

Panoramic Monocentric Light Field Camera

Glenn M. Schuster, Ilya P. Agurok and Joseph E. Ford

Department of Electrical & Computer Engineering, University of California San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA
Author e-mail address: gschuster@eng.ucsd.edu

Donald G. Dansereau and Gordon Wetzstein

Department of Electrical Engineering, Stanford University, 450 Serra Mall, Stanford, California 94305, USA

Abstract: We describe a monocentric wide-field camera that corrects field curvature by light field processing, showing a contiguous multi-sensor design, and results from a relay-imaged testbed that sequentially captures a 72 MPixel 138° light field panorama.

OCIS codes: (110.0110) Imaging systems; (220.3620) Lens system design; (110.1758) Computational imaging

1. Introduction

Monocentric lenses consist of rotationally symmetric refractive shells that share a common center of curvature. This allows low F/# diffraction-limited resolution over a wide field-of-view (FOV) [1], and has resulted in compact panoramic imagers where the spherical image surface is coupled either through relay imaging of overlapping regions [2] or by fiber bundle transport [3] to multiple CMOS focal planes. Here we present an alternative method to detect the spherical image surface, using computational light field (LF) processing to correct for field curvature and also provide the 3-D depth mapping and post-detection image refocus normally associated with LF imagers [4]. Here we describe a monocentric imaging testbed that uses large NA relay imaging to transfer regions of the monocentric image sphere through a microlens array (MLA) and into a CMOS image sensor. We use the testbed to demonstrate LF processing of the spherical image, and also to sequentially capture a wide FOV LF image. The eventual goal is compact wide-field imaging, so we describe how adjacent sensor planes can be directly integrated with the monocentric lens, and also on-going design work using faceted field optics to enable a contiguous LF image.

2. Optical relay and sequential testbed system

We chose a 12 mm focal length F/1.35 2-glass achromatic monocentric lens (described in [1]) as our objective. We needed a LF testbed to enable experimentation with different lenslet arrays, lenslet position relative to the CMOS sensor, and the option of introducing field elements between the monocentric objective and sensor. To accurately relay the light from the back of the MLA to the sensor, this relay must maintain the high resolution of the monocentric lens at the NA of the microlenses, preserve ray angles over the lens NA, and cover the field of view subtended by a single CMOS focal plane (several mm). This is beyond the capability of a conventional relay, which sacrifices either resolution or object field. We considered a $4f$ relay with long working distance infinity corrected microscope objectives for their high NA and resolution, but high-resolution microscope objectives have internal exit pupils, so mechanical interference prevents a telecentric relay. Our solution was to map the internal exit pupils of the microscope objectives onto each other using a second $4f$ relay of two double-gauss lenses. Our final telecentric relay used two 10X Mitutoyo Plan Apo objectives and two Sigma 85 mm F/1.4 EX DG HSM lenses. Figure 1 shows an approximate raytrace using Zemax Zbase prescriptions, and photos of the experimental system. The measured impulse response was confined to approximately $2.24 \mu\text{m}$ over the $\pm 12^\circ$ FOV of the CMOS sensor.

