Sampling Light Field for Photometric Stereo

Jiuai Sun, Melvyn Smith, Lyndon Smith, and Abdul Farooq

***Abstract*—To implement the photometric stereo technique, the radiance distribution of the respective light sources from the different illumination directions must be accurately known. Most previous work has tended to assume distance point sources, so that a collimated and uniform illumination distribution can be approximated, thereby allowing the photometric stereo problem to be easily solved in a linear way. However, there can be significant practical difficulties in realizing such idealized light sources in real world applications. In addition, the strategy of using distant light sources produces a low signal/noise ratio for the system, and is also unsuitable for applications where setup space is limited. These problems potentially limit new opportunities for the wider applications of photometric stereo beyond the research laboratory in evolving areas such as industrial inspection, security and medical applications. This paper proposes a compensation method for illumination radiance to allow the possibility of employing normal low-cost commercial light sources. A flat diffuse surface with either homogeneous or heterogeneous albedo distribution is used to sample the radiance distribution before implementing photometric stereo. The unevenly distributed light radiance is eliminated by using the acquired reference information. The experimental results demonstrate the efficacy of the proposed method.**

***Index Terms*—Light source, radiance, photometric stereo, compensation.**

I. Introduction

Although often overlooked, issues relating to illumination are almost always the most important aspect to be considered in designing any machine vision application. This is especially the case for those vision based methods which are directly based on geometrical parameters and the use of radiance variation of the lighting setup, such as shape from shading and photometric stereo (PS). In the case of photometric stereo, a 1% uncertainty in the intensity estimation will produce a 0.5-3.5 degree deviation in the surface normal orientation calculation [1].

In order to satisfy the parallel and uniform condition for the PS approach by using commonly available light sources, a distant point light source model is often used, i.e. when the working distance of an illuminator to an object surface is more than five times of the maximum dimension of the light emitting area, the illumination can be modeled as a point light source [2]. Clearly the radiance distributed over the surface will be more uniform when the working distance is larger. However, the radiance from the source at the surface falls off in accordance with the inverse square law. So a longer working distance will tend to cause the radiance to drop rapidly, correspondingly decreasing the signal/noise ratio of the whole system. In addition, such a distant lighting setup implicitly requires a large space for the whole system. So this approach is only suitable for those light sources which can produce high levels of energy and those applications which have large redundant space available. In terms of the availability and flexibility of current commercial illuminators, the distant illuminator solution may not be an optimal choice.

Nearby light source models have been used in some photometric stereo related work. Kim [3] considered the incident intensity drop-off passing along the light path. The photometric stereo problem was reduced to finding the local depth solution of a single nonlinear equation. Active photometric stereo is another example to use a point light source close to an object surface. The light source is moved in a known path so that only a linear equation is required to solve the photometric stereo problem [4].

The distribution of radiance, also called the light field, of an illuminate can be defined as a function of position and direction in space. In work to capture a BRDF surface model using the photometric stereo method, Paterson [5] does not attempt to model the attenuation of the radiance but rather uses a standard Lambertian surface to capture the incidence radiance and then models the radiance field using a bi-quadratic function. Similarly, Hansson et al. use a simpler model to compensate for uneven illumination in their paper inspection application [6]. The methods work well for uniformly diffusive light sources. However, any variation in lens or mirror geometry, spectrum response of the optical materials, or control and assembly of the optical components will cause the radiance to be distributed irregularly. This can be difficult to model as a closed form solution. For these reasons manufacturers usually specify their products using measurement datasheets corresponding to two-dimensional goniometric diagrams in matrix form for a far field, and four dimensional diagrams for a near field light source [7]. Clearly a mathematic function of two position variables will not be sufficient to characterize a complicated radiance distribution function for real light sources in 3D space.

Here we will not attempt to model the attenuation or distribution of the illumination radiance. Instead we will directly make use of the distribution of light irradiance sampled from a flat reference surface. The non-uniformity of the radiance distribution will then be compensated using the reference images. The method makes it possible to directly employ normal readily available commercial lighting components in practical photometric stereo applications. In summary the proposed approach has the following features:

1) Light sources need not be parallel.
2) Light sources need not be uniform.
3) Light sources need not be distant. They can be located in any position around the object(s) as long as the locations are able to be known.

