A Goniometric System for Measuring Surface Spectral Reflection Using Two Robot Arms

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Abstract

This paper proposes a gonio-spectral imaging system for measuring light reflection on an object surface using two robot arms, a multi-band lighting system, and a monochrome digital camera. It can change the incident and viewing angles of surface reflection with four degrees of freedom. The eight-band lighting system allows reliable spectral estimation of surface reflectance. The images captured for various incident and viewing angles are precisely warped as if they were all captured from the same viewing direction. This enables the proposed system to deal with objects with surface texture. Experiments on image warping, three-dimensional reflection measurement and spectral reflectance estimation are conducted for colored and textured objects. The results demonstrate the feasibility of the proposed imaging system.

Introduction

Knowing the behavior of light reflection on an object surface is important in a variety of image science studies, including color imaging, color image analysis, color reproduction, and image rendering [1][2]. The behavior of light reflection is mathematically described using a reflection model. A reflection model involves a number of physical parameters such as diffuse reflectance, specular intensity, and surface roughness [3].

The simplest system for estimating the reflection parameters is to use only a single RGB image captured for fixed illumination and camera geometry [4]. The generalized systems for reflection modeling are goniometric ones with variable angles of light incidence and viewing [5]. These systems, however, assumed that an object surface has a uniform colored material without texture. The systems accepting surface texture are based on simultaneous multi-point measurements [6]-[8], which use image pixels to sample different points of an object surface.

The spectral reflectance information is more important than color information for describing the object surface properties and rendering the object as digital images [9]. From the standpoint of spectral acquisition, the authors developed a measuring system consisting of a collimated light source, a turntable, and a six-channel camera [10]. This system had only two degrees of freedom in incident and viewing directions. Recently, a gonio-spectral imaging system was developed by Tsuchida *et al.* [11]. However, the system limited the object to a uniform colored surface and did not give any results of pixel-wise spectral reflectance measurement.

In this paper we propose a goniometric system for measuring surface spectral reflectance of an object using two robot arms, a multi-band lighting system, and a monochrome digital camera. The proposed system has the following features. First, it can change the incident and viewing angles of surface reflection with four degrees of freedom (4DOF). Second, a multi-band lighting system is constructed with seven narrow spectral bands and one broad band for reliable spectral estimation. Third, precise image warping is applied to spectral images obtained for various incident and viewing angles to ensure reliable measurement of three-dimensional (3D) surface reflection, based on calibration of the entire system including camera calibration and geometry calibration. Experimental results of image warping, 3D reflection measurement and spectral reflectance estimation for colored and textured objects are demonstrated.

Gonio-Spectral Imaging System

System construction

Figure 1 shows the proposed gonio-spectral measurement system consisting of two robot arms with six joints each, a multi-band lighting system, and a monochrome digital camera. One of the robot arms RA1 (Mitsubishi Electric RV-4A) holds an object on its end and rotates it around a fixed point on the surface of the object to change only its pose with three degrees of freedom (3DOF.) The other robot arm RA2 (Mitsubishi Electric RV-2A) hangs down a 10-bit monochrome digital CCD camera (Tokyo Electronic Industry CS3920, 1636x1236 pixels) from its end via a cantilever and rotates it horizontally to give 1DOF.

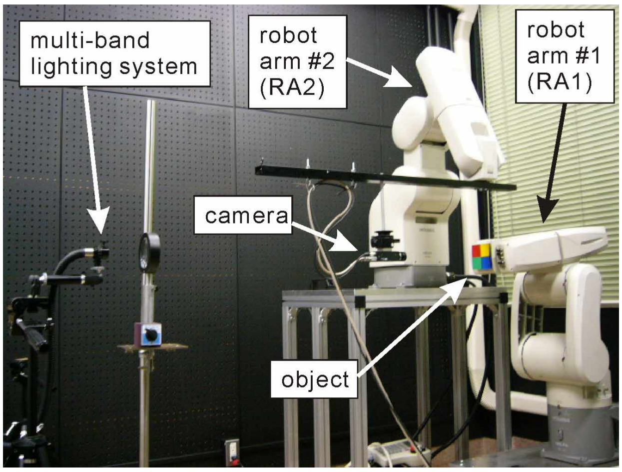


Fig. 1 Gonio-spectral imaging system consisting of two robot arms, a multiband lighting system and a monochrome digital camera.

