High Resolution 2D Imaging and 3D Scanning with Line Sensors

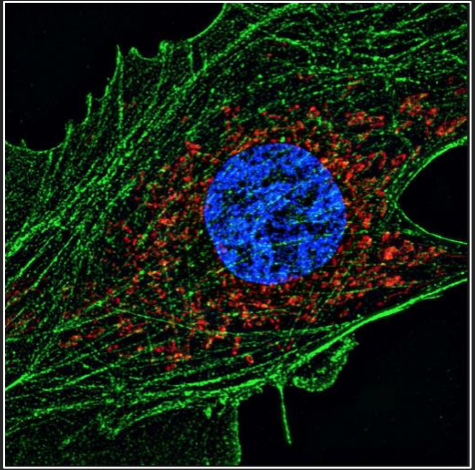
Thesis Defense

Jian Wang

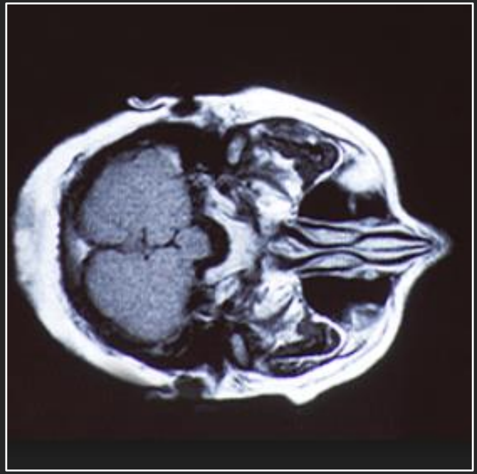
7/27/2018

Imaging – Key driver of the modern society

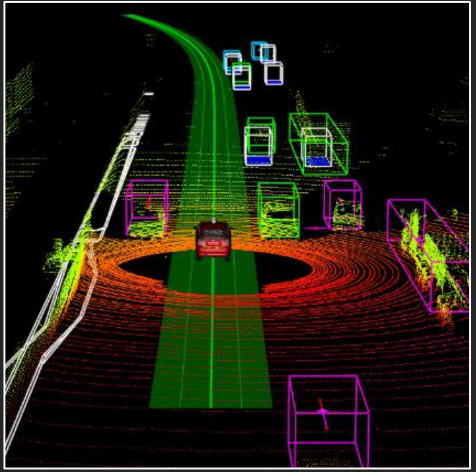
Hubble telescope



Super-res. microscopy



CT



LIDAR

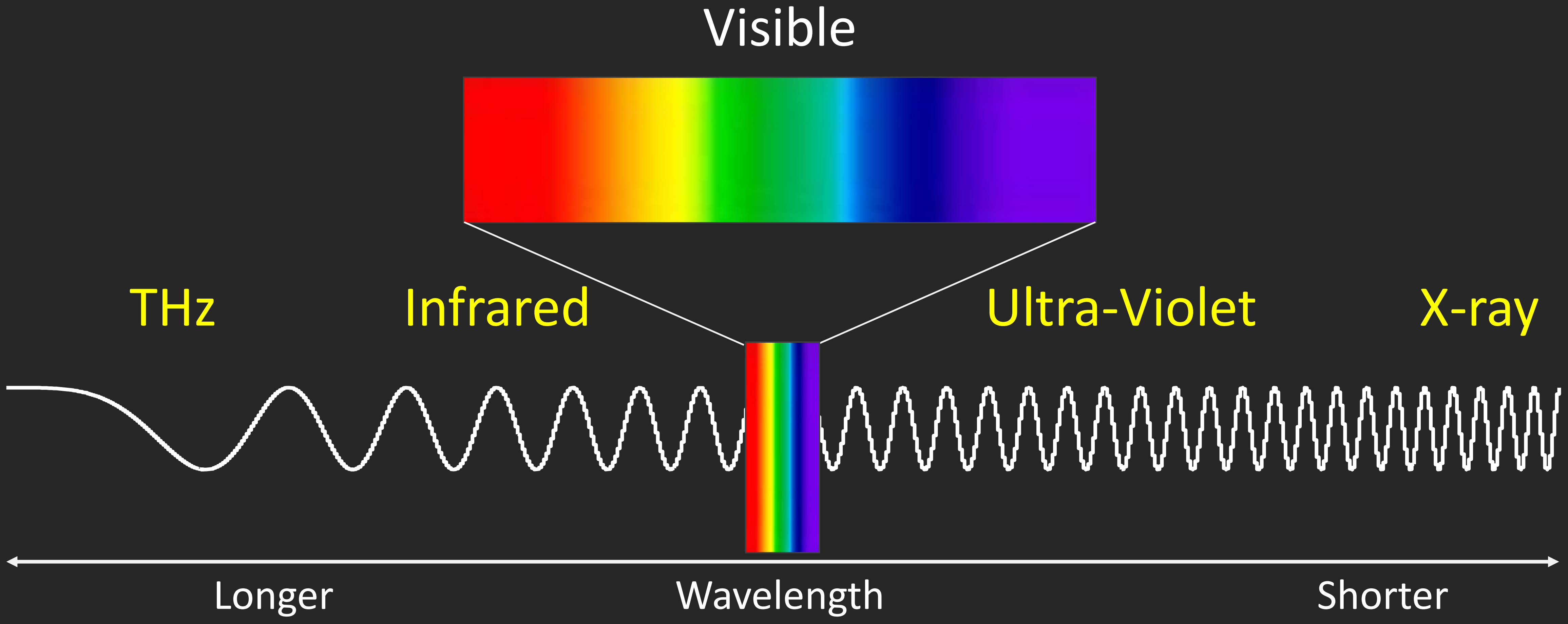
Cellphone entertainment

Traditional imaging methods are woefully inadequate

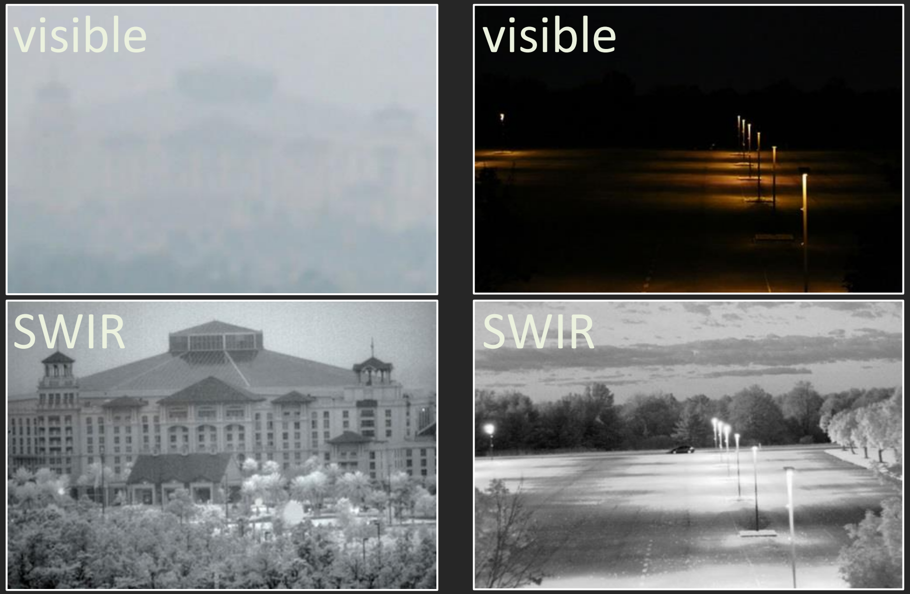
- Passive imaging
  - Non-visible light imaging (challenge I)
- Active imaging
  - 3D scanning under strong ambient light (challenge II)
  - 3D scanning under strong global light like in scattering media (challenge III)

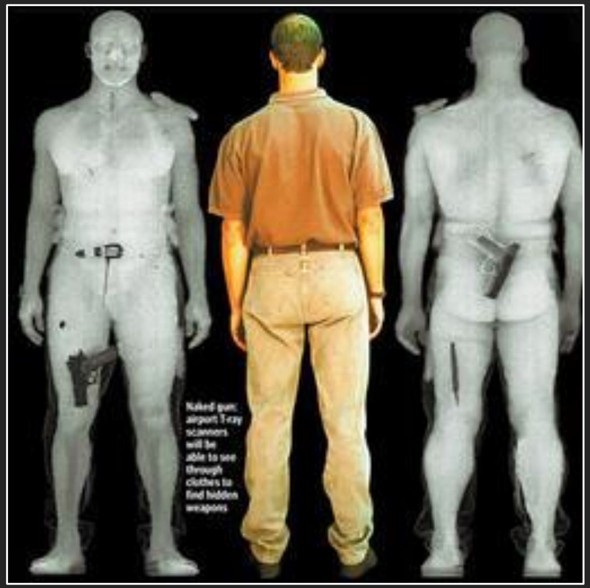
with high spatial resolution
high temporal resolution
low cost

Challenge I: Passive imaging in non-visible wavebands



Challenge I: Passive imaging in non-visible wavebands





SWIR
for seeing through fog
and night vision

MWIR
for high contrast thermal imaging

THz
for surveillance

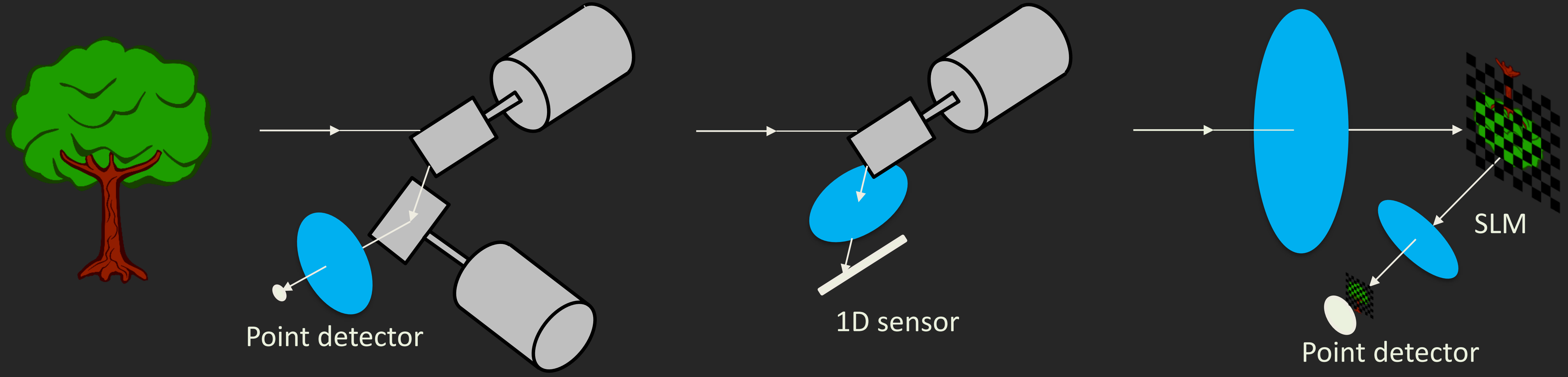
Images courtesy: http://www.sensorsinc.com/gallery/images
https://www.edmundoptics.com/resources/application-notes/imaging/what-is-swir/

Per-pixel price

Spectral band	Detector technology	Per-pixel price ($/pix)
mmW/THz	Multiple	$10^2 - 10^4$
LWIR	HgCdTe	$< 10^1$
	Bolometer	10^{-2}
MWIR	InSb/PbSe	10^{-1}
SWIR	InGaAs/PbSe	10^{-1}
NIR/VIS/NUV	Si	$< 10^{-6}$
MUV	Si (thinned)	$< 10^{-3}$
EUV	Si-PIN/CdTe	$10^2 - 10^3$
Soft x ray	Si (thinned)	10^{-2}
	Si-PIN/CdTe	$10^2 - 10^3$
Hard x ray/gamma	Multiple	$10^2 - 10^4$

Gehm, M. E., and D. J. Brady. "Compressive sensing in the EO/IR." Applied optics 54.8 (2015)

Inexpensive alternative designs for 2D imaging in non-visible wavebands



Point detector with 2D scanning | 1D sensor with 1D scanning | Point detector with multiplexing

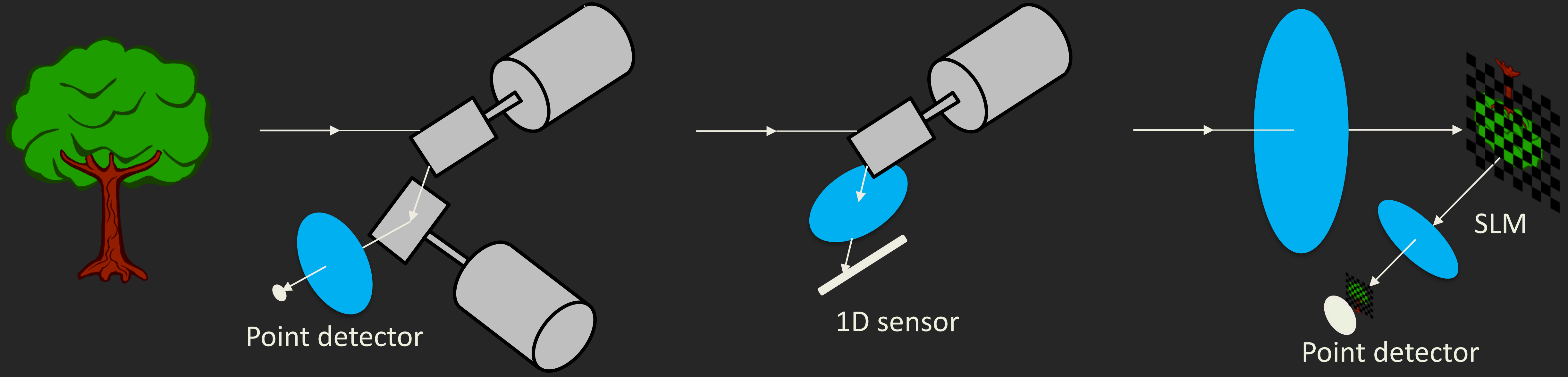
$R_{galvo} = 5000$

$R_{SLM} = 10^4$, $10 \times$ compression

Image resolution $N \times N$

Duarte, Marco F., et al. "Single-pixel imaging via compressive sampling." IEEE signal processing magazine 25.2 (2008): 83-91.

Inexpensive alternative designs for 2D imaging in non-visible wavebands



Point detector with 2D scanning | 1D sensor with 1D scanning | Point detector with multiplexing

Frame rate: $\frac{5000}{N^2}$ | $\frac{5000}{N}$ | $\frac{10^5}{N^2}$

$$N = 1000$$

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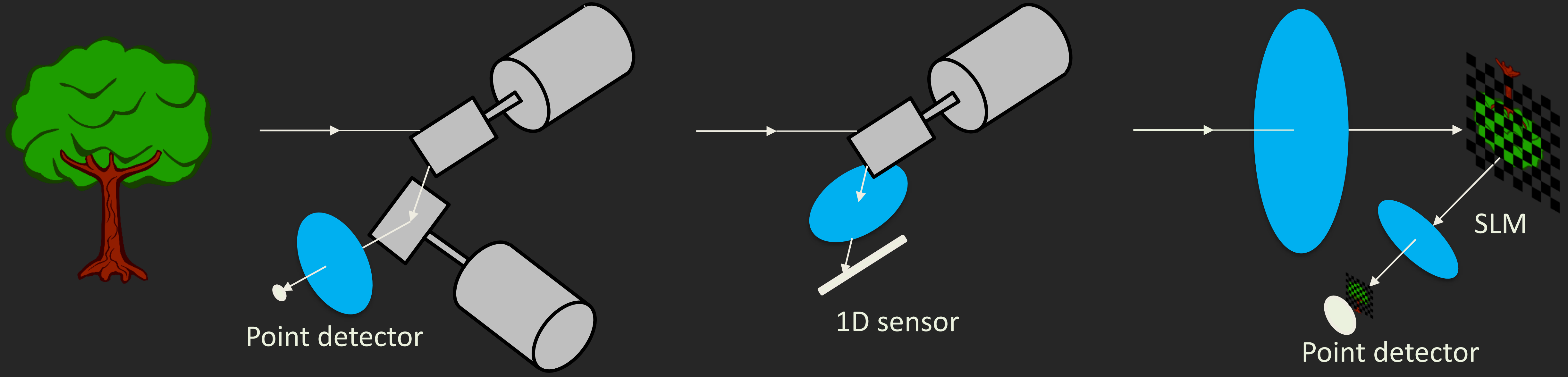
Inexpensive alternative designs for 2D imaging in non-visible wavebands

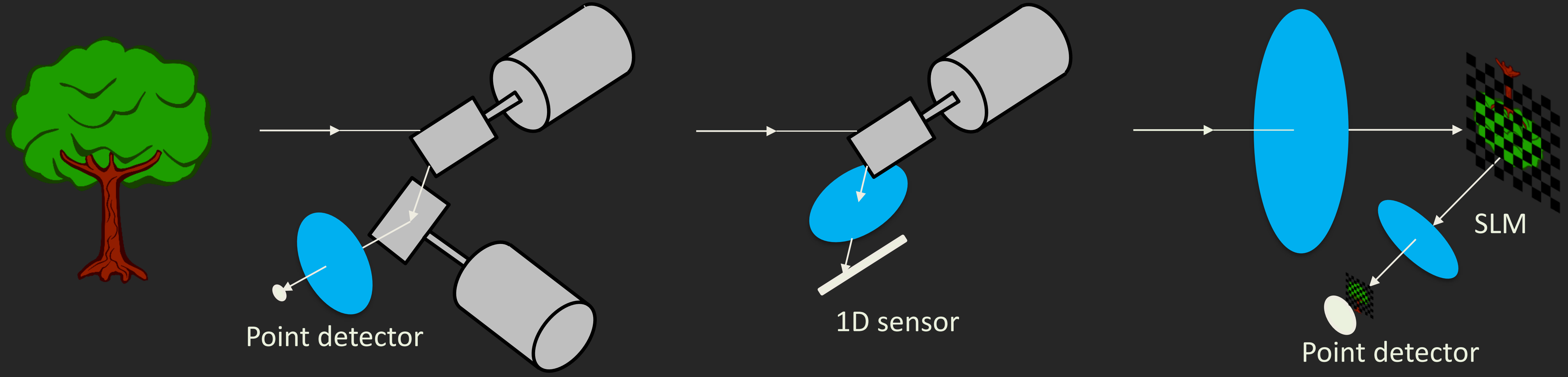


Point detector with 2D scanning | 1D sensor with 1D scanning | Point detector with multiplexing

	Point detector with 2D scanning	1D sensor with 1D scanning	Point detector with multiplexing
Frame rate	0.005	5	0.1

Duarte, Marco F., et al. "Single-pixel imaging via compressive sampling." IEEE signal processing magazine 25.2 (2008): 83-91.

Inexpensive alternative designs for 2D imaging in non-visible wavebands

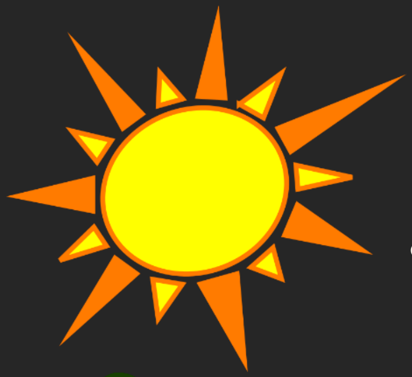


Point detector with 2D scanning | 1D sensor with 1D scanning | Point detector with multiplexing

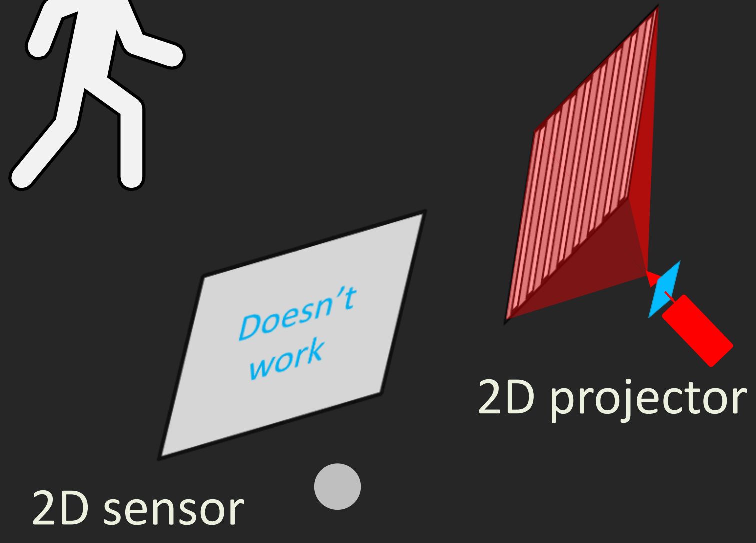
	Point detector with 2D scanning	1D sensor with 1D scanning	Point detector with multiplexing
Frame rate	$\frac{5000}{N^2}$	$\frac{5000}{N}$	$\frac{10^5}{N^2}$
Light throughput	Much light loss	Much light loss	Half light

Duarte, Marco F., et al. "Single-pixel imaging via compressive sampling." IEEE signal processing magazine 25.2 (2008): 83-91.

