Synthesizing an Image Invariant to Illumination Geometry when the Illumination Spectrum Cannot be Measured

Masaru Tsuchida [1,2], Takahito Kawanishi [1] and Shigeru Takagi [1]
[1)] NTT Communication Science Laboratories, NTT Corporation, Atsugi-shi, Japan
[2)] Currently, Research and Development Headquarters,
NTT-DATA Corporation, Chuo-ku, Japan

Abstract

This paper proposes a novel approach to synthesize an image invariant to illumination geometry when the illumination spectrum cannot be measured. Under the assumption that the kinds of illumination generally used are limited, the illumination invariant image is synthesized using an image and several illumination spectrum data. A light reflected from an object surface is projected onto the hyper-plane orthogonal to every conceivable illumination spectra. Using this method, images of an object captured under different illumination geometries are converted to the same image. In the experiments, texture hidden by the specular reflection was visualized well even when an object was illuminated by multiple light sources whose illumination spectra are different. This method requires multi-spectral image capturing, but RGB color images can be used only when one or two kinds of illumination are used and the illumination sources are specified.

1. Introduction

Pattern recognition systems have difficulty recognizing two images of an object captured under a different illumination direction as the same object. When illumination direction changes, the gloss and shade on the surface of an object change. To reduce gloss, the polarized imaging technique has been proposed.[1] However, this method requires special equipment and several images. Recently, reported have been techniques that reproduce a color image of an object captured under an illumination condition to a color image under different illumination spectrum.[2,3] A light reflected from an object is separated into a diffuse reflection component and specular reflection component. The separation calculation requires several images captured under various viewing angles or different illumination directions. Therefore, these methods can be used only in limited situations. These image reproduction techniques are useful, but they are not unique approaches to solving the pattern matching problem under different illumination conditions.

This paper proposes a novel approach to synthesize an image invariant to illumination geometry from an image and spectrum data of several generally used illumination light sources. Images of an object captured under different illumination geometries are converted to the same image.

2. Removing Specular Component using Illumination Spectrum

2.1 Reflection Model

Let an object be illuminated by a point light source and reflected light be captured with a N channel ($N \geq 3$) camera as shown in Fig. 1. Let the normalized illumination spectrum vector be $\hat{\mathbf{w}} = [\hat{w}_1, \cdots, \hat{w}_N]^T$ ($\sum_i \hat{w}_i^2 = 1$) and a reflected spectrum vector from a point $\mathbf{r} = [x, y, z]^T$ of the object be $\mathbf{I}(\mathbf{r}) = [i_1(\mathbf{r}), \cdots, i_N(\mathbf{r})]$. According to the dichromatic reflection model[4], $\mathbf{I}(\mathbf{r})$ is decomposed as

$$\begin{aligned} \mathbf{I}(\mathbf{r}) &= \mathbf{I}_d(\mathbf{r}) + \mathbf{I}_s(\mathbf{r}) \\ &= D_d(\mathbf{r})\{\mathbf{f}_d(\mathbf{r}) * \hat{\mathbf{w}}\} + D_s(\mathbf{r})\{\mathbf{f}_s(\mathbf{r}) * \hat{\mathbf{w}}\}, \\ & |\mathbf{f}_d(\mathbf{r}) * \hat{\mathbf{w}}|^2 = 1, \ |\mathbf{f}_s(\mathbf{r}) * \hat{\mathbf{w}}|^2 = 1, \end{aligned} \tag{1}$$

where $\mathbf{I}_d(\mathbf{r})$ and $\mathbf{I}_s(\mathbf{r})$ are the diffuse and specular reflection component vectors. $\mathbf{I}_d(\mathbf{r})$ and $\mathbf{I}_s(\mathbf{r})$ are further decomposed into geometrical terms ($D_d(\mathbf{r})$ and $D_s(\mathbf{r})$: scalars) and spectral terms ($\mathbf{f}_d(\mathbf{r}) * \hat{\mathbf{w}}$ and $\mathbf{f}_s(\mathbf{r}) * \hat{\mathbf{w}}$). The symbol " $*$ " defines a product of two vectors: $[a_1, \cdots, a_N]^T * [b_1, \cdots, b_N]^T = [a_1 b_1, \cdots, a_N b_N]^T$. $\mathbf{f}_d(\mathbf{r})$ is a spectral diffuse reflectance vector of the object and $\mathbf{f}_s(\mathbf{r})$ is a spectral specular reflectance vector. For most materials $\mathbf{f}_s(\mathbf{r}) = [1, \cdots, 1]$, then we assume $\mathbf{f}_s(\mathbf{r}) = [1, \cdots, 1]$. The geometrical terms vary with changes in lighting direction, and the spectral terms are independent of the geometry.

