Surround Structured Lighting for Full Object Scanning

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Outline

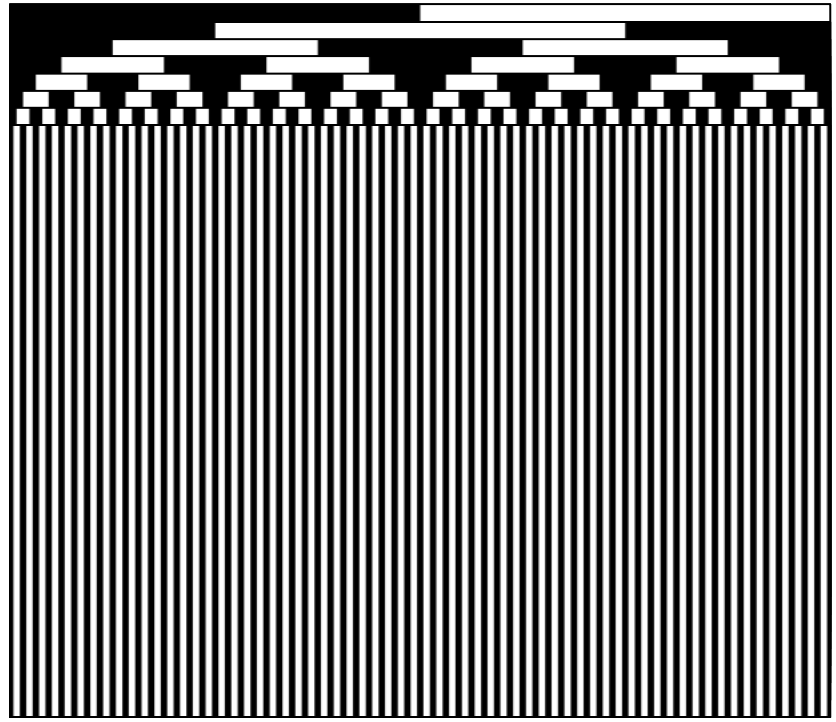
- *Introduction and Related Work*
- System Design and Construction
- Calibration and Reconstruction
- Experimental Results
- Conclusions and Future Work

Review: Gray Code Structured Lighting

3D Reconstruction using Structured Light [Inokuchi 1984]

- Recover 3D depth for each pixel using ray-plane intersection
- Determine correspondence between camera pixels and projector planes by projecting a temporally-multiplexed binary image sequence
- Each image is a bit-plane of the Gray code for each projector row/column

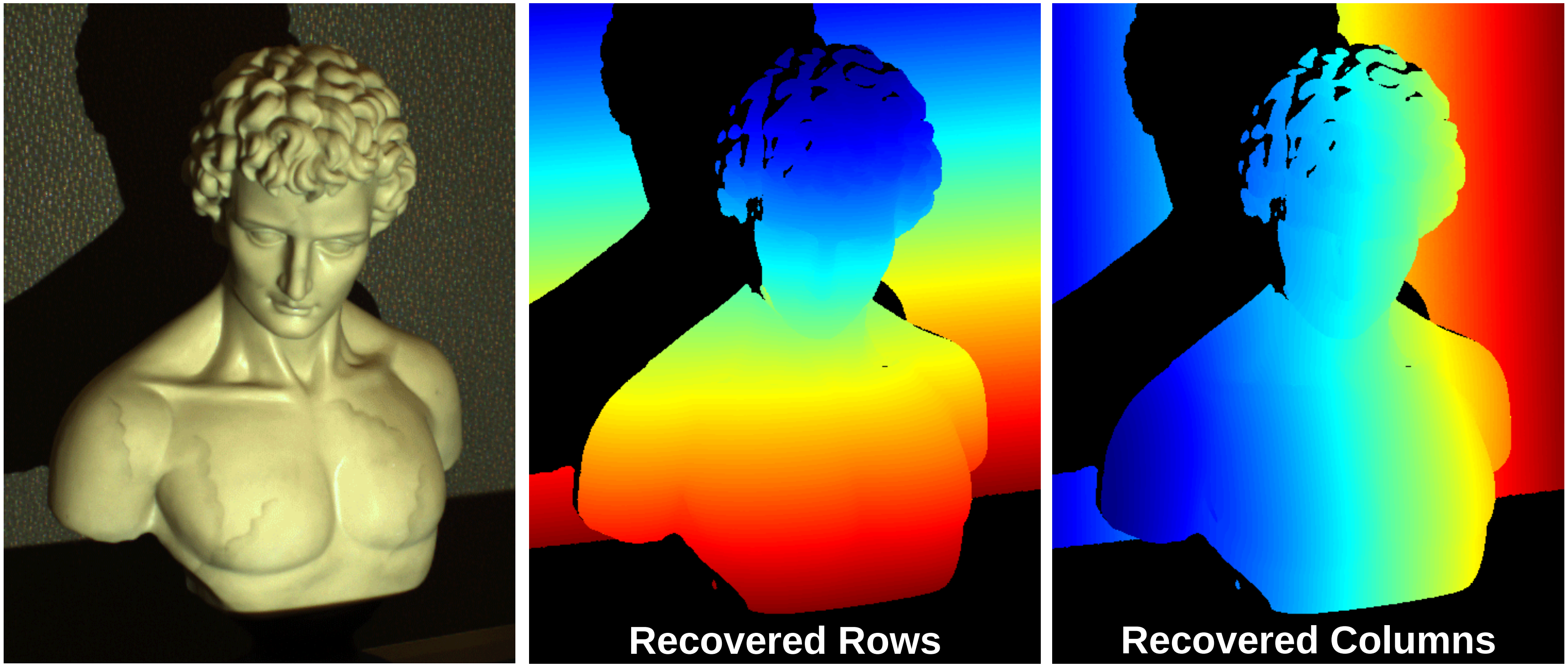
Review: Gray Code Structured Lighting



3D Reconstruction using Structured Light [Inokuchi 1984]