Challenge II: Active imaging under ambient light

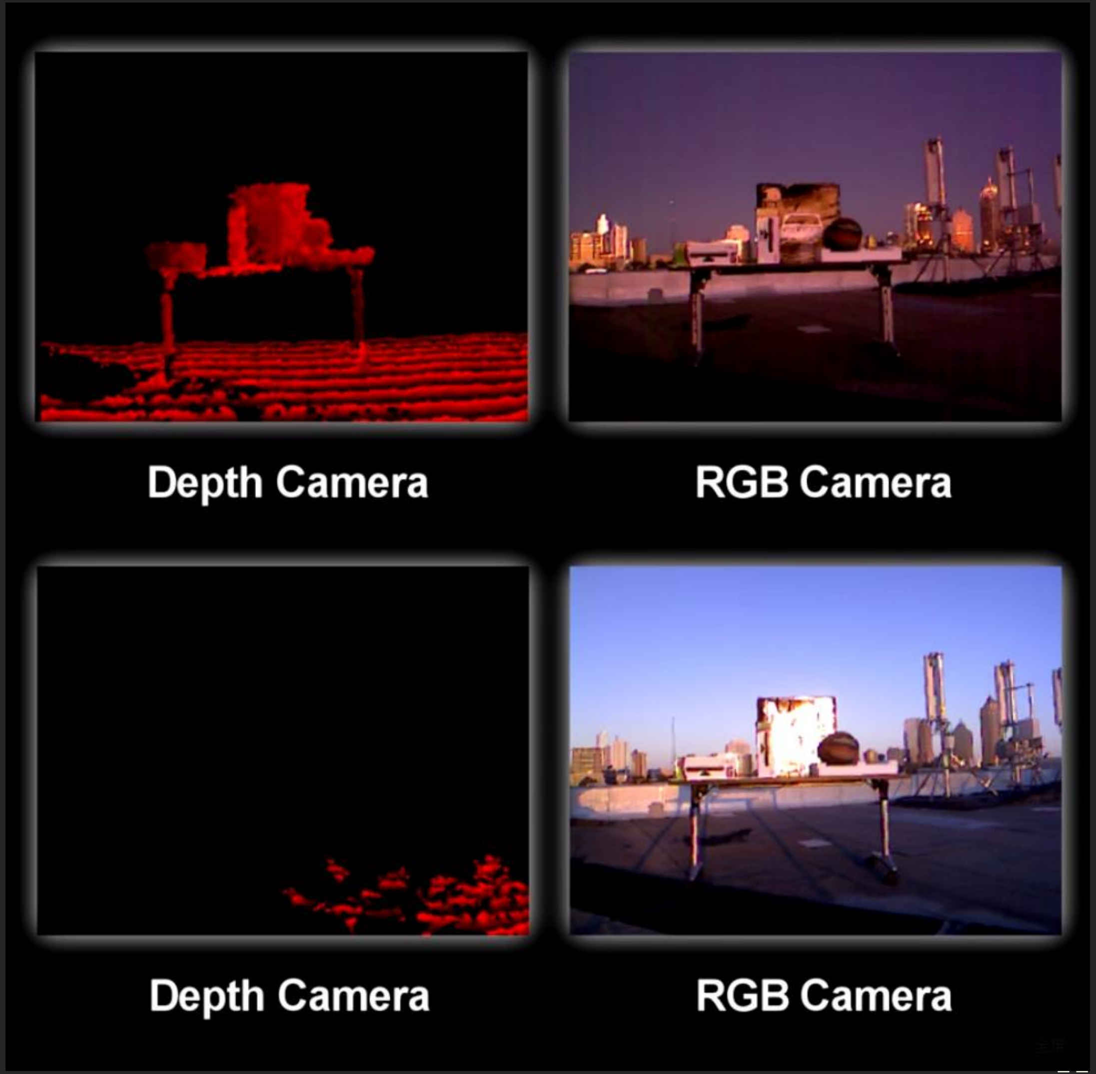


- Sunlight is orders of magnitude stronger than active light source
  - Photon noise



Microsoft Kinect

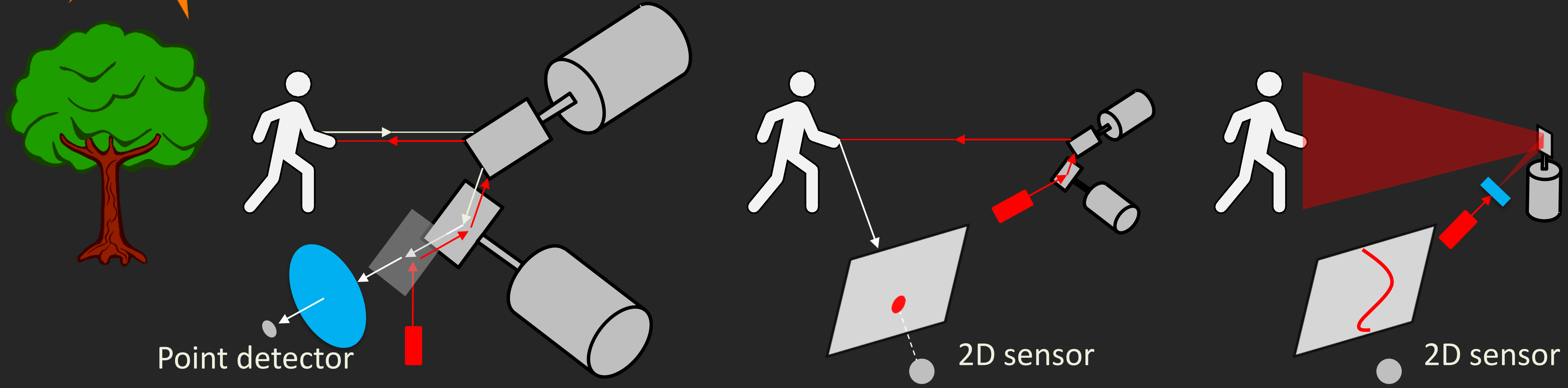
Fast but not robust



Images courtesy: https://www.youtube.com/watch?v=rl6CU9aRDIo

Strategy 1: concentrate and scan

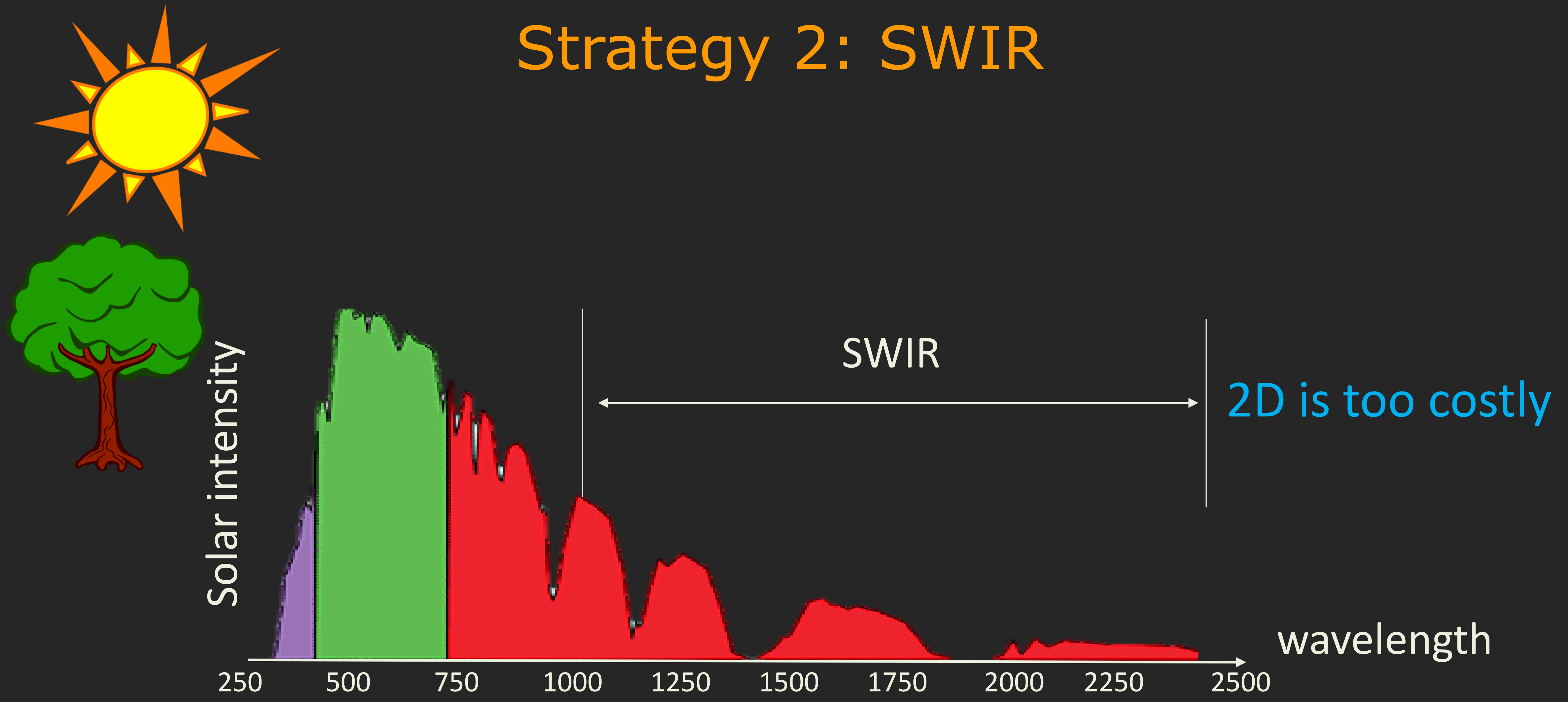
Too slow



Point scanning-based TOF | Point scanning-based SL | Line scanning-based SL

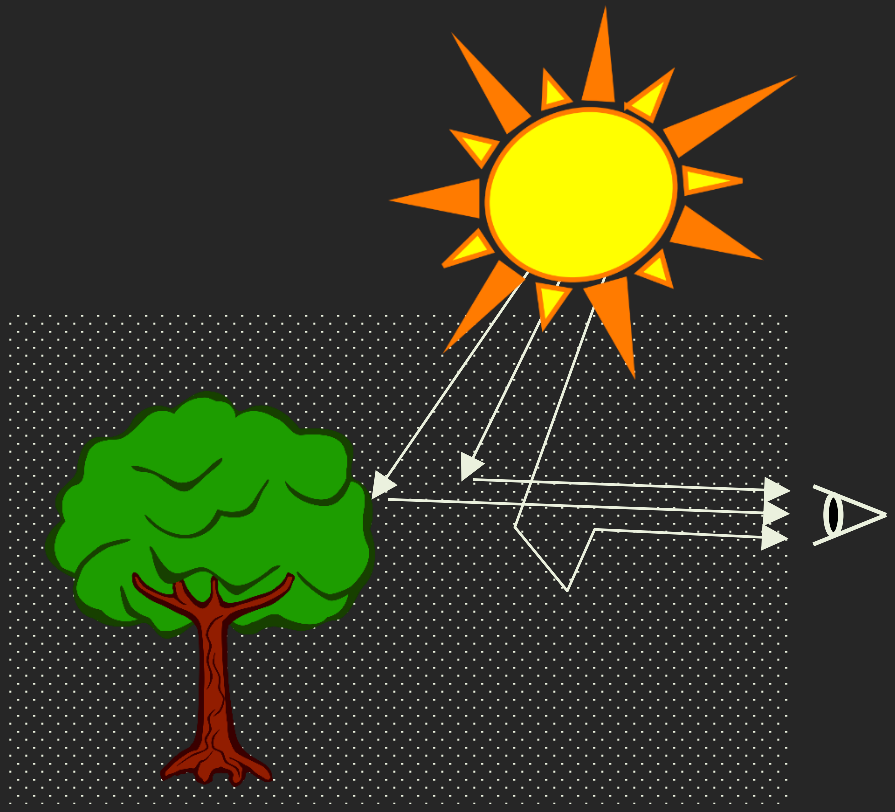
	Point scanning-based TOF	Point scanning-based SL	Line scanning-based SL
SNR increase	N^2	N^2	N
Frame rate	$\frac{5000}{N^2}$	$\frac{30}{N^2}$	$\frac{30}{N}$

Strategy 2: SWIR



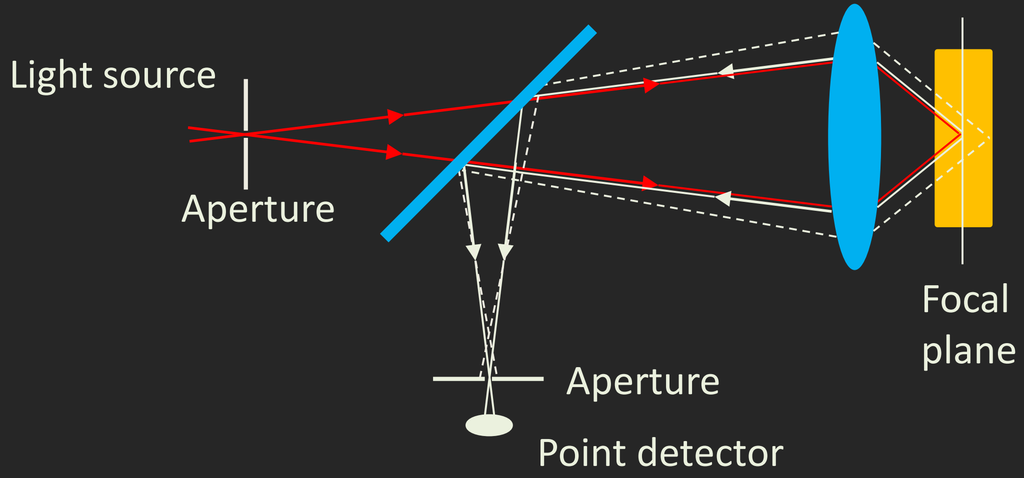
Solar energy distribution

Challenge III: Active imaging in scattering medium



Problem with imaging in scattering medium

Strategies:



Point scanning-based selective imaging: confocal imaging

Use of SWIR

Too slow

2D Too costly

Marvin, Minsky. "Microscopy apparatus." U.S. Patent No. 3,013,467. 19 Dec. 1961.

Traditional imaging methods are woefully inadequate

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- Active imaging
  - 3D scanning under strong ambient light (Challenge II)
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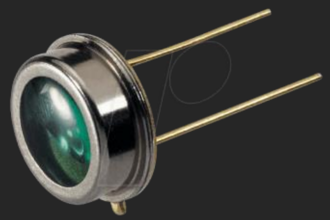
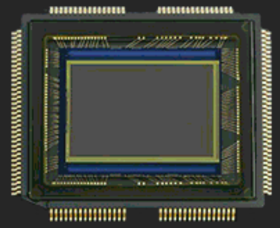


Point detector based

- Low cost
- Robust
- Too slow

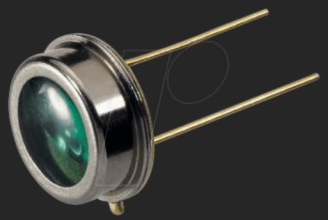


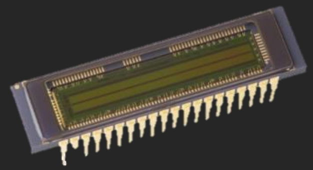
2D sensor based

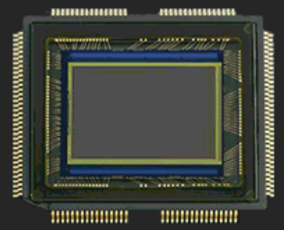
- High cost
- Not reliable in harsh envir.
- High ST resolution

Contributions

- Passive imaging
  - Non-visible light imaging
- Active imaging
  - 3D scanning under strong ambient light
  - 3D scanning under strong global light like in scattering media

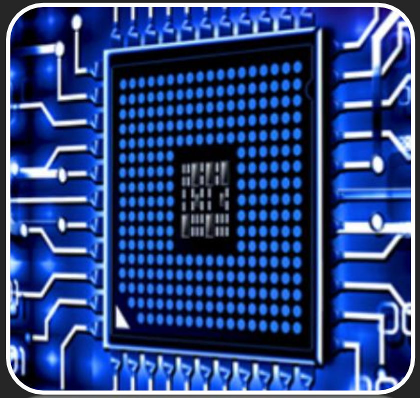




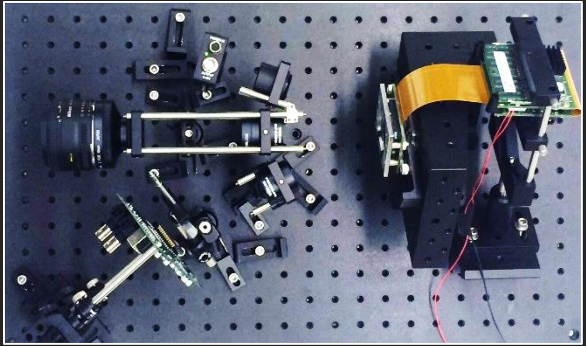


Point detector based	Line sensor based	2D sensor based
• Low cost	• Low cost	• High cost
• Robust	• Robust	• Not reliable in harsh envir.
• Too slow	• High ST resolution	• High ST resolution

Line sensor + Optics + Mechanics + Computation



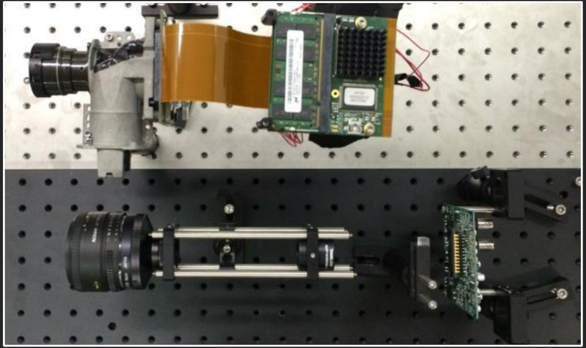
- Benefits
  - Affordable price / High resolution / High-speed readout / Bigger pixel / Have space on top/bottom / Frame transfer…
- Sensing modality
  - Visible light / SWIR / CW-TOF / SPAD / DVS / PSD…



LiSens

2D imaging architecture

Jian Wang, Mohit Gupta, and Aswin C. Sankaranarayanan. "LiSens-A scalable architecture for video compressive sensing." ICCP 2015.



DualSL

3D scanning architecture

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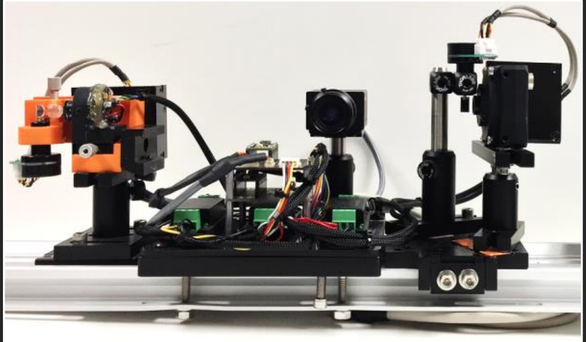

TriLC

Robust proximity sensor

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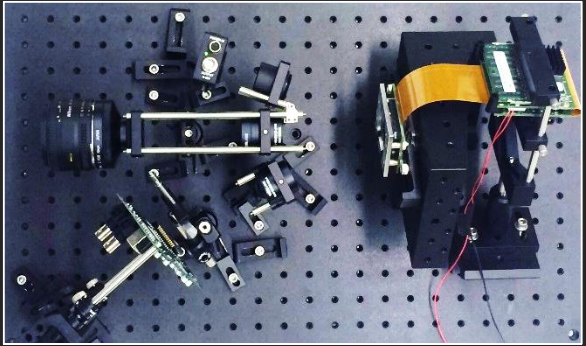
High spatial temporal resolution with line sensors



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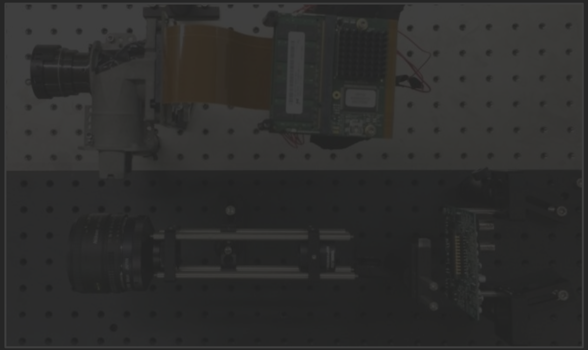

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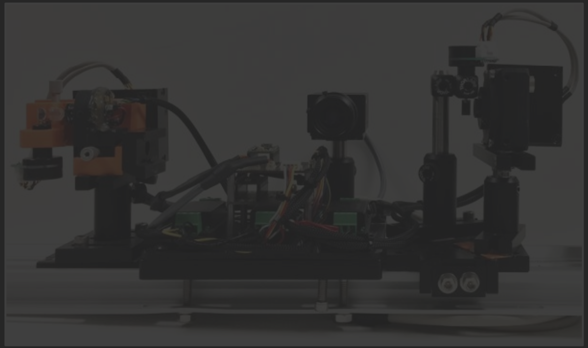

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High spatial temporal resolution
with line sensors

Task: Imaging beyond visible light

- Choice 1: 2D camera Too costly!
- Choice 2: camera based on single pixel
  - Option 1: single pixel + 2D galvomirror
  - Option 2 (better): single pixel + spatial light modulator, Single Pixel Camera

