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A per-pixel noise detection approach for example-based photometric stereo

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ABSTRACT

Photometric stereo is a classic Shape-From-Shading method which reconstructs surfaces from lighting responses with multiple images. In this paper, we focus on robust example-based photometric stereo with noisy images. By applying a novel per-pixel noise detection approach before intensity vector comparison, the noise maps of every input image are acquired first. Then they are used to guide the comparison afterwards by ignoring noisy lighting intensity components. Our approach can handle images with lighting noises, either self-shadows or casted shadows. Furthermore, the approach relaxes the material requirement for the target object, only dichromatic reflection model is needed instead of Lambertian model. Also, lighting calibration is unnecessary, making the approach very easy to test and apply. Experiments on both synthetic data and real world images show that the approach gives more robust reconstruction results when the input images are noisy.

1. Introduction

When observing an image of a smooth shading object under a certain light direction, we can clearly sense the shape of the object, because the lighting intensity of the object's surface changes while the surface normal changes. The Photometric Stereo (PS) problem reconstructs object's surface normal from a set of pictures taken from the same viewpoint. It is an important, classic, unsolved problem of computer vision. As a reconstruction method, it has been applied in varied areas like 3D face capture [1], outdoor scene relighting [2], material modeling [2,3], 3D imaging framework [4] and so on. Over the past decades, lots of work have been done and people came up with many methods. Basically, the main steps of all photometric stereo methods are similar:

1. Take images of a target object under different lighting conditions.
2. Estimate the surface normal.
3. Reconstruct the target object using the estimated normal information.

In the work on photometric stereo, many approaches make the assumption that the surface material is Lambertian and spatially uniform. Robert J.Woodham [5] first came up with the concept of photometric stereo and its general procedure in 1980. He also first brought the Lambertian material model to the PS problem. In his approach, every image lighting direction must be measured. In 1994, Hayakawa [6] gave another approach using the Lambertian model. By paying attention to the relation between lighting direction matrix and normal matrix, the method only needs to measure three lighting directions. However, both Woodham and Hayakawa made the assumption that the material had to be Lambertian and neither of them paid attention to the shadow and highlight in the images. Following Hayakawa's idea, Miyazaki and IKeuchi [7] used SVD to remove the requirement of three lighting directions, but the method did not pay attention to the shadow noise neither.

Barsky and Petrou [8] focused on the shadow problem in the PS problem of four images. They used the Lambertian model and gave a very enlightening conclusion about the relation between linear combination parameters of lighting directions and image pixel intense vectors. In their approach, there should be at most ONE image with significant shadow or noise. Also, the method needed exact lighting directions as input, which led to calibration work. Unlike Barsky and Petrou, Hernandez et al. [9] took a more challenging problem about shadow when only three input images were given. They fixed this ill-conditioned problem by applying a shading regularization process. In 2011, they presented a new shape regularization approach [10] for the exact same problem. While enhancing the result of the old problem, they successfully extended the method to color images, which belongs to the so-called Colored Photometric Stereo (CPS) problem. But less image quantity led to more restriction in shadow presences and the calibration was still needed.

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As to non-Lambertian material, Goldman's method [3] assumed dichromatic reflection model and constructed both normal and material parameters from images. In brief, the dichromatic reflection model models the surface's BRDF with not only diffuse part, but also specular part. Yang and Ahuja's approach [11] took the same dichromatic reflection assumption. By some simple user interaction, they first manually chose some surface points which fit to the Lambertian model, and split the highlight part of other surface points out of the lighting intensity. After that, all pixels fit to the Lambertian model and Lambertian PS model [5] was used to solve the problem. Still, both Goldman and Yang did not take shadow noise into consideration.

Hertzmann and Seitz [12] first introduced reference balls to this problem. Compared to other methods, they managed to reconstruct objects with arbitrary material model. Also, the measurement of lighting directions was unnecessary. By adopting the proposed orientation-consistency cue, they successfully made a significant progress in PS. But there were still some flaws. First, they needed a reference ball with the same material as the target object. If the target object was composed of several different materials, multiple reference balls should be prepared. This made the approach more difficult to apply in practice. Also, the images were taken in the absence of shadows, inter-reflections and overexposure.

Lu et al. [13] proposed a no-calibration, no-example photometric stereo approach with unknown object reflectance. Their method was based on uniform sampling in the lighting direction space and massive images were needed. Ackermann et al. [2] came up with a system that operated on time-lapse sequence images, which were captured by static outdoor webcams over the course of several months. The large amount of image need made these approaches hard to test and apply in practice.

