Development of BRDF and BTF Measurement and Computer-aided Design Systems Based on Multispectral Imaging

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ABSTRACT

The system we present in this paper offers the possibility of simulating precise test production with CAD, including color, as if the real object were in front of the designers. It consists of an automatic multispectral BRDF and BTF measurement unit, a multispectral CG rendering unit, and a multi-primary color display. The color reproduction with this system is based on the Natural Vision technique. In addition, the concept of a virtual multispectral camera (VMSC) for synthesizing multispectral images with different numbers of bands is applied to CG rendering. This system can simulate the appearance of color even when the illumination spectrum is changed.

1. INTRODUCTION

The computer-aided design system (CAD) is quite a powerful tool, improving the efficiency of production development, especially in solid modelling. However, the current CAD does not perform sufficiently well in determining material and colors. One reason is that fairly simple analytical models have been used to approximate the surface's reflectance properties. They only work well for a small set of materials such as plastics or metals, which is why most computer graphics (CG) today still look like "plastic". Another difficulty is simulating the appearance of color as if the real object were in front of the designers. The Bidirectional Reflectance Distribution Function (BRDF) or Bidirectional Texture Function (BTF) has often been used[1] to improve the simulated quality of surface textures. BRDF represents the statistical bidirectional reflectance properties of the textured surface. BTF represents variations in the image texture with viewing and illumination directions, and can model fine-scale shadows, occlusions, and specularities caused by surface microstructures. Although the quality of simulated images has improved a great deal[2], the color-reproduction problem still remains.

The system we present in this paper offers the possibility of simulating precise test production with CAD, including color, as if the real object were in front of the designers. It consists of an automatic multispectral BRDF and BTF measurement unit, a multispectral CG rendering unit, and a multi-primary color display. The image rendering process is divided into image rendering with geometrical calculation and color rendering with spectral calculation, which enables us to illumination replacement without geometrical calculations such as ray-tracing. The color reproduction with this system is based on the Natural Vision technique[3]. In addition, the concept of a virtual multispectral camera (VMSC) for synthesizing multispectral images with different numbers of bands[4] is applied to CG rendering. This system can simulate the appearance of color even when the illumination spectrum is changed. Final goal of our project is achievement of high-fidelity color, gloss and texture reproduction on computer graphic system using multispectral BTF. We have already developed the measurement system. Although BTF-based rendering has not implemented on our system yet, we can confirm the ability of our system for color reproduction by using multispectral BRDF calculated from the multispectral BTF. At the viewpoint of color reproduction using multispectral data, BRDF- and BTF-based rendering are quite similar, we think, except for texture stitching. Then, we focus on image rendering using multispectral BRDF in this paper.

2. METHOD

Geometrical coordinates and image-capturing model

An observed reflected spectrum from a point on object is calculated as follows. Let rendering illumination spectrum and spectral reflectance be $W(\lambda)$ and $f(\phi,\theta,\varphi,\psi,\lambda)$ (see Figure. 1). The observed spectrum $v(\phi,\theta,\varphi,\psi,\lambda)$ is represented as

$$v(\phi,\theta,\varphi,\psi,\lambda) = W(\lambda) f(\phi,\theta,\varphi,\psi,\lambda), \tag{1}$$

where ϕ and θ are angular parameters representing the direction of incident light, φ and ψ are angular parameters representing the viewing direction and λ is wavelength.

Let $\mathbf{f}(\phi,\theta,\varphi,\psi)$ be the spectral reflectance of the object represented in a M-dimensional space. Let $\mathbf{W}$ be a $M \times M$ matrix whose diagonal elements represent a rendering illumination spectrum. Equation (1) can be rewritten into vector representation as

$$\mathbf{v}(\phi,\theta,\varphi,\psi) = \mathbf{W}\mathbf{f}(\phi,\theta,\varphi,\psi), \tag{2}$$

Let us consider that N-bands $\mathbf{c}(\phi,\theta,\varphi,\psi)$ was obtained using our BRDF/BTF measurement unit. Let $\mathbf{H}$ be a $N \times M$ matrix, the row vectors of which represent the sensitivity of each band of the camera. When spectral reflectance $\mathbf{f}(\phi,\theta,\varphi,\psi)$ is estimated from camera signal $\mathbf{c}(\phi,\theta,\varphi,\psi) = \mathbf{H}\mathbf{W}\mathbf{f}(\phi,\theta,\varphi,\psi)$ as

$$\hat{\mathbf{f}}(\phi,\theta,\varphi,\psi) = \mathbf{G}\mathbf{c}(\phi,\theta,\varphi,\psi), \tag{3}$$

equation (2) is rewritten as

$$\mathbf{v}(\phi,\theta,\varphi,\psi) = \mathbf{W}\hat{\mathbf{f}}(\phi,\theta,\varphi,\psi) = \mathbf{W}\mathbf{G}\mathbf{c}(\phi,\theta,\varphi,\psi), \tag{4}$$

where $\mathbf{G}$ is the Wiener estimation matrix obtained from $\mathbf{H}$ and a priori knowledge about the spectral reflectance of objects.