- Recover 3D depth for each pixel using ray-plane intersection
- Determine correspondence between camera pixels and projector planes by projecting a temporally-multiplexed binary image sequence
- Each image is a bit-plane of the Gray code for each projector row/column
- Encoding algorithm: integer row/column index → binary code → Gray code

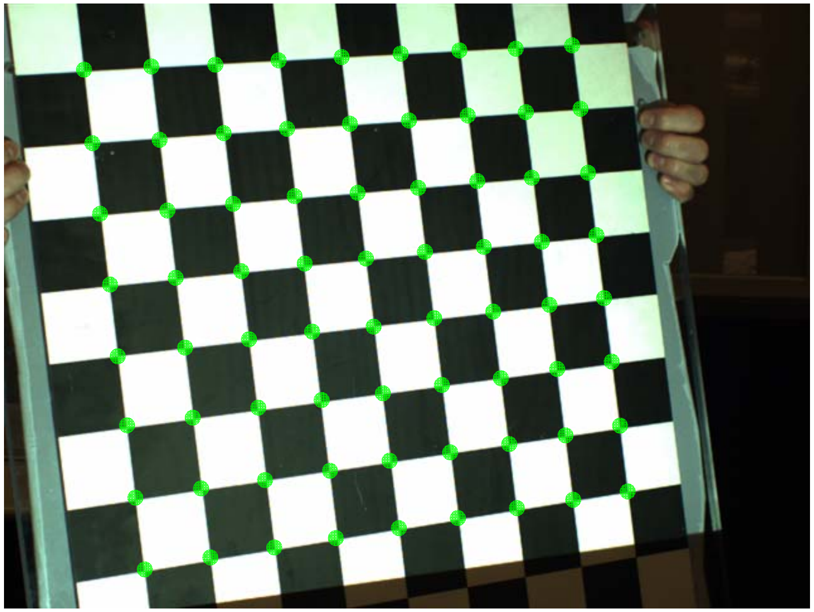
Recovery of Projector-Camera Correspondences

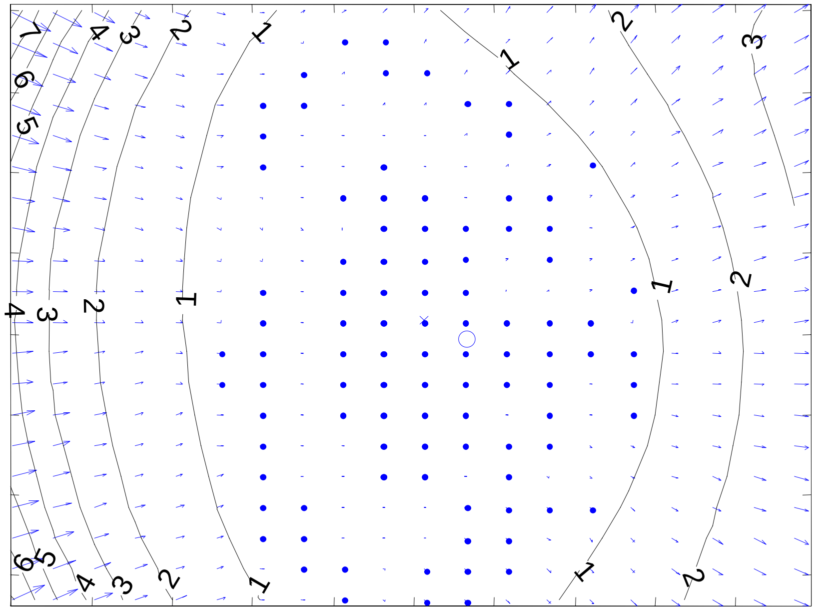


3D Reconstruction using Structured Light [Inokuchi 1984]

- Our implementation uses a total of 42 images
  (2 to measure dynamic range, 20 to encode rows, 20 to encode columns)
- Individual bits assigned by detecting if bit-plane (or its inverse) is brighter
- Decoding algorithm: Gray code → binary code → integer row/column index

