Computer Vision and Image Understanding 125 (2014) 16–36

Contents lists available at ScienceDirect

Computer Vision and Image Understanding

journal homepage: www.elsevier.com/locate/cviu

Optimal illumination directions for faces and rough surfaces for single and multiple light imaging using class-specific prior knowledge ☆

Vasileios Argyriou [a,*], Stefanos Zafeiriou [b], Maria Petrou [b]

[a] *Kingston University, London, United Kingdom*
[b] *Imperial College, London, United Kingdom*

ARTICLE INFO

Article history:
Received 1 November 2012
Accepted 31 January 2014
Available online 1 April 2014

Keywords:
Photometric stereo
3D imaging
Face reconstruction

ABSTRACT

The detection of image detail variation due to changes in illumination direction is a key issue in 3D shape and texture analysis. In this paper two approaches for estimating the optimal illumination direction for maximum enhancement of image detail and maximum suppression of shadows and highlights are presented. The methods are applicable both to single image/single illumination direction imaging and to photometric stereo imaging. This paper uses class-specific prior knowledge, where the distribution of the normals of the class of surfaces is used in the optimisation. Both the Lambertian and the Phong models are considered and the theoretical development is demonstrated with experimental results for both models. For each method experiments were performed using artificial images with isotropic and anisotropic distributions of normals, followed by experiments with real faces but synthesised images. Finally, results are presented using real objects and faces with and without ground-truth.

1. Introduction

The variation of the intensities observed in images depends on variation in both surface reflectance and surface relief. While the reflectance properties are intrinsic to a surface, the surface relief produces a pattern of shadings that depends strongly on the direction of illumination. The appearance of a 3D surface changes drastically with illumination [8]. Different image details are enhanced for different illumination directions. The idea of photometric stereo is to use this information to recover the intrinsic surface parameters, that is, local surface orientation and albedo, independent of the illumination direction. Photometric stereo estimates relief and reflectance information using three or more images of a surface illuminated from different directions captured from a single viewpoint. The method considers the isophotes in gradient space. The intersections of the isophotes from different illumination directions identify the gradients of individual surface facets (corresponding to pixels). Due to the non-linear nature of the problem, the shape, density and orientation of the isophotes affect the accuracy with which the gradient vectors can be estimated. The characteristics of the isophotes depend on the lighting directions. So, illumination directions play a crucial role in the quality of the produced image and they should be carefully chosen for applications in which this is possible. Sub-optimal geometric arrangements may crucially affect the reliability of the subsequently inferred information.

In this paper, two methods that estimate the optimal imaging configuration are proposed. The first one is based on maximising the level of detail in the reconstructed surfaces, revealing details and salient features of the imaged surface. In the second approach, we estimate optimal positions of the light sources by maximising the area covered by dense isophotes in gradient space for an arbitrarily shaped surface when the distribution of surface normals is roughly known. The problem has been studied before [32,15], but previous authors did not consider prior knowledge on the distribution of the normals of the facets of the surface. All previous optimisation methods effectively assumed uniform distribution of the normals. This paper uses class-specific prior knowledge, where the distribution of the normals of the class of surfaces is used in the optimisation. At this point we would like to stress that we do not expect to know the exact surface normals beforehand, as this would defeat the purpose of photometric stereo. We only assume the availability of the *statistical distribution* of the surface normals, which may be used for all objects of the same class, e.g. all human faces, although this statistical distribution might be obtained from the face of a plastic model, for example, using active sensing. The ultimate purpose is to take into consideration the statistical distribution of the normals, in order to design an optimal lighting

☆ This paper has been recommended for acceptance by Edwin R. Hancock.

* Corresponding author. Address: Faculty of Science, Engineering and Computing, Kingston University, Penrhyn Road, Kingston upon Thames, Surrey KT1 2EE, UK. Tel.: +44 0 2084172591; fax: +44 0 2084172972.

E-mail address: Vasileios.Argyriou@kingston.ac.uk (V. Argyriou).

http://dx.doi.org/10.1016/j.cviu.2014.01.012
1077-3142/

system for this class of object, and so achieve best reconstruction of the surfaces of *individual* objects of the same class.

This paper is organised as follows. In Section 2 previous work on photometric stereo and optimal illumination estimation is reviewed. In Section 3, we propose an overview of the proposed approach. In Section 4 the first proposed methodology is analysed both for the Lambertian and the Phong models. Also, details on how this approach can be generalised to n illumination sources are presented. In Section 5 the second approach is introduced based on the density of the isophotes in the gradient space, for Lambertian surfaces. In Section 6 initially an analysis of some preliminary results related to the estimations of some model parameters are presented for the first approach. Then in Section 7, the proposed illumination setups are compared with the one proposed in [10]. First, experiments are performed using artificial images with isotropic distribution of normals, followed by experiments with anisotropic distributions with four different dominant orientations. Subsequently, experiments with real faces but synthesised images are performed. Finally, in Section 8 results are presented using real objects with ground-truth and real faces without ground-truth but using the side views and the Hausdorff distance for evaluation. In Section 9 conclusions on the proposed methodology and the evaluation process are presented.

