mit media lab

Visual Machines

Thermal Non-Line-of-Sight Imaging

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MIT Media Lab[1], Visual Machines Group, UCLA[2]

ICCP2019

International Conference on Computational Photography

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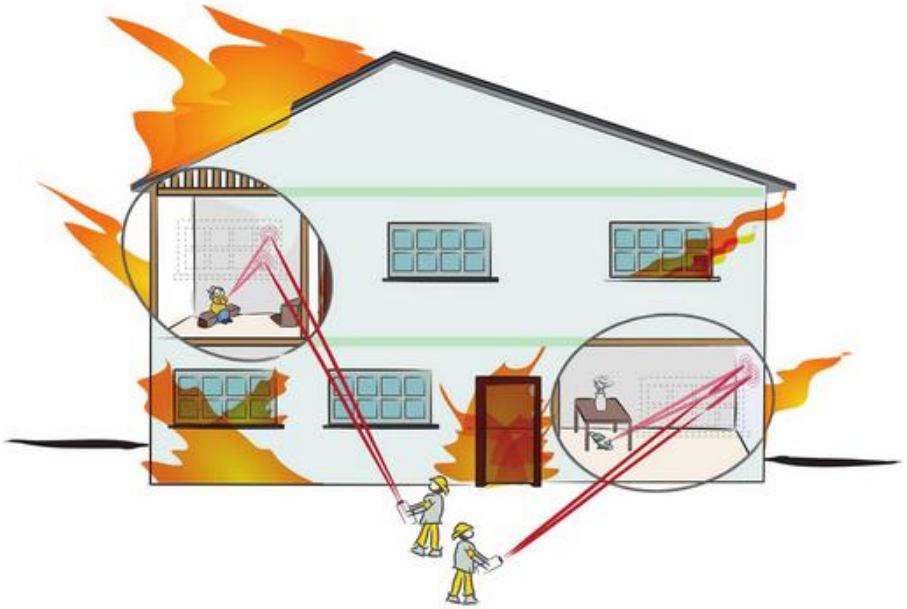
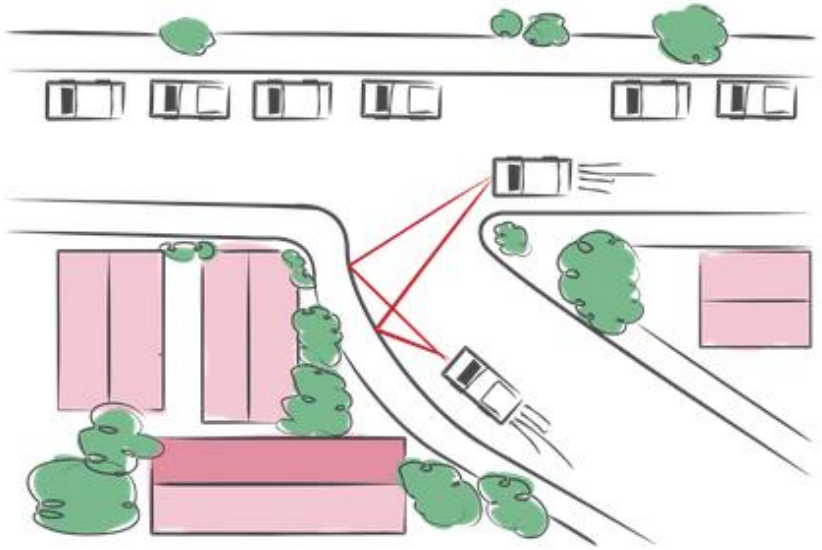
Non-Line-of-Sight Imaging

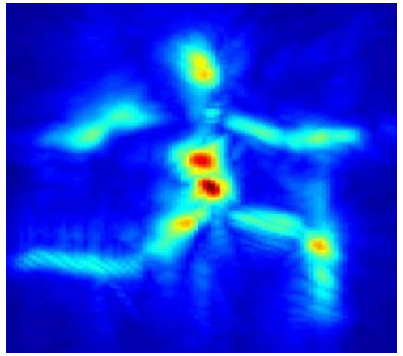




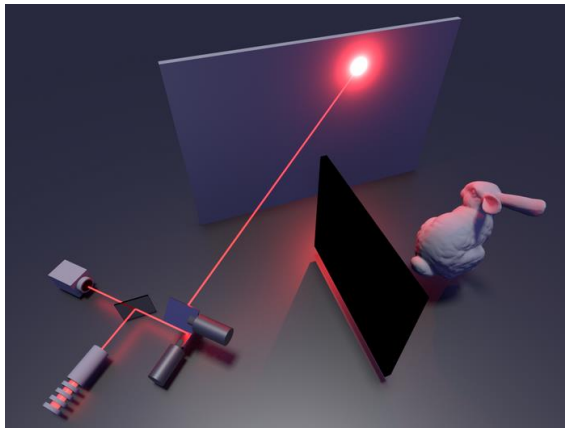
http://web.media.mit.edu/~raskar/cornar/