Overview of Projector-Camera Calibration





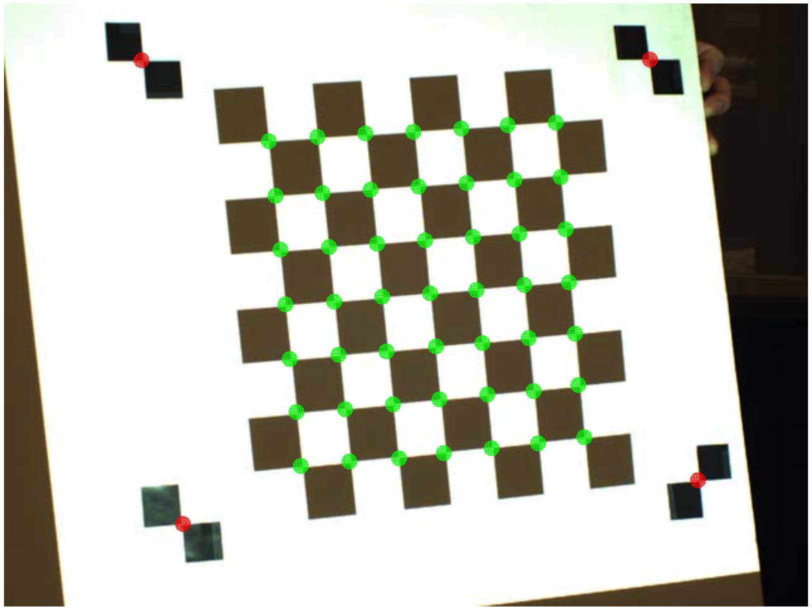
Estimated Camera Lens Distortion

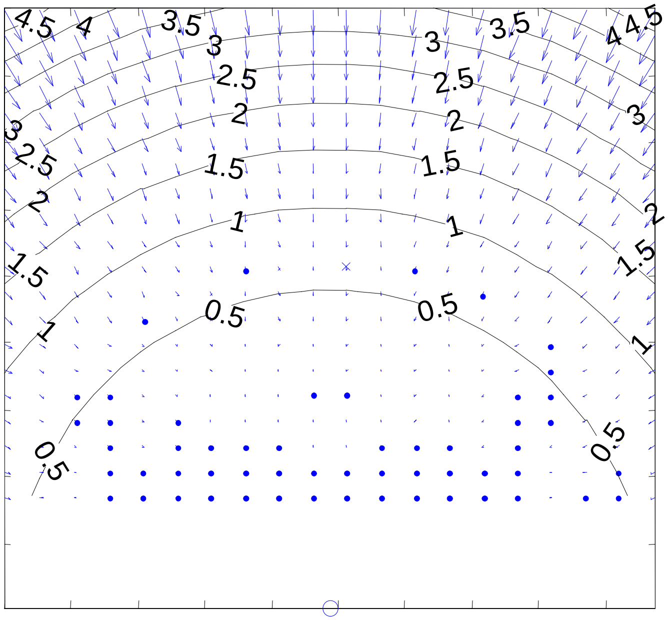
Camera Calibration Procedure

- Uses the *Camera Calibration Toolbox for Matlab* by J.-Y. Bouguet

Normalized Ray	Distorted Ray (4th-order radial + tangential)	Predicted Image-plane Projection
$x_n = \begin{bmatrix} X_c/Z_c \\ Y_c/Z_c \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix}$	$x_d = \begin{bmatrix} x_d(1) \\ x_d(2) \end{bmatrix} = \left(1 + kc(1)\,r^2 + kc(2)\,r^4 + kc(5)\,r^6\right) x_n + dx$ $dx = \begin{bmatrix} 2\,kc(3)\,x\,y + kc(4)\,(r^2 + 2x^2) \\ kc(3)\,(r^2 + 2y^2) + 2\,kc(4)\,x\,y \end{bmatrix}$	$x_p = fc(1)\,(x_d(1) + alpha\_c * x_d(2)) + cc(1)$ $y_p = fc(2)\,x_d(2) + cc(2)$

Overview of Projector-Camera Calibration



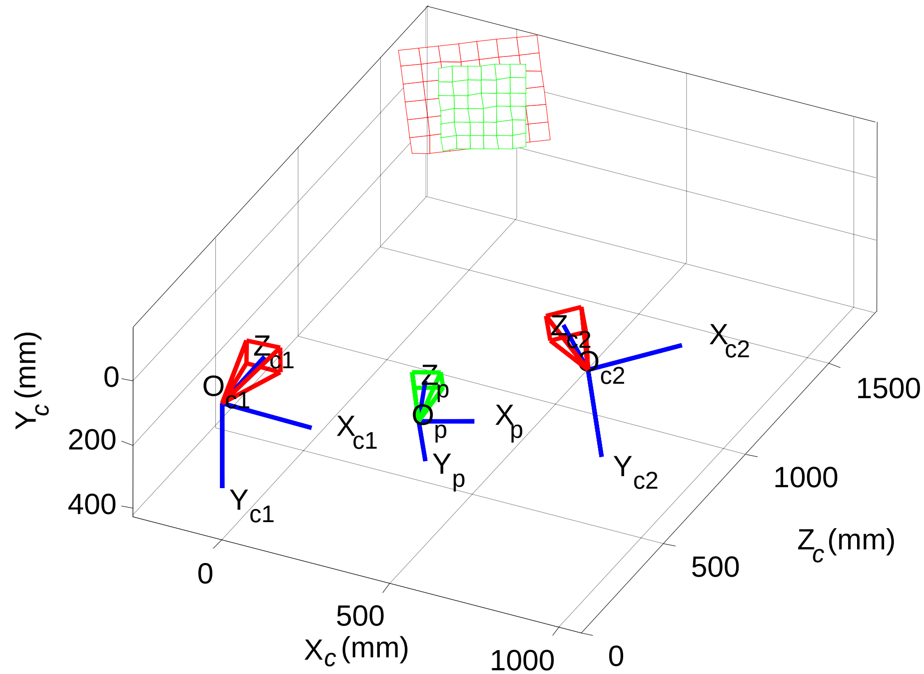


Estimated Projector Lens Distortion

Projector Calibration Procedure

- Consider projector as an inverse camera (i.e., maps intensities to 3D rays)
- Observe a calibration board with a set of fidicials in known locations
- Use fidicials to recover calibration plane in camera coordinate system
- Project a checkerboard on calibration board and detect corners
- Apply ray-plane intersection to recover 3D position for each projected corner
- Use *Camera Calibration Toolbox* to recover intrinsic/extrinsic projector calibration using 2D$\rightarrow$3D correspondences with 4th-order radial distortion

