Decomposition and Acquisition of Light Transport under Spatially Varying Lighting

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Distant illumination

Light is distant and diffuse at the scene

- Angular variation at the scene
- Little/no spatial variation

image credit: ict.usc.edu
Spatially varying illumination

Light focuses on the scene

- Spatial variation at the scene
- Small range of angles
Examples

Many applications

• Structured light
• Image/video projection
• Augmented Reality

image credit: volkswagen
Projector-camera system

Diffuse scene

Camera

Projector
Light transport

Input: projector pattern  Output: camera image
Light transport

Diffuse scene: subsurface scattering, interreflection

Projector pattern

Camera image

diffuse inter-reflections

subsurface scattering
Transport matrix

Camera

Projector

Scene

\[
T = \{
\}
\]

\[p\]
Transport matrix

\[ T = \begin{pmatrix} \ \end{pmatrix} \]
Transport matrix

\[ T = p \]
Transport matrix

\[
\begin{pmatrix}
T &= \begin{pmatrix}
C
\end{pmatrix}
\end{pmatrix}
\]
Transport matrix

$$T = \begin{bmatrix} c \end{bmatrix}$$
Transport matrix

\[ T = \begin{bmatrix} \mathbf{c} \end{bmatrix} \]
Transport matrix

2D slice of the 4D light transport at the scanline

\[ T = \]

direct component

subsurface scattering

diffuse inter-reflections
Acquisition

Acquire 360000 x 16384 matrix with 1060 patterns

SNR = 27.2 dB
Acquisition

Acquire 360000 x 16384 matrix with 1060 patterns

Original

Reconstructed
SNR = 24.7 dB
Decomposition

Reconstructed

Direct + Near + Far
Decomposition

Reconstructed

Direct + Near + Far
Contributions

Decompose light transport into physical components
- Direct, Near Range (subsurface), Far (interreflections)

Efficiently acquire the component transports
- Varying bandwidth in projector’s frequency-space
- Use minimal number proposed by the model
Acquisition and storage

• Distant illumination:
  - transport matrix is locally low-rank
  - Wang et al. 2009, O’Toole et al. 2010

• Spatially varying illumination
  - brute force, ignores diffuse inter-reflections
  - Masselus et al. 2003,
  - Sen et al. 2005, Garg et al. 2006
Decomposition

• Direct global separation
  - Nayar et al. 2006
  - separates floodlit images, not light transport

• Component separation
  - O’Toole et al. 2012
  - iterative process for a single image
Acquisition & Decomposition
Transport model

Direct: single bounce (mainly)

- Diagonal matrix, large magnitude
Transport model

Near-range: subsurface effects, local interreflection

• Banded diagonal matrix, sparse
Transport model

Far-range: diffuse interreflection

• Dense, small magnitude, low frequency
Direct transport

$$T = \text{direct transport} - q$$
Direct transport

Localized in space – 1 unknown at each camera pixel

Projector pixel support

Frequency support

\[ P_x \quad \text{q} \quad P_y \]

\[ k_x \quad k_y \]
Direct transport

1 high-freq. sinusoidal pattern

Projector pixel support

Frequency support

Sinusoidal sampling

Direct
Direct transport

$\mathbf{I}_+$

Projector pattern

$\mathbf{b}_+$

Camera image

$\mathbf{I}_-$

$\mathbf{b}_-$
Compute

\[ \frac{b_+ - b_-}{l_+ - l_-} \]
Far-range transport

Far-range transport - [0, P-1]
Far-range transport

Localized in frequency – $4k_{fx}k_{fy}$ unknowns

Projector pixel support

Frequency support

Far-range
Far-range transport

Use all $4k_{fx}k_{fy}$ sinusoidal patterns for measurement
Far-range transport

Example pattern

Projector pixel support

Frequency support

Sinusoidal sampling

Far-range
Far-range transport

Example pattern

Projector pixel support

Frequency support

Sinusoidal sampling

Far-range
Near-range transport

Camera

Projector

Scene

local inter-reflections

subsurface scattering

$T = \left[ q-W/2, q+W/2 \right]$

near-range transport

- $[q-W/2, q+W/2]$
Near-range transport

$W^2$ unknowns at each camera pixel
Near-range transport

$W^2$ sinusoidal patterns placed $1/W$ apart

Projected pixel support

Frequency support

Sinusoidal sampling

Near-range
Near-range transport

Example pattern

Projector pixel support

Frequency support

Sinusoidal sampling

Near-range
Near-range transport

Example pattern

- Projector pixel support
- Frequency support
- Sinusoidal sampling

Near-range
Far-range interference

Overlap of few patterns with far-range bandwidth

Projector pixel support

Frequency support

Sinusoidal sampling

Near-range

Far-range
Near-range measurements

Drop such sinusoidal patterns

- Projector pixel support
- Frequency support
- Sinusoidal sampling

Near-range
System of equations is underdetermined

\[
\min \| \mathbf{w} \|_1
\]

Projector pixel support

\(P_x\)

\(P_y\)

\(w\)

sparse and has a long tail distribution

Near-range
Near-range transport

$\text{Projector pattern}$

$\text{Camera image}$
Transport model

\[ T = \begin{cases} \text{direct transport} & - q \\ \text{near-range transport} & - [q-W/2, q+W/2] \\ \text{far-range transport} & - [0, P-1] \end{cases} \]
Frequency-space

Projector pixel support

Frequency support

Sinusoidal sampling

Direct  Near-range  Far-range
Number of measurements: Direct

1 unknown
1 pattern sufficient

Projector pixel support

Sinusoidal sampling

Direct
Number of measurements: Near

$W^2$ unknowns.

Less than $W^2$ patterns sufficient

Projector pixel support

Sinusoidal sampling

Near-range
Number of measurements: Far

$4k_{fx}k_{fy}$ unknowns.

$4k_{fx}k_{fy}$ patterns sufficient.

Frequency support

Sinusoidal sampling
Number of measurements: All

$1 + 4k_{fx}k_{fy} + W^2$ unknowns.

Less than $1 + 4k_{fx}k_{fy} + W^2$ patterns sufficient.
Results

Acquire 16384 x 16384 matrix with 788 patterns
Comparisons

Original transport

Our method

Compressive Light Transport

287dB  39dB  43dB  44dB

16dB  3dB  9dB  9dB
Limitations

Projector-camera correspondence
- Currently a preprocessing step
- Joint correspondence and transport estimation
- Tough for specular objects

Diffuse scenes
- Works well for diffuse scenes
- Specular and transparent scenes don’t follow low-frequency interreflections
Conclusions

Decomposition of transport
• Separates physically meaningful components
• Simple compact model for direct, near, far

Efficient acquisition of transport
• Simple projector-camera setup
• Close to optimal number of patterns
Thank you