Related Works

Time-of-flight

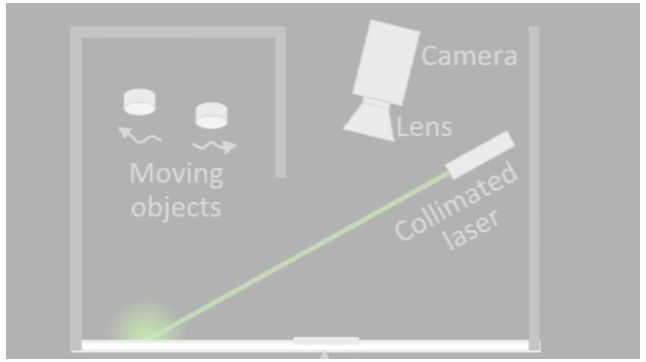


Velten et al. 2012

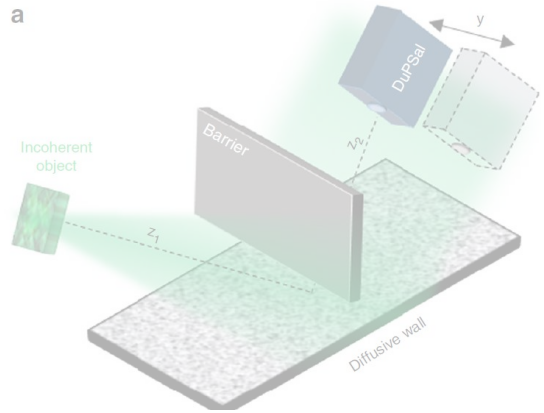


O'Toole et al. 2018

Coherence

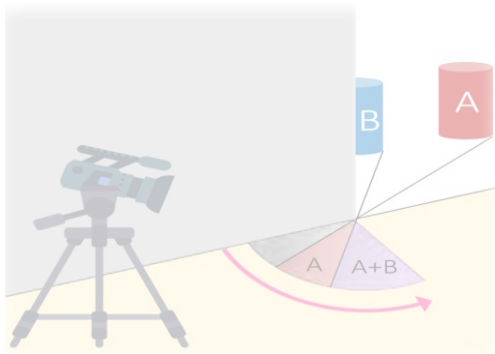


Smith et al. 2018

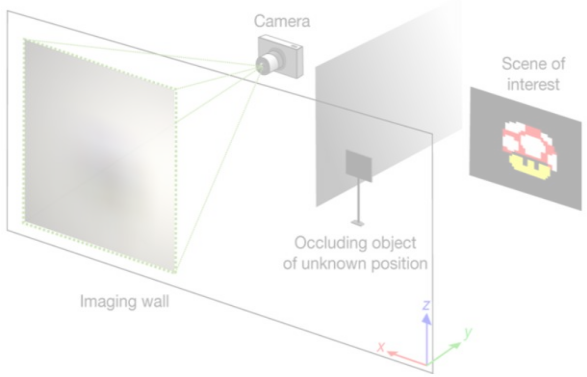


Batarseh et al. 2018

Intensity



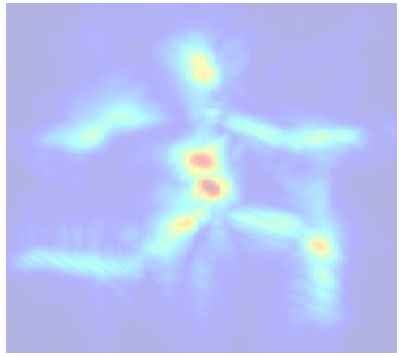
Bouman et al. 2017



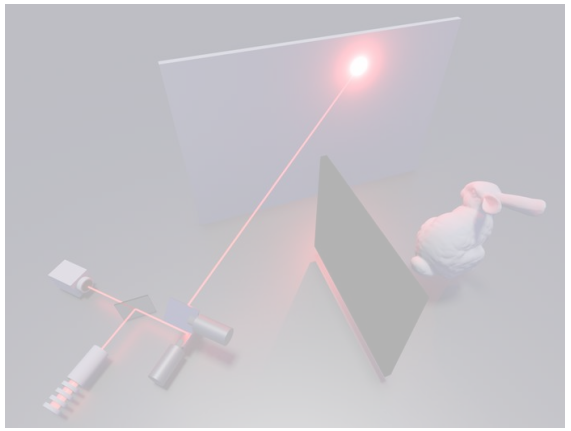
Saunder et al. 2019

Related Works

Time-of-flight

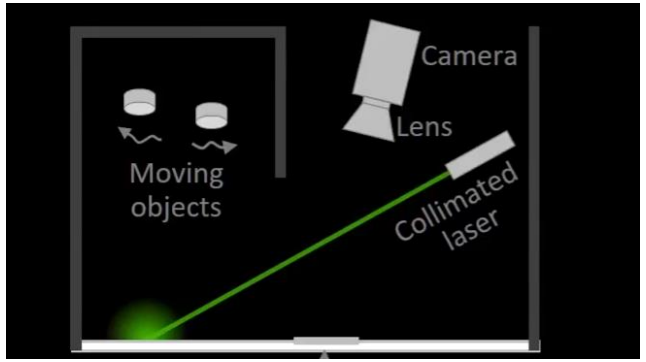


Velten et al. 2012

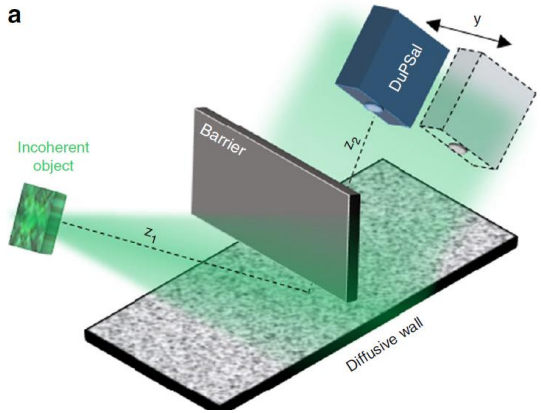


O'Toole et al. 2018

Coherence

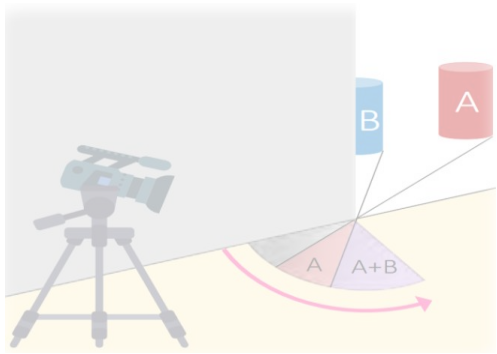


Smith et al. 2018

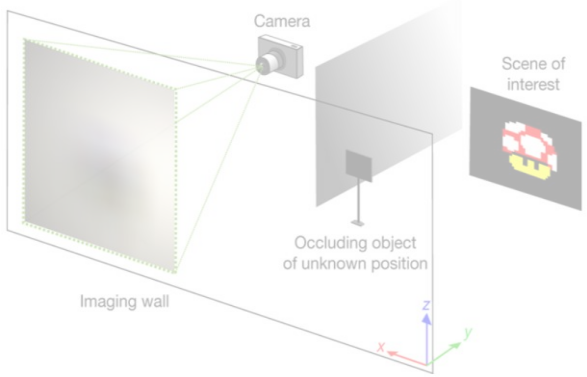


Batarseh et al. 2018

Intensity



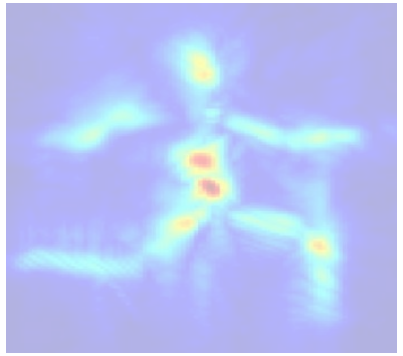