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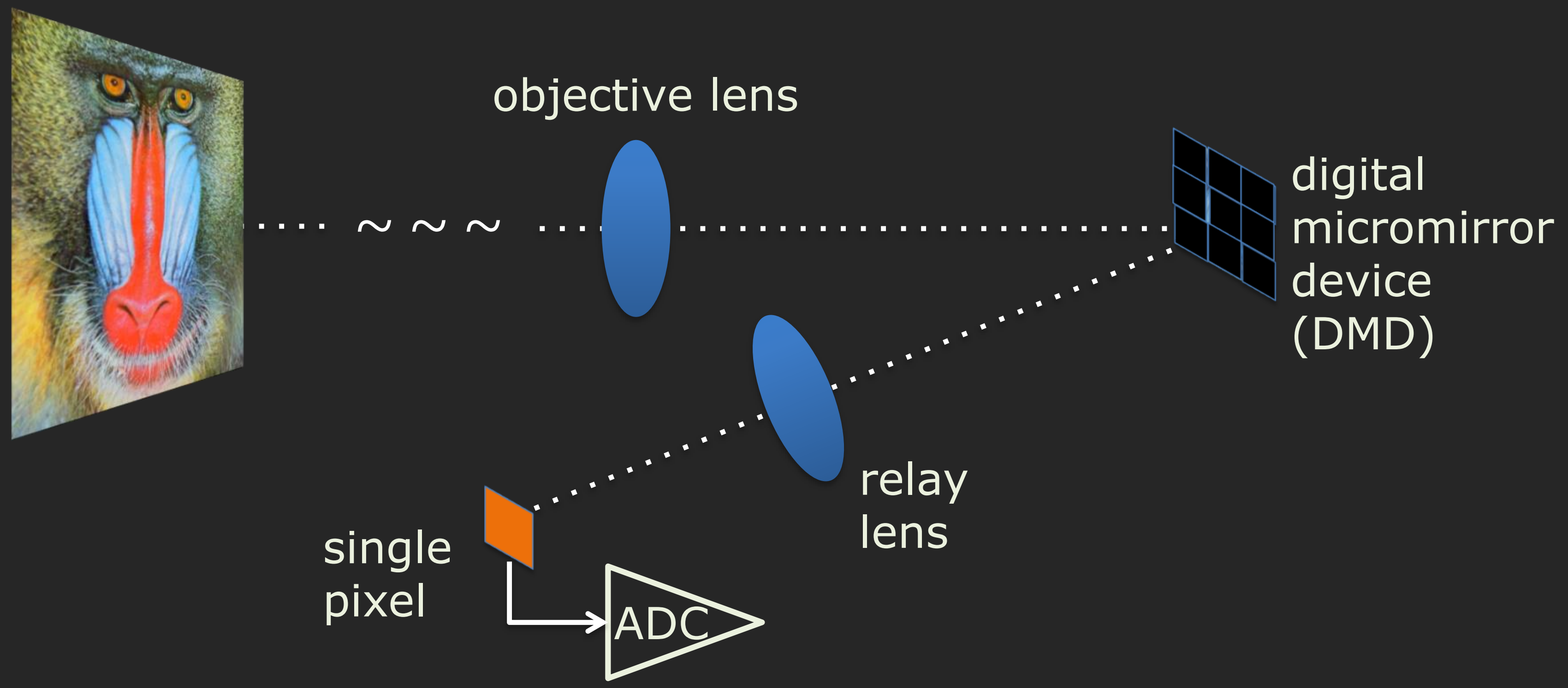

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Best result: 128×128 at video rate

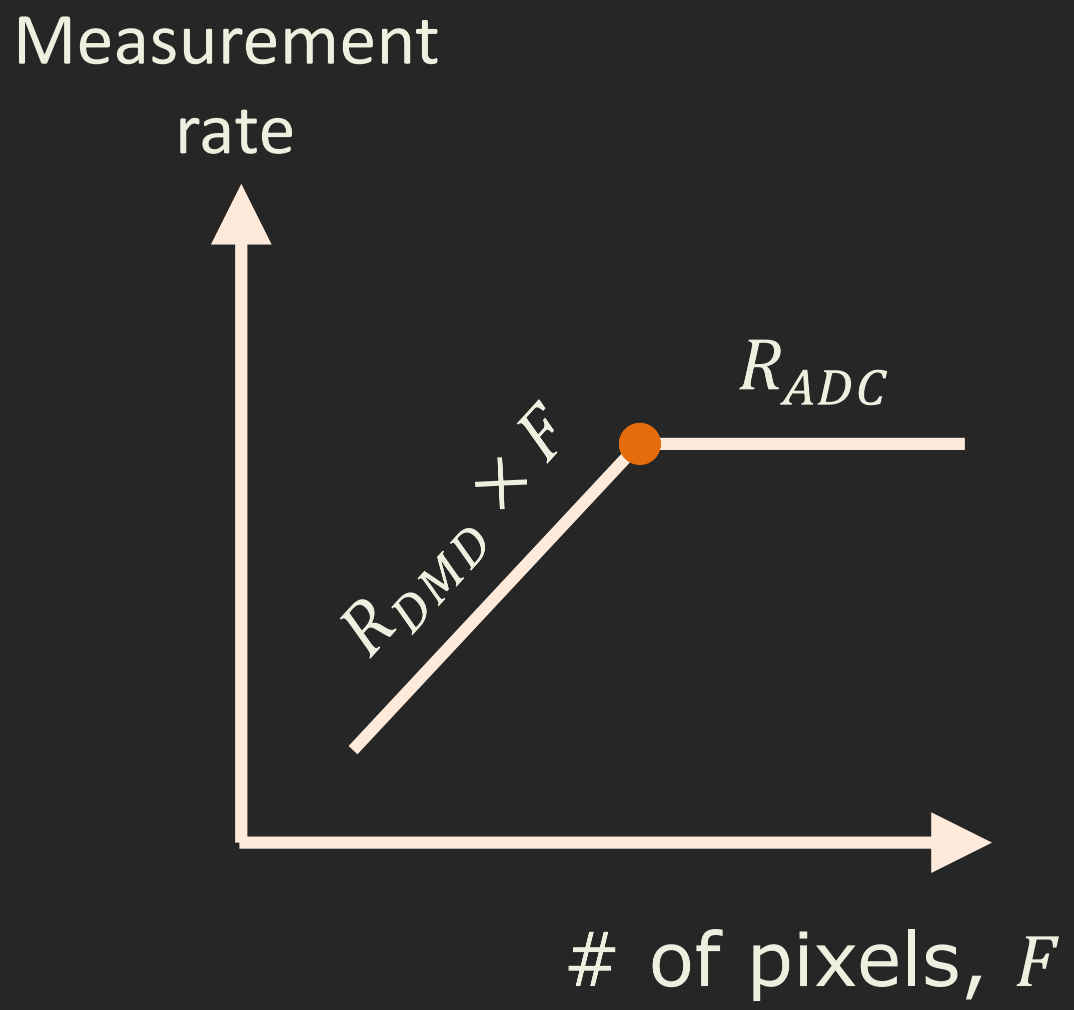
[Sankaranarayanan et al, Video Compressive Sensing for Spatial Multiplexing Cameras using Motion-Flow Models, arXiv:1503.02727]

Why cannot SPC capture mega-pixel video?

- DMD is slow

- Calculation
  - Mega-pixel video @ 10fps, $10^6 \times 10 = 10^7$ pixels' value
  - 10x compressive sensing is used
  - Need measurement rate: $\frac{10^7}{10} = 10^6$
    - measurement rate: # of measurements per second
  - DMD can only flip 10^4 times per second

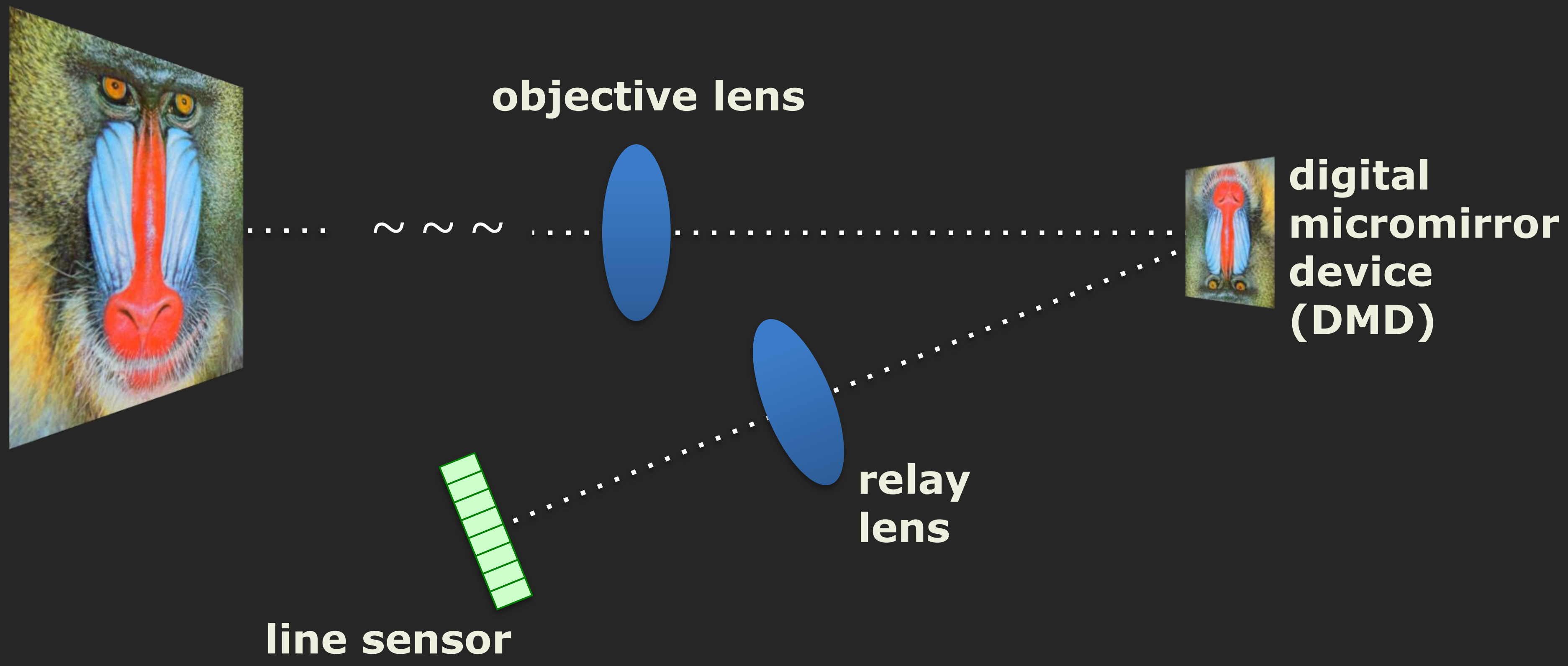
Proposed: Replace the single pixel by multiple pixels



Optimal # of pixels $= \frac{R_{ADC}}{R_{DMD}}$

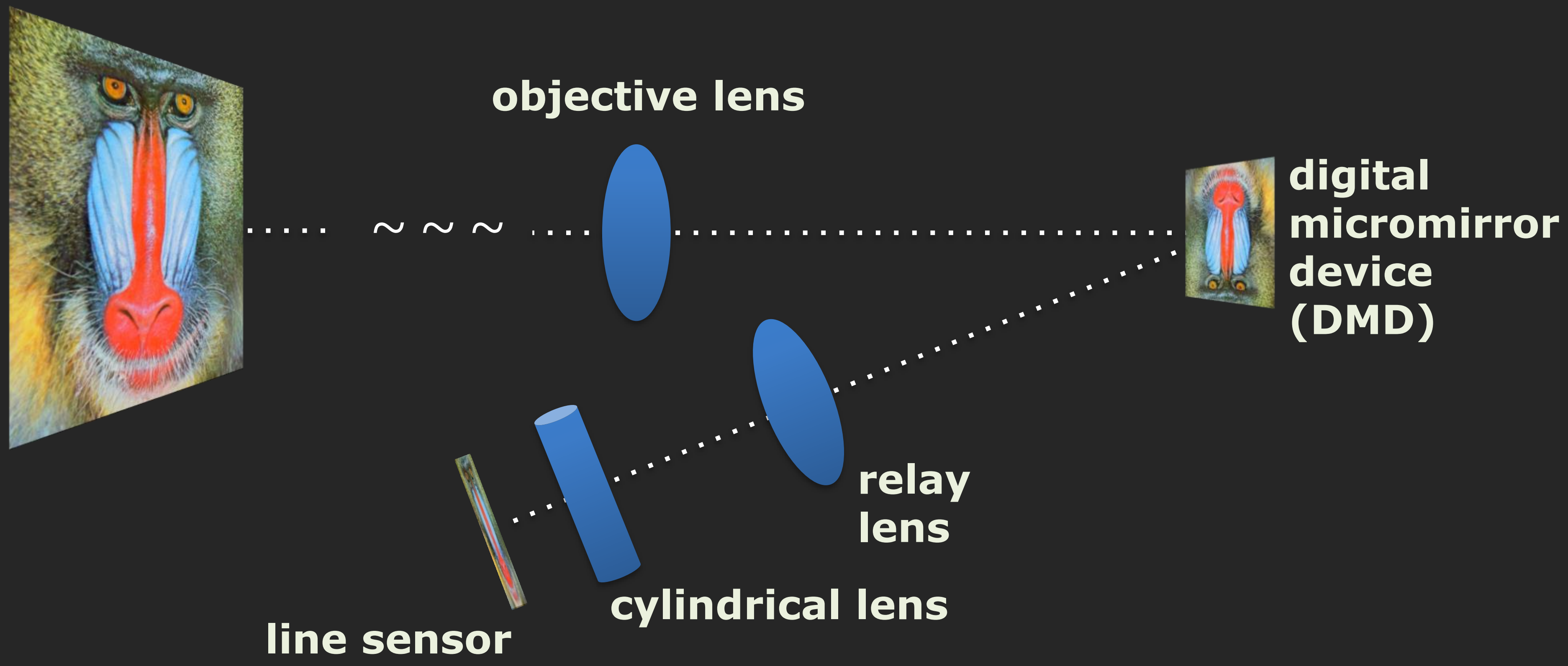
typically only 1000s of pixels

Line-Sensor-based compressive camera (LiSens)



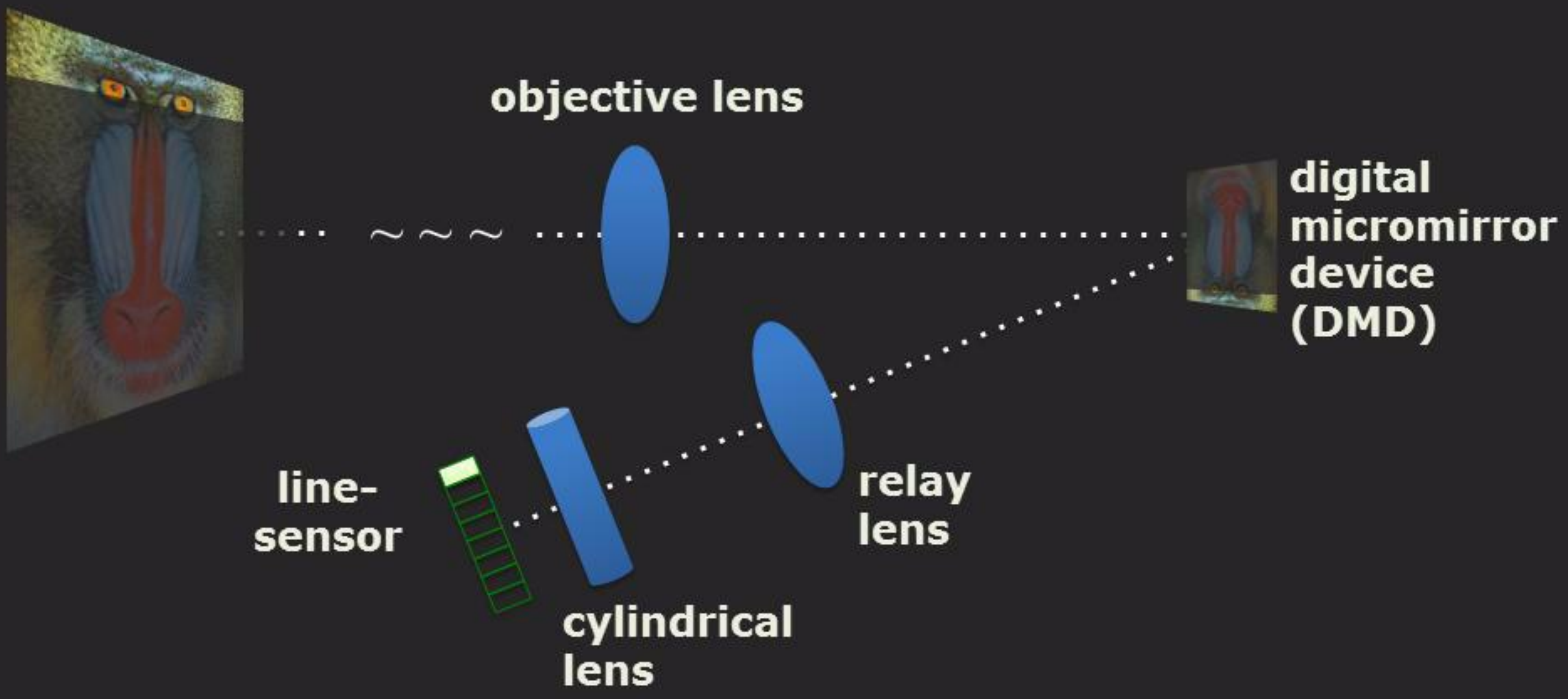
1. Use a linear array of pixels (a line-sensor)

Line-Sensor-based compressive camera (LiSens)



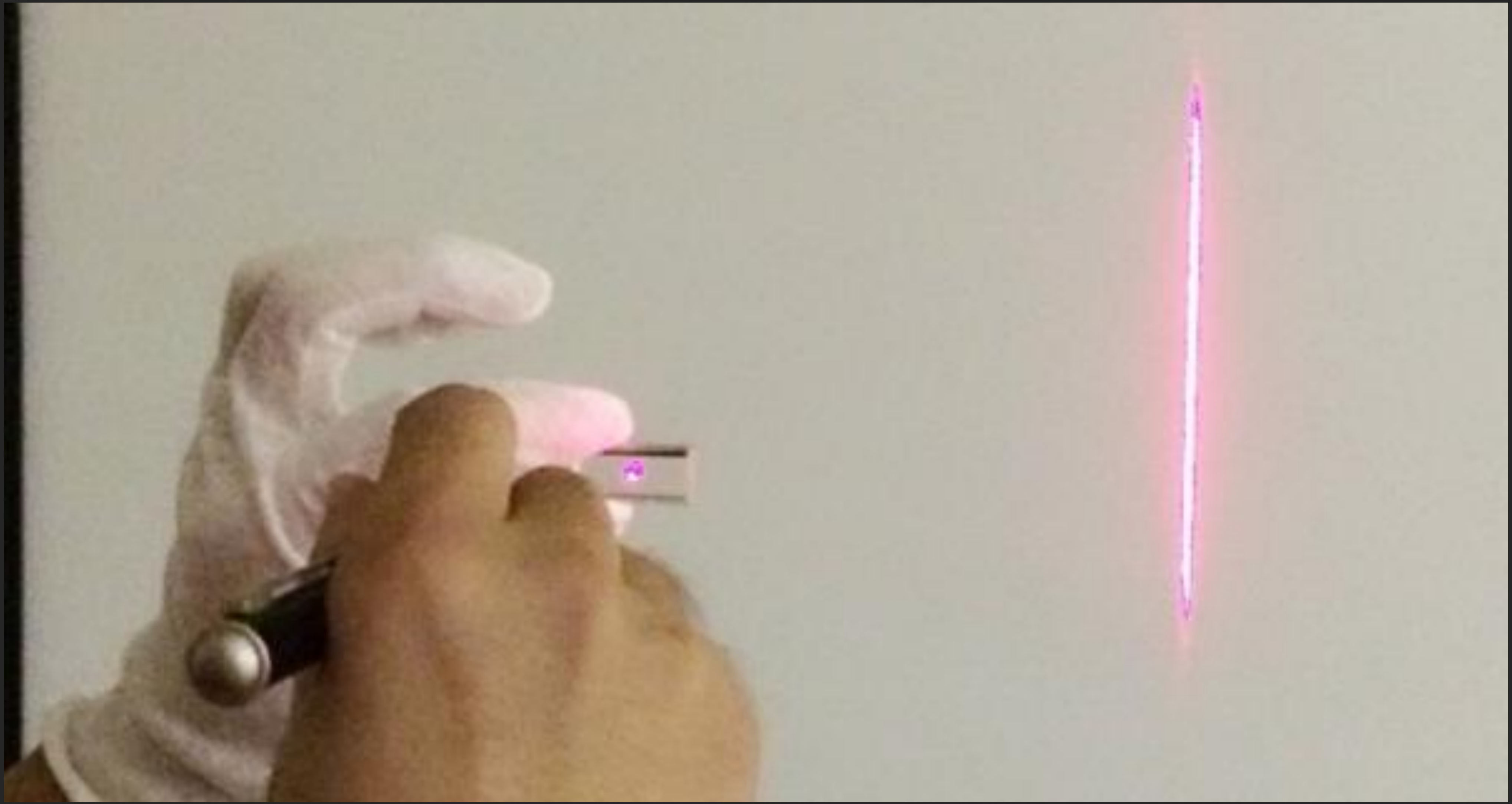
1. Use a linear array of pixels (a line-sensor)
2. Add a cylindrical lens

LiSens

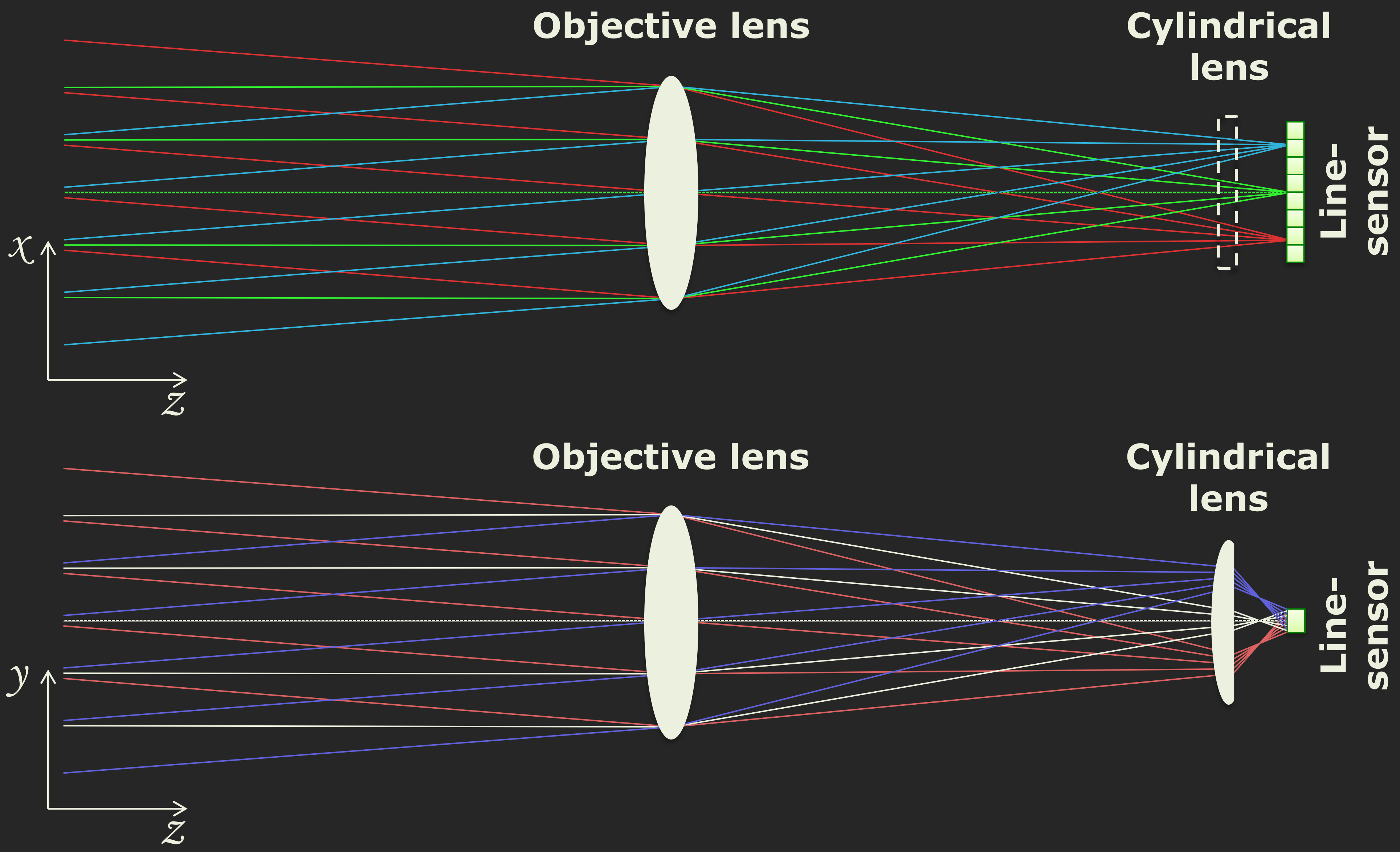


objective lens
digital micromirror device (DMD)
line-sensor
relay lens
cylindrical lens

