3D Shape and Indirect Appearance By Structured Light Transport

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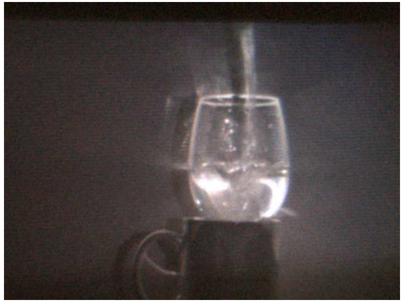
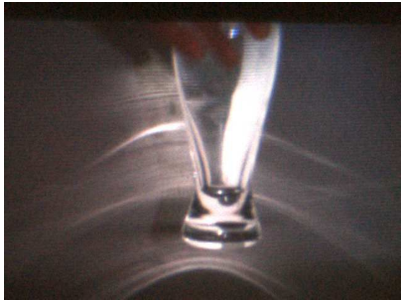
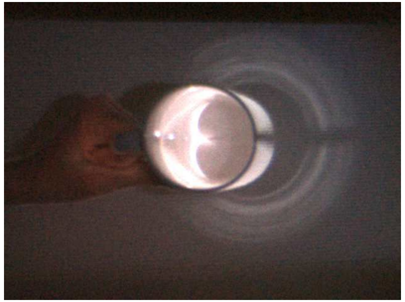
Presented by: Harrison Billmers, Allen Hawkes

Background - Indirect Light

- Indirect light can be dominant in natural scenes
  - Large contributor to actual appearance
- This paper develops framework for measuring/removing indirect light
  - General, unknown scene
  - Unrestricted motion of camera (video, scene changing)
  - 1 or more controllable sources (projectors)

Frames from indirect lighting video results

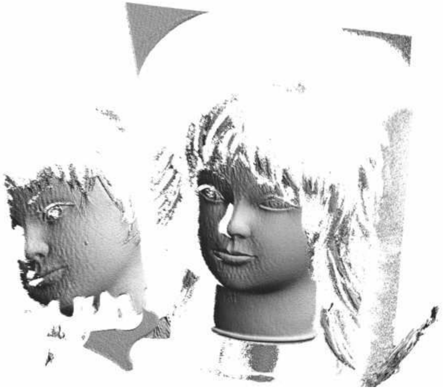
4 Imaging Problems Addressed

A. 1-shot Indirect-Only image
B. 1-shot Indirect-Invariant image
C. 2-shot Direct-Only image
D. 1-shot Multi-Pattern image

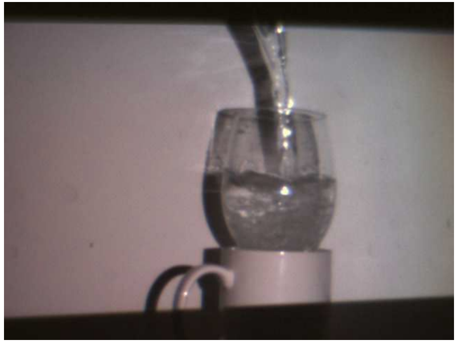
A. 1-Shot Indirect-Only

B. 1-Shot Indirect-Invariant

- Keep indirect light constant
- Appearance of direct light improves reconstruction