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4) The brightness of each light source need not be the same.
5) There is no additional significant time cost required to solve the photometric stereo problem as the procedure remains a linear problem.

II. METHOD

A. Radiance Distribution and Photometric Stereo

For a surface point of a Lambertian object, the image intensity observed by an optical sensor can be expressed as the product of the incidence radiance E, surface reflectance ρ (also called albedo) and the cosine of the incidence angle θ, which can itself be expressed as the product of two unit column vectors: l, describing the incident light direction, and n, the surface normal. Equation 1 describes this.

$$I = E \cdot \rho \cdot \cos(\theta) = E \cdot \rho \cdot (l \cdot n) \qquad (1)$$

In general m (m≥3) images should be provided for the recovery of the surface reflectance and orientation. The traditional photometric stereo methods approximate the illumination as collimated uniform light sources or distant point light sources. Therefore the incident radiance of illuminations from different directions will be same across the whole illuminated surface. As such the factor of incidence radiance is neglected and m linear equations with albedo and surface orientation as variables for each point can be easily solved through a linear least squares method. However, in reality it can be surprisingly difficult or even impossible to obtain such idealized light sources. So it is necessary to find other ways to eliminate the incidence illumination radiance.

B. Radiance Distribution Compensation

Fig. 1. shows an imaging system setup composed of one light sensor (camera) and m light sources. As described above, the radiance of normal light sources may not be easily modeled using mathematical functions. It is also unrealistic to assume that each light has a constant distance to all points on the object surface, especially for the case of non-distant light sources. Individual electrical characteristics also conspire to make the radiance of the sources differ from each other. In order to compensate for all these factors, an object with a flat homogeneous reflectance characteristic is first used to capture the variation of illumination intensity over the working surface as shown in the left of Figure 1. The image intensity I_i^r (the superscript represents the reference object or object to be recovered, the subscript represents the ith image produced from the ith illumination) can be expressed as:

$$I_i^r = E_i^r \cdot \rho^r \cdot \cos(\theta_i^r) \qquad (2)$$

After obtaining the reference images, i.e. one for each illuminate, the reference flat object is removed and the planar object (which need not be of uniform albedo or monochromatic) to be recovered is placed in the same position relative to the imaging sensor. We then obtain a similar equation with the object to be recovered:

$$I_i^o = E_i^o \cdot \rho^o \cdot \cos(\theta_i^o) \qquad (3)$$

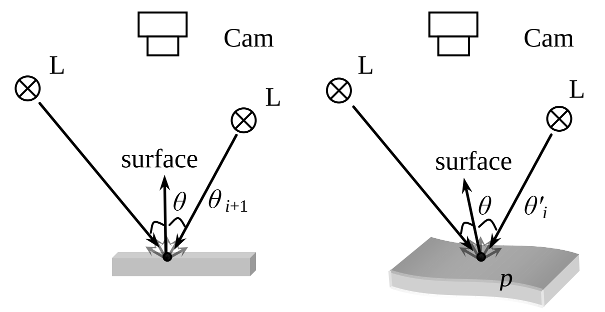


Fig. 1. An imaging system observing a flat reference surface (left) and a non-planar object surface (right)

Because the working area of the reference plane and the object to be recovered is similar, the radiance distribution E_i^r and E_i^o can be approximated to be same. By dividing equation (3) by equation (2), we can cause the effects of the non-uniform illumination distribution to be eliminated. So we have the following expression:

$$I_i = I_i^o \cdot \rho^r \cdot \cos(\theta_i^r) / I_i^r = \rho^o \cdot \cos(\theta_i^o) \qquad (4)$$