Cylindrical lens



Each line-sensor pixel integrates one row of the scene



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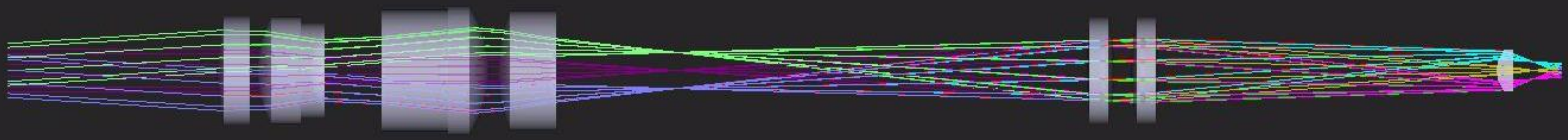
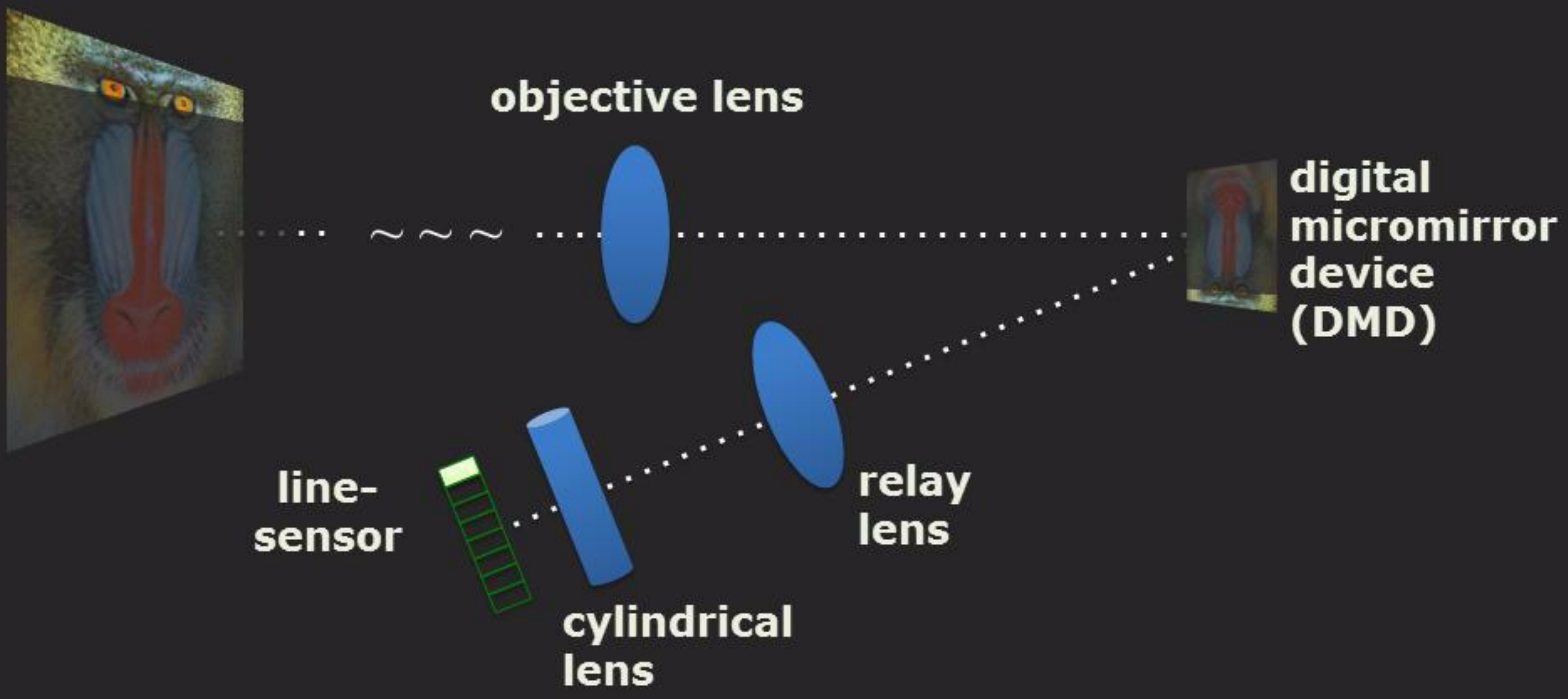


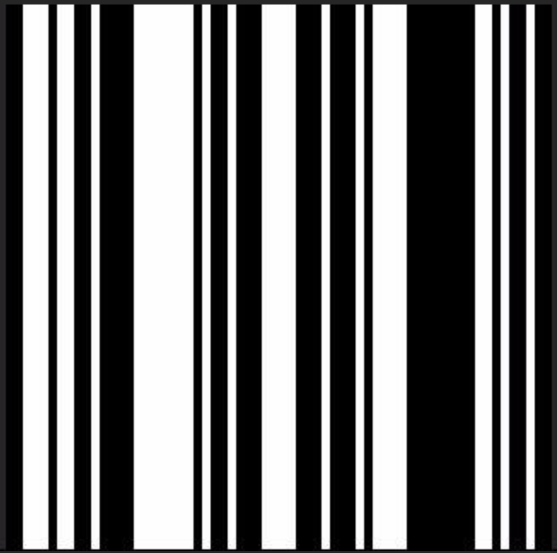
LiSens


objective lens
digital micromirror device (DMD)
line-sensor
relay lens
cylindrical lens

LiSens

(a) Image on DMD

(b) Code on DMD



(c) Coded image

(d) Image on sensor plane

Hardware prototype

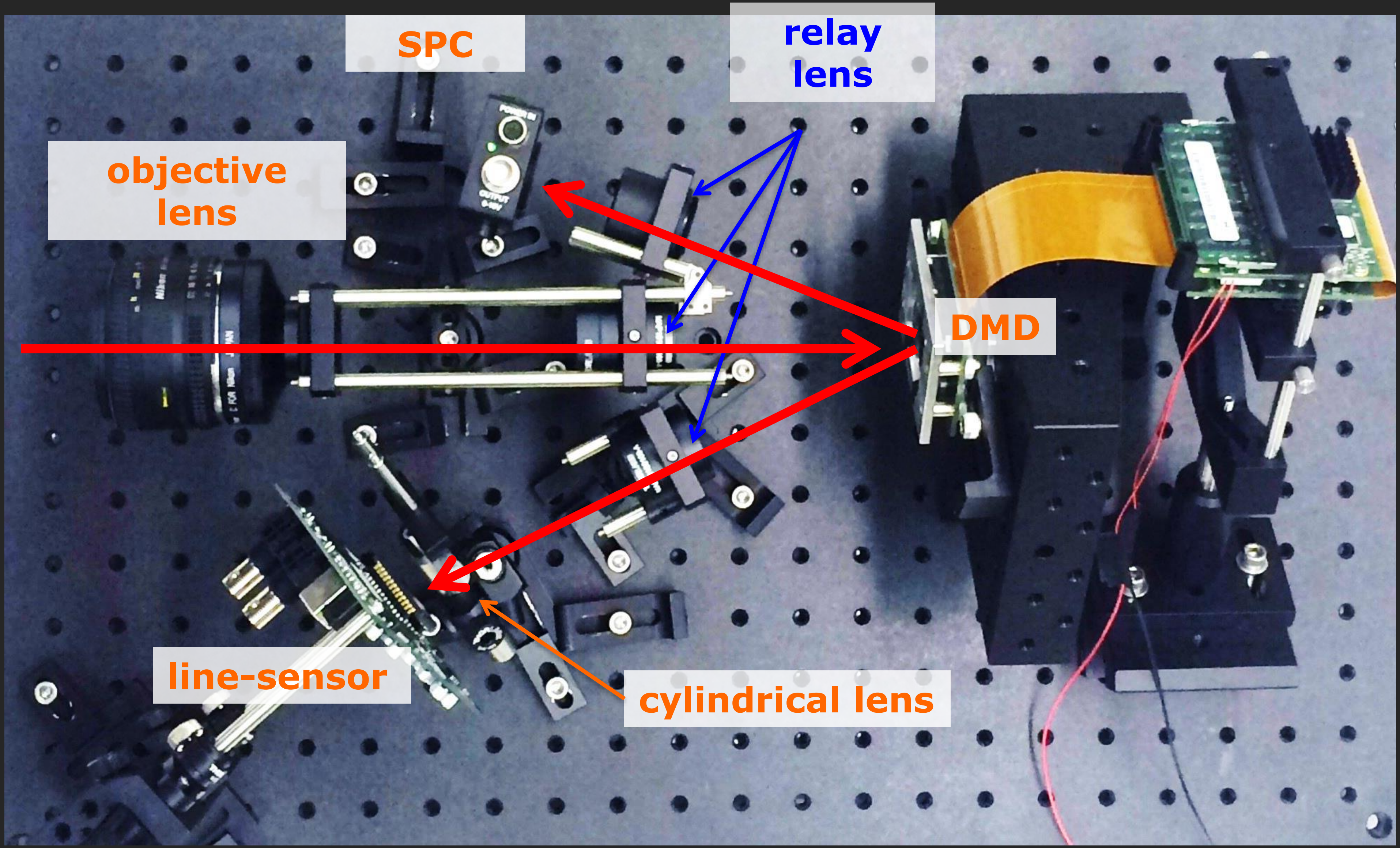


Image resolution: 1024 x 768
Capture duration: 880 ms
Compression ratio: 1x

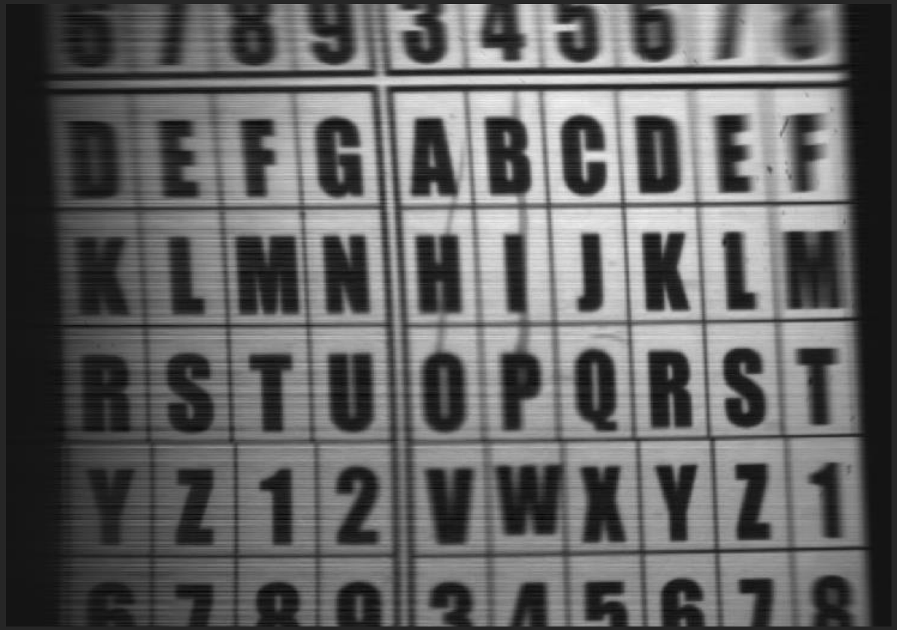

1024 x 768 pixels
9 fps
8x compression


Outdoor

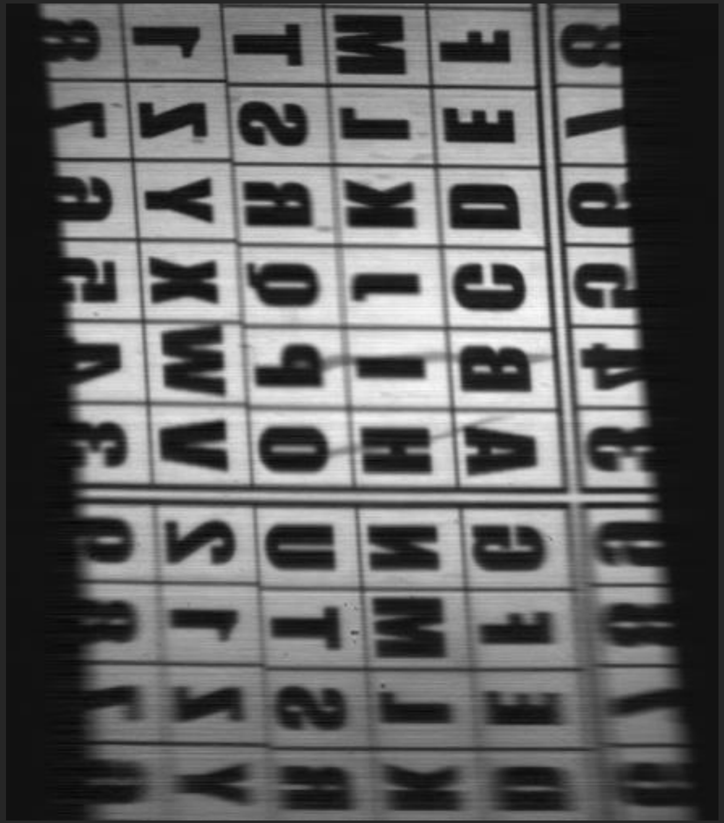

Outdoor

Build two LiSenses in both sides of the DMD

- No light loss
- Joint deblurring



By row-multiplexing LiSens



By column-multiplexing LiSens

Build two LiSenses in both sides of the DMD

- Joint deblurring

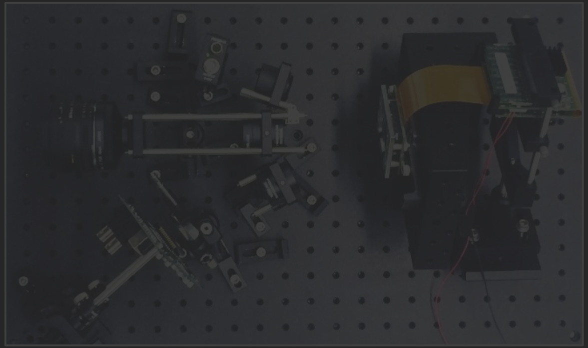
By row-multiplexing LiSens

By column-multiplexing LiSens

By both LiSenses

Summary of LiSens

- A 2D imaging architecture based on line sensor
  - Min. # of pixels to achieve max. possible measurement rate
  - Cost effective
  - High spatial and temporal resolution



LiSens

2D imaging architecture

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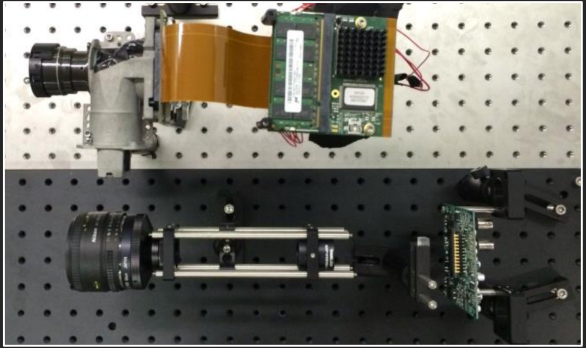

DualSL

3D scanning architecture

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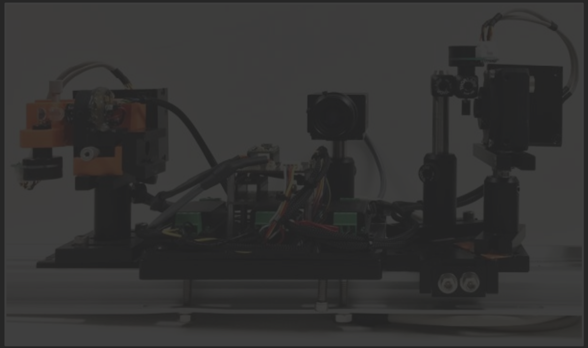

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Robust proximity sensor

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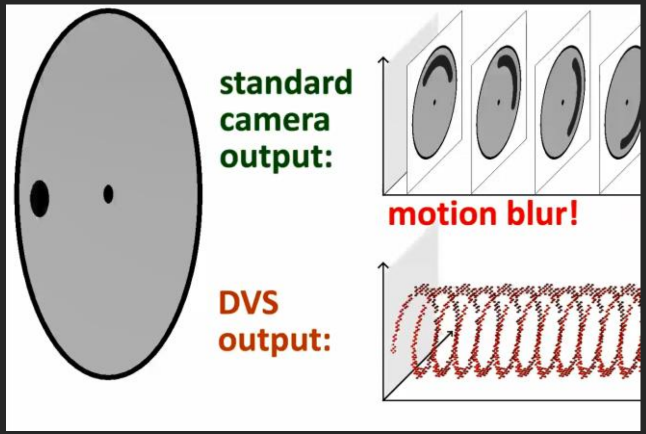
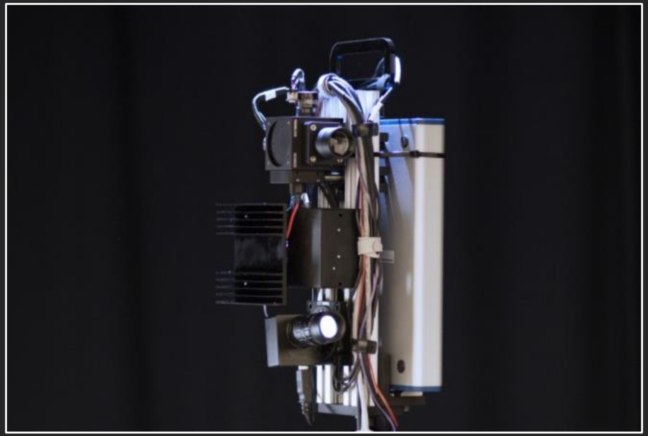
High spatial temporal resolution with line sensors