Projector-Camera Calibration



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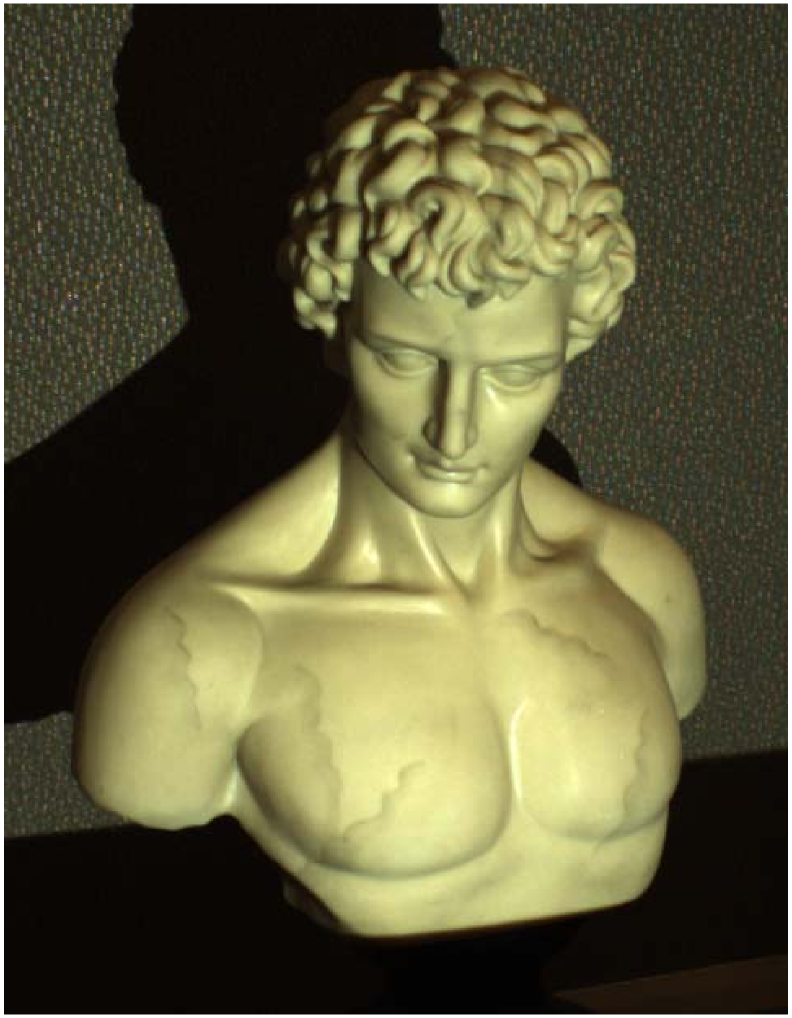
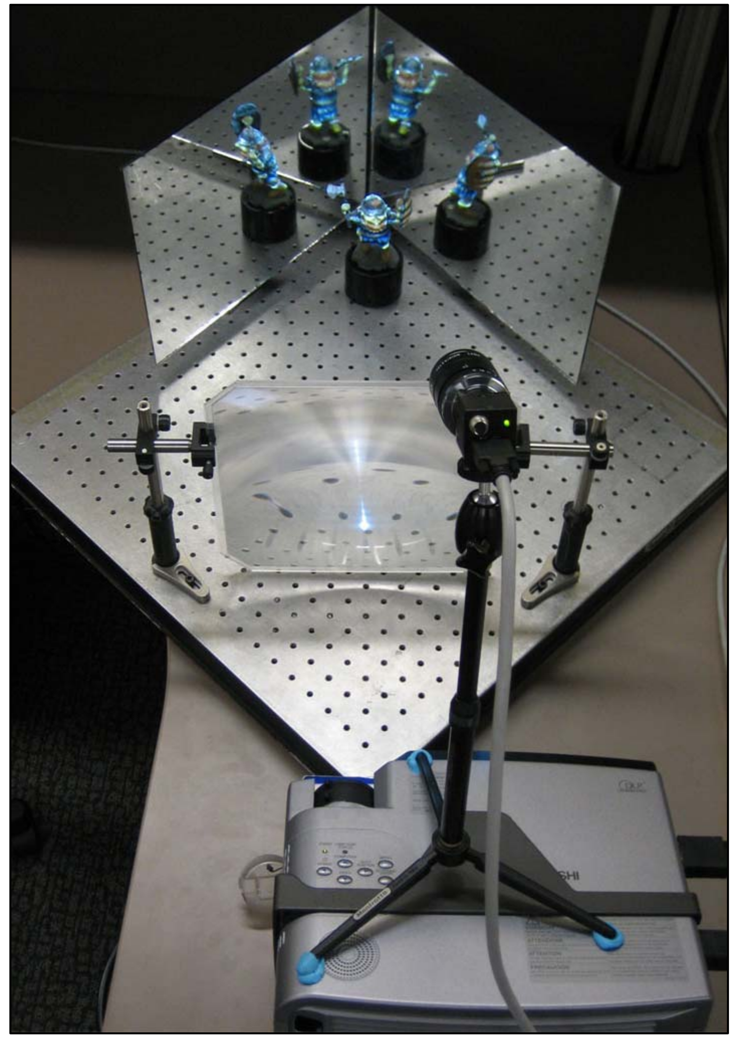
Gray Code Structured Lighting Results



Proposed Improvement: Surround Lighting

Limitations of Structured Lighting

- Only recovers mutually-visible surface (i.e., must be illuminated and imaged)
- Complete model requires multiple scans or additional projectors/cameras
- Often requires post-processing (e.g., ICP)



