Computational interferometric imaging

Alankar Kotwal
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SIGGRAPH 2023
What is interferometry?
OCT eye exam

Retinal scanning and angiography to diagnose glaucoma, diabetic retinopathy, macular degeneration, etc.

“Around 64% of adults working in computer and mathematical sciences use some vision correction option” (i.e., glasses, contacts, surgery)

From the Washington Post, May 2023

[Images from the American Academy of Ophthalmology]
Skin cancer imaging

Non-invasive imaging of breast and dorsal skin tumors

(Still at the pre-clinical level)

2 mm depth
10 μm resolution

[Images from Vakoc et al. 2012, Nature Reviews Cancer]
Seeing deep inside tissue

NSF Expedition project, https://seebelowtheskin.org
The need for micrometer resolutions

50 μm

[Image from Wikimedia Commons]
FMCW “4D” lidar

Depth and velocity using frequency-modulated continuous-wave lidar (a.k.a. swept-source optical coherence tomography)

[Images from Aeva, and Zhang et al. 2019]
Micrometer 3D sensing

Inspection: aircraft fuselage section

Fabrication: 3D-printed Euro coin
Very large-scale physics

first gravitational wave detection

Laser Interferometer Gravitational-wave Observatory (LIGO) at Hanford, WA (4 km-long Michelson interferometer)

first image of a black hole (center of Messier 87 galaxy)

Location of observatories making up the Event Horizon Telescope (EHT) (very-long-baseline interferometry)
Computational imaging

Non-line-of-sight imaging

Transient imaging

Separation of direct-indirect illumination
Course overview

introduction to interferometry

two-wavelength interferometry

partially-coherent interferometry

interferometric computational imaging

Yannis
Florian
Alankar
Florian
Yannis
Course overview

- Introduction to interferometry
- Two-wavelength interferometry
- Partially-coherent interferometry
- Interferometric computational imaging

Yannis
Florian
Alankar
Florian
Yannis
Interferometric imaging

- Coherent light source
- Collimating lens
- Beam splitter
- Reference mirror
- Camera
- Scene
- Reference
- Scene + reference
- Interference

Diagram showing the process of interferometric imaging.
Interferometric imaging

coherent light source

collimating lens

beam splitter

camera

scene

reference

scene + reference

interference
Interferometer designs

Many others: Sagnac, Fizeau, shearing, ...
Interferometer implementations

Full-field: 2D sensor and free-space optics

Scanning: single-pixel sensor and fiber optics

Many choices: circulators, balanced detectors
Phase-shifting interferometry

Coherent light source

Reference mirror

Tilted mirror
Phase-shifting interferometry

Single-frequency laser

Phase difference \( \delta \varphi \propto (d_r - d_t) \mod \lambda \)
Phase-shifting interferometry

Interference: correlation of two sinusoids $\rightarrow$ another sinusoid of sample frequency and phase $\delta \varphi$
Phase-shifting interferometry

Interference: correlation of two sinusoids → another sinusoid of sample frequency and phase $\delta \varphi$

Phase retrieval:

$$d = \frac{\lambda}{2\pi} \tan^{-1} \frac{E_4 - E_2}{E_1 - E_3} + n\lambda$$

Needs only 4 axial measurements
Example: surface deflectometry with PSI

single-frequency laser

reference shape

test shape

ideal

actual
Example: surface deflectometry with PSI

Phase-shifting interferometry:

- ✔️ sub-wavelength resolution
- ✗ wavelength depth range
- ✗ only for smooth surfaces
- ✗ very sensitive to vibrations
- ✗ very sensitive to aberrations
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Yannis
Computational 3D Imaging and Measurement (3DIM) Lab

Current Members

**Director**

Florian Willomitzer

**Students**

Jiazhang Wang, Manuel Ballester, Heming Wang, Patrick Cornwall, Yuanxin Guan, Jiwon Choi, Tianfu Wang, James Taylor, John Bass, Aniket Dashpute

