Homogeneous Codes for Energy-Efficient Illumination and Imaging

ACM SIGGRAPH 2015

Presented by Utkarsh Sinha and Jenna Lake

Motivation

Goal

- How can we use energy most effectively in structured light applications?

Applications

- Distinguish between translucency and inter-reflections
- Remove artifacts caused by structured light
- Reconstruct 3D objects in challenging conditions (smoke, strong lights)
- Record live video from the projector’s point of view
- Capture structured light video of very bright scenes
    - Outdoor gesture recognition

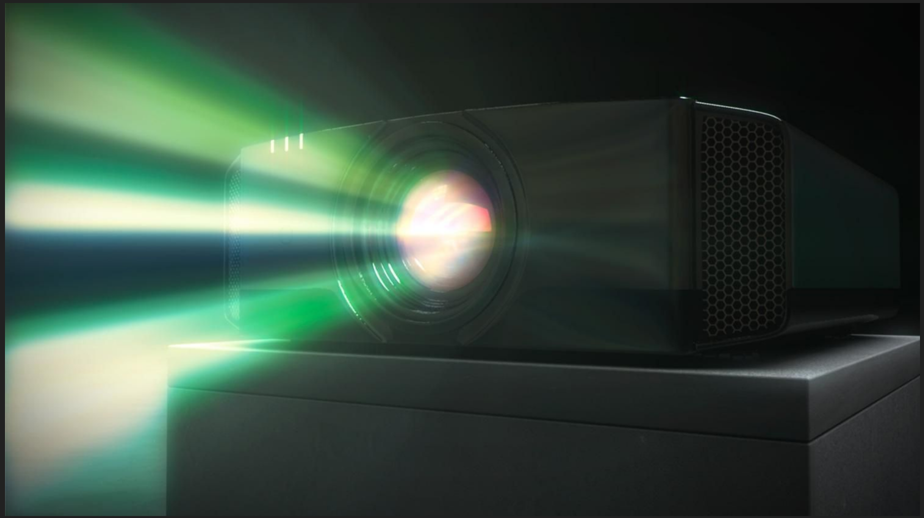
Challenges

- Masks are inefficient (blocked photons are wasted)
  - Required for light-field displays and indirect-only photography
- Live imaging requires short exposures
- Devices used are low-powered
- Photons emitted can cause unwanted artifacts in the image

Setup

VSYNC chip

- Rolling Shutter Camera
- Digital Micromirror Device (DMD) Projector
- A Laser Impulse Projector



Imaging with Rolling Shutter Cameras

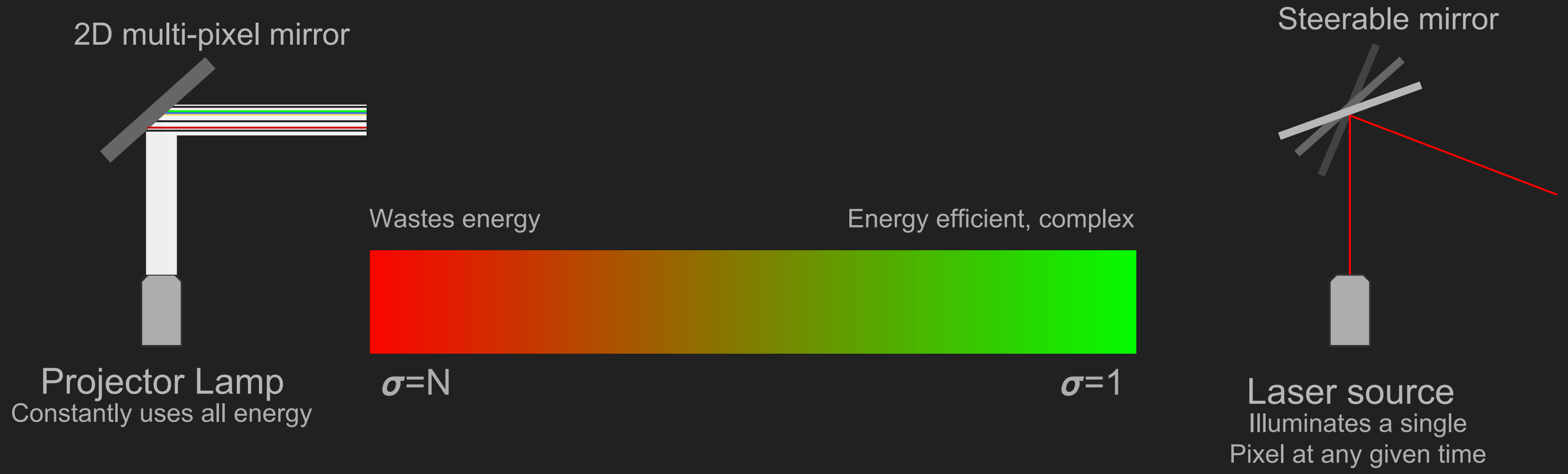
- A single exposure is taken over hundreds of microseconds
- Each row at a slightly different time
- Rolling shutter

