3D Shape and Indirect Appearance by Structured Light Transport

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What is "Structured Light Transport"?

An imaging technique for manipulating the direct and indirect light flowing through an unknown scene.

Contributions:

- take advantage of epipolar geometry to capture direct-only or indirect-only images, without assuming low-frequency transport [Nayar et al. 2006]
- perform one-shot acquisition at video rates, using optical masks and projection patterns
- capture video in three ways: (1) indirect-only or epipolar-only imaging, (2) indirect-invariant imaging, and (3) one-shot, multi-pattern imaging

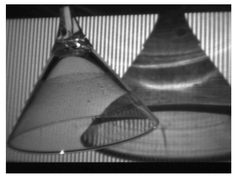
Three New Forms of Imaging

1. Indirect-only imaging

capture video that only records indirect light

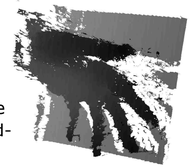
2. Indirect-invariant imaging

given a projection pattern, capture video that only structures direct transport



3. One-shot, multi-pattern imaging

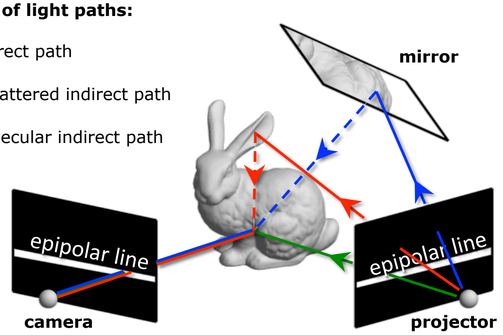
simultaneously capture multiple views of a scene lit by different structured-light patterns



Epipolar Geometry and Light Transport

Types of light paths:

- direct path
- scattered indirect path
- specular indirect path



Observation:

- direct light paths always satisfy the epipolar constraint
- indirect light paths almost never satisfy the constraint

Dominance of non-epipolar transport:

Proposition 1. If $\mathbf{T}$ is the discretized form of a transport function that is measurable and positive over the rectified projector and image planes, then

$$\lim_{\epsilon \to 0} \frac{\mathbf{T}^{\mathrm{EI}}\mathbf{p}}{\mathbf{T}^{\mathrm{NE}}\mathbf{p}} = 0$$

where division is entrywise, ϵ is the pixel size for discretization, $\mathbf{p}$ is a projection pattern, and $\mathbf{T}^{\mathrm{EI}}$ and $\mathbf{T}^{\mathrm{NE}}$ represent epipolar and non-epipolar transport.

Proposition 2. Two generic n-bounce specular transport paths that originate from corresponding epipolar lines do not intersect for n > 1.

Idea:

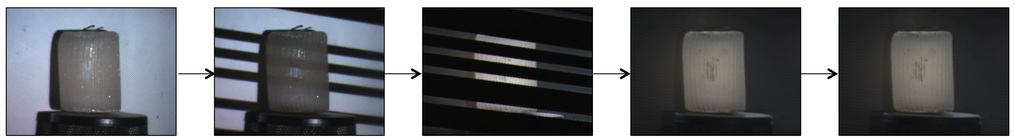
- exploit non-epipolar dominance using projector patterns and sensor masks
- derive patterns by solving a binary matrix decomposition problem [Zhong 2012]

Optical Procedure

Algorithm for generating live indirect-only video:

1. open electronic shutter
2. for i = 1 to N
3. project random epipolar pattern
4. block light with complementary mask
5. close electronic shutter

Steps occurring within a 36 msec video frame:

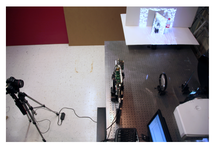


open electronic shutter → light scene with random binary epipolar lines → block direct light along epipolar lines with mask pattern → repeat previous steps for all N illumination and mask patterns → close shutter and read-out image

Camera Implementations

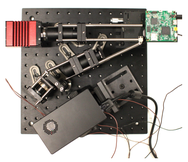
Version 1.0 [O'Toole et al. 2012]

- pattern rate: 0.02 kHz
- Size: 2 x 2 x 0.5 m
- LCD-based mask
- SLR camera
- Coaxial camera & projector



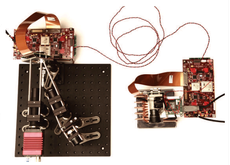
Version 2.0 (low-speed, low-cost)

- pattern rate: 2.7 kHz
- Size: 30x30x20 cm
- DMD-based mask
- Vision camera
- Non-coaxial camera & projector