High Cost of 2D Sensors

SWIR
See through scattering media

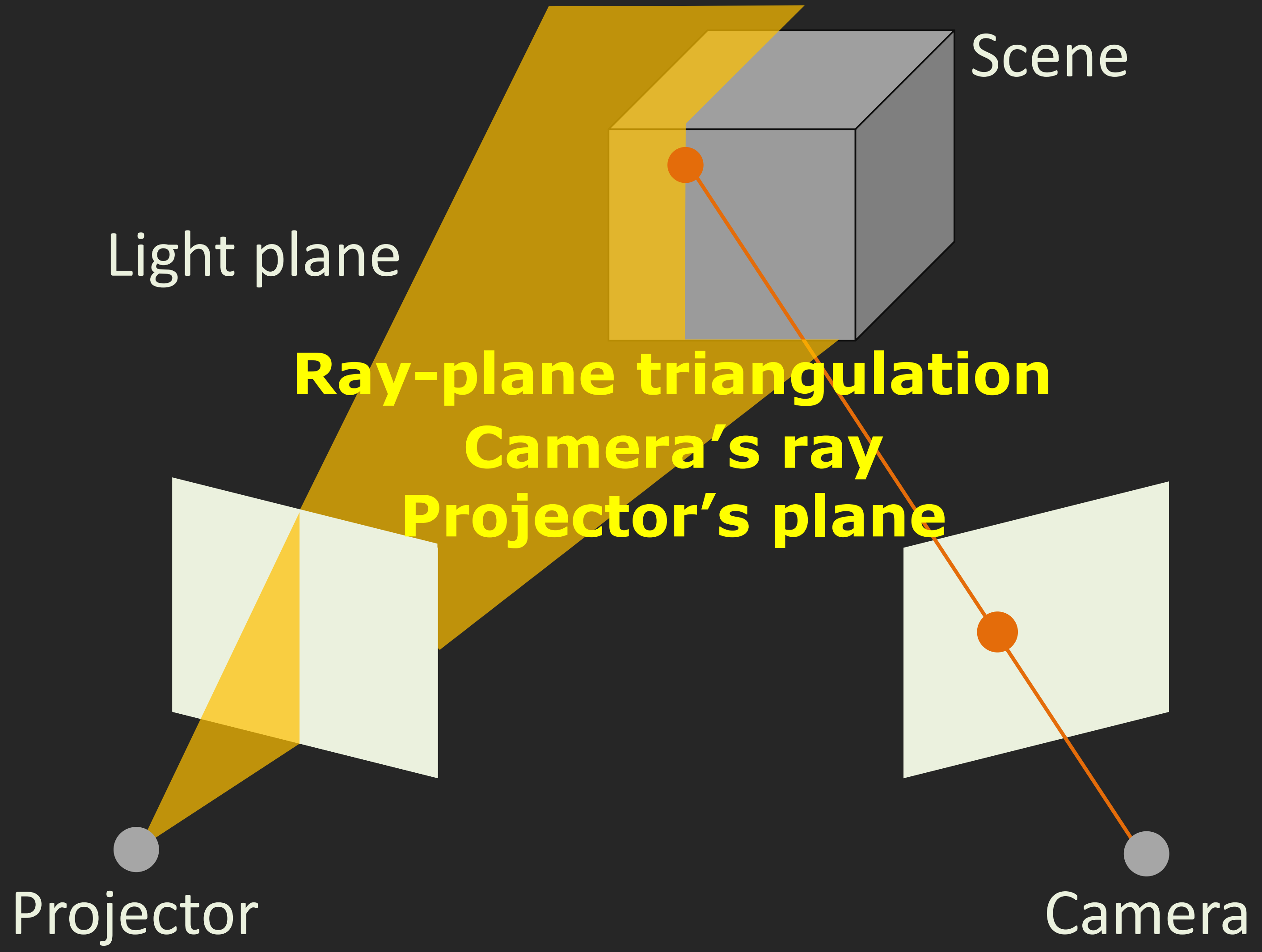
DVS sensor
Highly efficient 3D sensor



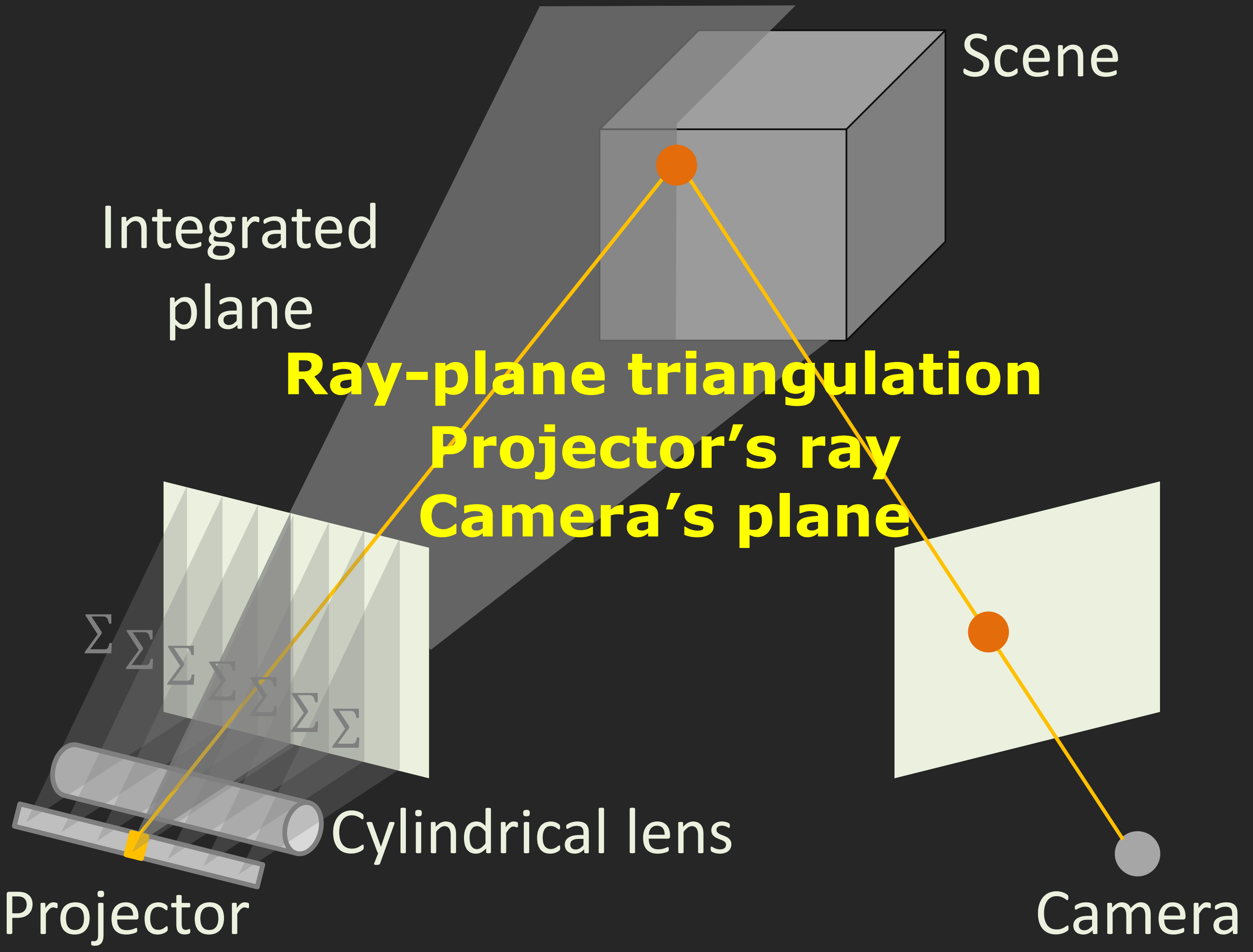


Structured Light 3D Imaging Using 1D Sensor? - Yes

Conventional structured light

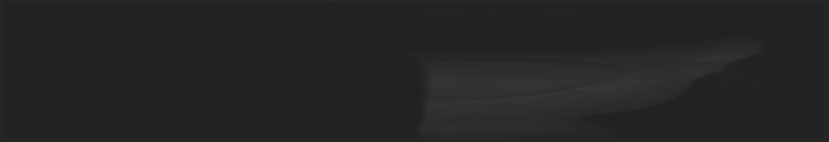


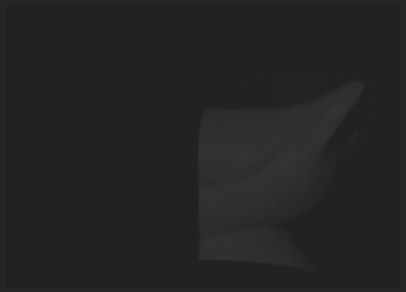
Proposed: Dual structured light (DualSL)



