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Object surface recovery using a multi-light photometric stereo technique for non-Lambertian surfaces subject to shadows and specularities

Jiuai Sun [a,*], Melvyn Smith [a], Lyndon Smith [a], Sagar Midha [a], Jeff Bamber [b]

[a] *Machine Vision Lab, Faculty of CEMS, University of the West of England, Bristol BS16 1QY, UK*
[b] *Ultrasound and Optical Imaging, Institute of Cancer Research and Royal Marsden NHS Trust, Surrey SM2 5PT, UK*

Abstract

This paper presents a new multi-light source photometric stereo system for reconstructing images of various characteristics of non-Lambertian rough surfaces with widely varying texture and specularity. Compared to the traditional three-light photometric stereo method, extra lights are employed using a hierarchical selection strategy to eliminate the effects of shadows and specularities, and to make the system more robust. We also show that six lights is the minimum needed in order to apply photometric stereo to the entire visible surface of any convex object. Experiments on synthetic and real scenes demonstrate that the proposed method can extract surface reflectance and orientation effectively, even in the presence of strong shadows and highlights. Hence, the method offers advantages in the recovery of dichromatic surfaces possessing rough texture or deeply relieved topographic features, with applications in reverse engineering and industrial surface inspection. Experimental results are presented in the paper.
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Keywords: Photometric stereo; Specular reflection; Shadows; Surface reflectance; Surface orientation; Height map; Linear least-squares solution

1. Introduction

From Horn's image formation theory [1], the factors determining the appearance of an object under observation can be divided into two types: extrinsic factors and intrinsic factors. Extrinsic factors include the illumination conditions and imaging sensor performance, while intrinsic factors include reflectance features and the 3D shape of the object. Because the extrinsic factors may vary between different imaging procedures, the final image acquired tends to be subject to variation, even with only small changes of the illumination conditions. This makes many computer vision based applications difficult to implement, for example, segmentation or object identification. However, the intrinsic factors concern the physical properties of the object and are free from the influence of the external environment. Thus, the extraction of intrinsic factors is significantly more important for both standard optical measurements and computer vision related applications.

Within the field of computer vision, a large body of work has been concerned with optical 3D shape measurement, including active laser scanning techniques, structured light source techniques, stereo vision and monocular techniques, such as shape-from-contour or shape-from-shading. All of these techniques are concerned with obtaining geometrical descriptions of 3D objects. However there has been relatively less published work specifically aimed at exploiting the object's surface reflectance properties.

Reflectance performance is largely determined by the characteristics, quantity and distribution of particle pigments embedded within the subsurface medium of an object. According to the standard definition of the bidirectional reflectance distribution function (BRDF), reflectance is the ratio of the reflected radiance to the incident

* Corresponding author. Tel.: +44 117 3282316; fax: +44 117 3283636.
E-mail address: jiuai2.sun@uwe.ac.uk (J. Sun).

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irradiance [2]. When a light beam interacts with an object, most of the photons will penetrate into the subsurface medium. If a photon is not absorbed, it may undergo hundreds of scattering interactions with pigment particles before finally exiting from the material. When the pigments are distributed uniformly, light exits in a uniform manner. In such a case the reflectance characteristics of the surface can be described by Lambert's Law, i.e., the amount of light reflected from the surface towards a viewer is proportional to the cosine of the angle between the local surface normal vector and the light source direction.

The photometric stereo method, based on the Lambertian reflectance model, is capable of deriving both orientation and reflectance features of an object from multiple images taken with the same viewpoint but under different illumination conditions [3]. Because of the simplicity of the Lambertian model, and its ease of implementation, the photometric stereo method has been successfully applied for shape recovery, defect inspection and classification tasks [4–9].