Figure 2(a) shows the multi-band lighting system, which consists of a source unit (Asahi Spectra MAX301), a filter wheel with eight filter pockets, seven narrow-band filters, and an optical guide with a lens. The light source is a 300-W xenon lamp. The seven filters are of interference type with 10-nm bandwidth. The filters are set to the seven of the eight filter wheel pockets, leaving one pocket empty. Rotating the filter wheel to one of the eight pocket positions, the lighting system projects either a narrow-band light through one of the seven filters or one broad-band light through the empty filter pocket directly from the xenon lamp. The output light is collimated by a lens and illuminates the object horizontally.

Figure 2(b) shows the spectral characteristics of the entire imaging system. The spectral curves are calculated as the multiplication of the spectral power distributions of the eight-band light sources with the spectral sensitivity function of the monochrome camera. The spectral characteristics allow a stable imaging system with eight-spectral bands in the visible wavelength range of 400-700 nm. All movements of the robot arms, filter selection of the light source, and image acquisition of the camera are controlled by one personal computer via TCP-IP network, serial interface and an image capture board, respectively.

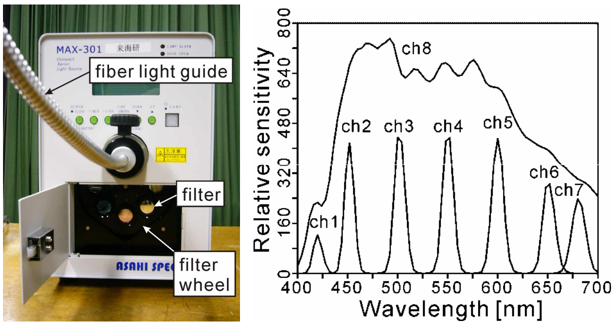


Fig. 2 Multi-band lighting system. (a) Light source unit with a filter wheel. (b) Spectral characteristics of the entire imaging system.

Image Warping

Light reflection is determined individually at each point of the object surface from images captured at a variety of incident and viewing angles. To model surface reflection, it is necessary to establish the same correspondence between pixel and surface point. To do this, we warp the captured images to a normalized form as if they were all viewed from the same frontal direction with respect to the object. This is done by finding the pixel location in the originally captured image that corresponds to a pixel in the frontal view image [8]. The accuracy of the warping heavily depends on that of the relative geometry of the object surface and the camera. To obtain this relative geometry accurately for any pose and position of the robot arms, we calibrate the camera and the whole system geometry. Once the calibration is done, we can obtain the relative geometry for each pose and position of the object and camera, using the calibration data and the joint angles of the two robot arms.

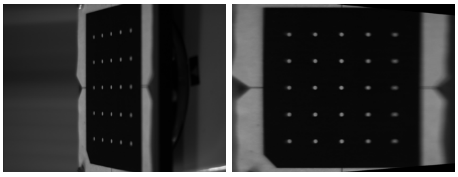
Reflectance Estimation

Most object surfaces in natural scenes are made of inhomogeneous dielectric materials. Light reflected from the surface is composed of two components, a diffuse component and a specular component. We estimate the 3D reflection properties from the goniometric data of the object surface. The Lambertian model and Torrance-Sparrow model are used as mathematical models for describing the diffuse component and the specular component, respectively. The model functions are fitted to the intensity profile of the warped images pixel by pixel for each spectral band, so that the 3D reflection model is determined at each surface point. This process yields the model parameters such as diffuse reflectance, specular intensity, and surface roughness. The diffuse spectral reflectance is estimated using noisy observations of eight sensor outputs of the imaging system. Thus, the surface spectral reflection is estimated at an arbitrary point on the object.

