Development of a Dynamic Relighting System for Moving Planar Objects with Unknown Reflectance

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Abstract. Relighting is a technique to modify an image to account for alternate illumination conditions. Conventionally, the reflectance characteristics of an object are provided, and a relighted image is calculated using input light source information. In this paper, we propose a dynamic relighting system for moving planar objects with unknown reflectance. By acquiring the surface spectral reflectance of moving objects, our system is able to reproduce accurate colors on a display device. In the reflectance acquisition, we use a programmable light source that can produce any spectral curve. The surface spectral reflectance of an object in a darkroom is obtained based on the lighting technique with five spectral basis functions that are generated by the programmable light source. The acquired reflectance and user-input illumination information are used to calculate accurate CIEXYZ values of the relighted image. Finally, CIEXYZ values are accurately transformed to RGB values. In the experiment, illuminant A and D65 are used as the illuminants for relighting. As a result, by comparing a computer simulation with actual experiments with real objects, we observe an average color difference ΔE^{*}_{ab} of approximately 7. This system operates at a rate of 1 frame per second. In addition, in this study, we have implemented another relighting system for objects under an environmental lighting condition by determining the spectral power distribution of the illumination source.

Keywords: Relighting · Spectral reflectance estimation · Color reproduction · Dynamic system · Illuminant estimation

1 Introduction

In general, when looking at an object, brightness and color in human perception depend on the type of the light source. Relighting is a technique to change the illumination environment within an image. Relighting is used in industrial product design to simulate the appearance of objects under a variety of light sources.

In previous studies, relighting has been implemented by various approaches. Zhen et al. [1] proposed a relighting method for human faces by changing the coefficients of the spherical harmonic function of the radiance environment map. This approach is based on the acquisition of three-dimensional model of a human face using a morphing model. Then the human face was relighted using this three-dimensional shape. The light source environments were approximated by a spherical harmonic function as a basis function. They performed this process in real time by only estimating the

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diffuse reflection. Debevec et al. [2] acquired a large number of shading images by using a lighting device called Light Stage. They were able to realize relighting under any illumination condition. However, these conventional methods perform poorly with RGB signals, as there is a limitation in the color reproduction accuracy. Accurate color reproduction is extremely important in relighting technology. In this regard, spectral imaging may perform better. Manakov et al. [3] have proposed a relighting technique that uses a multiband camera for obtaining spectral information. Park et al. [4] proposed a relighting technique by obtaining surface spectral reflectance of target objects from multispectral illumination with various types of LEDs. However, these relighting techniques using spectral information require a significant amount of time to acquire spectral reflectance of object surfaces. Then, the relighted objects are processed offline. Real-time relighting based on spectral information has not yet been established.

In this study, a dynamic relighting system is proposed for moving planar objects with unknown reflectance. We develop a high-speed spectral reflectance acquisition technique based on spectral basis lighting. In the proposed system, we assume that the target object is flat, and that the input illumination for relighting is a collimated light source. Under these conditions, our system can dynamically relight objects. In order to display an accurate color image, the tristimulus CIEXYZ values are calculated using the acquired surface spectral reflectance and the input illuminant spectrum. Finally, we display an RGB image sequence that has been properly transformed from the CIEXYZ values.

2 Proposed System

2.1 System Configuration and Processing Flowchart

In this study, we use a high-speed spectroscopic imaging system [5]. Figure 1 shows the configuration of the proposed system. The system is configured with a programmable light source device (Optronic Laboratories OL490), high-speed CMOS monochrome camera (EPIX SV642M), and a control computer. The advantage of this programmable light source is the ability to acquire a spectral image in real time by synchronizing with the frame rate of the camera. This source can be switched faster than the LCD-based light source. We also use a high-speed monochrome CMOS camera SV643M (resolution: 640 × 476 pixel, quantization bits: 10bit, frame rate: 200fps). The display used in the present study is EIZO ColorEdge (CG 221). The color gamut of the display is Adobe RGB. The CPU has an Intel Core i5-3470 3.2GHz and 3.48GB of RAM.

Figure 2 shows our processing flowchart. The sequence is:

1: Irradiate the object with the spectral basis illumination to acquire the corresponding pixel values of the target objects.

2: Calculate the spectral reflectance from the pixel values (See details in Section 2.2). In order to reduce the calculation time, we calculate the reflectance in 31-dimensional wavelengths in 10 nm intervals over the visible wavelength range from 400 nm to 700 nm.