Though the Lambertian model can accurately describe a diffuse surface very well, it sometimes oversimplifies the reflectance performance of those real world objects which exhibit shiny surface features or which are subject to problems of significant self-occluding of the light from points on the surface by other parts of the surface. For instance, while the traditional photometric stereo technique, which employs three light sources, has been successfully used in identifying surface defects in ceramic tiles and china products, even in the presence of very complex background reflectance (pigmentation) patterns, when ceramics have complicated 3D structures or polished surfaces it may not be possible to exactly recover the surface by using only three lights [4]. The new multi-light (six lights) photometric stereo method described in this paper is potentially useful for these kinds of applications because it is designed to cope with non-Lambertian surfaces, and specifically those that possess shadows and specularity.

2. Related work

2.1. Photometric stereo for Lambertian surfaces

For a scene consisting of a Lambertian surface illuminated by a single distant (parallel ray) light source, the observed image intensity I at each pixel can be simply written as the product of the composite albedo K_D and the cosine of the incidence angle θ_i, i.e., the angle between the direction of the incident light and the surface normal [1]. The angle of incidence can itself be expressed as the product of a two unit column vectors, $\mathbf{l}$, describing the incident light direction, and $\mathbf{n}$, the surface normal:

$$I = K_D \cos(\theta_i) = K_D(\mathbf{l} \cdot \mathbf{n}) \tag{1}$$

The composite albedo K_D is the coefficient related to the illumination intensity, surface reflectance and imaging parameters. When white incident light is distributed uniformly across an object surface, and the response of the imaging system is approximately constant over its spectral range, the composite albedo K_D is proportional to the reflectance of the surface and illumination intensity.

Without some prior knowledge of an object's surface, more than one image is needed to recover the surface orientation and reflectance of an object [3]. In general m ($m \geqslant 3$) images are taken using the same imaging system from the same observation point, but for each the object is illuminated by a single light source from a different position. If I^j ($j = 1, 2, \ldots, m$) represents the intensity value of each pixel in the jth image, we obtain m intensity values forming an intensity vector $\mathbf{I} = (I^1, I^2, \ldots, I^m)^T$. In the same way, we obtain an illumination matrix $\mathbf{L} = (\mathbf{l}^1, \mathbf{l}^2, \ldots, \mathbf{l}^m)^T$, where $\mathbf{l}^j$ represents the column unit vector along each incidence light direction. So m equations from (1) corresponding to the same pixel in m images can be written as the following linear system of equations:

$$\mathbf{I} = K_D(\mathbf{L} \cdot \mathbf{n}) \tag{2}$$

when the matrix $\mathbf{L}$ is known, and is of rank 3 at least, the composite albedo and the surface normal can be uniquely calculated from a linear least-squares method,

$$K_D = \left|\left(\mathbf{L}^T\mathbf{L}\right)^{-1} \cdot \mathbf{L}^T \cdot \mathbf{I}\right| \tag{3}$$

$$\mathbf{n} = \left(\left(\mathbf{L}^T\mathbf{L}\right)^{-1} \cdot \mathbf{L}^T \cdot \mathbf{I}\right) \Big/ K_D \tag{4}$$

In the case where $m = 3$, the above solution corresponds to that of the traditional three light sources photometric stereo. When there are more than three input images, the redundant information from the extra equations may serve to improve the accuracy and robustness of the recovery.

2.2. Difficulties in photometric stereo

When the surface of a shiny object such as a metallic component has regions that are very smooth or flat, the reflection of light from the surface tends to be specular. Highlights will be present in the images when the viewer lies near the reflecting direction. The existence of highlights saturates the imaging sensor and so makes the tasks of feature recovery challenging. At the other extreme, light may not be able to reach the object's surface because of self-shadows that occur when the angle of incidence is larger than 90°, or cast shadows that arise when the illumination is blocked by another parts of the object. The presence of shadows can modify the apparent reflectance characteristics of the object within images, and lead to errors in the measurement of the object's shape by the photometric stereo method.

Specularity and shadowing create inherent difficulties for the traditional three-light photometric stereo technique because of its simple assumptions of a Lambertian surface and local shading. Although the introduction of a linear least-squares method to solve Eq. (2) can serve to average