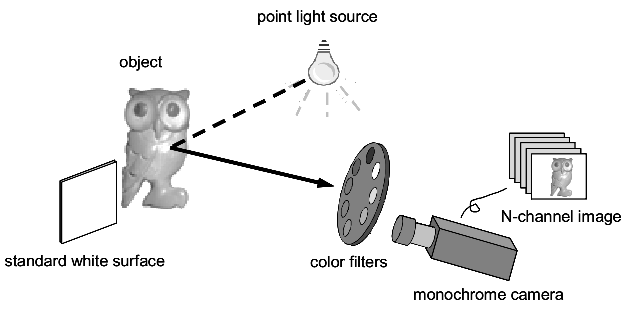


Figure 1. Image capturing setup.

2.2 Removing the Specular Reflection Component

2.2.1. Principle

Let us suppose that the illumination spectrum vector $\hat{\mathbf{w}} = [\hat{w}_1, \cdots, \hat{w}_N]^T$ is obtained by capturing a multi-spectral image of a standard white surface. The normalized color signal is regarded as the illumination spectrum vector. The specular reflection component $D_s(\mathbf{r})$ can be removed by projecting a reflected spectrum vector $\mathbf{I}(\mathbf{r})$ onto the hyper-plane whose normal vector is $\hat{\mathbf{w}} = [\hat{w}_1, \cdots, \hat{w}_N]^T$ (Fig. 2):

$$\mathbf{P}(\mathbf{r}) = \mathbf{I}(\mathbf{r}) - \{\mathbf{I}(\mathbf{r}) \cdot \hat{\mathbf{w}}\}\hat{\mathbf{w}}$$
$$= D_d(\mathbf{r})\{\hat{\mathbf{I}}_d(\mathbf{r}) - (\hat{\mathbf{I}}_d(\mathbf{r}) \cdot \hat{\mathbf{w}})\hat{\mathbf{w}}\}, \qquad (2)$$

where $\hat{\mathbf{I}}_d(\mathbf{r}) = \mathbf{f}_d(\mathbf{r}) * \hat{\mathbf{w}}$. Here the symbol "." represents the inner product operator of two vectors. Note that $\{(\mathbf{f}_s(\mathbf{r}) * \hat{\mathbf{w}}) \cdot \hat{\mathbf{w}})\}\hat{\mathbf{w}} = \mathbf{f}_s(\mathbf{r}) * \hat{\mathbf{w}}$. The projected result $\mathbf{P}(\mathbf{r})$ is not influenced by the specular reflection and does not correspond to the diffuse reflection component.

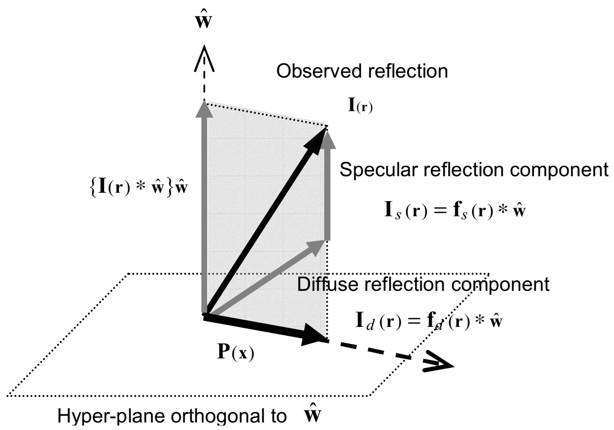


Figure 2. Projection onto the hyper-plane.

2.2.2. Synthesis of Images Invariant to Illumination Geometry

When the illumination spectrum cannot be measured, the method described in Sec. 2.2.1 cannot be used. However, the sources of illumination used generally are limited to sunlight, incandescent lamps, and fluorescent lamps, and the illumination spectra of these sources can be known easily in advance. Under the assumption that these sources are used and their spectra are known, images invariant to illumination geometry are synthesized in the following two steps.

