High-fidelity 3D reconstruction via photometric stereo

Department of Multimedia Engineering, Graduate School of Information Scienceand Technology

Professor Yasuyuki Matsushita

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Abstract

In this research, we are working on establishing a technique for restoring three-dimensional shapes and textures of real-world objects using the photometric stereo method for the purpose of high-fidelity three-dimensional digitization. In this study, we are developing a data-driven approach to photometric stereo and a one-shot photometric stereo method using a multi-wavelength light source and a multi-wavelength sensor. These methods can be applied to the quantification of real-world 3D objects and to the digital reproduction and preservation of shape and texture.

Background & Results

When we "see" an object in the real world, what our eyes actually perceive is the light that is projected toward our eyes from the object. The light is observed through interactions with the object, being reflected or transmitted on the object surface. Therefore, by correctly digitizing the three-dimensional shape, surface reflectance, and color of a real-world object, a digital 3D replica can be created that has the same appearance as the actual object under any light source. The digital replicas can be used for digital preservation of cultural assets and as contents in virtual spaces. The digital replication technology developed in this research corresponds to the quantification of real-world objects and is expected to be applied to industrial applications such as product appearance inspections.

Significance of the research and Future perspective

There is a technique called "photometric stereo" which is a method of 3D shape estimation using shading patterns in images. Photometric stereo can estimate the surface orientation at each point from brightness variations observed in multiple images taken under different illumination conditions. The surface orientation indicates the direction to which the surface on the object is looking at and is expressed as a surface normal vector that represents the direction in three-dimensional space. Since this can be computed for each pixel in the image, it is collectively called a surface normal map. Integrating the normal map yields a depth map, and conversely, the gradient of the depth map corresponds to the normal map. Thus, the normal map contains a lot of information about the three-dimensional shape. Moreover, because photometric stereo can estimate the shape of each pixel, it can provide high-fidelity 3D shape estimation.

While conventional photometric stereo methods have been applied to diffuse surfaces that are not shiny or glossy, objects in the real world have a variety of textures represented by different reflectance distributions (Figure 1) that were challenging for the previous methods. This research has revealed that a data-driven approach that utilizes prior knowledge of reflectances can be used to accurately estimate 3D shape. As shown in Figure 2, it is now possible to recover high-fidelity 3D shapes and textures from input image sequences taken under different light sources. We are also working on a photometric stereo method that can recover 3D shape in a single shot by multiplexing measurements at different wavelengths using a multi-wavelength light source and a multi-wavelength sensor, and are developing a 3D shape recovery method for dynamic objects (Figure 3).

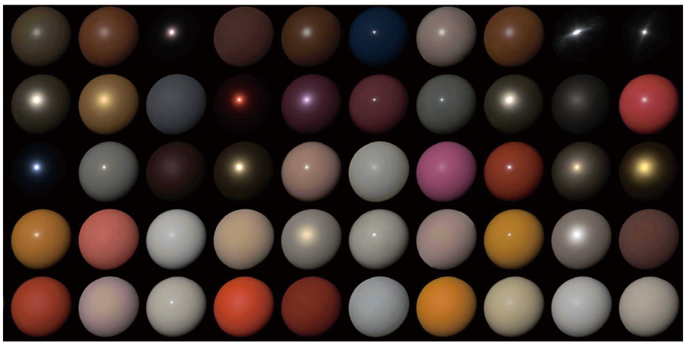

Figure 1: Reflectance dataset captured from real-world objects

Figure 2: 3D digitization from 2D photographs

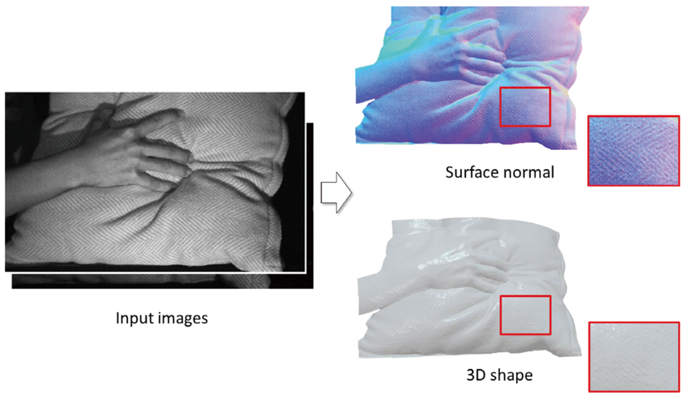

Figure 3: 3D reconstruction of a dynamic scene

Patent

Treatise
Enomoto, Kenji; Waechter, Michael; Okura, Fumio et al. Discrete search photometric stereo for fast and accurate shape estimation. IEEE Transactions on Pattern Analysis and Machine Intelligence. 2023, 45, 4355-4367. doi: 10.1109/TPAMI.2022.3198729
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