OPTIMAL SPECTRAL SENSITIVITY FUNCTIONS FOR A SINGLE-CAMERA ONE-SHOT MULTISPECTRAL IMAGING SYSTEM

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ABSTRACT

Multispectral imaging is highly demanded for precise color reproduction and for various computer vision applications. Recently, a single-camera one-shot multispectral imaging (SCOS) system that uses a single image sensor equipped with a multispectral filter array (MSFA) has been proposed. In this paper, we develop optimal spectral sensitivity functions (SSFs) for the SCOS system, in which multispectral image quality depends strongly on the performance of multispectral demosaicking. First, we propose a simple optimization algorithm that can incorporate a high-performance multispectral demosaicking algorithm. Then, we experimentally demonstrate that the optimized SSFs by our proposed algorithm improve the performance of spectral reflectance estimation and the accuracy of color reproduction.

Index Terms— Multispectral demosaicking, multispectral filter array (MSFA), multispectral imaging, spectral sensitivity functions (SSFs)

1. INTRODUCTION

Multispectral imaging is highly demanded for precise color reproduction and for various computer vision applications. In multispectral imaging, more than three-band color images associated with spectral sensitivity functions (SSFs) are acquired. We need to optimize the SSFs to maximize the advantages of multispectral imaging. For example, the performance of spectral reflectance estimation and the accuracy of color reproduction depend strongly on the SSFs. Many studies of optimal SSFs for a three-band color imaging system or for a multispectral imaging system have been reported [1–4], assuming that the imaging systems can acquire all color components at every pixel location.

Recently, a single-camera one-shot multispectral imaging (SCOS) system that uses a single image sensor equipped with a multispectral filter array (MSFA) has been proposed as a practical system [5–8]. In the SCOS system, only one color component is acquired at each pixel location. A full multispectral image is reconstructed using an interpolation process called multispectral demosaicking. The quality of the reconstructed multispectral image depends strongly on the performance of multispectral demosaicking. Therefore, we need to involve a high-performance multispectral demosaicking algorithm to optimize the SSFs for the SCOS system. However, very few studies have examined optimal SSFs involving a demosaicking algorithm. Parmar and Reeves have developed optimal SSFs for three-band color filter arrays using Wiener estimation for the demosaicking algorithm [9]. Although Wiener estimation is easy to analyze, it is known to yield lower-quality images than a state-of-the-art demosaicking algorithm.

In this paper, we develop optimal SSFs for the SCOS system. We first propose a simple optimization algorithm that emulates the entire SCOS system including the high-performance multispectral demosaicking algorithm. Then, we parameterize the SSFs by Gaussian functions and optimize the parameters by minimizing the difference between the estimated spectral reflectance by the emulated SCOS system and ground-truth spectral reflectance. We experimentally demonstrate that the optimized SSFs by our proposed algorithm improve the performance of spectral reflectance estimation and the accuracy of color reproduction.

2. SINGLE-CAMERA ONE-SHOT MULTISPECTRAL IMAGING SYSTEM

Fig. 1 presents a schematic block diagram of spectral reflectance estimation using the SCOS system. First, light emitted by illumination and reflected by a scene or an object is captured by a single image sensor equipped with a MSFA. More than three color filters associated with SSFs are arrayed in the MSFA; only one color component is acquired at each pixel location. Then, a full multispectral image is reconstructed from the acquired color components by multispectral demosaicking. Finally, the spectral reflectance of the captured scene or object is estimated at each pixel location.

