Estimation of Surface Spectral Reflectance on 3D Painted Objects Using a Gonio-Spectral Imaging System

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Abstract

This paper reports estimation of surface spectral reflectance on three dimensional (3D) painted objects using a gonio-spectral imaging system developed by the authors, which consists of two robot arms, a monochrome digital camera, a lighting system with eight spectral channels, and a personal computer. The most remarkable feature of this system is that it can measure surface spectral reflectances of objects with colored texture individually at each surface points. This feature makes the system suitable to reflectance measurement of painted objects with complex color texture. The system acquires gonio-spectral images of 3D painted objects for different combination of incident and viewing angles of light and for each spectral channel of the light source. The intensities of the captured images are sampled at each surface point of the painted object. From these intensities, parameters of spectral reflectance models are estimated at each individual surface points. The obtained reflectance models are used for rendering the painted objects for arbitrarily chosen illumination and viewing conditions. Experiments are carried out for real painted objects. The results confirm that surface spectral reflectance is successfully modeled by the proposed method.

Introduction

Surface spectral reflectance is an important physical property in color vision and color reproduction. Precise information on surface spectral reflectance allows us to identify surface material, surface roughness and geometry of the object, and also to render realistic object images for arbitrary illumination and viewing conditions. Surface spectral reflectance is a complex function of light wavelength, the position on the object surface, and incident and emitting directions of light. Wavelength-dependent, or spectral, characteristics are particularly important for precise colorimetry and realistic color reproduction.

To obtain a complete description of surface spectral reflectance for a real object, one has to perform spectrophotometry on the object by changing the wavelength, surface position, and incident and viewing directions over a wide range, which results in a huge volume of measured data. For practical applications in object recognition and image rendering, however, surface spectral reflectance should be modeled by a small number of parameters [1], [2] based on the measurement. In particular, the directional dependence of surface reflectance is usually described as bidirectional reflectance distribution function (BRDF) [3], or bidirectional texture function (BTF) [4] when two-dimensional distribution on the surface is considered.

Our goal is to realize a system for measurement and modeling of surface spectral reflectances of general objects. Toward this goal, we have recently constructed a gonio-spectral measuring device consisting of two robot arms, an eight-channel spectral light source, a monochrome digital camera, and a personal computer [5].

In this paper, we develop a total system for estimating the surface spectral reflectances of color-textured objects of arbitrary 3D shape, based on the previous system. Specifically, we propose a method for registering gonio-spectral images obtained by the measuring system to the 3D mesh data of an object acquired separately by a range finder. The registration is accurately done by use of a reference object of known shape and the calibration technique proposed previously [5]. We also devise a nonlinear fitting algorithm based on the Levenberg-Marquardt method for recursively estimating the parameters of a surface spectral reflectance function from the gonio-spectral image intensities at each surface point of the mesh data. From the fitting resutls, diffuse surface spectral reflectances are estimated by a Wiener filtering method [6].

We focus our target objects to industrial products and artworks, which are usually painted with specific materials such as oil, water, or plastic paints and easy to find in our daily life. These paints are classified as inhomogeneous dielectric materials, whose reflection behavior is appropriately modeled by a Torrance-Sparrow reflectance function [7], and thus allows us to easily verify our system.

In the following part, after summarizing previous work in the related area, we begin with the gonio-spectral measuring device. Next, we propose a method of registering gonio-spectral images to a 3D mesh model of the object, and also describe algorithms for modeling surface spectral reflectances. Then, we show experimental results for a painted 3D object. Finally, we summarize this paper.