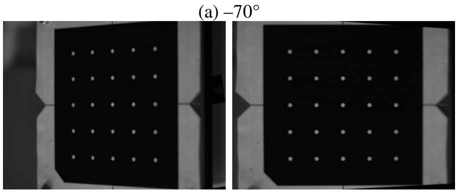
Experimental Results

Image Warping and System Calibration

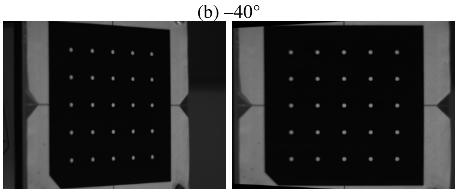
Figure 3 shows the image warping results. The images in the left column of Fig. 3 were captured for viewing angles of –70°, –40°, 40° and 70° of the camera. These images were all successfully warped to frontal view images, as shown in the right column of Fig. 3. These results also confirm that the system geometry is accurately obtained by calibration.



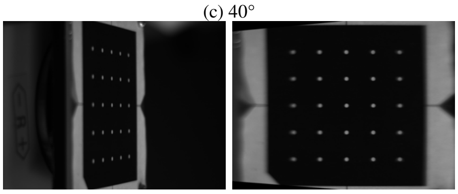
(a) –70°



(b) –40°



(c) 40°



(d) 70°

Fig. 3 Results of image warping for various viewing angles of the camera. Left: captured images. Right: warped images.

Fig. 4 Macbeth Color Checker used for spectral reflectance estimation.

Spectral Reflectance Estimation

Figure 4 shows the Macbeth Color Checker used for estimation of surface spectral reflectance. Figure 5 shows the spectral reflectance functions for the twelve color patches in the left half of the color checker, estimated by Wiener filtering [12]. Note that the estimated spectra agree well to the direct measurement results obtained with a spectroradiometer.