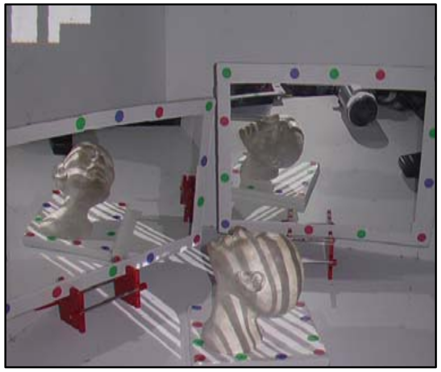
Proposed Solution

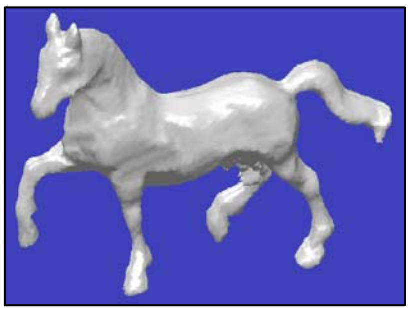
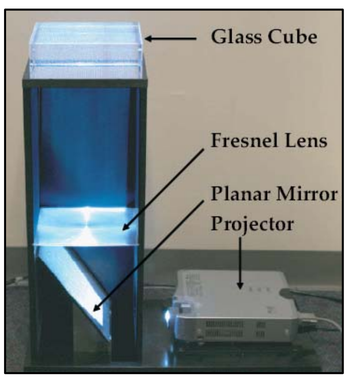
- Trade spatial for angular resolution
- Multiple views by including planar mirrors
- What about illumination inference?
  - Use *orthographic illumination*

System Components

- Multi-view: digital camera + planar mirrors
- Orthographic: DLP projector + Fresnel lens

Related Work



Structured Light for 3D Scanning

- Over 20 years of research [Salvi '04]
- Gray code sequences [Inokuchi '84]
- Recent real-time methods [Zhang '06]
- Including planar mirrors [Epstein '04]

Multi-view using Planar Mirrors

- Visual Hull using mirrors [Forbes '06]
- Catadioptric Stereo [Gluckman '99]
- Mirror MoCap [Lin '02]

Orthographic Projectors

- Recent work by Nayar and Anand on volumetric displays using passive optical scatterers [SIGGRAPH '06]
- Introduces orthographic projectors

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Surround Structured Lighting Components

- Mitsubishi XD300U Projector (1024x786)
- Point Grey Flea2 Digital Camera (1024x786)
- Manfrotto 410 Compact Geared Tripod Head
- 11"x11" Fresnel Lens (Fresnel Technologies #54)
- 15"x15" First Surface Mirrors
- Newport Optics Kinematic Mirror Mounts

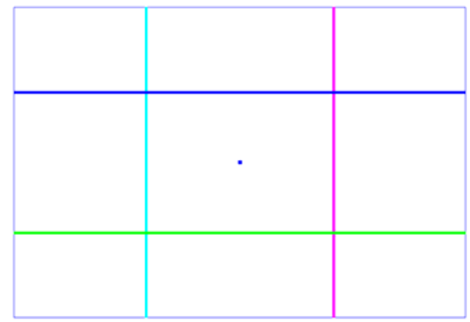




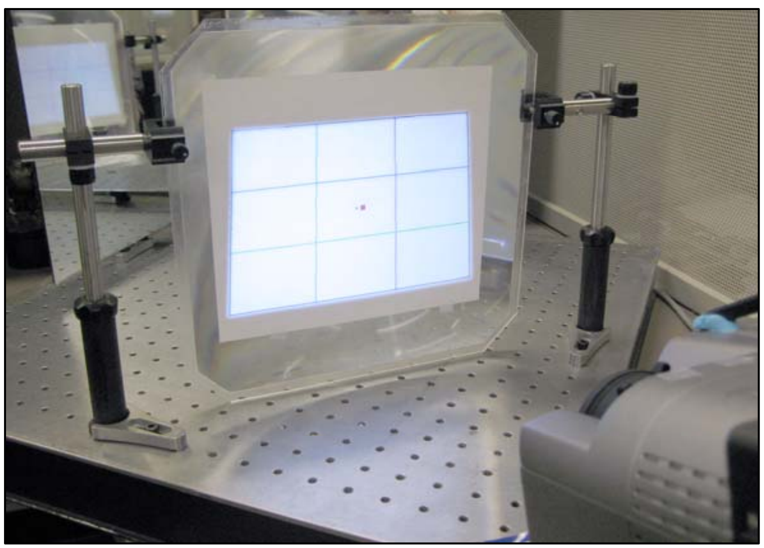
Mechanical Alignment Procedure

Manual Projector Alignment

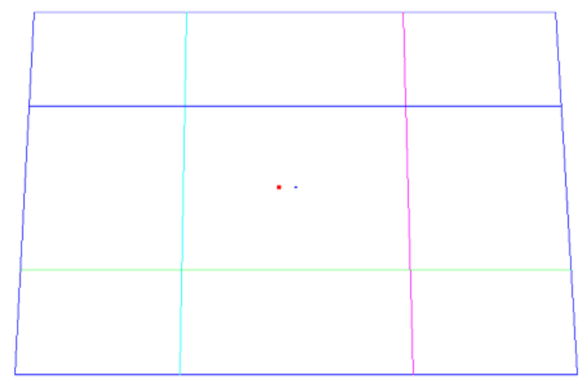
- Center of projection must be at focal point of Frensel lens for orthographic configuration
- Given intrinsic projector calibration, we predict the projection of a known pattern on the surface of the Fresnel lens



