Dealing with global illumination
Course announcements

• Homework assignment 6 has been posted.
  - Due on Sunday, December 5\textsuperscript{th}.
  - You can use all your remaining late days.

• Final project presentation logistics posted on Piazza.

• Optional extra lecture on Friday 11:40 am – 1:00 pm, at GHC 4303.
Final project competition judges

Matthew O’Toole

Jun-Yan Zhu

• Final project does not need to be fully done by presentation date.
• But judges will only see presentations, not final reports.
Overview of today’s lecture

• Direct and global illumination.

• Direct-global separation using high-frequency illumination.

• Back to structured light.
Slide credits

These slides were directly adapted from:

- Shree Nayar (Columbia).
- Matthew O’Toole (CMU).
- Supreeth Achar (Google, formerly CMU).
- Mohit Gupta (Wisconsin).
Direct and global illumination
Direct and Global Illumination

A : Direct
B : Interreflection
C : Subsurface
D : Volumetric
Easy to separate in a renderer

full image = direct + global
Direct-global separation using high-frequency illumination
Direct and Global Components: Interreflections

\[ L[c,i] = L_d[c,i] + L_g[c,i] \]

\[ L_g[c,i] = \sum_P A[i,j] L[i,j] \]

- Radiance
- Direct
- Global
- BRDF and geometry
High Frequency Illumination Pattern

\[ L^+(c,i) = L_a[c,i] + \alpha L_g[c,i] \]

fraction of activated source elements
High Frequency Illumination Pattern

\[ L^+[c,i] = L_d[c,i] + \alpha L_g[c,i] \]

\[ L^-[c,i] = (1 - \alpha) L_g[c,i] \]

fraction of activated source elements
Important insight:

- Global illumination is approximately invariant to high-frequency lighting.
- You can think of global illumination effects as a low-pass filter.
High Frequency Illumination Pattern

What does approximate invariance mean in this case?

\[ L^+[c,i] = L_d[c,i] + \alpha L_g[c,i] \]

\[ L^-[c,i] = (1 - \alpha) L_g[c,i] \]
Separation from Two Images

\[ \alpha = \frac{1}{2} : \]

\[ L_d = L_{\text{max}} - L_{\text{min}}, \quad L_g = 2L_{\text{min}} \]

- direct
- global
Other Global Effects: Subsurface Scattering
Other Global Effects: Volumetric Scattering

participating medium

source

camera
V-Grooves: Diffuse Interreflections

Psychophysics:
Gilchrist 79, Bloj et al. 04

Direct

Global
Real World Examples:

Can You Guess the Images?
Eggs: Diffuse Interreflections

Direct

Global
Wooden Blocks: Specular Interreflections

Direct

Global
Photometric Stereo using Direct Images

Source 1 
Source 2 
Source 3

Bowl

Global

Direct

Shape
Variants of Separation Method

- Coded Structured Light
- Shifted Sinusoids
- Shadow of Line Occluder
- Shadow of Mesh Occluders
Building Corner

\[ L_d = L_{\text{max}} - L_{\text{min}} , \quad L_g = L_{\text{min}} \]

direct \hspace{1cm} \text{global}
Building Corner
Shower Curtain: Diffuser

\[ L_d = L_{\text{max}} - \beta L_{\text{min}}, \quad L_g = \beta L_{\text{min}} \]
Shower Curtain: Diffuser

Direct

Global
Kitchen Sink: Volumetric Scattering

Volumetric Scattering:
Chandrasekar 50, Ishimaru 78

Direct

Global
Peppers: Subsurface Scattering

Direct

Global
Tea Rose Leaf

Leaf Anatomy: Purves et al. 03
Translucent Rubber Balls

Direct

Global
Hand

Skin: Hanrahan and Krueger 93, Uchida 96, Haro 01, Jensen et al. 01, Igarashi et al. 05, Weyrich et al. 05
Hands

Afric. Amer. Female

Chinese Male

Spanish Male

Afric. Amer. Female

Chinese Male

Spanish Male

Direct

Global
Face

Direct

Global

Sum
Blonde Hair

Hair Scattering: Stamm et al. 77, Bustard and Smith 91, Lu et al. 00 Marschner et al. 03
Pebbles: 3D Texture

Direct

Global
Pink Carnation

Spectral Bleeding: Funt et al. 91
Mirror Ball: Failure Case

Direct

Global
Application to structured light
Why is global illumination a problem?
Bowl on a Marble Slab
Captured images under conventional Gray codes
Issues due to global illumination effects

- Strong Inter-reflections
- Low-frequency pattern

- Blurring due to Sub-surface Scattering
- High-frequency pattern
3D Visualizations: State of the Art

Errors due to interreflections

Conventional Gray
(11 images)