Illumination patterns and masks

- Projector sends out an illumination pattern
- Camera sensor records single rows (masked)

- Exploit these two phenomena to efficiently capture photons

Spectrum of projectors



Energy Efficiency

Total Energy generated by Projector

$$0 \leq \mathbf{l}, \quad \|\mathbf{l}\|_1 \leq \Phi T,$$

Redistribution Factor

$$\|\mathbf{l}\|_\infty \leq \Phi T / \sigma,$$

$$0 \leq \mathbf{l}, \quad \|\mathbf{l}\|_{\dagger\sigma} = \max\left(\frac{\sigma \|\mathbf{l}\|_\infty}{\Phi}, \frac{\|\mathbf{l}\|_1}{\Phi}\right) \leq T,$$

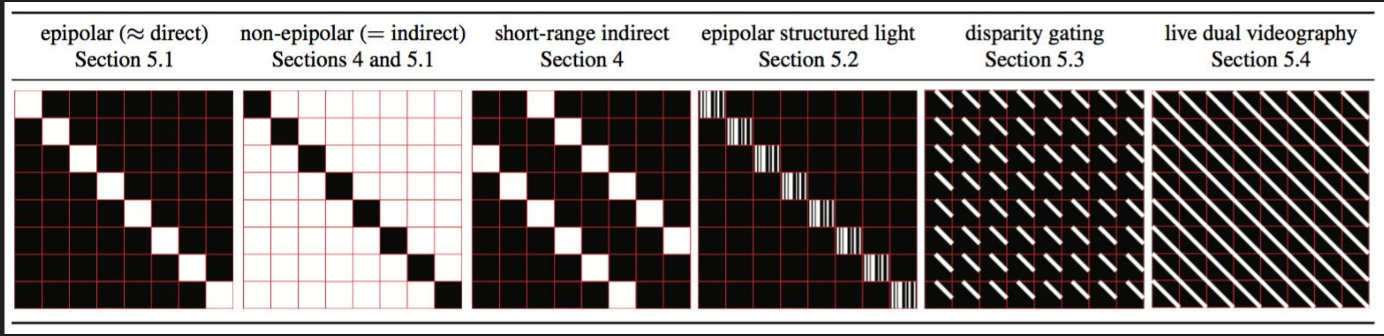
T is the total time

ϕ is the constant wattage of the light source

l is the illumination pattern (energy emitted by each projector pixel)

$\boldsymbol{\sigma}$ is the redistribution factor. This can range from 1 to N, where 1 means the projector is able to redirect all power from turned off pixels to one that are on.

Masks



$$0 \leq \mathbf{m}, \quad \|\mathbf{m}\|_\infty \leq 1.$$

Masks attenuation

$$\gamma\,\mathbf{\Pi} = \mathbf{m}\,\mathbf{1}^{\mathrm{T}},$$

Probing matrix & energy efficiency

m is a vector with each element is 0 to 1 that describes the mask attenuation on the sensor

γ: the scalar energy efficiency in Joules

Π: unit-less probing matrix (examples below)

High-Rank Probing Matrices

- High-rank probing matrices require changing the illumination K > 1 over the exposure time

$$\gamma\,\mathbf{\Pi} = \sum_{k=1}^{K} \mathbf{m}_k \,(\mathbf{l}_k)^{\mathrm{T}},$$

$$0 \leq t_k, \quad \sum_{k=1}^{K} t_k \leq T,$$

$$0 \leq \mathbf{m}_k, \quad \|\mathbf{m}_k\|_\infty \leq 1, \quad 0 \leq \mathbf{l}_k, \quad \|\mathbf{l}_k\|_{\dagger\sigma} \leq t_k,$$

Homogeneous Factorization

We want to maximize the energy efficiency

$$\gamma \, \mathbf{\Pi} = [\underbrace{\mathbf{m}_1 \; \mathbf{m}_2 \; \cdots \mathbf{m}_K}_{\text{masks } \mathbf{M}}][\underbrace{\mathbf{l}_1 \; \mathbf{l}_2 \; \cdots \mathbf{l}_K}_{\text{illuminations } \mathbf{L}}]^{\mathrm{T}}$$

$$\begin{aligned}
\max_{\gamma, \mathbf{M}, \mathbf{L}, t_1, \ldots, t_K} \quad & \gamma \\
\text{subject to} \quad & \gamma \, \mathbf{\Pi} = \mathbf{M}\mathbf{L}^{\mathrm{T}} \\
& 0 \leq \mathbf{m}_k, \quad \|\mathbf{m}_k\|_\infty \leq 1 \\
& 0 \leq \mathbf{l}_k, \quad \|\mathbf{l}_k\|_{\dagger\sigma} \leq t_k \\
& 0 \leq t_k, \quad \sum_{k=1}^{K} t_k \leq T.
\end{aligned}$$

