Recovering normal vectors and albedo under uncontrolled illumination with an RGB digital camera

Clara Plata, Juan Luis Nieves, Eva Valero, Javier Hernández-Andrés, Javier Romero.

Departamento de Óptica, Facultad de Ciencias, Universidad de Granada 18071 Granada (SPAIN); email: cplata@ugr.es;

Abstract

This paper proposes a spatio-spectral imaging device to simulate and acquire color images under different geometries of illumination. The method allows image analysis and synthesis, even for rough-textured surfaces, under different directions of the incident illumination. In addition the use of the albedo instead of directly the RGB information helps to avoid any shadows or highlights that might falsify results. For accurate color reproduction under uncontrolled illumination conditions an RGB digital camera is used in combination with a 4-source-based photometric stereo algorithm to estimate the normals at each image point and the albedo of the surfaces at each pixel. The experimental results show good colorimetric accuracy in the color reproduction of artificial texture objects.

1. Introduction

Color appearance in object imaging depends upon several factors: the imaging device and geometry, the lighting conditions and the object itself. When dealing with textured objects these factors become more evident, in particular when the 3 dimensional nature of texture is considered. The surface relief and surface reflectance can change the color appearance of such objects (e.g. keeping fix the position of the camera and the object, color appearance changes if we change the direction of illumination) resulting in a problem for object characterization. So, if we want to extract information from images of textured objects it will be useful to find a way to do it independent on lighting and imaging geometries.

Albedo can be defined as the fraction of the incident light reflected by a surface, which, when the surface is being imaged by a camera, is filtered by the camera's spectral sensitivity and can be affected by light intensity [1]. The main advantage of dealing with the albedo is that it is unaffected by the shape of the object. While the RGB values at a pixel of an imaged object can vary depending on the geometry of illumination, the spectrum of the illumination, the total intensity, etc., the albedo does not. That is the reason why albedo is a very attractive way of characterizing a textured surface.

There are several methods that allow obtaining the shape of a surface, like laser scans or different techniques that uses images captured with a CCD camera with that end [2]. These last techniques, which are usually called photometric stereo techniques, are especially interesting due to the fact that they allow the simultaneous recovery of color (related to the albedo of the surface) and the normal vector at each point of the surface [3-6]. Albedo can be used to simulate the chromatic appearance of objects (either uniform or textured) under a fixed illuminant but at different illumination angles. This can be useful in image simulation and psychophysical experiments. So, if we want to extract information from images of textured objects it will be useful to find a way to do it independent on lighting and imaging geometries.

All photometric stereo algorithms usually start from the constraint of Lambertian surfaces, i.e. surfaces that present the same radiance in all directions of illumination, to recover normals and albedo. Thus when images are visually inspected there are no highlights or cast shadows at all. In real objects those situations are not very common, meaning that the photometric stereo algorithm may fail in many real situations. For that reason, several authors [4,6,7] have developed different strategies with the aim of avoiding those non-Lambertian behaviors. In a previous work [8] we introduced a calibration method where a set of seven samples of different colors was used. Each sample was composed by five chips made with the same material (polymer clay) and having the same color. It was found that correcting for highlights and shadows lead to an improvement of about 50% in the accuracy of the recovering procedure thereby making technique suitable for visual applications.

This paper proposes a spatio-spectral imaging device to render images under different geometries of illumination. For accurate color reproduction under uncontrolled illumination conditions an RGB digital camera is used in combination with a 4-source-based photometric stereo algorithm and device to estimate the normal vectors and the albedo values at each pixel of the imaged surface. We introduce a calibration color set of samples, which is composed by uniform and non-uniform color textures, to evaluate the albedo values recovered by the photometric stereo method. Though different experiments it is confirmed that good colorimetric accuracy for color reproduction is achieved, even for textured objects under different kinds of fluorescent illuminations.

2. Methods

Photometric stereo fundamentals

Let's suppose a Lambertian surface, what means that the surface reflects light equally in all directions. We define the albedo ρ of such surface as the fraction of the incident light reflected by de surface. If we capture with a CCD camera a surface with albedo ρ and normal vector **N** in each point, which is illuminated with a source of light with a lighting direction **L** (see figure 1), the intensity at each pixel of the image can be described by:

$$I = \rho\left(\mathbf{L}\cdot\mathbf{N}^T\right) \tag{1}$$

where ***I*** is the intensity at one pixel, ρ is its albedo, **L** is the lighting (1x3) vector, **N** is the unitary (1x3) normal vector, T represents the transposed matrix and (·) represents the dot product of two vectors.