The spectral reflectance estimated by the SCOS system is affected by five factors: the illumination, MSFA, SSFs, multispectral demosaicking algorithm, and spectral reflectance estimation algorithm. In this paper, we optimize the SSFs, while the other four factors are fixed. The quality of the acquired multispectral image and therefore the accuracy of the estimated spectral reflectance depend strongly on the performance of multispectral demosaicking. Therefore, we should incorporate a high-performance multispectral demosaicking

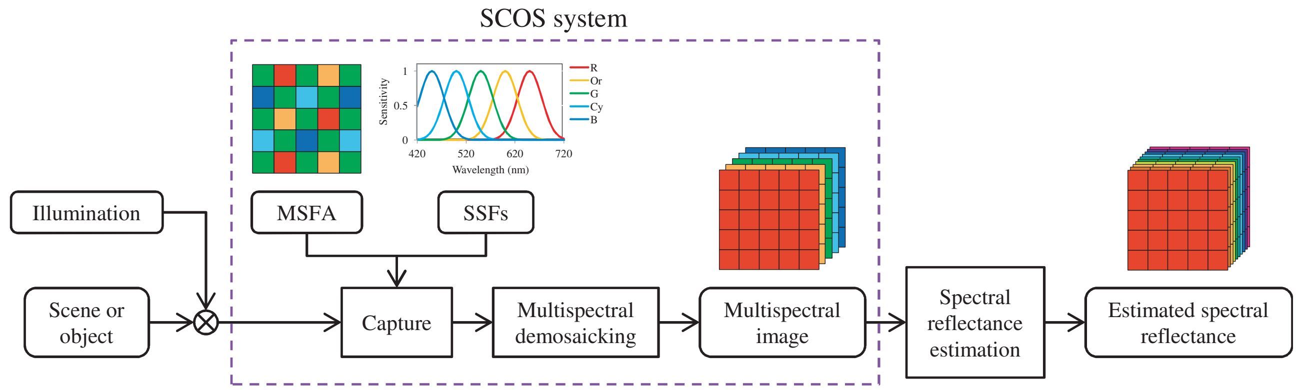


Fig. 1. The schematic block diagram of spectral reflectance estimation using the SCOS system.

algorithm to optimize the SSFs for the SCOS system.

3. PROPOSED OPTIMIZATION ALGORITHM

The goal of this study is to develop optimal SSFs that minimize the difference between the estimated spectral reflectance by the SCOS system and ground-truth spectral reflectance. In this paper, we discuss the SSFs for the five-band MSFA proposed in [7], as shown in Fig. 1. We refer to respective color filters as R, Or, G, Cy, and B filter from the long-wavelength end to the short-wavelength end. To reconstruct a full multispectral image, we apply the multispectral demosaicking algorithm using the guided filter (GF demosaicking) [8]. Although GF demosaicking is a non-invertible nonlinear algorithm, GF demosaicking can offer state-of-the-art performance. For spectral reflectance estimation, we use the model-based algorithm [10].

Fig. 2 shows our proposed optimization algorithm. The estimated spectral reflectance by the SCOS system can be regarded as a nonlinear function of illumination, input ground-truth spectral reflectance (31-band multispectral images), and assumed SSFs. In our proposed optimization algorithm, we find the optimal SSFs by minimizing the following cost function:

$$E(\boldsymbol{\theta}) = \sum_{k}^{N_L} \sum_{j}^{N_r} \sum_{i}^{N_j} \left|\left| \mathbf{r}_i^j - f\left(\mathbf{L}^k, \mathbf{r}_i^j, \mathbf{C}\left(\boldsymbol{\theta}\right)\right) \right|\right|_2^2, \qquad (1)$$

where $\mathbf{C}$ represents the SSFs, $\boldsymbol{\theta}$ is the parameter for the SSFs, $\mathbf{r}_i^j$ stands for the vector representation of the ground-truth spectral reflectance at the i-th pixel location of the j-th image, $\mathbf{L}^k$ represents the k-th illumination, f is the nonlinear function which represents the spectral reflectance estimation using the SCOS system, N_j is the number of pixels of the j-th image, N_r is the number of images to be used, and N_L is the number of illuminations to be evaluated.

