Probing Light Paths for
3D Shape and Indirect Appearance

Matthew O’Toole
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Stanford Computational Imaging (SCI)

Computational Imaging
- optics + sensing + computation

Computational Displays
- computation + optics & electronics + human visual system

Interaction
Stanford Computational Imaging (SCI)

Computational Imaging

- optics
- sensing
- computation

Computational Displays

- computation
- optics & electronics
- human visual system

Interaction
Stanford Computational Imaging (SCI)

Computational Imaging

HDR Imaging [Debevec, Nayar, ...]

Super-resolution [Baker, ...]

Light Fields [Levoy, ...]

Computational Displays

computation + optics & electronics + human visual system

interaction
Stanford Computational Imaging (SCI)

Computational Imaging
- HDR Imaging [Debevec, Nayar, ...]
- Super-resolution [Baker, ...]
- Light Fields [Wetzstein, ...]

Computational Displays
- HDR Display [Seetzen, ...]
- Super-resolution [Hirsch, Heide, ...]
- Light Fields [Levoy, ...]
Computational Imaging + Computational Displays → physical world
active lighting applications

Quality assurance

Autonomous vehicles

Tracking
active lighting applications

common issues:
- assumes light transport is well-behaved
- easily overwhelmed by bright ambient sources (e.g. sunlight)
transport probing
transport probing

epipolar-only video (direct)

non-epipolar video (indirect)
transport probing

epipolar-only video (direct)

regular image

shape robust to indirect & ambient light

non-epipolar video (indirect)
transport probing

epipolar-only video (direct)

regular image

shape robust to indirect & ambient light

non-epipolar video (indirect)

outdoor video under full sunlight

outdoor depth map
transport probing

cepipolar-only video (direct)

non-epipolar video (indirect)

shape robust to indirect & ambient light

outdoor video under full sunlight

outdoor depth map
basic light paths
basic light paths
basic light paths

camera

projector
basic light paths

camera

direct light

projector
basic light paths

indirect light (scattered)
basic light paths

camera

mirror

projector

indirect light
(specular)
basic light paths

- camera
- projector
- mirror

light paths:
epipolar constraint & light transport

direct paths satisfy epipolar constraints
epipolar constraint & light transport

indirect paths almost never satisfy constraints
epipolar constraint & light transport

indirect paths almost never satisfy constraints
blocking epipolar paths with patterns & masks
blocking epipolar paths with patterns & masks
blocking epipolar paths with patterns & masks
blocking epipolar paths with patterns & masks

camera

complementary random epipolar patterns

projector
blocking epipolar paths with patterns & masks

camera → mirror → projector

complementary random epipolar patterns
blocking epipolar paths with patterns & masks

camera

mirror

projector

complementary random epipolar patterns
blocking epipolar paths with patterns & masks

complementary random epipolar patterns
blocking epipolar paths with patterns & masks

1. open electronic shutter
2. for \( i = 1 \) to \( N \)
   use random epipolar mask &
   project complementary pattern
3. close electronic shutter
probing with DMD based projection
probing prototype with DMD projector

using two 4kHz DLP kits for projection & pixel masking
(96 codes / video frame)
probing prototype with DMD projector

using two 4kHz DLP kits for projection & pixel masking
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probing prototype with DMD projector

using two 4kHz DLP kits for projection & pixel masking
(96 codes / video frame)
all-optical probing procedure

step 1
open shutter

step 2
illuminate scene with vector $\mathbf{l}_i$

step 3
attenuate image with vector $\mathbf{m}_i$

step 4
repeat $K$ times

step 5
close shutter
all-optical probing procedure

step 1: open shutter
step 2: illuminate scene with vector $\mathbf{l}_i$
step 3: attenuate image with vector $\mathbf{m}_i$
step 4: repeat $K$ times
step 5: close shutter
all-optical probing procedure

**step 1**
open shutter

**step 2**
illuminate scene with vector $\mathbf{l}_i$

**step 3**
attenuate image with vector $\mathbf{m}_i$

**step 4**
repeat $K$ times

**step 5**
close shutter
all-optical probing procedure

\[ \sum_{i=1}^{K} \]

step 1 open shutter

step 2 illuminate scene with vector \( l_i \)

step 3 attenuate image with vector \( m_i \)

step 4 repeat \( K \) times

step 5 close shutter
all-optical probing procedure

\[ \sum_{i=1}^{K} \]

- step 1: open shutter
- step 2: illuminate scene with vector \( l_i \)
- step 3: attenuate image with vector \( m_i \)
- step 4: repeat \( K \) times
- step 5: close shutter
all-optical probing procedure

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>open shutter</td>
</tr>
<tr>
<td>2</td>
<td>illuminate scene with vector $l_i$</td>
</tr>
<tr>
<td>3</td>
<td>attenuate image with vector $m_i$</td>
</tr>
<tr>
<td>4</td>
<td>repeat $K$ times</td>
</tr>
<tr>
<td>5</td>
<td>close shutter</td>
</tr>
</tbody>
</table>
live indirect-only and direct-only video stream

conventional imaging
live indirect-only and direct-only video stream

conventional imaging

indirect-only imaging
live indirect-only and direct-only video stream

- Conventional imaging
- Indirect-only imaging
- Direct-only imaging
live indirect-only and direct-only video stream

conventional imaging

indirect-only imaging

direct-only imaging
live indirect-only and direct-only video stream

conventional imaging

indirect-only imaging

direct-only imaging
live indirect-only and direct-only video stream

- Conventional imaging
- Indirect-only imaging
- Direct-only imaging
indirect-invariant imaging
live indirect-invariant video stream

- conventional structured light

- indirect-invariant structured light
shape acquisition by structured light
shape acquisition by structured light
shape acquisition by structured light
conventional structured light
reconstructed 3D shape
indirect-invariant structured light
reconstructed 3D shape (same algorithm)
conventional structured light
reconstructed 3D shape
indirect-invariant structured light
reconstructed 3D shape (same algorithm)
energy-efficient imaging
DMD or LCD projection: attenuate light at each projector pixel

- 0% light blocked
- 50% light blocked
- 95% light blocked

DMD projector
**projector technologies**

**DMD or LCD projection:** attenuate light at each projector pixel

- 0% light blocked
- 50% light blocked
- 95% light blocked

**MEMs scanning projection:** reallocate energy of projector pixels

- 0% light blocked
- 0% light blocked
- 0% light blocked
our scanning projector based prototype
our scanning projector based prototype

30 lumens power, split between R,G and B channels
our scanning projector based prototype

rolling shutter CMOS cameras

cameras fitted with red bandpass filters
our scanning projector based prototype
scanning projectors - indirect probing

Epipolar Plane

Exposed Pixels
Masked Pixels

Laser Projector
Camera & Mask
scanning projectors – direct probing

short exposure → ambient light is blocked
robustness to ambient light

regular imaging

epipolar-only (direct) imaging

reducing aperture doesn’t make the pattern visible
structured light outdoors

regular imaging

epipolar-only (direct) imaging

ambient light level ≈ 80,000 lux
recovering shape under bright ambient conditions

depth map

3D reconstruction
active stereo in bright sunlight

raw image (left camera)

depth map
active stereo in bright sunlight

raw image (left camera)
depth map
taking transport probing everywhere

Medical Imaging

Industrial Inspection

Mobile Robotics

Consumer Electronics
taking transport probing everywhere

Medical Imaging

Industrial Inspection

Mobile Robotics

Consumer Electronics
taking transport probing everywhere

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Medical Imaging

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Consumer Electronics
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