Homogeneous Factorization Part 2

We relax the previous equation to solve more easily.

$$\begin{aligned} \min_{\mathbf{M},\mathbf{L}} \quad & \|\boldsymbol{\Pi} - \mathbf{M}\mathbf{L}^{\mathrm{T}}\|_F^2 + \lambda \sum_{k=1}^{K} \|\mathbf{m}_k\|_\infty \|\mathbf{l}_k\|_{\dagger\sigma} \\ \text{subject to} \quad & 0 \leq \mathbf{m}_k, 0 \leq \mathbf{l}_k \end{aligned}$$

λ is the regularization parameter which balances energy efficiency and the reproduction of the probing matrix

Details of how this equation is derived can be found in the appendix

Homogeneous Factorization Part 3

By dropping the non-negativity constraints and leaving the sequence K unconstrained, we get:

$$\min_{\mathbf{X}} \quad \|\mathbf{\Pi} - \mathbf{X}\|_F^2 + \lambda h(\mathbf{X}) \tag{13}$$

where function $h(\mathbf{X})$ is the *projective tensor norm*, defined as

$$h(\mathbf{X}) = \min_{\mathbf{X}=\mathbf{M}\mathbf{L}^{\mathrm{T}}} \left\{ \sum_{k=1}^{K} \|\mathbf{m}_k\|_p \|\mathbf{l}_k\|_q \right\} \tag{14}$$

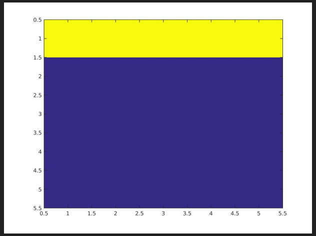
$$= \min_{\mathbf{X}=\mathbf{M}\mathbf{L}^{\mathrm{T}}} \left\{ \frac{1}{2} \sum_{k=1}^{K} \|\mathbf{m}_k\|_p^2 + \|\mathbf{l}_k\|_q^2 \right\} \tag{15}$$

with $p = \infty$ and $q = \dagger\sigma$ according to Eq. (12).

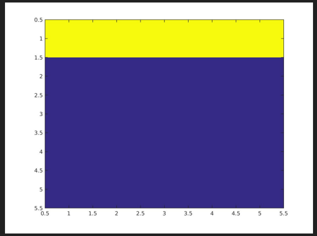
What does this homogeneous factorization mean?

- Impulse illumination is globally optimal
- For DMDs we need to create a code which will be energy efficient
- Epipolar illumination is globally optimal for epipolar and non-epipolar imaging
- Epipolar illumination and epipolar masking confer robustness to ambient light

Producing probing matrices



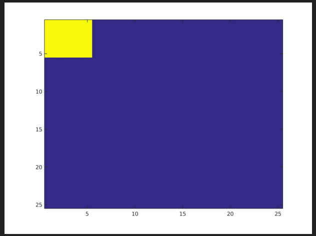
Illumination
(5x5)



Camera Mask
(5x5)

Illumination
(25x1)

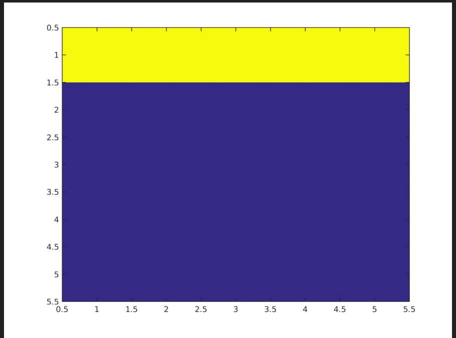
Camera Mask
(1x25)



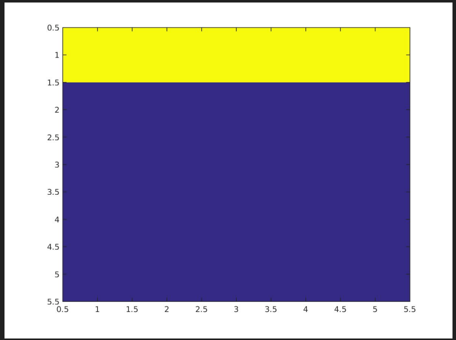
Probing Matrix
(25x25)

Producing probing matrices

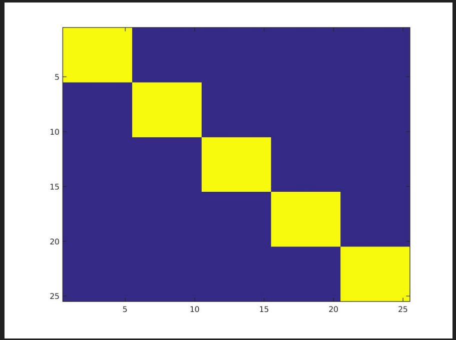
- Epipolar probing



Illumination
(5x5)