Since GF demosaicking is a non-invertible nonlinear algorithm, we can not analytically solve the optimization problem. To solve the optimization problem, we parameterize the

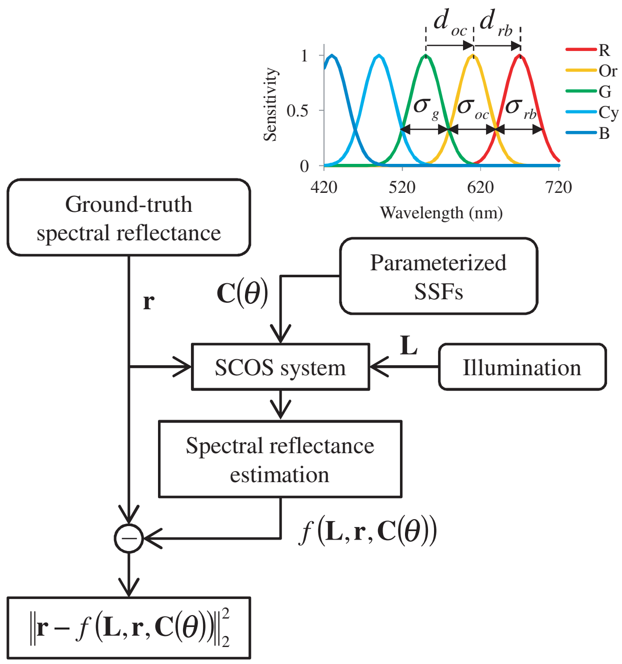
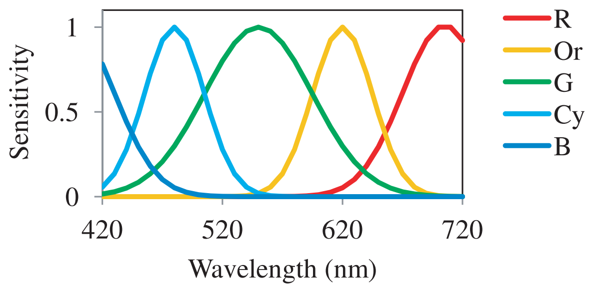


Fig. 2. Our proposed optimization algorithm.

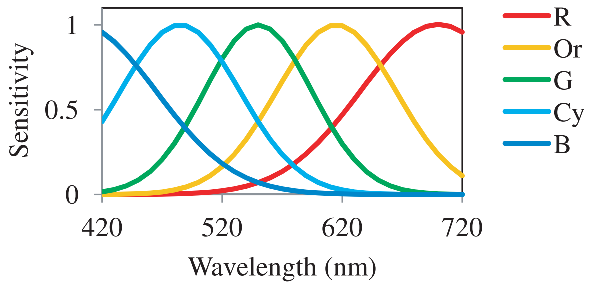
SSFs by Gaussian functions using the same method as that described in an earlier report [3]. Then, we find the optimal parameters that minimize Eq. (1) using a brute-force search. In the parameterization, we assume symmetric SSFs to reduce the number of parameters for the SSFs. First, we fix the peak wavelength of the G-filter to 550 [nm]. Then, we optimize the other five parameters as shown in Fig. 2: the standard deviation of the G-filter σ_g, that of the Or and Cy-filter σ_{oc}, that of the R and B-filter σ_{rb}, the distance between the peak wavelength of the G-filter and that of the Or and Cy-filter d_{oc}, and the distance between that of the Or and Cy-filter and that of the R and B-filter d_{rb}.

4. EXPERIMENTS

We captured 31-band multispectral images of 32 scenes using a monochrome camera with a liquid crystal tunable filter,



(a) Proposed SSFs.



(b) Optimized SSFs without multispectral demosaicking.

Fig. 3. Optimized SSFs. (a) the proposed SSFs for the SCOS system optimized using our proposed optimization algorithm. (b) the optimized SSFs without multispectral demosaicking.

Table 1. Parameters for SSFs.