Errors due to sub-surface scattering

Modulated Phase-Shifting
(162 images)
V-Groove Scene

Inter-reflections
Conventional Gray codes

Low frequency pattern

Inverse Pattern

Pattern Edge

Captured Image

Captured Image

\( I = 0.16 \)

\( \bar{I} = 0.25 \)
Binarization error

Errors due to inter-reflections

Incorrect Binarization

Ground-truth Binarization

One (illuminated)  Zero (not-illuminated)
Low-frequency patterns

\[ I = \text{Direct} + \alpha \cdot \text{Global} \]

\[ \bar{I} = (1 - \alpha) \cdot \text{Global} \]

\[ \alpha \approx 0, \quad \text{Direct} < \text{Global} \quad \Rightarrow \quad I < \bar{I} \]
High-frequency patterns

$I = \text{Direct} + 0.5 \text{ Global} \quad > \quad \bar{I} = 0.5 \text{ Global}$
High-frequency Patterns are Decoded Correctly

Captured Image

Binary Decoding
Logical Coding and Decoding
Logical Coding and Decoding

Incorrect Binarization

Correct Binarization

XOR

Binarization

Binarization

=
Depth Map Comparison

Errors due to Inter-reflections

Conventional Gray Codes (11 images)  Our XOR-04 Codes (11 images)

Depth (mm)

Pixels

Ground Truth  Gray Codes  Our XOR-04 Codes
Making the Logical XOR Codes

Conventional Gray Codes (10 patterns)

XOR of Last Pattern with Patterns 1-9 → XOR-02 Codes (10 patterns)

XOR of Second-last Pattern with Patterns 1-8 → XOR-04 Codes (10 patterns)
Ensemble of Codes for General Scenes

- Conventional Gray (10 images)
- Max min-SW Gray (10 images)
- XOR-04 (10 images)
- XOR-02 (10 images)
Reconstructing General Scenes
Ensemble of Codes for General Scenes

Conventional Gray (10 images)
Max min-SW Gray (10 images)
XOR-04 (10 images)
XOR-02 (10 images)

Return the consistent value
Shape Comparison

Conventional Gray (11 images)
Modulated Phase-Shifting (162 images)
Our Technique (41 images)
Translucent Wax Candle

Scene

Modulated Phase-Shifting (162 images)

Our Ensemble Codes (41 images)

Errors due to strong sub-surface scattering
Translucent Wax Object

Scene

Errors due to strong sub-surface scattering

Modulated Phase-Shifting (162 images)

Our Ensemble Codes (41 images)
Ikea Lamp

Diffusion + Inter-reflections
3D Visualization using our ensemble codes
Goal is to reconstruct the shape of the shower-curtain. Shape of the curtain is planar because it was taped to the rod to avoid movement while capture.
Shape Comparisons

Regular Gray Codes  (11 images)

Phase-Shifting (18 images)

Our XOR Codes (11 images)
Fruit Basket: Multiple Effects

Sub-surface Scattering

Inter-reflections
Depth-maps with previous state of the art

Regular Gray (11 images)  
Phase-Shifting (18 images)
Depth-maps with previous state of the art

Regular Gray (11 images)  Modulated Phase-Shifting (162 images)
Depth-maps with our Ensemble Codes

Our Ensemble Codes (41 images)
3D Visualizations with our ensemble codes
3D Visualization with our ensemble codes
Bowls and Milk: Multiple Effects

Subsurface Scattering

Interreflections
Phase-Shifting (18 images)

Modulated Phase-Shifting (162 images)

Regular Gray Codes (11 images)

Our XOR Codes (11 images)
3D Visualizations with our ensemble codes
Flower-Vase

Diffusion

Sub-surface Scattering
Comparison

Phase-Shifting (18 images)

Regular Gray Code (11 images)

Modulated Phase-Shifting (162 images)

Our Ensemble Codes (41 images)
Comparison

Phase-Shifting (18 images)

Regular Gray Code (11 images)

Modulated Phase-Shifting (162 images)

Our Ensemble Codes (41 images)
Multiple Global Illumination Effects

Wax Bowl

Shape Using Ensemble Codes
Multiple Global Illumination Effects

Deep Wax Container

Shape Using Ensemble Codes
Lamp made of shiny brushed metal

Strong and high-frequency inter-reflections
Depth Map Comparison

Regular Gray  (11 images)

Our Ensemble Codes  (41 images)
Application to time-of-flight imaging
Interreflections and ToF Imaging

![Diagram showing a scene with a source, sensor, direct radiance, and interreflections over time](image)

- scene
- source
- sensor
- direct radiance
- interreflections
- sensor radiance
- time
Interreflections and ToF Imaging

