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TRIDIMENSIONAL RECONSTRUCTION BY PHOTOMETRIC STEREO WITH NEAR SPOT LIGHT SOURCES

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ABSTRACT

In this paper, we propose a method for taking into account lighting conditions for photometric stereo. Indeed, with its classic form, the photometric stereo requires directional light sources and uniform intensity to determine the geometry and albedo of a surface from a reverse illumination model. These constraints are usually not realistic in practice for compact systems, our formulation thus takes account all lighting system properties. We use an iterative process to include the geometry of the surface in the reverse illumination model. Each iteration provides a refined reconstruction and significantly improves the results. Our method does not require a new illumination models and the iteration number is small. It allows to quickly recover geometry and albedo. To evaluate the performance of our method, we compare it to classical photometric stereo by simulation and on real surfaces.

Index Terms— image formation model, photometric stereo, tridimensional reconstruction, illumination model

1. INTRODUCTION

The image processing allows for metrology contactless and nondestructive. It is especially possible to acquire three-dimensional geometry of a surface or an object to facilitate their analysis by mathematical algorithms. In this context, we propose to use the *photometric-stereo* (PS) as acquisition technique and we present improvements to take into account the real application conditions. From several acquisitions of the differently-illuminated point, the PS separates the image components: surface geometry, surface color and the light properties. This method has the advantage of not requiring matching and for a very short acquisition time it provides a one millimeter or less accuracy.

As formulated by Woodham [1], PS method involves the use of directional light sources placed at an infinite distance to avoid the energy variations on the surface. This constraint is never respected in real systems, but most authors hypothesize that the sources are located at sufficiently high distance to the surface size in order to approximate this application constraint. Thus any surface point is considered illuminated by the same light intensity and the same light direction. In addition, all sources are supposed perfectly identical and only their geometric position relative to the surface is different. In practice and for many applications, this assumption is difficult or impossible to respect for size reasons. Indeed, the light sources are generally located at distance less than ten time of surface maximum size. This proximity allows the miniaturization of acquisitions systems [2] and the containment to eliminate the inter-reflection or ambient light phenomena. In addition, spot light sources are usually used. These assumptions simplifies the PS resolution, but generates the reconstruction errors because each surface point is illuminated with a different intensity and direction. The solution generally proposed [3, 4] is to make a preliminary image compensation based on a calibration of the illumination distribution. The compensation methods do not allow full and active correction. They do not take into account the direction variations at each surface point during the lighting model inversion. In addition, the compensation method application is not valid when the surfaces analyzed have important geometry varation because compensation map is acquired with flat surface.

In this paper, the PS method resolution is carried out with consideration of spot light sources located at a distance less than ten time of surface maximum size. The lighting distribution may be non-uniform and the calibration with a compensation map is useless. Our method is divided into two steps, first reconstruction called "coarse" is carried out with consideration of the actual positions of the light sources at each surface points with a flat initial topography. Then as [5] an iterative refinement allows taking into account the surface geometry. For each iteration, the light source geometry relative to the surface is recalculated.

2. PHOTOMETRIC-STEREO METHOD

The simplest model, formulated by Lambert in 1760 is the quantitative law for perfectly diffuse surfaces. Lambert stated that a perfectly diffuse surface illuminated by a single distant light source, appears equally bright from all viewing directions. He assumed that the diffuse surface has a homogeneous reflectance function (figure 1). According to the image acquisition process [6], the intensity M of a pixel corresponds to the transformation f of the radiance X emitted by the surface point $\alpha =< x, y, z >$ and his Albedo ρ, in response to the irradiance received. It is dependent on the main source intensity Il and the incidence angle θ well as the ambient light intensity Ib.

$$M_\alpha = f(X_\alpha) = f(Il_\alpha \rho_\alpha \cos\theta_\alpha) + f(Ib\rho_\alpha) \qquad (1)$$

The transformation f is the conversion of the luminous flux received by the sensor into a digital value. The numerical values M are close to X at a multiplicative constant k ($M_\alpha k \cong X_\alpha$) and under specific conditions [7], the transformation f can be considered linear and continuous.