Since we want to recover the normal vector at each pixel we will need at least three equations to solve for that system. We can recover the normal vector at each point by illuminating the surface successively from three different lighting directions $\mathbf{L}^1$, $\mathbf{L}^2$, and $\mathbf{L}^3$ and can rewrite Eq.(1) as:

$$I^k = \rho\left(\mathbf{L}^k\cdot\mathbf{N}^T\right) \tag{2}$$

where k= *1, 2, 3* are the three lighting directions. The three intensities can be stacked to form the intensity vector $\mathbf{I} = \left(I^1, I^2, I^3\right)$, and the lighting directions can be stacked row wise giving the lighting matrix $\left[\mathbf{L}\right] = \left(\mathbf{L}^1, \mathbf{L}^2, \mathbf{L}^3\right)$. If the lighting directions $\mathbf{L}^k$ are not coplanar, matrix [**L**] can be inverted, giving:

$$\left[\mathbf{L}\right]^{-1}\mathbf{I} = \rho\mathbf{N} \tag{3}$$

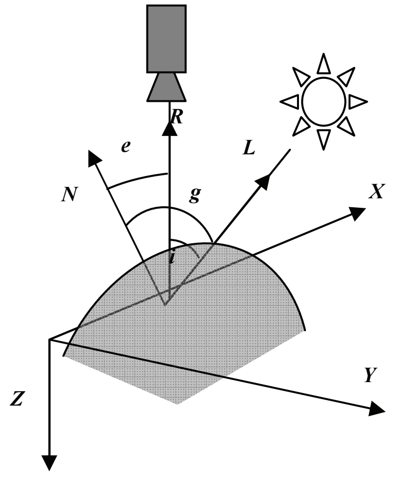


Figure 1: *Definition of the important vectors and reflectance angles for a CCD camera pointing to –z:* ***R****, viewer vector;* ***L****, illuminant vector;* ***N****, normal vector; i, incident angle; e, emittance angle; g, phase angle.*

Since normal vector **N** is unitary, both the normal vector (as the direction of the obtained vector) and the albedo (its modulus) can be recovered [1].

The first photometric stereo techniques were developed for gray images [2, 7] and did not take into account that intensities ***I*** at a pixel may depend on the spectrum of the light impinging on the object surface. There are several complex ways of extending photometric stereo to color images [3, 4, 9]. The one used in this work is just applied to each channel of our color images, by treating the R, G, B channels as independent gray channels. This method has a very low computational cost and has provided very good results [1].

Albedo recovery and image synthesis

We have introduced a four-source-based photometric stereo algorithm that detects if one of the intensities from a quadruplet contains a shadow or a highlight. We have developed an algorithm to decide the most appropriate actuation in each pixel of the image, depending on the values of the four intensities obtained for it.

For every pixel *x*, the average of the four intensities $\mathbf{I}^x = \left(I_1^x, I_2^x, I_3^x, I_4^x\right)$ is calculated as:

$$I_{mean}^x = \frac{\sum_{i=1}^{4} I_i^x}{4} \tag{4}$$

Next the difference between I_{mean} and the maximum and minimum values of intensity obtained for this pixel are defined as:

$$\mathbf{Mm}^x = \left(\max\left(\mathbf{I}^x\right) - I_{mean}^x, I_{mean}^x - \min(\mathbf{I}^x)\right) \tag{5}$$

and the selection process is made by analyzing the values of $\mathbf{Mm}^x$ in the following way:

1. If the highest value of this vector is the first one, the quadruplet contains a highlight, and the albedo value and normal vector will be recovered avoiding the highest value contained on I^x.

2. If the highest value of this vector is the second one, the quadruplet contains a shadow, and the albedo value and normal vector will be recovered avoiding the lowest value contained on $\mathbf{I}^x$.

3. If both components of $\mathbf{Mm}^x$ are the same or very similar, we can have two different situations:
   - The four intensities have Lambertian behavior, i.e. they have similar values.
   - In the quadruplet of intensities only two of them have Lambertian behavior and the other two are shadows or highlights.

   The actuation in the above two cases is the same: calculating the four albedo values and normal vectors from the four combination of the four intensities taken in groups of three and averaging results.