No moving parts

Data acquired by
the 1D sensor



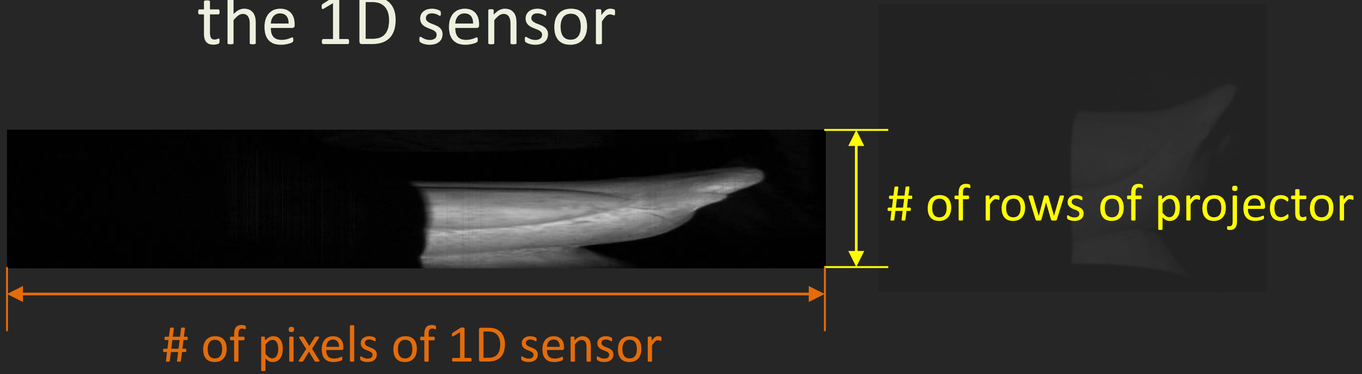


Scene

DualSL using Gray codes

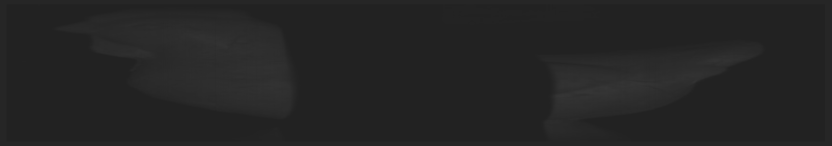
Data acquired by the 1D sensor

Scene



DualSL using Gray codes

Data acquired by
the 1D sensor



Scene

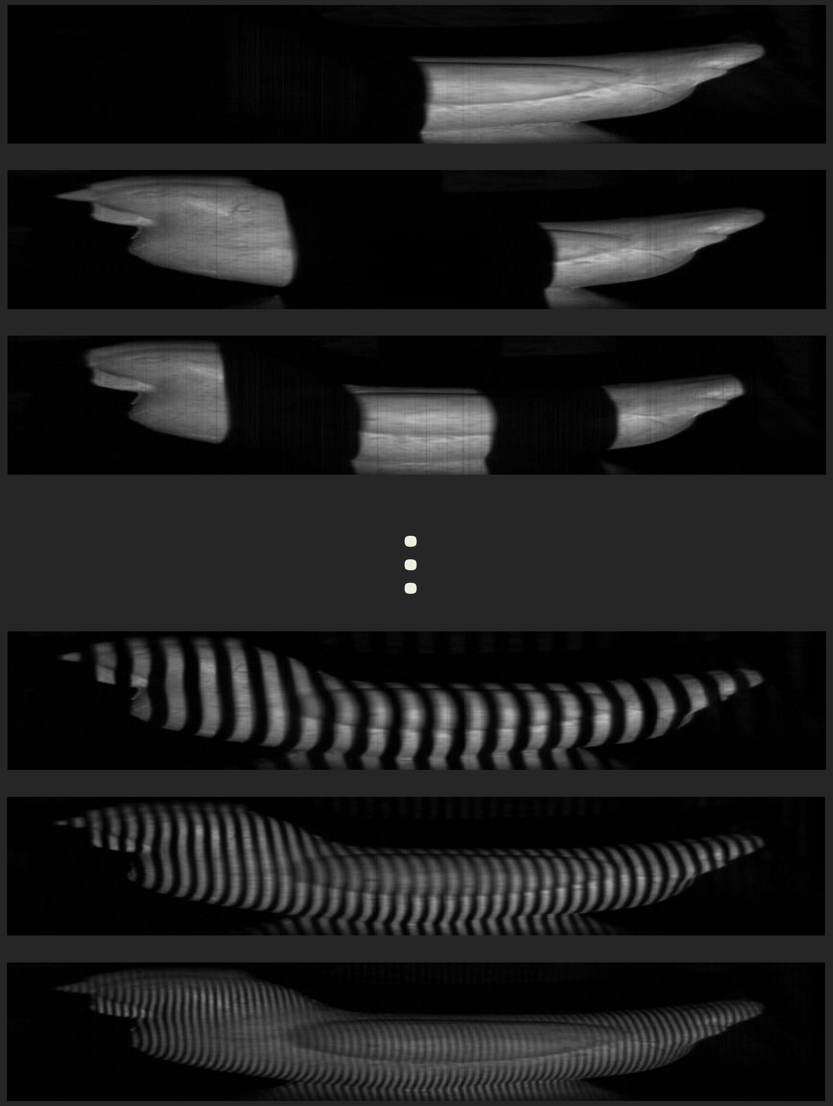
DualSL using Gray codes

Data acquired by the 1D sensor

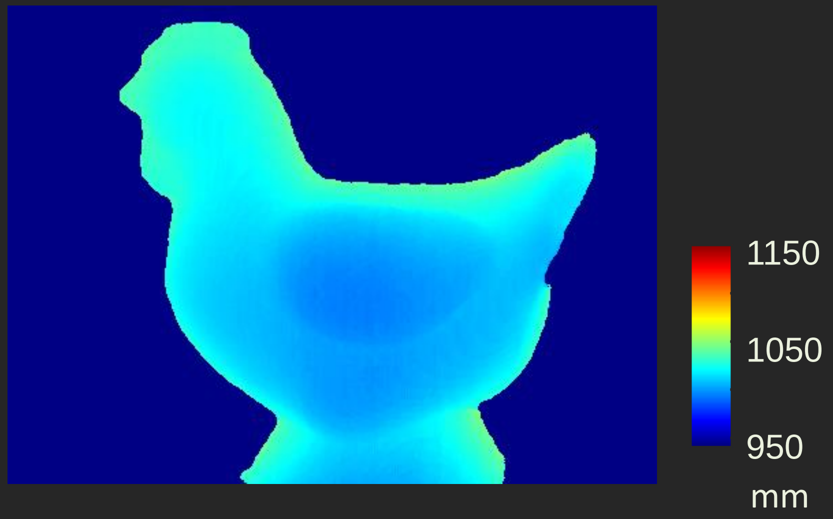
Scene

DualSL using Gray codes

Data acquired by the 1D sensor

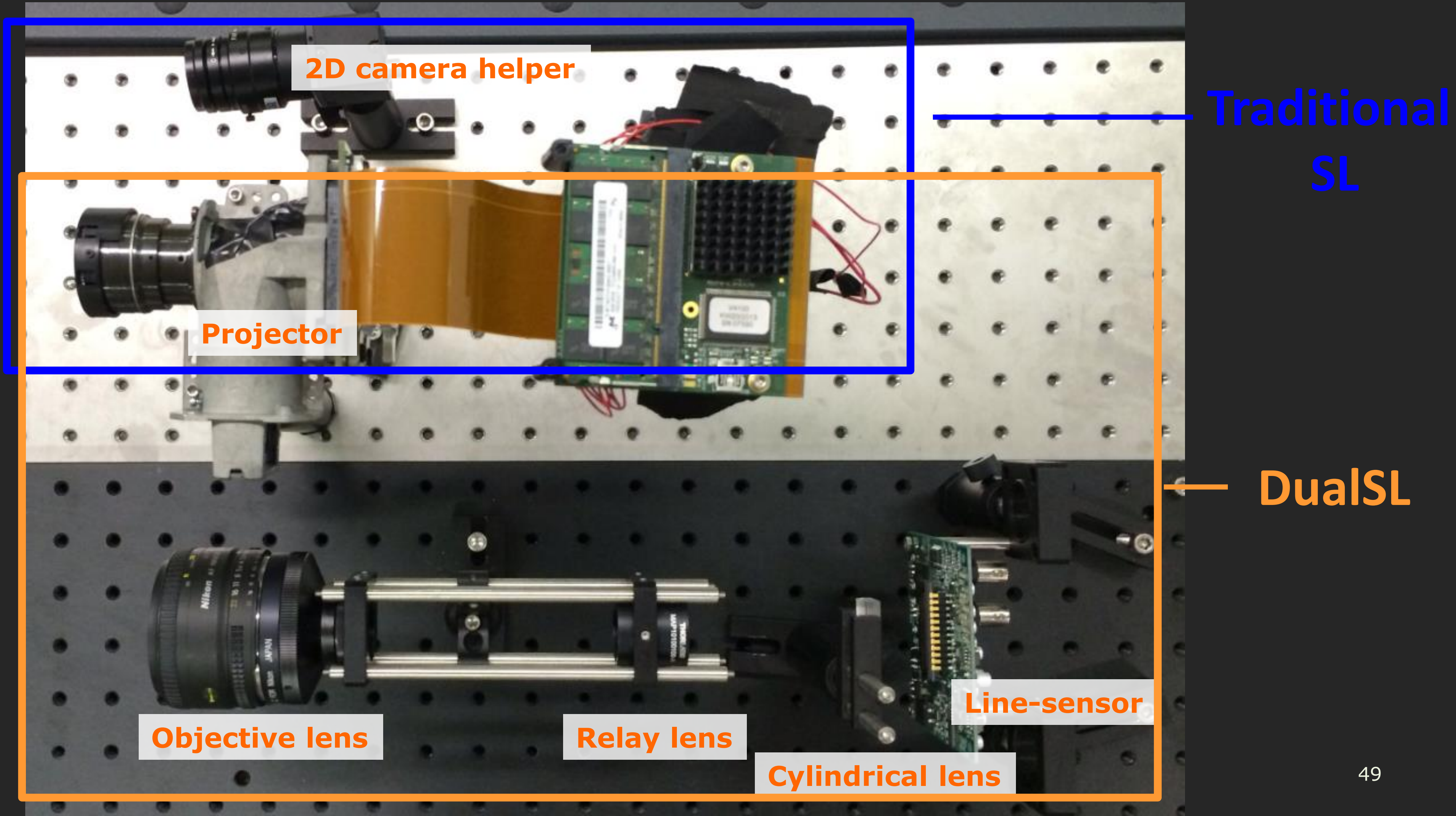


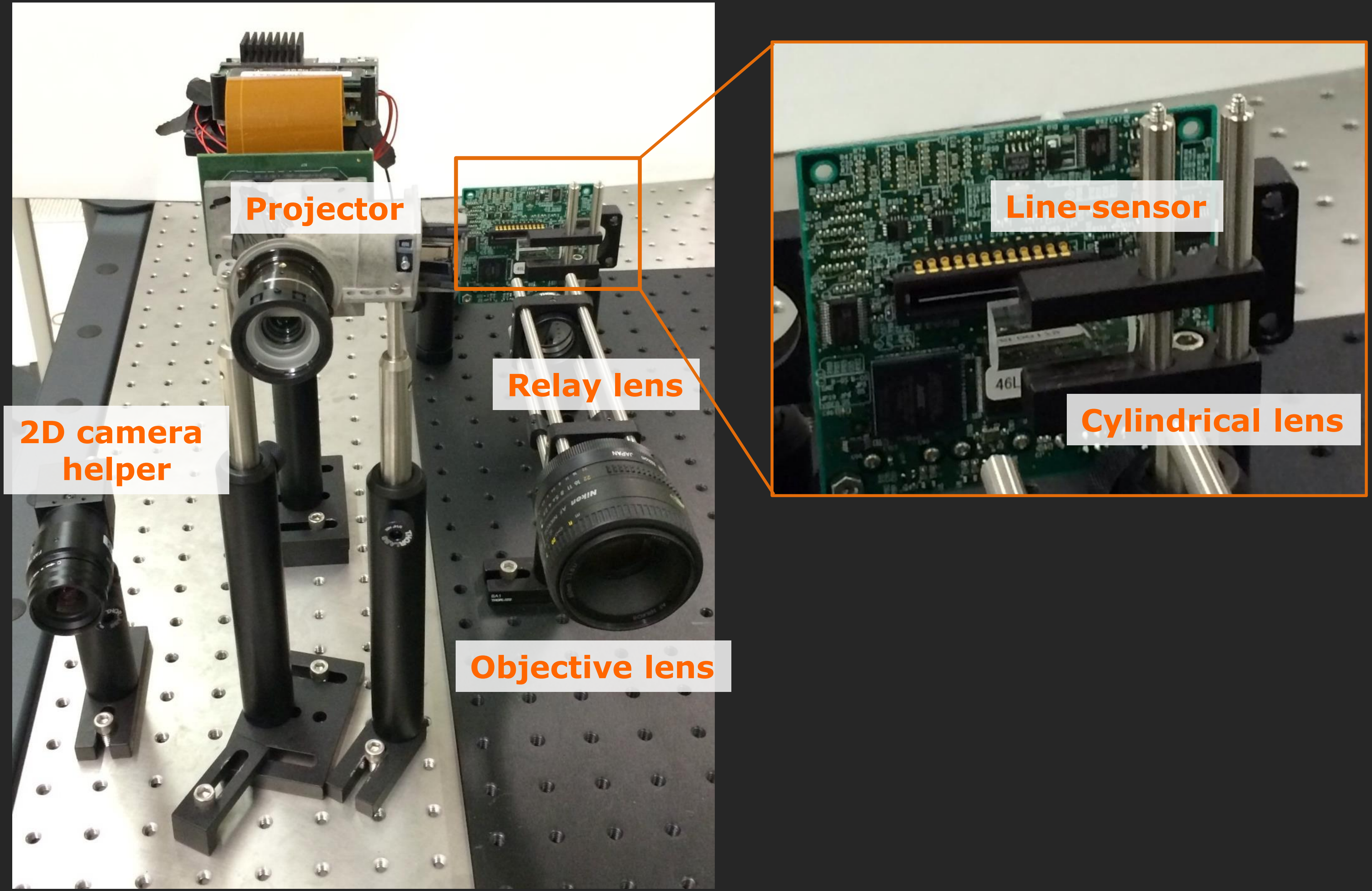
Depth map



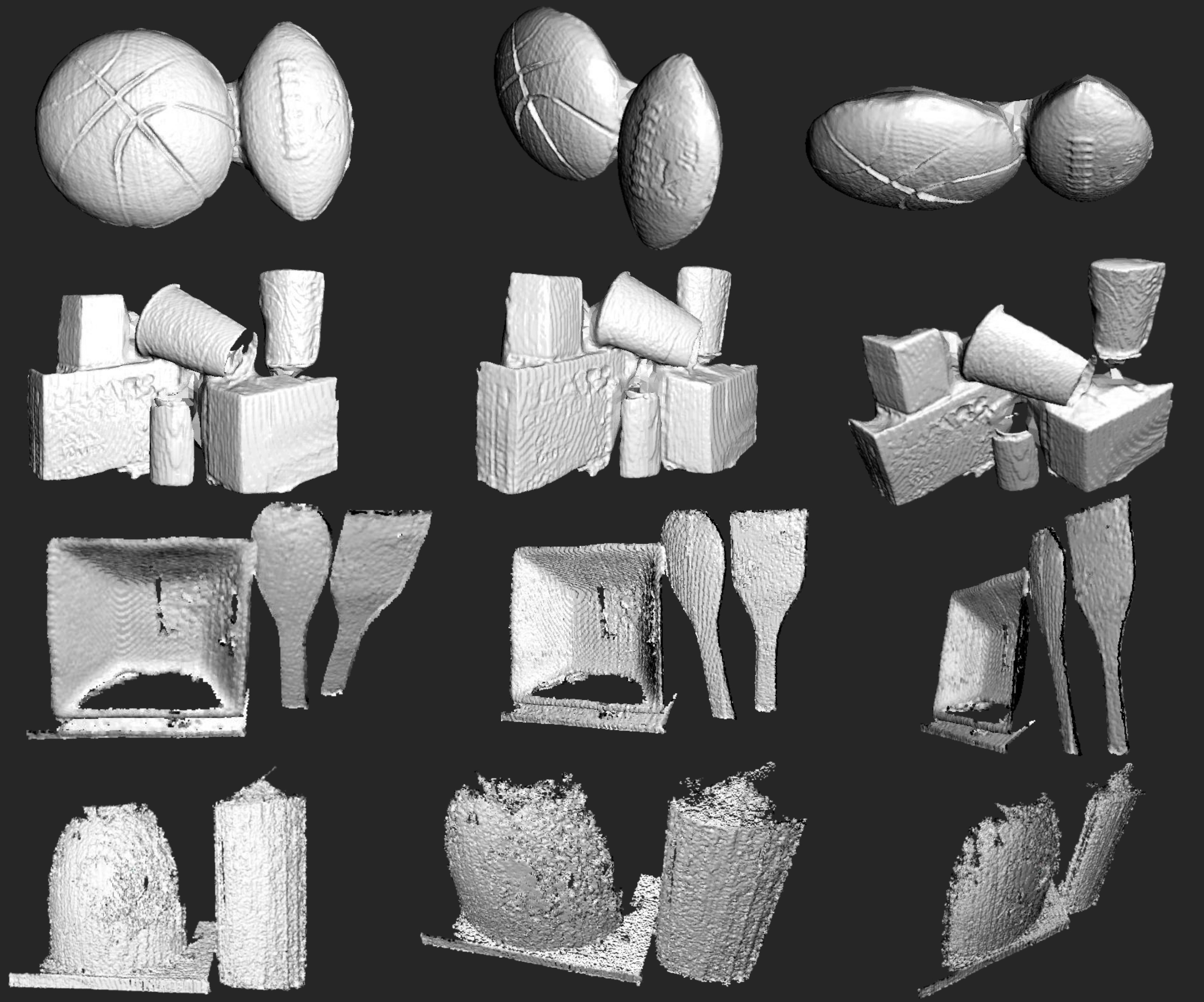
3D visualizations

Hardware prototype



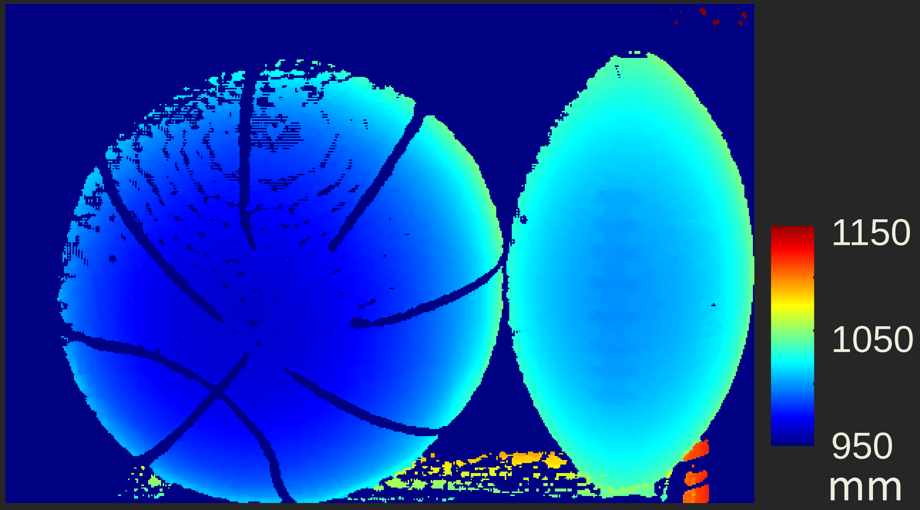

Projector
Relay lens
2D camera helper
Objective lens
Line-sensor
Cylindrical lens