In the normal-to-depth step of PS, the surface normal field is integrated to get the surface depth map. However, this naive approach may give unfavorable result due to the inaccurately estimated normal fields. Recently, several approaches have been brought up to deal with this problem. Harker and O'Leary [14] pointed out that the method based on Poisson equation [15] was misunderstood. It did not solve the integration correctly. They gave the N degree derivative formula of the image. Using that, they managed to reconstruct the surface within the $N-1$ order polynomial approximation. Harrision and Joseph [16] focused on the Gaussian noise in the original images. Nehab et al. [17] constructed surface by optimizing normal and position interactively.

In this paper, we focus on the noise in example-based photometric stereo. The contributions of this paper mainly are

- Using only ONE reference Lambertian ball, an example-based photometric stereo approach which can reconstruct objects with dichromatic reflection model is presented, which is easy to apply in practice.
- By applying a novel noise detection approach before the normal-estimating process, which keeps the pixel comparison process from the affection of noise, robust and visually acceptable reconstruction results are obtained.

The rest of this paper is organized as follows: Section 2 gives an overview of the PS problem and an overview of the proposed approach. Section 3 talks about the approach in detail. Section 4 gives results on both synthetic images and real-world images. Finally the conclusions are given in Section 5.

2. Problem overview

In the traditional example-based photometric stereo approach, presented by Hertzmann and Seitz [12], the important orientation-consistency cue was addressed, that is

> Two points with the same surface orientation reflect the same light toward the viewer.

Following this cue, they put a reference ball whose surface geometry is already known in the scene, then estimate normal fields of the target object by comparing the lighting intensity vectors of every pixel on the surface of reference ball and the target object.

However, when there are shadows or highlight areas on the target object surface, the comparison becomes fallibility and leads to poor results. Also, when the material model of the target object is different from the reference ball, the comparison also becomes questionable, which means that the reference ball with the same material as the target must be prepared before reconstruction.

Here, we follow Hertzmann's idea of intensity vector comparison, but paying more attention to the lighting noise on the target object surface. A reference ball and the target object are placed in one scene, in front of where a camera is set. The reference ball and the target object should have the similar distances from the camera. The distance between the scene and the camera should be properly chosen. If the distance is too small, the camera distortion can be significant. Meanwhile, if the distance is too large, the proportion of the scene in the images will be too small, which is not suitable for reconstruction. From the same viewpoint, several images are taken, under different lighting directions. Here, just as other literatures, we make the assumption that the projection is orthogonal and the lighting is parallel. Also the lens distortion brought by the camera is ignored. All these assumptions can be easily met during the practical operation.

For the reference ball, we assume that it has Lambertian surface, and there is no noise on the surface. In practice, this assumption is easy to fit because ball surface is convex at every position, which means that self-shadow is impossible to be created and casted shadow can be avoided by choosing proper lighting directions. However, we loose the restriction on the target object to dichromatic reflection model, which can be separated to a Lambertian component and a highlight component. Furthermore, the existence of noises on target object surface is allowed, which makes this approach capable with complex lighting conditions or rough object surface, where the noises like shadows cannot be avoided easily.

Fig. 1 shows the overview of our approach. First, by simple user interactions, the projected image area of reference ball, denoted by B, and the projected image area of target object, denoted by O, are marked in the input images. Then a novel per-pixel noise detection approach is applied to detect all the noise pixels in all images, and then the noise maps of every input image are created. With the help of the noise maps, we successfully obtain robust normal estimation of every pixel in O by comparing them with pixels in B. The final reconstructed result is generated by integrating the estimated normal.

3. Approach

We first introduce some notations used in this paper. For total N images, they have the same resolution of $w*h$, where w is the width and h is the height of the image. For every pixel in an image, there is a global coordinate (x, y, d), (x,y) is the 2D position and d is the depth of the pixel which is unknown and to be obtained. In this paper, we use a single p as pixel index other than (x,y). So, $\overrightarrow{n_p}$ is the surface normal at pixel p, d_p is the surface depth. The vector $\overrightarrow{I_p} = (I_{p1}, I_{p2}, \ldots, I_{pN})$ is the intensity vector of pixel p over the N images, where I_{pi} is the intensity of pixel p in image i. For every image i, its normalized lighting direction is $\overrightarrow{L_i}$.