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3D Shape and Spectral Reflectance Estimation Using Off-the-Shelf Camera and Projector

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Outline

Background and goal

3D shape and spectral reflectance are inherent geometric and photometric characteristics of an object. The geometric property is determined by the surface topography of the measurement objects in three-dimensional (3D) space, while the photometric property, which is also known as spectral reflectance, is determined by how the incident light is reflected at each wavelength and each 3D point of the object surface. The spectral reflectance reflects the essential reason of the object exhibiting different colors. Actually, The human vision system, as well as most cameras, reduces the dimension of geometric and photometric characteristics of the real world, and lost some information. Specifically, for geometric property, the 3D shape is projected to a 2D image plane and the depth information (distance to the camera) is lost; for photometric property, the spectral reflectance, which is a continuous electromagnetic radiation over a range of wavelength, is converted to a RGB tri-stimulus value.

In this thesis, our aim is to reconstruct the spectral 3D information (3D shape and spectral reflectances) of an object from RGB images captured using a standard RGB camera and an off-the-shelf LED projector. Since the 3D shape and the spectral reflectance provides the scene's geometric and photometric properties, respectively, simultaneously acquiring them has various potential applications such as cultural heritage, artwork authentication, material classification, plant modeling, and relighting.

Thesis organization

This thesis consists of 5 chapters:

Chapter 1, Introduction - This chapter introduces the background and applications of 3D reconstruction and the spectral reflectance estimation. 3D reconstruction and spectral reflectance estimation are well-studied research topics in computer vision. However, these two research fields have progressed separately. So in this chapter, we separately review the previous works related to 3D reconstruction and spectral reflectance estimation, and discusses the weakness of previous works from the viewpoints of the accuracy, the convenience for use, and the cost.

Chapter 2, Pro-Cam SSfM: 3D Shape and Spectral Reflectance Estimation Using Structured-light and Uniform Color Illuminations - In this chapter, we first propose a novel projector-camera system called Pro-Cam SSfM, for structure and spectral reflectance from motion. In Pro-Cam SSfM, we use a standard RGB camera and leverage an off-the-shelf projector for two roles: structured light and multi-spectral imaging. For our data acquisition, structured light patterns (for geometric observations) and uniform color illuminations (for multispectral observations) are sequentially projected onto the object surface while alternately moving the camera and the projector to arbitrary positions around the object. Using the captured multi-view structured light data, we first reconstruct the dense 3D points of the whole shape while estimating the poses of all moved cameras and projectors in a self-calibration manner based on SfM using the tracked feature correspondences among all the projector and the camera viewpoints. Using the captured multi-view multispectral data, we then estimate the spectral reflectance of each 3D point considering the geometric relationship between the reconstructed 3D points and the estimated projector positions. Owing to the proposed self-calibrating 3D reconstruction, the reconstructed 3D points and the estimated projector positions can be used to construct a lighting model to eliminate the baked-in effect of the shading and the shadows from the estimated spectral reflectance without requiring any geometric calibration.

Chapter 3, Spectral MVIR: Joint Optimization of 3D Shape and Spectral Reflectance - In contrast to the separate estimation of 3D shape and spectral reflectance for Pro-Cam SSfM (Chapter 2), we propose a novel Multi-View Inverse Rendering (MVIR) method called Spectral MVIR for jointly reconstructing the detailed 3D shape and the spectral reflectance for each point of object surfaces from multi-view images. Unlike Pro-Cam SSfM, Spectral MVIR has no limitation of the selection on lighting devices. Spectral MVIR is suitable to a setup that using a low-cost smart LED bulb as light source. The smart LED bulb can emit several types of illumination with different spectral power distributions. (Note that, instead of a smart LED bulb, we can use separate light sources with arbitrary positions for our method.) Using the captured input images, we first estimate camera poses and an initial mesh model based on SfM and MVS, and then jointly optimize each vertex's 3D position and spectral reflectance by minimizing multi-view and multispectral rendering errors. Spectral MVIR can also be directly applied to the initial 3D model obtained by Pro-Cam SSfM to refine 3D model via the joint optimization exploiting the shading information observed by the camera, which has a much higher pixel resolution than the projector.

Chapter 4, Learning-Based Single-Shot Estimation Using Color-Dot Projection - These 3D spectral acquisition methods introduced in previous chapters observe spectral measurements by temporally changing illumination spectrum, thus they are limited to static scenes and not applicable to dynamic scenes. In this chapter, we propose a novel single-shot system to simultaneously acquire the depth and the spectral reflectance using a standard RGB camera and an off-the-shelf projector. Our system is based on a single random color-dot projection, which simultaneously acts as structured light for depth reconstruction and spatially-varying color illuminations for spectral reconstruction. Since the random color dot provides a unique code pattern and three distinct RGB color illuminations for each local region, we exploit these cues for the depth and the spectral reconstruction. To effectively reconstruct the depth and the spectral reflectance from a single color-dot image, we propose a novel end-to-end deep learning method. Since the location of the observed color-dot pattern depends on the scene depth, we perform the joint learning of the depth and the spectral reflectance to improve the accuracy of each other, by considering the geometric warping of the color-dot pattern. Furthermore, to address the difficulty of constructing a real-world hyperspectral-depth dataset, we develop a spectral renderer to generate a synthetic dataset using a spectral rendering model under the color-dot illumination.

Chapter 5, Conclusions and Future Works - This chapter concludes the key ideas, combs the dissertation, and outlines possible future directions of the works.