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Photometric stereo with quasi-point light source

Zhao Song [a,b], Ying Nie [b], Zhan Song [a,c,*]

[a] Shenzhen Key Laboratory of Virtual Reality and Human Interaction Technology, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, China
[b] Shenzhen College of Advanced Technology, University of Chinese Academy of Sciences, China
[c] The Chinese University of Hong Kong, Hong Kong SAR, China

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ABSTRACT

This paper presents a complete computational framework for the photometric stereo system composed of some LED lamps and a single web-camera. To describe the lighting condition accurately, the angular and distance attenuation factors, as well as the LED radiance property, are considered in the modeling of the light source. The calibration of the system's parameters is a critical step for our setup, and a two-step calibration procedure is proposed in this work. A multiple-sphere-based approach is first used to estimate the light source positions. Then, a reference-plane-based approach is applied to estimate the principal optical axis of each light source and its principal energy. For each surface point on the target, the direction and intensity of its incidental light ray can be precisely determined by the calibration parameters and the quasi-point light model. Based on the initial 3D reconstruction result, an iterative procedure is applied to optimize the model's parameters for each surface point with respect to its initial estimated depth. In the experiments, both regular and free-form surfaces including a real human face are used. The results show that accurate 3D reconstruction results can be obtained by the proposed approach based on the low-cost setup.

1. Introduction

Photometric stereo (PS) is a technique for the shape recovery of objects by observing the target under varying illuminations [1]. Various PS-based techniques have been successfully applied to 3D modeling [2], facial expression capturing [3,4], medical analysis [5,6], etc. Compared with other 3D scanning techniques such as laser and projector-camera-based structured light, the performance of the PS-based 3D systems is quite dependent on the illumination sources [7,8]. According to the working distance, existing PS methods can be generally classified into distant light sources and close-range light sources [9,10]. The first one solves the distant PS problem, which assumes that the lighting condition is parallel and uniform. The second category solves the close-range PS problem by considering the incident angle and attenuation of light rays. Moreover, categorized by the requirement of lighting parameters, the close-range PS problem with the point light source can also be divided into three main categories, which are calibrated [10], semicalibrated [11,12] and uncalibrated [13].

The motivation for our research comes from a photometric stereo system that is designed for 3D facial reconstruction, as shown in Fig. 1. The device has a compact size, and some single LED lamps are used as light sources. A similar ring-light setup that contains 24 LEDs was also reported in [14] to show its merit for photometric stereo applications. Because of the near lighting distance and nonisotropic luminous property of LED lamps [15,16], both the directions and intensities of incident light rays are different for various surface points. We named such a light source as a quasi-point light source. The purpose of this article is to establish a complete photometric stereo computational framework for such a light source, including the light source calibration, lighting field modeling, and surface normal calculation. We show that, with the proposed system calibration method and quasi-point light model, accurate 3D reconstruction can be realized based on low-cost devices.

The paper is organized as follows. In Section 2, some related works are briefly reviewed. The quasi-point light model is introduced in Section 3. The calibration algorithms of the introduced photometric stereo system are presented in Section 4. The integration method for 3D reconstruction is introduced in Section 5. The experimental results and comparisons with conventional and state-of-the-art methods are provided in Section 6, and a conclusion is offered in Section 7.

2. Previous works

Photometric stereo has been a classical research topic in the computer vision domain. A typical photometric stereo system consists of one camera and some light sources. In its implementation, a calibration procedure is usually applied first to estimate the parameters of the

* Correspondence author at: Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China.
E-mail address: zhan.song@siat.ac.cn (Z. Song).

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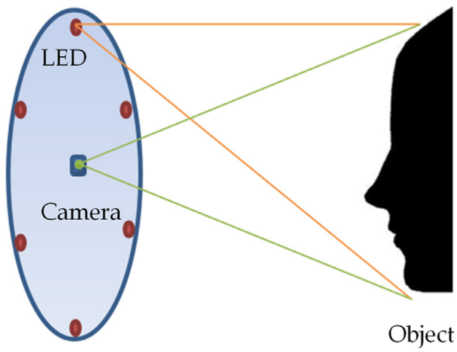

Fig. 1. Illustration of the proposed photometric stereo system, which is composed of one camera and some LED lamps.

light source and camera. By analyzing the obtained images with varying illuminations from different light sources, the surface normal for each surface point can be estimated. Then, the 3D shape of the target surface can be retrieved via the integration of surface normals [17,18].

