3D Recording and Rendering of Art Paintings

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Abstract

This paper proposes a method for recording and rendering of art paints using both shape and spectral reflectance properties of the object surfaces. A laser range finder is used for measuring the surface shape. A six-channel camera is used as a multiband camera for spectral imaging. We propose a method for precisely estimating surface-spectral reflectance using a set of the reflectance observed at different illumination directions and the constructed shape of the object surface. At the rendering stage, we use a 3D light reflection model for creating computer graphics images. The recovered object shape and spectral reflectance are combined for synthesizing object images under arbitrary conditions of illumination and viewing. Experiment results using an oil painting of a natural scene are shown.

Introduction

So far the digital archives for art paintings have been based on surface spectral information of the object surfaces (see [1]-[3]). The spectral reflectance information is more important than color information for recording and rendering of paintings as digital images. However, realistic images of art paintings cannot be created by the surface-spectral reflectances alone, because its geometric condition of illumination and viewing is fixed to the original image.

Let us suppose an oil painting. The surface material of this object consists of a thick oil layer. The surface is not smooth. Although the surface is rough, gloss and highlight appear on the surface. The whole effect including shading and specular reflection provides us a realistic feel of the material of oil paints. If only the diffuse component of the object surface is used for image rendering, specular highlights and glosses cannot be represented correctly in the synthesized images. Moreover, if highlights are observed in the original painting, the highlights are treated as diffuse texture and, therefore, remain on the surface permanently regardless of illuminating and viewing conditions.

The present paper proposes a method for recording and rendering of art paints using both shape and spectral reflectance properties of the object surfaces. The shape and spectral reflectance are the inherent surface properties. We acquire the 3D shape and spectral reflectance data for recoding the object surfaces by using separate measuring systems. The two types of measurements are then combined for rendering the object under arbitrary conditions of illumination and viewing by a computer graphics technique.

Figure 1 depicts the flow for digital archives of art paints from measurement to image rendering. Estimation of surface-spectral reflectance is an important stage. The surface of a painting has the dichromatic reflection property that light reflected from the surface is composed of two additive components, the body (diffuse) reflection and the interface (specular) reflection. The spectral reflectance function is then estimated from the diffuse reflection component. We propose a precise estimation method using a set of the reflectance observed at different illumination directions and the constructed shape of the object surface. At the rendering stage, we use a 3D light reflection model for creating computer graphics images. Finally, the recovered shape and spectral reflectance are combined for synthesizing object images with realistic shading effects under arbitrary conditions of illumination and viewing.

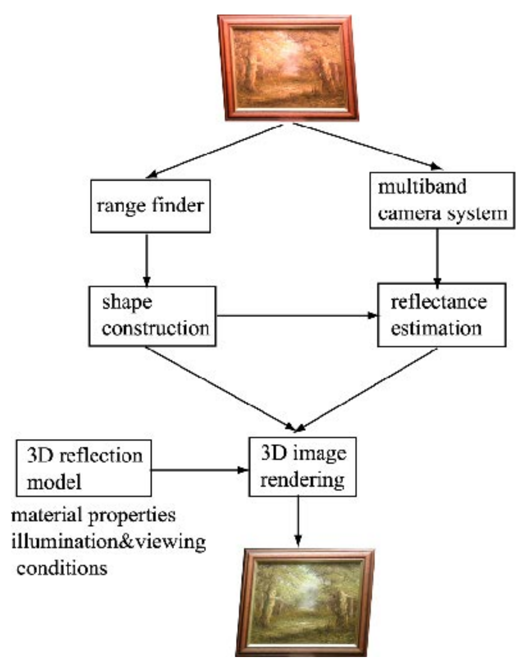

Figure 1 Flow for digital archives of art paints from measurement to image rendering.

Measuring System

Figure 2 depicts the measuring system. First, we use a laser range finder for 3D measurement of the surface shape of a painting object. In this system, a horizontal stripe laser beam is emitted to the surface. This light produces a bright spot on the surface that is imaged by a calibrated CCD camera. The 3D position of the spot is then reconstructed by triangulation. This process is repeated by scanning the stripe light vertically on the object surface to obtain a 3D image data. We transform a set of measured 3D points into the data of triangular meshes to represent the 3D surface.

Second, a six-channel camera is used as a multiband camera for spectral imaging. The camera system is composed of a monochromatic CCD camera, a standard photographic lens, six color filters, and a personal computer. The camera outputs are described as

$$\rho_k = \int E(\lambda) S(x, \lambda) R_k(\lambda) d\lambda \ , \ (k = 1, 2, ..., 6) \quad (1)$$

where $E(\lambda)$ is the illuminant spectral-power distribution, $S(x, \lambda)$ is the surface-spectral reflectance at the spatial location x on an object, and $R_k(\lambda)$ is the spectral sensitivity functions of the sensor k.