2. Previous work

In [41] photometric stereo was introduced. He proposed a method which was simple and efficient, but was sensitive to noise. In his method, the surface gradient can be recovered by using two photometric images, assuming that the surface albedo is already known for each point on the surface. In [9] photometric stereo was extended to four light sources, where specular reflections were discarded and estimation of surface shape could be performed by means of diffuse reflections and the use of the Lambertian model. In [27] a photometric approach which uses a linear combination of the Lambertian model was developed and an impulse specular component to obtain the shape and reflectance information for a surface. In [3–5] an algorithm for estimating the local surface gradient and albedo using four source colour photometric stereo was presented in the presence of highlights and shadows. In [22] an approach that utilises nine illumination sources was presented. It is also worth mentioning the related work presented in [31] focusing on 4-lights PS based on shape information and statistical segmentation techniques to determine which pixels are specular and which are non-specular. In [7] an algorithm for Lambertian photometric stereo in the presence of shadows is proposed based on fast graph cuts estimating per pixel light source visibility. Also, it allows images to be acquired with multiple illuminants, and there can be fewer images than light sources. In [24] a method to remove shadows from real images based on a probability shadow map is introduced and in [12] a shadow removal method is presented from a 3-band colour image finding an intrinsic reflectivity image based on assumptions of Lambertian reflectance. In the work presented in [30] a method for cast shadow removal from obliquely illuminated images of faces is suggested based on a statistical model of surface normal directions. [34] proposed a multi-light source photometric stereo system for reconstructing images of various characteristics of non-Lambertian rough surfaces with widely varying texture and specularity. An algorithm that no calibration is needed for recovery of geometry of objects with general reflectance properties from images was introduced in [17]. In [1] a technique for resolving the GBR ambiguity based on minimisation of the entropy of the recovered albedos was proposed. In [13] an uncalibrated photometric stereo technique for unknown light sources and general reflectance model was suggested. A review of different reflectance maps proposed in the literature for modelling reflection from real-world surfaces as presented in [35] and in [28] the problem of estimating the proportions of Lambertian and specular reflection components in order to improve the quality of surface normal information recoverable using shape-from-shading was discussed. Recursive approaches for shadow and highlights estimation for advanced reconstruction using photometric stereo of any number of lights were presented in [38,39]. In [18] a technique for face recognition was presented that combines the Fisherface method with the ridgelet transform and high-speed Photometric Stereo. In [21] was shown that a plausible shape can be obtained based on two light sources and in [11] a multiple illumination technique that directly recovers the viewer-centered curvature matrix and being independent of knowledge of incident illumination orientation, local surface orientation, or diffuse surface albedo was presented. A scheme to resolve handwriting from background printing using photometric stereo to recover the surface was suggested in [25] and in [19] a photometric stereo algorithm was presented that reconstructs object shapes from multiple images, in which 3D surfaces were approximated by Legendre polynomials. In [37] an algorithm for shape from shading was introduced based on the assumption that a single input image will be matched to a second image through a uniform disparity field.

The influence of a lighting arrangement to the accuracy of surface reconstruction based on photometric stereo has been considered in the past [41,23,32,8] and suggestions for optimal illumination configurations in terms of azimuth φ_l and zenith θ_l angles have been reported. In [40], using reflectance maps, dense iso-intensity contours were recommend to obtain maximal accuracy.

Lee and Kuo in [23], using two reflectance maps in the case of a two image photometric stereo, deduced that it is desirable to incorporate reflectance maps that compensate each other's weaknesses (i.e. the accuracy of the reconstructed surface height is related to the slope of the reflectance map function and therefore using a second reflectance map can be combined to improve the reconstruction in certain areas), in order to determine the optimal illumination configuration.

Based on [23], it was further confirmed that the two image photometric stereo is more sensitive to the azimuth rather than the zenith angle difference and that the optimal value for azimuth difference is 90°. In [15] three light photometric stereo was considered and it was suggested that distributing the illumination azimuth angles uniformly through 360° is optimal. A theoretical analysis of Gullon's arrangement was presented in [32,33], based on the sensitivity analysis of photometric stereo and by deriving expressions of each surface normal vector with respect to image intensities.

It was discovered in [32] that the optimal azimuth and zenith angles cannot be specified without any assumptions and that the configuration that results the minimum noise is not unique. Instead, it was determined for a two lights Photometric Stereo that an orthogonal arrangement of the illumination vectors (with an angle of 90° to each other) is the only restriction to obtain the optimal configuration. In the case of the common zenith angle being constrained, the optimal values for azimuth angles for three lights Photometric Stereo were estimated and it was suggested to use 120° difference in a three-image Lambertian photometric stereo configuration.

The optimal zenith angle in the case of uniformly distributed light sources according to the azimuth was found to be around 55°, but if shadows are present the angle should be reduced [32,15]. On the contrary, if the surface is smooth and shadows are not an issue, the zenith angle can be increased. Furthermore, in [10] the above was extended for n light sources and derived