For the calibrated photometric stereo systems, system calibration is a critical step that aims to determine the directions and positions of light sources. Some geometric objects with known spatial positions are often used to calculate the positions and directions of point light sources [10,19–21]. In [10], a photometric stereo setup using LEDs as light sources was studied. The experimental setup consisted of eight white LEDs and a high-resolution digital single-lens reflex camera. The distance and angular attenuations were considered in the LED lighting model. A printed checkerboard pattern was used for the calibration of the system parameters, including the principal directions and the intensities of the LEDs. To solve the calibration parameters and calculate the surface normal, a numerical solution based on the alternating reweighted least-squares approach was introduced, which was provably convergent. In [19], three spheres with known relative positions were used to calibrate the proposed photometric stereo system. In detail, one matt sphere was used for the camera calibration, and the highlight points formed by the light source on the other two specular spheres were used for the calibration of the light sources. According to the specular reflection property, the angle between the incident and reflected light rays is equal at the highlight point. Therefore, the position of each light source could be estimated via the triangulation principle. In [20], the authors proved that if the radiant intensity distribution of a light source is radially symmetric with respect to its dominant direction, the shading observed on a Lambertian plane is bilaterally symmetric with respect to a 2D line on the plane. Then, the symmetry axis was used to estimate the dominant light axis. The positions and distribution parameters can be calculated by a linear method as well. In [21], a pair of reference spheres and the difference sphere were introduced to estimate the directions and intensities of near point light sources with the existence of a few directional light sources and ambient light using a twofold iterative algorithm.

For the near-field photometric stereo systems with point light sources, some methods were proposed to address the problem of unideal lighting conditions. In [22,23], a straightforward means was introduced by using a reference plane. For each light source, the reference plane was illuminated and imaged. The average intensity of each image was calculated and assumed as the intensity under a virtual parallel light. For each image point, its intensity deviation with respect to the average intensity was calculated and stored in a compensation-map. However, such an approach can only work with the near planar surfaces that were placed at a similar distance as the reference plane. In [9,24], the authors showed that partial differential equations (PDEs) can be used to represent the near-field lighting condition. A set of quasi-linear PDEs was used to approximate the general lighting scenarios, and several kinds of light attenuation models were tested with synthetic data that contained nonuniform albedo and extra noise. In addition, regarding the modeling of the radiation properties of LEDs [25,26], a lighting model for close-range point light sources was also investigated in [10,27].

There are also some works to address the semicalibrated PS issues [11,12,28] and uncalibrated PS issues [13] with the near-field point light source. In [11], a mesh deformation-based method was introduced to solve the near-field lighting problem. Each facet of the target mesh corresponded to a pixel in the image captured by the camera. In addition, the mesh deformation was decoupled into an iteration of interlaced steps of local projection and global blending. With the positions but not the brightnesses of the point light sources known, a robust stepwise numerical solver was proposed in [12] that can estimate the depth, light source brightness, albedo, light attenuation maps and reflectance coefficients in sequence using a heuristic means. In [13], the uncalibrated PS issue with the near-field point light source was investigated. The authors proposed a solution for reconstructing the normal map, the albedo, the light positions and the light intensities of a scene given only a sequence of near-light images in an alternating minimization framework. It first estimates both the normal and the albedo and then the positions and intensities.

This paper focuses on a low-cost calibrated photometric stereo system, which consists of some infrared LEDs and a web-camera. A similar LED lighting model as described in [10] was adopted to describe the lighting condition for each image point. To improve the surface normal calculation accuracy, a practical and accurate two-step calibration method is introduced. Using a comparison with the classical calibrated and uncalibrated photometric stereo methods, we show that accurate 3D reconstruction can be realized based on a low-cost photometric stereo device.

3. Modeling of LED light source

The proposed close-range PS system adopts some LED lamps as light sources. Subject to the inhomogeneous radiance of an LED and the near lighting distance, the lighting condition for each surface point should be accurately calculated. To describe such a close-range lighting condition, three major factors are considered in the proposed light model, which are the radiance property of the light source, the incident light angle and the intensity. To differentiate it from the conventional point light model, we named it the quasi-point light model.

3.1. Radiance model with angular attenuation

For a single LED lamp, it can be treated as a nonisotropic point light source, which usually has three intrinsic attributes: the principal optical axis $\boldsymbol{l}_0$, the principal energy E_0 along the principal optical axis, and the angular distribution function F. E_0 is the maximum radiance emitted by the light source, and its direction is defined as the principal optical axis $\mathbf{l}_0$. F is an angular distribution function that describes the radiance with respect to the included angle θ between $\mathbf{l}_0$ and any emergent light ray direction $\boldsymbol{l}$. Therefore, the light source can be represented as $Lsource < E_0, \mathbf{l}_0, F >$.

According to the rotational symmetry property of the light source radiance, the angular distribution function F can be illustrated by Fig. 2 and is formulated as follows:

$$F = \cos^g \theta, \tag{1}$$

where g is an angular attenuation factor related to the luminous property of light sources. The value of g is usually not provided with the product specification of the light source. To calculate g, we need to use another attribute named the half angle θ_{half}, which is the included angle between $\mathbf{l}_{half}$ and the principal optical axis $\mathbf{l}_0$. With the angular attenuation taken into consideration, the radiant energy along direction $\mathbf{l}_{half}$ is always half of that along $\mathbf{l}_0$, i.e., $\cos^g \theta_{half} = 0.5$. Therefore, once the half angle θ_{half} is known, the value of g can be calculated as follows:

$$g = \frac{\ln(0.5)}{\ln(\cos(\theta_{half}))}. \tag{2}$$