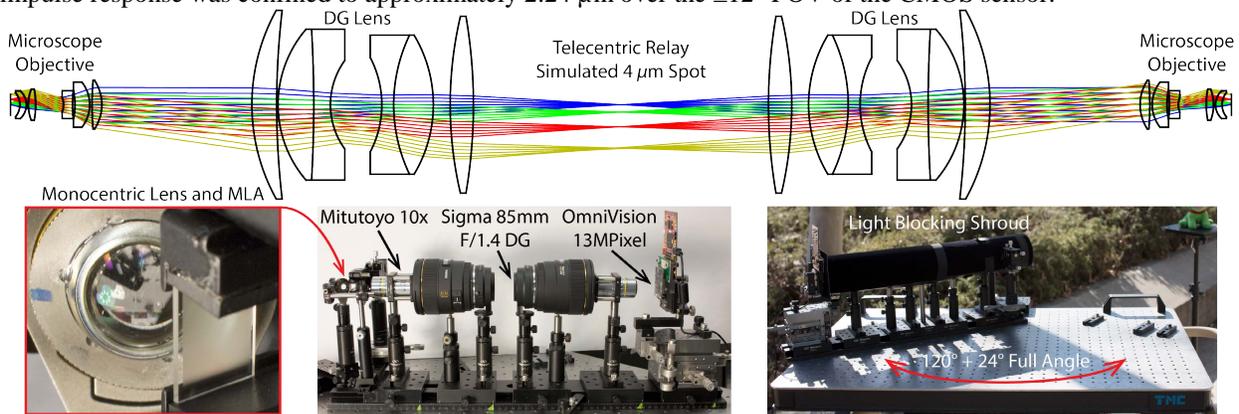


Fig. 1. Optical ray trace of Zemax double $4f$ relay, and photos of assembled prototype sequential capture light field system.

The double $4f$ optical relay was placed between a F/2 Lytro Illum 20 μm pitch MLA and a 13 MPixel 1.12 μm pitch OV13850 CMOS image sensor. The monocentric lens was placed one focal length in front of the MLA. To prevent overfilling of the F/2 MLA by the F/1.35 monocentric lens, we placed an external iris in front of the system to match the NA of the MLA. The external iris, MLA, optical relay, and sensor were all mounted on a single optical rail which could be rotated over 120° to capture 140° panoramas (including the 24° per-frame FOV). Rotating the external iris prevents additional vignetting and maintains a constant pupil across the image, emulating the angle-independent total internal reflection virtual aperture possible with monocentric lenses [5]. The system captured both indoor (Figure 3) and outdoor panoramas through sequential exposures and demonstrated post-capture spherical defocus correction of the curved image plane, refocusing, depth estimation, and resolution enhancement, the processing side of which is detailed in [6]. Correcting the nearly 390 μm defocus at the diagonal extremes of the image sensor proves the concept of merging a monocentric wide FOV lens with LF computation.

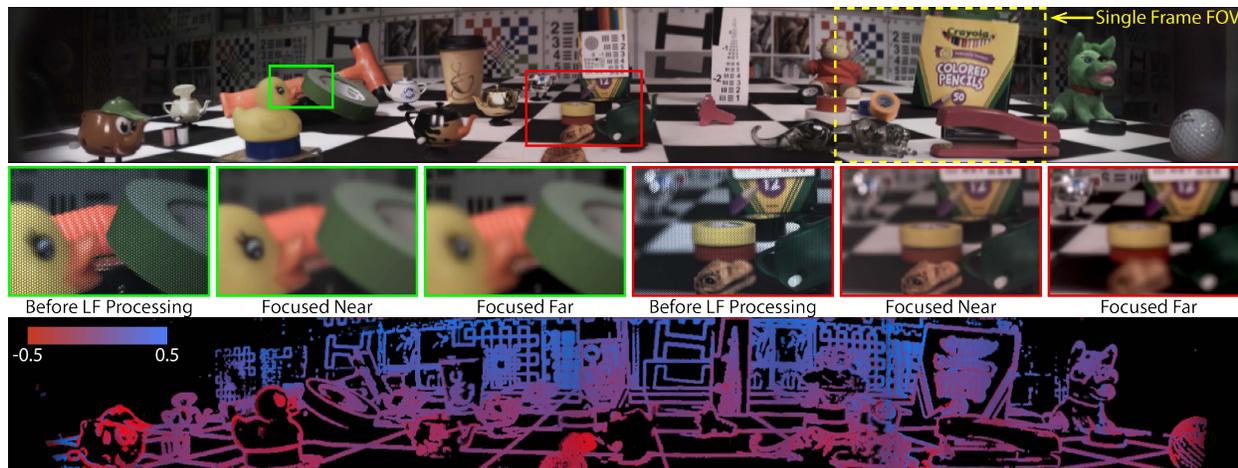


Fig. 2. Stitched 2D slice (top) of the 138° 72 MPixel ($15 \times 15 \times 1600 \times 200$) LF panorama with detail views (center) and depth estimate (bottom).