Bouman et al. 2017



Saunder et al. 2019

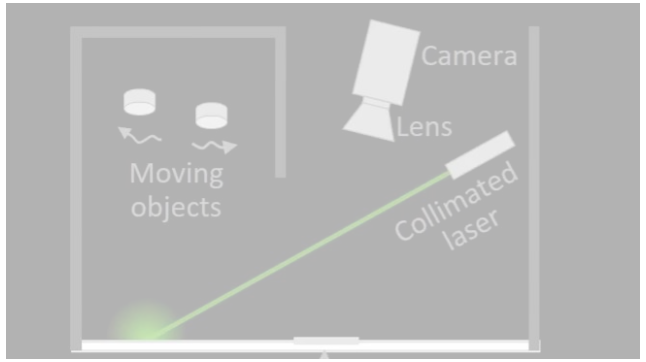
Related Works

Time-of-flight



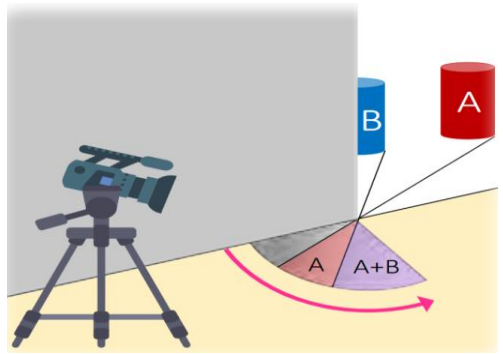
Velten et al. 2012

Coherence

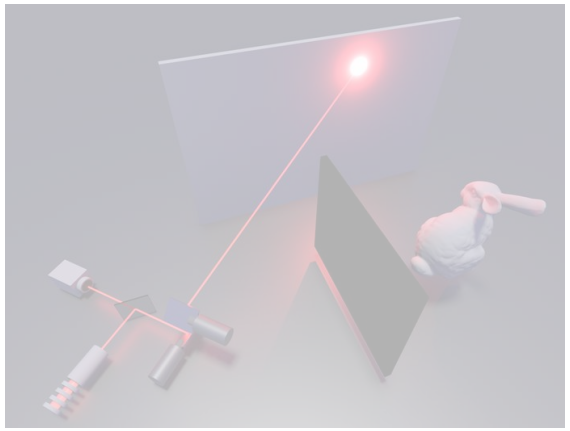


Smith et al. 2018

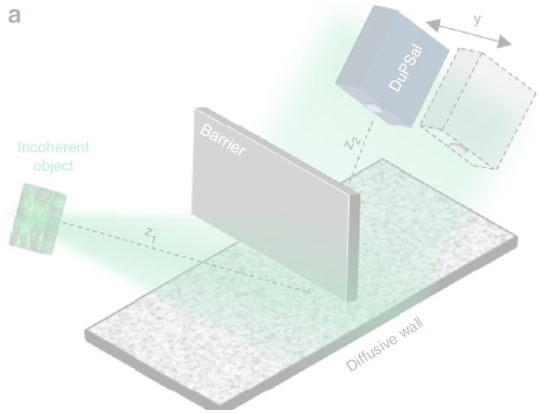
Intensity



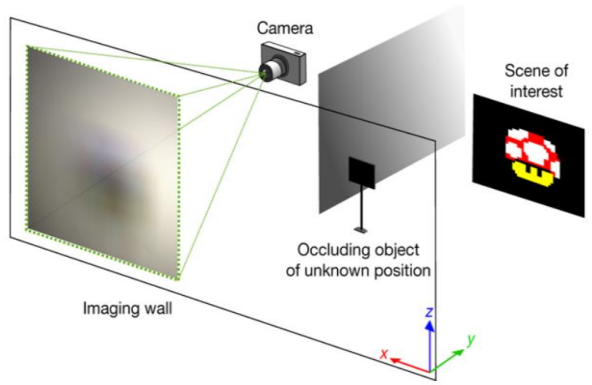
Bouman et al. 2017



O'Toole et al. 2018

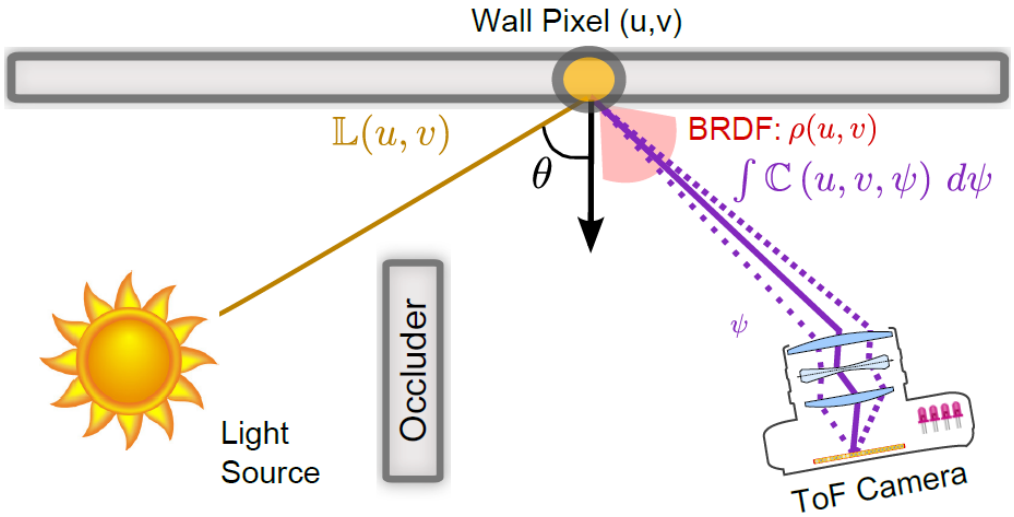


Batarseh et al. 2018

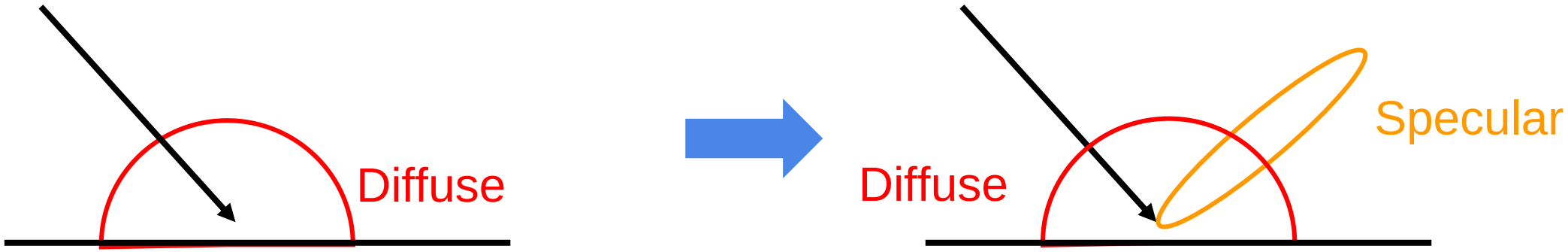


Saunder et al. 2019

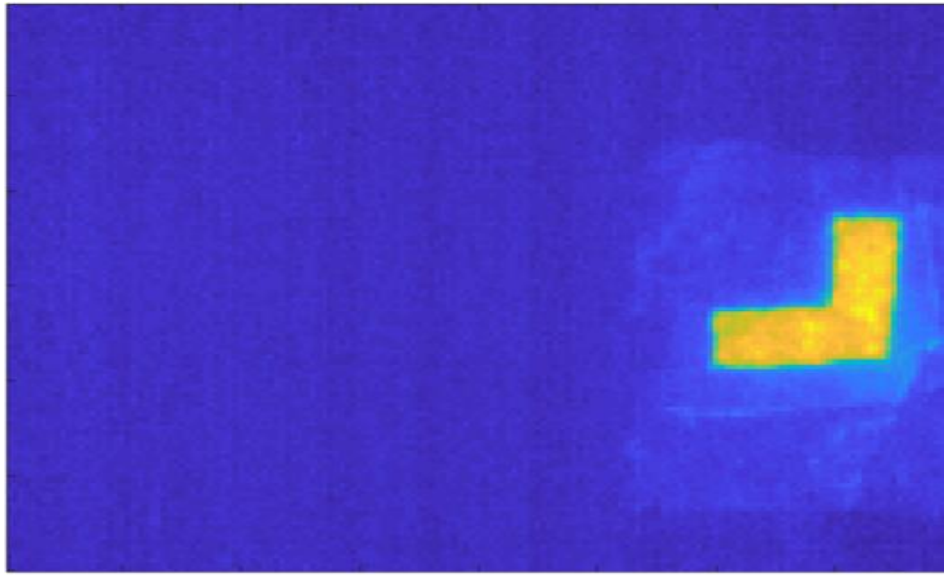
More Complex BRDF

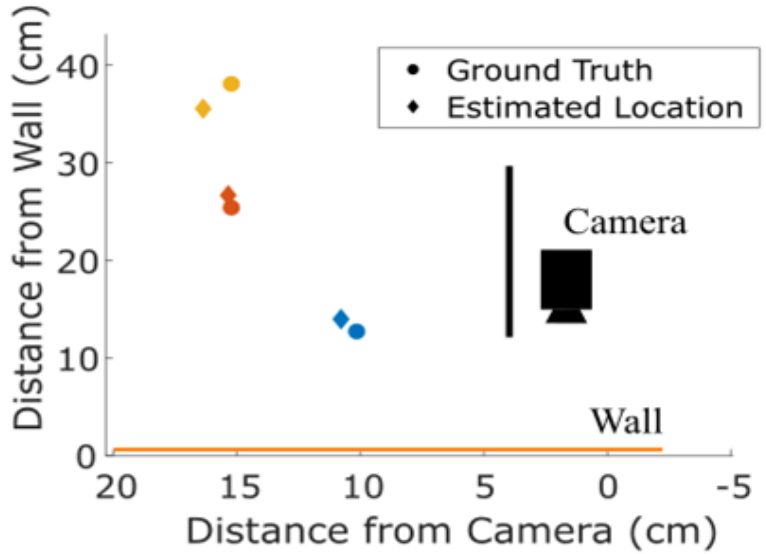


Kadambi et al. 2016

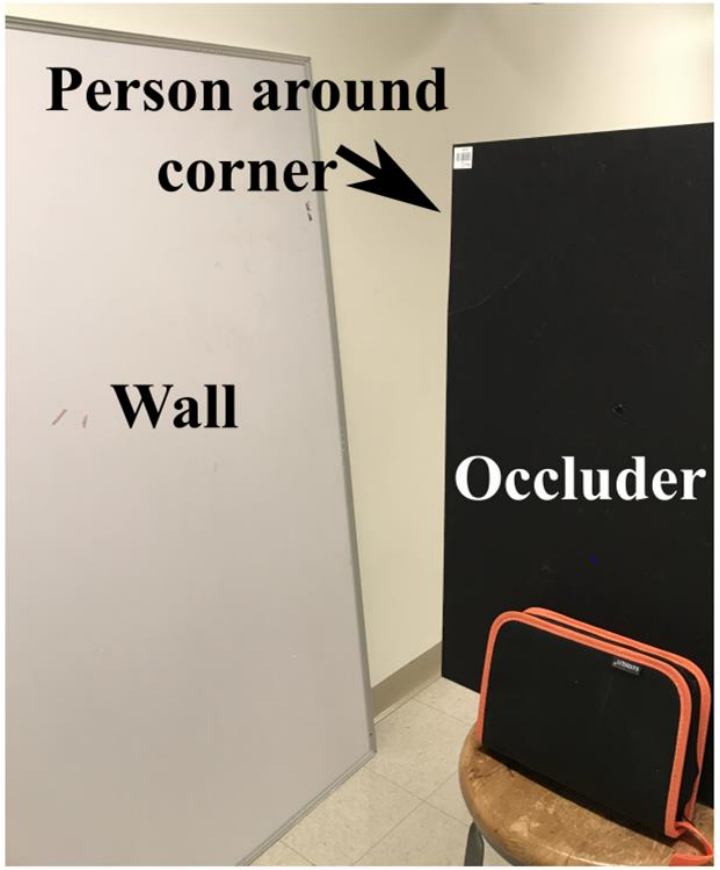


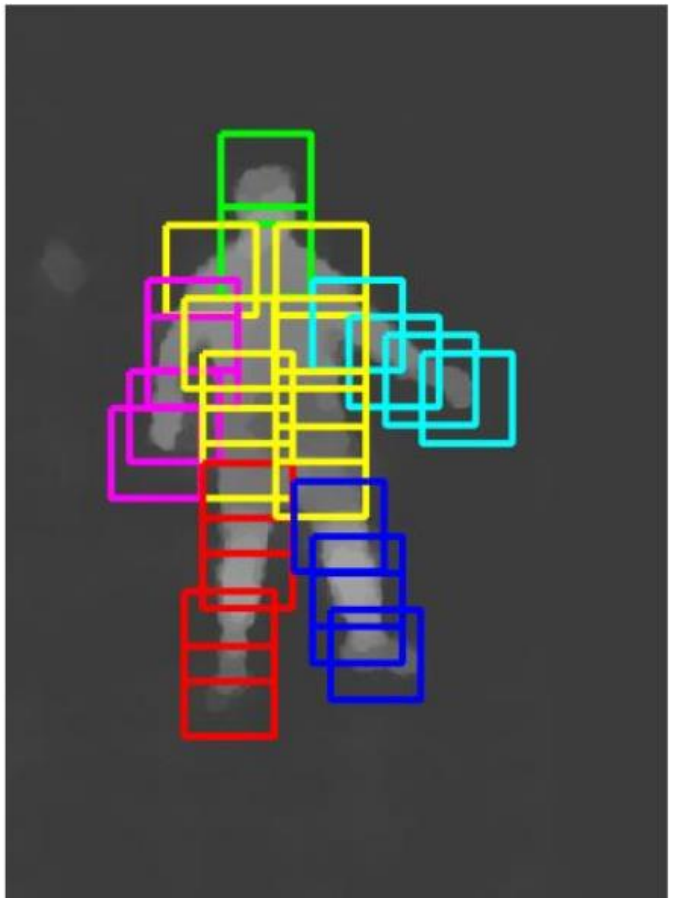
Results – Localization without Occlusions



