Top-down Illumination Photometric Stereo Imaging Using Light-Emitting Diodes and a Mobile Device

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Abstract: 3D reconstruction of objects can be achieved using a top-down illumination, photometric stereo imaging configuration with four modulated white LEDs and a mobile phone. The Standard deviation for the reconstruction is ranging from 3.5% to 10.4%.

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1. Introduction

Photometric stereo imaging relies on having one fixed camera perspective and different illumination directions to image an object in three dimension (3D) [1]. This technique determines the surface normal vectors and surface albedo at each pixel of the captured frames assuming a perfectly diffuse (Lambertian) surface of the imaged object [1]. Surface normal components can then be integrated to recover the 3D shape. So far, the most common photometric stereo configuration is as implemented with: a commercial camera placed in front of the object and, at least, four white light-emitting diodes (LEDs) surrounding it in a top/bottom/left/right or X shape [2,3]. A fast 3D reconstruction has been reported with white LEDs surrounding a camera, where LEDs were sequentially lit by a USB programmable board [2]. These 3D reconstructions showed a standard deviation error ranging from 2.65 mm to 15.60 mm for objects of size 50 mm and 160 mm, respectively [2].

In order to unlock the potential use of LEDs in industrial or public spaces for monitoring, security check or 3D imaging on mobile devices, the combination of lighting/camera system has to be easy to set up and flicker free. LEDs are affordable, energy efficient and have a fast modulation bandwidth ranging from several MHz up to GHz [4]. Thanks to a convenient interfacing with digital electronics [5], LED lighting enables advanced functionality such as wireless optical networking through the illumination itself.

Here we report the 3D reconstruction of objects using a top-down illumination photometric stereo imaging configuration. Four white modulated LEDs, mounted on a ceiling, illuminate the object while a mobile phone captures frames at 960 frame per second (fps). The LEDs are modulated at the camera frame rate with orthogonal multiple access carriers such that visible flicker is minimal and no electronic synchronization is needed between the LEDs and the phone. The 3D reconstruction shows a root mean square error (RMSE) ranging from 3.5% to 10.4% depending on the complexity of the object.

2. Experiment

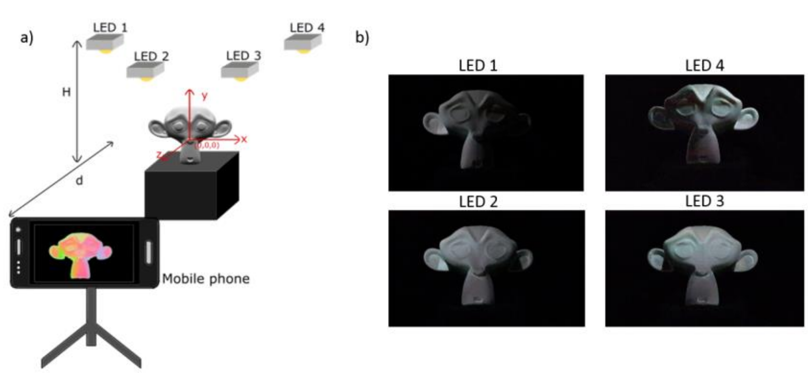

Fig. 1. a) Schematic of the experimental setup, b) Four images obtained from each fours LEDs after decoding

As illustrated in Fig. 1.a), four white LEDs (Osram OSTAR Stage LE RTUDW S2W) were placed on a gantry above the object at a height of H = 46 cm. In our experiments we used a number of 3D printed objects, including geometric solids and more complex shapes such as the monkey head in Fig. 1. The objects were ~130x94.5 mm wide and 79 mm deep, with the reference (0,0,0) point taken as their geometric centre. A mobile phone device

(Samsung Galaxy 9) was mounted on a tripod in front of the object on the z axis at a distance d = 30 cm with a field of view of 59 degrees. The phone was in a "side acquisition" configuration. The phone captured frames with a resolution of 1280x720 at a rate of 960 frame per second (fps) for 0.2 s. Fig. 1.b) shows the four images obtained after decoding the frames. For the illumination, we used an USB programmable controller board (Arduino Uno) to modulate the four LEDs at a frequency of 960 Hz. Each LED was modulated with an individual multiple access carrier signal at a frequency of 960 Hz, which is above visual flicker recognition and therefore suitable for digital lighting applications. The carriers were designed such that, analogous to orthogonal frequency division multiple access, no synchronization between the LEDs and the mobile phone was required.

3. Results

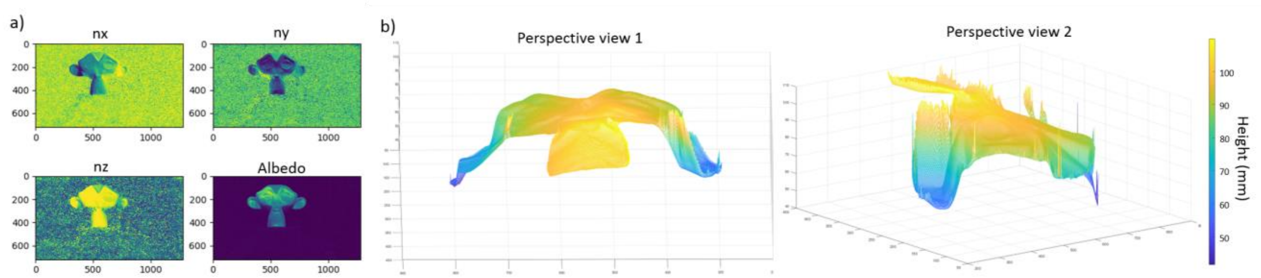

Fig. 2. a) Components of the surface normal vectors and the albedo, b) Different views of the monkey head 3D reconstruction

Surface normal integration has been a challenge for years in computer vision [6]. In this work, we integrate the surface normal vectors with the Fast Marching method [7] to take advantage of its reconstruction speed. A representative set of the surface normal components n_x, n_y, n_z, and the surface albedo are shown in Fig. 2.a). Yellow and blue color respectively represent positive and negative value of the surface normal components. As expected from the scheme in Fig. 1.a), n_x correctly distinguishes left and right facing surfaces of the object. Similarly, n_y correctly identifies up and down facing surfaces (clearly visible around the nose region), though we generally observe a poorer fidelity as compared to n_x due to the top-down illumination configuration. Finally, as we cannot see the back of the object, n_z is always positive with some variations due to the depth of the object.

Despite errors in n_x, n_y and n_z, especially in the ear area and the bottom of the face, 3D results plotted in Fig. 2.b) are comparable to the work done in [2]. As a reference, for a 48 mm diameter sphere and a 75 mm cube, in a similar configuration, we obtained a RMSE of respectively 5 mm and 2.6 mm which corresponds to the same RMSE range as [2]. The normalized RMSE of both objects equals to 10.4 % and 3.5 %, respectively.

4. Conclusion

Accurate 3D reconstruction is possible in a new photometric stereo configuration that can readily be employed in conventional room lighting scenarios. Top-down illumination photometric stereo can be directly applied to digital lighting application in public areas or industrial applications in the near future. Furthermore, we demonstrated that this method can then be implemented using commercially available, handheld mobile devices. Importantly, operation above the visual flicker recognition threshold is possible and there is no requirement for synchronization between LEDs, thus significantly simplifying installation and deployment.

5. References

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