Multispectral BRDF capturing

The angular parameters, ϕ,θ,φ and ψ are changed and multispectral BTF is captured page by page. All pixel values on the images for each band were averaged to obtain the multispectral BRDF. Then, these data $\mathbf{c}(\phi,\theta,\varphi,\psi)$ are recorded in a table along with data on different illumination angles to create a database.

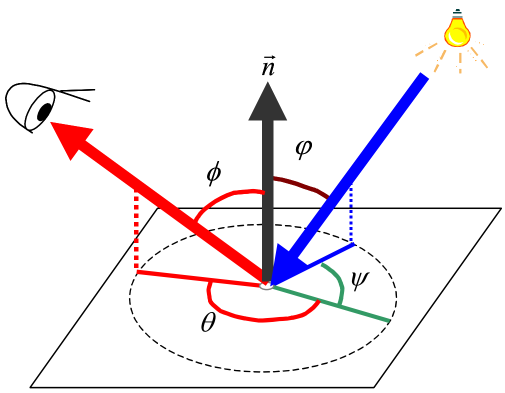

Figure 1: Geometrical coordinates.

Multispectral CG rendering

First, the angular parameters, ϕ,θ,φ and ψ for all pixels are specified by ray-tracing and a N-bands multispectral computer graphics is rendered using averaged camera signal $\mathbf{c}(\phi,\theta,\varphi,\psi)$. Note that $\mathbf{c}(\phi,\theta,\varphi,\psi)$ should not be divided or multiplied with vector corresponding to illumination spectrum for keeping spectral accuracy in this process. This geometrical calculation is done for all pixels on image and a multispectral CG is generated. The multispectral CG and the Wiener estimation matrix $\mathbf{G}$ are saved on PC.

Next, the multispectral CG is transferred into a spectral image using rendering illumination spectrum $\mathbf{W}$ and the matrix $\mathbf{G}$. Finally, the spectral image is converted into display signals for multi-primary color display[3].

According to this method, geometrical calculations for $\mathbf{c}(\phi,\theta,\varphi,\psi)$ are done in N-dimensional space of N-bands measurement system, which enables us to avoid increasing the amount of calculation. In addition, rendering illumination spectrum can be changed without any geometrical calculations such as ray-tracing. When there are some kinds of BRDF or BTF data which are measured by different kind of multispectral camera or spectroradiometer, the idea of VMSC[4] can be applied to obtain N-bands multispectral data.

3. EXPERIMENTAL SYSTEM

Automatic BRDF and BTF measurement unit

Using this measurement system, 4-D multispectral BRDF and BTF are obtained. The measurement unit consisted of a digital monochrome camera and a lighting-direction-control unit and multi-band illumination (see Figure. 2). The lighting-direction-control unit was in a box to avoid ambient illumination light. This unit is 80 x 80 x 80 cm and weighs 60 kg, enabling us to use it in an office environment. A target object, with a maximum size of 4 x 4 cm, was fixed on a table in the centre of the lighting-direction-control unit. With an object of this size, the table rotates 360 degrees vertically and horizontally. Each stage or table rotates at intervals of 1 degree and is controlled from a PC. This unit also includes an arm on which a lens and light guide are mounted. This enables the object to be illuminated from every angle. Light from xenon lamps was decomposed by, at a maximum, 16 narrow band-pass filters attached to a rotating turret and controlled from a PC (Figure. 3). Light from the xenon lamp was decomposed by 16 narrow band-pass filters attached to a rotating turret and the extracted light was guided to the lens attached to the top of an arm on the lighting-direction-control unit through an optical fiber. A target object was fixed on the stage and could be illuminated from all surrounding angles. The camera was fixed and multispectral images of the object were taken at different lighting and different viewing angles. A digital monochrome camera (ORCA-ER-1394, Hamamatsu Photonic) was used in our system. The size of the sensor is almost 1 x 1 k and the signal depth is 12 bits. Our system supports a multi-exposure mode to expand the dynamic range of the camera, and 16-bit images can be obtained. In addition, we could replace the camera with a spectroradiometer to measure spectral information more precisely.