Contributing collaborators and previous group members:

Northwestern University

SMU

Rice University

Florian Willomitzer - Computational 3D Imaging and Measurement Lab - www.optics.arizona.edu/3dim
Part 2:
Interferometry on Rough Surfaces
and
Synthetic Wavelengths

Florian Willomitzer
Associate Professor
Wyant College of Optical Sciences
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https://www.optics.arizona.edu/3dim
Coherent imaging on rough surfaces - Speckle

Rough surface

Objective speckle

Speckle pattern

Detector

Plane wave with wavelength $\lambda$
Coherent imaging on rough surfaces - Speckle

Object with rough surface

Laser

Camera readout

Amplitude $|E(\lambda)|$

Phase $\angle E(\lambda) = \phi(\lambda)$
When is a surface “optically rough”?

- Rough surface
- Resolution cell
- Wavefront in
- $\Psi$
- $\lambda$

When is a surface “optically rough”? To understand this, consider the concept of a resolution cell and the wavefront's interference patterns. The term “optically rough” refers to the surface characteristics that affect how light interacts with it, leading to measurable interference patterns. This is crucial in computational interferometric imaging, where the goal is to extract detailed information about the surface from the interference patterns formed by the light waves.
When is a surface “optically rough”?

- Rough surface

Resolution cell

Destructive Interference if: 

\[ 2\psi \geq \frac{\lambda}{2} \]

Wavefront out

Speckle-free imaging if:

\[ \frac{\lambda}{4} \geq \psi_{max} \]
**Approaches measuring the Time-of-Flight of light**

\[ \delta z \propto \lambda \]

- **Conventional Interferometry** (single Wavelength)
  - Speckle for scattering scenes
  - \( \sim \mu m \)
- **“ToF Cameras”** (CW or pulsed)
  - Poor resolution
  - \( \sim m \)
- **Synthetic Wavelength Interferometry**
  - Depth resolution
  - Modulation wavelength

Depth resolution \( \propto \) modulation wavelength
Millimeter-sized waves with visible light?

NO! ... well ... let’s look at sound waves!

Sine wave
\[ \nu = 240 \text{Hz} \Rightarrow \lambda \approx 1.429 \text{m} \]

Sine wave
\[ \nu = 242 \text{Hz} \Rightarrow \lambda \approx 1.417 \text{m} \]

Beat note
\[ \Lambda_{\text{beat}} \approx 171.5 \text{m} \]
**Synthetic Waves**

Laser 1 \((\lambda_1, \nu_1)\)
- e.g. \(\lambda_1 = 800\, nm\)

Laser 2 \((\lambda_2, \nu_2)\)
- e.g. \(\lambda_2 = 800.6\, nm\)

**Beat note**

Detection & Processing

\[ \Lambda = \frac{\lambda_1 \cdot \lambda_2}{|\lambda_1 - \lambda_2|} \]

- e.g. \(\Lambda = 1\, mm\)

Fercher et al., Applied Optics 24(14) (1985)
Dändliker et al., Optics Letters 13(5) (1988)
High-precision “ToF Camera”

\[ E(\lambda_1) = A_1 \cdot e^{i\phi(\lambda_1)} \]

\[ E(\lambda_2) = A_2 \cdot e^{i\phi(\lambda_2)} \]

\[ \phi(\lambda_1) \quad \phi(\lambda_2) \quad \phi(\Lambda) \]

\[ E(\Lambda) = E(\lambda_1) \cdot E^*(\lambda_2) = A_1 A_2 \cdot \exp(i(\phi(\lambda_1) - \phi(\lambda_2))) \]

High-precision “ToF Camera”

Object

Wrapped phase map

Depth map

\( \Lambda = 120 \text{mm} \) \( \Lambda = 6.2 \text{ mm} \) \( \Lambda = 3.2 \text{ mm} \)

Sub-mm depth resolution easily achievable!

Sidenote

Synthetic wavelengths are also useful in absence of scattering!