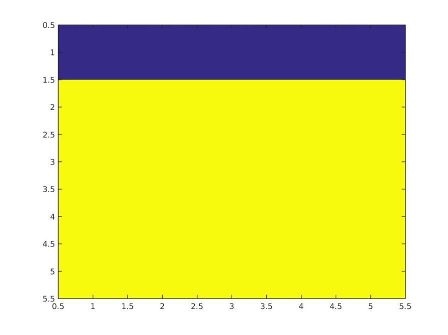
Camera mask
(5x5)



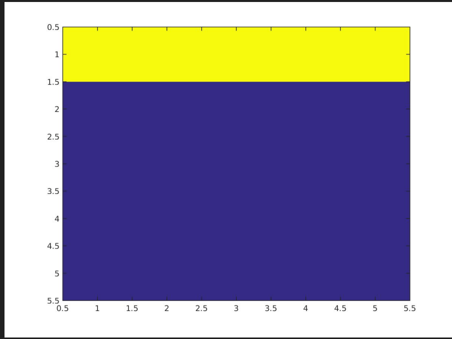
Probing Matrix
(25x25)

Producing probing matrices

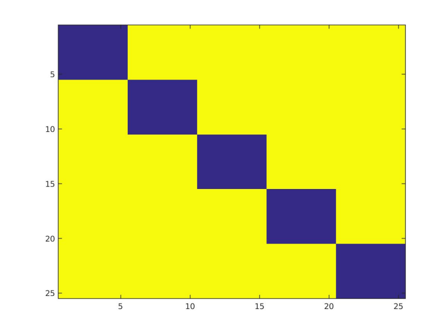
- Non-epipolar probing



Illumination
(5x5)



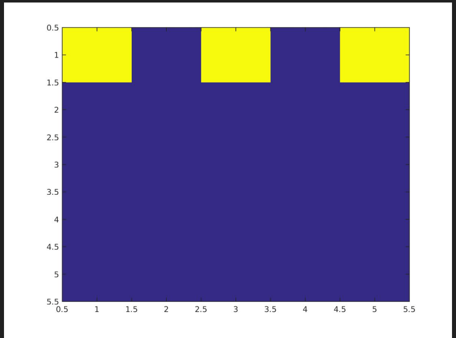
Camera mask
(5x5)



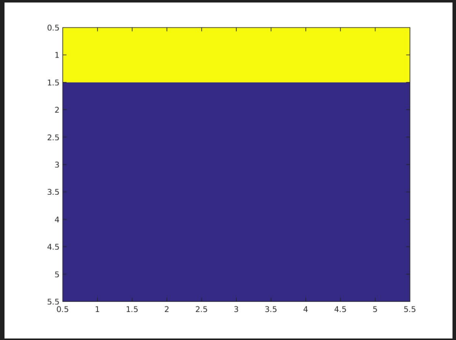
Probing Matrix
(25x25)

Producing probing matrices

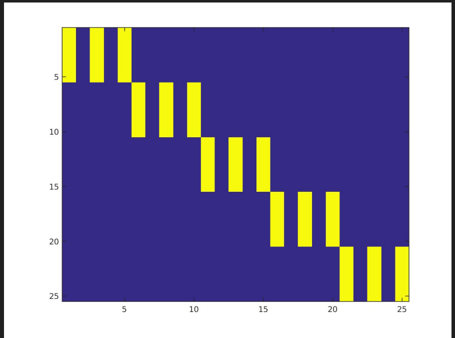
- Structured light



Illumination
(5x5)



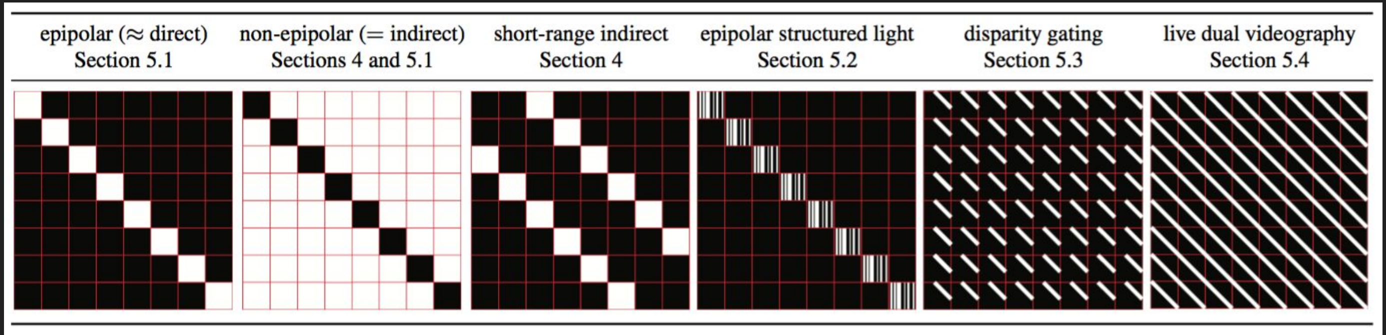
Camera mask
(5x5)



