Optimization of camera and illumination directions on Gonio spectral imaging methods

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Abstract

Gonio spectral imaging method is significant to record the shape, reflectance spectra, gloss and texture of 3-D object for digital archives. This method, however, takes much time to record the object. In this paper, a new method based on the genetic algorithm is introduced to reduce the taking time by optimizing the configuration of camera and illumination. We confirmed the effectiveness of the method by the computer simulation. We also confirmed the significance of the algorithm by using the developed gonio spectral imaging system based on the result of computer simulation.

Introduction

In an electronic museum or internet shopping, reproducing the color and glossiness of a 3-D object with high fidelity is desired for observers or consumers to recognize more clearly how the object looks like. Spectral information is necessary for the exact representation of color objects and many researchers have conducted studies to obtain it. However, none of those studies have addressed the extraction of the characteristics necessary to reproduce the glossiness of the object.

In order to obtain the characteristics of the glossiness, many researchers have proposed the methods to measure the gonio-spectral information of the object as shown in Figure 1 [1-3]. In these methods, light sources and a camera are located at several different positions to measure the BRDF (bi-directional reflectance distribution function) of the object. Although the detail BRDF values can be measured by varying the position of light sources and the camera at every small interval, it takes huge amount of time to complete measurement. To overcome such problem, we propose a new method which optimizes the camera and illumination directions to reduce the measurement time. The purpose of this study is to measure the gonio-spectral distribution on the object's surface that is assumed as independent at each point. In this study, to define the evaluation functions of the camera and the illumination optimization, we assume the roughness of the surface, verify the assumption in comparison with some measurement, and update the value of the invalid assumption. By using this method, we can obtain gonio-spectral information in less time than before.

Gonio-spectral imaging

For the reflection analysis of inhomogeneous dielectric objects, the dichromatic reflection model shown in Figure 2 is usually used [4]. In this model, the reflection of an object is composed of diffuse reflection (body reflection) and specular reflection (surface reflection). The perception of glossiness is basically induced by specular reflection from the object surface. According to the dichromatic reflection model, the reflection from the object surface $\mathbf{f}(\mathbf{r},\omega)$ is denoted as follows,

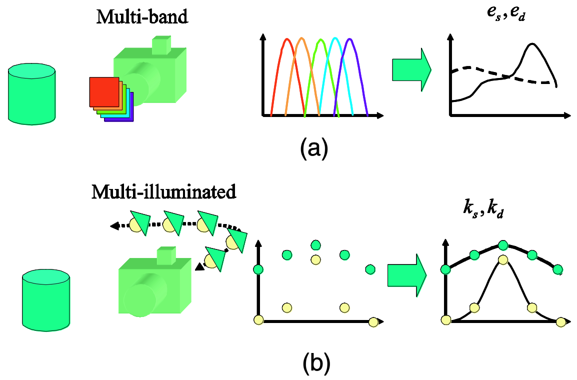

Figure 1 Gonio spectral imaging methods. (a)Multi-band imaging. (b) Multi-illumination imaging.

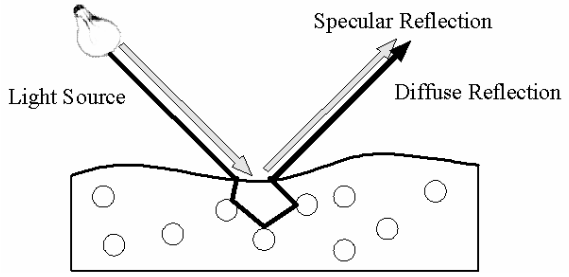

Figure 2 Dichromatic reflection model.

$$\mathbf{f}(\mathbf{r},\omega)=k_s(\mathbf{r},\omega)\mathbf{e}_s+k_d(\mathbf{r},\omega)\mathbf{e}_d(\mathbf{r}) \tag{1}$$

where $\omega=[\theta_i,\phi_i,\theta_r,\phi_r]$ denotes the elevation and azimuth angles of incident light, and these of reflection light, respectively. $\mathbf{e}_s$ denotes normalized color vector of specular reflection component and $\mathbf{e}_d(\mathbf{r})$ denotes normalized color vector of diffuse reflection component at position $\mathbf{r}$. $k_s(\mathbf{r},\omega), k_d(\mathbf{r},\omega)$ are the intensity coefficients of the specular component and the diffuse component, respectively and they can be separated numerically when $\mathbf{e}_s$ and $\mathbf{e}_d(\mathbf{r})$ are not the same vectors. By fitting the large amount of measured data onto some reflectance model[5-8], images from the light sources from any angle can be reproduced.