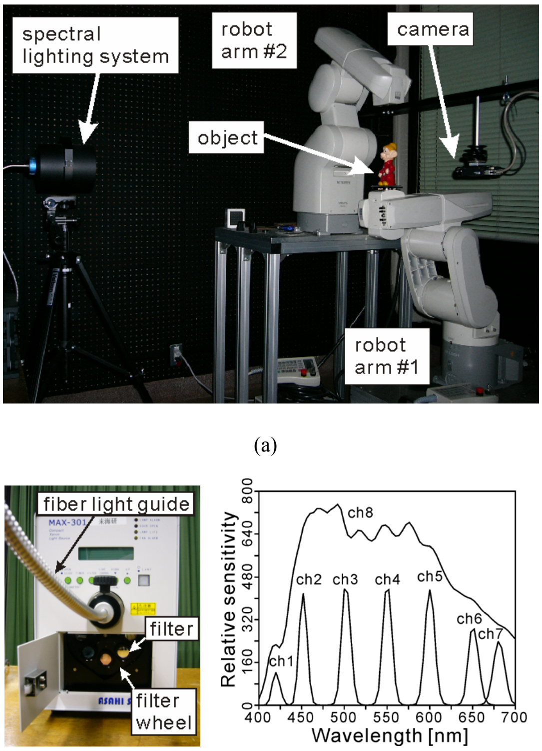
Related Work

A number of methods have been proposed for measurment and modeling of surface reflectance. They can be roughly categorized into RGB-based methods and spectral methods. A large part of the RGB-based methods can deal with only planar or textureless object surfaces [4], [8], [9]. Among the RGB-based methods for 3D objects, Sato *et al.* [10] proposed a system that can simultaneously model surface shape and surface reflectance of a colored object. Lensch *et al.* [11] estimated BRDFs of 3D objects, whose surface shape is acquired separately by a range finder, from a small number of goniometric images based on the Lafortune model [12] and a BRDF categorization algorithm. These systems, however, can achieve only sparse sampling of incident and viewing directions. On the other hand, the measuring system used in Grabli *et al.* [13] can realize fully goniometric imaging, but lacks spectral measurement capability.

The spectal methods comprise a much smaller group than the RGB-based ones. Tanaka and Tominaga [14] proposed a system consisting of a collimated white light, a turntable for the object, and a coaxially rotatable multi-band camera with six color filters. They further used it to estimate refractive index of the object surface [7]. Haneishi *et al.* [15] introduced a five-band spectral camera and applied it to a textured 3D surface. As a drawback, these systems cannot achieve full goniometry. Tsuchida *et al.* [16] developed a spectral imaging system consisting of a special goniometric device, a 16-channel spectral light source, and a monochrome camera. They have not yet reported results for 3D and textured surfaces. Kimachi *et al.* [5] constructed a measuring system consisting of two commercial robot arms, a collimated light source with eight spectral channels and a monochrome digital camera. They also proposed algorithms for calibrating system geometry and spectral sensitivity of the imaging system. However, they could not apply their system to 3D objects. The system proposed in this paper aims to overcome this limitation to realize measurement and modeling of surface spectral reflectance for 3D painted objects.

Measuring Device

Figure 1(a) shows the measuring device for surface spectral reflectance [5], comprised of two robot arms, a collimated light source with eight spectral channels, and a 10-bit monochrome digital camera. One of the robot arms rotates an object around a fixed point with three degrees of freedom (3DOF), and the other rotates the camera horizontally with 1DOF, thus resulting in 4DOF necessary for specifying the incident direction of the illumination and the viewing direction of the camera independently. Spectral images are obtained from the camera by illuminating the object with the eight-channel light source shown in Fig. 1(b), which consists of a xenon lamp, a filter wheel with seven narrow-band interference filters and an empty window, a fiber light guide, and a collimating lens. The spectral sensitivities of the entire imaging system combining the light source and the camera are measured as shown in Fig. 1(c). For each spectral channel and each pose and position of the robot arms, three images are captured with different exposure times by the powers of two. The three 10-bit images were combined into a single 12-bit image of higher dynamic range. The whole system is controlled by a personal computer to sequentially acquire gonio-spectral images of the object for different settings of the incident and viewing directions and the spectral channel of the illumination.



(a)

(b) (c)

Figure 1: Gonio-spectral imaging system for measuring surface reflectances of a 3D object. (a) Goniometric system consisting of two robot arms, a collimated spectral light source, and a monochrome digital camera. (b) Spectral lighting system with eight channels. (c) Spectral sensitivity of the entire imaging system.

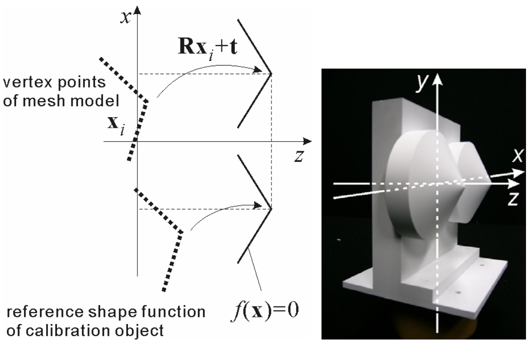
For precise modeling of the surface reflectances of a 3D object, the 3D pose and position of the object captured in each gonio-spectral image must be obtained with good accuracy. This is achieved by calibrating the relative geometry of the robot arms and the camera.