BRDF-based rendering software

The obtained BRDF data was read into consumer CG software (AliasWavefront Maya™) to enable rendering with plug-in software (developed by Digital Fashion Ltd.). Figure 4 shows a screen

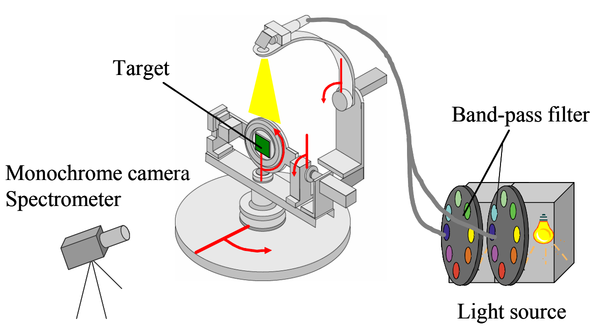

Figure 2: BRDF and BTF measurement unit.

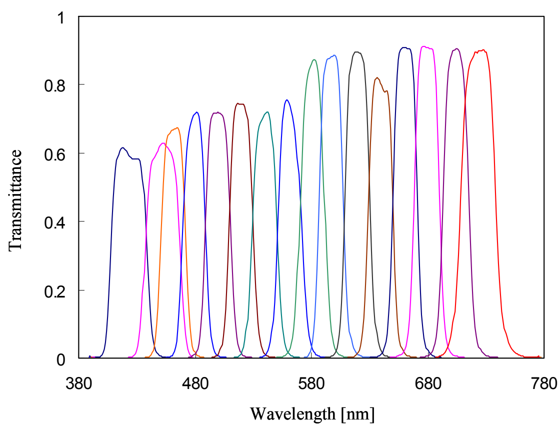

Figure 3: Spectral transmittance of 16 narrow band-pass filters.

shot of this software. The speed of BRDF-based rendering was almost the same as when Phong's shading or other general algorithms were used for software rendering. To render multispectral images using this software, the multispectral BRDF were decomposed into several 3-channel BRDF and 3-channel images of each BRDF were synthesized. After image rendering, each 3-channel image was combined into a multispectral image.

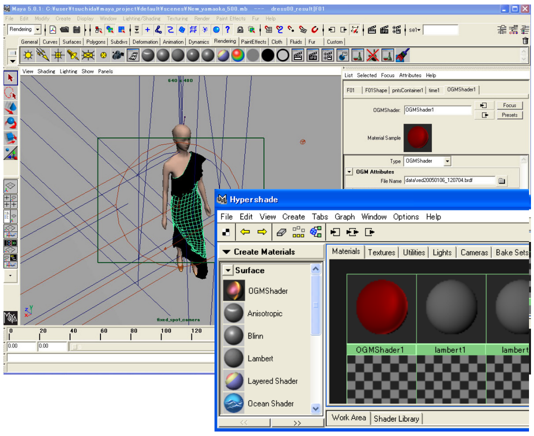

Figure 4: Screen shot of rendering software.

4. RESULTS

We made a simulation movie of a red dress with our system. First, BRDF of the red cloth (satin) was measured (see Figure 5). The interval between each different angle was 20 degrees (almost 6500 samples) and it took 13 hours to obtain the multispectral BRDF. Figure 6 has two frames of the movie. The movie was played on a 6-primary DLP projector[5] and visually compared with a "real" dress. Although the "real" dress did not move, we gained almost the same feeling for the material and color from the simulation movie.

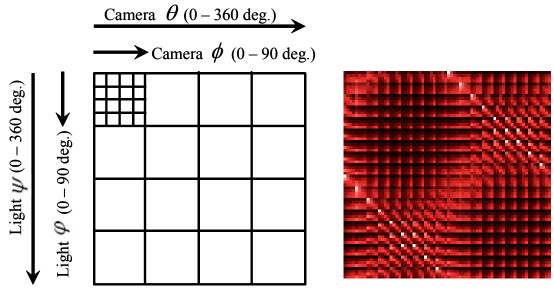

Figure 5: Captured BRDF.

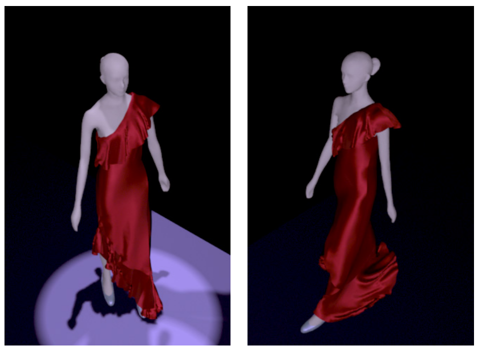

Figure 6: Simulation results for red dress.

5. CONCLUSIONS

We described a computer-aided design system that can simulate accurate color and gloss reproduction, based on multispectral acquisition and rendering To produce this system, we developed a compact BRDF and BTF measurement system, and a plug-in software of a consumer CG software for BRDF-based rendering. Our system supports 4-D multispectral BRDF, the data for which can be measured within a practical length of time. In future work, we intend to do similar experiments with other materials and evaluate color differences numerically. And BTF-based rendering will be implemented.

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