Here we adopt the Phong model[5] as the surface reflectance model, and then each coefficient can be defined as,

$$k_s(\omega) = A\cos^G \alpha$$

$$k_d(\omega) = B\cos\theta_i \tag{2}$$

where α denotes the angle between specular reflection of incident light and viewing direction and A, B are the intensity coefficient of each component. Larger number of G represents smoother surface and acuter specular property. Consequently, the purpose of gonio-spectral imaging is to obtain the values of A, B, G which represent essentially the BRDF characteristics.

In this study, the multi-spectral images are obtained by estimating the spectral distribution from five-bands images taken with five color filters and a monochromatic camera. The response vector of the camera $\mathbf{v}(\mathbf{r},\alpha)$ can be described as follows,

$$\begin{aligned}\mathbf{v}(\mathbf{r},\alpha) &= \mathbf{Hf}(\mathbf{r},\alpha) \\ &= k_s(\mathbf{r},\omega)\mathbf{He}_s + k_d(\mathbf{r},\omega)\mathbf{He}_d(\mathbf{r}) \\ &= A(\mathbf{r})\cos^{G(\mathbf{r})}\alpha\mathbf{He}_s + B(\mathbf{r})\cos\theta_i\mathbf{He}_d(\mathbf{r})\end{aligned} \tag{3}$$

where $\mathbf{H}$ means the system matrix of the camera. By estimating $\mathbf{H}^{-1}$ with a multiple regression method, $\mathbf{f}(\mathbf{r},\alpha)$ can be figured out from $\mathbf{v}(\mathbf{r},\alpha)$, then $k_s(\mathbf{r},\omega), k_d(\mathbf{r},\omega)$ are able to be obtained.

Optimization of the camera and illumination direction

In order to reduce the measurement times for the gonio-spectral imaging, we perform an optimization process. The schematic flow of proposed method is shown in Figure 3. First, we measure the object's 3D shape scanned by range finder as a pre-processing. Before the optimization process, we assume the roughness value of the surface and then the evaluation functions of camera and illumination direction can be obtained. Considering the discontinuous surface parameter distribution and occlusion by its shape, we need to solve the combinatorial optimization problems. In this study, genetic algorithm is employed for solving the problem. In order to increase the convergence speed, we perform the camera optimization and illumination optimization separately and iteratively. After the convergence, we actually take the images using the obtained directions' configuration. From these measurement samples, the value of the roughness assumed in this process can be verified at each point. When the result of verification is valid, the roughness of the point can be obtained. On the other hand, the result is found as invalid, the roughness of the point can't be fixed and then we update the assumption of roughness of the point. These processes need to be iterated until roughness values of all points are obtained.

Camera optimization

In order to decide the camera positions, one condition is defined that all the pixels on the surface must be taken at least once. With satisfying this condition, the camera configuration is optimized. In this study, to simplify the problem, we assume that elevation angle is fixed with 90 degree. The azimuth angle is divided to number of n_p. The gene representation of the camera configuration as shown in Figure 4 can be described as follows,