On the left side of equation (4), the albedo ρ^r of the reference object surface is assumed to have a constant value (say 0.9 for white paper). It will be shown that the exact value of the constant has no effect for the recovery of surface orientation. Providing that the direction of the flat reference plane and light source position can be known through accurate calibration, the left side of equation is known. So equation (4) makes the problem similar to solving that of traditional photometric stereo. However, the compensation procedure is different from conventional regularization techniques, which simply average or adjust image intensity for uniform effects. Instead, the proposed method considers the illumination distribution across the object surface directly. At the same time the directionality is also considered by involving the factor $\cos(\theta_i^r)$. Furthermore, as the geometric setup and reflectance of the reference object can be obtained in advance, and the task converted to the traditional linear photometric stereo problem, there will be little extra computational cost.

The above method uses a flat reference object with a known uniform albedo value, which may be practically difficult to obtain for many applications. To solve this problem we can further relax the requirement on the reference surface. From equation (4), if we divide the ith value by the kth value (for example, let us assume k=0, corresponding to the first image, and i =1: m-1 to the rest of the images), we can obtain the following equation:

$$R_{i0} = \cos(\theta_i^o) / \cos(\theta_0^o) \qquad (5)$$

where R_{i0} can be calculated as $R_{i0} = (I_i^o \cdot I_0^r \cdot \cos(\theta_i^r)) / (I_i^r \cdot I_0^o \cdot \cos(\theta_0^r))$, which shows that the effect from the uniform reference albedo is removed.

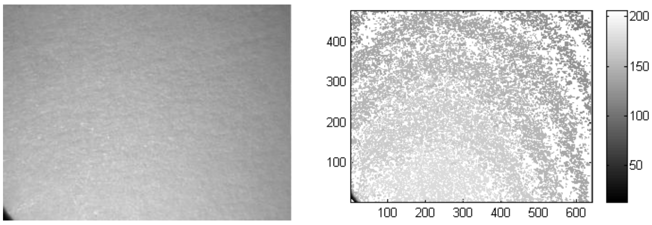
There are only two gradient unknowns on the right hand side of equation (5), so 3 images are enough to recover the orientation of the surface. The reflectance feature can be obtained by substituting the solved gradients into equation

(4). Note that due to the absolute reflectance of the reference object not being exactly known, the albedo obtained is a scaled value of that of the reference surface.

III. Experiments

The experiments were carried out using a compact portable photometric stereo system, whose principle and application can be found from the work described in [8]. The light sources are six surface-mounted phosphor LEDs, whose effective light emitting areas have a diameter of 2.4mm. The working area is 16mm x 12mm and the working distance is 50mm. The light sources can be approximated as nearby point light sources and their directions can be readily and accurately calibrated by using specular spheres of known size [9].

The first scene examined is composed of the word 'king' handwritten by the author on white paper. A blank piece of white paper is sampled as a reference flat object. One of the images and its intensity distribution are shown in Figure 2. We find that the distribution of the intensity is not uniform due to the close distance between lighting source and objects. Although the distribution exhibits some primal regularity, there is chaotic noise dominating some areas and the distribution cannot be described correctly by an ideal bi-quadratic or even higher degree of polynomial function. So a compensation method is required for such a complicated radiance distribution.



(a) (b)

Fig. 2. Image of a reference (white paper) object illuminated from one nearby point source (a) and its intensity distribution displayed as a contour map of intensity values (b)

After obtaining the reference images, another group of six images containing the word written on the paper were acquired. One of the images is shown in Figure 3(a). Then both the traditional photometric stereo method and the compensation method proposed here are applied to the images respectively. Figure 3(b), (d) and (f) show the recovered albedo image, recovered albedo values along the line drawn in (a) and rendered bump map image obtained using the traditional method. It is noticeable from Figure 3(b) and (d) that there is some uneven albedo distributed beyond the center area occupied by the script, particularly visible towards the image sides, which may be considered as an effect resulting from the unevenly distributed light sources as the white paper has a homogeneous albedo distribution. Figure 3(c), (e) and (g) are the results obtained from our compensation method, which shows a relatively uniform intensity distribution over the images when compared with the results obtained from the traditional method. This would seem to imply that the compensation method works better than the traditional method.