3: Load the light source information. The light source for relighting is determined by the user in advance.
4: Calculate the tristimulus values (CIE XYZ) using the loaded light source information, the recovered spectral reflectance of objects, and the color matching functions. In our dynamic process, we can change the relighting conditions by reloading a variety of light sources. (See Section 2.3)
5: Convert CIE XYZ to RGB values. We properly reproduce a relighted RGB image on the display. (See also Section 2.3)

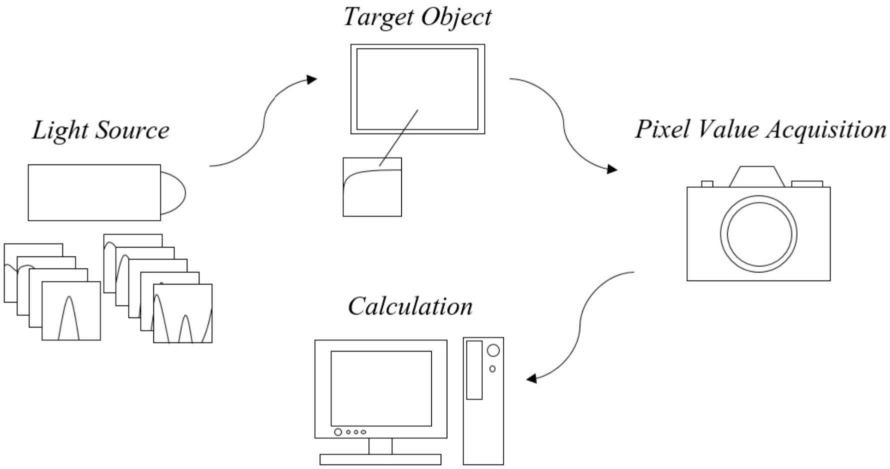

Fig. 1. Configuration of the proposed system

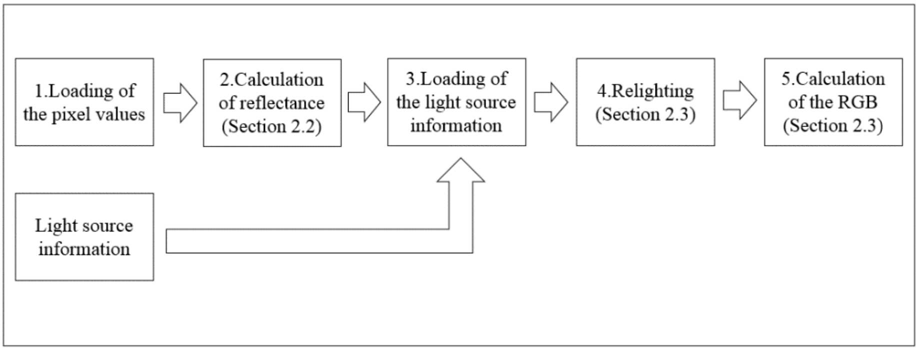

Fig. 2. Algorithm of the proposed system

2.2 Reflectance Estimation Method

The reflectance estimation used in this study is described in [6]. We use an orthogonal basis $\psi_m(\lambda)$ to represent the surface spectral reflectance. The surface spectral reflectance $S(\lambda)$ can be expressed as

$$S(\lambda) = \sum_{m=1}^{M} w_m \psi_m(\lambda) \qquad (m = 1,2,\ldots,M) \tag{1}$$

where M is the number of principal components of the orthogonal basis, w_m are the weights of the basis and λ indicates the wavelength. In this study, we selected five spectral basis functions, i.e., $M = 5$. The basis functions were computed from a spectral reflectance database with 507 samples. Figure 3 shows the five orthogonal basis functions. We were unable to irradiate with the light source that is calculated from Eq. (1), because the orthogonal basis can include negative values. In this study, we irradiated with an orthogonal basis light source divided into positive and negative functions. We estimate the spectral reflectance using acquired values:

$$\psi_m(\lambda) = \psi_m^+(\lambda) - \psi_m^-(\lambda), \tag{2}$$

$$w_m = O^+(t_m) - O^-(t_m) \tag{3}$$

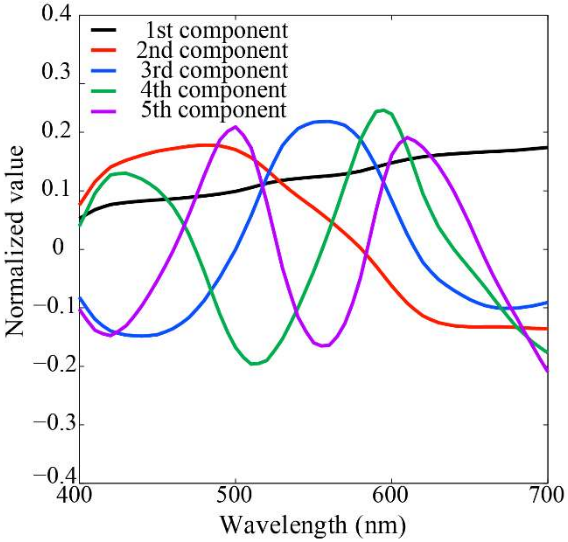

Fig. 3. Orthogonal basis used in our experiment

We divided the orthogonal basis into positive and negative elements from Eq. (2). We determined the camera output $O^+(t_m), O^-(t_m)$ by irradiating with an illumination light source calculated from Eq. (1). We estimated the surface spectral reflectance by substituting Eq. (3) into Eq. (1). Using this method, the dynamic range of the base is retained, without the need to generate a flat offset value. Figure 4 shows the illumination designed in this study. The figure shows the waveforms of nine orthogonal bases with the negative values inverted and which are divided by the spectral sensitivity of the camera $R(\lambda)$. The solid lines are the waveforms that are divided by the spectral sensitivity $R(\lambda)$ of the camera in the positive original orthogonal basis; a dashed lines are the waveforms that are divided by spectral sensitivity $R(\lambda)$ of the camera to reverse the negative component. The second to fifth main components require illumination of two sources each, in order to design the illumination light source from a total of nine waveforms.

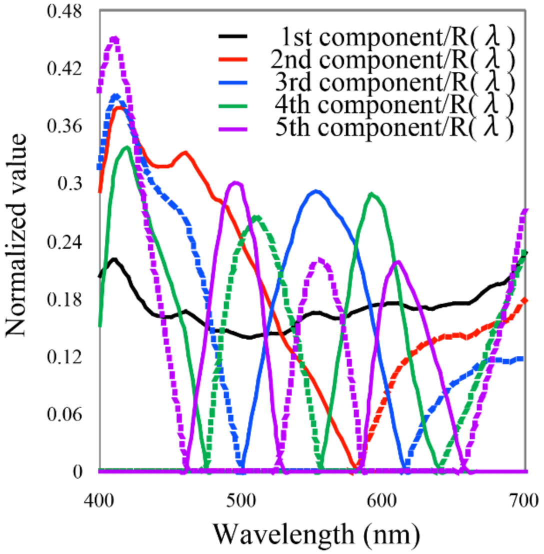

Fig. 4. Waveforms divided by the camera sensitivity are decomposed into positive and negative orthogonal basis (Solid line: Waveforms obtained by dividing the camera sensitivity are the positive values of the principal component. Dashed line: Waveforms divided by the camera sensitivity are the inverted negative values of the main component.)

2.3 Principle of Relighting

In general, the tristimulus values (CIE XYZ) at a certain point on the object surface are obtained by Eq. (4).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \int S(\lambda) E_T(\lambda) \begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} d\lambda \tag{4}$$

Where $S(\lambda)$ is the acquired surface spectral reflectance of the object described in the previous section, $E_T(\lambda)$ is the spectral power distribution of the light source for relighting as input by the user, and $(\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda))$ is the color-matching function. We calculate CIE XYZ from Eq. (1) and the estimated reflectance. We then converted to RGB from the CIE XYZ values. After that, we displayed the image on the monitor. By setting the light source information $E_T(\lambda)$ appropriately in Eq. (1), the image is relighted. The relighting is performed assuming the two-dimensional, light source used is collimated.

We compute the monitor RGB by substituting CIE XYZ into Eq. (5). $\mathbf{M}_{3x3}$ is the matrix used to convert RGB from CIE XYZ in this display. We also used a correcting LUP (Look Up Table) for the RGB values.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M}_{3\times 3} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{5}$$

3 Experiments

3.1 Experimental Setup

To verify the accuracy of the proposed system, an X-Rite Mini ColorChecker was used as a target object for relighting under the illuminant D65 and illuminant A. The object was moved to the left and right at a constant speed of 20 mm/sec by a stepping motor (Sigma Koki TSDM60-20). Figure 5 shows the experimental setup. The system is configured with a programmable light source, a high-speed CMOS monochrome camera, and a calibrated monitor.