Optical phase $\rightarrow$ strong wrapping!
\[ \lambda = 854.3 \text{ nm} \]

Synthetic phase $\rightarrow$ no wrapping!
\[ \Lambda = 1.29 \text{ mm} \]

Y. Wu*, F. Li*, F. Willomitzer, A. Veeraraghavan, O. Cossairt, WISHED: Wavefront Imaging Sensor with High resolution and Depth ranging, EEE International Conference on Computational Photography (ICCP), 2020
How to detect the synthetic field $E(\Lambda)$?
(or the two optical fields $E(\lambda_1), E(\lambda_2)$)

- Phase shifting
- Temporal heterodyning
- Spatial heterodyning
- Iterative phase retrieval
- Deep learning
- .......

→ Vast playfield!  → No free lunch!
Better question to ask by an “adopter”:

**What are important modalities for your application?**

- Full field
- Single-shot
- Reference-less
- No prior object knowledge
- COTS CCD/CMOS cameras

* Coming up now…
Susceptibility to motion

\[ |E(\lambda_1)| \quad |E(\lambda_2)| \]

Object must remain static!

\[ \phi(\lambda_1) \quad \phi(\lambda_2) \]

\[ |E(\Lambda)|^{1/2} = |E(\lambda_1) \cdot E^*(\lambda_2)|^{1/2} \]

\[ \phi(\Lambda) = \phi(\lambda_1) - \phi(\lambda_2) \]


‘Single-shot ToF sensing with sub-mm precision using conventional CMOS sensors’, Arxiv Preprint, 2022
Solution: Single-shot acquisition

![Diagram showing the solution for single-shot acquisition](image)

- **Object**
- **Laser 1**
- **Laser 2**
- **Reference beams**
- **CCD/CMOS Camera chip**
- **Image**

**Experimental Setup**

1. **Object beam**
2. **Reference beams**
3. **CCD/CMOS Camera chip**

**References**

- Takeda et al., *JoSA* 72(1), 1982
Solution: Single-shot acquisition

Cam Image $I(x, y)$

FT

Shift & Filter & IFT

Synth. Phase $\phi(\Lambda)$

Mixing $E(\lambda_1) E^*(\lambda_2)$

$|\mathcal{F}[I(x, y)]|$

Takeda et al., JoSA 72(1), 1982

Results
(single-shot)

Object

Small figure

\[ \phi_{\text{wrapped}}(\Lambda = 10\,\text{mm}) \]

\[ \phi_{\text{unwrapped}}(\Lambda = 10\,\text{mm}) \]

3D model

\[ \Lambda = 10\,\text{mm} \]

\[ \delta z \approx 1.8\,\text{mm} \]

\[ \Lambda = 10\,\text{mm} \]
Quantitative analysis of distance precision $\delta z$

<table>
<thead>
<tr>
<th>$\Lambda$ [mm]</th>
<th>40</th>
<th>10</th>
<th>5</th>
<th>3</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta z_{\text{single}}$ [mm]</td>
<td>5.56</td>
<td>1.78</td>
<td>1.64</td>
<td>0.79</td>
<td>0.33</td>
</tr>
</tbody>
</table>

$\Lambda = 50\text{mm}$

$\Lambda = 10\text{mm}$

Results (dual shot)

Object

Clay pot

\[ \Phi_{\text{wrapped}}(\Lambda = 3\text{mm}) \]

\[ \Phi_{\text{unwrapped}}(\Lambda = 3\text{mm}) \]

3D model

\[ \Lambda = 3\text{mm} \]

\[ \delta z \approx 0.8\text{mm} \]
Results

3D model $\Lambda = 10\text{mm}$

Dual-shot vs. Single-shot

Object

Small figure

$65\text{mm} \times 65\text{mm}$
Video acquisition

Object: metronome

3D Video

Object: metronome

10 mm

10 mm

End Part 2
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Time-domain optical coherence tomography