Woodham [1] proposes to compute the gradient (p, q) of a surface point α along x and y, by reversing the Lambertian model. This inversion requires at least three different values X_α of the same point.

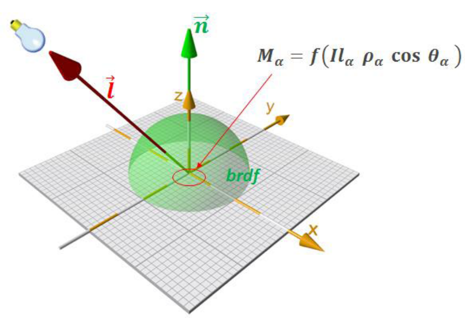

Fig. 1. Lambertian model.

To satisfy this constraint three images are acquired from a fixed viewpoint for three different lighting directions where the ambient light is null or constant. The estimate of p and q is to solve a linear system comprised of a vector $\vec{X}$ and a single illumination matrix $\mathbf{L}$ for each surface point, the ambient light intensity Il is considered constant.

$$\vec{N_\alpha} = \begin{bmatrix} p_\alpha \\ q_\alpha \\ 1 \end{bmatrix} = \frac{\left((\mathbf{L}^T\mathbf{L})^{-1}.\mathbf{L}^T.\vec{X_\alpha}\right)}{\left|(\mathbf{L}^T\mathbf{L})^{-1}.\mathbf{L}^T.\vec{X_\alpha}\right|} \qquad (2)$$

with $\mathbf{L}$ the illumination matrix with any α corresponding to the directions of the light sources according to their azimuth τ and σ zenith angles relative to the optical center.

$$\mathbf{L} = \begin{bmatrix} \cos\tau_1 \sin\sigma_1 & \sin\tau_1 \sin\sigma_1 & \cos\sigma_1 \\ \cos\tau_2 \sin\sigma_2 & \sin\tau_2 \sin\sigma_2 & \cos\sigma_2 \\ \cos\tau_3 \sin\sigma_3 & \sin\tau_3 \sin\sigma_3 & \cos\sigma_3 \end{bmatrix} \qquad (3)$$

The estimate of the topography map $\hat{Z}$ is obtained by numerical integration [8] of all vectors $\vec{N_\alpha}$.

3. PROPOSED METHOD

From a 2D cross section of the Lambert model (figure 2), it is easy to see that a point source located at a relatively short distance d_{LC} from the surface center does not produce the same lighting conditions at any point. To study the influence of these variations, we analyze the difference Δ in the incidence angle θ, intensity Il and radiance X according to the distance ratio $r = d_{LC}/d_{\alpha\alpha'}$ between two distinct points α and α' located around the surface center.

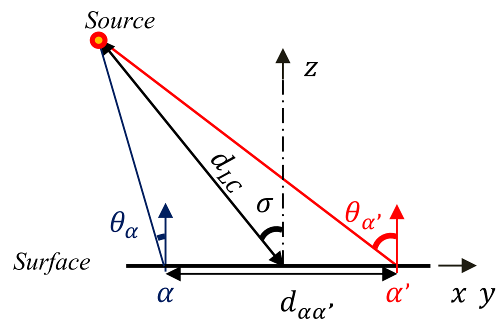

Fig. 2. 2D cross section of the Lambert model.

These differences depend on the zenith angle σ and affect values X_α and $X_{\alpha'}$ in proportion to the ratio r. Curves (figure 3) are obtained by Lambertien model computation with a flat surface where the albedo and the reflectance are constant. This analysis demonstrate that the variations of illumination (angle $\Delta\theta$ and intensity ΔIl) are insignificant when the ratio r is higher than 100 whatever the zenith angle. The difference $\Delta\theta$ is limited geometrically by the value σ. The $X_{\forall\alpha}$ values have a strong disparity due to the lighting geometry so that the topography of the surface is zero. The gradient fields and the estimate of the topography map $\hat{Z}$ are biased during PS application. The flat surfaces are reconstructed in the dome form (figure 4a) whose vertex is the point which has the three light sources maximum illumination. The more complex surfaces have deformations of the macro (variations $> 1mm$) and micro (variations $< 1mm$) geometry.