The spectral imaging by this multiband camera is repeated at different illumination directions as shown in Figure 3. The angle of elevation is about 45-degree for all the light sources. The illumination direction is precisely determined using two specular mirrored balls. Eight sets of the spectral reflectances for a painting object are analyzed to estimate the most suitable function of spectral reflectance without such noisy effects as specularity, shadowing, and masking.

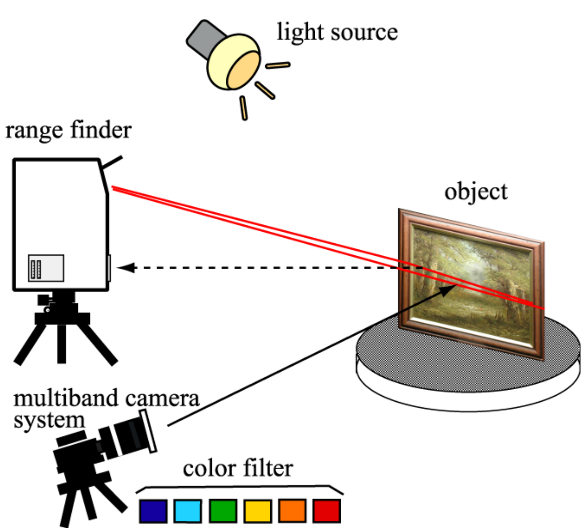

Figure 2 Measuring system for a painting object.

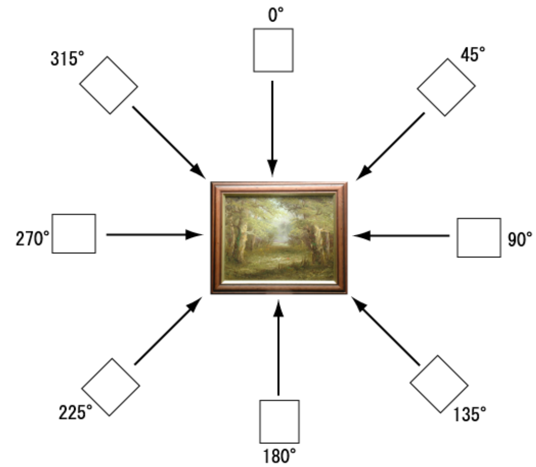

Figure 3 Illumination directions.

Reflectance Estimation

A linear finite-dimensional model is used to represent the surface spectral function. This model is effective in the sense that the number of unknown parameters can be reduced significantly when surface-spectral reflectance functions with continuous spectra are represented by only a small number of basis functions. The spectral reflectance function $S(x, \lambda)$ can be expressed as a linear combination of n basis functions as

$$S(x, \lambda) = \sum_{i=1}^{n} \sigma_i(x) S_i(\lambda) \ , \quad (2)$$

where $\{S_i(\lambda), i = 1, 2, ..., n\}$ is the set of basis functions for the reflectance, and $\{\sigma_i(x)\}$ is the set of weights. Because the basis functions are known, given the above formulation in terms of linear models, the estimation problem becomes one of inferring the set of weight coefficients $\{\sigma_i(x)\}$ from the camera outputs.

As we use six spectral bands, the model dimension n is bounded to be six or less. The number is set to n=5 in this study. A database of surface spectral reflectances for about 500 different objects was used for our reflectance analysis. The five principal components of this set of reflectances are selected as the basis functions $\{S_i(\lambda), i = 1, 2, ..., 5\}$. The estimation of $\{\sigma_i(x)\}$ is done using the algorithms shown in Ref. 4

The most suitable reflectance function is determined using the estimated reflectances at different illumination directions and the constructed shape of the object surface. This process is composed of three steps: (1) check on shadow and masking, (2) selection of diffuse reflectance, and (3) correction.

(1) Check On Shadow and Masking:

We examine that each pixel point of the image is properly illuminated by a light source. If the pixel point belongs to a shadow area or a masking area, reflectance estimated for the illumination direction is discarded from the candidate set of the reflectance function.

We construct the surface shape by complexes of triangular patches with shared vertices. Note that the appearance of an object's visible patch is affected by other patches. Figure 4 shows two effects of shadowing and masking on an object surface. The upper figure represents the shadow cast by a patch. The patches in the shadow area are shielded by other patches. If the patch A casts a shadow on the patch B, then we know that A is between B and a light source. Therefore, the problem of determining that B is shielded can be reduced to finding an intersection between a viewing ray (shadow ray) from B to the light source and any other patch. This shadow examination requires the intersection analysis for all triangular patches constructing the object surface. To perform the intersection analysis effectively, we develop an algorithm based on the Octree data structure that is a hierarchical structure of spatial-occupancy enumeration.[5]

The lower figure in Figure 4 shows a patch that is shielded from the light. Note that the patch C is masked. Examination of masking is performed easily by inner product between two vectors. Let **L** be the light directional vector and **N** be the surface normal vector of the patch C. If $(\mathbf{N}\cdot\mathbf{L}) \le 0$, then the surface patch is shielded.