- Broadband light source
- Isolator
- Fiber splitter
- Collimator
- Scene
- Beam steering
- Detector
- Reference arm
Time-domain optical coherence tomography

- Broadband light source
- Fiber splitter
- Isolator
- Collimator
- Beam steering
- Scene
- Detector
- Reference arm

$d - x$
$	au_c$

$x$
$0$
$d - x$
Time-domain optical coherence tomography

- Broadband light source
- Isolator
- Fiber splitter
- Collimator
- Retina
- Detector
- Reference arm scanning
Frequency-domain optical coherence tomography

- Broadband light source
- Fiber splitter
- Isolator
- Collimator
- Beam steering
- Fixed reference arm (no scanning!)
- Retina
- Spectrometer

[UHB Trust]

300 µm [Huang et al., 1991]
Swept-source optical coherence tomography

- Fiber splitter
- Isolator
- Collimator
- Beam steering
- Retina
- Detector
- Fixed reference arm (no scanning!)

- Frequency swept laser (wavelength scanning)

[Huang et al., 1991]
Swept-source optical coherence tomography

[Figure showing a cross-sectional image of the retina with labeled structures: Retina, Vitreous, SRF, RPE, Sclera, BV (Huang et al., 1991)]

2 mm
Full-field OCT

point light, broadband

lens

beam splitter

reference mirror

camera

scene
Full-field TD-OCT

reference mirror

scene = toy cup

point light, broadband

lens

beam splitter

camera

[Gkioulekas et al., 2015]
Micron-scale shape scanning

depth resolution $\sim 5 \, \mu m$

captured image

coin

gnocchi

soap carving

gummy bear

scanned shape

[Gioulekas et al., 2015]
<table>
<thead>
<tr>
<th></th>
<th>full-field OCT</th>
<th>full-field SWI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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# OCT v/s SWI

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<tr>
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<th>full-field OCT</th>
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<tbody>
<tr>
<td>depth range</td>
<td>constrained by reference translation</td>
<td>synthetic wavelength (separation between wavelengths)</td>
</tr>
<tr>
<td>phase wrapping</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td></td>
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<td><strong>full-field SWI</strong></td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------------------------------------------------------</td>
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<td>separation between wavelengths</td>
</tr>
<tr>
<td>scanning</td>
<td>axial proportional to depth range <strong>OR</strong> lateral proportional to scene size</td>
<td>fixed axial scanning possibly single shot!</td>
</tr>
</tbody>
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## OCT v/s SWI

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<tr>
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<td>spectral bandwidth</td>
<td>separation between wavelengths</td>
</tr>
</tbody>
</table>
| scanning            | axial proportional to depth range  
                        OR lateral proportional to scene size | fixed axial scanning  
                        possibly single shot! |
| measurement         | full tomography                                     | surface-only                                        |
Fiber v/s full-field

light source
fiber splitter
detector
reference arm

scene
point light
reference mirror

OCT (multiple)
SWI (two)
camera
Cup: image formation

'direct' + 'retroreflective specular' = scene-only image
Depth corruption due to indirect light
Image formation and light transport

Light source elements

Camera pixels

Light transport matrix

$$I_{cs}$$

$$c$$

$$I_{cs}$$

$$s$$
Image formation and light transport

\[ I = \text{image} \times \text{light transport matrix} \times \text{light source elements} \]
Probing

\[ \text{probed image} = \begin{bmatrix} \text{light transport matrix} \end{bmatrix} \begin{bmatrix} \alpha_{cs} \\ \vdots \end{bmatrix} \]

Adding up
Interferometric probing

area light, broadband

$A(\theta)$

reference mirror

scene

camera

light transport matrix

Toeplitz probing matrix
Direct-indirect separation

scene
direct-only
indirect-only
Seeing through scattering

camera

source

source
Dichromatic area light?

\[ \lambda_1 \quad \lambda_2 \]

green laser

green laser

single frequency lasers

reference mirror

camera
Swept-angle synthetic wavelength interferometry
Swept-angle SWI results: 1 mm depth range