Projected Calibration Pattern



Result of Mechanical Alignment (coincident projected and printed patterns)



Printed Calibration Pattern (affixed to Frensel lens surface)

Mechanical Alignment Procedure

Manual Mirror Alignment

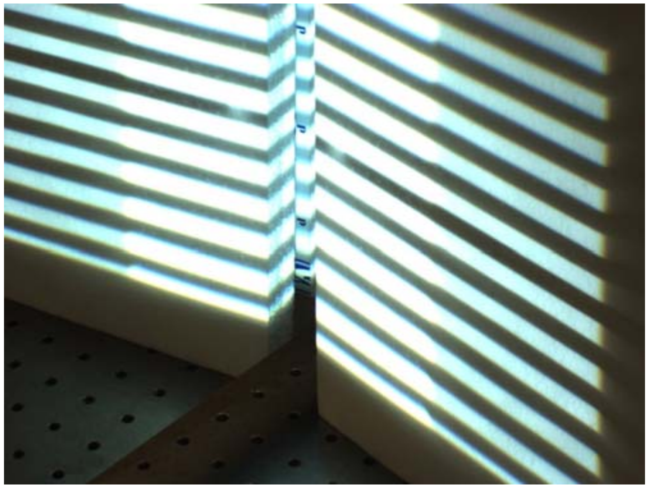
- Mirrors must be aligned such that plane spanned by surface normals is parallel to the orthographic illumination rays
- Projected Gray code stripe patterns assist in manually adjusting the mirror orientations

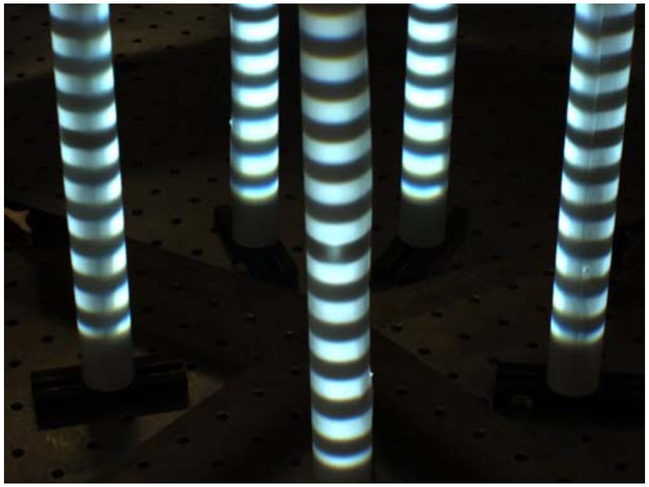
Step 1: Alignment using a Flat Surface

- Cover each mirror with a blank surface
- Adjust the uncovered mirror so that the reflected and projected stripes coincide

Step 2: Alignment using a Cylinder

- Place a blank cylindrical object in the center of the scanning volume
- Adjust both mirrors until the reflected stripes coincide on the cylinder surface





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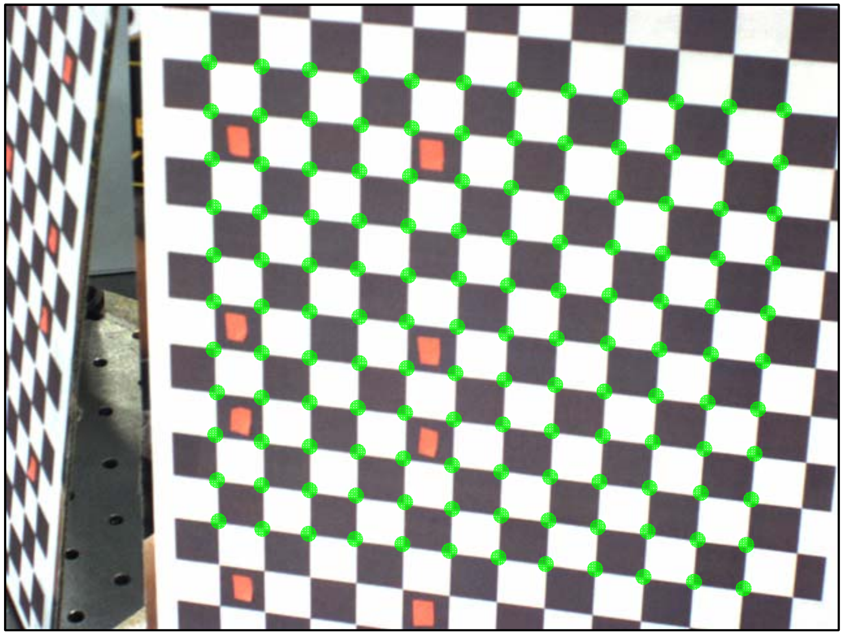
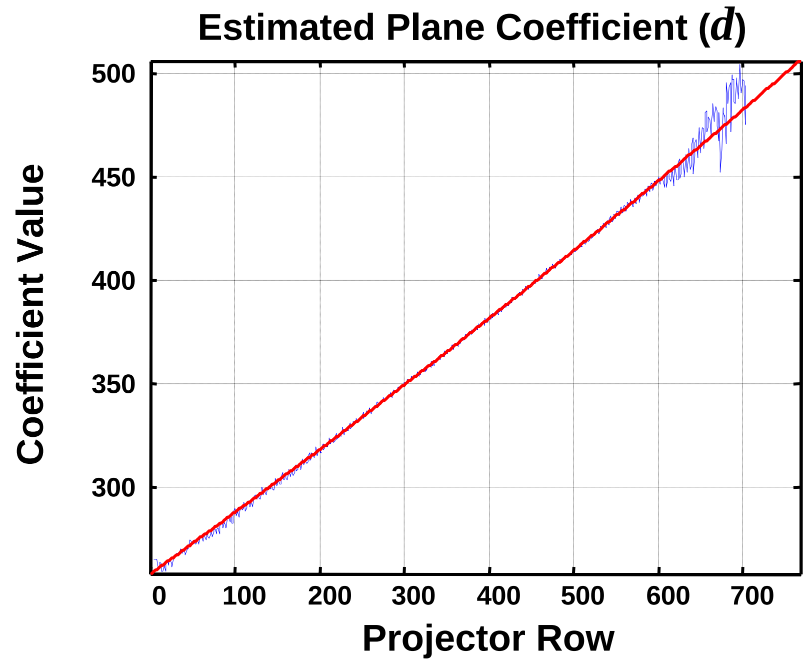
Orthographic Projector Calibration





