This CVPR2015 extended abstract is the Open Access version, provided by the Computer Vision Foundation.

Depth from Shading, Defocus, and Correspondence Using Light-Field Angular Coherence

Michael W. Tao[1], Pratul P. Srinivasan[1], Jitendra Malik[1], Szymon Rusinkiewicz[2], and Ravi Ramamoorthi[3]
[1]University of Calfiornia, Berkeley. [2]Princeton University. [3]University of Calfiornia, San Diego.

Light-field cameras are now used in consumer and industrial applications. Recent papers and products have demonstrated practical depth recovery algorithms from a passive single-shot capture. However, current light-field capture devices have narrow baselines and constrained spatial resolution; therefore, the accuracy of depth recovery is limited, requiring heavy regularization and producing planar depths that do not resemble the actual geometry. Using shading information is essential to improve the shape estimation. We develop an improved technique for local shape estimation from defocus and correspondence cues, and show how shading can be used to further refine the depth.

Light-field cameras are able to capture both spatial and angular data, suitable for refocusing. By locally refocusing each spatial pixel to its respective estimated depth, we produce an all-in-focus image where all viewpoints converge onto a point in the scene. Therefore, the angular pixels have **angular coherence**, which exhibits three properties: **photo consistency**, **depth consistency**, and **shading consistency**. We propose a new framework that uses angular coherence to optimize depth and shading. The optimization framework estimates both general lighting in natural scenes and shading to improve depth regularization. Our method outperforms current state-of-the-art light-field depth estimation algorithms in multiple scenarios, including real images.

We make the common assumption of Lambertian surfaces under general (distant) direct lighting. We differ from shape from shading from single images, by exploiting the full angular data captured by the light-field. Our algorithm uses images captured with the Lytro cameras. We compare our results against the Lytro Illum software and other state of the art methods, demonstrating that our results give accurate representations of the shapes captured.

Shape from shading given an initial depth is a heavily under constrained problem and usually only produces accurate results when fairly accurate depths are available. Unfortunately, captured light-field data typically does not provide such information, because of the narrow baseline and limited resolution. The depth estimation performs poorly, especially in smooth surfaces where even sparse depth estimation is either inaccurate or non-existent. However, because Light-fields [1, 2] can be used to refocus images [3] and enable passive and general depth estimation [4, 5, 6], we exploit these properties to build a robust depth estimation with shading constraints.

In this paper, our main contributions are

1. Analysis of refocusing and angular coherence.
We show the relationship between refocusing a light-field image and angular coherence to formulate new depth measurements and shading estimation constraints.

2. Depth estimation and confidence metric.
We formulate a new local depth algorithm to perform correspondence and defocus using angular coherence.

3. Shading estimation constraints
We formulate a new shading constraint, that uses angular coherence and confidence map to exploit light-field data.sh

4. Depth refinement with the three cues.
We design a novel framework that uses shading, defocus, and correspondence cues to refine shape estimation.

Our algorithm is shown in the pseudocode on the right and Fig. 1. The input is, L_0, the light-field image input. The outputs are S, the estimated shading, l, the estimated lighting, and, Z^*, the final output regularized with a our estimated shading constraint. Angular coherence plays a large role in our algorithm to establish formulations for both depth estimation and shading constraints. We show how angular coherence provides us data redundancy that enables robust estimation of shading and depth even with noisy

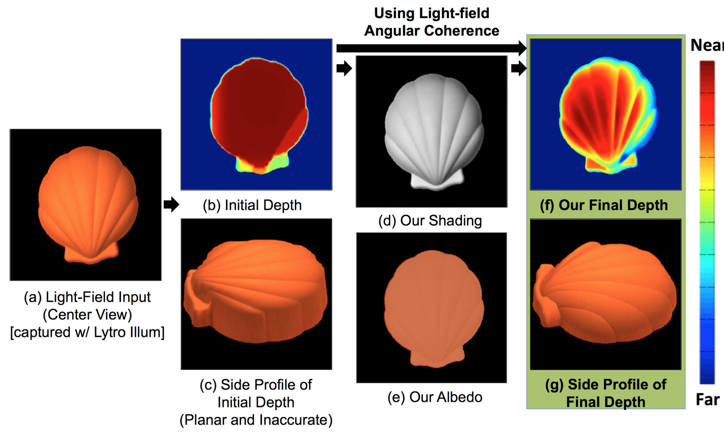

Figure 1: Light-field Depth Estimation Using Shading, Defocus, and Correspondence Cues. *In this work, we present a novel algorithm that estimates shading to improve depth recovery using light-field angular coherence. Here we have an input of a real scene with a shell surface and a camera tilted slightly toward the right of the image (a). We obtain an improved defocus and correspondence depth estimation (b,c). However, because local depth estimation is only accurate at edges or textured regions, depth estimation of the shell appears regularized and planar. We use the depth estimation to estimate shading, which is S (d), the component in $I = AS$, where I is the observed image and A is the albedo (e) With the depth and shading estimations, we can refine our depth to better represent the surface of the shell (f,g). Throughout this paper, we use the scale on the right to represent depth.*

input. The algorithm extends the depth estimation framework introduced by Tao et al. [5].

Algorithm 1
Depth from Shading, Defocus, and Correspondence

```
procedure DEPTH(L_0)
    Z, Z_conf = LocalEstimation(L_0)
    Z*        = OptimizeDepth(Z, Z_conf)
    S         = EstimateShading(L_0)
    l         = EstimateLighting(Z*, S)
    Z*        = OptimizeDepth(Z*, Z_conf, l, S)
    return Z*
end procedure
```

This is an extended abstract. The full paper is available at the Computer Vision Foundation webpage.

[1] S.J. Gortler, R. Grzeszczuk, R. Szeliski, and M. Cohen. The lumigraph. In *ACM SIGGRAPH*, 1996.

[2] M. Levoy and P. Hanrahan. Light field rendering. In *ACM SIGGRAPH*, 1996.

[3] R. Ng, M. Levoy, M. Bredif, G. Duval, M. Horowitz, and P. Hanrahan. Light field photographhy with a hand-held plenoptic camera. *CSTR 2005-02*, 2005.

[4] M. Tao, T.-C. Wang, J. Malik, and R. Ramamoorthi. Depth estimation for glossy surfaces with light-field cameras. In *ECCV LF4CV*, 2014.

[5] M. W. Tao, S. Hadap, J. Malik, and R. Ramamoorthi. Depth from combining defocus and correspondence using light-field cameras. In *ICCV*, 2013.

[6] S. Wanner and B. Goldluecke. Globally consistent depth labeling of 4D light fields. In *CVPR*, 2012.