<table>
<thead>
<tr>
<th>scene</th>
<th>input image</th>
<th>ours, swept-angle</th>
<th>no swept-angle scanning</th>
</tr>
</thead>
<tbody>
<tr>
<td>quarter</td>
<td><img src="quarter.png" alt="Image" /></td>
<td><img src="swept-angle-quarter.png" alt="Image" /></td>
<td><img src="no-swept-angle-quarter.png" alt="Image" /></td>
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<tr>
<td>euro</td>
<td><img src="euro.png" alt="Image" /></td>
<td><img src="swept-angle-euro.png" alt="Image" /></td>
<td><img src="no-swept-angle-euro.png" alt="Image" /></td>
</tr>
<tr>
<td>soap</td>
<td><img src="soap.png" alt="Image" /></td>
<td><img src="swept-angle-soap.png" alt="Image" /></td>
<td><img src="no-swept-angle-soap.png" alt="Image" /></td>
</tr>
<tr>
<td>music box</td>
<td><img src="music-box.png" alt="Image" /></td>
<td><img src="swept-angle-music-box.png" alt="Image" /></td>
<td><img src="no-swept-angle-music-box.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Swept-angle SWI results: 1 mm depth range
Swept-angle SWI results: $20 bill eagle
Swept-angle SWI results: 1 cm depth range

corner

pawn

toy cup

scene input image ours, swept-angle no swept-angle scanning
Applications: industrial inspection
Applications: precision fabrication

- photo of scanned object
- image of scanned scene
- ours, swept-angle
- without swept-angle

Sudershan Boovaraghavan / Yuvraj Agrawal
lasers
swept-angle mechanism
camera
ref mirror
scene
Course overview

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Part 4:
Non-Line-of-Sight imaging using Synthetic Wavelengths

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Wyant College of Optical Sciences
University of Arizona, USA

https://www.optics.arizona.edu/3dim
Non-Line-of-Sight Imaging – Potential Applications

- Imaging around Corners
- Imag. through Scattering Media

F. Willomitzer et al., Nature Communications 12, 6647 (2021)
Approaches measuring the Time-of-Flight of light

\[ \delta z \propto \lambda \]

- depth error
- modulation wavelength

Conventional Interferometry (single Wavelength)

- "ToF Cameras" (CW or pulsed)
- Poor resolution

Dual-Wavelength Interferometry

- Speckle for scattering scenes
- \(~ \mu m\) to \(~ 10 cm\)
High-precision “ToF Camera”

\[ E(\Lambda) = E(\lambda_1) \cdot E^*(\lambda_2) = A_1 A_2 \cdot \exp(i(\phi(\lambda_1) - \phi(\lambda_2))) \]

RECAP

**Synthetic Wavelength Holography**

Object

Scatterer (Tissue, Rough Wall, Fog, ...)

CW Tunable Laser Source

Detector

|\( |E(\lambda_1)| \rangle

|\( |E(\lambda_2)| \rangle

\( \phi(\lambda_1) \)

\( \phi(\lambda_2) \)

Numerical Backpropagation at \( \Lambda \)

Reconstruction

**EXPERIMENT**
Experiment: Looking around corners

Rough Wall

Virtual Source

Virtual Detector

SW Hologram

Hidden Object

Latent field

BS

Camera

Reference

Laser

\lambda_1, \lambda_2

15 mm

20 mm
Imaging around corners at multiple SWLs

\[ \Lambda = 1.30 \text{ mm} \quad \Lambda = 0.92 \text{ mm} \quad \Lambda = 0.56 \text{ mm} \quad \Lambda = 0.44 \text{ mm} \]

Phase \( \phi(\Lambda) \)

Reconstruction

Fundamental limit
Where is the limit?

Fundamental limit:

\[ \Lambda \geq 4 \Psi_{\text{max}} \]

Tunable!

How to estimate the performance of our system?