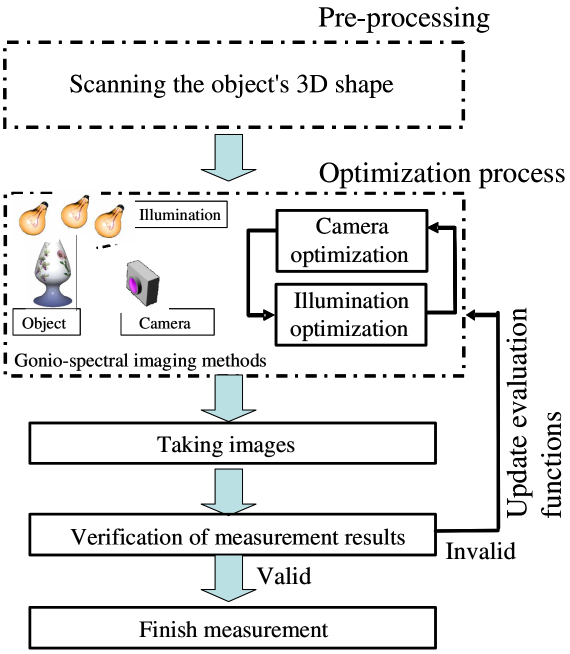

Figure 3 Schematic flow of optimization process.

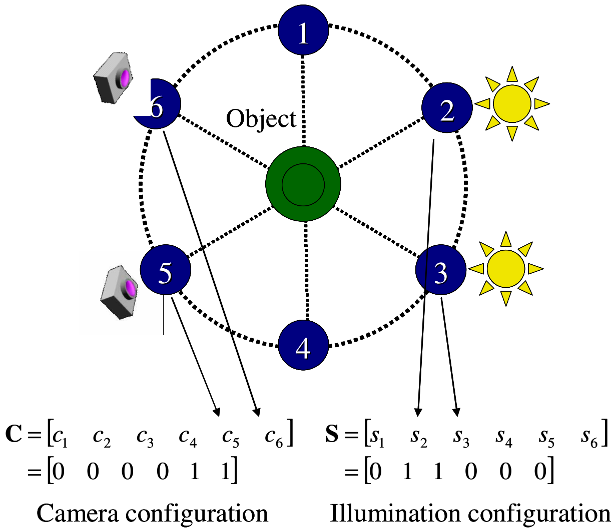

Figure 4 Gene representation of camera and illumination configuration.

$$\mathbf{C} = \left[c_1, c_2, \cdots, c_{n_p}\right] \tag{4}$$

$$\text{where} \quad c_j = \begin{cases} 0 & \text{when the camera is not put on place } j \\ 1 & \text{when the camera is put on place } j \end{cases}$$

When the number of whole pixels on the surface is given as n_s, the necessary condition can be obtained as,

$$\sum_{j=1}^{n_p} \mathbf{L}_{i,j} c_j \geq 1 \qquad \forall i, i = \{1, \cdots, n_s\} \tag{5}$$

$$\text{where} \quad \mathbf{L}_{i,j} = \begin{cases} 1 & \text{when pixel } i \text{ is visible from direction } j \\ 0 & \text{when pixel } i \text{ is invisible from direction } j \end{cases}$$

where $\mathbf{L}$ is the pre-computed matrix from the shape. When the angle between the mirrored reflection of the light source and the camera is given as $\mathbf{D}_{i,j,k}$, the evaluation function of the camera configuration can be defined as,

$$F'_c = \sum_i \sum_j \sum_k c_j s_k \mathbf{L}_{i,j} \mathbf{L}_{i,k} \cos\left(D_{i,j,k}\right) \tag{6}$$

where s_k is the gene representation of the illumination configuration described in the next section. In order to reduce the number of taking times of the camera, we give additional evaluation function as follows,

$$F''_c = \left(n_p - \sum_{j=1}^{n_p} c_j \right)^2 \tag{7}$$

Then total evaluation function is,

$$F_c = F'_c + F''_c \tag{8}$$

To maximize this function, we perform the genetic algorithm to find the best combination $\mathbf{C}$ of the camera configuration with 500 genes. After 100 age iteration, we choose the camera configuration which has the highest value of evaluation function.