3D Mesh Data Registration

Our goal is to build a surface spectral reflectance model at each point on the object surface with arbitrary 3D shape. To obtain surface points, we acquire a 3D mesh model of the object before reflectance modeling using a commercial range finder. A structured light method using a projector [10] is also possible.

A registration problem occurs when the mesh model is acquired in a different environment from the imaging system in Fig. 1(a). In this case, the acquired mesh model is not defined in the coordinate system of the measuring device, but of the range finder.

To solve the registration problem, we use a reference object with some known shape and acquire the mesh models of both the reference object and the target object at the same time. Note that we must make sure that the relative pose and position of both objects do not change whether they undergo gonio-spectral image capture or mesh model acquisition. This constraint ensures that the transformation between the reference object coordinate system and the range finder coordinate system becomes exactly identical for both objects. Estimating the coordinate transformation of the acquired mesh model of the reference object relative to its reference position, we can therefore register the mesh model of the target object in the object coordinate system by applying the same transformation.



(a) (b)

Figure 2: Registration of a 3D mesh model. (a) Fitting of vertex points to a reference surface shape function by rotation matrix $\mathbf{R}$ and translation vector $\mathbf{t}$. (b) Reference object used.

We estimate the coordinate transformation by fitting the mesh model of the reference object to a reference surface shape function, as illustrated in Fig. 2(a). Figure 2(b) shows the reference object we are currently using, which has two identical cone-shaped surfaces. Since the shape function is nonlinear, we devised a Levenberg-Marquardt optimization algorithm to recursively estimate the transformation. Let $f(\mathbf{x})=0$ and $\{\mathbf{x}_i\}$ be the reference surface shape equation of the reference object defined in the object coordinate system, and the vertex points of the 3D mesh model defined in the range finder coordinate system, respectively. The estimation algorithm recursively finds the rotation matrix $\mathbf{R}$ and the translation vector $\mathbf{t}$ of the coordinate transformation that minimizes the error functional

$$E=\sum_i [f(\mathbf{R}\mathbf{x}_i+\mathbf{t})]^2 . \tag{1}$$

Once estimated, $\mathbf{R}$ and $\mathbf{t}$ are applied to the mesh model of the target object to register it to the object coordinate system.

Surface Spectral Reflectance Modeling

Surface Point-wise Resampling of Gonio-Spectral Images

The gonio-spectral images captured by the system in Fig. 1(a) are essentially an array of measured light intensity reflected on the object surface. To model surface spectral reflectance at a point on the object, we resample the intensity of each image at the corresponding location for the surface point. Our method for finding this correspondence follows Sato *et al.* [10], Lensch *et al.* [11] and Kimachi *et al.* [5], who discussed this problem as image warping for a planar object. This resampling requires precise registration of the images to the 3D mesh data of the object. Fortunately, we can obtain the relative geometry of the object and camera through the calibration technique proposed previously [5].

The resampling is formulated as follows. Consider a gonio-spectral image $I_{jkl}(\mathbf{p})$ captured for the j-th spectral channel, k-th incident direction of the illumination, and l-th viewing direction of the camera, with $\mathbf{p}$ denoting the pixel coordinates. The image intensity $\hat{I}_{jkl}(\mathbf{x})$ for a surface point $\mathbf{x}$ on the object is resampled as

$$\hat{I}_{jkl}(\mathbf{x})=I_{jkl}(\mathbf{p}) . \tag{2}$$

In Eq. (2), the pixel location $\mathbf{p}$ onto which $\mathbf{x}$ is imaged is found by the following relation

$$s\begin{bmatrix}\mathbf{p}\\1\end{bmatrix}=\mathbf{A}(\mathbf{R}_l\mathbf{x}+\mathbf{t}_l) , \tag{3}$$

where $\mathbf{R}_l$ and $\mathbf{t}_l$ denote the rotation matrix and translation vector of the object relative to the camera coordinate system for the l-th viewing direction, $\mathbf{A}$ the perspective projection matrix of the camera, and s a scaling parameter, respectively. Figure 3 illustrates the correspondence between $\mathbf{p}$ and $\mathbf{x}$. $\mathbf{R}_l$ and $\mathbf{t}_l$ are obtained from calibration data and the joint angles of the two robot arms [5]. $\mathbf{A}$ is also obtained by camera calibration. Since $\mathbf{p}$ usually does not coincide with the image grid, $\hat{I}_{jkl}(\mathbf{x})$ is computed from neighboring intensities by bilinar interpolation.