To eliminate these problems, our method reverses the Lambertian model for the spot light source geometry. The estimate of the gradient fields is performed from an illumination matrix $\mathbf{L}_\alpha$ calculated for each surface point relative to the light source positions $< x_L, y_L, z_L >$. In addition, the radiance values $\vec{X_\alpha}$ are weighted by distance $d_{LCs\alpha}$ because the source intensities Il_s decrease proportionally with the square of the distances between emission points ($s = 1 \ldots 3$ sources) and the illuminated point α.

$$\vec{N_\alpha} = \begin{bmatrix} p_\alpha \\ q_\alpha \\ 1 \end{bmatrix} = \frac{\left((\mathbf{L}_\alpha^T\mathbf{L}_\alpha)^{-1}.\mathbf{L}_\alpha^T.\vec{E_\alpha}\right)}{\left|(\mathbf{L}_\alpha^T\mathbf{L}_\alpha)^{-1}.\mathbf{L}_\alpha^T.\vec{E_\alpha}\right|} \qquad (4)$$

where :

$$\mathbf{L}_\alpha = \begin{bmatrix} \vec{L}_{1\alpha} \\ \vec{L}_{2\alpha} \\ \vec{L}_{3\alpha} \end{bmatrix} \ with\ :\ \vec{L}_{1\alpha} = \begin{bmatrix} x_{L1} - x_\alpha \\ y_{L1} - y_\alpha \\ z_{L1} - z_\alpha \end{bmatrix} / \left| \vec{L}_{1\alpha} \right|$$

$$\vec{E}_\alpha = \begin{bmatrix} X_1\alpha / {d_{LC1\alpha}}^2 \\ X_2\alpha / {d_{LC2\alpha}}^2 \\ X_3\alpha / {d_{LC3\alpha}}^2 \end{bmatrix} \ with\ :$$

$${d_{LC1\alpha}}^2 = (x_{L1} - x_\alpha)^2 + (y_{L1} - y_\alpha)^2 + (z_{L1} - z_\alpha)^2$$

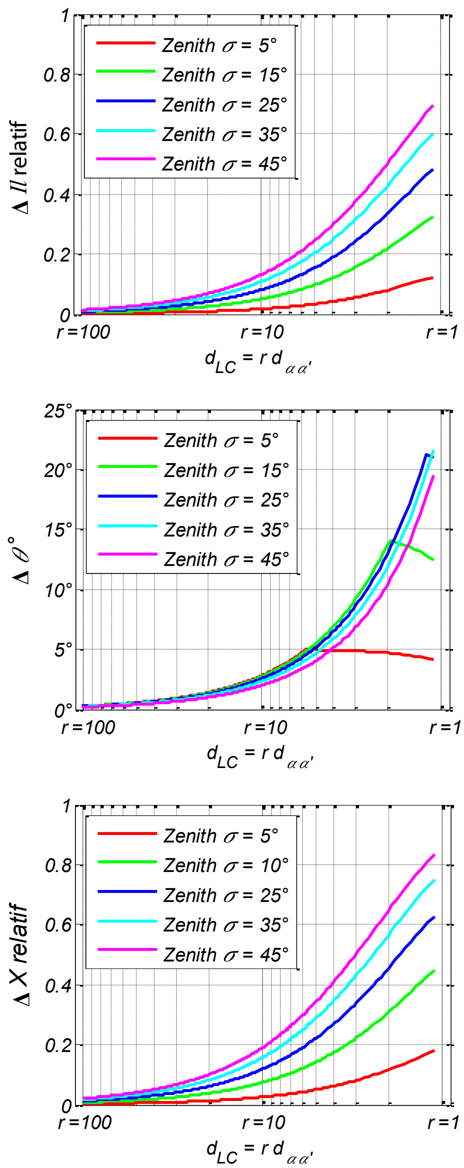

Fig. 3. Variations of angle θ, intensity Il and radiance X for two distinct points.