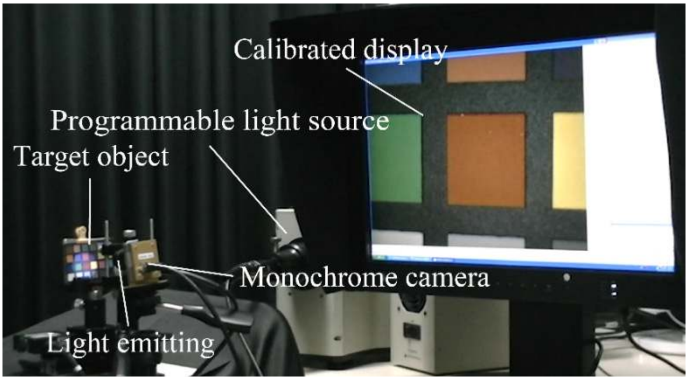

Fig. 5. Relighting system

3.2 Relighting Accuracy

In order to verify the accuracy of the relighting system, an X-Rite Mini ColorChecker was compared by setting the illuminant D65 illuminant A and re-lighting. We show the results in Fig.6. The system can process the data dynamically, and display a moving object with relighting on the calibrated monitor. Figure 7 shows the results for a moving object.

The results of the measurement are summarized in Table 1 showing CIE 1976 ΔE^{*}_{ab} color differences with respect to the 24 colors of the ColorChecker. The average color difference is 7.17 for illuminant A and 6.55 for illuminant D65, respectively. Table 2 shows CIE 1976 ΔE^{*}_{ab} color difference of spectral reflectance estimation with respect to the 24 colors of the ColorChecker and color reproduction error of the display. The accuracy of this study is due to the errors on reflectance estimation (Section 2.2) and color reproduction of the display (Section 2.3). In this study, the spectral reflectance with respect to moving object is estimated with an average color difference of about 5.36. In Ref. [6], the spectral reflectance with respect to a stationary object is estimated with an average color difference of about 2.5. The accuracy of our experiment is lower than Ref. [6], probably due to noise and variations in the lighting. The color reproduction error of the display is a 2.1. Total speed of the proposed system was 1 fps (frame per second).

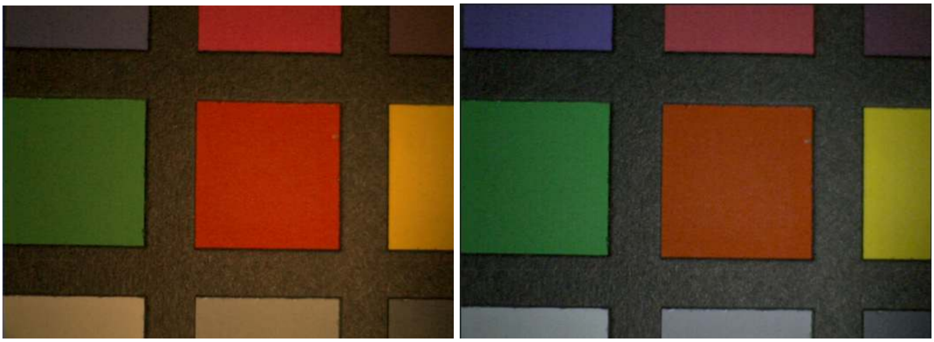

Fig. 6. Relighting result (Left: Illuminant A, Right: Illuminant D65)

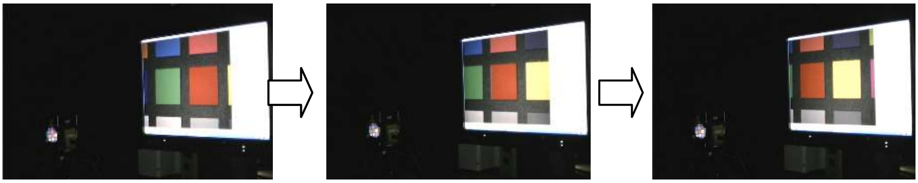

Fig. 7. Relighting result for moving object (ColorChecker is moving from right to left.)

Table 1. Color reproduction error in this system

	Illuminant A	Illuminant D65
Average color difference ΔE^*ab	7.17	6.55
Maximum color difference ΔE^*ab	14.1	15.5
Minimum color difference ΔE^*ab	3.11	1.93

Table 2. Color differences of spectral reflectance estimation and color reproduction of the display

	Reflectance estimation	Color reproduction of display
Average color difference ΔE^*ab	5.36	2.1

3.3 Relighting of Commonly used Objects

We tested our relighting system using a real-world object. The target light sources were illuminant A and illuminant D65. Figure 8 shows a real sample object of a piece of cloth. Figure 9 shows the relighting result. The system is able to reproduce the appearance under a different light source illumination on the monitor. This demonstrates that our system is capable of relighting commonly used objects.

