Non-line-of-sight imaging
Course announcements

• Homework 6 will be posted tonight.
  - Will be due Sunday 10th.
  - Almost no coding, only data capture and using existing code.
  - You will need high-sensitivity cameras, so use the DSLRs you have picked up.

• Final project report deadline moved to December 15\textsuperscript{th}.
  - Originally was December 11\textsuperscript{th}. 
Overview of today’s lecture

- The non-line-of-sight (NLOS) imaging problem.
- Active NLOS imaging using time-of-flight imaging.
- Active NLOS imaging using WiFi.
- Passive NLOS imaging using accidental pinholes.
- Passive NLOS imaging using accidental reflectors.
- Passive NLOS imaging using corners.
Many of these slides were directly adapted from:

- Shree Nayar (Columbia).
- Fadel Adib (MIT).
- Katie Bouman (MIT).
The non-line-of-sight (NLOS) imaging problem
Time-of-flight (ToF) imaging
Looking around the corner

Can you look around the corner?

Without any gadget in the line of sight
Looking around the corner
Active NLOS imaging using time-of-flight imaging
Processing a single-pixel transient

light source

single-pixel transient camera

VD VS

intensity

time

VS

time

camera

single-pixel

light source
Processing a single-pixel transient

A light source emits a transient pulse, which is captured by a single-pixel transient camera. The intensity of the pulse is measured over time. The time constant $t_1 = 10$ ps.
Processing a single-pixel transient

Where in the world can we find points creating this pathlength?

\[ I_{\text{nlos}} = t_1 \cdot c - I_{\text{in}} - I_{\text{out}} \]
Processing a single-pixel transient

Ellipse with foci on the virtual source and detector and pathlength $l_{\text{nlos}}$

$$l_{\text{nlos}} = t_1 \cdot c - l_{\text{in}} - l_{\text{out}}$$

Intensity graph with $t_1 = 10$ ps
Processing a single-pixel transient

Ellipse with foci on the virtual source and detector and pathlength $l_{\text{nlos}}$

$$l_{\text{nlos}} = t_2 \cdot c - l_{\text{in}} - l_{\text{out}}$$

$t_2 = 20$ ps

Pathlength $l_{\text{nlos}}$
Processing another single-pixel transient

• What assumption are we making here?
• Is there any other information we are not using?
Processing another single-pixel transient

- What assumption are we making here?
- Is there any other information we are not using?

Photons only interact with the NLOS scene once (3-bounce paths)

\[ t_2 = 20 \text{ ps} \]
Processing another single-pixel transient

Photons only interact with the NLOS scene once (3-bounce paths)

- What assumption are we making here?
- Is there any other information we are not using?

\[ t_2 = 20 \text{ ps} \]

We need to also account for intensity
Elliptic backprojection
Elliptic backprojection
Elliptic backprojection
Reconstructing Hidden Rooms

Visible wall
Invisible walls
Reconstructing Hidden Rooms: One plane at a time

Visible wall
Invisible walls
Reconstructing Hidden Rooms: One plane at a time

Visible wall
Invisible walls
Reconstructing Hidden Rooms: One plane at a time
Reconstructing Hidden Rooms: One plane at a time

Visible wall
Invisible walls
Reconstructing Hidden Rooms: One plane at a time

Visible wall
Invisible walls
Reconstructing Hidden Rooms: One plane at a time

Visible wall
Invisible walls
Reconstructing Rectangular Rooms

- Average AICP error for all the walls is TBD mm (TBD %). – Normalized with average room length of 1.1m
Reconstructing Complex Shape and Reflectance

what depth our camera sees

what a regular camera sees

what shape our camera sees

what a regular camera sees

what depth our camera sees
Active NLOS imaging using WiFi
Imaging through occlusions
Imaging through occlusions using radio frequencies
Key Idea
Wall reflection is 10,000x stronger than reflections coming from behind the wall

Tracking people from their reflections
Wi-Vi: Small, Low-Power, Wi-Fi

• Eliminate the wall’s reflection
• Track people from reflections
• Gesture-based interface
• Implemented on software radios
How Can We Eliminate the Wall’s Reflection?
Idea: transmit two waves that cancel each other when they reflect off static objects but not moving objects.

- Wall is static → disappears
- People tend to move → detectable
Eliminating the Wall’s Reflection

Receive Antenna: $\alpha x$

Transmit Antennas
Eliminating the Wall’s Reflection

Receive Antenna: \( y = h_1 x + h_2 \alpha x \)

\[ \alpha = -\frac{h_1}{h_2} \]
Eliminating All Static Reflections
Eliminating All Static Reflections

Static objects (wall, furniture, etc.) have constant channels

\[ y = h_1 x + h_2 \alpha x \]

People move, therefore their channels change

\[ y = h_1' x + h_2' \left( -\frac{h_1}{h_2} \right) x \]

Not Zero
How Can We Track Using Reflections?
At any point in time, we have a single measurement.
Tracking Motion

Direction of motion

Antenna Array
Tracking Motion

Direction of motion

Human motion emulates antenna array
A Through-Wall Gesture Interface

- Sending Commands with Gestures

- Two simple gestures to represent bit ‘0’ and bit ‘1’

- Can combine sequence of gestures to convey longer message
Gesture Encoding

Bit ‘0’: step forward followed by step backward
Bit ‘1’: step backward followed by step forward
Gesture Decoding

Matched Filter

Peak Detector

Gesture interface that works through walls and none-line-of-sight
Imaging through occlusions using radio frequencies

Our output

Camera image
**Traditional Imaging**

- Cannot image through occlusions like walls
- Form 2D images using lenses

**RF Imaging**

- Walls are transparent and can image through them
- No lenses at these frequencies
Imaging with RF

No lens at these frequencies

Antenna cannot distinguish bounces from different directions
Imaging with RF

Beamforming: Use multiple antennas to scan reflections within a specific beam.