The surface points are chosen only within the triangle patches of the mesh model, because surface normal vectors, with respect to which surface spectral reflectance is modeled, are difficult to define on the vertices and edges of a raw mesh model acquired with a range finder. We sample surface points along a grid defined within each triangle patch [10], [11], as depicted in Fig. 3.

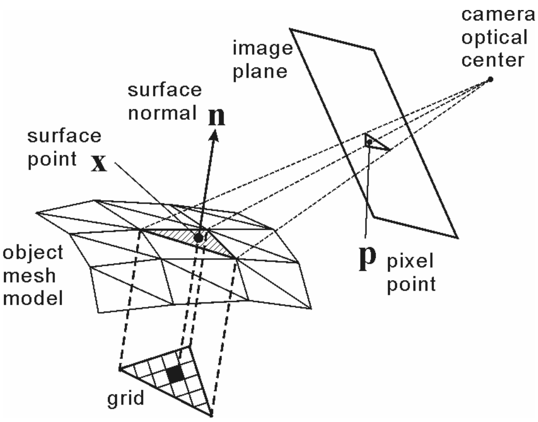


Figure 3: Image resampling at grid points within a surface patch of an object mesh model.

For each spectral channel and each direction of incidence and viewing, the resampled image intensity $\hat{I}_{jkl}(\mathbf{x})$ is averaged over $\mathbf{x}$, at the cost of losing spatial resolution of reflectance models. This averaging reduces errors in modeling surface spectral functions, which occur if the pixel location $\mathbf{p}$ to which the surface point $\mathbf{x}$ is imaged is not correctly obtained by Eq. (2) due to insufficient calibration of $\mathbf{R}_l$ and $\mathbf{t}_l$.

Estimation of Surface Reflectance Model Parameters

From the resampled image intensities $\hat{I}_{jkl}(\mathbf{x})$, we model surface spectral reflectance at each surface point $\mathbf{x}$. We are particularly interested in the Torrance-Sparrow (TS) model [1], [2] because it can be applied to quite a wide range of objects, especially for inhomogeneous dielectric materials such as oil, water, or plastic paints, which are the target in this paper. Consider a light reflection geometry on an object surface depicted in Fig. 4. For a light coming from the direction of a unit vector $\mathbf{i}$ with spectral irradiance $E(\lambda)$ and observed from the direction of a unit vector $\mathbf{e}$, the TS model expresses the spectral radiance of the reflected light as

$$L(\lambda,\mathbf{i},\mathbf{e}) = \alpha S(\lambda)E(\lambda)\cos\theta_i + \beta\frac{F(n,\theta_i)D(\theta_b,\gamma)}{\cos\theta_e}E(\lambda), \qquad (4)$$

where θ_i, θ_e and θ_b are the angles between the surface normal vector $\mathbf{n}$ and $\mathbf{i}$, $\mathbf{e}$, or their bisector $\mathbf{b} = (\mathbf{i}+\mathbf{e})/\|\mathbf{i}+\mathbf{e}\|$, respectively, as illustrated in Fig. 4. The first and second terms in Eq. (4) represent the diffuse and specular reflection components, respectively. $S(\lambda)$ denotes the diffuse spectral reflectance. $D(\theta_b,\gamma)$ denotes the Gaussian distribution function of microfacets inclined from $\mathbf{n}$ by θ_b, which accounts for the sharpness of specular reflection with a parameter γ

$$D(\theta_b,\gamma) = \exp\left(-\log 2\cdot\frac{\theta_b^{\,2}}{\gamma^2}\right). \qquad (5)$$

$F(n,\theta_i)$ denotes the Fresnel reflection coefficient for an inhomogeneous dielectric material of refractive index n

$$F(n,\theta_i) = \frac{1}{2}\left(\frac{g-\cos\theta_i}{g+\cos\theta_i}\right)^2 \cdot\left\{1+\left[\frac{(g+\cos\theta_i)\cos\theta_i - 1}{(g-\cos\theta_i)\cos\theta_i + 1}\right]^2\right\}, \qquad (6)$$

with $g = [n^2 + \cos^2\theta_i - 1]^{1/2}$. α and β are strength coefficients of the diffuse and specular reflection components, respectively. The geometrical attenuation factor [1], [2] is omitted since painted objects usually have fairly smooth surfaces.

