# Polarized 3D: High-Quality Depth Sensing with Polarization Cues

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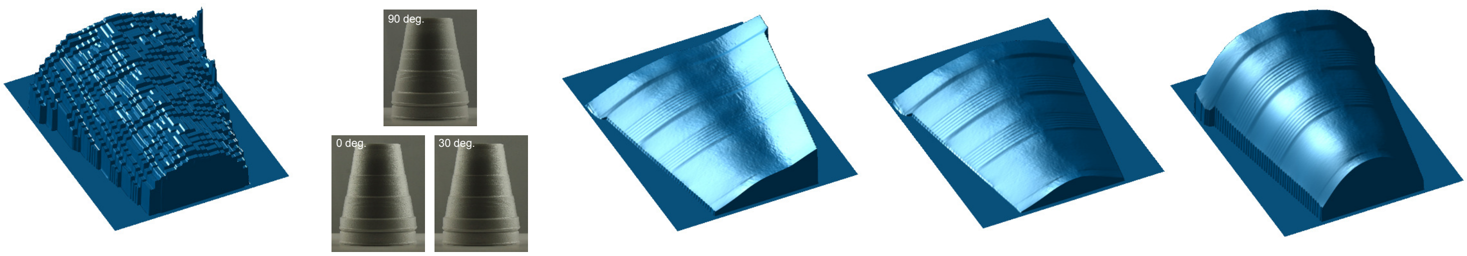


**(a)** Input: Kinect Only — *Microsoft Kinect Version II*

**(b)** Input: Polarization Photos — *Canon T3i DSLR Hoya CIR-PL Filter*

**(c)** Naive Shape from Polar. — *Shape from Polarization*

**(d)** Our Intermediate Result — *Coarse depth to correct azimuthal ambiguity artifacts*

**(e)** Our Final Result — *Correcting refractive distortion and physics-based integration*

Figure 1: Outline of proposed technique. (a) The Kinect depth of an object is combined with (b) three photos at different rotations of a polarizing filter. (c) Integration of surface normals obtained from Fresnel equations. Note the azimuthal ambiguity (observed as a flip in the shape) and distortion of the zenith angle (observed as flatness in the shape). (d) Integration of surface normals after correcting for azimuthal ambiguity removes the flip, and the final result is shown in (e) after correcting for zenith distortion and using physics-based integration. Project page: www.media.mit.edu/~achoo/polar3D/

Today, consumer 3D cameras produce depth maps that are often noisy and lack sufficient detail. Enhancing 3D depth maps obtained from compact sensors such as the Kinect is therefore an increasingly popular research area. One of the most promising solutions is to combine the captured, coarse depth map with surface normals obtained from photometric stereo (PS) or shape-from-shading (SfS). This depth-normal fusion is logical—the coarse depth map provides the geometric structure and the surface normals capture fine detail to be fused. There are dozens of papers that combine low-quality depth maps with surface normal maps obtained from SfS or PS. Well-regarded papers include [2, 6, 7] using SfS, and [3, 5] using PS. As a complementary technique, we propose the first use of surface normals from polarization to enhance depth maps.

The shape of an object causes small changes in the polarization of reflected light, best visualized by rotating a polarizing filter in front of a digital camera. Obtaining surface normals through polarization has potential advantages over SfS and PS, including:

- Passive capture: assuming light incident on an object is unpolarized, the surface normals can be obtained by rotating a polarizer at the imaging sensor.
- Robustness to diffuse interreflections: unlike SfS and PS, diffuse interreflections do not significantly corrupt the estimated shape.
- Material invariant capture: the physics of the shape from polarization problem hold for materials ranging from dielectrics to metals to translucent objects.
- Lighting robust capture: if the incident light is unpolarized shape estimation is robust and can be conducted indoors, outdoors, or under patterned illumination.

However, obtaining surface normals through polarization is not yet a mature technique. The obtained normals are drastically distorted. Specific open problems [1, 4] include:

1. **Ambiguity**: The azimuth component of the surface normal contains an ambiguity of $\pi$ radians, which leads to ambiguous flips in the 3D shape.
2. **Refractive distortion:** Obtaining the zenith component of the surface normal requires knowledge of the refractive index to estimate accurate 3D shape.
3. **Fronto-parallel surfaces:** When the zenith angle is close to zero, the obtained normals are noisy.
4. **Depth discontinuities:** Even if the normals are obtained correctly, integration of gradients must be performed to recover the 3D shape.
5. **Relative depth:** Integrating surface normals obtains only relative 3D shape, up to offset and scaling constants.

In this paper, we address each of these challenges by starting with a coarse depth map as a constraint to correct the normals obtained from polarization. While we do not solve all open problems, our correction is sufficient to use the polarization normals to enhance the depth map. An overview of our approach is summarized in Figure 1.

## Summary of technical contributions

Conceptually, this paper introduces the first technique that exploits normals from polarization cues to enhance the quality of a coarse depth map. In particular, we devise a physics-based framework, wherein the coarse depth map is used to resolve azimuthal ambiguity (addressing problem 1) and correct for refractive distortion (solving problem 2). To recover 3D shape, we propose a spanning tree integration scheme that uses the degree of polarization as a weighting parameter. This approach, specifically designed for polarization normals, addresses problem 3. As is well-known, the general fusion of depth and normals solves problems 4 and 5.

Taken together, the proposed technique is benchmarked against ground truth data and state-of-the-art 3D enhancement techniques [6].

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