Combining spectral and photometric stereo techniques for reflectance estimation using an RGB digital camera

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Abstract

In this work we describe one experiment investigating the combination of a photometric stereo and a multispectral technique to recover spectral information with an RGB digital camera. A 4-source based-photometric device is used to recover the scene normals and the albedo at each image pixel. We use a multispectral technique based on a linear pseudo-inverse method, which directly relates spectral reflectances and RGB camera values. The suggested method uses the recovered albedo for each channel as RGB components to recover the spectral reflectance pixel by pixel. It is possible then to avoid finding different reflectances in different points of the surface due to shadows, as the albedo recovered by photometric stereo techniques is not affected by shadows. We expect that analyzing the difficulties and problems encountered will be useful in applications such us color image reproduction, three-dimensional surface analysis and spectral characterization of materials and micro-facets.

Introduction

There are many techniques which allow us to obtain 3D information about surfaces. These methods can be classified in what Woodham [1] refers to as direct methods and indirect methods. The first methods are those which try to measure distance ranges directly, while the indirect methods attempt to determine distance by measuring parameters calculated from images of the illuminated objects. Shape from photometric stereo was conceived by Woodham in the early eighties and has been extensively studied with both theoretical and experimental approaches [2-5]. All approaches published since then can be classified according to the assumptions the authors make about the surface they are dealing with and the type of problem they want to solve.

Most of those algorithms have been proposed in digital imaging, for color reproduction as a function of RGB values provided by the capture device. But, as the object's color depends on the registered color signal [6], sometimes is more useful to obtain the spectral reflectance for complete object characterization, which is independent of illumination. Multispectral imaging can recover spectral radiance or reflectance for each pixel of a scene of interest [7]. Usually a multispectral system consists of an RGB or monochrome digital camera coupled with a number of wide-band or narrow-band color filters [8]. As opposing to conventional imaging devices, they capture illuminant-independent images and allow accurate spectral and colorimetric reproduction of color images for any lighting conditions.

Photometric Stereo Fundamentals

Two assumptions are made in photometric stereo [9]. The surface is generally flat, parallel to the image plane of the camera, and is lit by a single light source. The coordinate system is chosen so that the image plane coincides with the *xy* plane and the z-axis coincides with the viewing direction, as it is shown in figure 1.

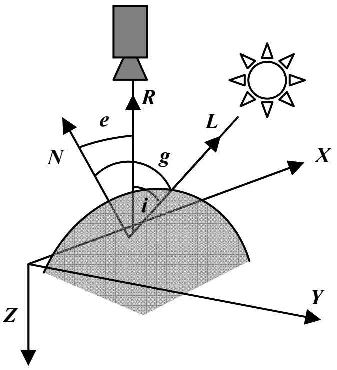

*Figure 1: Definition of the important vectors and reflectance angles: **R**, viewer vector; **L**, illuminant vector; **N**, normal vector; i, incident angle; e, emittance angle; g, phase angle.*

Then the surface can be described by a 2D height function $z = S(x,y)$ and we can define the gradient components for every point on the surface as:

$$p(x,y) = \frac{\partial S(x,y)}{\partial x}, \quad q(x,y) = \frac{\partial S(x,y)}{\partial y} \tag{1}$$

And the normal unit vector **N** as:

$$\mathbf{N} = \frac{1}{\sqrt{p^2 + q^2 + 1}} (p, q, -1)^T \tag{2}$$

Let us consider a Lambertian surface patch with albedo ρ and normal **N** (see figure 1), lit with three light sources with directions $\mathbf{L^1}$, $\mathbf{L^2}$ and $\mathbf{L^3}$. In this case, the intensities of the obtained pixels can be expressed as:

$$I^k = \rho\left(\boldsymbol{L^k} \cdot \boldsymbol{N}\right) \tag{3}$$

where $k = 1, 2, 3$ represents the illuminant directions and $(\cdot)$ the scalar product of two vectors. The pixel intensities can be stacked to obtain the pixel intensity vector $\boldsymbol{I} = \left(I^1, I^2, I^3\right)^T$. The light vectors can also be stacked row-wise to form the illumination matrix $[L] = \left(\boldsymbol{L^1}, \boldsymbol{L^2}, \boldsymbol{L^3}\right)^T$. Then, equation (3) could be rewritten in matrix form:

$$\boldsymbol{I} = \rho[L]\boldsymbol{N} \tag{4}$$

If the three light directions L^k do not lie on the same plane, matrix $[L]$ is non-singular and it can be inverted, giving:

$$[L]^{-1} \boldsymbol{I} = \rho \boldsymbol{N} \tag{5}$$

Since $\boldsymbol{N}$ has unit length, both the normal (as the direction of the obtained vector) and albedo (as its length) can be recovered [1].