Interreflections Produce Incorrect Phase
Errors in Shape Recovery

- Computed shape error = 1.0 meters
- Ground truth error = 0.6 meters

Camera view
Multipath Interference: Existing Work

How To Separate Different Components?
Interreflections vs. Modulation Frequency

For High Temporal Frequency
Interreflections Do Not Affect Phase

 emitted signal (frequency $\omega$)
different path lengths
direct

sensor
source
scene
time

sensor
radiance

total radiance
direct radiance
interreflection
Phase Ambiguity

Unambiguous Depth Range: \[ R_{\text{unambiguous}} = \frac{1}{2\omega} \]
Disambiguating Phase

Compute Phases at Two High Frequencies

[Jongenelen et al. 2010, 2011]
Micro Time-of-Flight Imaging

Modulation Signals With Micro (Small) Periods
Conventional vs. Micro ToF Imaging

Conventional ToF Shifting: One Low Frequency
Three Measurements

Micro ToF Shifting: Two High Frequencies
Four Measurements
Cornell Box: Input Images

957 MHz.

930 MHz.
Cornell Box: Phase Maps

Ambiguities

957 MHz.

930 MHz.

\[ 0 \leq 2\pi \]
Cornell Box: Shape Comparison

- Conventional ToF imaging (10 MHz.): error = 1.0 meters
- Micro ToF imaging: error = 0.6 meters
- Ground truth: 3 meters
Scattering in Real World

Driving through fog/mist

Driving through a dust storm

Images from: drivinglessonsedinburgh.blogspot.com, ngm.nationalgeographic.com
Scattering and ToF Imaging

Scattering Produces Incorrect Phase

Scattering medium
**Sphere: Shape Comparison**

- Micro ToF Achieves High Accuracy
- Depths Underestimated

**Comparison: Micro ToF vs. Conventional ToF**
- Micro ToF Error: 0.4 meters
- Conventional ToF Error: 1.2 meters

Diagram shows 2 meters distance with ground truth andMicro ToF curves compared.
Direct-Indirect Separation

Direct-Global Separation Using Three Measurements

\[ D = 2A \quad G = O - A \]
Direct-Global Separation

Color Bleeding due to Interreflections

Direct Component
Global Component (x2)

Direct Component
Global Component (x2)
Experimental Setup

light source
(bank of laser diodes)

sensor
(PMD CamBoard Nano)

Maximum System Modulation Frequency = 125 MHz.
Experiments: V-Groove

movable wall

interreflections

θ

fixed wall

2.0 meters

2.0 meters

5.0 meters

sensor
Scene Images Captured By PMD Sensor

- Apex angle = 45°
- Apex angle = 60°
- Apex angle = 90°

Image resolution = 120 x 165
Reconstructed Shape using Micro ToF

concave edge
Shape Comparisons

conventional ToF
mean error = 86.6 mm

Micro ToF [proposed]
mean error = 2.8 mm

ground truth
Reconstructed Shapes: Different Angles

\[ \theta = 60^\circ \]

concave edge

\[ \theta = 90^\circ \]

concave edge
Shape Comparisons

conventional ToF
mean error = 69.8 mm

Micro ToF
mean error = 6.7 mm

conventional ToF
mean error = 56.9 mm

Micro ToF
mean error = 6.2 mm
Recovered Shape vs. Frequency

\[ \omega = 1 \text{ MHz.} \]
Direct-Global Separation Vs. Apex Angle

Direct

Global

apex angle = 45°
apex angle = 90°

decreasing global component
How High Should The Frequency Be?

Material Property (Increasing Smoothness)

Geometric Scale (Decreasing Scene Size)

MegaHz.

Increasing Frequency

GigaHz.

TeraHz.

10^3 m  10^1 m  10^{-1} m  10^{-3} m
Technology (Devices) Required

Material Property
(Increasing Smoothness)

Available
Off-the-Shelf

Geometric Scale (Decreasing Scene Size)

PMD Camboard Nano
Technology (Devices) Required

Material Property (Increasing Smoothness)

Geometric Scale (Decreasing Scene Size)

Available Off-the-Shelf

Sensors/Sources in Research Labs

GHz. LED
Chen et. al.
1999

GHz. MSM Sensor
Buxbaum et. al.
2002
Technology (Devices) Required

Material Property (Increasing Smoothness)

<table>
<thead>
<tr>
<th>Scale</th>
<th>Available Off-the-Shelf</th>
<th>Sensors/Sources in Research Labs</th>
<th>Future Sensors/Sources?</th>
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References

Basic reading:
  The paper on separation of direct and global illumination using high-frequency illumination.
  The paper on using XOR codes to deal with global illumination in structured light 3D.
  The paper on using high-frequency modulation to deal with interreflections and MPI in CW-ToF imaging.

Additional reading:
  This early paper shows a way to exactly decompose light transport by number of bounces, under certain assumptions for the imaged scene.
  These two papers have additional analysis about the relationship between direct and global illumination and illumination frequency.
  This paper more formally discusses the notion of light transport frequency, and the frequency characteristics of different light transport effects (specular versus diffuse reflections, hard versus smooth shadows).