SSFs	σ_g	σ_{oc}	σ_{rb}	d_{oc}	d_{rb}
Non-optimized	40	35	30	40	40
Optimized without dem.	45	50	65	65	85
Proposed	45	25	35	70	85

Varispec [11]. The 31-band multispectral images are obtained at every 10 [nm] from 420 [nm] to 720 [nm]. We used 16 scenes as ground-truth spectral reflectance for the optimization. To simplify the optimization problem, we assume only white illumination and noise-free data. We search the optimal SSFs changing each parameter at intervals of 5 from 10 to 80.

Fig. 3 (a) shows the proposed SSFs for the SCOS system optimized using our proposed optimization algorithm, whereas Fig. 3 (b) shows the optimized SSFs without multispectral demosaicking, i.e., assuming all color components are acquired at every pixel location. To demonstrate the effect of the optimization of the SSFs including multispectral demosaicking for the SCOS system, we compare the proposed SSFs with the non-optimized SSFs used in [7, 8] and the optimized SSFs without multispectral demosaicking. The parameters for the three SSFs are presented in Table 1.

First, we evaluate the performance of spectral reflectance estimation. For all 31-band multispectral images, the spectral reflectance is estimated using the SCOS system with the above three SSFs. The optimized SSFs without multispectral demosaicking are optimized neglecting multispectral demosaicking, which is required for spectral reflectance estimation using the SCOS system. We calculate the PSNR between the estimated spectral reflectance and the ground-truth spectral reflectance. Fig. 4 plots the average PSNR of all 32 scenes for each band, while Table 2 shows the average PSNR of all 31-band images. The two optimized SSFs significantly improve the performance of spectral reflectance estimation in 420-450 [nm] and 660-720 [nm]. As a consequence, the two optimized SSFs improve the total performance of spectral reflectance estimation. Furthermore, the proposed SSFs yield better performance than the optimized SSFs without multispectral demosaicking. Fig. 5 shows the estimated reflectance images of Wool at 700 [nm] wavelength. Fig. 5 (a) shows the ground-truth reflectance image. Fig. 5 (b), (c), and (d) respectively show the estimated reflectance images by the SCOS system with the non-optimized SSFs, the optimized SSFs without multispectral demosaicking, and the proposed SSFs. As shown in Fig. 5, the proposed SSFs can significantly reduce the artifacts on the yellow cloth. These quantitative and visual comparisons demonstrate that the proposed SSFs improve the performance of spectral reflectance estimation.

Next, we visually evaluate the accuracy of color reproduction in the sRGB domain. The estimated spectral reflectance by the SCOS system and the ground-truth spectral reflectance are converted to sRGB images. Fig. 6 shows the converted sRGB images of Cloth. Fig. 6 (a) shows the ground-truth sRGB image. Fig. 6 (b), (c), and (d) respectively show the estimated sRGB images by the SCOS system with the non-optimized SSFs, the optimized SSFs without multispectral demosaicking, and the proposed SSFs. As shown in Fig. 6, the sRGB image estimated using the

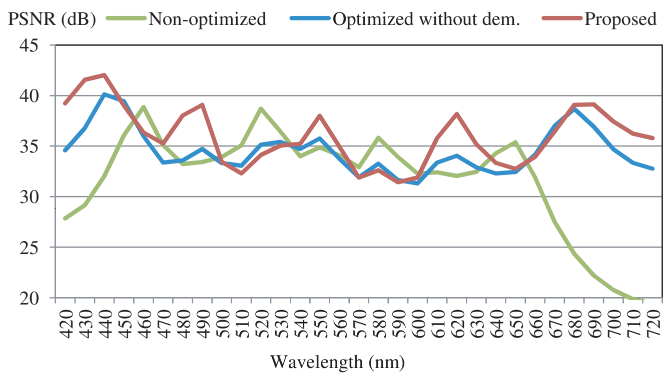
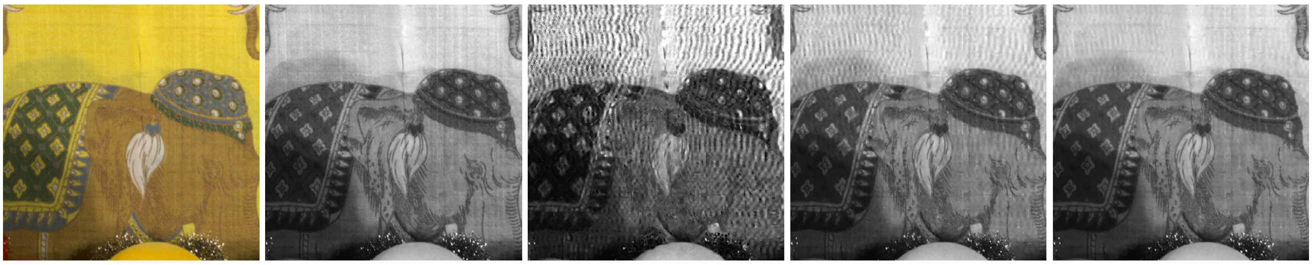