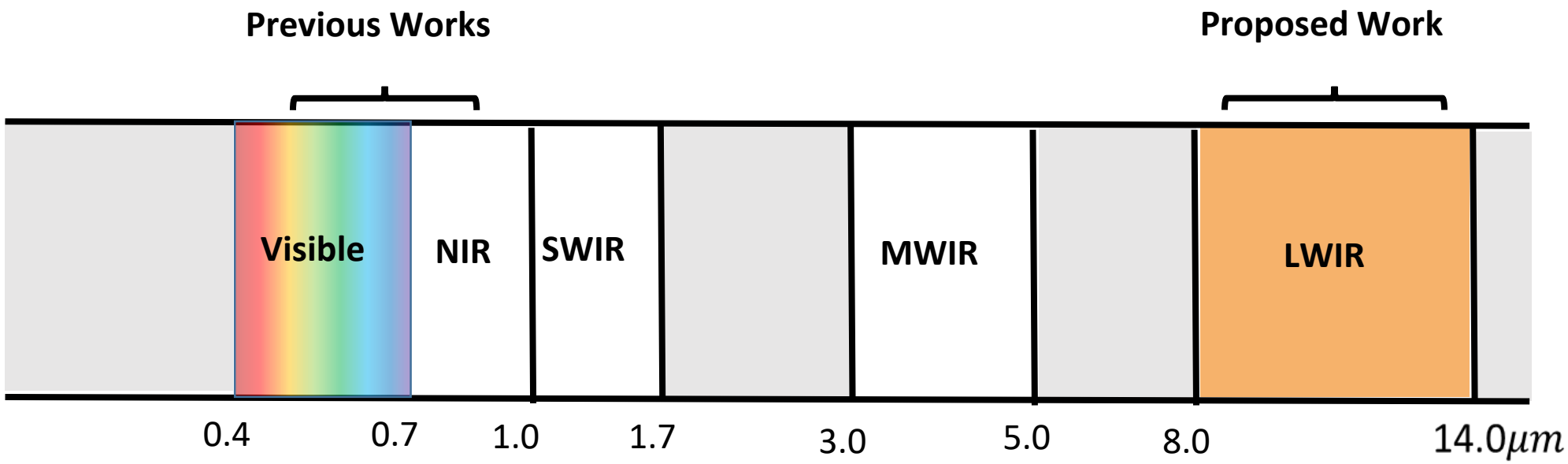


Results – Fast Pose Estimation

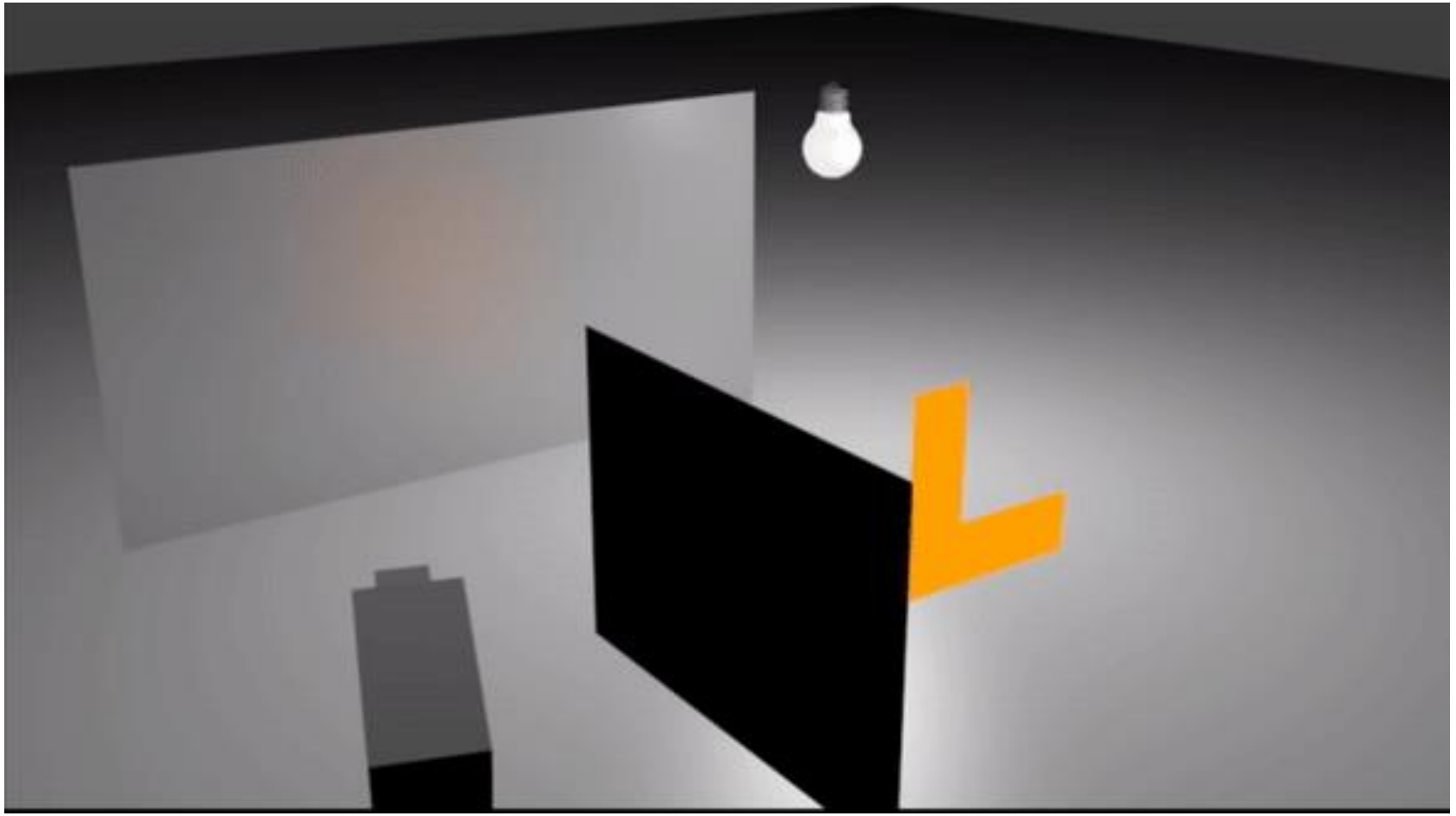




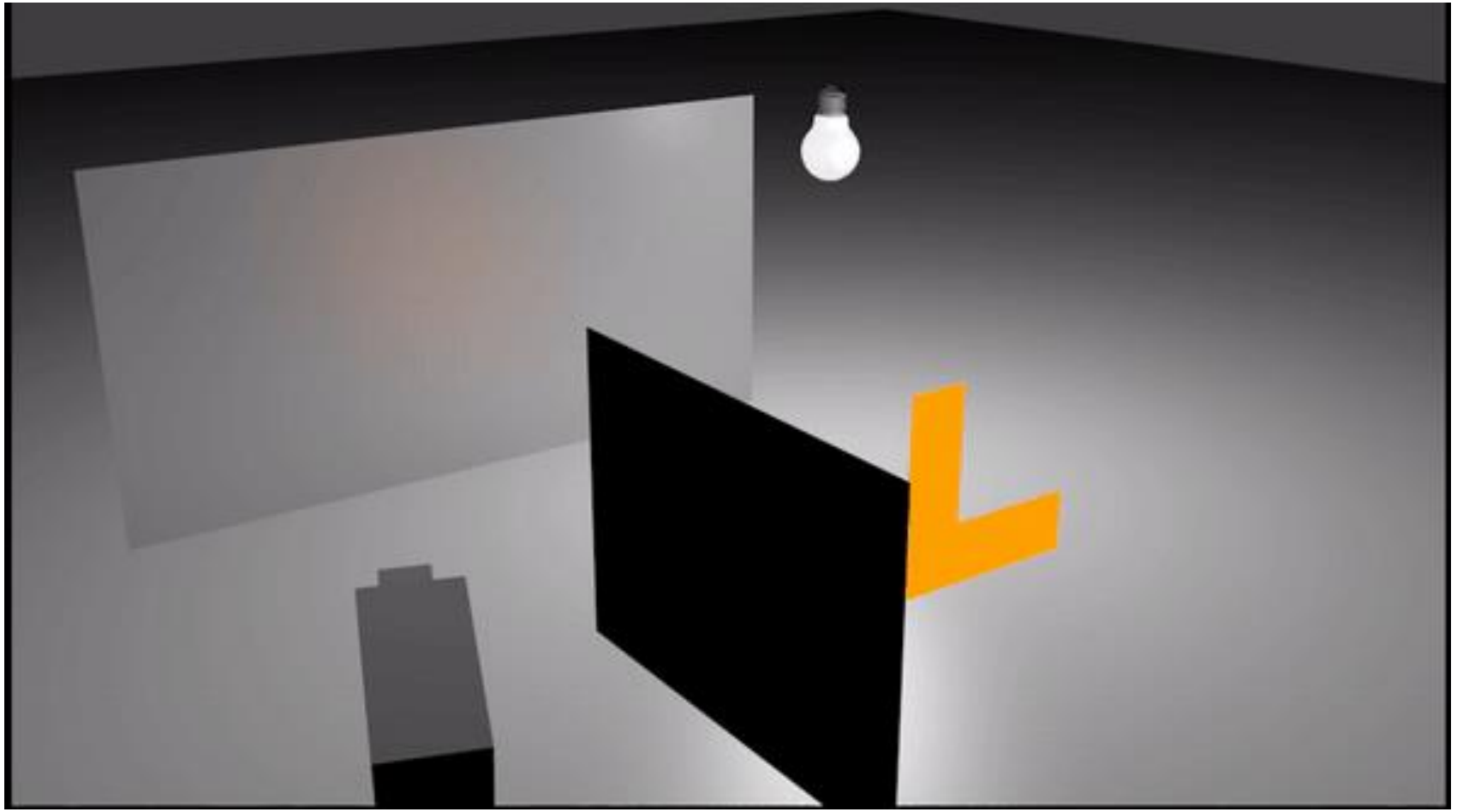
Long-wave IR


Previous Works
Proposed Work
Visible
NIR
SWIR
MWIR
LWIR
0.4
0.7
1.0
1.7
3.0
5.0
8.0
14.0μm

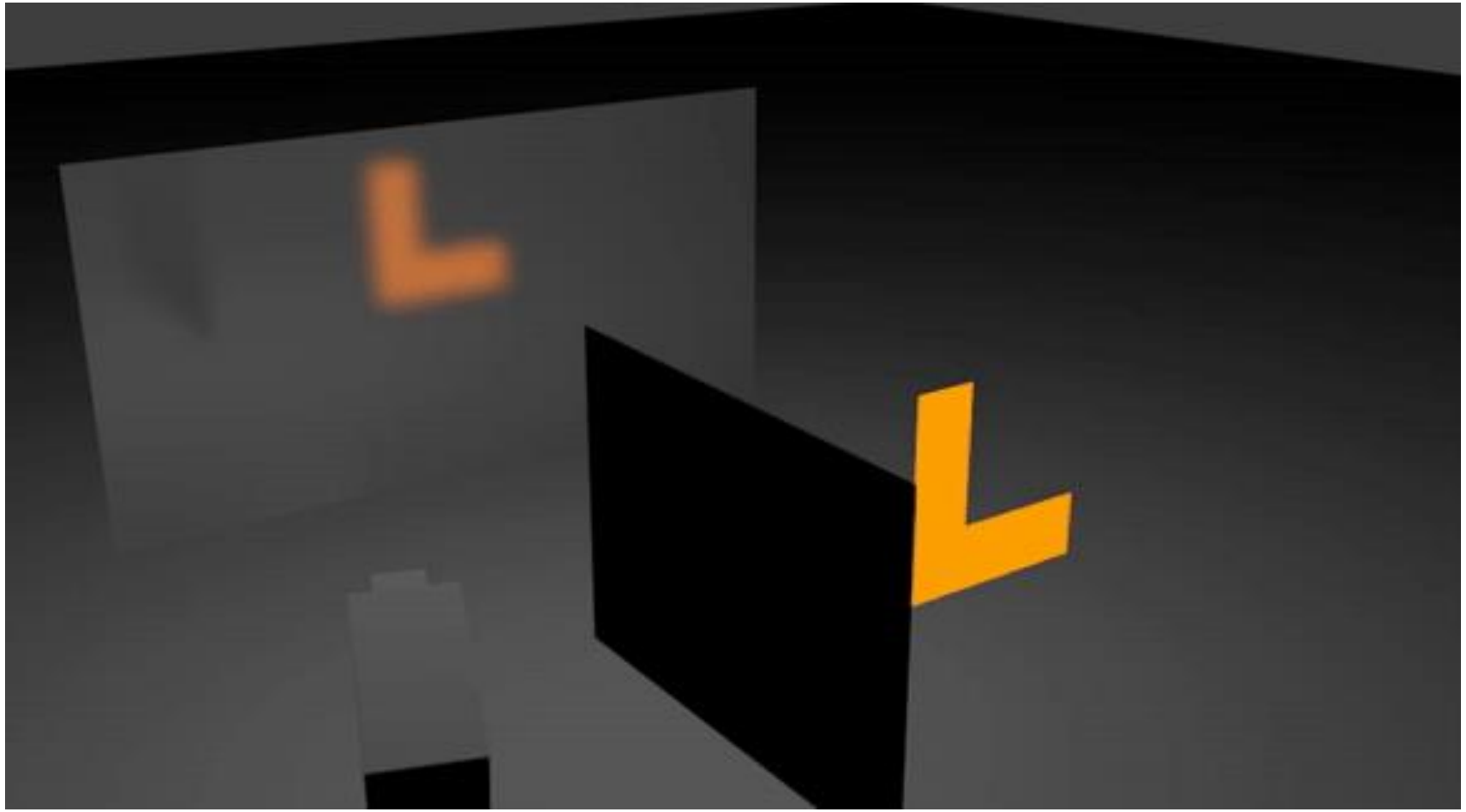
Two Photon Bounces with Visible Light



Ambient Photons with Visible Light



Single Specular Reflection with Long-wave IR



Temperature and Long-wave IR Emission

Stefan-Boltzmann Law

$$E = \epsilon\sigma T^4$$

- E: Radiance (W/m^2)
- ϵ : Emissivity
- σ : Stefan-Boltzmann Constant
- T : Temperature (K)

Temperature and Long-wave IR Emission

With background subtraction, object's radiance is

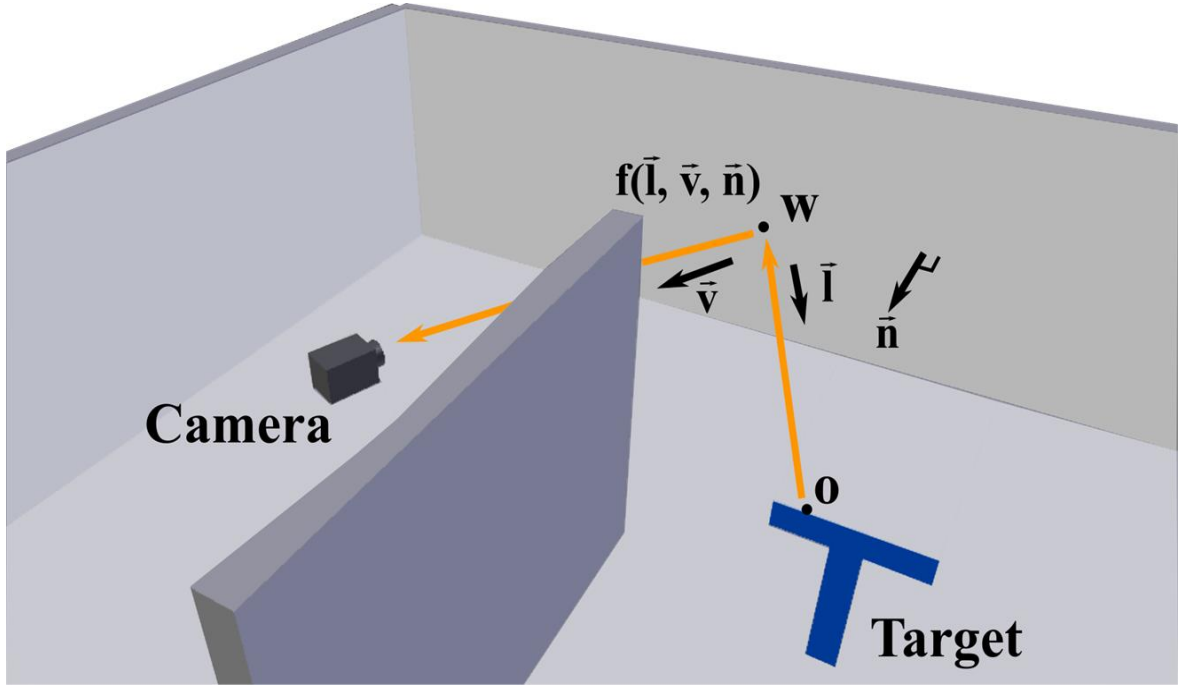
$$E_{obj} = \epsilon_{obj}\sigma\left(T_{obj}^4 - T_{amb}^4\right)$$

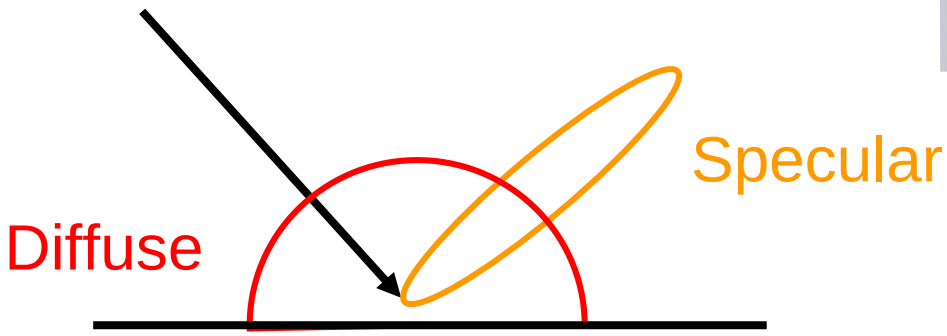
- Thermal measurement can be translated to the intensity information
- Radiance of the object can be estimated with temperature and emissivity