3D visualizations of DualSL results

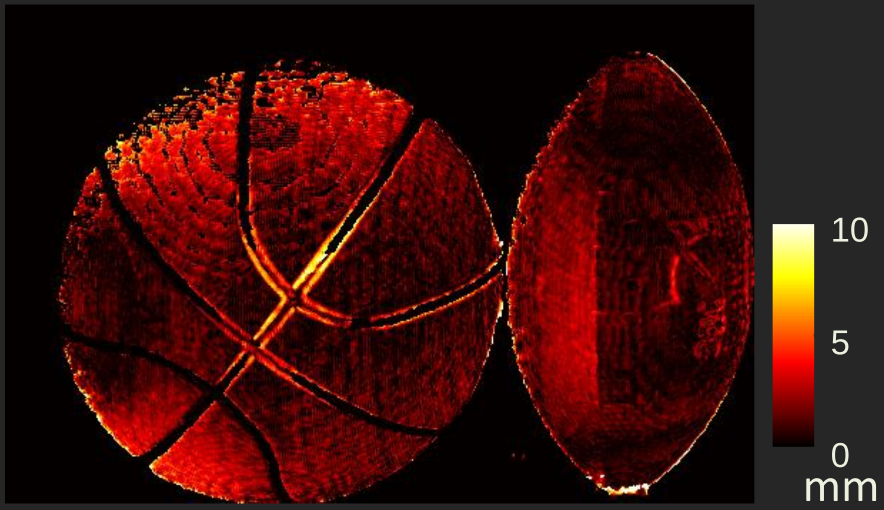


Target scene

Traditional SL
with 2D sensor

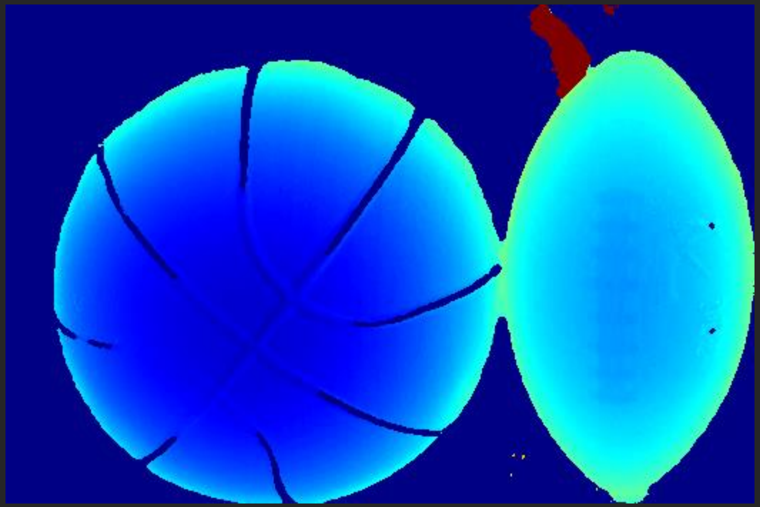


Difference map



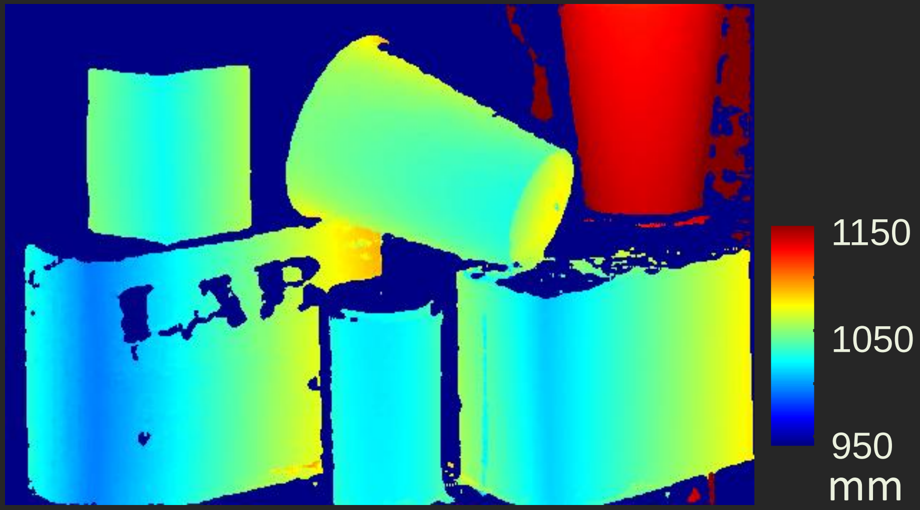
RMSE = 1.49mm

DualSL
with 1D sensor

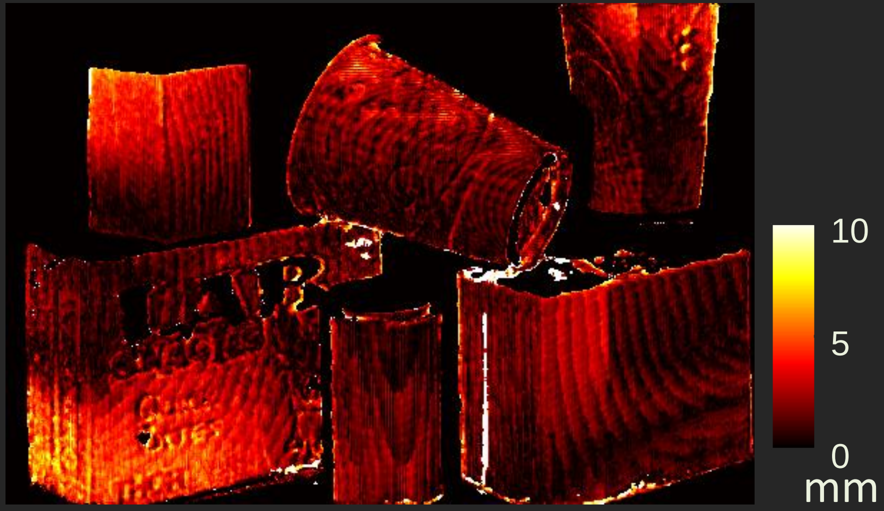


Target scene

Traditional SL
with 2D sensor

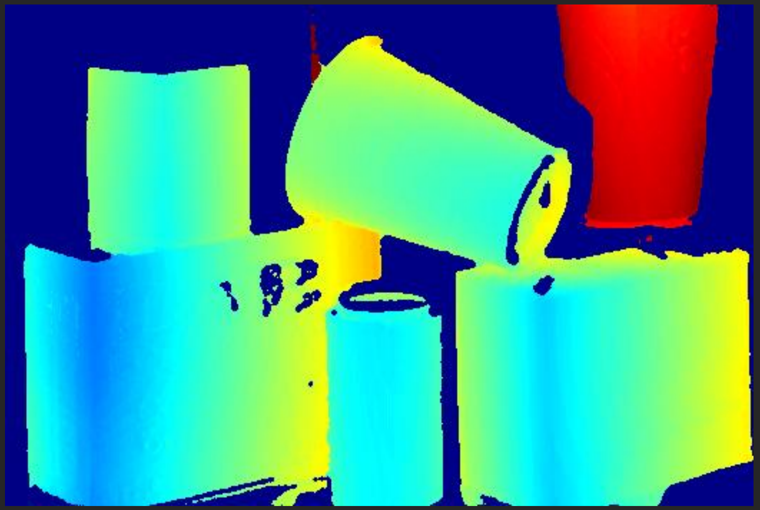


Difference map



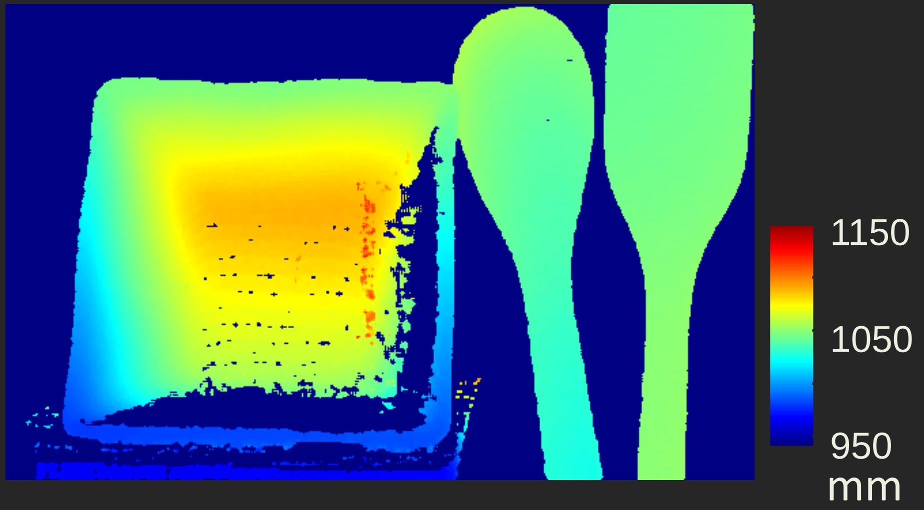
RMSE = 2.4mm

DualSL
with 1D sensor

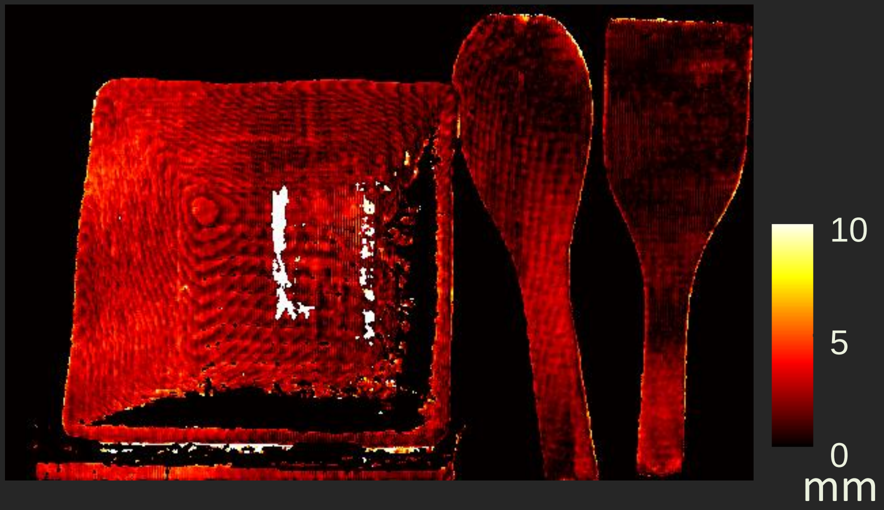


Target scene

Traditional SL with 2D sensor

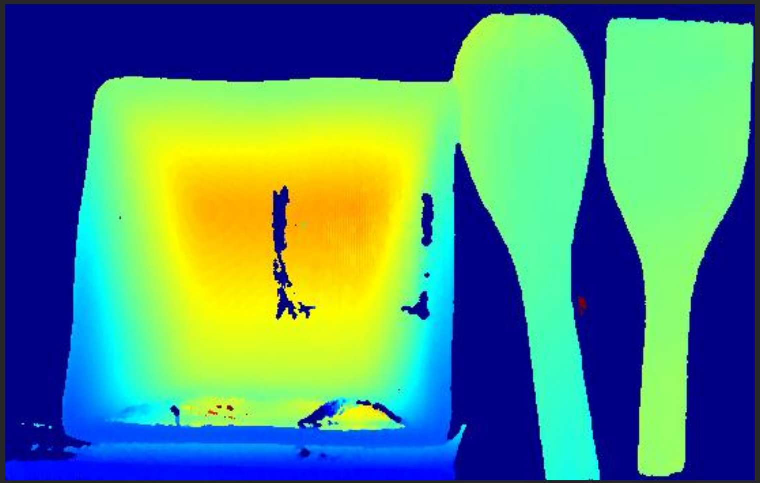


Difference map



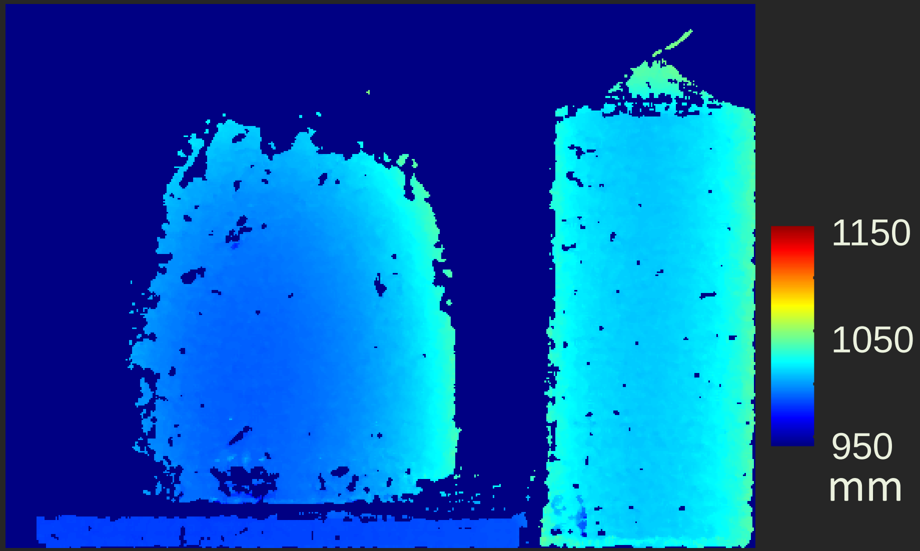
RMSE = 3.7mm

DualSL with 1D sensor

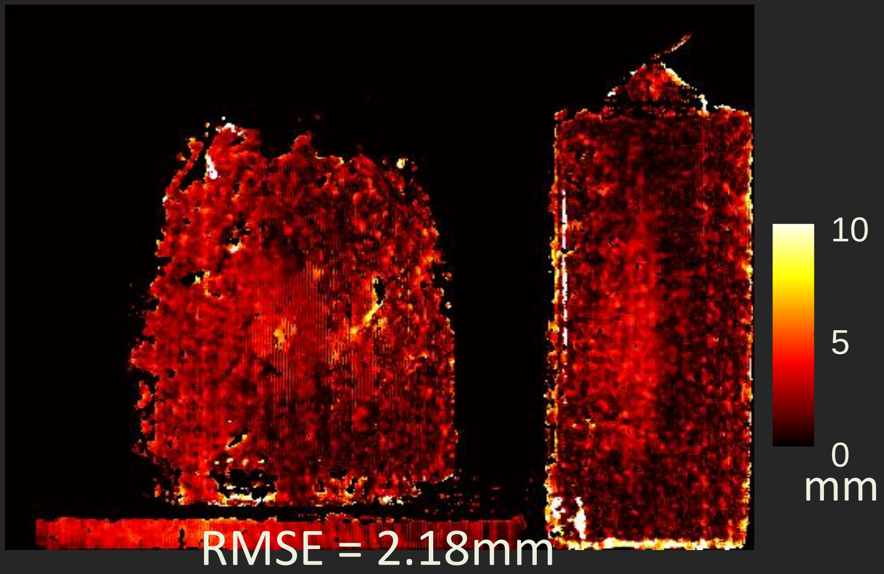


Target scene

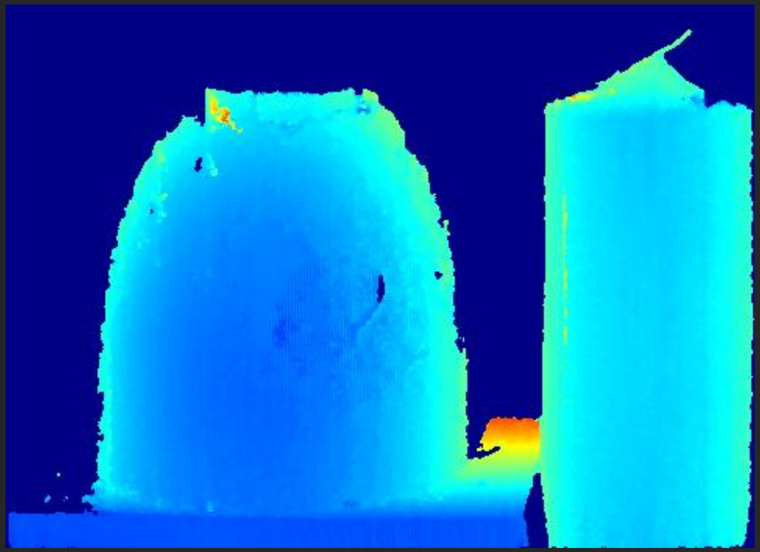
Traditional SL with 2D sensor



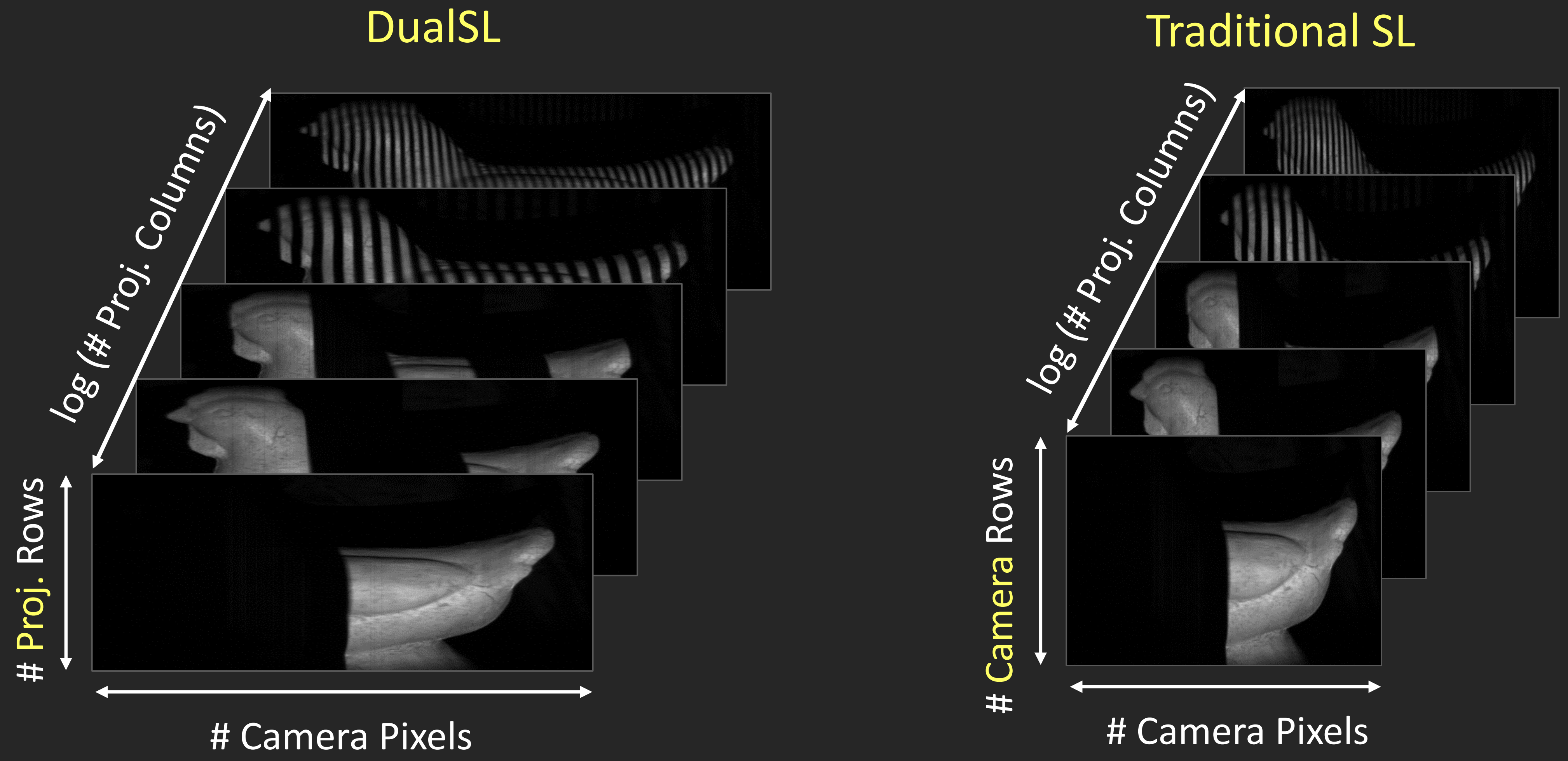
Difference map



DualSL with 1D sensor



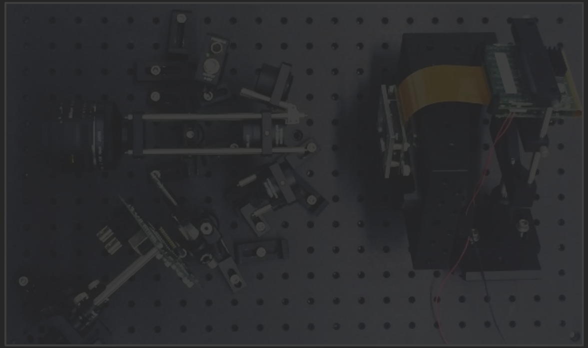
Analysis: Acquisition Speed



Same acquisition speed

Summary of DualSL

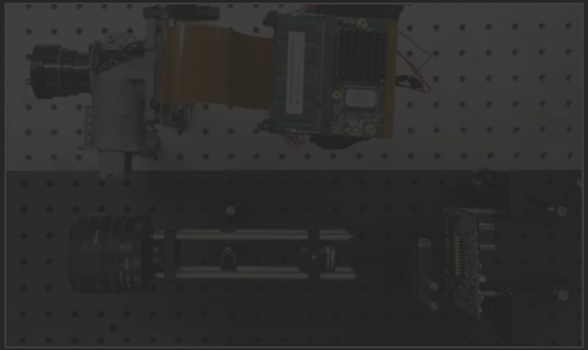
- Structured light 3D scanning architecture with line sensor
  - Cost effective
- Same performance as traditional SL
  - Temporal resolution
- Better performance
  - Spatial resolution
  - Under ambient light
  - Under global light



LiSens

2D imaging architecture

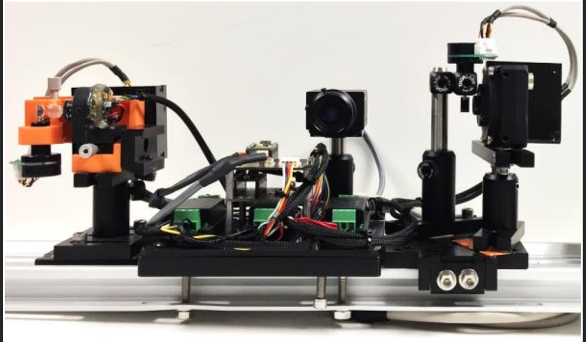
Jian Wang, Mohit Gupta, and Aswin C. Sankaranarayanan. "LiSens-A scalable architecture for video compressive sensing." ICCP 2015.



DualSL

3D scanning architecture

Jian Wang, Aswin C. Sankaranarayanan, Mohit Gupta, and Srinivasa G. Narasimhan. "Dual structured light 3d using a 1d sensor." ECCV 2016.



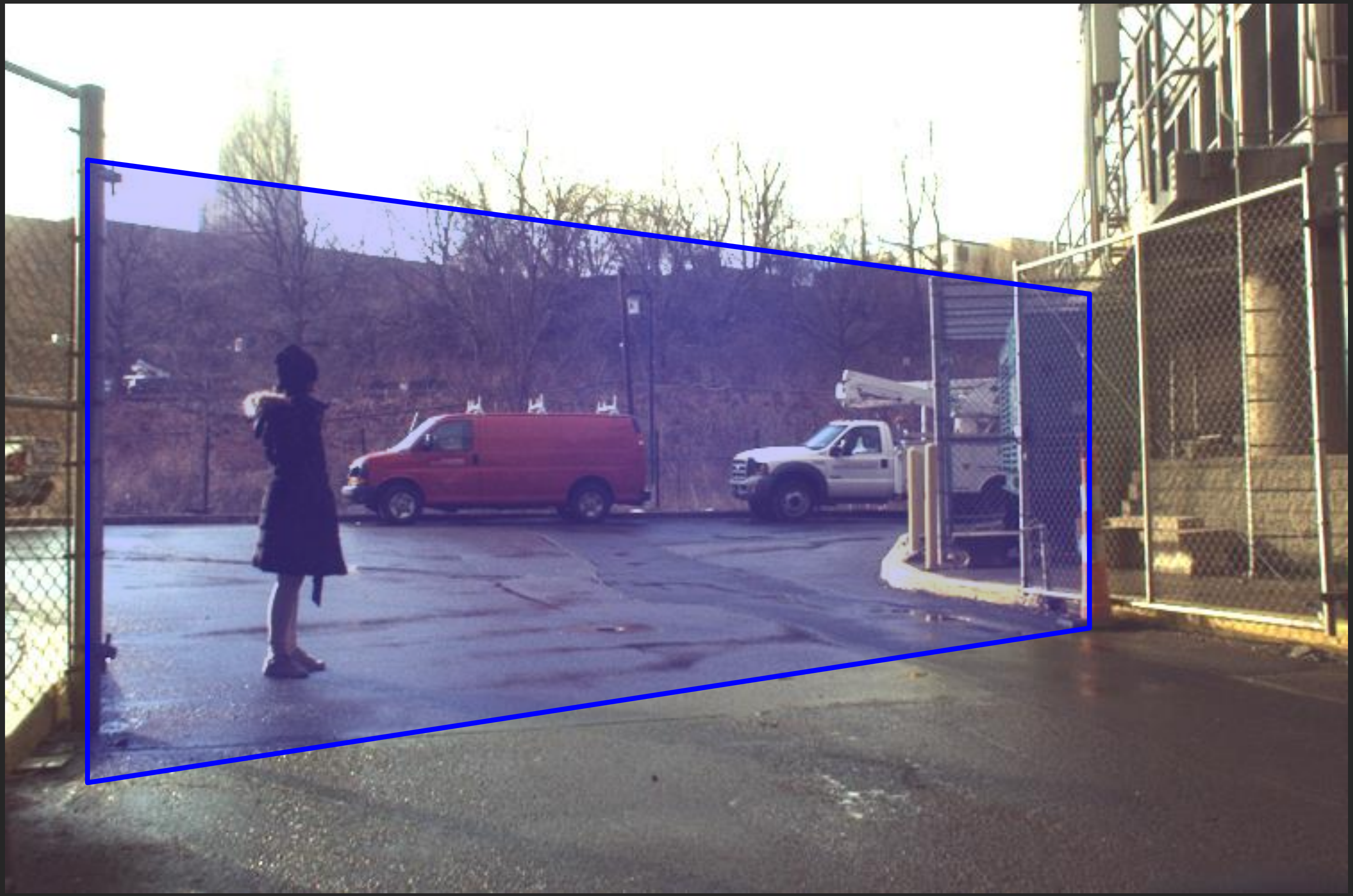
TriLC

Robust proximity sensor

Jian Wang, Joe Bartels, William Whittaker, Aswin C. Sankaranarayanan, and Srinivasa G. Narasimhan. "Programmable Triangulation Light Curtains." ECCV 2018 .

High spatial temporal resolution with line sensors

Task: detect object at specific depth (proximity sensor)



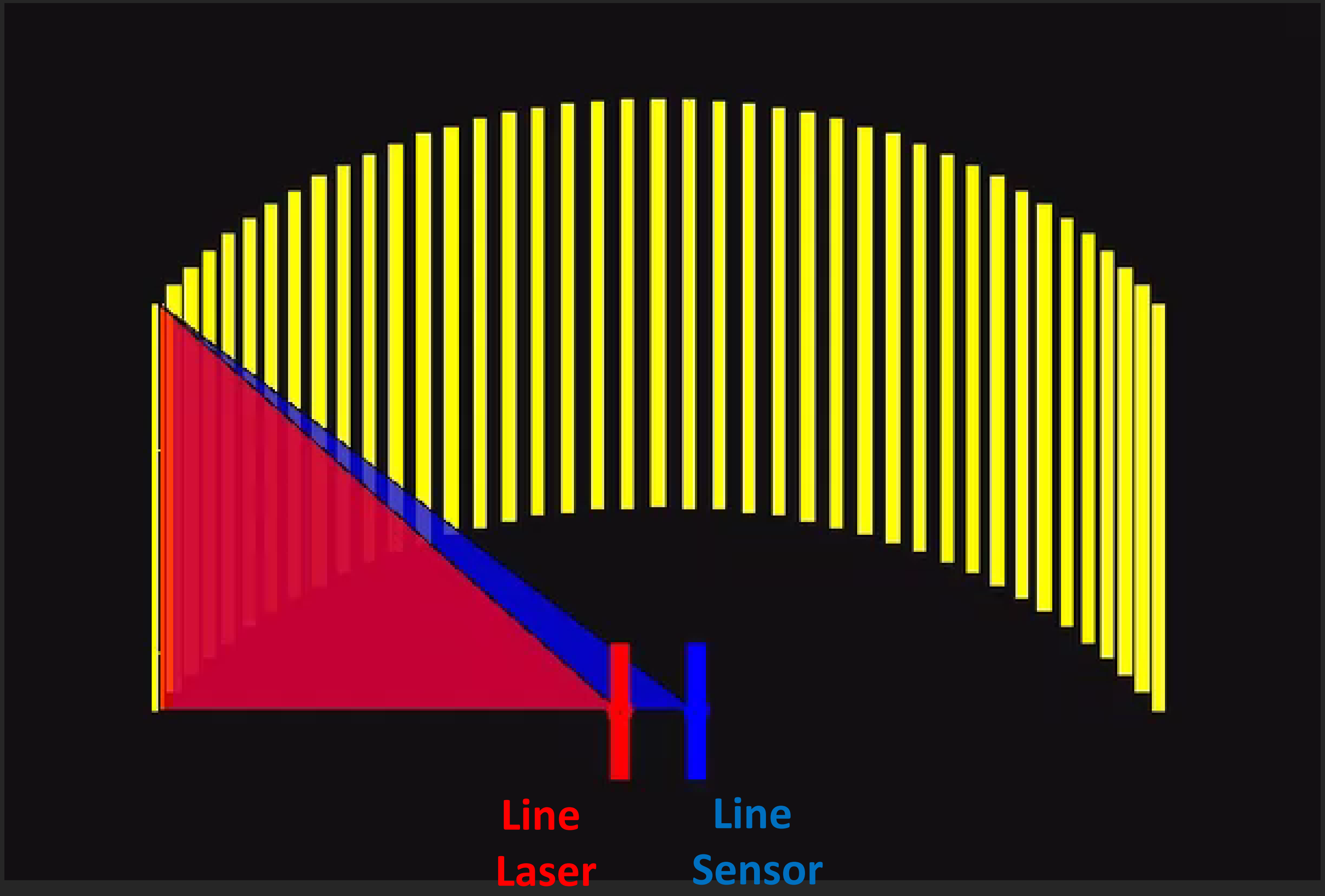
- Workable under strong sunlight
- Cost effective
- Energy efficient
- Computationally efficient

Task: see through scattering media

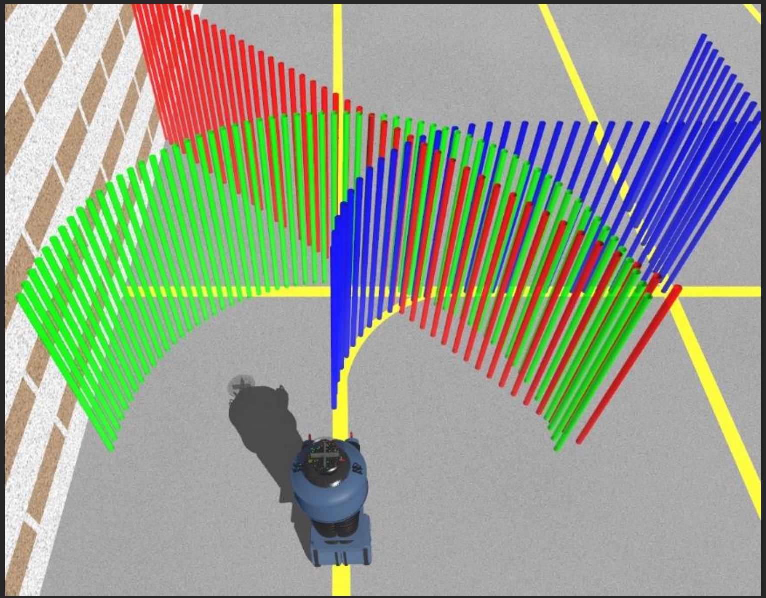
With smoke

- High spatial-temporal resolution
- Cost effective
- Energy efficient
- Computationally efficient