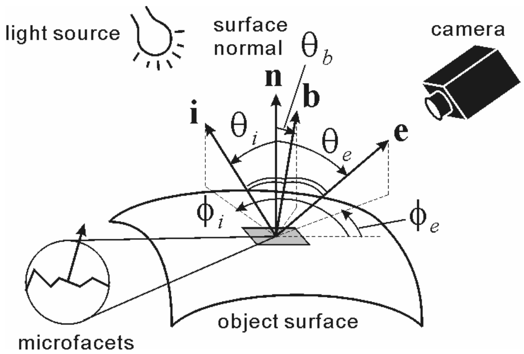


Figure 4:Geometry of light reflection on a surface.

For an object surface modeled by Eq. (4), our imaging system records an integral of the reflected light intensity in each channel in the visible range from 400 to 700 nm as a sensor output

$$\rho_j(\mathbf{i},\mathbf{e}) = \int_{400}^{700} L(\lambda,\mathbf{i},\mathbf{e})R(\lambda)d\lambda = \rho_{Dj}\cos\theta_i + \rho_{Sj}\frac{F(n,\theta_i)D(\theta_b,\gamma)}{\cos\theta_e}, \qquad (7)$$

where $R(\lambda)$ denotes the spectral sensitivity of the camera, ρ_{Dj} and ρ_{Sj} are defined as

$$\rho_{Dj} \equiv \alpha\int_{400}^{700} S(\lambda)E_j(\lambda)R(\lambda)d\lambda, \qquad (8)$$

$$\rho_{Sj} \equiv \beta\int_{400}^{700} E_j(\lambda)R(\lambda)d\lambda, \qquad (9)$$

and $E_j(\lambda)$ denotes the spectral power distribution of the j-th channel illuminant. In Eq. (7), the angles θ_i, θ_e and θ_b are known from the object mesh data, joint angles of the robot arms, and system calibration data. Hence the quantities $F(n,\theta_i)$ and $D(\theta_b,\gamma)$ are also known. The composite spectra $E_j(\lambda)R(\lambda)$ are obtained by measurement as plotted in Fig. 1(c).

Our task is to estimate the unknown parameters γ, n, ρ_{Dj} and ρ_{Sj} $(j=1,\cdots,8)$ of the model in Eq. (7) at each surface point $\mathbf{x}$ by fitting the image intensity $\hat{I}_{jkl}(\mathbf{x})$ to the sensor output model $\rho_j(\mathbf{i},\mathbf{e})$. To estimate γ, n, ρ_{Dj}, and ρ_{Sj}, we devised a recursive algorithm of Levenberg-Marquardt nonlinear estimation for all of these parameters by minimizing an error functional

$$J=\sum_{j,k,l}[\hat{I}_{jkl}(\mathbf{x})-\rho_j(\mathbf{i}_k,\mathbf{e}_l)]^2 . \qquad (10)$$

Initial values are determined from the maximum and average of $\hat{I}_{jkl}(\mathbf{x})$ for ρ_{Dj} and ρ_{Sj}, and specified empirically for γ and n. The estimation fails if $\hat{I}_{jkl}(\mathbf{x})$ contains no specular reflection. In this case, we estimate only ρ_{Dj} by neglecting the specular reflection component.

Estimation of Diffuse Spectral Reflectance

The diffuse spectral reflectance $S(\lambda)$ is important for accurate colorimetry and color reproduction of the object. We estimate it from the estimated ρ_{Dj} $(j=1,\cdots,8)$ in Eq. (7) using a Wiener filtering technique [6]. We omit α by including it in $S(\lambda)$ for convenience.

Following a framework of Wiener filtering, we begin with a noisy observation model of image acquisition for $S(\lambda)$ by discretizing Eq. (8) as

$$\boldsymbol{\rho}=\mathbf{P}\mathbf{s}+\boldsymbol{\varepsilon}, \qquad (11)$$

where $\boldsymbol{\rho}=[\rho_{D1},\cdots,\rho_{D8}]^T$ denotes the estimated diffuse reflection parameters ρ_{Dj}, $\mathbf{s}=[S(\lambda_1),\cdots,S(\lambda_N)]^T$ the diffuse surface spectral reflectance of the object at N discrete wavelengths λ_n, $\mathbf{P}$ a known $8\times N$ matrix whose (n,j) element is $E_j(\lambda_n)R(\lambda_n)$, and $\boldsymbol{\varepsilon}$ a white noise term in each spectral channel with a covariance matrix $\sigma^2\mathbf{I}$. $\mathbf{s}$ is then estimated as

$$\hat{\mathbf{s}}=\mathbf{P}^T(\mathbf{P}\boldsymbol{\Sigma}_{\mathrm{SS}}\mathbf{P}^T+\sigma^2\mathbf{I})^{-1}\boldsymbol{\rho}, \qquad (12)$$

where $\boldsymbol{\Sigma}_{\mathrm{SS}}$ denotes a correlation matrix of $\mathbf{s}$ over a large number of samples.