BRDF and Wavelength

- Diffuse $\propto 1/\lambda^4$
- Specular $\propto 1/\lambda^2$

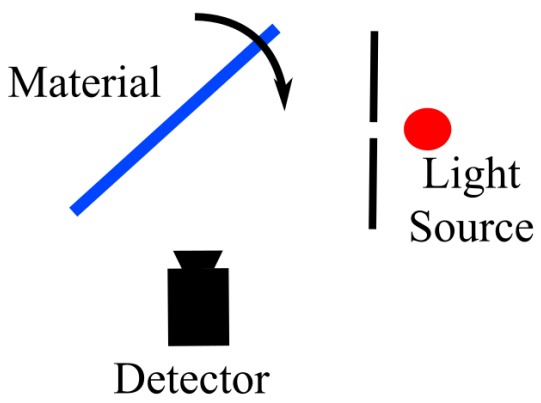
[Bennett and Porteus, 1960]



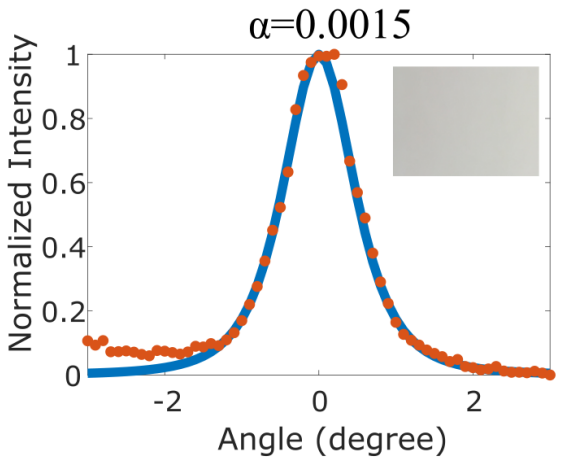


BRDF in the Long-wave IR Spectrum

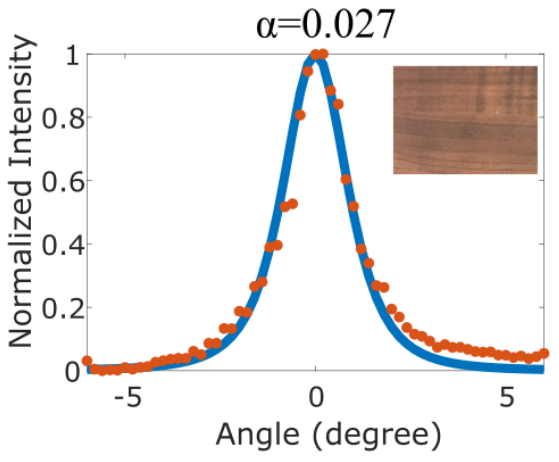
BRDF in the long-wave IR can be well approximated with specular models



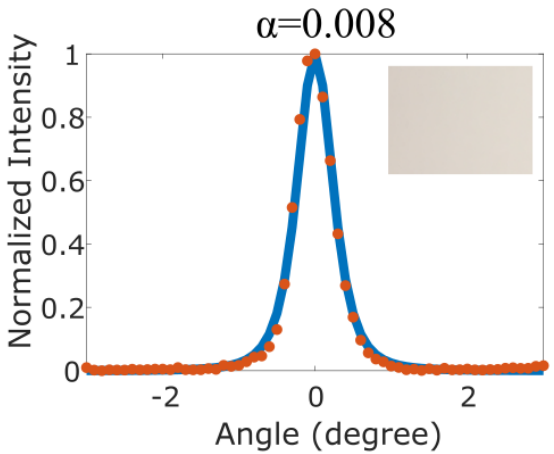
BRDF Caption Scheme



Foam Board



Wood



White Board

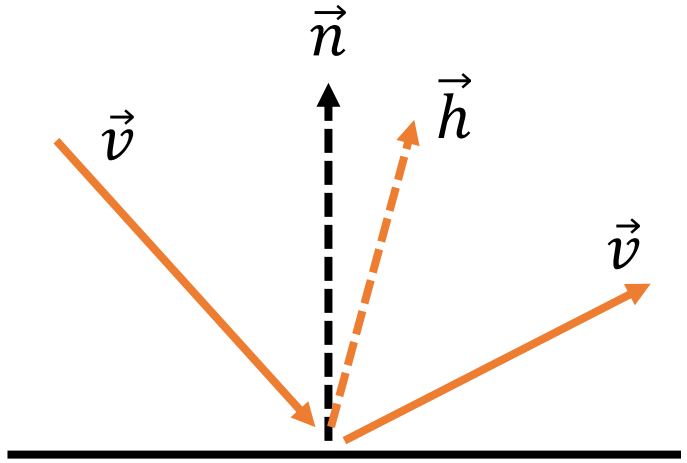
Specular BRDF Model

$$f\left(\vec{l},\vec{v},\vec{n}\right)=\frac{D\left(\vec{h},\vec{n}\right)F\left(\vec{v},\vec{h}\right)G\left(\vec{l},\vec{v},\vec{h},\vec{n}\right)}{4(\vec{l}\cdot\vec{n})(\vec{v}\cdot\vec{n})}$$

$D\left(\vec{h},\vec{n}\right)$: Normal distribution function parameterized by roughness α

$G\left(\vec{l},\vec{v},\vec{h},\vec{n}\right)$: Shadowing function parameterized by roughness α

$F\left(\vec{v},\vec{h}\right)$: Fresnel term ≈ 1 for narrow specular reflection



Light Transport Model

Irradiance at the wall

$$L(o,w) = \frac{E_{obj}}{\pi\left|\left|o-w\right|\right|^2},$$

Intensity that camera sees

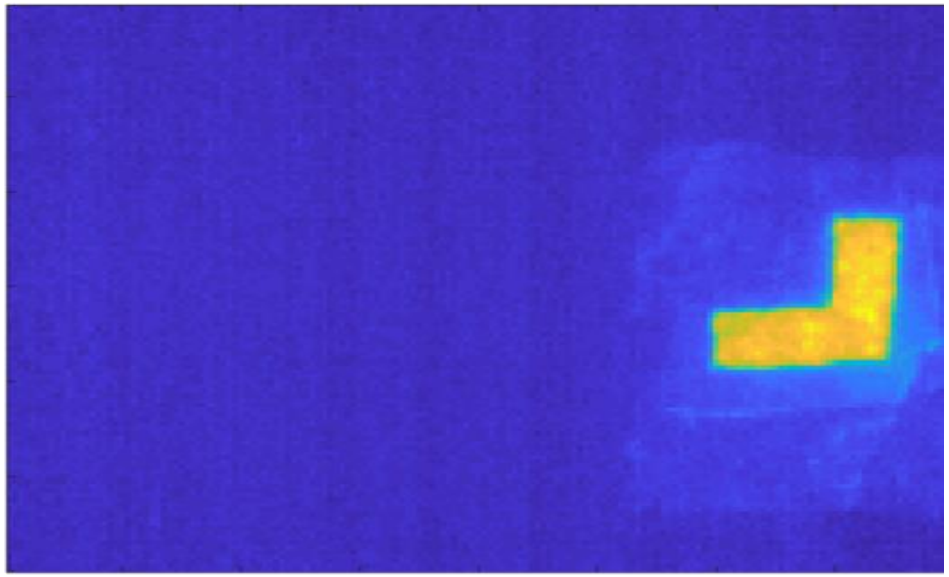
$$I(W_i) = \int\int\int (1-\epsilon)L(o,w)f\left(\vec{l},\vec{v},\vec{n}\right)\, d\vec{v}\, dw\, do$$

w: point on a wall surface

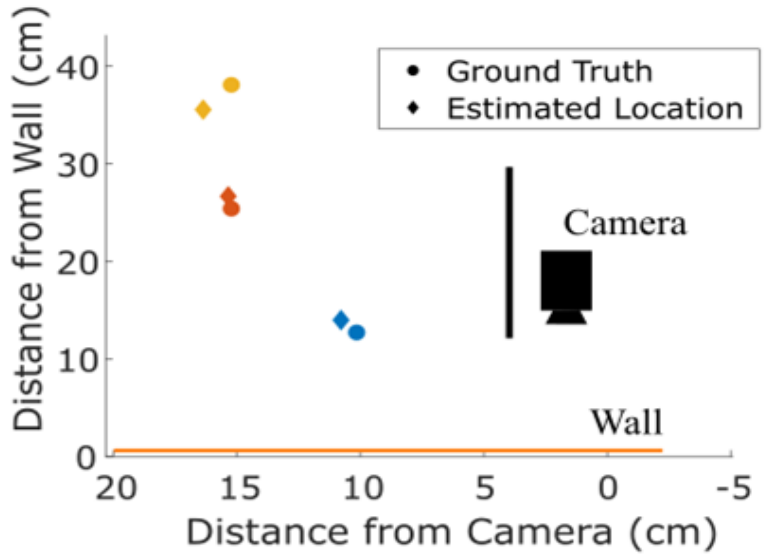
o: point on a object surface

ϵ: emissivity (1-albedo)