Probing Matrix
(25x25)

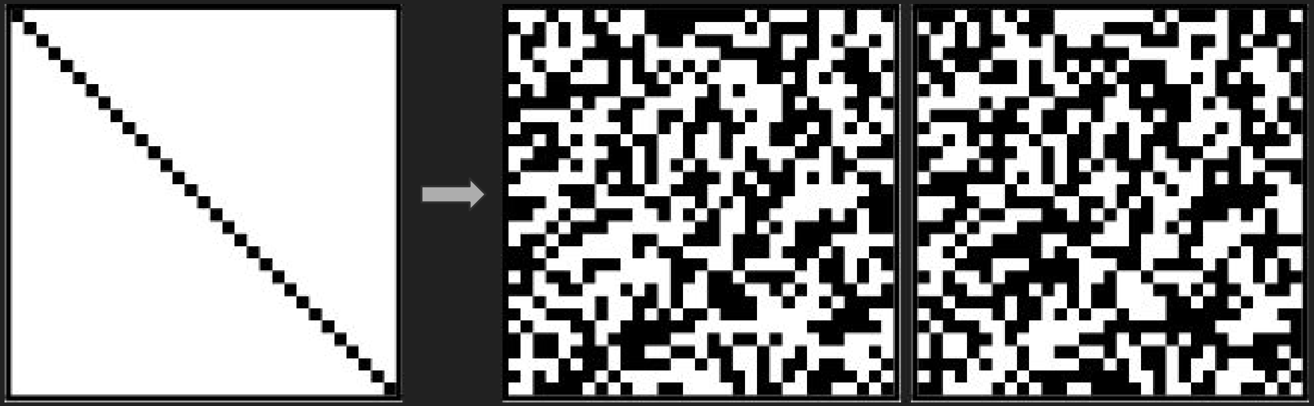
Producing probing matrices

- Different probing matrices capture different characteristics of the scene



Producing probing matrices

- Can we go in the other direction?
  - Factorization
  - Maximize efficiency while doing this



Imaging with DMDs

- Distributes power over the entire screen (σ=N)
- Requires solving the factorization to produce the illumination pattern and mask

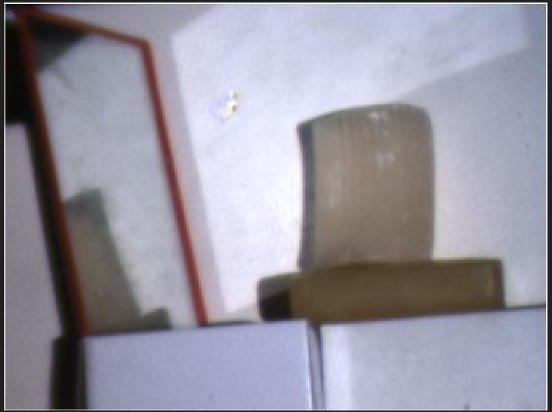
Imaging with DMDs

- Epipolar imaging

Original scene | Results from 2014 | This paper

Imaging with DMDs

- Non-epipolar imaging



Original scene

Results

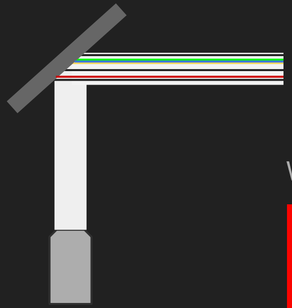
Imaging with DMDs

- Allows probing matrices with high ranks too!

Non-epipolar / Indirect lighting | Short-range indirect | Long-range indirect

Spectrum of projectors

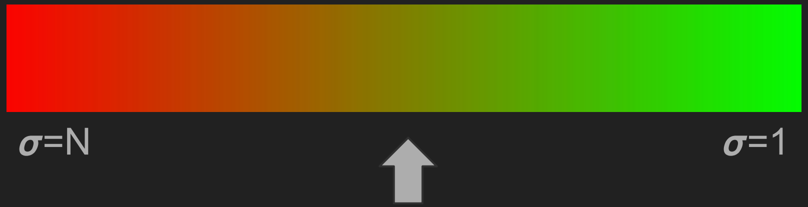
2D multi-pixel mirror



Projector Lamp
Constantly uses all energy

Wastes energy

Energy efficient, complex

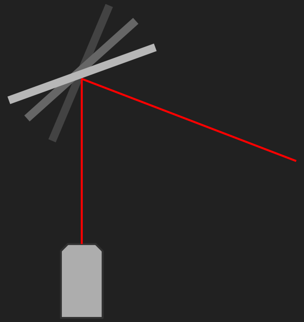


σ=N

σ=1

Hybrid systems (don't exist yet)
Solving the optimization is mathematically challenging