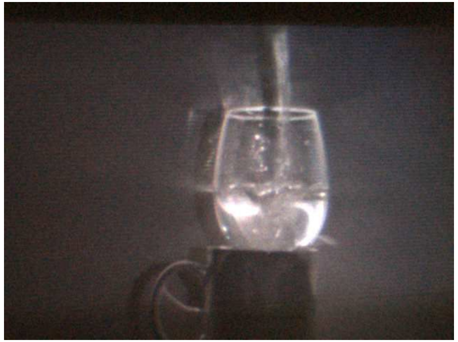


C. 2-Shot Direct-Only



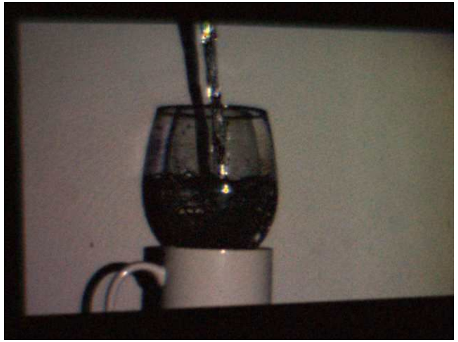
Full Illumination

-



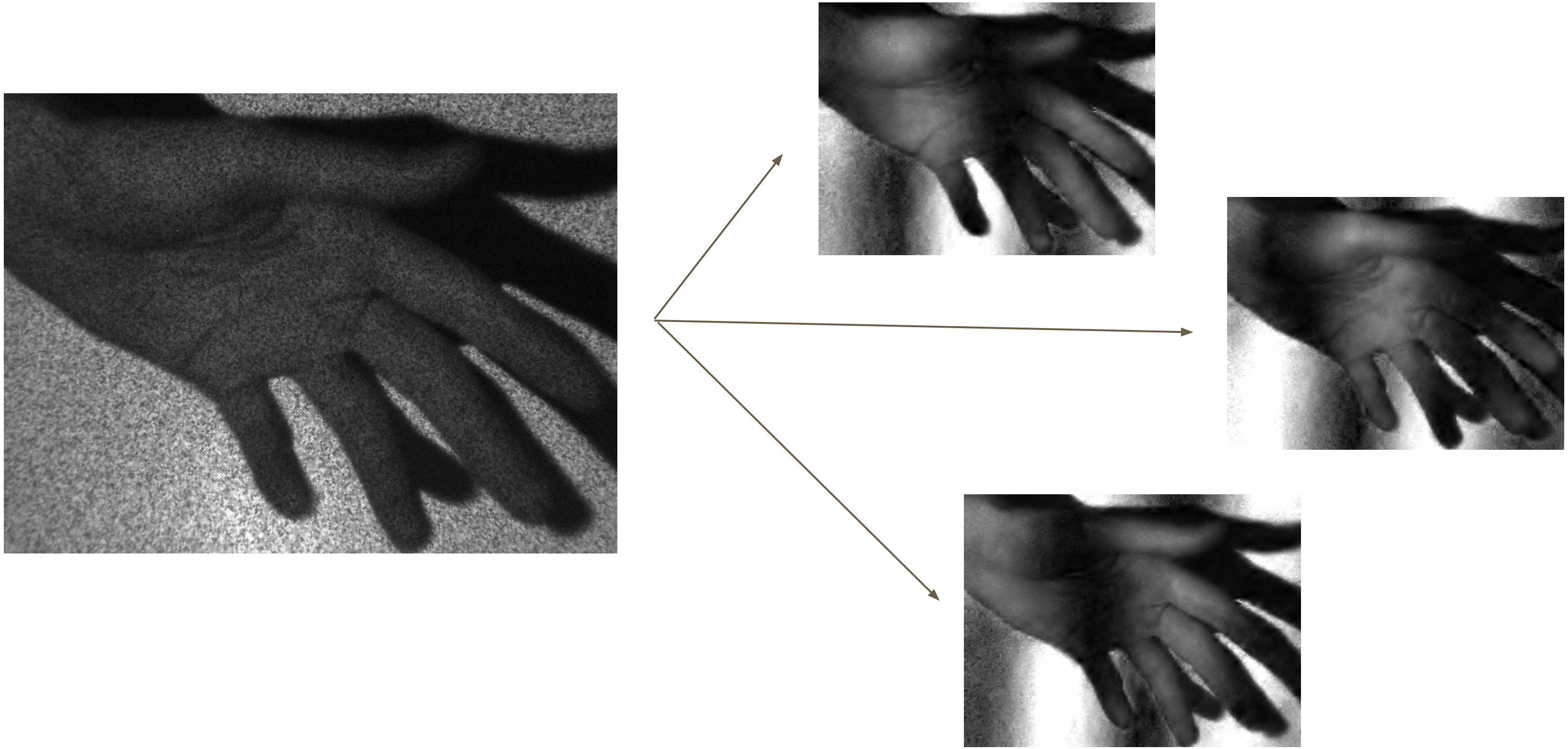
Indirect-only

=



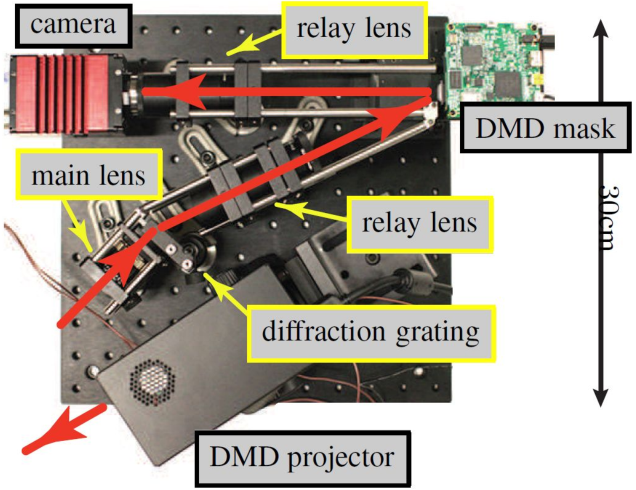
Direct-Only

D. 1-Shot Multi-Pattern



Setup

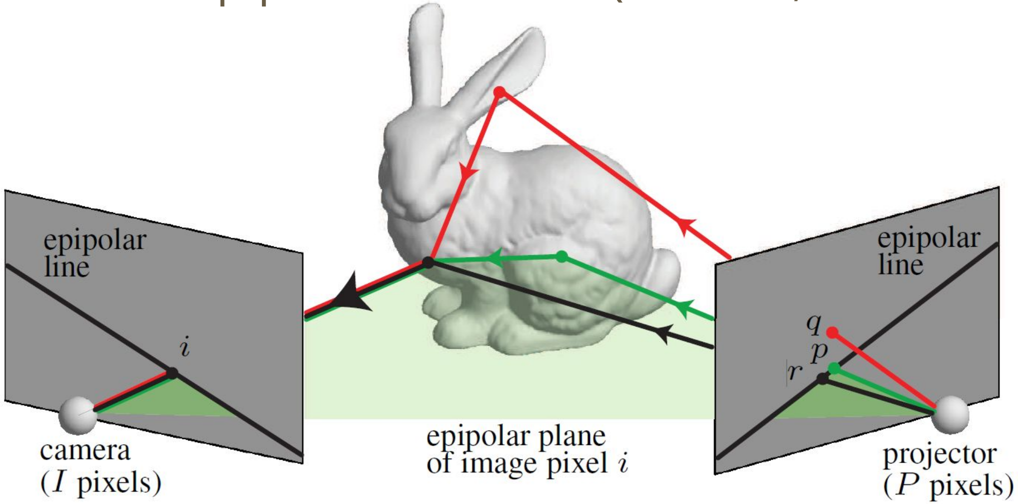
- 1 Camera: 28 Hz
- 2 Digital micromirror devices (DMDs): 2.7-24 kHz
- Do simultaneous projection & masking within single camera image
  - “Geometric” light analysis



