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A practical means for calibrating an LED-based photometric stereo system

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ABSTRACT

Conventional Photometric Stereo (PS) techniques are usually based on the assumption that the light sources are assumed sufficiently far from the object that all incoming light can be modeled using parallel rays. Meanwhile, for near-field lighting conditions the light sources are close to the object so the parallel ray model cannot be used. To determine the surface normal for each point on the object more accurately, the incoming light direction should be calculated individually for each point. In this work, based on a simple PS setup consisting of LED lamps and one camera, we present a practical method for calibrating lighting directions. First, an optical model of an LED was introduced in the calibration procedure to represent the surface irradiance and image irradiance more accurately. A reference sphere was used for the calibration so that the LED optical axis could be estimated by extracting the specular points from the reference sphere. By introducing the LED emitting model, distance between the LED and the specular point along the optical axis can be calculated. Thus, the incident lighting directions for various image points can be estimated individually. To improve the estimation robustness, a non-linear fitting approach was also applied. Experiments were conducted using objects and the results are compared with traditional methods to demonstrate its feasibility and improvement.

1. Introduction

Photometric Stereo has been an important vision technology for estimating the surface normals of objects by observing that object under different lighting conditions [1]. For most PS-based methods, the calibration of lighting directions is usually the first step, and is crucial because it directly determines the precision of recovered surface orientations. For simplicity, in most applications the light sources are usually assumed sufficiently far from the surface that all incoming light can be modeled using parallel rays. However, for PS systems with compact size where the light source is mounted very close to the target, the discrepancy of incoming light directions cannot be neglected. For this reason, the lighting direction for each image point needs to be determined individually. This problem is addressed using near-field lighting calibration [2].

There are two common ways to calibrate the near-field lighting. The first one is based on surface shading, and the second one is based on geometric references. In [3], the diffuse and specular components of the surface reflectance were modeled using Lambertian and Torrence-Sparrow models respectively, then the spatial positions of the near-field light sources were estimated. A similar approach was proposed in [4], in which the author assumed the diffuse component varied arbitrarily over the surfaces and the specular component of the total reflectance remained constant. A more general model for point light-source calibration was introduced in [5], in which the lighting positions were recovered from the shading information of a reference cube with surface properties that approximate an ideal Lambertian reflector. The calibration error was then estimated by minimizing the intensity errors between the actual images and virtual images, which were rendered by the estimated light positions. In [6], a dimensionality reduction technique was investigated to estimate the light positions. In [7], the point light source was estimated by utilizing the intensity difference between two image regions on a reference sphere. For the shading-based calibration methods, reflectance property of the reference object should be known *a priori* and assumed constant. In comparison, the geometric reference-based calibration methods use only the geometric information of the reference object and less image information, thus is more practical for many applications.

The geometric reference-based methods use geometric objects with known dimensions or spatial positions for the lighting

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direction calibration. By extracting the image features like specular point that formed by the light source on the object surface, lighting directions can be calculated with reference to the known geometric information. In [8], three reflective spheres with known relative positions were used to calibrate lighting directions. A matt sphere was used to determine the imaging system parameters. The other two reflective spheres generated two highlight points in the image. Because the angle of incoming light from the illuminant and the angle of outgoing light to the camera were equal, they could be used to determine the locations of the two highlights and triangulate the position of the light source. In [9], the spatial position of the light source was calculated by the triangulation of two different rays reflected from the inside and outside of a single clear hollow sphere. In the calibration process, the epipolar constraint was introduced to boost the accuracy. In [10], one or two mirrors were used to estimate the lighting directions and positions. Highlight points produced by the mirrors were extracted and triangulated to determine their 3D coordinates as well as directions. A simple and feasible method was also presented in [11] that utilized a specular sphere that was placed at different positions and captured by the camera. The intersections of these light vectors were calculated as the positions of the light sources. Generally, existing near-field lighting calibration methods only determine the principle direction of the light source, and assume all incident light rays with the same direction. However, if the size of the light source is very small and it is very close to the object, the incident light directions among various image regions can be quite different. Ignorance of the lighting direction discrepancies among different image areas will definitely degrade the precision of surface normal calculation as well as the final 3D reconstruction quality.