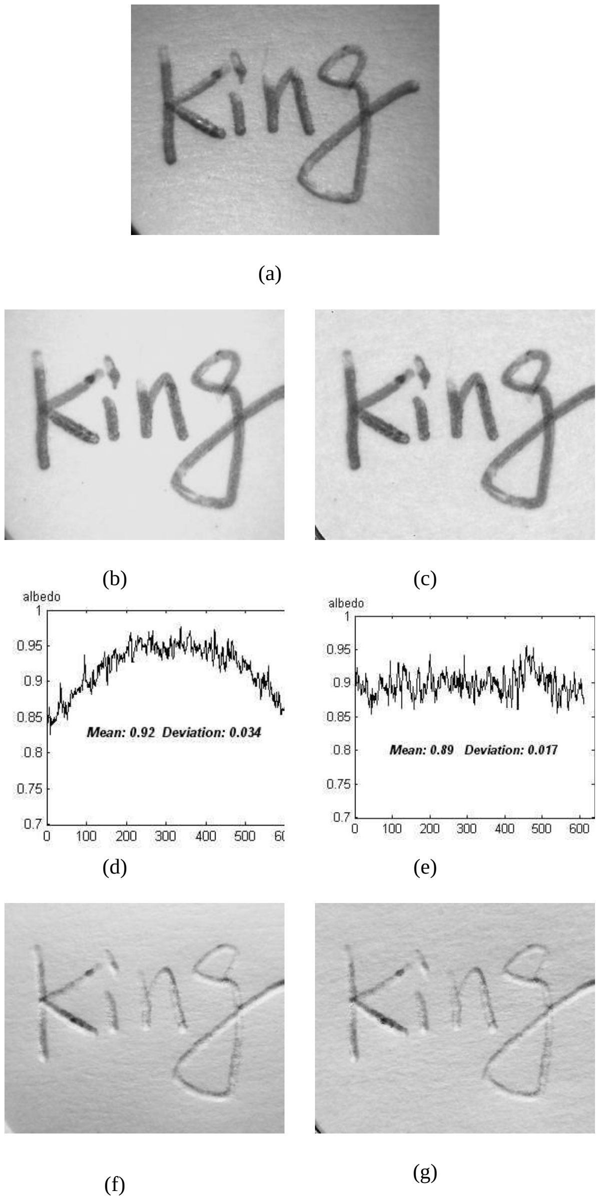
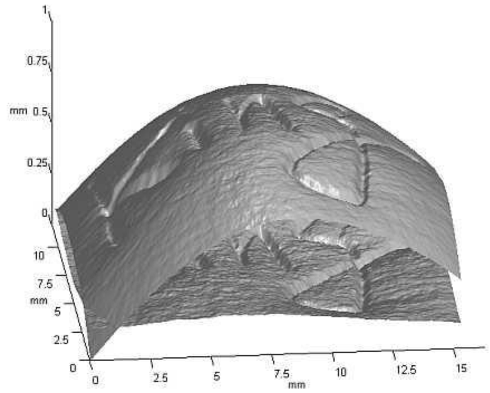
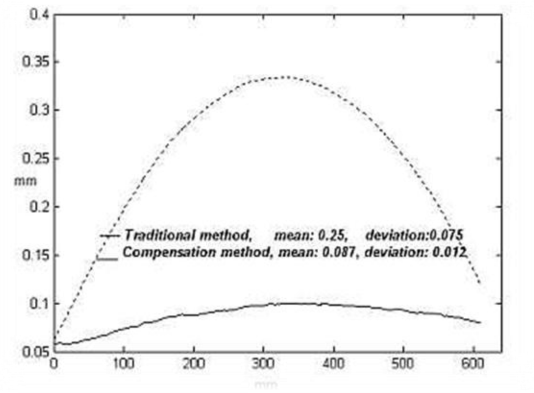


Fig. 3. One of the original images of a handwritten word 'king' on a white paper (a), the albedo images (b, c), plots of albedo values along the line (d, e) and rendered bump map (f, g) recovered from traditional photometric stereo and our proposed compensation method.