Extend to 3D with time-of-flight measurements by repeating this at every depth.
Coarse-to-fine Scan

- Larger aperture (more antennas) means finer resolution
Coarse-to-fine Scan

Reflectors

Used antennas
Coarse-to-fine Scan

Scanned region

Used antennas
Coarse-to-fine Scan

Scanned regions

Used antennas
Traditional Imaging

- Cannot image through occlusions like walls
- Form 2D images using lenses
- Get a reflection from all points: can image all the body

RF Imaging

- Walls are transparent and can image through them
- No lenses at these frequencies
- No reflections from most points: all reflections are specular
Challenge: Don’t get reflections from most points in RF

Output of 3D RF Scan

Blobs of reflection power
Challenge: Don’t get reflections from most points in RF

At frequencies that traverse walls, human body parts are specular (pure mirror)
Challenge: Don’t get reflections from most points in RF

At frequencies that traverse walls, human body parts are specular (pure mirror)

At every point in time, get reflections from only a subset of body parts
Solution Idea: Exploit Human Motion and Aggregate over Time
Solution Idea: Exploit Human Motion and Aggregate over Time
Human Walks toward Sensor

Chest (Largest Convex Reflector)

Use it as a pivot: for motion compensation and segmentation
Human Walks toward Sensor

Combine the various snapshots
Human Walks toward Sensor
Implementation

• Hardware
  – 2D Antenna Array
  – Built RF circuit
    • 1/1,000 power of WiFi
    • USB connection to PC

• Software
  – Coarse-to-fine algorithm implemented in GPU to generate reflection snapshots in real-time
Evaluation

- RF-Capture sensor placed behind the wall
- 15 participants
- Use Kinect as baseline when needed
Sample Captured Figures through Walls
Sample Captured Figures through Walls
Tracking result
Writing in the air

Device

Our Tracking Result

Median Accuracy is 2cm

Kinect (in red)
Passive NLOS imaging using accidental pinholes
What does this image say about the world outside?
Accidental pinhole camera
Accidental pinhole camera

window is an aperture

projected pattern on the wall

upside down

view outside window

window with smaller gap
Accidental pinspeck camera
Passive NLOS imaging using accidental reflectors
Ophthalmology
• Anatomy, physiology

Computer Vision
• Iris recognition

HCI
• Gaze as an interface

Computer Graphics
• Vision-realistic Rendering
Corneal Imaging System
Geometric Model of the Cornea

Iris
Pupil
Sclera
Cornea

\[ t_b = 2.18 \text{mm} \quad r_L = 5.5 \text{mm} \]

eccentricity = 0.5

\[ R = 7.6 \text{mm} \]
Self-calibration:
3D Coordinates, 3D Orientation
Viewpoint Loci

camera pupil

cornea
Viewpoint Loci

camera pupil

cornea

X

Z
Viewpoint Loci

camera pupil

cornea

27°

45°
Resolution and Field of View

gaze direction

cornea
Resolution and Field of View

gaze direction

resolution

cornea

FOV

Z

X
Resolution and Field of View

cornea
res

gaze direction

X

FOV

27°

person’s FOV

45°

resolution

Z
Environment Map from an Eye
What Exactly You are Looking At

Eye Image:

Computed Retinal Image:
Watching a Bus
From Two Eyes in an Image ...

Reconstructed Structure (frontal and side view)
Eyes Reveal ...

- Where the person is
- What the person is looking at
- The structure of objects
Implications

Human Affect Studies: Social Networks

Security: Human Localization

Advanced Interfaces: Robots, Computers

Computer Graphics: Relighting [SIGGRAPH 04]
Dynamic Illumination in a Video
Point Source Direction from the Eye
Inserting a Virtual Object
Sampling Appearance using Eyes
Sampling Appearance using Eyes
Computed Point Source Trajectory

intensity
Fitting a Reflectance Model

albedo map

normal map
3D Model Reconstruction

albedo map

3D model
Relighting under Novel Illumination
VisualEyes™
http://www.cs.columbia.edu/CAVE/

with Akira Yanagawa
Passive NLOS imaging using corners
What You Would See
A person makes a 0.1% difference in the reflected light at the base of a corner.
References

Basic reading:
  the two papers showing how ToF imaging can be used for looking around the corner.
• Abib et al., “Capturing the Human Figure Through a Wall,” SIGGRAPH Asia 2015.
  the two papers showing that WiFi can be used to see through walls.
• Torralba and Freeman, “Accidental Pinhole and Pinspeck Cameras,” CVPR 2012.
  the paper discussing passive NLOS imaging using accidental pinholes.
  the paper discussing passive NLOS imaging using accidental reflectors.
  the paper discussing passive NLOS imaging using corners.

Additional reading:
  the paper on NLOS room reconstruction using ToF imaging.
  a follow-up paper to the paper on corneal imaging, show how similar ideas can be used for relighting and other image-based rendering tasks.