Stereo Transport Matrix

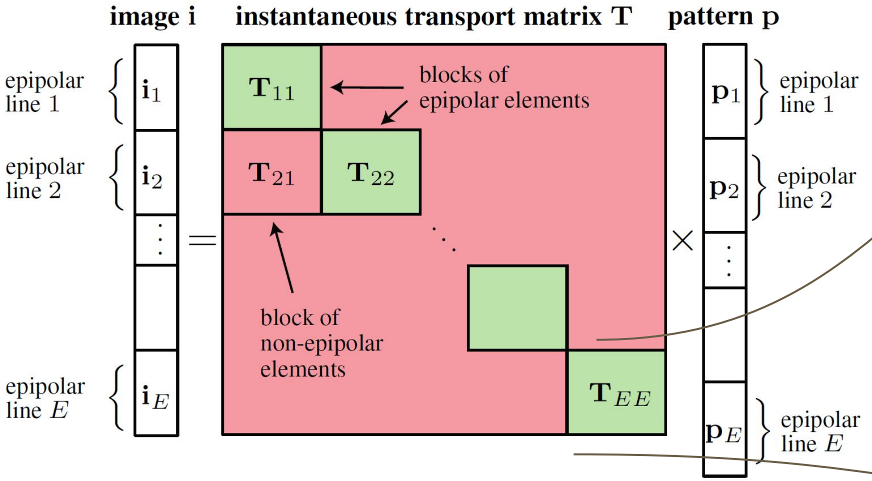
3 types of light that can reach a camera (left) from the projector (right)

1. Epipolar + Direct (black line, 1 bounce)
2. Epipolar + Indirect (green line, 2+ bounces but in-plane)
3. Non-epipolar + Indirect (red line, 2+ bounces out of plane)

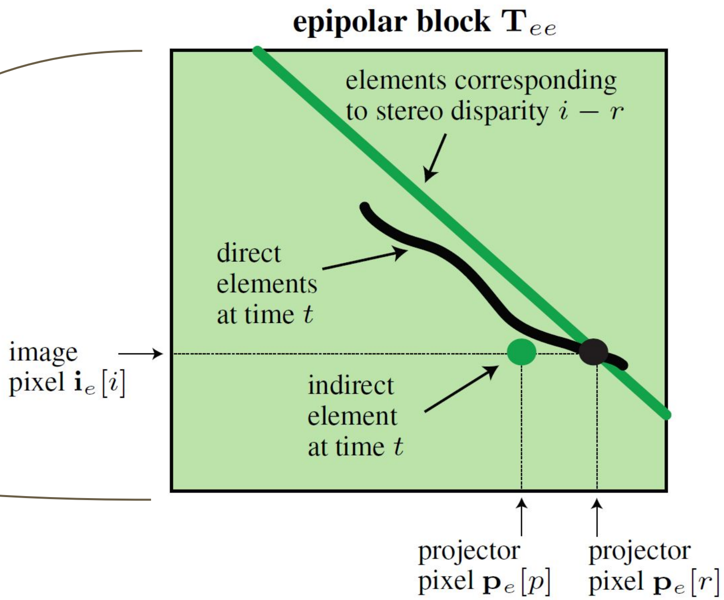


$$\mathbf{i} = \underbrace{\mathbf{T}^{\mathrm{D}}\mathbf{p}}_{\text{direct image}} + \underbrace{\mathbf{T}^{\mathrm{EI}}\mathbf{p}}_{\text{epipolar indirect image}} + \underbrace{\mathbf{T}^{\mathrm{NE}}\mathbf{p}}_{\text{non-epipolar indirect image}}$$

Stereo Transport Matrix



Order of pixels rearranged to be in epipolar lines



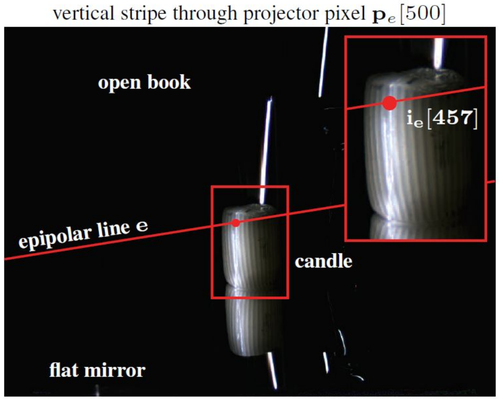
Direct/epipolar: contours
Indirect/epipolar: off-contour points

Dominance of Non-Epipolar Transport

In practical applications, indirect + non-epipolar far outweighs indirect + epipolar transport.