We confirm this by next integrating the surface normal recovered from two different methods and show them together in the same coordinate frame. We are particularly interested in how our approach impacts on the reconstructed 3D relief and because the device used to take the images and the reconstruction method [10] used are same for both methods, the only difference results from the application of the compensation method. The relatively flat surface shown in Figure 4 (a) results from the deployment of the compensation method, which almost eliminates the curved effect in the result obtained from the traditional method, i.e. without any illumination compensation. The top of the recovered curved surface reaches 0.84mm, while the flat surface from the compensation method only has a 0.11mm deviation, which approximates the actual depth of the signature impression. It is worth noting that this curved distortion is a common problem encountered when reconstructing 3D surfaces using photometric stereo within a compact working space. Figure 4 (b) shows a cross section of the reconstructed results along the line indicated in Figure 3 (a). Although the profile from the compensation result is not a theoretic straight line, the small average value (0.087mm) of the profile makes the measurement from the object more meaningful.



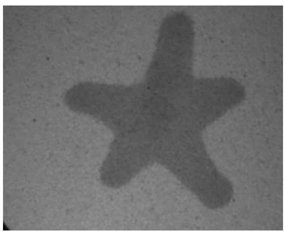
(a)



(b)

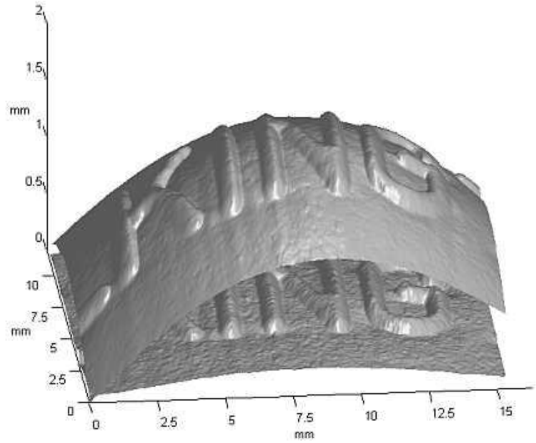
Fig. 4. Cross section through 3D reconstruction results from both the traditional method and the proposed compensation based technique.

The second scene consists of a ceramic tile, of varying albedo, and with the word ‘KING’ formed in the 3D topography of the otherwise flat surface. The reference images are taken from a flat area of same tile, but with heterogeneous albedo distribution, i.e. a varying albedo was used in the reference images. One reference image and the object image are shown in Figure 5 (a) and (b) respectively. The reconstructed surfaces obtained by using both traditional method and the proposed compensation method are shown together in Figure 5 (c). The compensation based reconstructed result (0.22mm) is close to that measured using a Vernier caliper (0.24mm). This verifies that a flat surface with non-uniform albedo may be used as a reference object.



(a)

(b)



(c)

Fig. 5. A pigmented flat reference surface (a), object surface with word ‘KING’ in 3D relief (b), and 3D reconstruction results obtained using both a traditional PS method and the proposed illumination compensation method (c)

IV. Discussion and Conclusions

This paper describes an investigation into the consideration of illumination radiance, one of the essential but often oversimplified or even ignored uncertainties present during the practical application of the photometric stereo method. A flat Lambertian surface, that need not have uniform albedo, is proposed to serve as a physical reference to compensate for the effects of irregular distribution in light radiance across the working area. By utilizing a simple reference surface and assuming the lights sources are small, i.e. point source, the light source specifications can be considerably relaxed to be non-collimated, non-distant and non-uniform. The results demonstrate that the method can work well on planar objects. The approach has the potential to expand the practical application of photometric stereo in areas such as industrial surface inspection and quality control, by allowing common, low-cost commercially available light sources to be readily used. Based on these promising results, in follow-on work we will further investigate how to apply the method to very different materials and highly curved non-planar objects. Other illumination radiance based 3D imaging techniques, such as shape from shading, shape from focus/defocus, are also our next targets.

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