Spectral Reflection Modeling for Image Rendering of Water Paint Surfaces

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Abstract

This paper describes a method for measurement and analysis of surface reflection properties of water paints under a variety of conditions. First, a gonio-spectro photometer is used for measuring the radiance factor of a painting surface at different incidence and viewing angles. Then, we analyze the reflection properties of water paint. A 3D light reflection model is derived based on the Torrance-Sparrow model and the Oren-Nayar model. An algorithm is presented for determining the model parameters including specular coefficient, diffuse roughness, specular roughness, refractive index from the observed spectral reflectance data. Finally, we show the validity of the proposed model in experiments and render color images of water-painted objects by using the estimated parameters.

Introduction

In recent years, digital archiving attracts attention for recording historic buildings, art objects, artifacts and so on by digital image information. The authors are much interested in digital archiving of art paintings [1][2]. Because the digital archives are appreciated under various illumination and viewing conditions, it is necessary to render the image based on inherent information of a painting surface. The surface-spectral reflectance presents an inherent physical property of the painting surface. Image rendering uses a 3D reflection model for precisely simulating the light reflection from a painting surface. The reflection model can describe various reflection properties mathematically, including shading, gross, specular reflection, and surface roughness. Thus, the spectral reflectance and the reflection model are absolutely necessary for realistic image rendering of art paintings.

In the previous work [3], we investigated the reflection properties of art paintings. The materials were limited to oil paints. We measured gonio-photometrically various object surfaces of oil paints and analyzed the surface reflection properties. As a result, the Cook-Torrance model [4] described well the 3D reflection properties of oil painting surfaces.

On the other hand, the reflection property of water paint on a drawing paper is quite different from the one of oil paint on a canvas. This reason can be considered that the reflection property changes by the quantity of water that is medium, and the surface reflection is strongly affected by the support. Therefore the reflection is much more complicated than the reflection on oil paints, and it is difficult to describe the appropriate surface reflection model mathematically.

In this paper, first, we measure light reflected from various water painting surfaces by using a gonio-spectral photometer. Next we analyze the surface reflectances of water painting objects observed under different conditions. Then we derive a new model for well describing the surface reflection properties. We present an algorithm for determining the model parameters from the observed spectral reflectances. Finally, in experiments we show good fitting results of the proposed model functions to the measured radiance factor and some image rendering results.

Measuring system

Gonio-spectrophotometric measurement is used for determining the reflection properties of painting materials. For making samples, we painted different paint materials on black acrylic plates and drawing papers with an applicator. In the gonio-meter system, the sensor position is fixed, and the light source can rotate around the sample as shown in Figure 1. The ratio of the radiance from the sample to the one from the reference diffuser, called the radiance factor, is output as reflectance.

Figure 2 shows an example of the spectral radiance factors measured from Cobalt Blue Hue that is blue water paint, where the incidence angle is 40 degrees and the spectral curves are depicted as a function of viewing angle. The paint surface was rough and did not have strong specular reflection at any viewing angle.