Experimental Results

3D Mesh Data Registration

Figure 5(a) shows a doll used as a 3D object in the experiment, which has color paints on its surface. We acquired 3D mesh data of the object using a Konica-Minolta VIVID 910 range finder. Figure 5(c) shows a part of the mesh data within the rectangle marked in Fig. 5(b). Each triangle patch of the mesh data has a dimension of about 0.3 mm.

To register the mesh data of this object, we also acquired mesh data of the reference object in Fig. 2(b), and applied the proposed registration algorithm. We estimated the rotation matrix $\mathbf{R}$ and translation vector $\mathbf{t}$ in Eq. (1). Using the estimates, we registered the mesh model of the reference object to its reference shape function with a root mean square error of 0.17 mm, whereas the catalog value of measurement accuracy of the range finder is about 0.1 mm. These results confirm that the proposed registration algorithm has successfully registered the 3D mesh data of the reference object to the measuring device coordinate system.

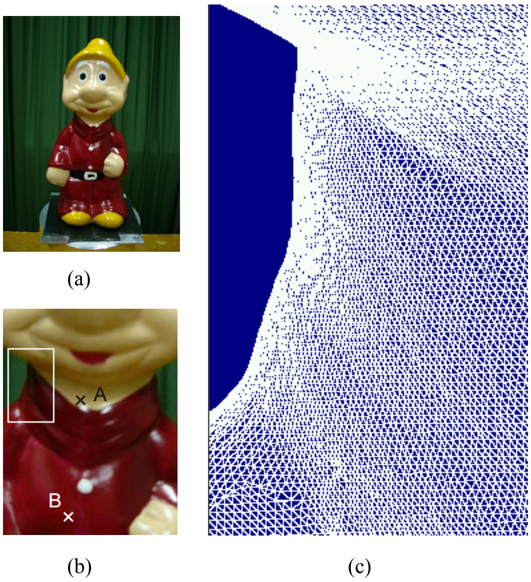


Figure 5: An object used in the experiment. (a) Frontal view. (b) Test surface points. (c) Part of the 3D mesh data within the rectangle area in (b).

Surface Spectral Reflectance Modeling

We captured gonio-spectral images using the measuring device in Fig. 1(a). The object in Fig. 5(a) was placed upright on one of the robot arm and rotated horizontally from 30° to 70° in 5° steps. For each object pose, the camera was also scanned horizontally from the frontal direction (0°) to 80° away in 1° steps. For each pose and position of the object and camera, eight-channel spectral images were captured. The images were processed for surface spectral reflectance modeling by the proposed algorithms.

For performance evaluation, we selected two points on the object surface as marked in Fig. 5(b). Figure 6 plots the curves of the TS function at surface point A modeled by the estimated parameters, with the abscissa representing the polar viewing angle of the pixel that observes A. Each single curve corresponds to a fixed incident angle of the illumination. The model curves are in good agreement with the image intensities. Similar fitting results were also obtained at point B.

Figure 7 plots the estimated diffuse surface spectral reflectances at A and B. The estimated reflectance in Fig. 7(b) agrees well to the spectrum obtained from a spectroradiometer. The reason the estimation in Fig.7(a) is not good is considered to be due to low intensities of the original gonio-spectral images at point B, especially for short wavelength channels.