Thermal NLOS Imaging – Passive Localization



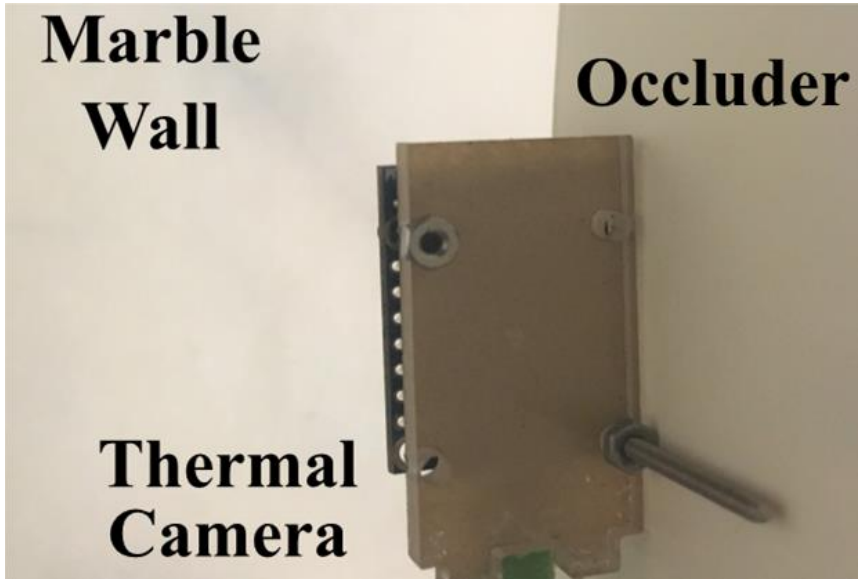
Reflection Image



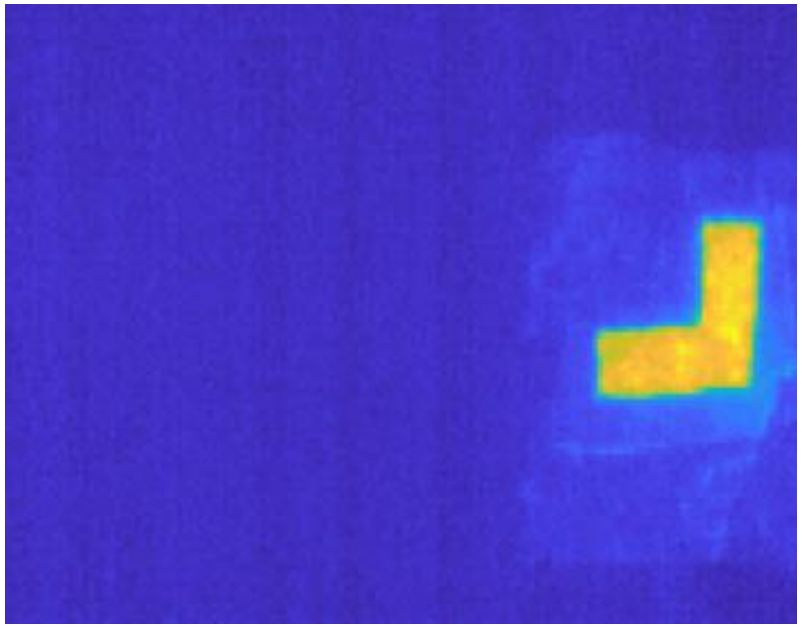
Location

Thermal NLOS Imaging – Passive Localization

Corner Setup

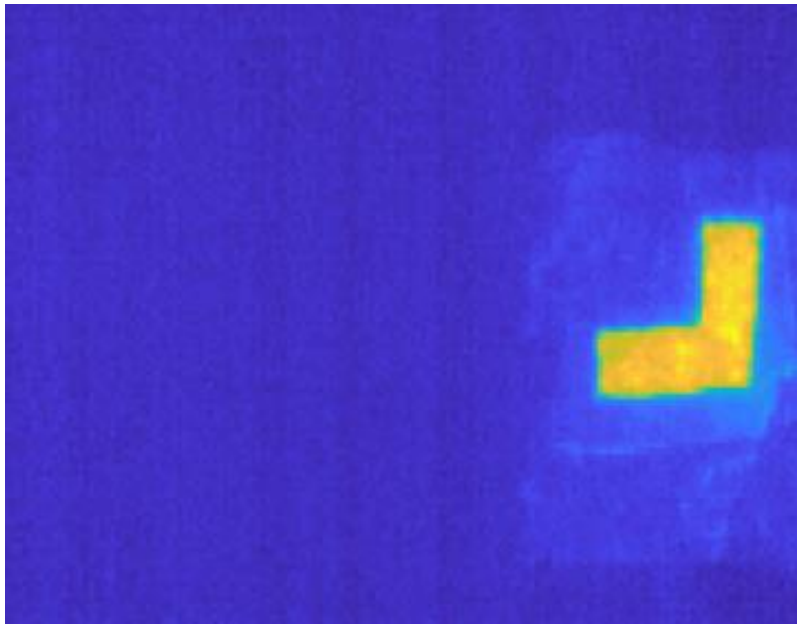


Intensity Measurement
from Marble Wall

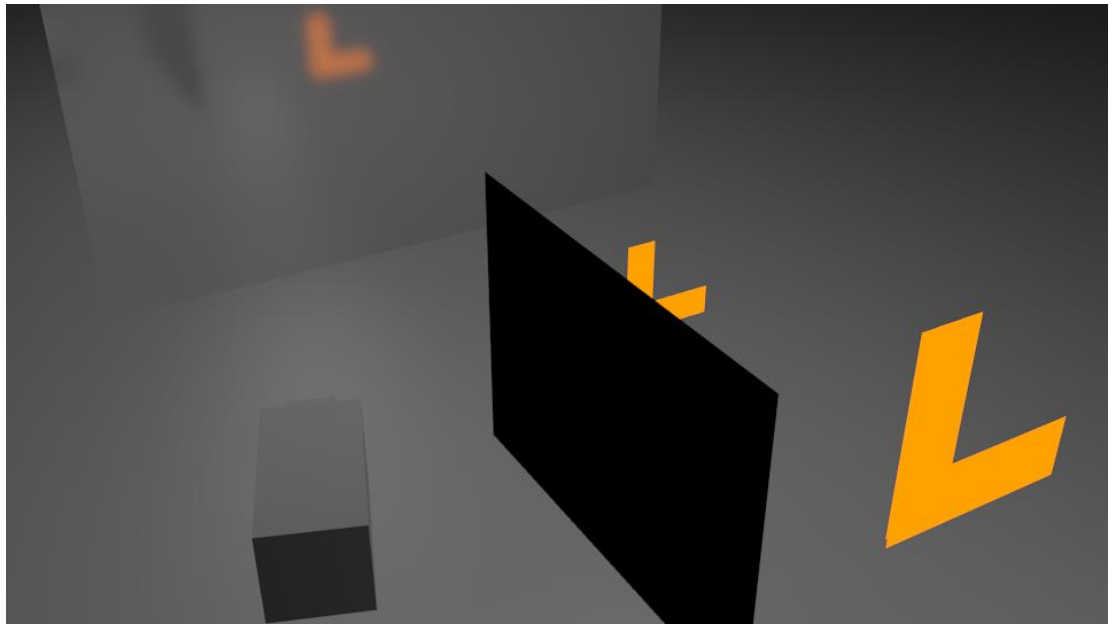


Size-depth Ambiguity

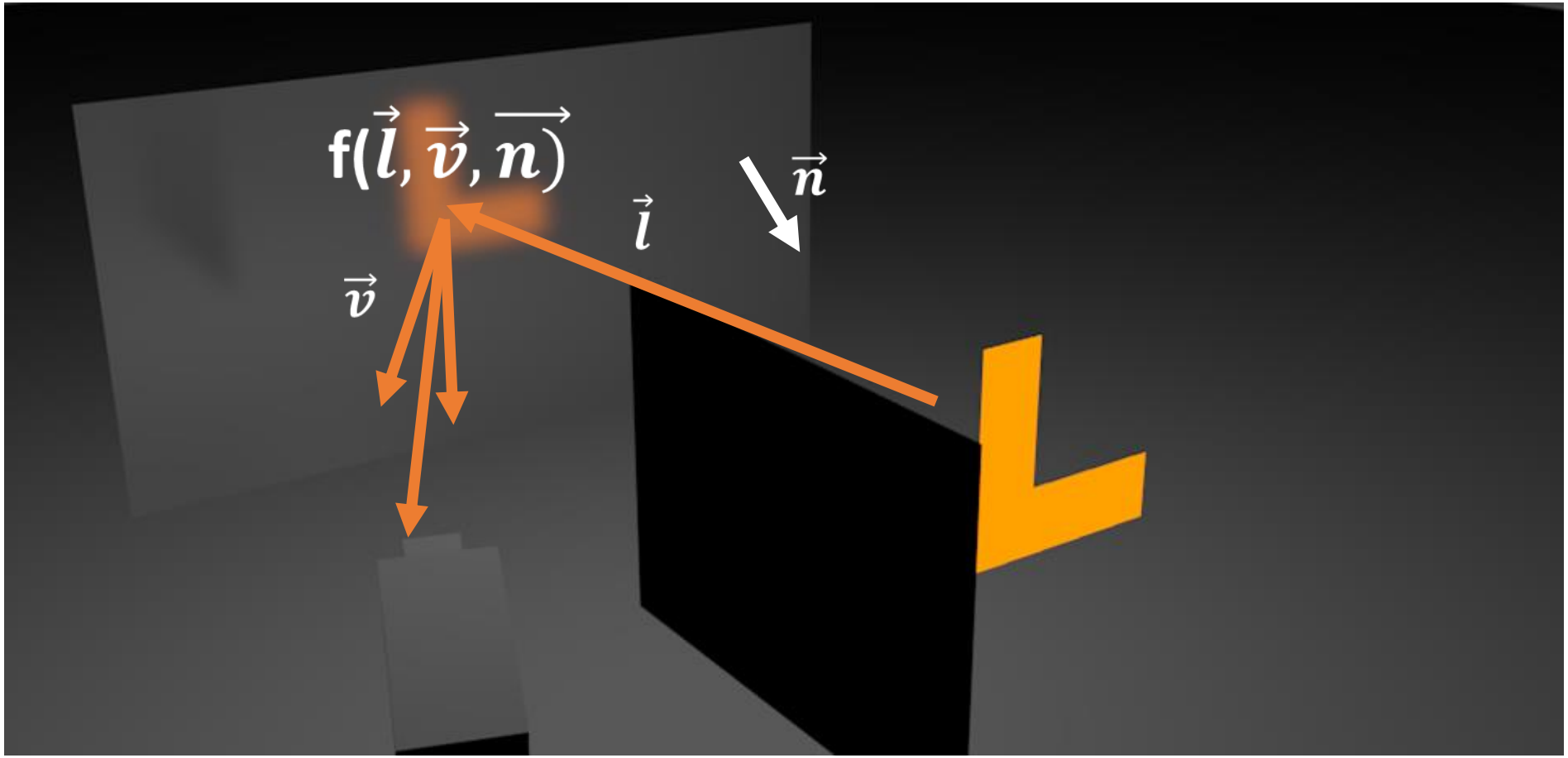
Intensity Measurement from Marble Wall



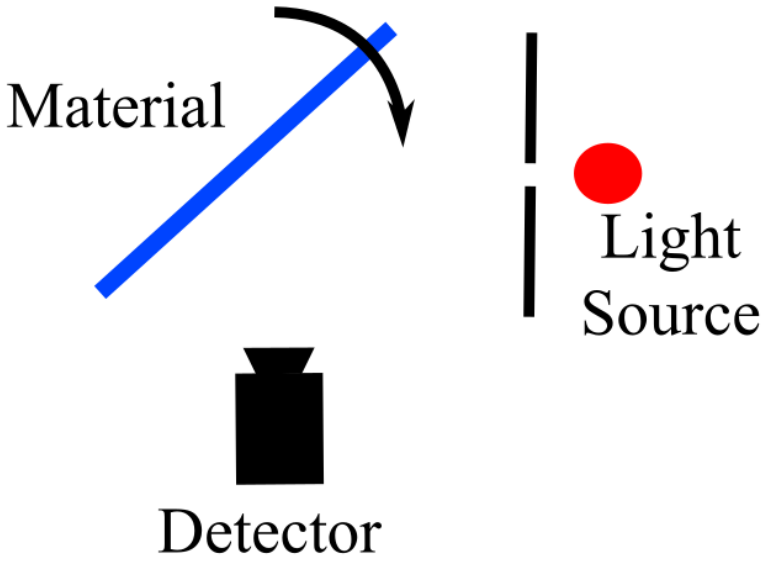
Size depth Ambiguity



