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Reconstruction of normal and albedo of convex Lambertian objects by solving ambiguity matrices using SVD and optimization method ☆

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ABSTRACT

Photometric stereo (PMS) can reconstruct shape and albedo of an object by using multiple images captured under varied illumination directions. However, PMS may fail if light intensity is varied across different images captured under different unknown lighting directions. This paper presents a method that can estimate shapes and albedo of inhomogeneous Lambertian objects with much less constrained lighting conditions, i.e. the illumination directions are unknown and there can be arbitrary combination of different light sources and ambient light; meanwhile the light intensity can be different in different images. By placing a reference object alongside an object, the ambiguous matrix produced by SVD can be estimated effectively. This matrix is then used to generate more accurate shape and albedo. The reconstructed results are further refined using an optimization algorithm. Both synthetic and real objects are used in our experiments and the results show the effectiveness of our method.

1. Introduction

Photometric stereo (PMS) can reconstruct surface normal and albedo of an object captured with a fixed camera and under varied illumination directions, whose parameters need to be accurately recorded. These constraints limit traditional PMS to be performed in practical application.

The lighting parameters in uncalibrated PMS in Refs. [1–4] are not required to record, however abundant input images (10–64 images in Ref. [1]) under different lighting conditions are necessary. Moreover the reconstructed results are not robust for the different light intensity or color in different input image [5,6]. This paper introduces a new method to estimate the albedo and surface normal of an inhomogeneous Lambertian object with much less constrained lighting conditions. The lighting conditions may include different light sources, whose directions and intensity can be different across different images. A white zirconia ball (probe sphere) is placed alongside an object, which shares the similar lighting conditions with the probe sphere. With only 3–6 input images of the probe sphere and object under different lighting conditions, the albedo and shape of an inhomogeneous object can be reconstructed efficiently and accurately. Moreover our reconstructed results are more robust for the different light intensity or color than those in Refs. [1,2].

Based on the assumption of Lambertian reflectance, singular value decomposition (SVD) is used to factorize the matrix comprised of input images into scaled surface normals (scaled by albedo) and lighting components [3]. However, the ambiguity exists in the result of factorization, as both the surface normal and lighting directions are unknown. We use the term “ambiguity matrix” (AM) to represent this ambiguity. Differing from our previous work [7], we prove that AM for the probe sphere and for the object is different, and the assumption in [4], which had set the same AM for the sphere and the object, is only suitable for the conditions of the similar shape between the probe sphere and the object.

Since the probe sphere and the object have the same imaging set-up, AM for the object can be deduced from the sphere. Hence in this paper we solve the AM for the object by estimating the ambiguity of the object in [4]. That is to say the lighting conditions can be estimated. Our algorithm in this paper has two major advantages. First, the constraints of the lighting conditions of the input images are relaxed. The light direction and intensity can be arbitrarily combined, such as combination of ambient, multiple point lights and natural light in one input image or in different

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☆ Fully documented templates are available in the elsarticle package on CTAN.
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input images. The accurate object surface normal can be estimated efficiently by solving ambiguity matrices based on the probe sphere placed in the same scene. Second, less input images are required than the method proposed in [1], for example, only 3–6 input images are needed to reconstruct the albedo and shape of the object.

The paper is organized as follows. Related works are described in Section 2. Section 3 introduces the proposed method for reconstructing surface normal and albedo. Experiments and results are presented in Section 4. The last section concludes this paper.

2. Related works

Woodham first presented photometric stereo (PMS) [8], which can reconstruct shape and albedo from the object images captured under varied illumination directions and a fixed viewpoint. Since then many works followed, such as those focusing on non-Lambertian objects [9,10], optimal image processing methods [11,12], 3D shape matching [13–17] and real-time situation [18,19]. The assumption of the classical PMS is a point light, which can produce self-shadow and cast shadow, and cause error in reconstructed results. Hence the method in Ref. [20] presented a procedure for selecting image areas without shadow so as to improve the estimation accuracy. However, the application of classical PMS is still limited for images captured in well-designed lighting environment [21,22]. Ref. [23] described that one reason of inaccuracy of PMS is the measurement error in the calibration of light sources. In order to decrease the error in calibration, Ref. [24] recommended the optimal placement of the point light sources. Due to the assumption of the distant point light sources, the application of the classical PMS is also constrained.