Step 1: Removal of the Specular Reflection Component

Let the number of conceivable illuminations be L. Let us consider a hyper-plane orthogonal to every conceivable illumination spectra. The specular reflection component $D_s(\mathbf{r})$ is removed by projecting a reflected spectrum vector $\mathbf{I}(\mathbf{r})$ onto the hyper-plane. A projected vector on the hyper-plane $\mathbf{P}(\mathbf{r})$ is obtained by using a projection matrix W to a subspace spanned by the illumination spectrum vectors.

$$\mathbf{P}(\mathbf{r}) = \mathbf{I}(\mathbf{r}) - (W^{\mathrm{T}}W)\mathbf{I}(\mathbf{r}), \qquad (3)$$

where $W = [\mathbf{e}_1, \cdots, \mathbf{e}_k]^{\mathrm{T}}$ (k: norm of the matrix $[\hat{\mathbf{w}}_1, \cdots, \hat{\mathbf{w}}_L]^{\mathrm{T}}$, $k \le L$), and $\mathbf{e}_i$ is the i th basis vector of the subspace spanned by the illumination spectrum vectors. The projected result $\mathbf{P}(\mathbf{r})$ can be dealt with in the same way as the projected vector described in Eq. (2).

Step 2: Normalization

To remove the geometrical effect, the projected result $\mathbf{P}(\mathbf{r})$ is normalized to unit length vector $\hat{\mathbf{P}}(\mathbf{r})$.

$$\hat{\mathbf{P}}(\mathbf{r}) = \mathbf{P}(\mathbf{r}) / |\mathbf{P}(\mathbf{r})|, \qquad (4)$$

The normalized projected vector $\hat{\mathbf{P}}(\mathbf{r})$ can be used for pattern matching. The $\hat{\mathbf{P}}(\mathbf{r})$ does not include any geometrical effect and is decided by the diffuse reflectance nature of the surface, which is invariant for illumination conditions. Note that the proposed method cannot be applied for a three-channel image (red, green and blue) when the number of conceivable illuminations is more than three.

Although it is assumed that an object is illuminated by a point light source in the descriptions above, the proposed method can be applied in the case of multiple light sources even if their illumination spectra are different.

$$\mathbf{P}(\mathbf{r}) = \mathbf{I}(\mathbf{r}) - (W^{\mathrm{T}}W)\mathbf{I}(\mathbf{r})$$
$$= \sum_{i=1}^{L}\mathbf{I}(\mathbf{r})^{[i]} - (W^{\mathrm{T}}W)\sum_{i=1}^{L}\mathbf{I}(\mathbf{r})^{[i]}$$
$$= \sum_{i=1}^{L}\{\mathbf{I}(\mathbf{r})^{[i]} - (W^{\mathrm{T}}W)\mathbf{I}(\mathbf{r})^{[i]}\}, \qquad (5)$$

where $\mathbf{I}(\mathbf{r})^{[i]}$ is the observed spectrum when the object is illuminated only by the i th light source.

However, a black and white object has a pattern similar to $\hat{\mathbf{w}}$, and $\mathbf{P}(\mathbf{r})$ becomes around 0. Then, the $\hat{\mathbf{P}}(\mathbf{r})$ calculation becomes unstable and unreliable.

3. Experiments

A multi-spectral camera[5] was used for experiments. The multi-spectral camera consists of a monochrome digital CCD camera (Sony XCD-X700) and a liquid-crystal tunable filter (CRI VariSpec, visible model, 20nm bandwidth), which can electrically select a transmitted wavelength range, placed in front of camera lens (Fig. 3). The wavelength was selected from the 420 to 720 range at 20 nm intervals and 16-channel images were obtained. Exposure parameters were adjusted to avoid camera saturation. To obtain the illumination spectrum vector, three multi-spectral images of the standard white surface were captured under halogen, metal-halide, or fluorescent lamps in advance. A sheet of glossy paper of uniform color was used as an object.

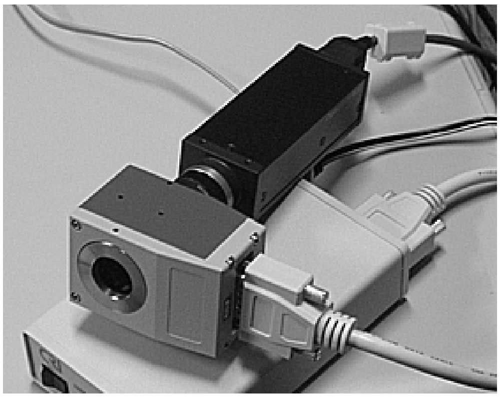


Figure 3. Multi-spectral camera used in the experiments.