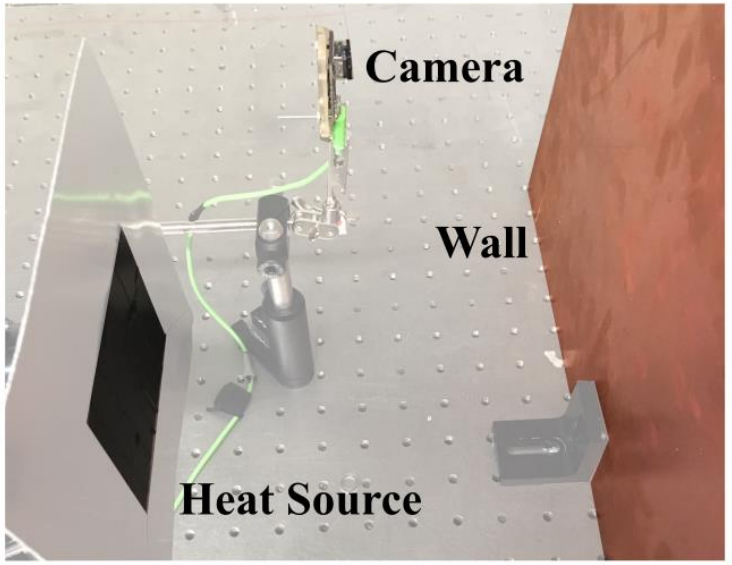
BRDF to Disambiguate Size and Depth



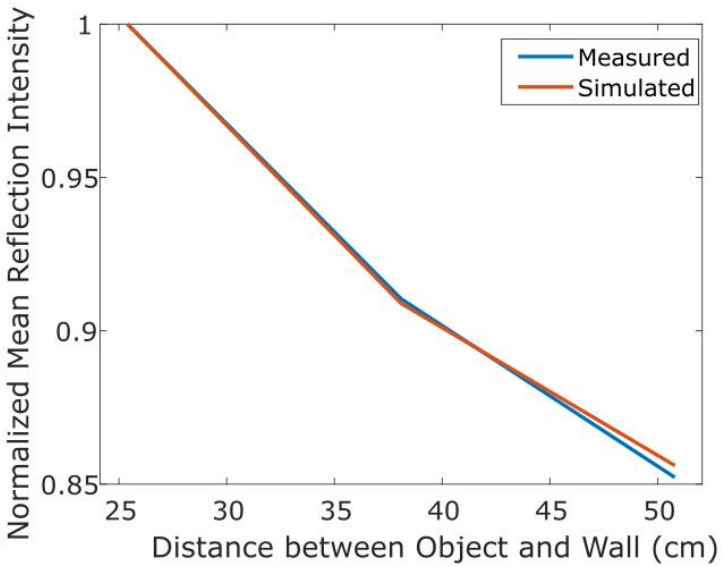
BRDF Estimation



BRDF Caption Scheme

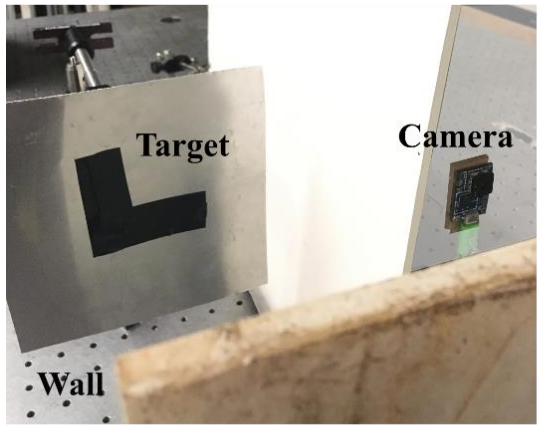


(a) BRDF estimation experimentl setup

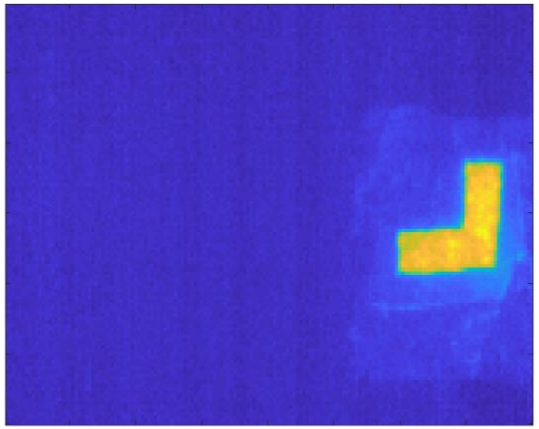


(b) Plot of measured reflection intensity and fitted simulation

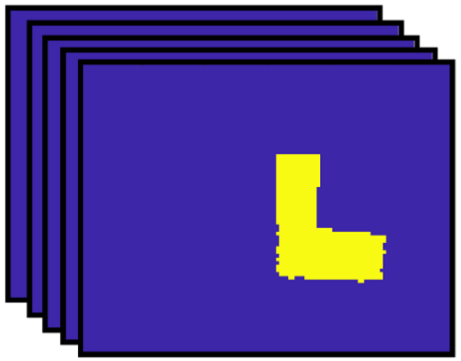
Localization Steps



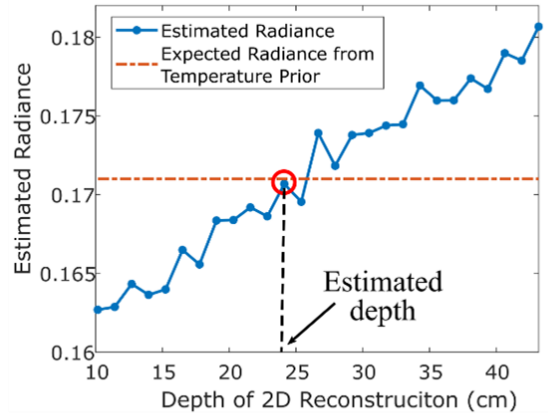
(a) Corner setup



(b) Measurement
(Object 25.4cm away from wall)

