論 文 の 内 容 の 要 旨

論文題目　Photometric Stereo with Auto Radiometric Calibration
(カメラ応答関数の自動校正を伴う照度差ステレオ)

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Scene structure recovery from images is one of the fundamental problems that has been studied since the early day of computer vision. It is well-known that scene appearance in images does not only rely on scene geometric structure but also surface properties, illumination, and the properties of camera that is used to capture the images. Then, the scene geometric structure can be estimated from the appearance of the images under some assumption regarding surface reflection properties and surrounding environment such as illumination, hence the name photometric-based scene recovery. However, many photometric-based scene recovery studies emphasize only in the relationship of scene appearance, surface properties, and illumination, while take for the granted that the camera properties are calibrated or measured beforehand.

In this work, we focus on improving the photometric-based surface recovery method to account for the camera properties such as radiometric response function so we can avoid time-consuming and cumbersome camera calibration with no additional images are required. The key idea behind this work is to make use of inherent properties that lie inside the input images such as the consistency between the irradiance converted from the camera's image formation model and the irradiance estimated from a reflection model. In other words, we use the physical clues that reside in the images to perform camera calibration while simultaneously estimate the scene structure.

First, we present photometric stereo techniques that can estimate surface orientations from a sequence of object images taken under different lighting directions with a radiometrically uncalibrated camera. The original photometric stereo assumes the images are captured by a camera with a linear response function. However, cameras often have a non-linear response function, and thus, the radiometric calibration is required to cancel the effect of nonlinear response function before taking images which are later used for physics-based analysis of the scene. Unfortunately, the radiometric calibration is a time-consuming pre-process that requires either many additional images or a calibration target.

Here we use the consistency between the irradiance converted from the inverse response function and the irradiance estimated from Lambertian reflection model to formulate a linear optimization problem to estimate the surface normals of a Lambertian surface and the response function simultaneously. We empirically show that our proposed method can produce surface orientation from images accurately even though the images were captured by radiometrically uncalibrated cameras.

Then, we extend the proposed method for the surfaces that do not follow Lambertian reflection model. Many real-world objects contain reflections that do not follow Lambertian reflection property such as specular highlights or weak specular lobe. Our simultaneous estimation model does not account for these kinds of reflection so it produces distorted surfaces when specular highlights are observed in the input images.

However, many non-Lambertian surfaces exhibit reflection similar to Lambertian surfaces where no specular highlight is not observed. Therefore, we can treat specular highlights pixels as outliers to Lambertian reflection model and use a robust estimation technique such as RANSAC to determine inverse response function and surface normals that maximize the number of diffuse reflection. The experiments on synthetic images and real images illustrate that our proposed method can compensate the nonlinearity of response function even though there exist corrupted measurements such as specular highlights in the scene.

Finally, we refocus ourselves into a more practical ground of photometric stereo by pursuing a radiometric calibration method for uncalibrated photometric stereo where light source directions and intensities are unknown. Without light source directions, there exist multiple solutions of surface normals, light source directions, and response functions that satisfy the given photometric stereo images.

Assume that the target object has Lambertian reflection property, we can express radiometrically calibrated images of the object as an image matrix with the rank of three that exhibits linear dependency property under linear response function. However, this assumption is no longer true under nonlinear response functions as the nonlinearity of the response function variates the images so that each element of the image matrix deviates from the linear model we assume. As the result, the image matrix loses its rank-3 structure and becomes full rank.

Here we propose a radiometric calibration method for uncalibrated photometric stereo. Given the response function is monotonicity increasing, there exists an inverse function that can restore the rank-3 property of the image matrix. Therefore, we formulate a singular value minimization problem with a rank constraint to find an inverse response function that produces the best rank-3 image matrix from the full-rank input matrix.

With this method, ones can compensate the nonlinearity of the response function even when the light source directions and intensities are not known beforehand. Therefore, our method allows existing uncalibrated photometric stereo techniques to estimate surface normals without neither the calibration of light sources and the calibration of the camera response function. Moreover, we do not assume that the input images must be color and our method works well with grayscale objects. That is, our method allows one to estimate response function for each color channel separately.

We conducted experiments on both synthetic and real images to validate the inverse response function calibration of our method. We used existing uncalibrated photometric stereo techniques to estimate surfaces from images calibrated with our method and compared that to those estimated from radiometrically calibrated and uncalibrated images. The experimental results illustrated that our proposed method can compensate the nonlinearity of the response function used for capturing the scene even when light source directions and intensities are unknown so that the surfaces estimated from images calibrated with our method were similar to ones estimated from radiometrically calibrated images.