At the first iteration, the elevation of the surface points is fixed to zero $z_{\forall\alpha} = 0$. In the following iterations, the elevations are values $\hat{Z}$ previously estimated. Each iteration converges to an estimate closer to reality. The stopping criterion of the iterative loop is a function of the difference between two successive iterations:

$$SNR_{dB}(\hat{Z}^n, \hat{Z}^{n+1}) \geq T \quad (5)$$

The threshold value T is arbitrarily set depending on the reconstruction desired quality. For example, a threshold $T = 110dB$ involves very little change between two successive reconstructions and the refinement does not lead to significant improvements. The convergence speed depends of the surface complexity and topography. In the case of a flat surface a single iteration is sufficient to correct the illumination variations (Fig 4b), because initial elevation corresponds to the real surface elevation.

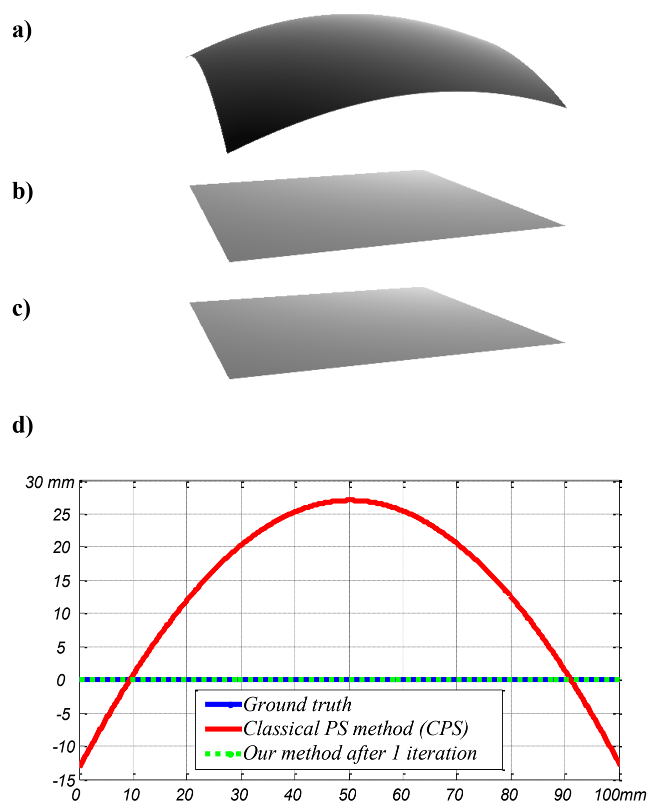

Fig. 4. Flat surface reconstruction analysis, a) with classical PS method (CPS), b) with our method after one iteration, c) ground truth and d) a cross-dimension profile.

4. EXPERIMENTS AND RESULTS

4.1. Synthetic surface

Our method is compared with the classical PS method (CPS) on synthetic images. The synthetic images are obtained from a ray tracing (POV-Ray), the resolution is $800 \times 800\, pixels$ for an area of $100 \times 100\, mm$ representing a hemisphere in which we add a sinusoidal roughness with $16\ pixels$ period. The lighting system consists of three identical spot lights placed at $400mm$ on a plane parallel to the surface being analyzed and distributed every 60^o on a circle of $150mm$ radius whose center is the camera.