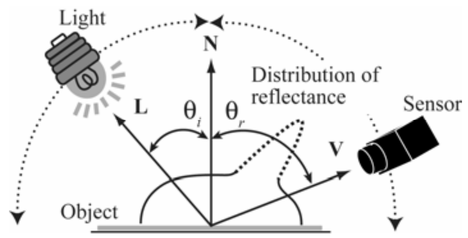


Figure 1. *Surface reflectance measurements*

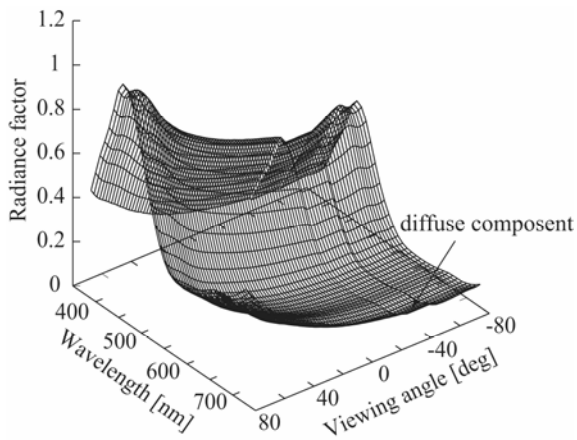


Figure 2. *Spectral radiance factors measured from a water-painted paper*

Reflection analysis of water paints

Let us considers the reflection properties of water painting surfaces. Surface appearance of water paint on a drawing paper is quite different from the one of oil paint on a canvas. The water paint surface includes little gross and specular highlight, but it is often textured and rough. The medium of water paint is water and the supporting material is a drawing paper. The medium evaporates soon after painting and the surface reflection is strongly affected by the support. Thus, the reflection is much more complicated than the reflection on oil paints.

Figure 3 shows a set of samples of water paints which were painted on black acrylic boards and on white papers. Three color paints called Cadmium Red, Hooker's Green, and Cobalt Blue Hue were painted on the papers (upper) and on the plastic (lower) in Figure 3. Water painting on black plastic boards is rare usage, but the painting on white papers is general usage. In the latter case, we cannot neglect the influence of absorption and reflection by the supporting paper. The reflectance properties depend on the supporting materials.

Light reflection on the plastic board can include not only diffuse reflection of the paint but also strong specular reflection. On the other hand, light reflection on the paper can include little specular reflection, but mostly diffuse reflection and inter-reflection.

The reflection properties depend greatly upon the quantity of water. Figure 4 shows the observed radiance factors from Cobalt Blue Hue on paper with different quantities of water, in case of the incident angle is 40 degrees. In case of water quantity is 0% or 20%, the highlight peak appears at specular reflection angle. On the other hand, the highlight peak is getting lower with water quantity and backscattering appears in the diffuse reflection. It can be considered that the painting surface becomes rougher as the quantity of water increases. Therefore, it is difficult to mathematically modeling the surface reflection in the same way as oil paintings.

Figure 3. *Water paint samples*

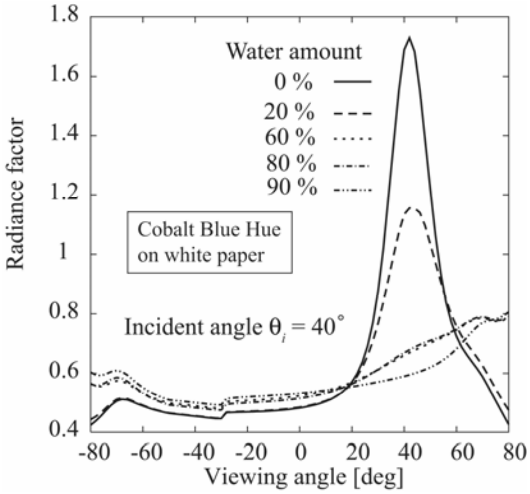


Figure 4. *Observed reflectances with different water quantities*

3D reflection model

Painting materials can be regarded as inhomogeneous dielectric substances. Light reflected from the paint surface is composed of two different reflection components; the diffuse reflection and the specular reflection. The specular reflection is mirror-like; the reflected light can be seen only over a narrow range of viewing geometries. The reflection property of two additive components is called the dichromatic reflection. The characterization is summarized well by Cook and Torrance. The specular term is derived from the Torrance-Sparrow model [5].

The spectral radiance factor $Y(\lambda)$ from a painting surface is modeled as a function of the wavelength λ as

$$Y(\lambda) = S(\lambda) + \beta' \frac{D(\varphi,\gamma)G(\mathbf{N},\mathbf{V},\mathbf{L})F(\theta_Q,n)}{\cos\theta_i \cos\theta_r}, \qquad (1)$$

where the first and second terms represent, respectively, the diffuse and specular reflection components. α and β are respectively the diffuse and specular reflection coefficients. A specular surface is assumed to be an isotropic collection of planar microscopic facets by Torrance and Sparrow. The area of each microfacet is much smaller than the pixel size of an image, and so the surface normal vector **N** represents the normal vector of a macroscopic surface. Let **Q** be the vector bisector of an **L** and **V** vector pair, that is, the normal vector of a microfacet. The symbol θ_i is the incidence angle, θ_r is the viewing angle, φ is the angle between **N** and **Q**, and θ_Q is the angle between **L** and **Q**.