Recently, researchers have dedicated themselves to reduce the constraints and extend the application to complex lighting environment. In 2001, Ramamoorthi put forward a lighting model for simulating the irradiance under complex light sources [25,26]. The model is mainly based on low order spherical harmonics. The average error of 4 parameters approximation for irradiance environment was under 14%; 9 parameters approximation was under 3% for any physical input lighting distribution.

With this low order spherical harmonics, uncalibrated PMS were proposed for implementing PMS under unknown lighting conditions. SVD was the commonly used method in uncalibrated PMS. Because the decomposition of SVD is not unique, the main problem for uncalibrated PMS is how to solve the ambiguity in factorization. Solutions for reducing or eliminating the ambiguity in SVD can be divided into three main categories: using known light parameters or surface parameters, using integrability constraint, and using optimization methods.

For the first category, if additional information about the light parameters or surface parameters are available [27,8], the ambiguity produced by SVD can be reduced. An extreme case of ambiguity reduction is, for example, the case when three linearly independent true scaled normals(the unit normal scaled by albedo) are known; the ambiguity matrix is determined uniquely and the ambiguity vanishes. Refs. [28,3,27] assume that some light sources are of equal light strengths or albedo is uniform for some surface normals; six known normals are acquired for determining the ambiguity produced by SVD. However, the assumption of equal strength of the light or albedo will make the albedo up to a certain scale. In the case, the ambiguity matrix is also determined up to a scale factor. Consequently, the reconstructed results will represented by ambiguous scaled orthogonal transformation.

For the second category, with the constraints of integrability [3,27], the original ambiguity is reduced into three-parametric generalized bas-relief (GBR) transformation, which is called linear ambiguity. Many techniques have been proposed for resolving the GBR ambiguity, typically by exploiting prior knowledge of the light sources [3,27], the object geometry [29], or non-Lambertian effects such as specularities. Ref. [3] used two methods to resolve the raised linear ambiguity. The first method used the prior knowledge of the object class; the second method used surface consistency to reduce the ambiguities to GBR. Ref. [2] proposed a method by exploiting prior on the albedo distribution, i.e. the entropy of the distribution should be low. Then a global optimization algorithm was used to estimate the parameters of GBR ambiguity matrix. Nevertheless, this method still need to decide the scaled parameter of the estimated surface normal, such as using the classical PMS to decide the scale.

Methods in the third category used the relationship between a low order spherical harmonics model and the surface normal of the object to add the constraint. The method in Ref. [1] used a constraint on the decomposition result produced by SVD to transfer the ambiguity to a seven degree of freedom scaled by the Lorentz transformation, and then the optimization methods were used to resolve the remained ambiguity. However, abundant input images (15–64 images) were necessary. Other works started from analyzing lighting conditions in order to estimate the shape of an object, for example in Ref. [30], four face images under unknown lighting conditions were factorized using the symmetrical Schur decomposition to estimate the light parameters, which further contributed to estimation of the surface normal and albedo.

In addition to the above commonly used methods, there are many effective methods, which can be used to resolve the ambiguity produced by SVD [31,32] or avoid dealing with this problem. Because the projection of normal onto the image plane is perpendicular to the projection of the occluding boundary itself, Refs. [33,34] used the set of normals on an occluding boundary to resolve the ambiguity matrix. Refs. [35–37] assumed that many reference objects (the small balls) with similar materials, color and known geometry were imaged with the object under the same lighting conditions; the normal of the object was calculated according to the known shapes of reference objects. Though this method does not require considering the ambiguity problem, it required many reference balls of similar materials. Ref. [42] found two fundamental reflectance properties, which were useful for solving the ambiguity of non-Lambertian surfaces: the first reflectance property was the separable isotropic BRDF (bidirectional reflectance distribution function); the second reflectance property was the consistent viewpoint constraint, which presented sufficient constraints for solving ambiguity of non-Lambertian surfaces.

As discussed above, the ambiguity matrix (AM) will be produced using SVD for uncalibrated PMS. There are 10 unknown parameters in AM, and then at least more than 10 input images are needed to estimate the 10 unknowns in AM without considering other constraints. In order to reduce the number of the input images and strength the robustness for different lighting conditions (even the different light intensity or different light color), a reference object (a probe sphere in this paper) is placed alongside an object and shares the same lighting conditions with the object. Then based on the same lighting conditions between the probe sphere and the object, AM produced by SVD can be estimated effectively. Moreover, we require much fewer images and allows a wider range of combination of inconsistent lighting conditions than the method in Ref. [1].

3. Our methods

The orthographic projection was commonly used in 3D reconstruction based on PMS, such as Refs. [20,3,1,27]. The input images