	Our						*CPS*
iteration	***1***	***2***	***3***	***4***	***5***	***6***	***none***
(a) in dB	53.7	79.3	80.5	80.6	82.6	***82.7***	*-2.19*
(b) in dB	23.7	51.7	78.3	94.9	114.1		

Table 1. Synthetic surface (a) SNR_{dB} comparison between reconstruction and ground truth $SNR_{dB}(\hat{Z}^n, Z)$, (b) Our method stopping criterion $SNR_{dB}(\hat{Z}^n, \hat{Z}^{n+1})$

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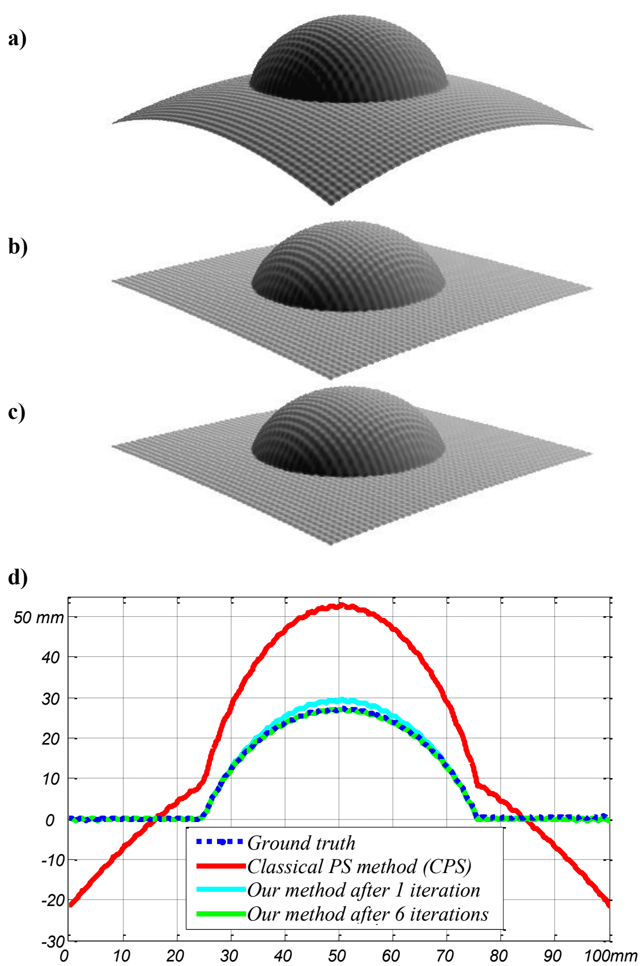

Fig. 5. Synthetic surface reconstruction analysis, a) with classical PS method (CPS), b) with our method after six iterations, c) ground truth and d) a crossdimension profile.

The results (figure 5a) illustrate the geometric distortions generated by the conventional SP method when using spot light sources. The three-dimensional reconstructions are affected by a global deformation in the form of a dome. This deformation visible on profile curve (figure 5d) affects the macro and micro geometry. The $SNR_{dB}(\hat{Z}, Z) = -2.19dB$ between the reconstruction and the ground truth reflects these important errors. We can see Figure 5b that our method can correct all these defects. In the first iteration the macro geometry is globally corrected. The following iterations allow a surface refinement (table 1a). After 6 iterations the inter-iteration difference (table 1b) is not significant and the iteration loop is automatically stopped when $T > 110dB$. The SNR_{dB} value between our reconstruction method after 6 iterations and the ground truth exceeds $82dB$.

4.2. Real surface

The real acquisition system is composed of a single-lens reflex camera Nikon D300S and a Nikon AF-S VR $105mm$ - $f/2.8G$. The image resolution obtained is $1434 \times 2160\, pixels$ for $60 \times 103\ mm$ surface area. As any PS method, the prior knowledge of the exact light source positions is required. This measurement is generally carried out manually but automatic algorithms exist. In our case, we implemented a variant of the algorithm proposed by Powell [9]. We use five hemispheres mirror to make a crosstriangulation with points specular detected. The zeniths and azimuths angular error is less than 0.2^o for an average standard deviation of 0.5^o. For distance d_{LC} estimation error ($> 100mm$) is too important to be used, we prefer the manual measurement.