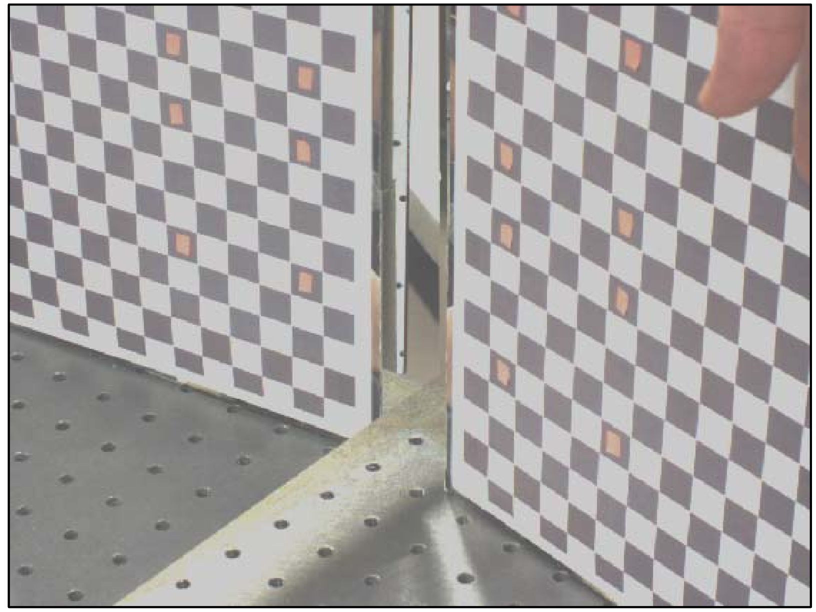
Orthographic Projector Calibration using Structured Light

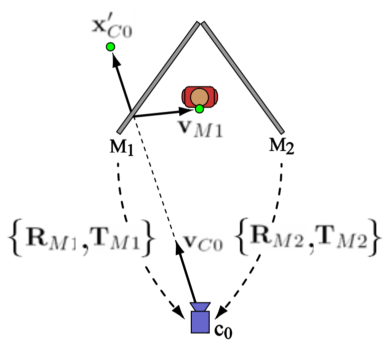
- Observe a checkerboard calibration pattern at several positions/poses
- Recover calibration planes in camera coordinate system
- Find camera pixel → projector plane correspondence using Gray codes
- Apply ray-plane intersection to recover a *labeled* 3D point cloud
- Fit a plane to the set of all 3D points corresponding with each projector row
- Filter/extrapolate plane coefficients using a best-fit quadratic polynomial

Planar Mirror Calibration

Calibration Procedure

- Record planar checkerboard patterns (place against mirrors in two images)
- Find corners in real/reflected images
- Solve for checkerboard position/pose (also find initial mirror position/pose)
- Ray-trace through "reflected" corners
- Optimize $\{\mathbf{R}_{M1},\mathbf{T}_{M1}\}$ to minimize back-projected checkerboard corner error
- Repeat for second mirror $\{\mathbf{R}_{M2},\mathbf{T}_{M2}\}$