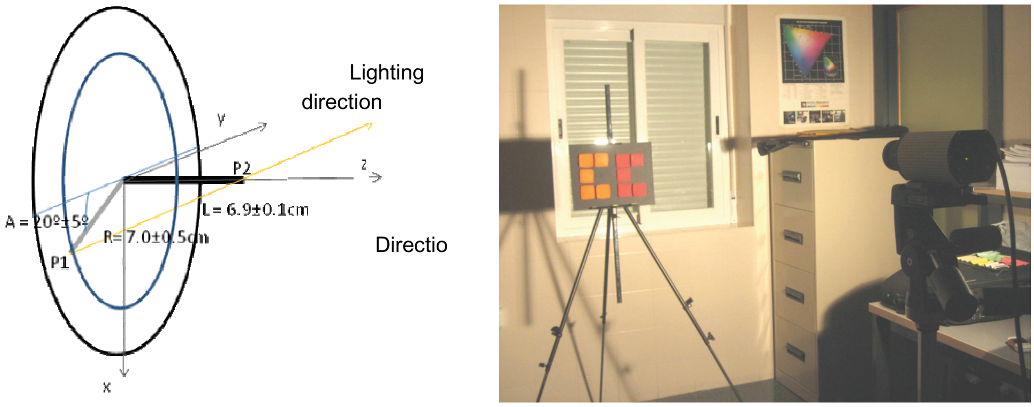


Figure 2: *(Left) Example of determination of the lighting direction using the sun-clock like card; (right) experimental setup.*

The above algorithm applies to each channel in a separate way to obtain albedo and normal vector at a pixel in each channel. Combining the obtained results for all channels we can obtain in each pixel the "color albedo" and, averaging the three obtained normal vectors, a normal vector for that pixel.

If the above method is going to be applied to real situations it will be necessary to evaluate the lighting directions when making a capture (e.g. under outdoors daylight conditions). To solve for this issue we have used a sun-clock like card to estimate the lighting directions through the angle (with an error of 5°) and the length (with an error of 0.5 cm) of the shadow projected by the stick onto this card (figure 2).

It's easy to demonstrate that the elevation angle θ and the slant angle φ can be calculated through the expressions:

$$\theta = \arctan\left(\frac{R}{L}\right) \quad ; \quad \varphi = A - 180^{\circ} \qquad (6)$$

where R is the length of the shadow, A is its angle and *L* is the stick's length.

This process was used to determine the lighting directions when the light source was placed in four different positions to obtain the four images required to apply the recovery algorithm.

3. Experiment and results

Calibrating an algorithm that allows albedo recovery is not an easy task. There are no devices capable of measuring it, so is not possible to have reference values to compare with. With the aim of having a method to evaluate the accuracy of recovered albedo, in the present work we introduce a set of calibration color samples. Although it is easy to find several kinds of color charts that can be used to calibrate different systems and devices, none of them contains textured samples. The proposed calibration samples set is composed by thirty five samples of different texture characteristics (figure 3), made with polymer clay whose commercial name is FIMO. The samples are organized in seven sets of five samples of the same color (pale pink, yellow, orange, red, green, blue and purple), having each one of the five samples of the same color different textures (flat, random, convex hemispheres, irregular in one direction and concave hemispheres).

Having a flat sample allows us using the albedo values recovered from it as reference albedo. Since this flat surface is the simplest we can find its albedo will be the better we can obtain. The evaluation of an albedo recovery algorithm will consist on comparing the albedos recovered for the textured samples with the reference albedo of the same color. The better algorithm will give albedo values for the textured samples very similar to the reference albedo.

Images were captured with a Retiga 1300 CCD camera (12 bit intensity range per channel) from QImaging, Canada, with a LINOS MeVis-C lens with a fixed 5.6 aperture and focal length of 25mm. The camera was incorporated into a setup like the one shown in Figure 2 (right), in which the relative position between the camera and the sample is fixed. The camera was adequately calibrated to remove the effects of fixed pattern non-uniformity and spatial variation in dark current.

To quantify the quality of the image rendering results we used the RGB error (RGBE) defined as:

$$RGBE_x = \sqrt{\frac{1}{3}\left(\Delta R_x^2 + \Delta G_x^2 + \Delta B_x^2\right)} \qquad (7)$$

where ΔR, ΔG and ΔB are the pixel-by-pixel differences between the three channels, the RGB relative error (RGBr) defined as:

$$RGBr = \frac{|q_1 - q_2|}{\frac{|q_1| \cdot |q_2|}{2}} \times 100 \qquad (8)$$

Figure 3: The seven textured colored sample set. The samples are organized in seven sets of five samples of the same color (pale pink, yellow, orange, red, green, blue and purple), having each one the same color but different texture (flat, random, convex hemispheres, irregular in one direction and concave hemispheres).

where q_1 and q_2 are the two RGB vectors to compare, and $|\cdot|$ represents the modulus of a vector, the angular error (AE) defined as:

$$EA_x = \arccos\left(\mathbf{q}_{\mathbf{o}x} \cdot \mathbf{q}_{\mathbf{r}x}\right) \quad (9)$$

where $\boldsymbol{q}_{ox}$ and $\boldsymbol{q}_{rx}$ are the RGB vectors in the same pixel of the two images that are being compared, and the CIELAB color difference (ΔE_{Lab}).