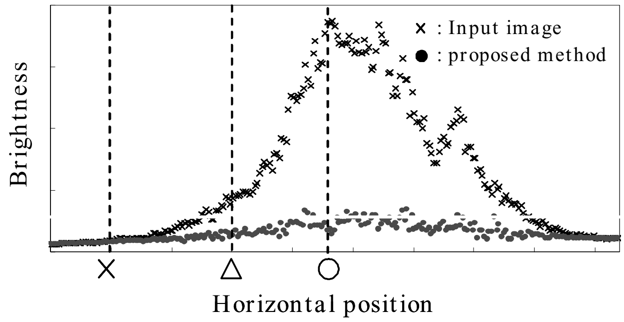


Figure 5. Brightness of input and resulting images.

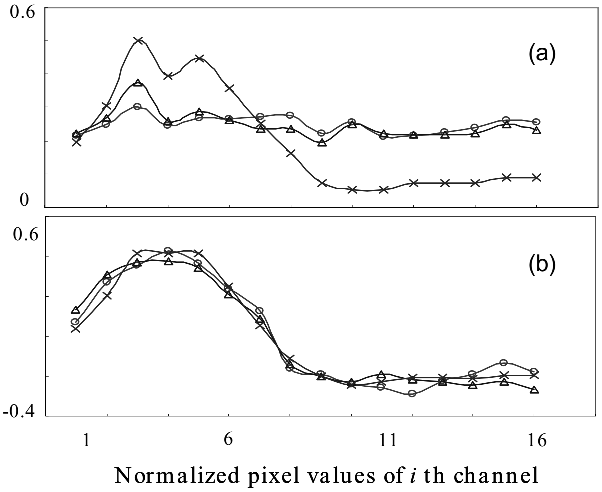
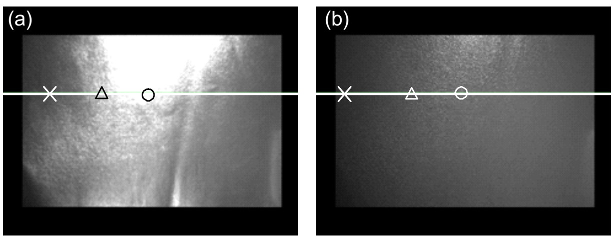


Figure 6. Normalized spectrum pattern.

3.1. Experiment for a Single Light Source

The projected vector $\hat{\mathbf{P}}(\mathbf{r})$ should not include the specular component (gloss) and should be constant for a uniform color object. To confirm this property, a subspace W spanned by the halogen, metal-halide, and fluorescent spectrum vectors is calculated. A multi-spectral image of the object under a single light source is cap tured and projected vector $\mathbf{P}(\mathbf{r})$ is obtained according to Eq. (3). Figure 4 shows the images of $|\mathbf{I}(\mathbf{r})|$ and $|\mathbf{P}(\mathbf{r})|$ when a halogen lamp is used. It is clear that the effect of specular reflection is almost completely removed in the resulting image. Figure 5 shows intensity profiles of $|\mathbf{I}(\mathbf{r})|$ and $|\mathbf{P}(\mathbf{r})|$ along horizontal lines (white line in Fig. 4). Symbols ○, × and Δ designate the same address. Intensity varies largely across the gloss region in the captured image. On the other hand, intensity becomes almost flat for the projected vectors image. Figure 6(a) and (b) respectively show the normalized spectral vectors of $\mathbf{I}(\mathbf{r})$ and $\hat{\mathbf{P}}(\mathbf{r})$ at locations ○, × and Δ. The normalized spectrum patterns of $\mathbf{P}(\mathbf{r})$ become almost totally invariant for the locations. This means that effects of the specular reflection are almost completely removed in $\hat{\mathbf{P}}(\mathbf{r})$.



(a) Input image, *(b) resulting image.*

Figure 4. Result of removing the specular reflection component.