Space-Bandwidth Product (SBP):

\[ \text{SBP} = \frac{W}{\delta x} \leq \frac{D_{VD}}{2 \Psi_{\text{max}}} \]

Field of view width
Smallest laterally resolvable distance
System constants

* Related calculations given in:
Experiment: Imaging through Scattering Media
Imaging through scatterers - Results

\[ \Lambda \approx 4 \Psi_{\text{max}} \]

\[ \Lambda = 1.30 \text{ mm} \]
\[ \Lambda = 0.80 \text{ mm} \]
\[ \Lambda = 0.36 \text{ mm} \]
\[ \Lambda = 0.28 \text{ mm} \]

Sub-mm resolution!
**Synthetic Pulse Holography/Interferometry**

**Computational coherent superposition of multiple synthetic holograms → “synthetic pulse”**

\[ N_\Delta = 1 \]

\[ N_\Delta = 2.3 \]

Hidden Object

\[ \Delta z \approx 33 \text{mm} \]

\[ z = 0 \text{mm} \]
\[ z = 33 \text{mm} \]

\[ 10 \text{ mm} \]

**→ Similarity to OCT, WLI, light-in-flight imaging, transient imaging**


Transient imaging using interferometry at 1000x larger temporal resolution.
Transient imaging

Transient imaging using interferometry at 1000x larger temporal resolution

[Velten et al. 2013]
Gummy bear and diffuse corner

[Images from Gkioulekas et al., 2015]
Chess knight and mirror

mirror

diffuser

resolution
$10^{-15}$ s

surface reflection

mirror-object

object-mirror

mirror-object-mirror

[Images from Gkioulekas et al., 2015]
Subsurface scattering

- Surface reflection scattering
- Paths transmitted through ground glass
- Diffuse-diffuse reflections

[Gkioulekas et al., 2015]

Resolution: $10^{-15}$ s
Dispersion

- mirror
- diffuser
- plastic bead

resolution $10^{-15}$ s

- facets changing color
- surface reflections
- surface-wall reflections
- rainbow

[Images from Gkioulekas et al., 2015]
Non-line-of-sight (NLOS) imaging

visible wall

scan point

source & sensor

occluder

NLOS object

what a regular camera sees
Non-line-of-sight (NLOS) imaging

visible wall
scan point
source & sensor
occluder
NLOS object
what a regular camera sees
Picosecond-scale setup

ultra-sensitive lidar capturing later returns
(single-photon avalanche diode)
Lidar scanning procedure

\[ \mathcal{F} = \tau_{\text{NLOS}} \]

\[ \tau_{\text{LOS}} \]

\[ \tau_{\text{NLOS}} \]

LOS Reconstruction

NLOS Reconstruction
Non-line-of-sight (NLOS) imaging

- Room-scale scanning (2 m x 2m)
- Object-scale scanning (0.5 m x 0.5 m)

Can we do this at micron scales?
Femtosecond-scale setup

interferometric time-of-flight setup
Micron-scale NLOS imaging

ground truth (LOS scan)  NLOS reconstruction

interferometric setup
resolution: 10 μm (33 fs)

[Images from Xin et al., 2019]
Micron-scale NLOS imaging

500 μm

NLOS

LOS

horizontal location

ground truth (LOS scan) NLOS reconstruction

interferometric setup resolution: 10 μm (33 fs)

[Images from Xin et al., 2019]
Deploying interferometric systems is hard.