Calibration samples under controlled illumination

With the aim of evaluating our algorithm, we used in a first step the calibration samples captured under known lighting directions. The calibration samples were captured using a fluorescent lamp as illumination source whose spectral power distribution (SPD) is shown in figure 4. Four images were captured for each sample using a fixed elevation angle of the illumination source of 55º in all cases, and azimuth angles of 0º, 90º, 180º and 270º.

Those four images of each sample were used to recover albedo values and normal vectors in each pixel of the imaged surface using two different algorithms. The first algorithm is the one proposed in this work (*corrected algorithm*) and the second one just take the four intensities, makes the four possible recovery taking the four intensities in groups of three and average them making no correction on the non Lambertian behaviors (*uncorrected algorithm*).

In the evaluation process we have used the method described before, where the albedo recovered from the flat sample is used as reference albedo. As evaluation metric we used the relative error, because albedo cannot be used as RGB values. When comparing the mean reference albedo obtained by both algorithms, we found a difference of only 0.0543%, which means that the reference albedo obtained by both algorithms were very similar. The fact of finding such similar reference albedos with both methods is a good starting point for our calibration method.

The next step is to compare pixel by pixel the albedo recovered for the rest of chips with the reference albedo of the same colour. Global results are shown in Table 1, where is easy to see that our algorithm provides the better results.

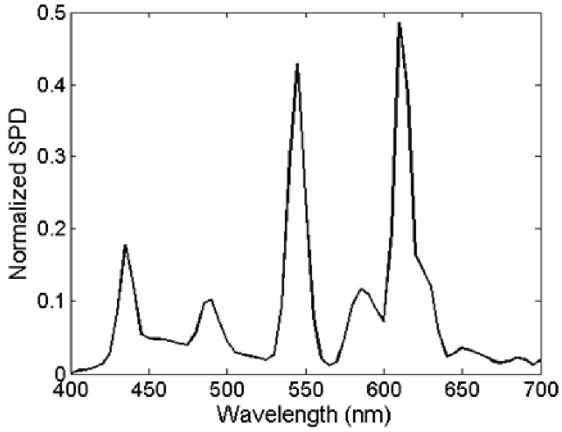


Figure 4: Spectral Power Distribution (SPD) of the fluorescent source used to capture the calibration samples.

Table 1: Results of the comparison between albedo recovery algorithms.

Uncorrected			Corrected		
Mean	**Median**	**P95**	**Mean**	**Median**	**P95**
5.8	4.4	15.3	5.2	3.8	14.4

Calibration samples under uncontrolled illumination

Once we have evaluated the accuracy of our albedo recovery algorithm, we tried to extend it to a new situation where the lighting directions used to capture the calibration samples were unknown.

All 35 calibration samples were captured now under four uncontrolled directions of illumination that were determined using the method presented before. The source in this case was an incandescent lamp whose SPD is shown in figure 5. Those images were used to recover albedo values and normal vectors and then this information were used to simulate the scenes under the same conditions used to capture them.

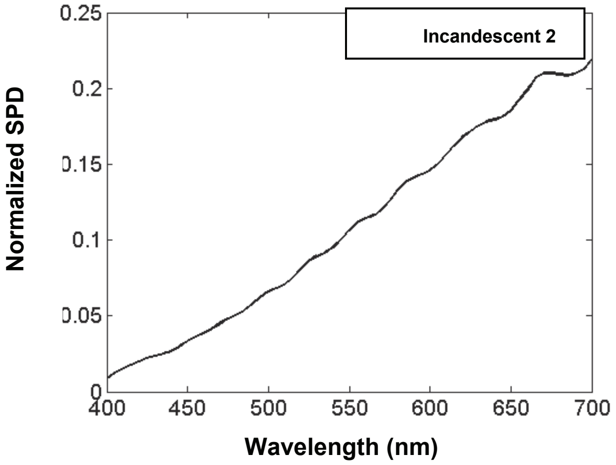
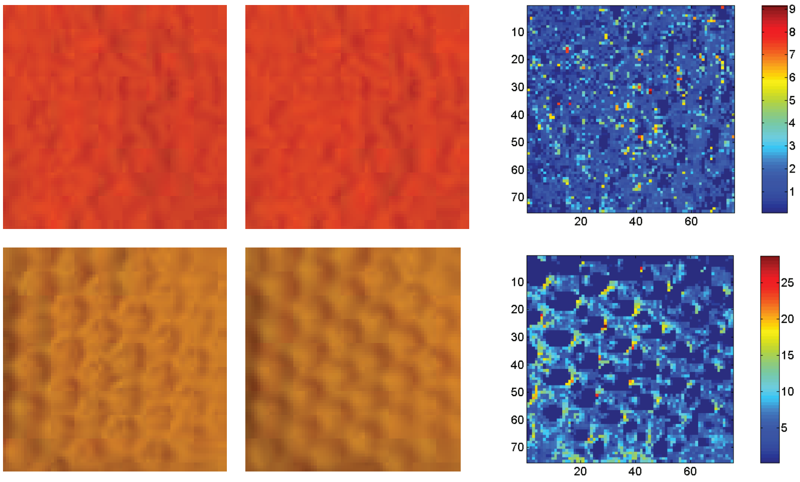