Fig. 8. Target object

Fig. 9. Relighting results for a plaid cloth (Left: A light source, Right: D65 light source)

3.4 Relighting Under Environment Lighting Condition

The spectral power distribution by illuminating with a different light source is given by the product of the spectral distribution of the light source and the surface spectral reflectance of the object. Therefore, the surface spectral reflectance of the object can be estimated by detecting the spectral distribution of the light source. By using a reference object in the image with known surface spectral reflectance, the spectral distribution of the light source can be detected.

In this study, we conducted an experiment using artificial sunlight as the environmental light source. Figure 10 shows the setup of the experiment. We used X-Rite Mini ColorChecker as the moving object and a white patch was used as the reference for detecting the spectral distribution of the light source. Figure 11 shows one experimental result. The left figure shows an input image taken under artificial sunlight, and the right figure shows a relighting result under the illuminant D65.

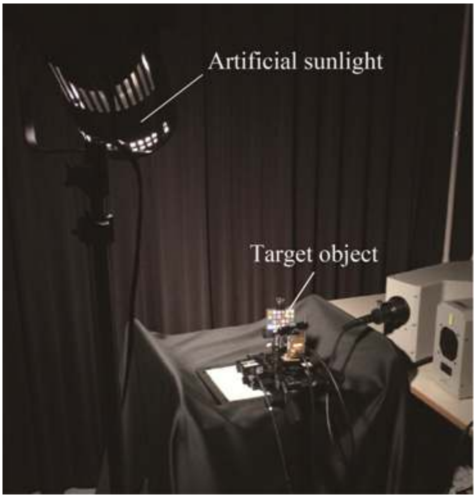

Fig. 10. Experimental setup under environment lighting condition

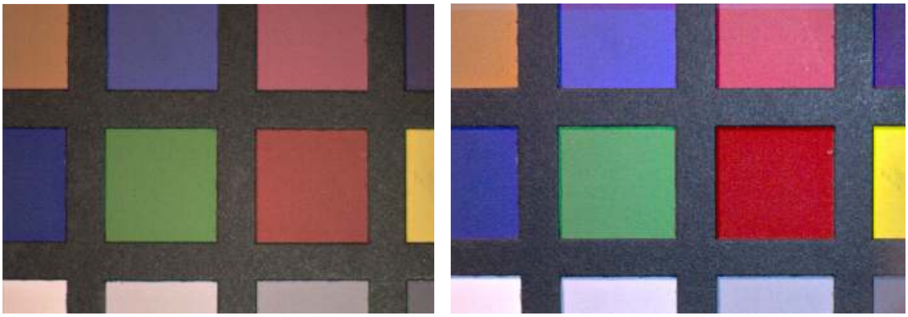

Fig. 11. (Left) Image captured under artificial sunlight. (Right) Image relighted by illuminant D65.

4 Conclusion

In this study, we have constructed a dynamic relighting system for moving planar objects with unknown reflectance. The averaged color difference ΔE^{*}_{ab} between the measured value and the true colors of X-Rite Mini ColorChecker was 7.17 for the illuminant A, and 6.55 for the illuminant D65. We demonstrated the capability of our system by relighting to a real object, in this case a piece of cloth.

One problem with the proposed system is the low processing speed of 1 fps. This could be improved in the future by using a GPU and multi-core CPU system. Since the application to glossy objects is very difficult, we will address to glossy object in the future. By using an RGB-D camera, a relighting system for an object with a complicated shape could be tackled as a future problem.

References

1. Wen, Z., Liu, Z., Huang, T.S.: Face relighting with radiance environment maps. In: Proc. CVPR, pp.158–165 (2003)
2. Debevec, P., Hawkins, T., Tchou, C., Duiker, H.-P., Sarokin, W., Sagar, M.: Acquiring the reflectance field of a human face. In: Proc. SIGGRAPH, pp.145–156 (2000)
3. Manakoy, A., Restrepo, J.F., Klehm, O., Hegedus, R., Eisemann, E., Seidel, H.-P., Ihrke, I.: A reconfigurable camera add-on for high dynamic range, multispectral, polarization, and light-field imaging. ACM Trans. Graph. **32**(4) (2013); Proc. SIGGRAPH
4. Park, J.-I., Lee, M.-H., Grossberg, M.D., Nayar, S.K.: Multi spectral imaging using multiplexed illumination. In: Proc. ICCV (2007)
5. Tominaga, S., Nishioka, D., Horiuchi, T.: An integrated spectral imaging system for producing color images of static and moving objects. Color Research and Application (Early View, April 2014)
6. Tominaga, S., Horiuchi, T.: Spectral Imaging by Synchronizing Capture and Illumination. JOSA A **29**(9), 1764–1775 (2012)