3.2. Experiment for Multiple Light Sources Whose Illumination Spectra Are Different

The proposed method should work well even when an object is illuminated by several light sources whose illumination spectra are different. To confirm this, visualization of texture hidden by the specular reflection was carried out. Here, an image of a cover of a journal captured under two different illuminations was used. Figure 7(a) shows the input image $|\mathbf{I}(\mathbf{r})|$. The image includes the specular reflection of each light source [halogen (left), metal-halide (right)] and some characters are hidden by the reflection. Figure 7(b) shows the resulting image $|\mathbf{P}(\mathbf{r})|$ obtained by the proposed method. The texture hidden by specular reflections can be observed. A comparison of these two indicates that the effects of specular reflections of each illumination seem to be almost totally removed and the proposed method works well.

(a)

(b)

Figure 7. Visualization of the texture hidden by specular reflections. (a) Input image, and (b) result of applying the method to image (a).

5. Discussion

The light reflected from a metal surface consists of only the specular reflection component, and the specular reflectance of the metal is not constant along the light incident angle to the surface. However, the specular reflectance can be approximated as the dichromatic mode as follows[6]:

$$\mathbf{f}_s(\mathbf{r}) = D_{s1}(\mathbf{r})\mathbf{f}_{s1}(\mathbf{r}) + D_{s2}(\mathbf{r})\,. \qquad (6)$$

This equation has the same form as Eq. (3) and the same method can be applied.

Some kinds of paper and fabric (e.g. rayon-satin and velour[7]) do not follow the dichromatic reflection model. Their specular reflectance $\mathbf{f}_s(\mathbf{r})$ is not constant. It is thought that this is caused by the complex fiber structure. In addition, these materials often exhibit luminescent effects. Another approach should be investigated for these materials.

6. Conclusion

This paper described a novel approach to synthesize an image invariant to illumination geometry when the illumination spectrum cannot be measured. Under the assumption that the kinds of illumination generally used are limited, the image is synthesized using an image and several illumination spectrum data. A light reflected from an object surface is projected onto the hyper-plane orthogonal to every conceivable illumination spectra. In the experiments, texture hidden by the specular reflection was visualized well even when an object was illuminated by multiple light sources whose illumination spectra are different. This method requires multi-spectral image capturing, but RGB color images can be used only when one or two kinds of illumination are used and the illumination sources are specified.

A feature of the proposed method is its simple algorithm, which makes it easy to use for real-time image processing. The technique is expected to have various applications, including character recognition, image retrieval, video surveillance, analysis of medical images (such as endoscopic images), and object modeling based on correspondent tracking.

References

1. S. N. Nayer, X. Fang, and T. Boult, "Removal of specularities using color and polarization," in Proc. of CVPR'93, pg. 583-589, (1993).
2. N. Tanaka, S. Tomonaga, and T. Kawai, "A method for estimating parameters of a 3D spectral reflection model," in Proc. of Int. Symp. on Multispectral Imaging and Color Reproduction for Digital Archives, pg. 127-130, (1999).
3. H. Haneishi, T. Iwanami, T. Honma, N. Tsumura, and T. Miyake, "Goniospectral imaging of three-dimensional objects," J. Img. Sci. and Tech., vol. 45, pg. 451-456, (2001).
4. S. Tominaga, and B. A. Wandell, "The standard surface reflectance model and illuminant estimation," J. Opt. Soc. Am/A, vol. 6, pg. 576-584 (1989).
5. S. Tominaga, and R. Okajima, "Object Recognition by Multi-Spectral Imaging with a Liquid Crystal Filter," in Proc. of ICPR'02, vol. 1, pg. 708-711 (2002).
6. S. Tominaga, and S. Ohhashi, "A Color Reflection model for Object Surface," J. IPSJ, vol. 33, no. 1, pp. 37-45, 1992 (in Japanese)
7. S. Tominaga, and R. Okajima, "Object Recognition by Multi-Spectral Imaging with a Liquid Crystal Filter," in Proc. of ICPR'02, vol. 1, pp. 708-711 (2002).

Biography

Masaru Tsuchida received his Ph.D. degree in Engineer from the Tokyo Institute of Technology, Japan in 2002. He joined NTT Communication Science Laboratories in 2002. Since 2003 he has worked in NTT DATA corporation. His research interests include 3-D image display, computer vision, image recognition and multi-spectral imaging. E-mail: tsuchidams@nttdata.co.jp