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論文内容の要旨

Photometric Stereo Using Constrained Regression
(制約付き回帰に基づく照度差ステレオ)

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Photometric stereo is an inverse problem of recovering surface normals of a scene from appearance variations under different lightings. When the reflectance of a scene obeys a simple Lambertian assumption, the problem is well-constrained and there is a very simple algorithm capable of recovering the surface normals and albedos of the scene. However, the image formation process of the real world scene involves more complex interactions between scene shape, reflectance and illumination, making the problem more difficult.

Nearly all current approaches to this problem can be viewed as performing the standard regression analysis which finds the relationship between actual observation and unknown model parameters (e.g., surface normals and unknown parameters of the image formation model) by minimizing the residual between the observation and estimated model output. From this standpoint, the statistical complexity of the photometric stereo problem can be discussed with regard to the behavior of outliers deviated from the underlying model assumption, and its complexity i.e., the number and non-linearity of parameters in the model. For instance, the Lambertian diffuse reflectance model has only 3-DOF assuming the lightings are known a priori, and therefore less complex and easy to be solved inversely. However, more stable outlier rejection techniques are required when the behavior of non-Lambertian effects becomes more complex. On the other hand, some of non-Lambertian effects can be considered as inliers with the complex reflectance model and the derivative image formation model, however the increased complexity may make the inference difficult or even impossible. Thus, there is a constant struggle between model complexity and tractability.

This dissertation argues that new penalties and constraints applied to a simple (therefore mostly linear) image formation model well formulate the photometric stereo problem of the non-Lambertian scene. The dissertation begins by deriving optimal solutions to the sparse regression formulation of the photometric stereo problem, where a sparsity penalty is applied to outliers of Lambertian diffuse reflectance model to robustly neglect various non-Lambertian effects such as shadows, specular highlights, and sensor noises.

Then, we develop a branch to handle the non-Lambertian diffuse reflections with sparse non-diffusive outliers, where the inlier model can no longer be represented by a simple Lambertian reflectance model. Additionally, we present that the assumption on BRDF that a diffuse component is represented by a monotonic function of the surface normal and lighting dot-product, reasonably resolves the non-linearity of BRDF in the regression, which dramatically reduces the complexity of the problem. This function is constructed using a piecewise linear approximation, which is modeled as latent variables embedded within a hierarchical Bayesian model such that we may accurately compute the unknown surface normals while simultaneously separating diffuse from non-diffuse components.

Finally, we challenge to recover the surface normals of general isotropic materials without assuming any parametric BRDF nor special light configurations. A simple bivariate reflectance model is derived from a non-linear but versatile sum-of-lobes representation of the isotropic BRDF. Then, we prove that the non-linearity of the model is also canceled by assuming the monotonicity of the BRDF which is commonly observed in most physically plausible BRDF. Approximating the regression function by smooth, bivariate Bernstein polynomials, the unknown normal vector is separated from the unknown inverse reflectance function, and then we may accurately compute the unknown surface normals by solving a simple and efficient quadratic programming problem.