Figure 5: Spectral Power Distribution (SPD) of the incandescent source used to capture the calibration samples.

Figure 6 shows two examples where the first one was captured and simulated under an elevation angle of 23.5° ± 0.7° and a slant angle of 275° ± 5°, and the second one under an elevation angle of 30.1° ± 0.7° and a slant angle of 115° ± 5°. In both cases the first image is the original one, the second image is the simulated one and the third image shows the distribution of CIELAB color differences over the image. In the first example is very difficult to find visual differences between both images. The observed differences in the second case are placed in areas that presents cast shadows. Table 2 summarizes the global results.



RGBE = 27
RGBr = 1.3
ΔE = 1.3
EA = 0.25

RGBE = 89
RGBr = 4.6
ΔE = 4.2
EA = 0.52

***Figure 6:** Examples of rendered images. In each row, the first image is the original one, the second image is the rendered image and the third image shows the distribution of CIELAB color differences in the simulated images.*

4. Conclusions

This paper presents a method for recovering normal vectors and albedos from color images. The spatio-spectral device mention above allows simulating the samples registered under different angles of lighting. The condition of illumination plays an important role in this device. By using a calibrated card, natural colors and spatial surface information can be reproduced with good color accuracy. The results are very promising when comparing these simulations with real images captured in the same conditions. Even for surfaces that are not uniform and show cast shadows the method leads to good color reproduction.

Table 2: Results of comparison between simulated and original images.

	Mean	Median	Std Dev	90 percentile
RGBE	27	0	59	84
RGBr	2.1	0.0	4.4	7.3
ΔE	1.6	0.0	2.9	4.9
EA	0.43	0.00	0.83	1.32

Acknowledgements

This work was supported by Spanish Ministry of Education and Science and FEDER through the grant number FIS2007-60736.

References

1. C. Plata, J. L. Nieves, E. M. Valero, J. Romero, “Trichromatic red-green-blue camera used for the recovery of albedo and reflectance of rough-textured surfaces under different illumination conditions”, Applied Optics, 48, 3643-3653 (2009).
2. R. J. Woodham, “Photometric method for determining surface orientation from multiple images”, Optical Engineering, 19, 139-144 (1980).
3. K. Ikeuchi, “Determining surface orientations of specular surfaces by using the photometric stereo method”, IEEE Transactions on Pattern Analysis and Machine Intelligence 3, 141-184 (1981).
4. M. S. Drew, “Photometric stereo without multiple images”, Human Vision and Electronic Imaging 3016, 369-380 (1997).
5. R. Woodham, Y. Iwahori, R. Barman, “Photometric stereo: Lambertian reflectance and light sources with unknown direction and strength”, Technical Report 91-18, University of Britsh Columbia, Laboratory for Computational Intelligence (1991).
6. S. Barsky, M. Petrou, “The 4 source photometric stereo technique for 3 dimensional surfaces in the presence of highlights and shadows”, IEEE Transactions on Pattern Analysis and Machine Intelligence (2003)
7. E. Coleman Jr., R. Jain, “Obtaining 3-Dimensional shape of textured and specular surfaces using four-source photometry”, Comp. Graph. and Im. Process., 18, 309-328 (1982).
8. C. Plata, S. M. C. Nascimento, J. L. Nieves, “Accuracy of photometric stereo with textured calibration samples” 20th –ICVS, Braga, Portugal, 123 (2009).
9. S. Barsky, M. Petrou “Colour photometric stereo: Simultaneous reconstruction of local gradient and colour of rough textured surfaces”, International Conference on Computer Vision, 600-605 (2001).

Author Biography

Clara Plata received her grade in physics from the University of Granada (2004) and her M S. in physics from Granada University (2006). Since 2004 she has worked in the department of Optics in the University of Granada in the field of color image processing where she has recently finished her PhD. degree (2009).