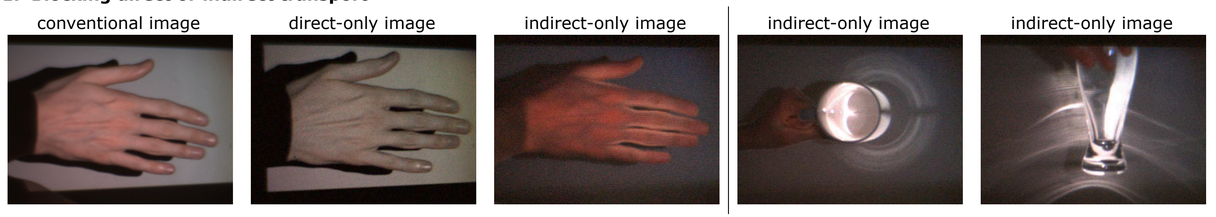
Version 3.0 (high-speed)

- pattern rate: 24kHz
- Size: 30x60x20 cm
- DMD-based mask
- Vision camera
- Non-coaxial camera & projector

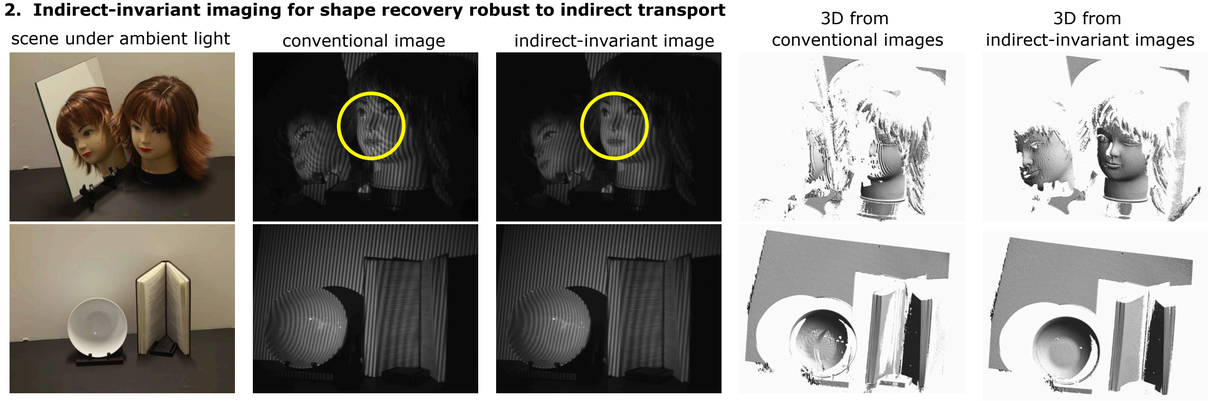


Results

1. Blocking direct or indirect transport



2. Indirect-invariant imaging for shape recovery robust to indirect transport

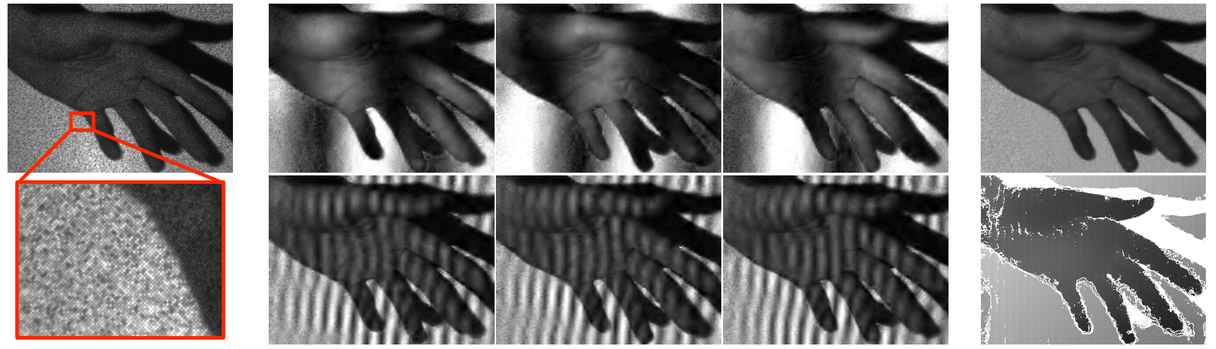


3. One-shot, multi-pattern, indirect-invariant imaging for dynamic shape recovery

Step 1: capture a one-shot, multi-pattern image by spatially multiplexing 6 images

Step 2: demosaic the captured image to infer the multiplexed images, one for each of 6 sinusoidal structured-light patterns

Step 3: recover albedo and shape by using the 6 images as input to a phase-shifting algorithm



References

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Nayar, S., Krishnan, G., Grossberg, M., Raskar, R. 2006. Fast separation of direct and global components of a scene using high frequency illumination. ACM SIGGRAPH.

Zhong, J. 2012. Binary ranks and binary factorizations of nonnegative integer matrices. Electron. J. Linear Algebra.

Website

http://www.dgp.toronto.edu/~motoole/slt.html