This study is based on an LED-based photometric stereo system. The system consists of seven LED lamps and one camera. By synchronizing the LEDs and camera, several images with various lighting conditions were acquired in less than one second. Because the LED lamps are relatively close to the target surface, determining the lighting directions at various image points became a critical issue for the photometric procedure as well as the major concern in this work. In comparison with previous lighting calibration methods, a mathematical LED emitter model was first developed to represent the relationship between incident light and image intensities more accurately. A reference spherical object was then used to calibrate the lighting directions. The specular points were extracted and used to calculate the direction of LED optical axis. Additionally, with the introduced LED emitting model, the distance between the LEDs and the specular point along the optical axis was estimated. As a result, the spatial position and orientations of each of the light sources were well defined within the camera reference frame. Thus, the incident lighting directions for various image points were obtained accurately. In order to obtain more accurate results, a non-linear fitting method was used. Additionally, a computationally-efficient position-estimation algorithm was also developed to reduce the computational cost.

The paper is organized as follows. In Section 2, we show how the LED emitting model was developed and related to the image intensities. In Section 3, the method for estimating the light source position and direction is introduced. Experimental results and evaluations of the proposed method are presented in Section 4. The conclusion is provided in Section 5.

2. Modeling of light source and image irradiance

LED lighting techniques have been used widely in our daily lives as well as machine vision applications [12,13]. Compared with conventional light sources, LED lamps have distinct advantages including selective emitting angle, adjustable color temperature control, higher lighting frequency, and longer usage life. The compact size of an LED diode also makes it convenient for integration into various machine vision systems. In this work, a simple PS setup was constructed consisting of seven LED lamps and one camera for the 3D reconstruction task. This section shows how the LED lighting was precisely modeled and then associated with the image irradiance.

2.1. Modeling of LED light source

In most previous work, the light sources are usually assumed to be ideal point lights infinitely far from the surface [14,15] so a parallel light ray model is typically employed. However, the parallel ray model is usually inaccurate for near-field lighting conditions. While the size of light source is small and very close to the object, there often exist distinct lighting direction discrepancies among different image areas. Meanwhile, most previous research has focused on the surface reflectance or irradiance, but the characteristics of the light source are usually ignored [3,4,8,9,11], which is likely to cause considerable errors in the calculation of surface normals.

According to the definition in [16], the intensity of an LED can be formulated as:

$$I_{LED}(\theta) = \sum_{i=1}^{n} c_{1i} \cos\,(\theta - c_{2i})^{c_{3i}}, \tag{1}$$

where θ is its emitting angle as shown in Fig. 1(a), I_{LED} denotes the radiant intensity (W/sr), c_{1i}, c_{2i}, c_{3i} are all the parameters to be determined, and n represents the number of the cosine-power term, which is based on the intensity distribution. In this work, the generalized Lambertian LED is considered. Its intensity function is expressed as a power function of cosine of θ [17], i.e.$n=1$, $c_{1i}=I_0, c_{2i}=0, c_{3i}=m$. Eq. (1) can be rewritten as:

$$I_{LED}(\theta) = I_0 \cos^m(\theta), \tag{2}$$

where $m = -\ln 2/\ln(\cos\theta_{1/2})$ and depends on the relative position of LED chip from the curvature center of the spherical encapsulant as shown in Fig. 1(b). I_0 denotes the intensity along the optical axis. For an ideal Lambertian condition, $m=1$. In practice, taking into account the light decay and manufacturing errors, m is commonly larger or less than 1.

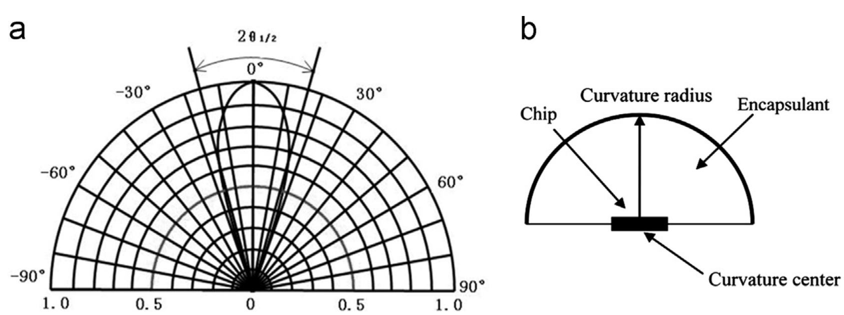

Fig. 1. (a) Radiance distribution of an LED with viewing angle 30°; (b) a simplified schematic diagram of an LED lamp.