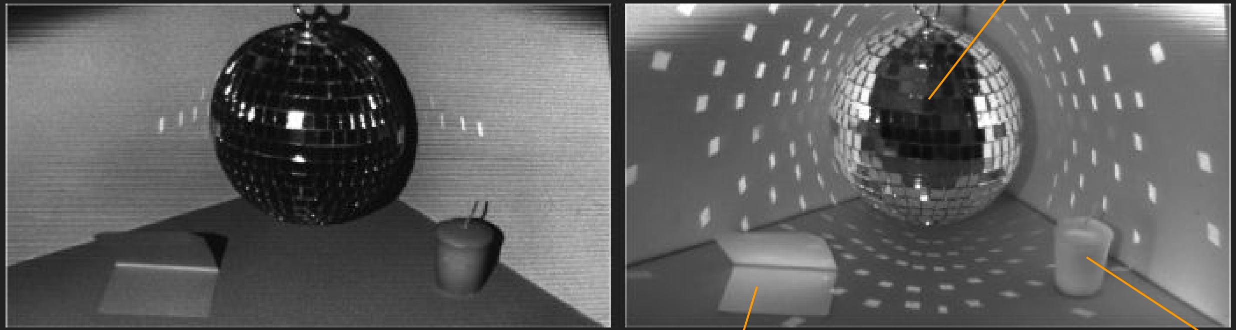
Steerable mirror



Laser source
Illuminates a single
Pixel at any given time

Imaging with Laser Projectors

- Epipolar and Non-epipolar imaging
  - Can be achieved in real-time

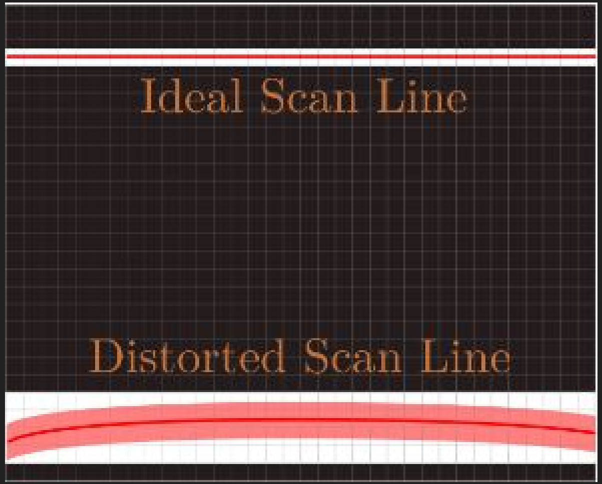


Epipolar imaging

Non-epipolar imaging

Imaging with Laser Projectors

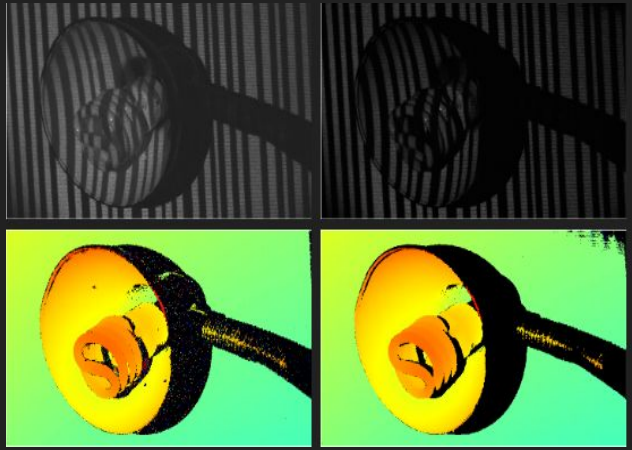
- Problems
  - The projector's scanlines aren't perfect
  - Thicken the region to accommodate errors