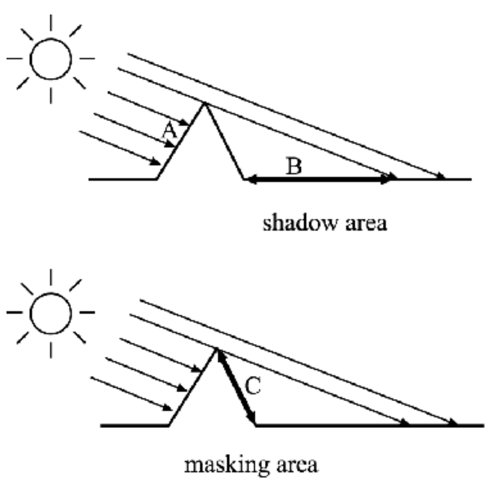

Figure 4 Shadowing and masking effects on an object surface.

(2) Selection of Diffuse Reflectance

The second step is to select the most suitable reflectance among the remaining candidate reflectances, except for the case of shadow or mask. These reflectances are obtained under a proper light source. Note that the reflectance is not necessary estimated from the diffuse component of the dichromatic reflection. It is possible that the estimated reflectance includes the specular reflection component. To exclude the specular component, we calculate the vector lengths of all spectral reflectances and select the spectral reflectance with the minimal length as the most suitable reflectance function.

(3) Correction

The final step is to correct the non-uniformity of illumination and the slant of reflecting surface. A standard white board is used as a reference white for calibrating non-uniform illumination. These corrections can be performed by the form

$$S'(x,\lambda) = \left(S(x,\lambda)/\cos(\theta_i)\right)\Big/\left(W(x)/\cos(\theta_W)\right), \quad (3)$$

where θ_i is the angle of light incidence at x on the object surface, θ_W is the incidence angle at the corresponding location on the standard white board, and $W(x)$ is a relative reflectance value of the white board.

3D Reflection Model and Image Rendering

The Torrance-Sparrow model is used as a 3D light reflection model for creating computer graphics images. The spectral radiance $Y(x,\lambda)$ is a function of the spatial location x and the wavelength λ, which is described as

$$Y(x,\lambda) = \alpha\cos(\theta_i)S(x,\lambda)E(\lambda) + \beta\frac{D(\varphi)G(\mathbf{N},\mathbf{V},\mathbf{L})F(\theta_i,n)}{\cos(\theta_r)}E(\lambda), \quad (4)$$

where the first and second terms represent, respectively, the diffuse and specular reflection components. **V** is the view vector, θ_i is the angle of incidence, θ_r is the viewing angle, and φ is the angle between the vector **N** and the bisector vector of **L** and **V**. The estimated reflectance $S'(x,\lambda)$ in Eq.(3) is used as $S(x,\lambda)$ in the diffuse reflection term. $E(\lambda)$ is the spectral distribution of illumination of an expected light source.

The specular reflection component in Eq.(4) consists of several terms: First, D is a function providing the index of surface roughness defined as $\exp\{-\ln(2)\varphi^2/\gamma^2\}$, where the parameter γ is constant. Second, G is a geometrical attenuation factor. Third, F represents the Fresnel spectral reflectance, where n represents the index of refraction. The surface material of a paining object can be regarded as an inhomogeneous dielectric material like plastic. The index of refraction is constant and the absorption coefficient is zero over the visible wavelength. Therefore the Fresnel term $F(\theta_i,n)$ is constant on wavelength. We determine the reflection parameters of α, β, γ, and n empirically.

A ray tracing algorithm is adopted for image rendering using the above 3D reflection model and the 3D shape data. Thus, realistic images of a painting object are created under arbitrary conditions of illumination and viewing.

Experimental Results

Figure 5 shows an oil painting of a natural scene. The object surface was illuminated by a slide projector at eight directions and photographed by the maltiband camera from the normal direction. The rectangular areas, Part 1 and Part 2 in Figure 5 indicate two parts of the trunk of a tree in the scene. These parts of surface are rough and correspond to a thick layer of oil paints. Figure 6 represents the surface shape of Part 1 constructed by regular meshes. The range data in coordinates (X, Y, Z) are depicted in the unit of mm. We can see big roughness at the edges of the trunk. The difference in height between peak and valley is less than 1 mm.