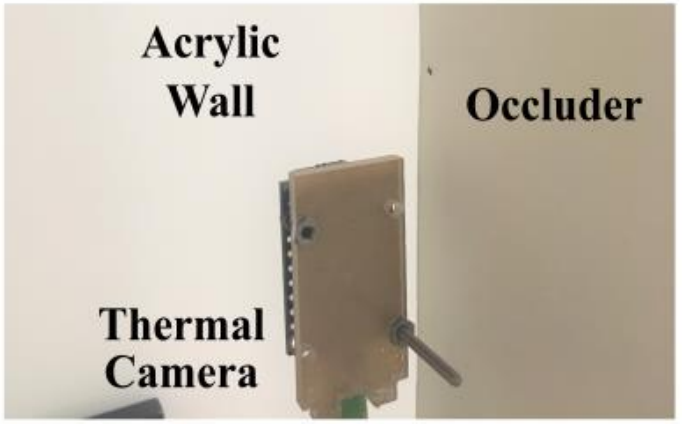


(c) 2D reconstructions for different depths

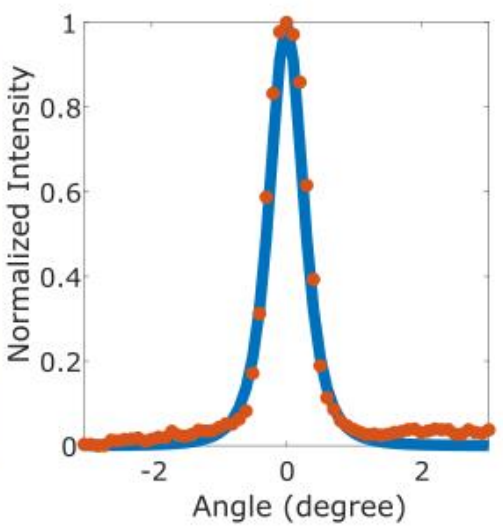


(d) LWIR radiance estimation
for each 2D reconstructions

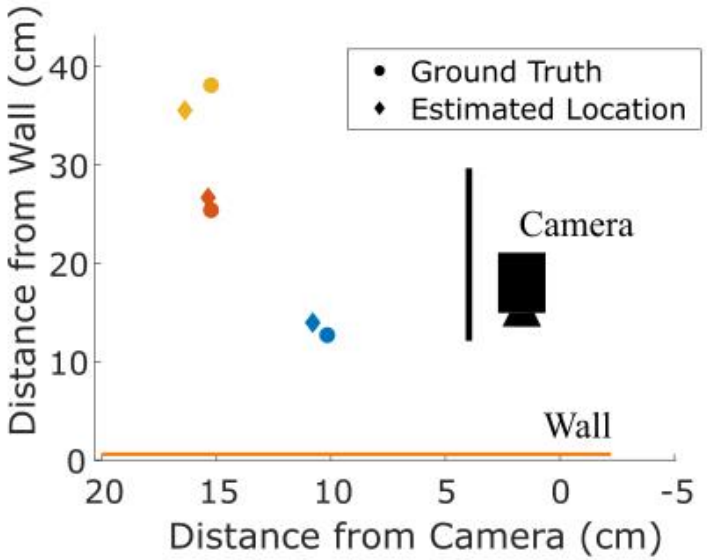
Localization Results



(a) Corner setup

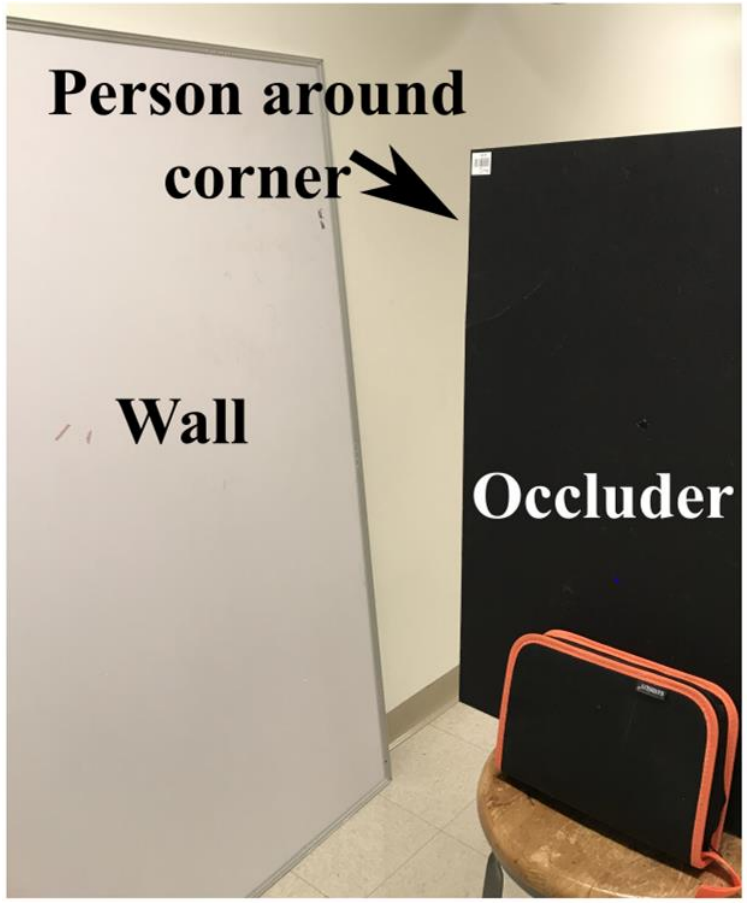


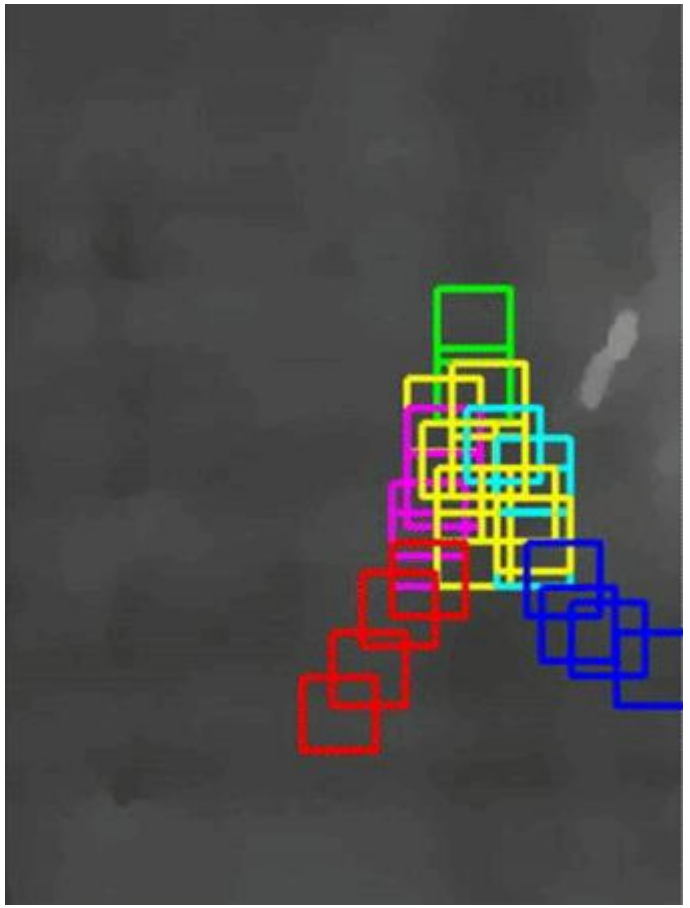
(b) BRDF Estimation



(c) 2D shape/ 3D location estimations

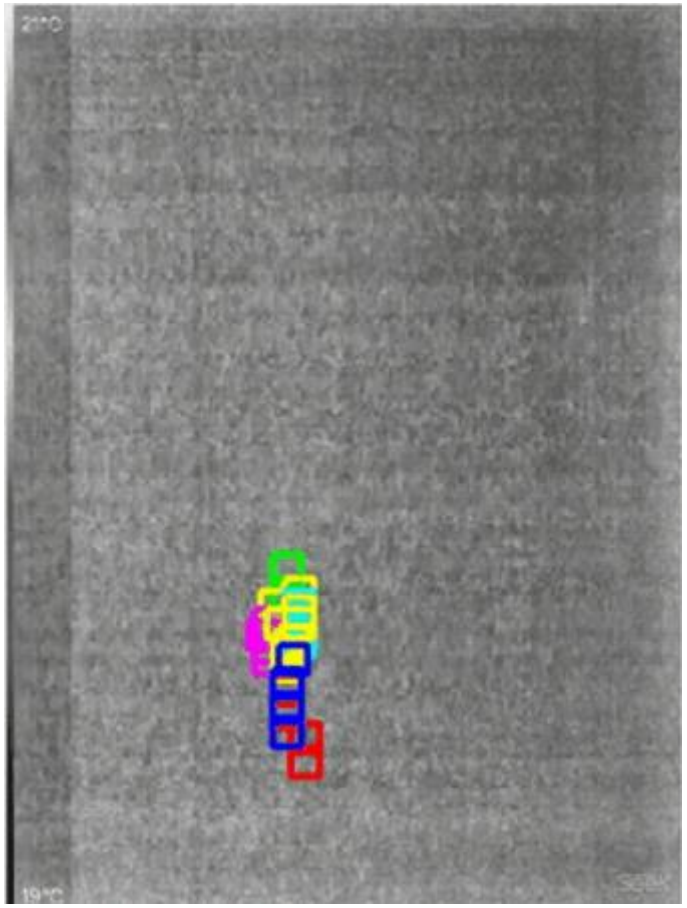
NLOS Imaging – Pose Estimation



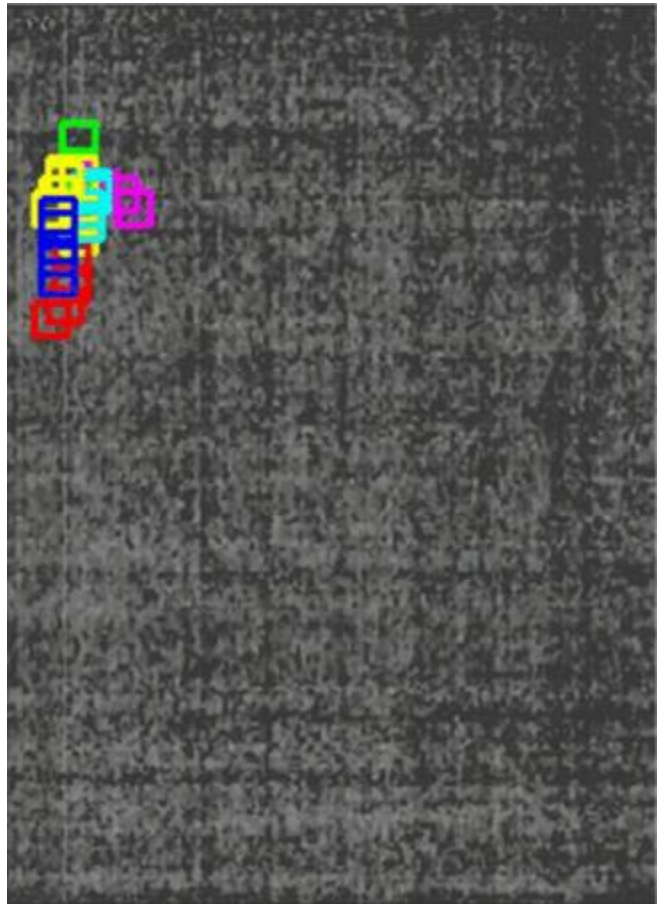


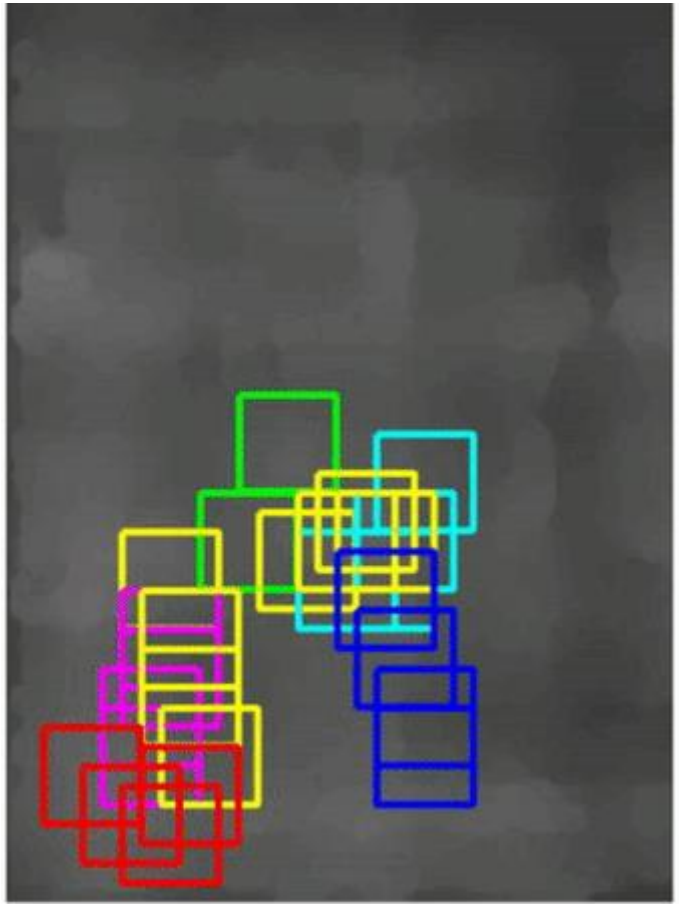
Denoising for Robust Pose Estimation

Raw Frames



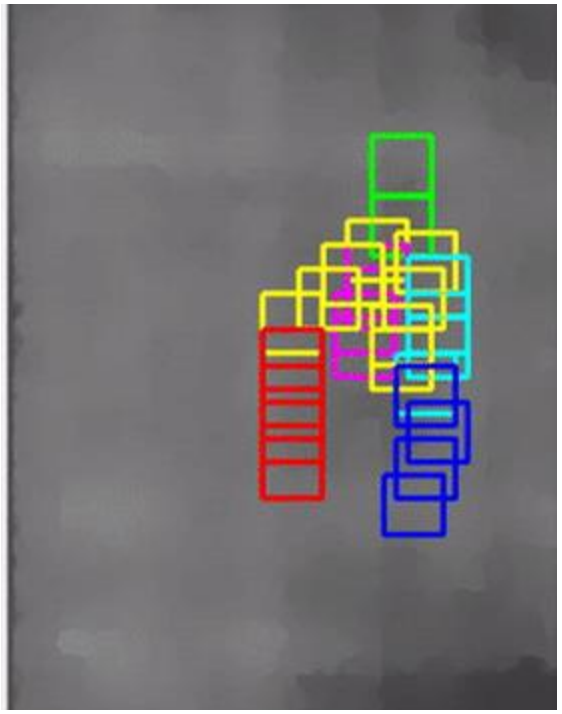
Proposed Methods





Human Detection via Score Thresholding

Without Threshold



With Threshold

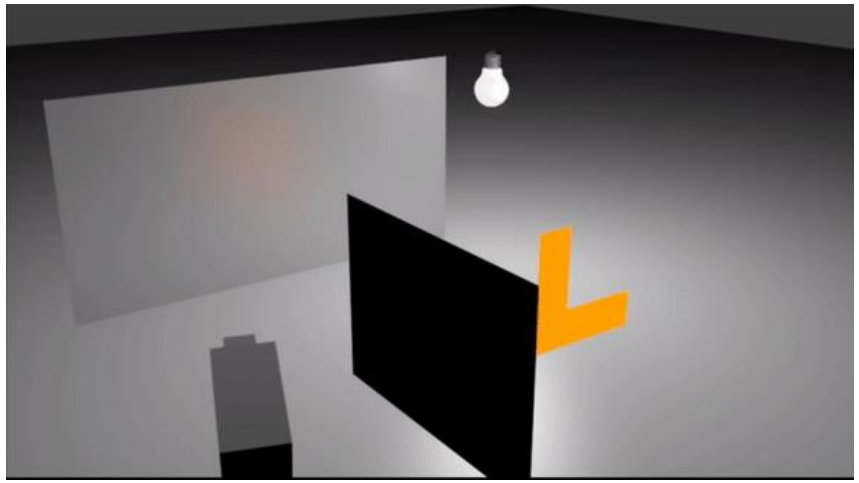
Limitations and Applications

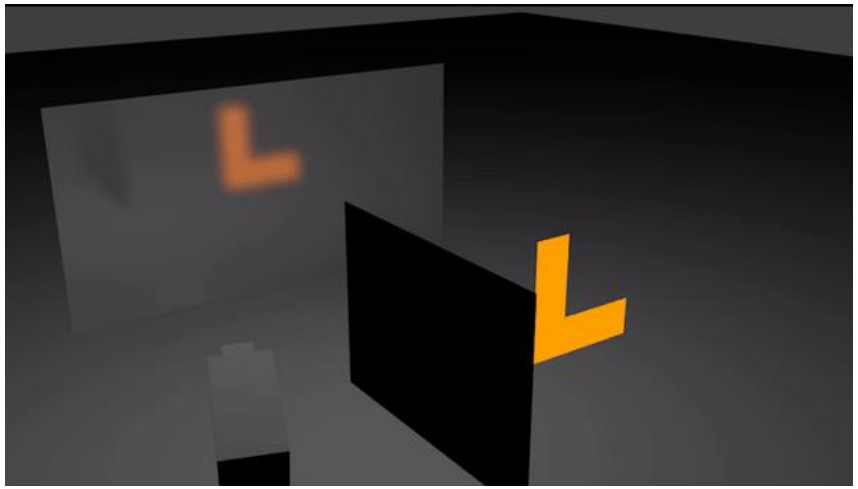
- Limitations
  - Limited object type
  - Absorption of long-wave IR at surfaces

- Applications
  - Passive localization
  - Real-time computer vision algorithms

Conclusions

- Novel NLOS imaging with long-wave IR
- Passive 3D localization
- Pose Estimation around corners





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