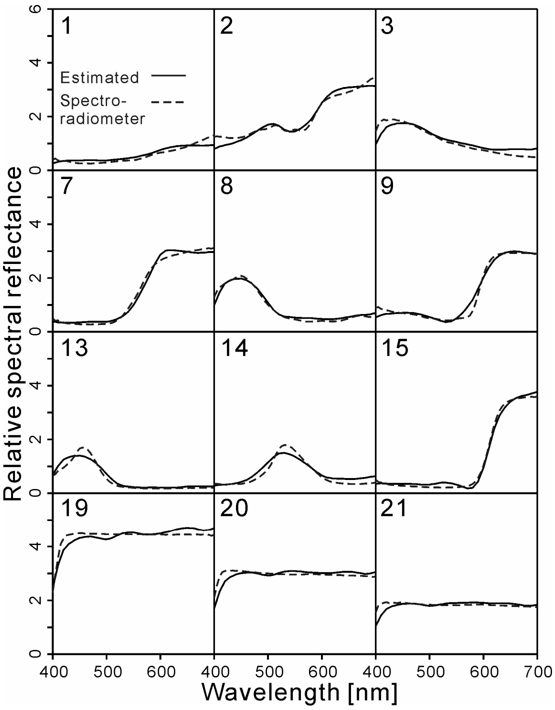


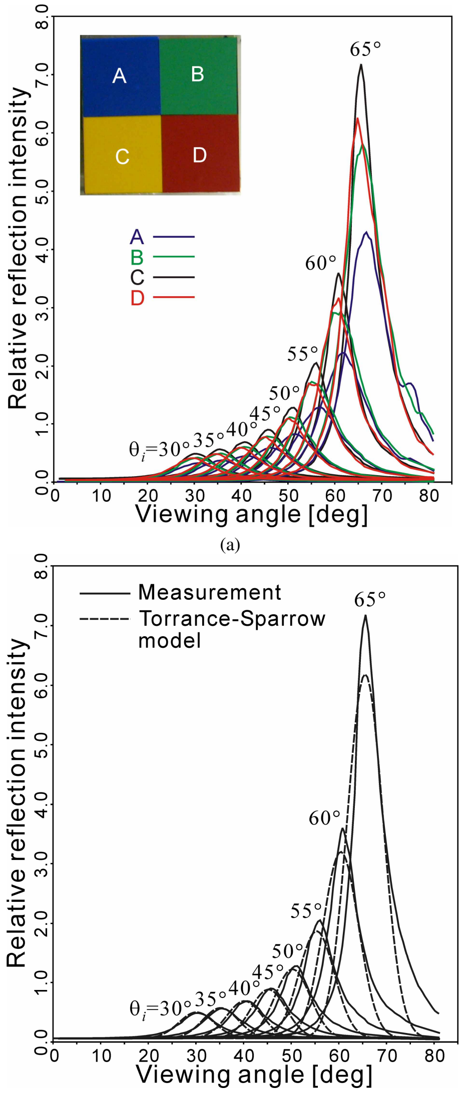
Fig. 5 Results of spectral reflectance estimation for the left half patches of the Macbeth Color Chekcer.

3D Reflection Measurement

Figure 6 shows the results of measuring 3D surface reflection for the object in the top-left part of Fig. 6(a). The object consists of four different color patches of plastic sheets. The incident angle of the illumination was varied from 30° to 65° in 5° steps. The camera was moved within the plane of incidence, with the viewing angle varied from 30° to 80° in 0.5° steps around the specular angle and in 5° steps otherwise. Each curve in Fig. 6(a) plots the intensity profile of light reflected on each color patch for each fixed angle of light incidence. Figure 6(b) compares the measured light intensity for patch C with Torrance-Sparrow model functions. It is seen in Fig. 6(b) that the plots of the measurement and model agree well.

Measurement on Textured Surface

Figure 7(a) shows an object with color surface texture. Spectral reflectance and 3D reflection intensity were measured at the locations indicated in Fig. 7(b). The pixel value of warped images was averaged over 10x10 pixels, which corresponds to a 0.5x0.5 mm^2 area on the object surface. Figure 8 plots the 3D reflection intensity at A and C, with the incident and viewing angles being the same as in the experiment in Fig. 6. Note that the plots exhibit intensity curves similar to those in Fig. 6, consisting of a constant diffuse component and a specular peak function. Figure 9 plots the estimated surface spectral reflectance at A and C along with direct measurements by a spectroradiometer. The result shows that the two spectra agree well at both locations.



(a)

(b)

Fig. 6 Results of measuring 3D surface reflection on color plastic sheets. (a) Measured intensities of reflected light for each color patch. (b) Comparison of the plots for patch C to a Torrance-Sparrow reflection model.

(a) (b)

Fig. 7 An object with surface texture. (a) Overview. (b) Measurement locations.

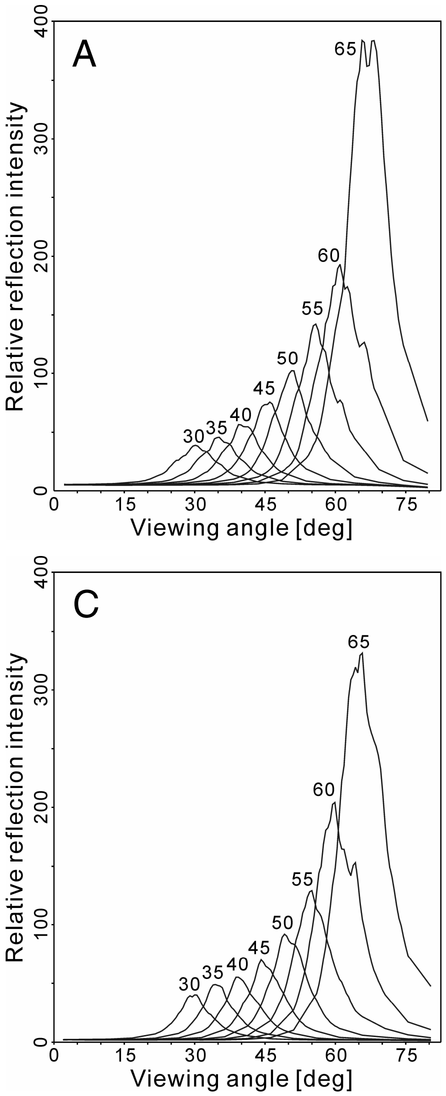


Fig. 8 Results of 3D reflection measurement for the textured object at locations A and C.