The specular reflection component consists of several terms: D is the distribution function of the microfacet orientation, and F represents the Fresnel spectral reflectance of the microfacets. G is the geometrical attenuation factor.

The above model is effective for describing surface reflection on a thick paint layer on an opaque-waterproof support. However, let us consider water paint on paper. The painting material is then absorbed in the paper. In this case, surface reflection does not show the dichromatic reflection property of the inhomogeneous dielectric material.

The Oren-Nayar model [6] is used for describing diffuse reflection of a rough surface without specular reflection. The diffuse radiance is expressed in two terms as follows:

$$Y_d(\lambda) = Y_d^1(\lambda) + Y_d^2(\lambda), \qquad (2)$$

where the first and second terms represent, respectively, the direct reflection component by illumination and the indirect reflection component by interreflection. θ_i and ϕ_i are the elevation and azimuth angles for incident light, θ_r and ϕ_r are the elevation and azimuth angles for viewing. The parameter σ_d represents surface roughness. The direct illumination component of radiance Y_d^1 is given as follows

$$Y_d^1(\lambda) = \frac{S(\lambda)}{\pi}\Big[C_1(\sigma_d) + \cos(\phi_r-\phi_i)C_2(\alpha,\beta,\phi_r-\phi_i,\sigma_d)\tan\beta + (1-|\cos(\phi_r-\phi_i)|)C_3(\alpha,\beta,\sigma_d)\tan\left(\frac{\alpha+\beta}{2}\right)\Big], \quad (3)$$

where $\alpha = \max(\theta_r, \theta_i)$ and $\beta = \min(\theta_r, \theta_i)$. The detailed descriptions for the terms C_1, C_2 and C_3 are given in Ref.[6]. Moreover, the interreflection component Y_d^2 is given as follows

$$Y_d^2(\lambda) = 0.17\frac{S(\lambda)^2}{\pi}\frac{\sigma_d^2}{\sigma_d^2+0.13}\left[1-\cos(\phi_r-\phi_i)\left(\frac{2\beta}{\pi}\right)^2\right]. \quad (4)$$

Our analysis results show that the Oren-Nayar model is useful for the limited range of viewing angle. As the angles of incidence and viewing increase, a discrepancy between the model and the observed reflectance enlarges. We note that the observed reflectance is much larger than the diffuse reflection model. The reflection curve increases monotonically as shown in Figure 2. From these considerations, we add a specular term to the original Oren-Nayar model.

We propose a composite reflection model of combining the diffuse function of the Oren-Nayar model and the specular function of the Torrance-Sparrow model. The total radiance factor is then described as

$$Y(\lambda) = Y_d(\lambda) + \beta'\frac{D(\varphi,\gamma)G(\mathbf{N},\mathbf{V},\mathbf{L})F(\theta_Q,n)}{\cos\theta_i\cos\theta_r}. \quad (5)$$

The unknown parameters in this model are the coefficient β', the diffuse roughness σ, the specular roughness γ and the refractive index n. The reflectance models are fitted to the observed spectral radiance factors by the method of least squares. In the fitting computation, we used the average radiance factors on wavelength in the visible range. We can use a priori knowledge about physical parameters. First, the refractive index n of water paint is assumed to be larger than the refractive index of water 1.3 because the assumption of inhomogeneous dielectric for water paint. Moreover, the diffuse roughness σ and the specular roughness γ are assumed to be larger 0.01 empirically. The weighting coefficient β' is determined in an arbitrary range. Then, minimize the squared sum of the fitting error