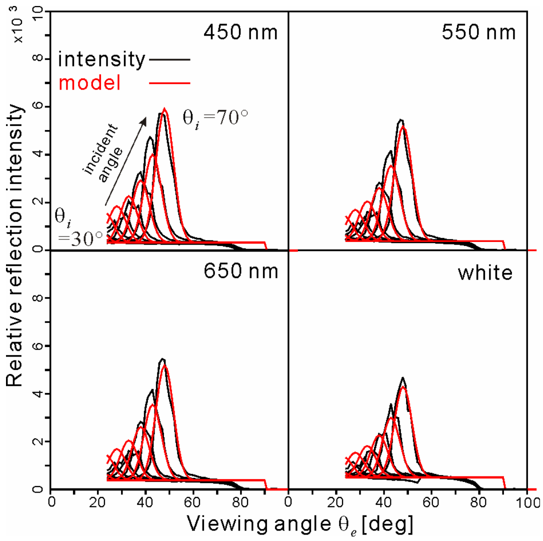


Figure 6: Results of surface reflectance modeling at surface point A. The curves are plotted against the polar viewing angle of the pixel corresponding to surface point A. Each single curve corresponds to a fixed incident direction of the illumination.

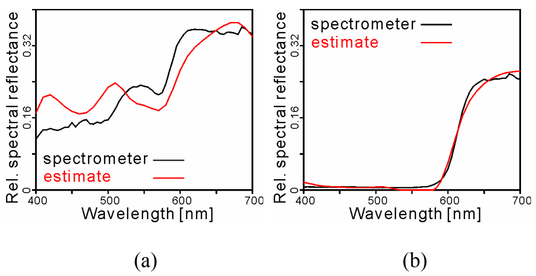


Figure 7: Estimated diffuse surface reflectances at surface points (a) A and (b) B.

Summary

We have proposed a total system for estimating the surface spectral reflectances of 3D painted objects of arbitrary shape. We proposed algorithms for registering the mesh data of the 3D painted object using a reference object, and also for modeling surface spectral reflectance at each point on the object surface from the gonio-spectral images captured by the measuring device.

We have sucessfully registered the mesh data with an accuracy of 0.17 mm. We have also conducted experiments on modeling surface spectral reflectance of a 3D painted object and found that satisfactory results have been obtained. We are currently making further analysis of the results to improve the system performance.

References

[1] K. E. Torrance and E. M. Sparrow. Theory for off-specular reflection from roughened surfaces. J. Opt. Soc. Am., 57(9):1105-1114, 1967.

[2] S. K. Nayar *et al.* Surface reflection: physical and geometrical perspectives. IEEE Trans. Pattern Anal. Machine Intell., 13(7):611-634, 1991.

[3] B. K. P. Horn. Robot Vision. 3rd ed., chap. 10, Cambridge: The MIT Press, 1986.

[4] K. J. Dana et *al.* Reflectance and texture of real-world surfaces, ACM Trans. Graphics, 18(1):1-34, 1999.

[5] A. Kimachi *et al.* Development and calibration of a gonio-spectral imaging system for measuring surface reflection. IEICE Trans. Inf. & Syst., E89-D(7):1994-2003, 2006.

[6] H. Haneishi *et al.* System design for accurately estimating the spectral reflectance of art paintings. Appl. Opt., 39(35): 6621-6632, 2000.

[7] S. Tominaga and N. Tanaka. Refractive index estimation and color image rendering. Pattern Recognition Letters, 24:1703-1713, 2003.

[8] G. J. Ward. Measuring and modeling anisotropic reflection. ACM SIGGRAPH '92, Comput. Graphics, 26(2):265-272, 1992.

[9] W. Matusik *et al.* A data-driven reflectance model. ACM SIGGRAPH '03, ACM Trans. Graphics, 22(3):759-769, 2003.

[10] Y. Sato *et al.* Object shape and reflectance modeling from observation. ACM SIGGRAPH '97, Comput. Graphics, 31:379-387, 1997.

[11] H. P. A. Lensch *et al.* Image-based reconstruction of spatial appearance and geometric detail. ACM Trans. Graphics, 22(2): 234-257, 2003.

[12] E. P. F. Lafortune *et al.* Non-linear approximation of reflectance functions. Proc. SIGGRAPH '97, 117-126, 1997.

[13] S. Grabli *et al.* Image-based hair capture by inverse lighting. Proc. Graphics Interface, 51-58, 2002.

[14] N. Tanaka and S. Tominaga. Measurement of surface reflection properties. IS&T/SID Ninth Color Imaging Conference, 52-55, 2001.

[15] H. Haneishi *et al.* Goniospectral imaging of three-dimensional objects. J. Imaging Science and Technology, 45(6):451-456, 2001.

[16] M. Tsuchida, *et al.* Development of BRDF and BTF measurement and computer-aided design systems based on multispectral imaging. Proc. AIC Colour 05, 129-132, 2005.