Summary

We have proposed a gonio-spectral imaging system for measuring surface reflection using two robot arms, a multi-band lighting system and a digital camera. Experimental results confirm that the proposed system has several advantages as follows:

1. It can measure 3D surface reflection by precise control of the incident direction of the illumination and viewing direction of the camera with 4DOF.
2. It can reliably estimate the spectral reflectance function from eight-band spectral images.
3. It can achieve point-wise measurement of surface reflection via precise image warping based on system calibration.

References

[1] S. Tominaga, T. Matsumoto and N. Tanaka, "3D recording and rendering of art paintings," *Proc. of the Ninth Color Imaging Conference*, pp.337-341 (2001).

[2] Y. Miyake, "Multispectral imaging: past, present and future," *Proc. of AIC Colour 05*, pp.447-479 (2005).

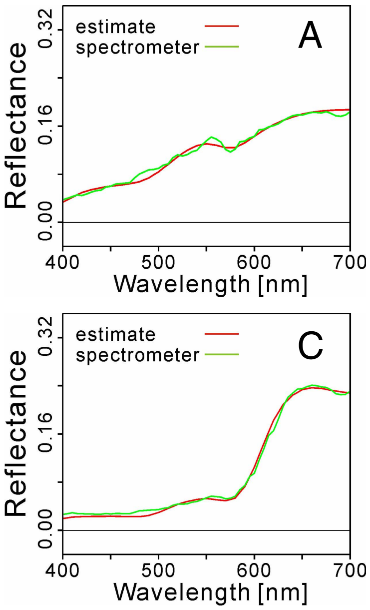


Fig. 9 Estimation results for surface spectral reflectance of the textured object at locations A and C.

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

[4] S. Tominaga and N. Tanaka, "Estimating reflection model parameters from a single color image," *IEEE Comput. Graph. Appl.*, **20**(15), pp. 58-66 (2000).

[5] S. R. Marschner *et al.*, "Image-based bidirectional reflectance distribution function measurement," *Appl. Opt.*, **39**(16), pp. 2592-2600 (1999).

[6] Y. Sato, M. D. Wheeler and K. Ikeuchi., "Object shape and reflectance modeling from observation," *ACM SIGGRAPH '97, Comput. Graphics*, **31**, pp. 379-387 (1997).

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

[8] M. L. Koudelka *et al.*, "Acquisition, compression and synthesis of bidirectional texture functions," *Proc. of the 3rd International Workshop on Texture Analysis and Synthesis*, pp.59-64 (2003).

[9] H. Haneishi *et al*, "Goniospectral imaging of three-dimensional objects," *J. Imaging Sci. Technol.*, **45**(6), pp.451-456 (2001).

[10] N. Tanaka and S. Tominaga, "Measurement of surface reflection properties," *Proc. of Ninth Color Imaging Conference*, pp. 52-55 (2001).

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

[12] M. H. Hayes, *Statistical Digital Signal Processing and Modeling*, Chap.7, John Wiley & Sons, New York (1996).

Author Biography

Akira Kimachi received his BE (1993), ME (1995) and PhD (1999) degrees in mathematical engineering and information physics from the University of Tokyo, Japan. In 2001 he joined Osaka Electro-Communication University, Neyagawa, Osaka, Japan. Since 2004 he has been an associate professor of the Department of Engineering Informatics. His research interest includes image sensing, photo-optical measurement, computer vision, image processing and imaging devices. He is a member of IEEE, OSA and SPIE.