Imaging with Laser Projectors

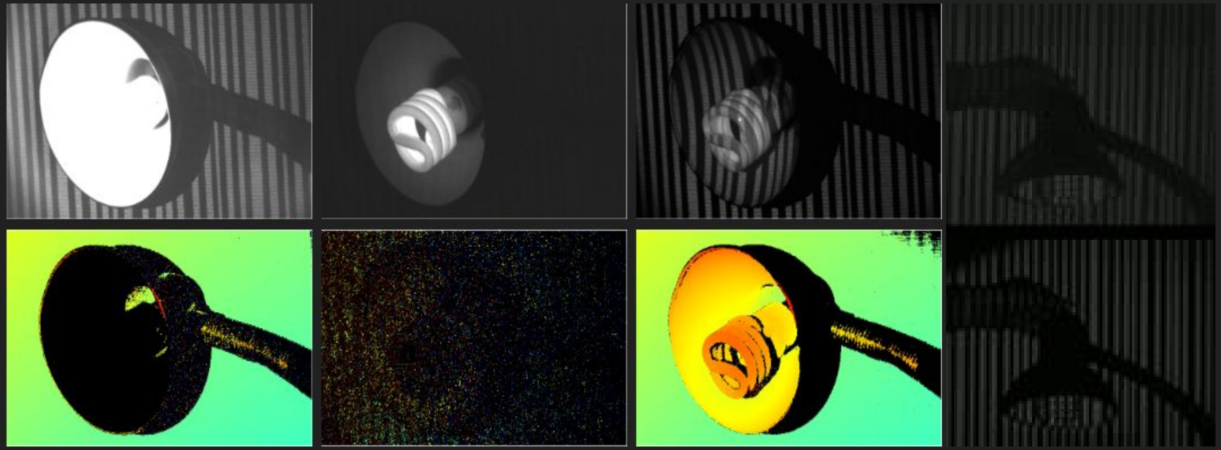
- Epipolar structured light

Reducing the iris size



Lamp off

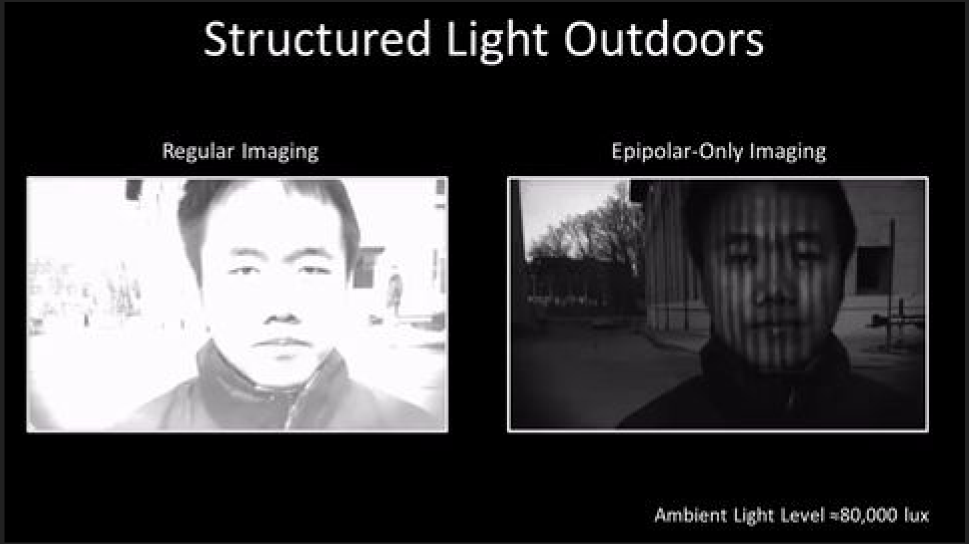
Reducing the iris size



Lamp on

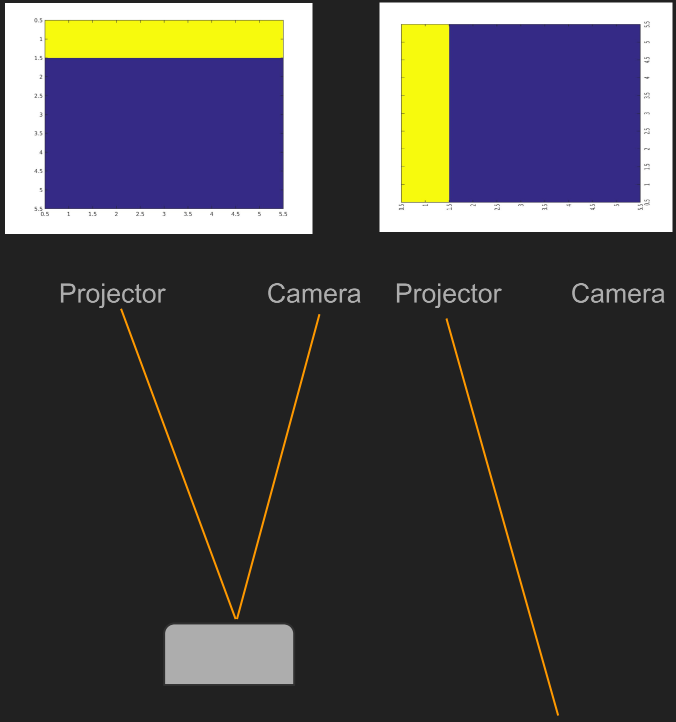
Imaging with Laser Projectors

- Epipolar structured light



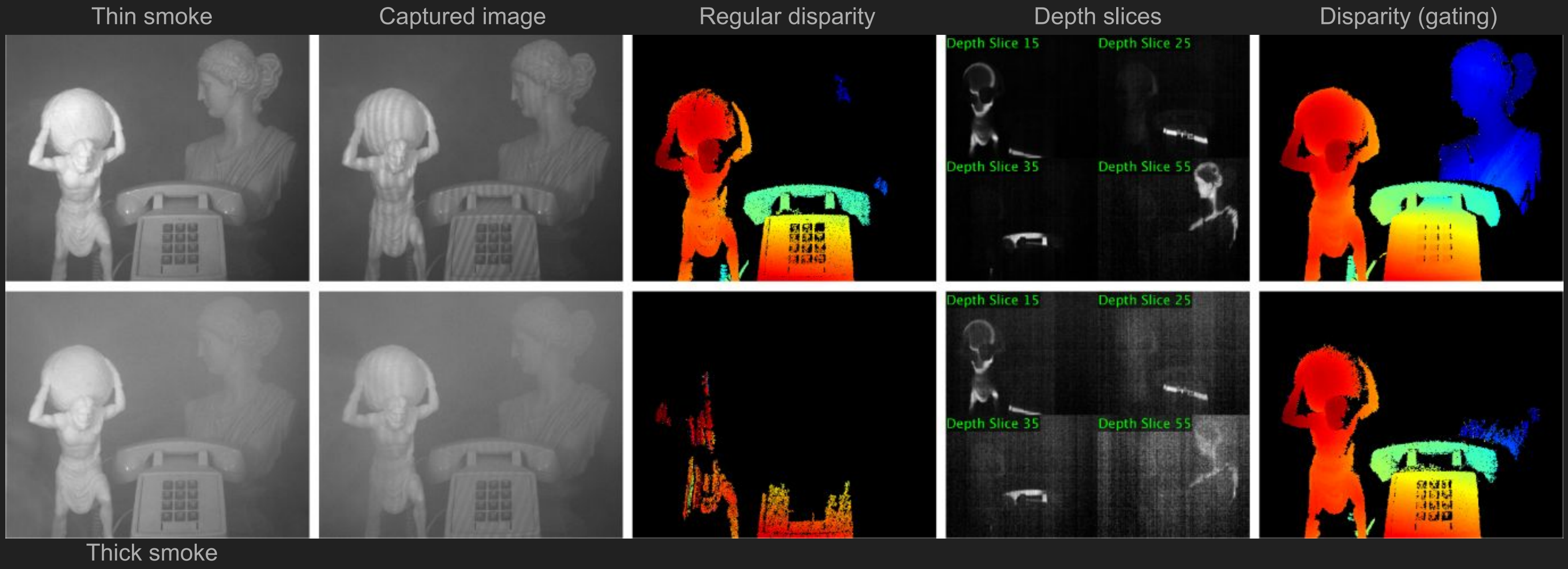
Imaging with Laser Projectors

- Disparity Gating
  - Allows triangulating a point
  - The illumination pattern and camera mask allow us to locate the position of a pixel



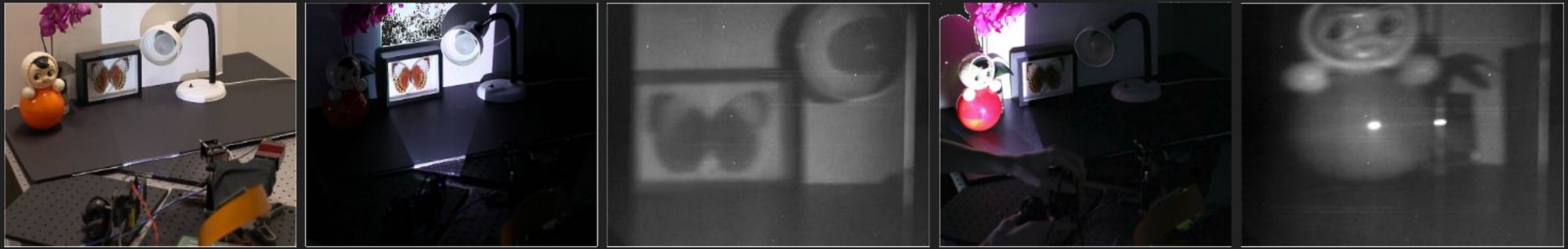
- Rotate the camera 90 degrees
- Set a depth plane
- Capture images

Imaging with Laser Projectors



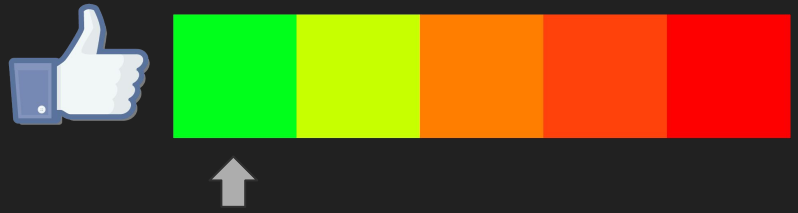
Imaging with Laser Projectors

- Dual Videography
  - Similar to Disparity Gating but with the plane at infinity
  - Capturing the physical transport matrix is still challenging
  - This method captures an approximate epipolar image from the projector's view



Conclusion

- Energy efficient codes product sharp, artifact-free images
- **Rating:** 1.0



- **Pros**
  - Uses physical limitations of the sensor
  - Produces sharp images
  - Uses off-the-shelf components
  - Several applications
  - Poses problem statement for potential future projectors
- **Cons**
  - The math can be hard to understand

Questions?