$ that contains 33 unknowns for each filter, at least more than 33 different color patches are necessary.

On the other hand, since each transmittance of our band pass filter follows a Gaussian distribution-like shape, a certain band of spectrum is only affected by a few neighboring bands. Therefore, we only take ± 20 nm spectrums into account and modify the transformation model by using a polynomial regression as follows:

$$ b^{390+k\times 10} = \alpha_{k,0} + \alpha_{k,1}p_{k-2} + \alpha_{k,2}p_{k-1} + \alpha_{k,3}p_k + \alpha_{k,4}p_{k+1} + \alpha_{k,5}p_{k+2} \quad (6) $$

As a result, there are only 6 unknown parameters ($\alpha_{k,0} \sim \alpha_{k,5}$) to estimate one element of $B$ in our method. Accordingly, we can use the ColorChecker from GretagMacbeth that contains only 24 color patches. Eq. (6) is valid for LCTF with narrow band pass filters.

### 2.3 Estimation of the spectral reflectance of the object

After applying the coefficient of the regression model to each pixel, the estimated spectral property of both the object and the illuminant is represented as $\tilde{B}$, $\tilde{B} = [\tilde{b}^\lambda_{\text{min}} \cdots \tilde{b}^\lambda_{\text{max}}]^T$. Since we know the irradiance of the illuminant, the spectral reflectance of the object can be acquired by dividing the estimated $B$ by $l^\lambda$. The estimated spectral reflectance of the object, $\tilde{s}^\lambda$, is represented as:

$$ \tilde{s}^\lambda = \tilde{b}^\lambda \cdot \frac{1}{l^\lambda} \quad (7) $$

### 3 Experimental results

We built a multispectral system by combining a 12-bit black and white (BW) CCD camera and a liquid crystal tunable filters (LCTF). We examined our characterization method under several illumination conditions including D65, D50, A, CWF, and TL84. We measured the irradiance of each illuminant.
Fig. 2. The accuracy of the proposed characterization method. (a) the characterization result with ΔE.
(b) the accuracy of the estimated spectral reflectance by using the spectrophotometer. To identify the influence of the orientation and position of the spectrophotometer, we measured the irradiance at various orientations and positions. As a result, we conclude that orientation or position of spectrophotometer does not affect our characterization result since the measured irradiance at each orientation and position is almost same. We measured it at 25 different positions and orientations and their standard deviations are very small (0 ~ 0.09).

We divided the patches into training and test sets for more reliable evaluation. We tied 5 columns in the training set, and used 4th column as the test set. We calculated the model based on Eq. (6) by using the training set, and then applied the estimated model to the test set.

Fig. 2 (a) shows the result of our characterization method by applying the CIE color matching function to the estimated spectral properties for display. The synthesized chart image under each illumination is also shown with the characterization result. The first row shows the characterized multispectral images. The second row shows the reference chart which applied the CIE color matching function to the display under different illumination. ΔE is the color difference between the characterized chart image and the reference. ΔE_{training} and ΔE_{test} are the color difference for the training and test sets, respectively. The numerical difference between ΔE_{training} and ΔE_{test}
is 0.02 ~ 0.06, which means the model works well. The last row shows the synthesized images under different illuminations by the estimated spectral reflectance from the chart image using D65. Fig. 2 (b) shows the estimated spectral reflectance and the ground truth data measured by i1 for each patch of the chart. It gives the average RMS (root mean square) error of 0.0068 for the test set, which is very small.

Since we can identify the spectral information of a scene, a realistic image composition is possible. Current research activities on a digital matting and composition focus on how to extract accurate foreground information from an image [7]. However, if the illumination conditions between an original image and a new background are very different, the resulting composite image becomes unnatural regardless of the accuracy of the foreground information. As shown in Fig. 3, when a foreground object of an original image taken under reddish illumination needs to be pasted into a new background that is taken under the D65 standard illumination, the reddish effect must be removed for realistic composition. Our method can remove this effect and generate a realistic composite image as demonstrated in the figure.

4 Conclusion

We propose a robust and convenient characterization method for a multispectral imaging system that uses a camera and the narrow band pass filters. Our method requires the irradiance of an illuminant rather than setting a standard illuminant or using a spectroradiometer to capture the reference data of the color chart. Our transformation model works well under a variety of illumination, which gives the color difference range of 1.2~3.7. The average RMS of the estimated spectral reflectance under D65 illumination is less than 0.01. We demonstrated that our method can easily characterize the multispectral imaging system while maintaining high-accuracy. In addition, the proposed method can estimate the spectral reflectance of an object, by which a realistic image composition is possible.
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