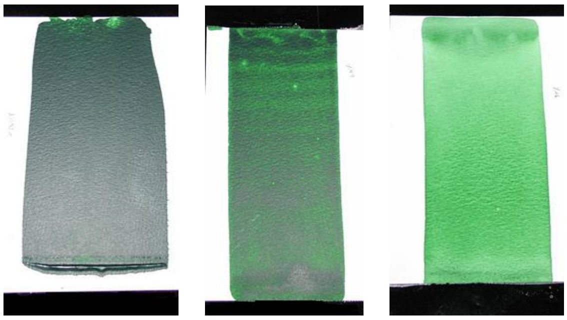
$$e = \min\sum_j\left\{Y(j)-\hat{Y}(j)\right\}^2, \quad (6)$$

where $Y(j)$ is j-th measurement of the radiance factors acquired from the gonio-photometer and $\hat{Y}(j)$ is the corresponding model estimate. The optimal parameters are determined to minimize the error in the given ranges of the parameters.

Experimental results

We have examined the validity of the proposed reflection models for a variety of water paint surfaces. The samples of water paints are shown in Figure 5. Figure 5 shows samples of water paints on the paper where the same water paint of Hooker's green was used with different quantities of water. The notation x % indicates that the quantity of added water is equal to x percent of the weight of the original paint. Note in Figure 5 that surface colors are different with the quantity of water.

The reflection models were fitted to the observed radiance factors by the fitting algorithm. In the fitting computation, we used the average radiance factors on wavelength in the visible range. Figure 6 shows the fitting results for Hooker's Green on the acrylic board shown in Figure 3. The proposed model was used for curve fitting at incident angles 10, 20, ⋯, 60 degrees. The parameters were estimated as $\sigma = 0.35$, $\gamma = 0.05$, $\beta' = 126.0$, and $n = 1.40$. Although water paints on the acrylic board have sharp specular reflection, the proposed model provides good fitting results.



(a) 0 % (b) 60% (c) 90%

Figure 5. *Water paints on paper with different quantities of water*

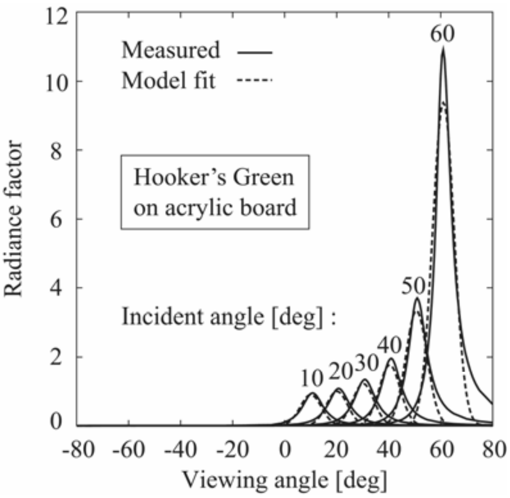
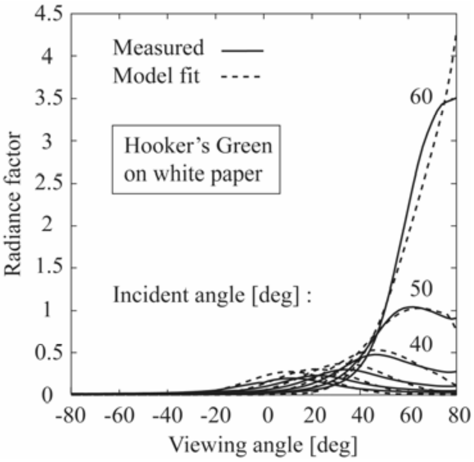
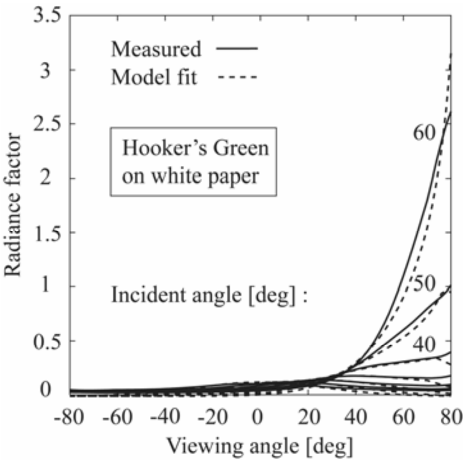