$$\mathbf{i} = \underbrace{\mathbf{T}^{\mathrm{D}}\,\mathbf{p}}_{\text{direct image}} + \underbrace{\mathbf{T}^{\mathrm{EI}}\,\mathbf{p}}_{\substack{\text{epipolar}\\ \text{indirect image}}} + \underbrace{\mathbf{T}^{\mathrm{NE}}\,\mathbf{p}}_{\substack{\text{non-epipolar}\\ \text{indirect image}}}$$

$$\mathbf{i} \approx \underbrace{\mathbf{T}^{\mathrm{D}}\,\mathbf{p}}_{\text{direct image}} + \underbrace{\mathbf{T}^{\mathrm{NE}}\,\mathbf{p}}_{\text{non-epipolar indirect image}}$$



Intuition: non-direct light mostly leaves epipolar plane

Result: all epipolar light is direct light (easily separate epipolar/non-epipolar)

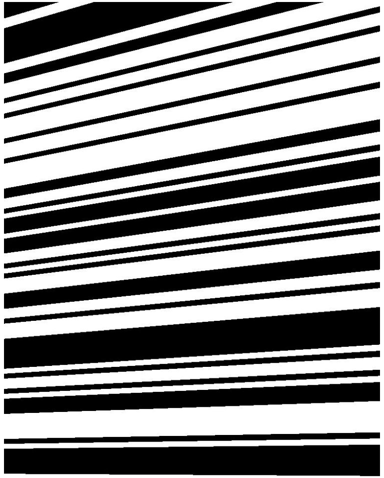
Structured Light Transport: Probing Matrix

“To make full use of **T**’s structure, we structure the flow of light itself”

Probe the light transport matrix using a pattern

Use the a technique inspired by the Primal-dual method

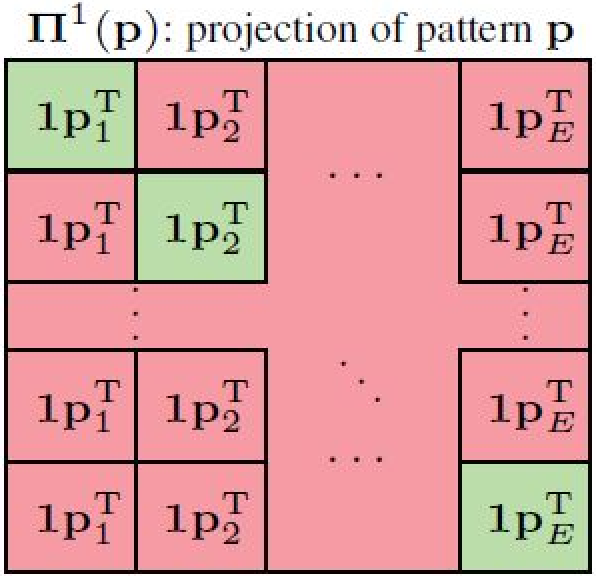
$$\mathbf{i} = [\mathbf{\Pi} \circ \mathbf{T}]\mathbf{1}$$



Epipolar light/mask

Structured Light Imaging

Pattern is projected across entirety of the probing matrix (no consideration of epipolar structure)

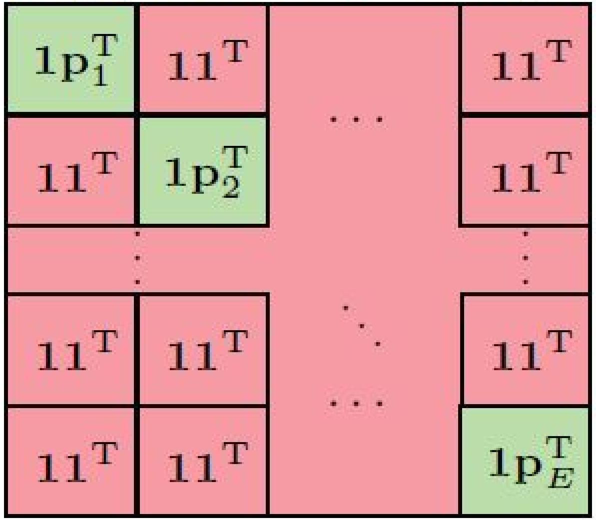


$$\mathbf{i}_e = \sum_{f=1}^{E} \mathbf{T}_{ef}\,\mathbf{p}_f = \left[\sum_{f=1}^{E} \underbrace{(\mathbf{1}\mathbf{p}_f^{\mathrm{T}})}_{\substack{\text{block of}\\ \text{probing matrix}}} \circ \underbrace{\mathbf{T}_{ef}}_{\text{block of } \mathbf{T}}\right] \mathbf{1}$$