Spectral reflectance estimation via linear pseudo-inverse algorithm

In the so-called "direct pseudo-inverse method" [10], Given a set of training spectra $\boldsymbol{S}$ (which can be spectral radiances or reflectances) and the corresponding set of experimental camera responses $\boldsymbol{\rho}$, a recovery transformation matrix $\boldsymbol{D}$ is defined by

$$\boldsymbol{D} = \boldsymbol{S\rho}^{+} \tag{6}$$

where $\boldsymbol{\rho}^{+}$ is the pseudo-inverse of $\boldsymbol{\rho}$. If $\boldsymbol{\rho}$ has full rank, then $\boldsymbol{\rho}^{+} = (\boldsymbol{\rho}^{T} \boldsymbol{\rho})\, \boldsymbol{\rho}^{T}$, where $\boldsymbol{\rho}^{T}$ is the transpose of $\boldsymbol{\rho}$. An estimate of $\hat{\boldsymbol{S}}_{1}$ of a set of test spectra $\boldsymbol{S}_{1}$ may then be obtained from the corresponding set of camera responses $\boldsymbol{\rho}_{1}$ by applying the transformation $\boldsymbol{D}$, that is:

$$\hat{\boldsymbol{S}}_{1} = \boldsymbol{D\rho}_{1} \tag{7}$$

Using this method, there is no need to use any mathematical bases or to know the spectral sensitivity of the camera sensors. Besides, this kind of devices are cheaper and faster than convencional multispectral devices. Previous results using a linear pseudo-inverse algorithm in recovering radiance and spectral reflectances with an RGB camera have shown that adding successive color filters to the camera, can improve the spectral and colorimetric quality of the recovered signals [10].

Method

Images are captured with a CCD camera Retiga 1300 (QImaging, 12 bits), and it is used a small gray (Munsell N7) sphere as a test object. To capture the images for the photometric stereo, the camera is placed in a set like the one shown in figure 2, pointing to the object from the top. Since both are placed in the same arm, it is possible to move it around, so that the relative position between camera and sample is always the same. Fixing a light source outside this setting will allow to get all the illumination angles we want just moving the coupled camera-sample. As light source, a common commercial fluorescent lamp was used.

In the experiment we use four different illumination directions (0º, 90º, 180º and 270º) instead of three. The reason is that sometimes very dark shadows or very bright highlights may cause an algorithm failure, so before recovering we look for the appropriate set of three images among this four. Eq. (5) is used with each RGB channel to get the respective albedos. Thus the albedos can be used as new RGB channels (without the influence of shadows) to recover the spectral reflectances, as expressed by Eq (7).

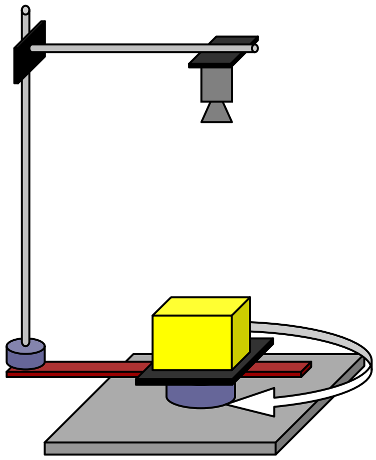

Figure 2: *Experimental setup. The camera is fixed over the sample (in the z-axis), pointing towards it, and it is possible to make them go round together.*

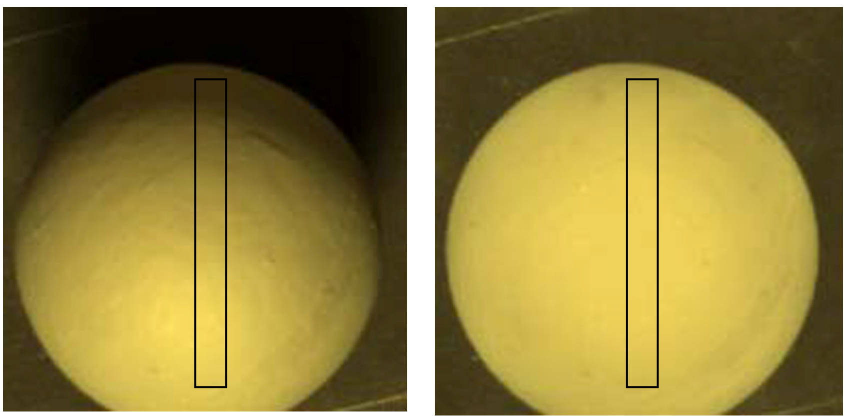

Figure 3: *Original image (left) and reconstructed image (right) using albedos as RGBs. The pixels inside the black box were the pixels used in the experiment.*

Results and comments

Once normals and albedos are recovered, the albedo information will be used to recover the spectral reflectances at a pixel. The Munsell color chart was used as training set and two test sets were used: the first was a selection of pixels of one image of the sphere where the change of brightness with light is evident (see figure 3), and the second was a set of albedos recovered from the same set of pixels. The pixels inside the rectangles in figure 3 were the ones whose reflectances were recovered: a total of 966 pixels. The ball looks yellowish due to the illumination characteristics, besides we didn't use white balance.