- Dark room
- Specialized light sources
- Very slow operation (hours per scan)
- Cannot work in ambient light
- Very sensitive to global illumination
- Very sensitive to aberrations

Typical interferometry setup:
- Vibration isolation

Sunlight interferometry:
- Natural light
- No active isolation
- Bright outdoors
Passive interferometry with sunlight
Sunlight interferometry

- Sun tracker
- Reference mirror
- Splitter
- Camera
- Scene
- Input images
- Scene transient
- Depth map
Optical setup

- tracking mirror on rotation stages
- imaging camera
- scene
- ref mirror
- tracking camera
Where we ran our experiments
Passive 3D sensing: Raspberry Pi
Passive transient imaging: metallic coin

Images from Kotwal et al., 2023
Passive transient imaging: diffuse pill

[Images from Kotwal et al., 2023]
Passive transient imaging: scattering chocolate

scene  transient response  depth

[Images from Kotwal et al., 2023]
Passive NLOS imaging

direct imaging

[Images from Kotwal et al., 2023]
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A coherent world...
Speckle rendering

what real laser images look like

what standard Monte Carlo renderings look like

A Monte Carlo Framework for Rendering Speckle Statistics in Scattering Media

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Fig. 1. Simulation of memory effect in scattering. Coherent images of translucent materials typically involve highly-fluctuating speckle structure. Despite their semi-random structure, speckles have strong statistical properties. For example, the memory effect property states that, as one tilts the illumination direction (setup at left), the resulting speckles shift. This property is at the core of multiple computational imaging applications. The memory effect is valid over a limited angular range that depends on material properties. Due to the absence of analytical formulas, it is generally necessary to measure this angular range for materials of interest empirically in the lab. We present a Monte Carlo rendering approach for simulating physically-accurate speckle images, as well as their statistics, as a function of material parameters. The figure shows speckle images rendered by our algorithm for a few illumination directions, as well as their auto-correlation (black insets), demonstrating the speckle shift property. As the angle difference increases, the correlation decays, and the decay rate is different for different material parameters—in this case, materials with Henyey-Greenstein (HG) phase functions of different parameters $g$. For the isotropic scattering case, $g = 0$, the pattern similarity is lost at the third column, whereas for the forward scattering case, $g = 0.5$, correlation is preserved. We verify the accuracy of our algorithm against an exact yet computationally heavy, wave solver, as well as against analytical formulas derived under limiting assumptions.
Other coherent effects

https://en.wikipedia.org/wiki/Thin-film_interference

thin film interference

≈ 1 µm

diffraction

Some work in this area

A Generic Framework for Physical Light Transport

SHLOMI STEINBERG, University of California, Santa Barbara, USA
LING-QI YAN, University of California, Santa Barbara, USA

Reflectance Model for Diffraction

TOM CUYPERS, TOM HABER and PHILIPPE BEKAERT
Hasselt University

SE BAEK OH and RAMESH RASKAR
MIT

We present a novel method of simulating wave effects in graphics using ray-based renderers with a new function: the Wave BSDF (Bidirectional Scattering Distribution Function). Reflections from neighboring surface patches represented by local BSDFs are mutually independent. However, as many surfaces with wavelength-scale microstructures, interference and diffraction requires a joint analysis of reflected wavefronts from neighboring patches. We demonstrate a simple method to compute the BSDF for the entire microstructure, which can be used independently for each patch. This allows us to use traditional ray-based rendering pipelines to synthesize wave effects. We exploit the Wigner Distribution Function (WDF) to create transmissive, reflective, and emissive BSDFs for various diffraction phenomena in a physically accurate way. In contrast to previous methods for computing interference, we circumvent the need to explicitly keep track of the phase of the wave by using BSDFs that include positive as well as negative coefficients. We describe and compare the theory in relation to well-understood concepts in rendering and demonstrate a straightforward implementation. In conjunction with standard raytracers, such as PRK, we demonstrate wave effects for a range of scenarios such as multibounce diffraction materials, holograms, and reflection of high-frequency surfaces.

Fig. 1. We generalize the rendering equation and the BSDF to simulate wave phenomena. The new Wave BSDF behaves like a local scattering function, creates interference globally, and allows easy integration into traditional ray-based methods.

Categories and Subject Descriptors: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling

General Terms: Algorithms, Theory
We still can’t render an interferometer (for general scenes)

But it would be awesome if we could!

Physics-based rendering and its applications in computational photography and imaging

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