Indirect-invariant Imaging

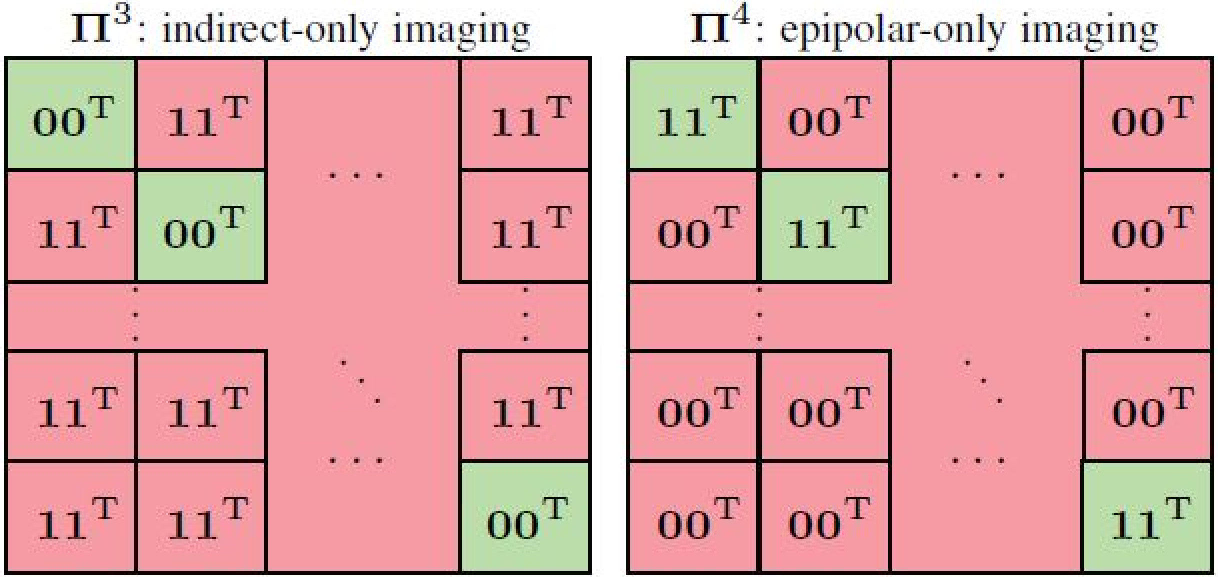
Utilize the structure to separate components

$\mathbf{\Pi}^2(\mathbf{p})$: indirect-invariant imaging



$$\mathbf{i}_e = \underbrace{\left[(\mathbf{1}\mathbf{p}_e^{\mathrm{T}}) \circ \mathbf{T}_{ee} \right] \mathbf{1}}_{\text{direct image (depends on } \mathbf{p}\text{)}} + \underbrace{\left[\sum_{f=1, f \neq e}^{E} \mathbf{T}_{ef} \right] \mathbf{1}}_{\text{non-epipolar indirect image (ambient)}}$$

Indirect-only and Epipolar-only imaging



One-shot,multi-pattern, indirect-invariant imaging

Allow for a whole array of structured light patterns (spatially multiplexed) in a single capture.

color filter mosaic

R	G	R
G	B	G

6-pattern mosaic

$\mathbf{p}(1)$	$\mathbf{p}(2)$	$\mathbf{p}(3)$
$\mathbf{p}(4)$	$\mathbf{p}(5)$	$\mathbf{p}(6)$

6-pattern indirect-invariant mosaic

$\mathbf{\Pi}^2(\mathbf{p}(1))$	$\mathbf{\Pi}^2(\mathbf{p}(2))$	$\mathbf{\Pi}^2(\mathbf{p}(3))$
$\mathbf{\Pi}^2(\mathbf{p}(4))$	$\mathbf{\Pi}^2(\mathbf{p}(5))$	$\mathbf{\Pi}^2(\mathbf{p}(6))$

$$\mathbf{\Pi}^5(\mathbf{p}(1),\ldots,\mathbf{p}(S)) = \sum_{s=1}^{S}\left[\,\mathbf{b}(s)\,\mathbf{1}^{\mathrm{T}}\,\right]\circ\mathbf{\Pi}^2(\mathbf{p}(s))$$

Digital Micromirror Device (DMD)-based setup

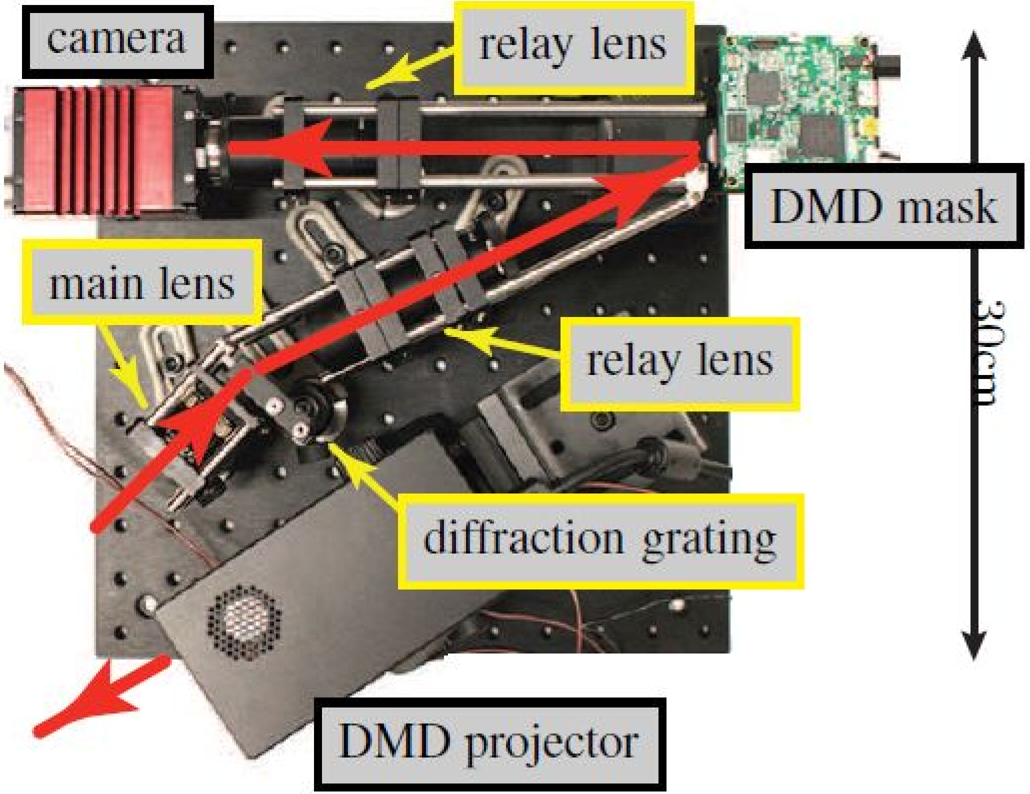
Rewrite probing equation as:

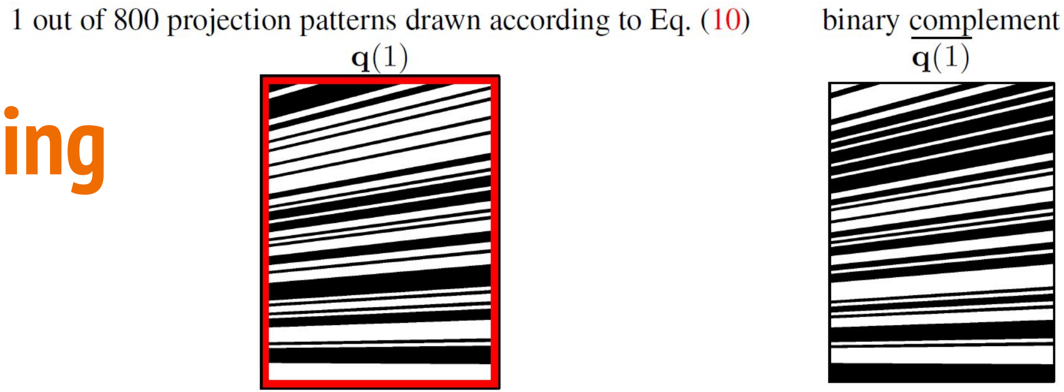
$$\mathbf{i} = \sum_{t=1}^{T} \mathbf{m}(t) \circ [\, \mathbf{T}\,\mathbf{q}(t)\,]$$

And now:

$$\mathbf{\Pi} = \sum_{t=1}^{T} \mathbf{m}(t)(\mathbf{q}(t))^{\mathrm{T}}$$

Which is a ROD





Indirect-only Imaging

For a given epipolar line e,

q(e) is 1 only along line e

m(e) is 1 everywhere except line e

Thus, $\mathbf{\Pi}^3 = \sum_{e=1}^{E} \mathbf{m}(e)(\mathbf{q}(e))^{\mathrm{T}}$

This is slow. Instead, use randomly selected lines, giving:

$$\mathcal{E}[\mathbf{i}_e] = \mathcal{E}[\overline{\mathfrak{q}_e}] \circ \sum_{\substack{f=1 \\ f\neq e}}^{E} \mathbf{T}_{ef}\, \mathcal{E}[\mathfrak{q}_f] = 0.25 \sum_{\substack{f=1 \\ f\neq e}}^{E} \mathbf{T}_{ef}\, \mathbf{1}$$

Epipolar-Only Imaging

Special case where no short ROD exists.

However,

$$\mathbf{\Pi}^4 = \mathbf{\Pi}^1(1) - \mathbf{\Pi}^3$$

Meaning that this probing matrix can be generated from a captured white image and subtracting indirect-only result. Two video frames are used.

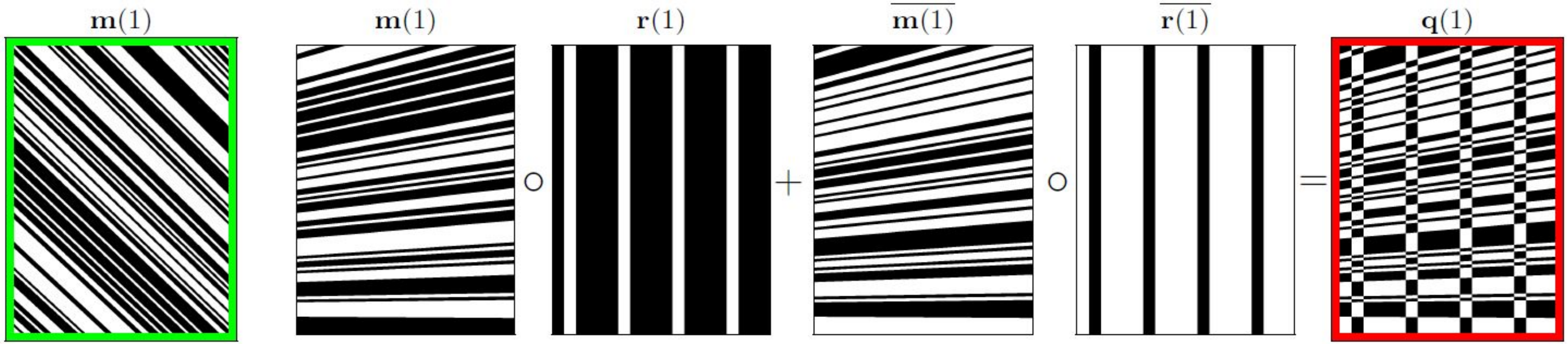
Indirect-invariant imaging

$$\mathbf{q}(t) = \mathbf{m}(t) \circ \mathbf{r}(t) + \overline{\mathbf{m}(t)} \circ \overline{\mathbf{r}(t)}$$

Allow for both direct and indirect components to be viewed.