Figure 4 shows some examples of the spectral recovery results. In the left column we show the results obtained directly using the original or un-processed image and in the right column the results correspond to that using the albedo image. To quantify the spectral quality of the recovered reflectance we used the goodness-of-fit-coefficient (GFC). The GFC is based on Schwartz's inequality and is defined as the cosine of the angle between the original signal $f(\lambda)$ and the recovered signal $f_r(\lambda)$, thus

$$\mathrm{GFC} = \frac{\sum_{\lambda=400}^{700} f(\lambda) f_r(\lambda)}{\left(\sum_{\lambda=400}^{700} f(\lambda)^2\right)^{1/2} \left(\sum_{\lambda=400}^{700} f_r(\lambda)^2\right)^{1/2}} \quad (8)$$

This measurement of spectral similarity has the advantage of not being affected by scale factors. Colorimetrically accurate reflectance estimations require GFC > 0.995; GFC > 0.999 indicates quite good spectral fit, and GFC > 0.9999 an almost-exact fit [11].

The histograms show the GFC values derived from the 966 spectral reflectances recovered for each of the two examples. The average GFC was 0.9988 for the first case while for the latter case was of 0.9993. The lower row of the figure shows the original (continuous line) and the recovered (dashed line) spectral reflectances of the sphere. When both histograms are compared, it can be seen that using the albedo image we obtain less variability in the GFC values e.g. less differences among the recovered reflectances and similar spectral values over the whole sphere surface. This is also what we are finding because all the pixels selected come from the same homogeneous object surface.

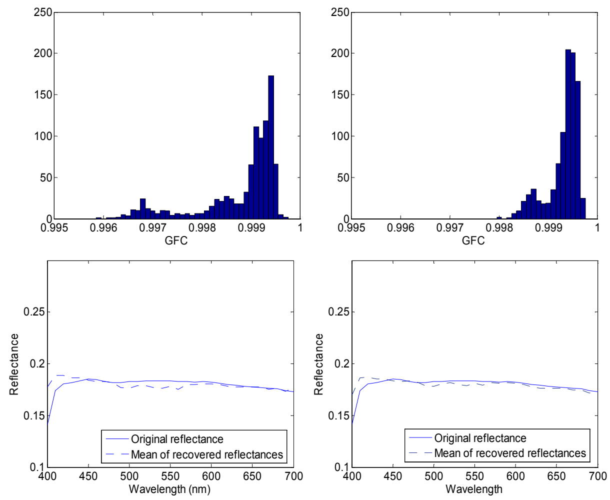

Figure 4: *Comparison of results: in first column we show results derived using the original image while the second column shows results for the albedo image.*

The results suggest that it is possible to combine a photometric stereo device and spectral imaging techniques for spectral reflectance recovery. Avoiding shadowing effects we can improve the spectral performance for homogeneous color objects.

Acknowledgements

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

References

[1] R. J. Woodham, "Reflectance map techniques for analyzing surface defects in metal castings", *Technical Report* AI-TR-457, MIT A.I. Laboratory, June 1987

[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] G. McGunnigle, M. Chantler, "Rouge surface description using photometric stereo", *Measurement Science and Technology* 699-709 (2003).

[5] M. S. Drew, "Photometric stereo without multiple images", *Human Vision and Electronic Imaging* 3016, 369-380 (1997).

[6] B. A. Wandell, "The synthesis and analysis of color images", *IEEE Transactions on Pattern Analysis and Machine Intelligence* 9, 2-13 (1987).

[7] J. Hardeberg, F. Schmidtt, H. Brettel, "Multispectral color image capture using a liquid crystal tunable filter", *Optical Engineering*, 41, 2532-2548 (2002).

[8] F. H. Imai, R. Berns, "Spectral estimation using trichromatic digital cameras", *International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives*, 42-49, 1999.

[9] 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.

[10] E. M. Valero, J. L. Nieves, S. M. C. Nascimento, K. Amano, D. H. Foster, "Recovering spectral data from natural scenes with an RGB digital camera and colored filters", *Col. Res. and Appl.*, 32, 352-360, 2007.

[11] J. Hernández-Andrés, J. Romero, J. L. Nieves, R. L. Jr Lee, "Color and spectral analysis of daylight in southern Europe", J. Opt. Soc. Am. A **18**, 1325-1335 (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 her Ph.D. in the field of color image processing.