The position $< x_\alpha, y_\alpha >$ of each surface point is calculated from the intra extrinsic camera parameters and the distance d_c between the camera and the surface origin plane:

$$\begin{aligned} x_\alpha &= (u - u_0) d_x (d_c/d_f) \\ y_\alpha &= (v - v_0) d_y (d_c/d_f) \end{aligned} \tag{6}$$

where $< u, v >$ are the pixel indices, $< u_0, v_0 >$ are the image center indices, d_x and d_y are the relative dimensions along x and y of a sensor pixel element and d_f is the focal distance.

	Our						*CPS*
iteration	***1***	***2***	***3***	***4***	***5***	***6***	***none***
(a) in dB	27.7	30.9	31.0	31.2	***31.6***	31.6	*3.51*
(b) in dB	37.7	70.9	106.6	139.4	186.7		

Table 2. Real surface (a) SNR_{dB} comparison between reconstruction and ground truth $SNR_{dB}(\hat{Z}^n, Z)$, (b) Our method stopping criterion $SNR_{dB}(\hat{Z}^n, \hat{Z}^{n+1})$

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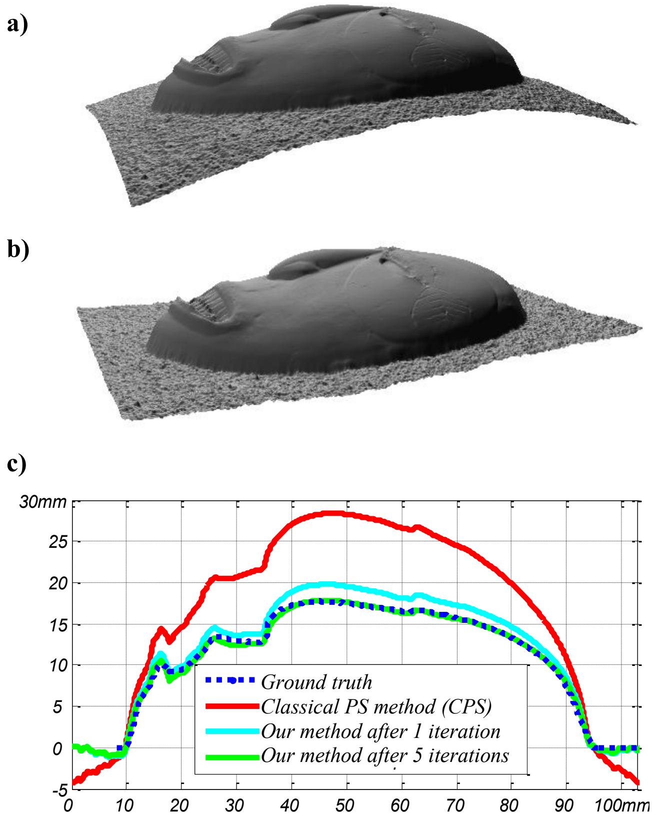

Fig. 6. Real surface reconstruction analysis, a) with classical PS method (CPS), b) with our method after five iterations, c) ground truth and d) a cross-dimension profile.

For this analyzed surface we know only profile for the truth ground. As before, the results (figure 6) show the defects of the classic method and the improvement by our method. Our method requires only 5 iterations (table 2b) for the SNR_{dB} value exceeds the threshold T. SNR_{dB} value (table 2a) between the ground truth profile and the profile obtained by our method is 10 times higher than that obtained by the classical PS method.

5. CONCLUSION

We have introduced a new PS method to increase the accuracy of three-dimensional reconstructions taking into account the non-uniform illumination distribution produced by spot light sources. The light source positions relative to each surface point are used to reverse the lighting model. And the iterative process can include the surface topography when solving the PS linear system (equation 4). The obtained results demonstrated that our method allows the use of spot light source and thus the miniaturization of photometric stereo acquisition system. As this method is based on conventional PS method and the Lambertien model, the computation time and complexity is low. It is easily adaptable to other lighting model or other improvements [10] such as the shadows or specularity detection.

6. REFERENCES

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