Illumination optimization

In the similar way, we optimize the illumination configuration. The gene representation of the illumination configuration as shown in Figure 4 can be described as follows,

$$\mathbf{S} = \left[s_1, s_2, \cdots, s_{n_p} \right]$$
$$\text{where} \quad s_j = \begin{cases} 0 & \text{when illumination is not put on place } j \\ 1 & \text{when illumination is put on place } j \end{cases} \tag{9}$$

As the condition of the optimization, we assume that all surface points must be illuminated at least twice. This condition is given as,

$$\sum_{j=1}^{n_p} \mathbf{L}_{i,j} s_j \geq 2 \qquad \forall i, i = \{1, \cdots, n_s\} \tag{10}$$

Then the evaluation function of the illumination configuration can be defined as follows,

$$F'_l = \sum_i \left\{ e_i\left(\mathbf{C}, \mathbf{S}, G^A\right) \right\}^{-p} \tag{11}$$

where $e_i\left(\mathbf{C}, \mathbf{S}, G^A\right)$ is the error function between assumed value G^A and surface property estimated from the configuration of the camera $\mathbf{C}$ and illumination $\mathbf{S}$. And p is the affection coefficient of the error. In order to also reduce the number of taking times of the illumination, we give additional evaluation function as follows,

Figure 5 The object used in the experiment which consists of 6253 polygons.

Table 1 Accuracy comparison between 54 times shooting and proposed method.

	54 times shooting	Proposed method
Number of shooting	54	32
RMSE of specular intensity (A)	10.2	8.4
RMSE of surface roughness (G)	2.4	1.2

$$F''_l = \left(n_p - \sum_{j=1}^{n_p} s_j \right)^2 \tag{12}$$

Then total evaluation function is,

$$F_l = F'_l + F''_l \tag{13}$$

To maximize F_l, we perform the genetic algorithm to find the best combination $\mathbf{C}$ of the camera configuration with 500 genes. After 100 age iteration, we choose the camera configuration which has the highest value of evaluation function.

Evaluation of proposed method

Here we evaluate the effectiveness of the method. In this experiment, we use the scanned 3D model of a bottle which has 6253 polygons on the surface as shown in Figure 5. For the

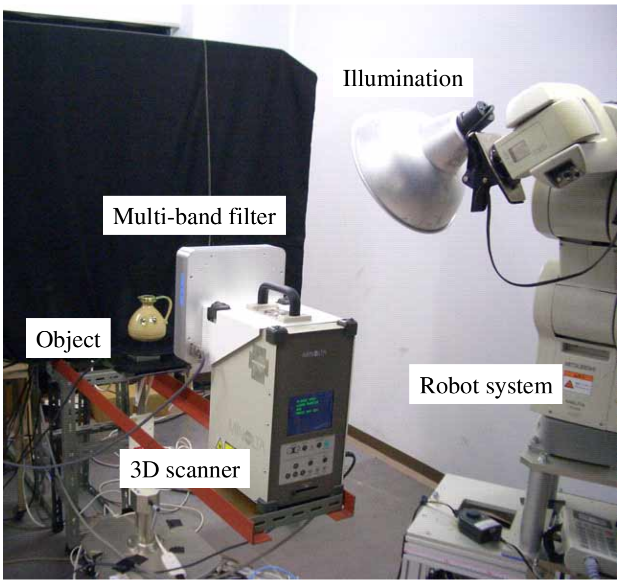

Figure 6 Automatic imaging system.

Figure 7 Digital reproduction result of the object taken by the proposed method.

experiment, we give gonio-spectral characteristics $G = \{10,20,50,100\}$, randomly for each point. Proposed method is compared with the method which measures by varying the positions of the camera and illuminations at every small interval. The result is shown in Table 1. Proposed method with reducing the shooting times can measure the gonio-spectral information more accurately than conventional method.

Implementation of the imaging system

We developed the gonio spectral imaging system as shown in Figure 6. Illumination is controlled by the robot accurately and the object can rotate on the controllable table. 3D shape and spectral image can be obtained by using range finder (customized Vivid 910, Konica-Minolta Co., Ltd.) Obtained data can be reproduced in the virtual space calculating the reflection from the environmental light distribution as shown in Figure 7.

Conclusion

In this study, we propose more effective method to measure the gonio-spectral characteristics of a 3D object than conventional method. This method optimizes the camera and illumination directions, separately and iteratively by assuming the roughness value of the surface. Since we confirm the validation of the assumption at each point, roughness distribution can be obtained with reducing the shooting times. The effectiveness of the developed gonio spectral imaging system is evaluated by computer simulation.

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Author Biography

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