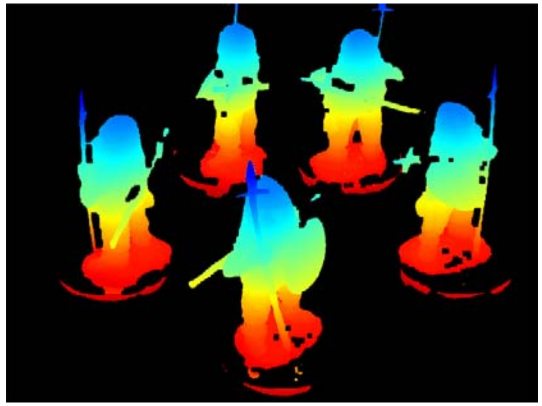




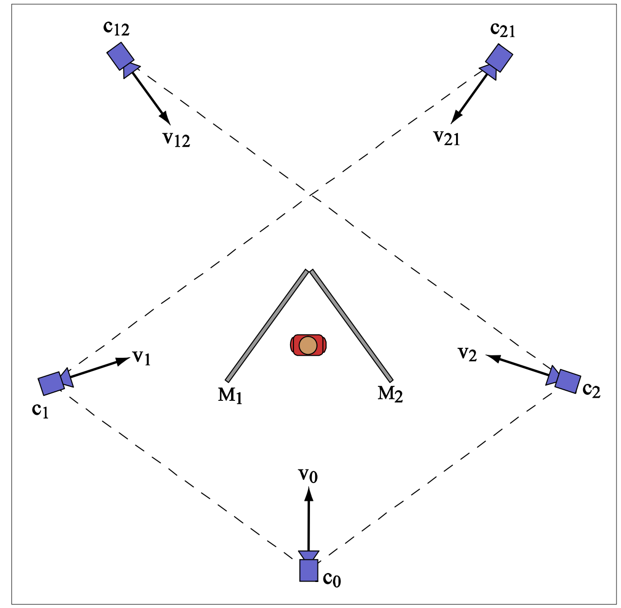
Mirror → Camera	Point Reflection	Ray Reflection
$\mathbf{x}_{C0} = \mathbf{R}_{M1}\mathbf{x}_{M1} + \mathbf{T}_{M1}$ $\mathbf{x}_{C0} = \mathbf{R}_{M2}\mathbf{x}_{M2} + \mathbf{T}_{M2}$	$\mathbf{x}'_{C0} = \mathbf{Q}_{M1}\mathbf{x}_{M1} + (\mathbf{I} - \mathbf{Q}_{M1})\mathbf{T}_{M1}$ $\mathbf{Q}_{M1} = \mathbf{R}_{M1}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}\mathbf{R}^T_{M1}$	$\mathbf{v}_{M1} = \mathbf{Q}_{M1}\mathbf{v}_{C0}$ $\mathbf{v}_{M2} = \mathbf{Q}_{M2}\mathbf{v}_{C0}$

Reconstruction Algorithm

Gray Code Sequence



Recovered Projector Rows



Real and Virtual Cameras

Step 1: Recover Projector Rows

- Project Gray code image sequence
- Recover projector scanline illuminating each pixel
- Post-process using image morphology

Step 2: Recover 3D point cloud

- Reconstruct using ray-plane intersection
- Consider each real/virtual camera separately
- Assign per-point color using ambient image

Camera Centers	Optical Rays
$\mathbf{c}_0 = (0,0,0)^T$	
$\mathbf{c}_1 = (\mathbf{I} - \mathbf{Q}_{M1})\mathbf{T}_{M1}$	$\mathbf{v}_1 = \mathbf{Q}_{M1}\mathbf{v}_0$
$\mathbf{c}_2 = (\mathbf{I} - \mathbf{Q}_{M2})\mathbf{T}_{M2}$	$\mathbf{v}_2 = \mathbf{Q}_{M2}\mathbf{v}_0$
$\mathbf{c}_{21} = \mathbf{Q}_{M2}\mathbf{c}_1 + (\mathbf{I} - \mathbf{Q}_{M2})\mathbf{T}_{M2}$	$\mathbf{v}_{21} = \mathbf{Q}_{M2}\mathbf{Q}_{M1}\mathbf{v}_0$
$\mathbf{c}_{12} = \mathbf{Q}_{M1}\mathbf{c}_2 + (\mathbf{I} - \mathbf{Q}_{M1})\mathbf{T}_{M1}$	$\mathbf{v}_{12} = \mathbf{Q}_{M1}\mathbf{Q}_{M2}\mathbf{v}_0$

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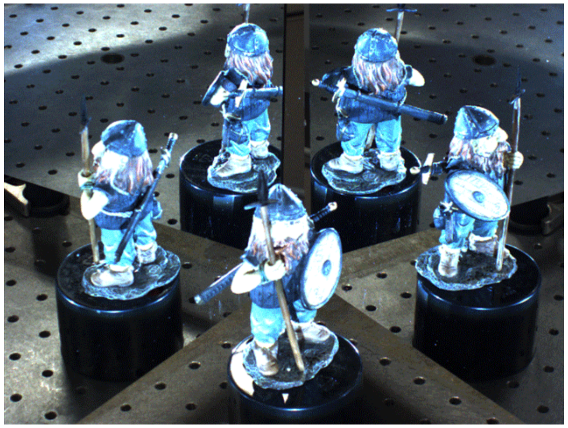
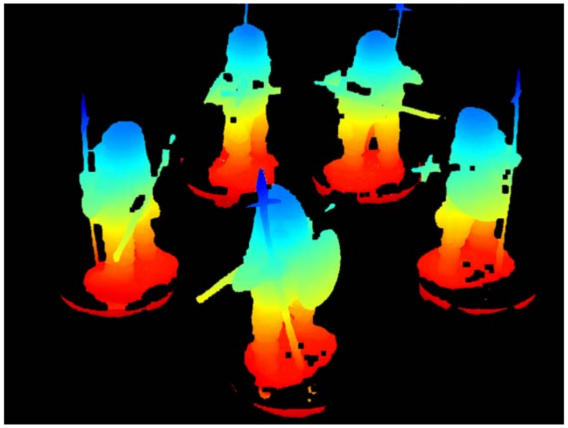
Experimental Reconstruction Results

Ambient Illumination



Gray Code Sequence



Recovered Projector Rows

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Conclusions and Future Work

Primary Accomplishments

- ✓ Experimentally demonstrated Surround Structured Lighting
- ✓ Developed a complete calibration procedure for prototype apparatus

Secondary Accomplishments

- ✓ Proposed practical methods for orthographic projector construction/calibration
- ✓ Extended *Camera Calibration Toolbox* for general projector-camera calibration

Future Work

- Sub-pixel light-plane localization
- Evaluate quantitative reconstruction accuracy
- Apply post-processing to point cloud
  (e.g., filtering, implicit surface, texture blending)
- Increase the scanning volume
- "Flatbed" scanner configuration (i.e., no projector)
- Extend to real-time shape acquisition "in the round"

de Bruijn Pattern [Zhang '02]

References

3DIM 2007: Surround Structured Lighting

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Multi-view Reconstruction using Planar Mirrors

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