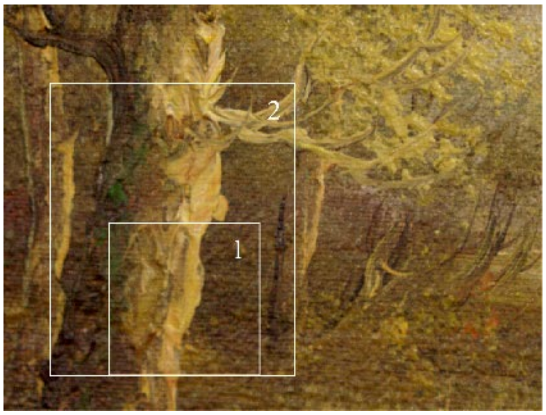

Figure 5 Oil painting of a natural scene.

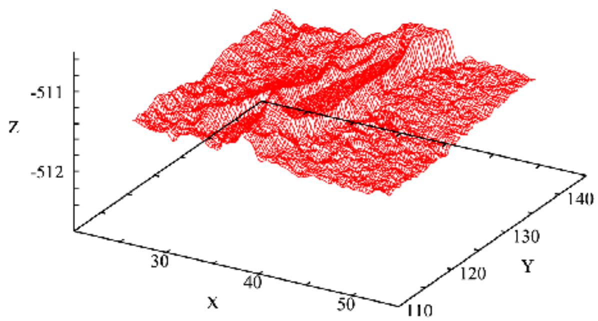

Figure 6 Shape by regular meshes for part 1.

Despite a small change of the surface shape, the surface appearance remarkably changes as illumination and viewing directions change. We have created computer graphics images of Part 2 to be seen under D65. We used numerical values of β/α=5.0, γ=0.1, and n=1.45. Figure 7 shows a set of the created images at different illumination directions. The elevation angle of illumination was set to 40-degree for all the images.

From the image at 0-degree we see that the greater parts of the painting object are specularly reflected with the color of the light source. The contrast between highlights and shades imitates reality of the 3D painted object. Next, we note that the location of shadow on the surface depends on illumination direction. For example, compare the shadow location between the right and left images, such as 45-315, 90-270, and 135-225. Shadows appear at different locations along the edges of the trunk.

Finally, the validity of the created CG images was confirmed by a visual experiment. The images displayed on a calibrated CRT monitor were compared with the real painting observed under a lamp of D65. Color reproduction on the CRT monitor was done in two steps of (1) color coordinate transformation and (2) Gamma correction. First, the tristimulus values of each image pixel were transformed into the RGB values by a transformation matrix, and second the RGB values were corrected into the practical monitor RGB digital values by a lookup table.

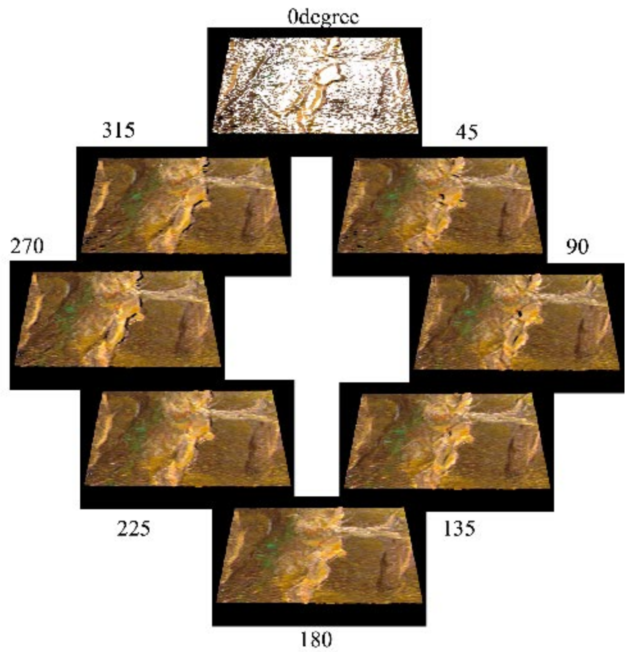

Figure 7 CG images for part 2 under D65 at different illumination directions.

Conclusion

Using the surface-spectral reflectance alone limits the image creation of art paintings to the fixed geometric conditions of illumination and viewing when the original image was captured. Shape information as well as spectral reflectance information is important for the digital archives of art paintings. The paintings should be recorded and rendered as three-dimensional (3D) objects.

The present paper has proposed a method for recording and rendering of art paints using both shape and spectral reflectance properties of the object surfaces. A laser range finder was used for measuring the surface shape. A six-channel camera was used as a multiband camera for spectral imaging. At the estimation stage of surface-spectral reflectance, we have proposed a precise estimation method using a set of the reflectance observed at different illumination directions and the constructed shape of the object surface. At the rendering stage, we have used a 3D light reflection model for creating computer graphics images. The recovered object shape and spectral reflectance were combined for synthesizing object images under arbitrary conditions of illumination and viewing. Experiment results using an oil painting of a natural scene have shown the feasibility of the proposed method.

References

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