3. Contiguous multi-sensor optical design

To capture the contiguous image without edge-to-edge sensors the field angles must be consolidated. Furthermore, flattening the spherical image lessens the burden on the LF processing. Optics which consolidate the fields tend to increase the curvature of the image, while conventional field flatteners extend the edge field angles and exacerbate continuity conflicts. By trading between these parameters and LF correctible distortions, we are exploring a design regime where typical sensor packaging may still yield a contiguous multi-sensor camera. One layout is shown in Figure 3, where an aspheric front surface consolidates the field angles and directs them to a flat rear surface where the MLA relays the image onto the sensor creating a contiguous ‘focused’ LF camera [7]. Here the resulting image is not flattened, but the field consolidation allows for space for sensor packaging. This is an ongoing design effort, including the option for chirped and curved lenslet arrays, to balance between LF processing and analog optics.

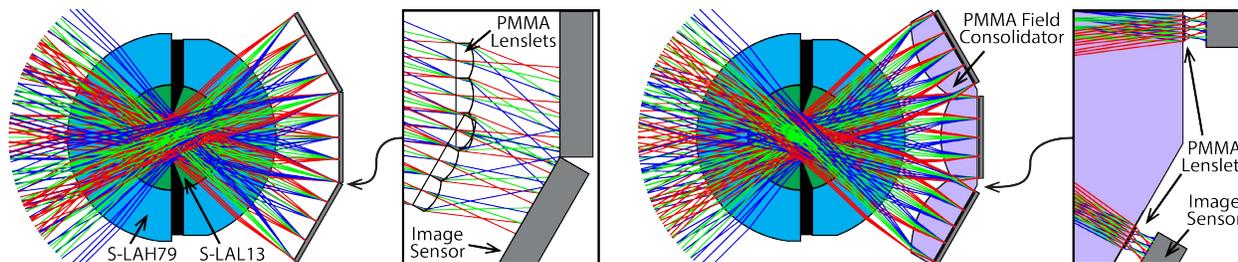


Fig. 3. Optical ray traces of contiguous designs, without (left) and with (right) field consolidators to provide room for CMOS sensor packaging. This research was enabled by the NSF/Intel Partnership on Visual and Experiential Computing (Intel #1539120 and NSF #IIS-1539120).

4. References

- [1] I. Stamenov, et al, “Optimization of two-glass monocentric lenses for compact panoramic imagers,” *Appl. Opt.* **51**, pp.7648-7661, (2012).
- [2] I. Stamenov, et al, “Panoramic monocentric imaging using fiber-coupled focal planes,” *Optics Express* **22**(26), pp. 31708-31712, (2014).
- [3] E. J. Tremblay et al, “Design and Scaling of Monocentric multiscale imagers,” *Applied Optics*, **51**(20), pp. 4691–4702, (2012).
- [4] R. Ng, et al. “Light field photography with a hand-held plenoptic camera,” *Computer Science Technical Report CSTR*, **2**(11), pp.1-11, (2005).
- [5] I. P. Agurok, and J. E. Ford, “Angle-invariant imaging using a total internal reflection virtual aperture,” *Appl. Opt.* **55**, 5345-5352, (2016).
- [6] D. G. Dansereau, et al, “A Wide-Field-of-View Monocentric Light Field Camera” IEEE 2017 Conf. on Comp. Vision & Patt. Rec. (in press).
- [7] A. Lumsdaine, and T. Georgiev, “The focused plenoptic camera” IEEE 2009 Conf. on Comp. Photography, pp. 1-8, (2009).