Figure 6. *Fitting result of proposed model on acrylic board*

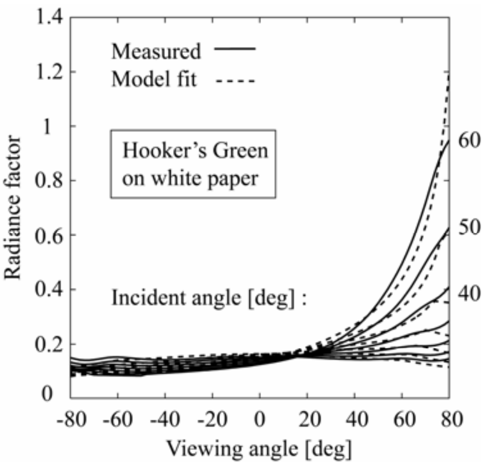
Our model was applied to the observations shown in Figure 5. Figure 7 shows the fitting results to the paint sample with the water quantity 0%, 60% and 90 % at various incident angles, respectively. The model parameters were estimated as $\sigma = 0.2$, $\gamma = 0.2$, and $\beta' = 1\ 5.7$ $n = 1.7$ in case of water quantity 0%, $\sigma = 0.3$, $\gamma = 0.07$, and $\beta' = 7.6$ $n = 1.70$ in case of water quantity 60%, $\sigma = 0.5$, $\gamma = 0.08$, and $\beta' = 1.6$ $n = 2.42$ in case of water quantity 90%, respectively. We have good fitting results to the whole reflectance curves including the highlight area and the backscattering area. In most art paintings, we use paints diluting with water on papers. We have confirmed that the proposed composite reflection model works well for most water paintings.



(a) Water quantity 0%



(b) Water quantity 60%

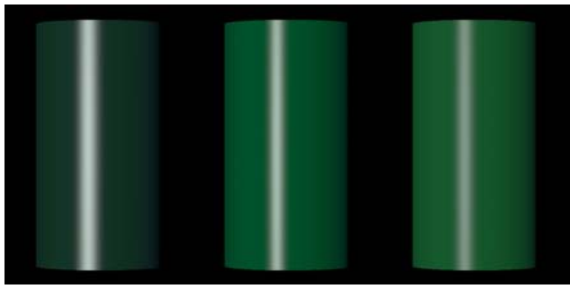


(c) Water quantity 90%

Figure 7. *Fitting results of proposed model to water paint on paper*

Rendering application

We render color images by using the proposed reflection model and the estimated reflection parameters. The ray-tracing algorithm based on wavelength computation was used for realistic 3D images of painted objects under arbitrary conditions of illumination and viewing. Figure 8 demonstrates the computer graphics images of a cylinder painted with Hooker's green. We assume that the illuminant is D65 with parallel beam and the incident angle is 20 degree. Comparison with between three pictures in Figure 8 shows clearly difference in appearance caused by the estimated reflection parameters. Moreover, these pictures greatly represent the feature in Figure 5. That is, although the color of painting surface is deep and the highlight is strong in case of a small amount of water, the saturation of object color decreases and the highlight becomes weaker as the water quantity increases.



(a) 0 % *(b) 60%* *(c) 90%*

Figure8. *Rendering result with estimated parameters*

Conclusion

We have measured water painting surfaces under a variety of conditions and analyzed the surface reflection properties in detail. First, we have used a gonio-spectral photometer for precisely measuring light reflected from a variety of painting surfaces. The painting surface becomes rougher as the quantity of water increases. Moreover, the highlight peak is getting lower with water quantity and backscattering appears in the diffuse reflection. Next we derive a composite model of the Cook-Torrance model and the Oren-Nayar model. The proposed model has been used for describing the 3D reflection properties of water painting surface even if the water quantity has changed. Moreover, we present an algorithm for determining the model parameters from the observed spectral reflectances. Finally, we have rendered color images of the three types of objects by using the estimated reflection parameters.

References

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