Spherical Catadioptric Arrays:
Construction, Multi-View Geometry, and Calibration

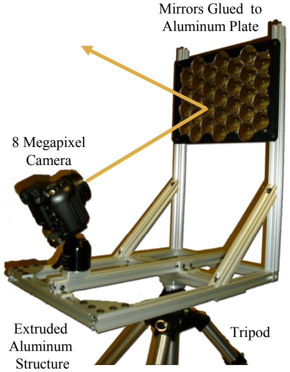
Douglas Lanman, Brown University
Daniel Crispell, Brown University
Megan Wachs, Stanford University
Gabriel Taubin, Brown University

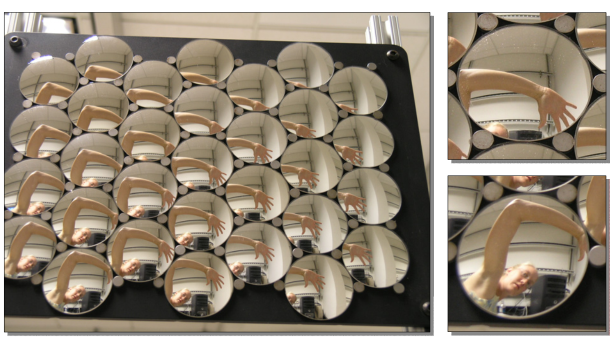
Overview

We present a new method for acquiring data for image-based rendering and 3D reconstruction using an array of spherical mirrors and a single high-resolution digital camera. The main advantages of this system include automatic color calibration and frame synchronization, however the design of calibration and reconstruction algorithms presents a challenge since this system generates non-central projections. In this poster, we describe the mechanical design of a prototype, analyze the geometry of image formation, present a tailored calibration algorithm, and demonstrate preliminary reconstruction results.

Mechanical Design

The prototype system consists of an aluminum plate with cylindrical stainless steel pins pressed into holes. These pins hold 31 spherical mirrors. The plate is positioned in space to roughly fill the field of view of an Olympus C-8080 8 megapixel digital camera such that a single image captures all 31 mirrors. A structure built out of aluminum extrusions holds the mirror assembly and camera.





Typical image captured by the Olympus 8 megapixel digital camera. Images from individual mirrors demonstrate the wide field of view.

Calibration

System calibration involves: 1) intrinsic camera calibration, 2) extrinsic calibration of the plate with respect to the camera, and 3) calibration of each mirror with respect to the plate.

1) Intrinsic camera calibration is achieved using the Zhang method, as implemented by the Camera Calibration Toolbox for Matlab.

2) An ellipse detection algorithm is used to locate the four corner pins. Using the precise location of these pins (in the plate), we estimate an initial plane equation. Afterwards, we predict the coordinates of the remaining pins, reapply the ellipse-fitting routine, and then refine the planar homography using all located pins.

3) Individual mirrors are modeled as spheres. Initial estimates for the sphere centers and radii are available from the mechanical design.

These initial estimates are refined using a new bundle adjustment procedure. Nayar's [3] method of converting an image point u to a ray

$$R_u = \{p = q(u,\Lambda) + \lambda v(u,\Lambda)\}$$

is used, where Λ is a set of parameters including the sphere centers and radii. Each world point p_j and corresponding image point u_{ij} associated with the i^{th} mirror gives one ray equation $q_{ij} + \lambda_{ij} v_{ij} = p_j$. To eliminate the additional λ_{ij} unknowns, the estimated sphere centers and radii are determined by minimizing the following error function

$$E(\Lambda) = \sum_j \sum_i \left\| v_{ij} \times (p_j - q_{ij}) \right\|^2$$

Alternatively, we also include refraction (due to the protective mirror coating) in the ray model and use non-linear optimization to estimate the mirror centers, their radii, and the position of the checkerboard.

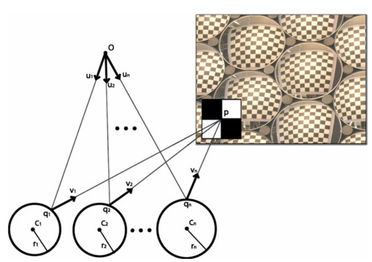
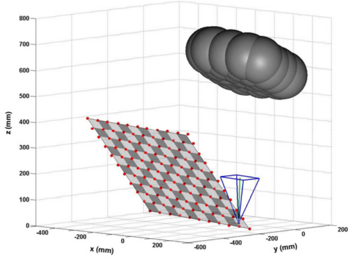


Illustration of bundle adjustment using a planar calibration target. (Features are manually selected.)

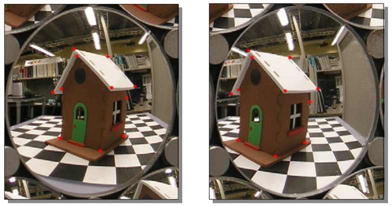


Calibration results using a checkerboard. Red circles represent the reconstructed positions of the checkerboard corners.

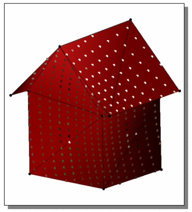
3D Reconstruction

The proposed system is ideally-suited for data acquisition in image-based rendering and 3D scene reconstruction. To demonstrate its utility, we reconstructed the simple house model shown below. By manually selecting image correspondences, we recovered a mesh containing 11 vertices and 9 faces. The surface texture was estimated by back-projecting pixels in each mirror image onto the reconstructed mesh. The resulting point cloud was rendering as an array of oriented, colored disks.

Original scene



Catadioptric images and selected features



Reconstructed surface

3D point-based reconstruction results

Future Work

Future research will focus on developing similar systems for acquiring light field data which effectively exploit the combined properties of camera arrays and non-central projection optics.

References

[1] Gortler, S. J., Grzeszczuk, R., Szeliski, R., and Cohen, M. F. 1996. The lumigraph. In *ACM SIGGRAPH*, 43-54.
[2] Levoy, M. and Hanrahan, P. 1996. Light field rendering. In *ACM SIGGRAPH*, 31-42.
[3] Nayar, S. 1988. Sphereo: Determining depth using two specular spheres and a single camera. In *Proc. of SPIE Conference on Optics, Illumination, and Image Sensing for Machine Vision III*, 245–254.
[4] Yang. J. 2000. Light fields on the cheap. Technical Report, MIT.