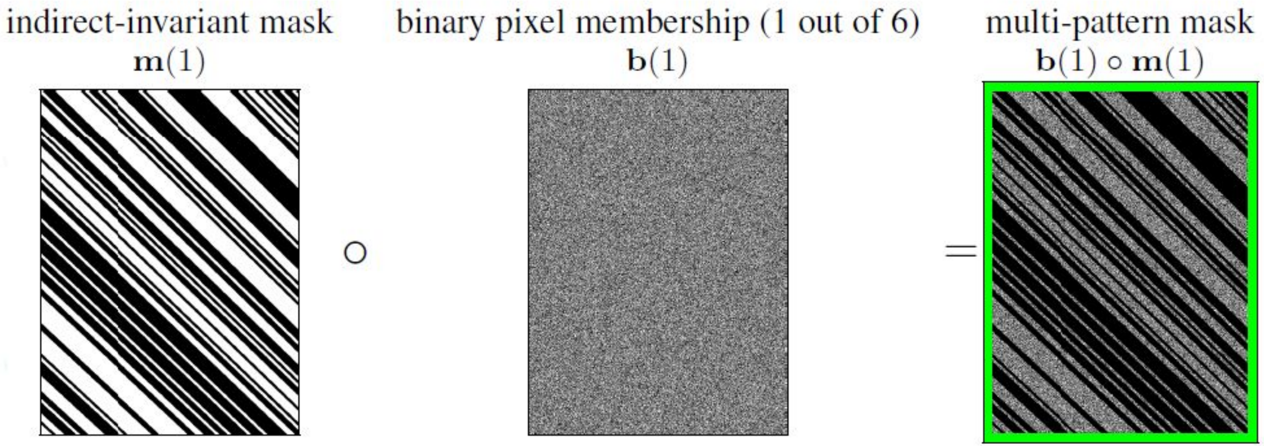
$$\begin{aligned}\mathcal{E}[\mathbf{i}_e] &= 0.5\mathbf{T}_{ee}\mathbf{p}_e + 0.25 \sum_{f=1, f\neq e}^{E} [\mathbf{T}_{ef}\mathbf{p}_f + \mathbf{T}_{ef}(\mathbf{1} - \mathbf{p}_f)] \\ &= \underbrace{0.5\mathbf{T}_{ee}\mathbf{p}_e}_{\substack{\text{direct image} \\ \text{(depends on } \mathbf{p})}} + \underbrace{0.25 \sum_{f=1, f\neq e}^{E} \mathbf{T}_{ef}\mathbf{1}}_{\text{indirect image (ambient)}} ,\end{aligned}$$

$$\mathbf{r} = \{\text{pixel } p \text{ on epipolar line } e \text{ is 1 with probability } \mathbf{p}_e[p]\} .$$



Epipolar light + mask for indirect-invariant imaging (i.e. for reconstruction)

One-shot, multi-pattern, indirect-invariant imaging

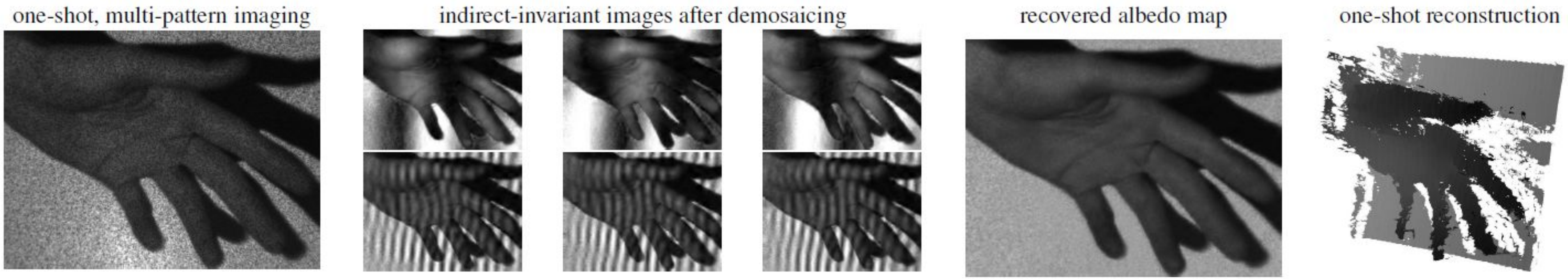


$$\text{minimize} \quad \left\| \mathbf{W}^{\mathbf{T}} \begin{bmatrix} \mathbf{i}(1) & \dots & \mathbf{i}(S) \end{bmatrix} \right\|_{n}$$

$$\text{subject to} \quad \left\| \sum_{s=1}^{S} \mathbf{b}(s) \circ \mathbf{i}(s) - \mathbf{i} \right\|_{2} \leq \epsilon$$

Results

Holding indirect lighting constant greatly improves 3D existing reconstruction algorithm



Multiplexed patterns in 1 image allow for single-capture depth reconstruction

Review of Work

Score: 1

Contributions:

- Indirect video streaming
- Greatly improve shape-from-shading algorithms
- Dynamic 3D shape capture for single images

Questions?