Fig. 4. The average PSNR of all 32 scenes for each band.

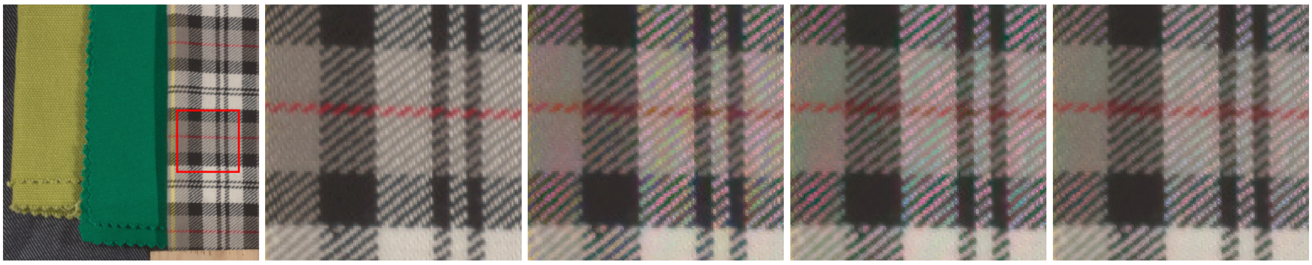
Table 2. The average PSNR of all 31-band for Wool and Cloth images and for average of all 32 scenes.

SSFs	Wool	Cloth	Average of 32 scenes
Non-optimized	29.46	31.46	31.63
Optimized without dem.	32.77	34.63	34.53
Proposed	**35.54**	**36.33**	**35.96**



Wool (a) Ground truth (b) Non-optimized (c) Optimized without dem. (d) Proposed

Fig. 5. Visual comparison of reflectance images at 700 [nm] wavelength. (a) the ground truth, (b) the estimated image using the non-optimized SSFs, (c) the estimated image using the optimized SSFs without multispectral demosaicking, and (d) the estimated image using the proposed SSFs.



Cloth (a) Ground truth (b) Non-optimized (c) Optimized without dem. (d) Proposed

Fig. 6. Visual comparison of sRGB images. (a) the ground truth, (b) the estimated image using the non-optimized SSFs, (c) the estimated image using the optimized SSFs without multispectral demosaicking, and (d) the estimated image using the proposed SSFs.

proposed SSFs can reduce the color artifacts on the diagonal edges. This visual comparison demonstrate that the proposed SSFs improve the accuracy of color reproduction in the sRGB domain. More results can be found at http://www.ok.ctrl.titech.ac.jp/res/MSI/SSF.html.

5. CONCLUSION

In this paper, we developed optimal SSFs for the SCOS system. First, we propose a simple optimization algorithm that can incorporate a high-performance multispectral demosaicking algorithm. Then, we parameterize SSFs by Gaussian functions and optimize the parameters. Experimental results demonstrate that the SSFs optimized using our proposed algorithm improve the performance of spectral reflectance estimation and the accuracy of color reproduction in the sRGB domain.

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