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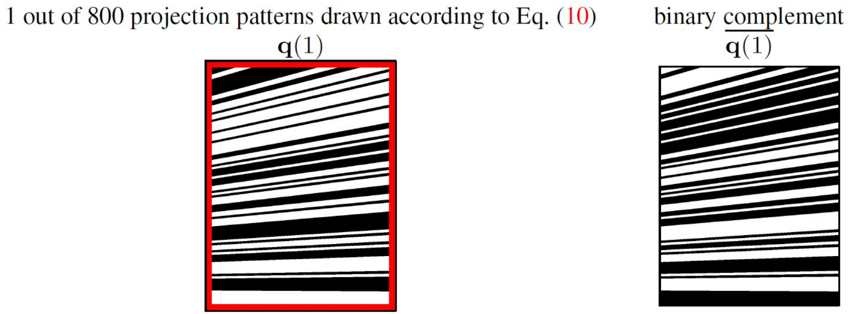
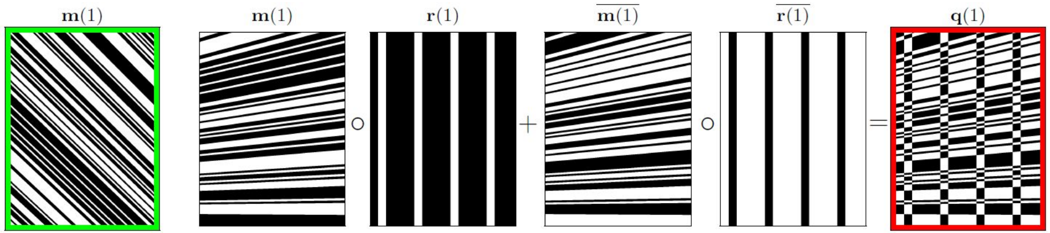
Presented by: Harrison Billmers, Allen Hawkes

Reference: Epipolar Illumination+Masks

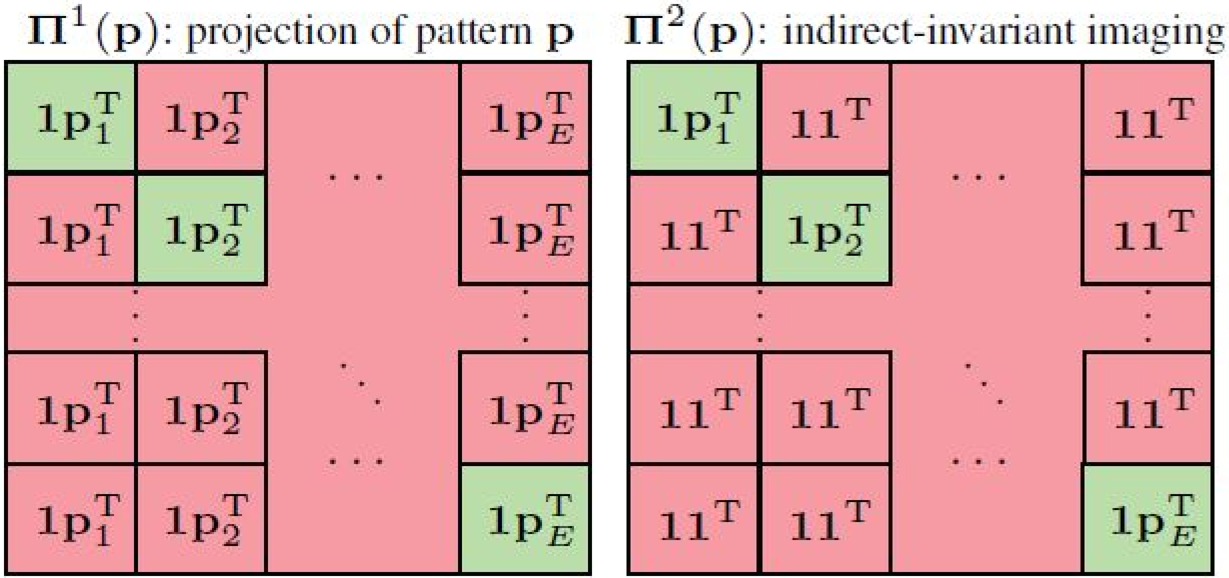


Epipolar light + mask for indirect-only imaging



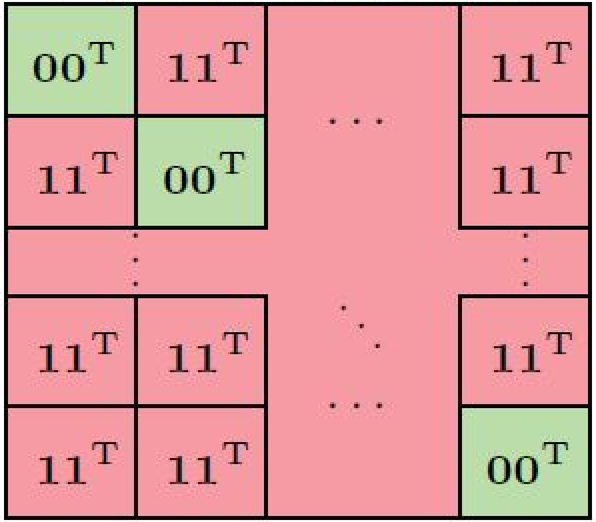
Epipolar light + mask for indirect-invariant imaging (i.e. for reconstruction)

Designs for the probing matrix Π



Designs for the probing matrix Π

Π^3: indirect-only imaging



Π^4: epipolar-only imaging