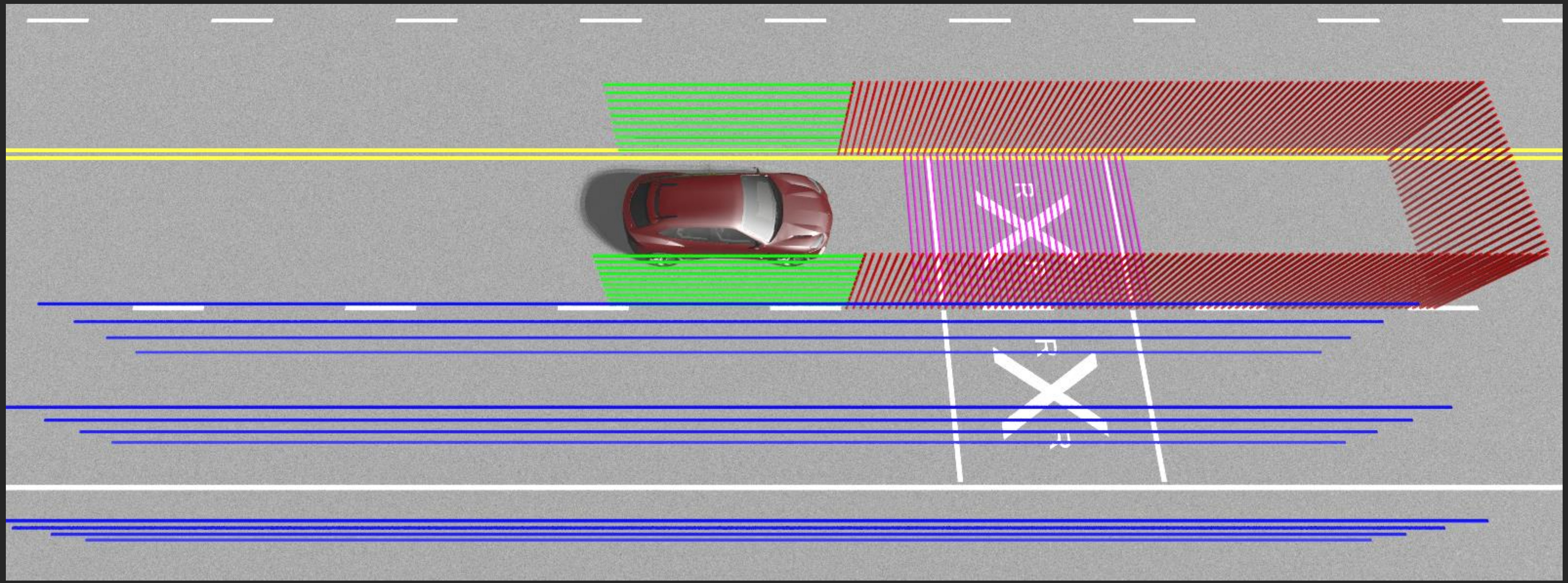
Proposed: light curtain device



Applications

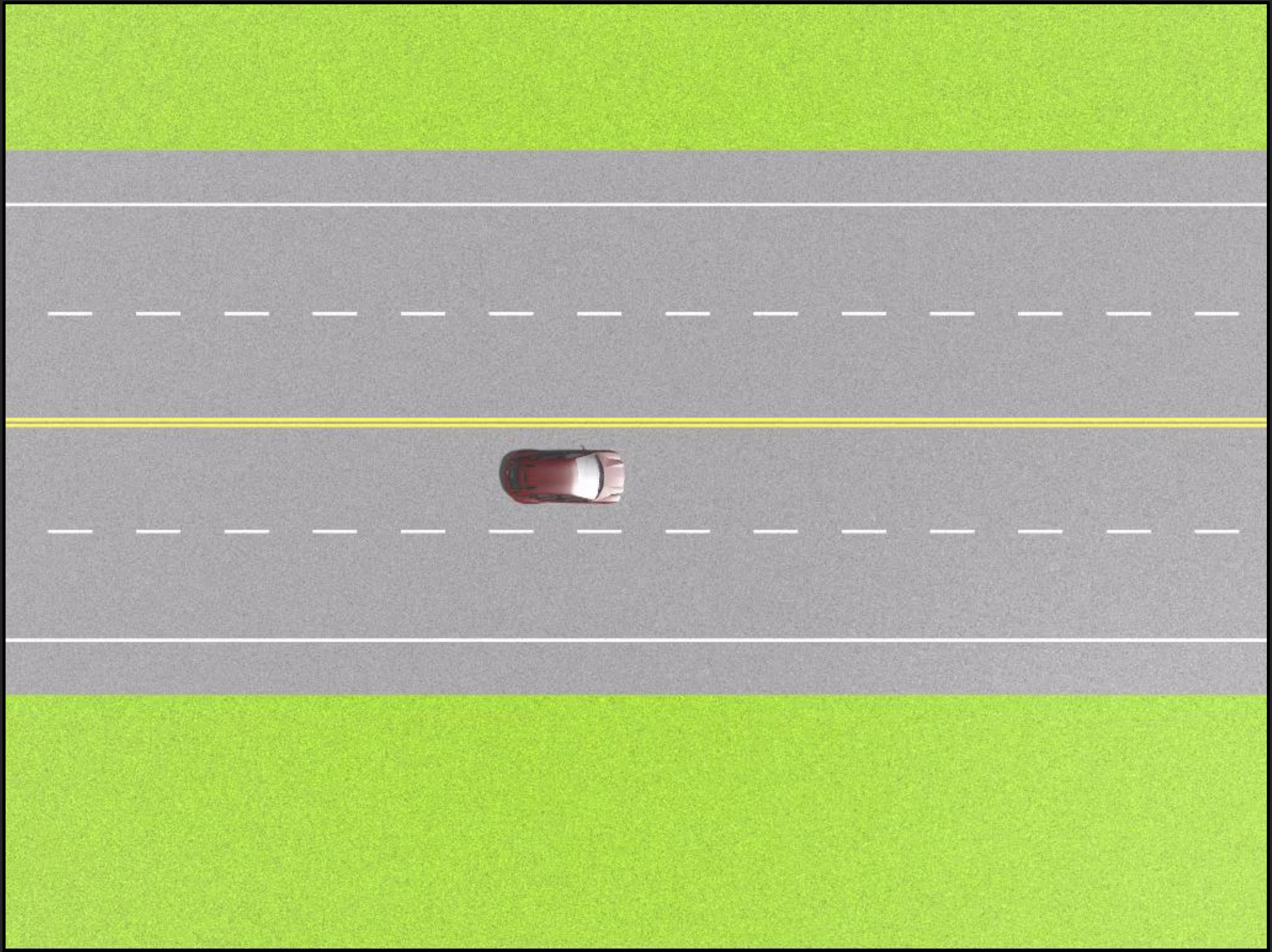


Light Curtains for Robots

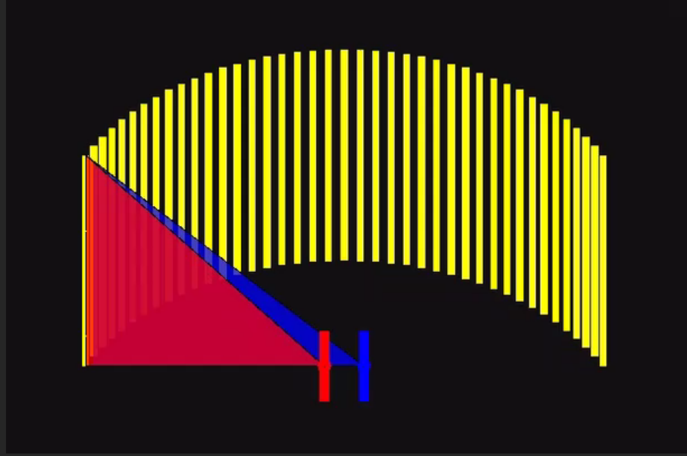


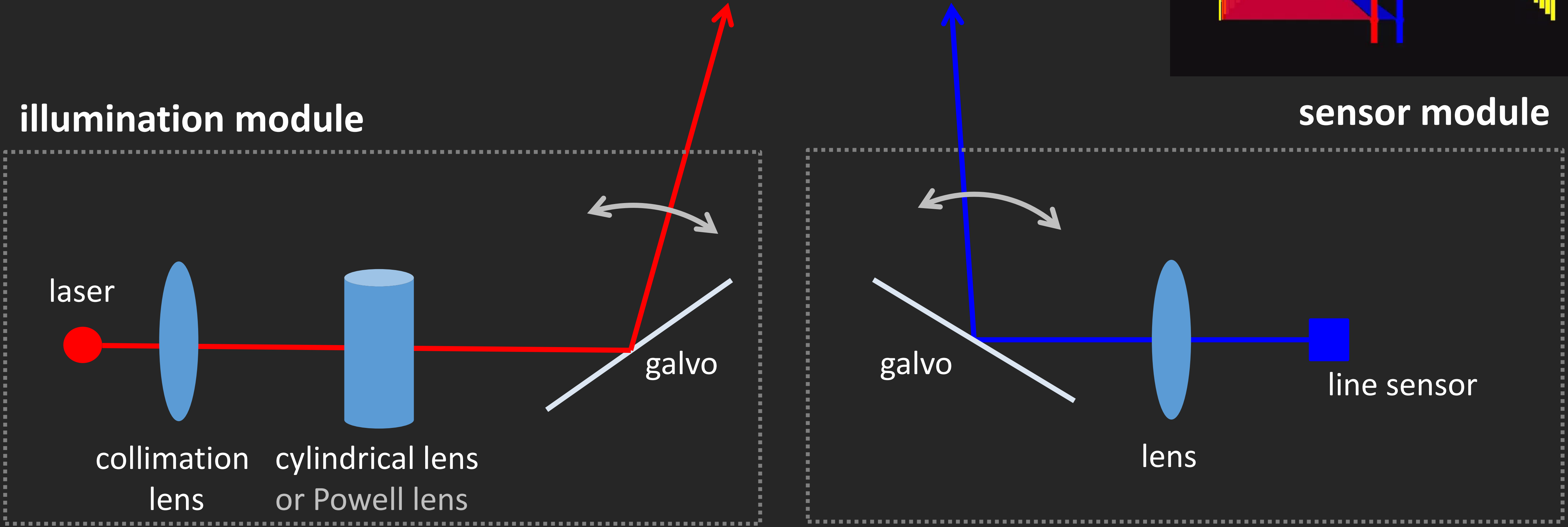
Light Curtains for Vehicles

Vehicle lane monitoring



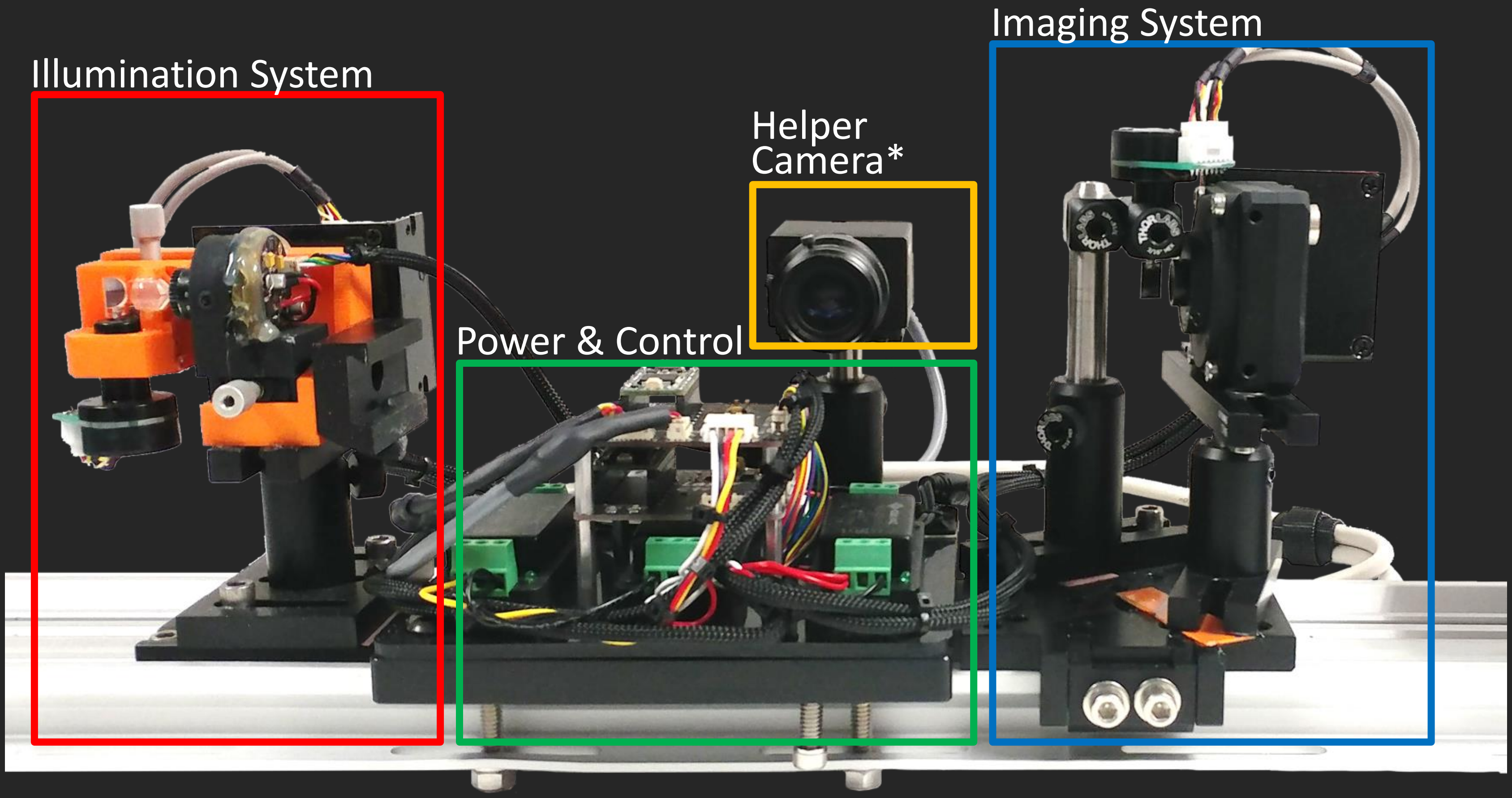
Optical schematic





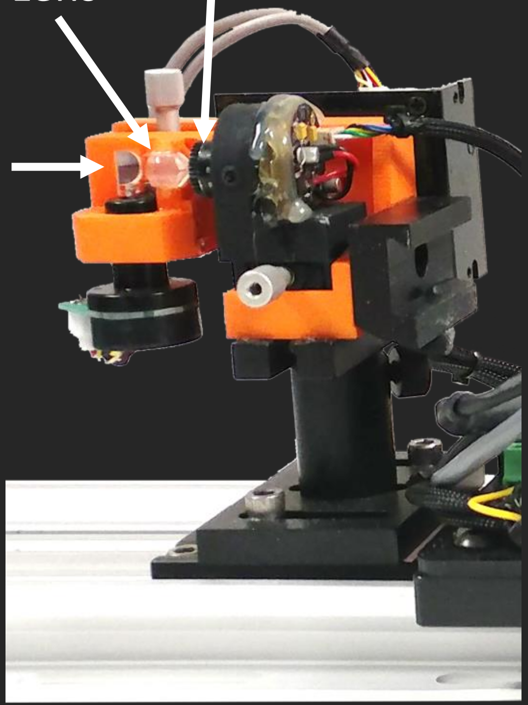
Top view

Hardware prototype

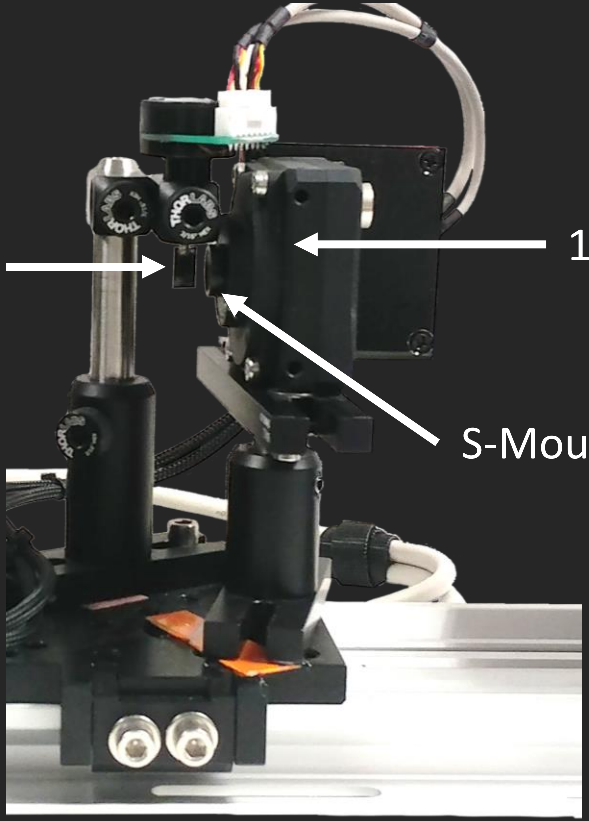


*For Calibration and Visualization Only

Hardware prototype

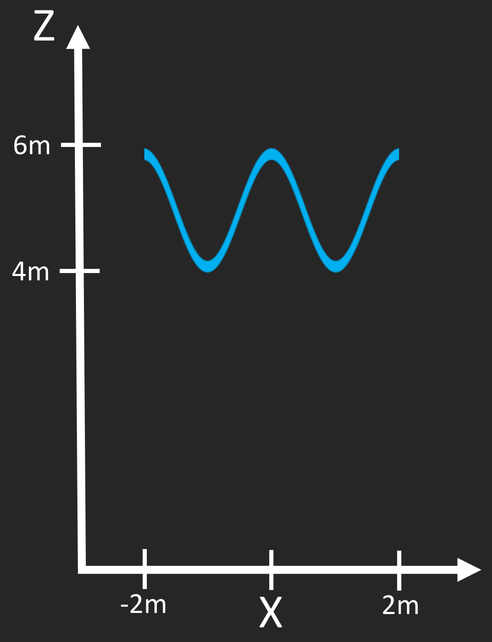


Illumination System

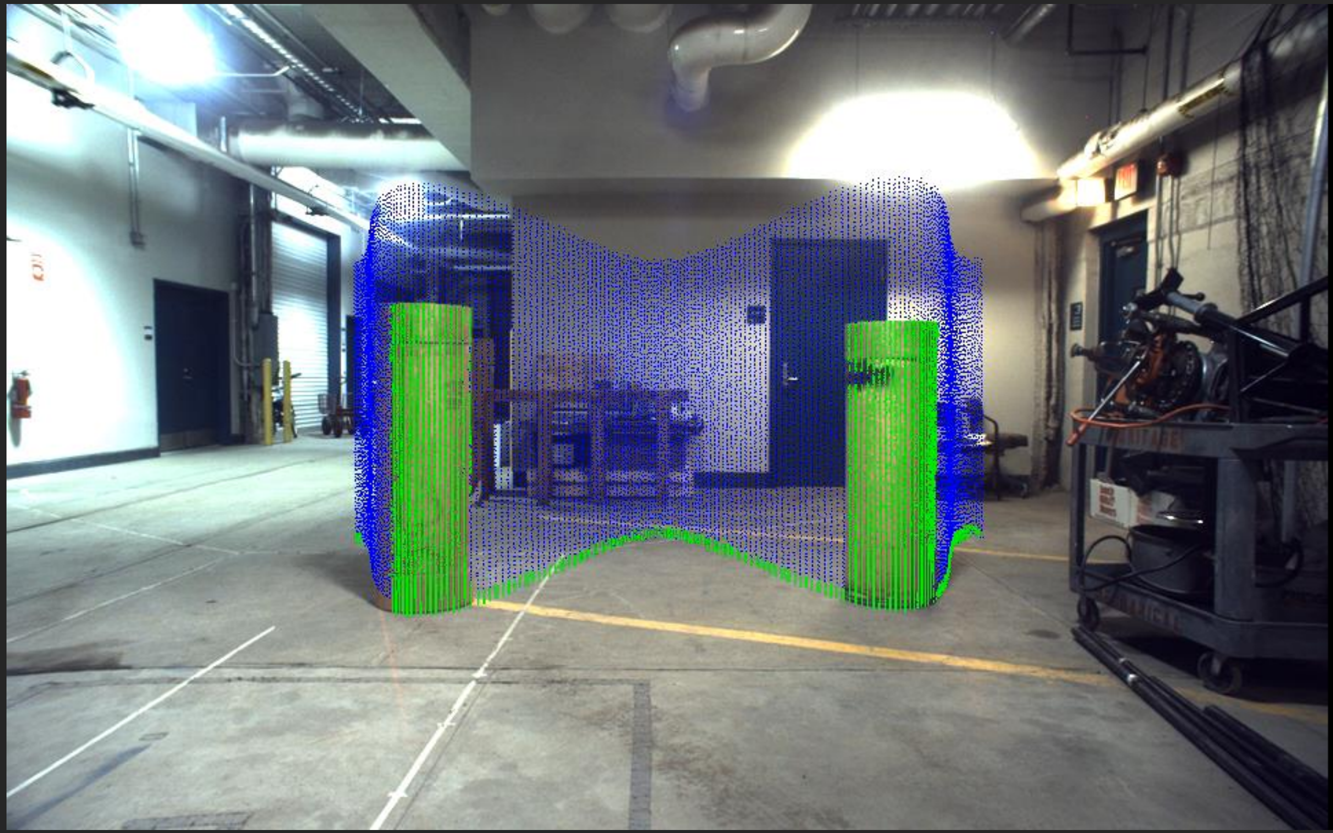


Imaging System

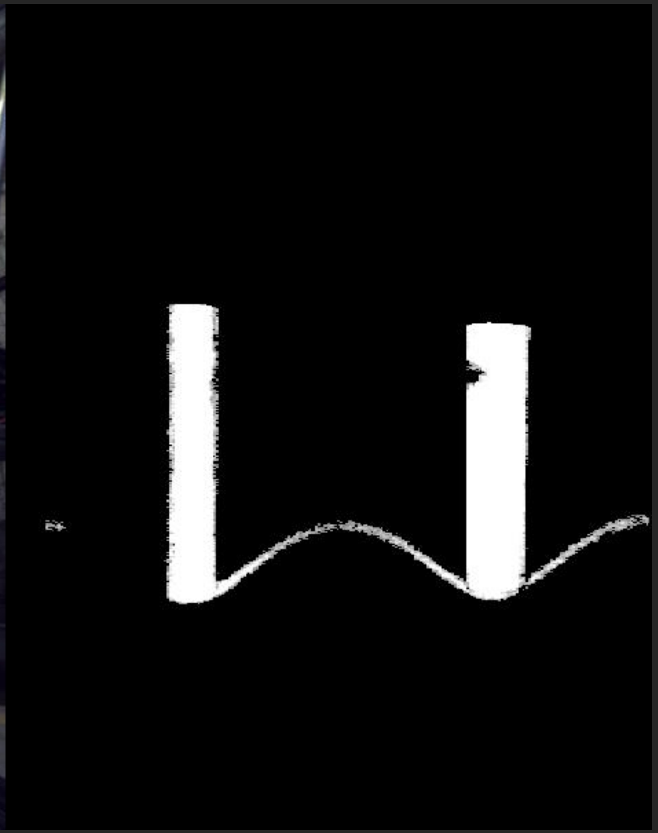
Cosine light curtain



Light Curtain

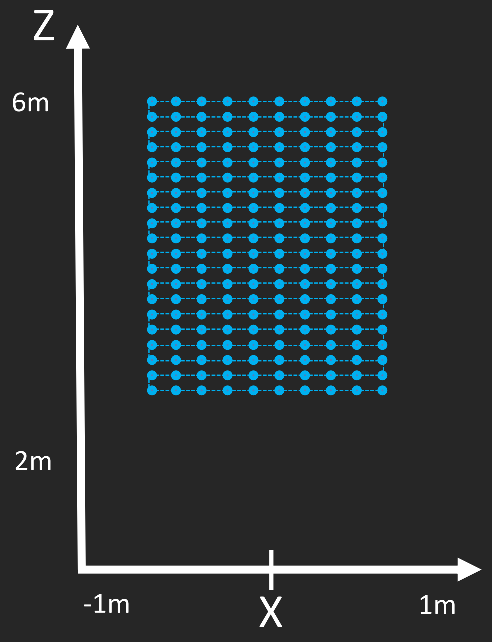


Scene

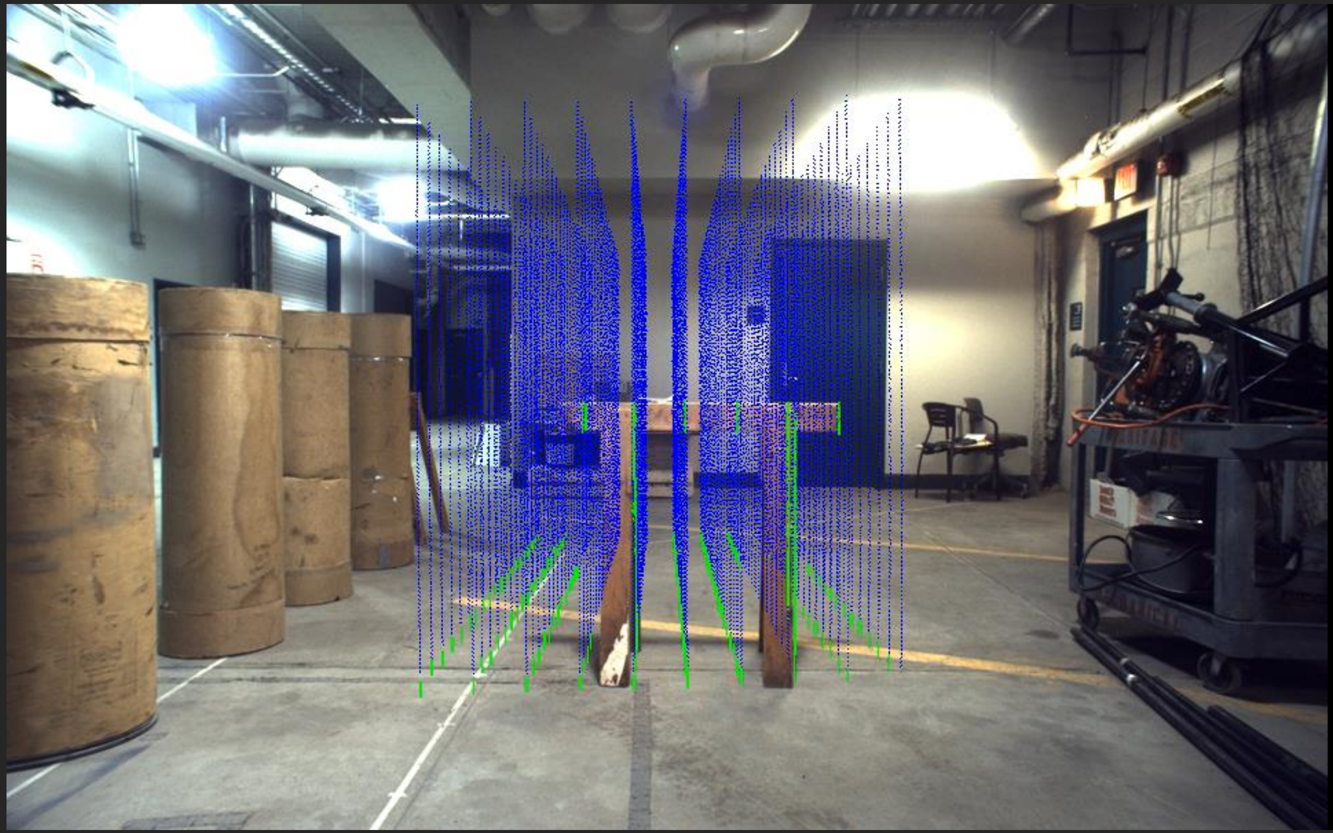


Imaged Curtain

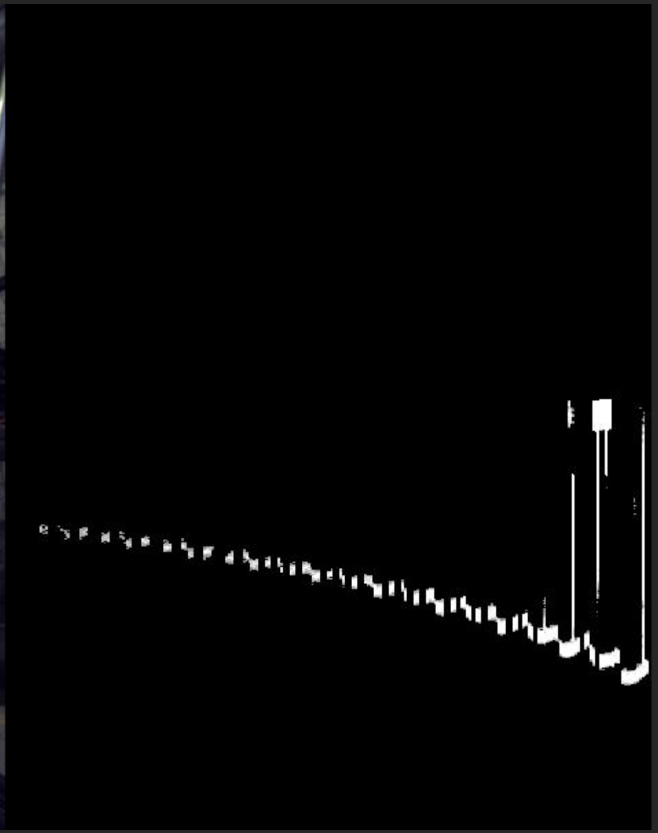
Volume light curtain



Light Curtain

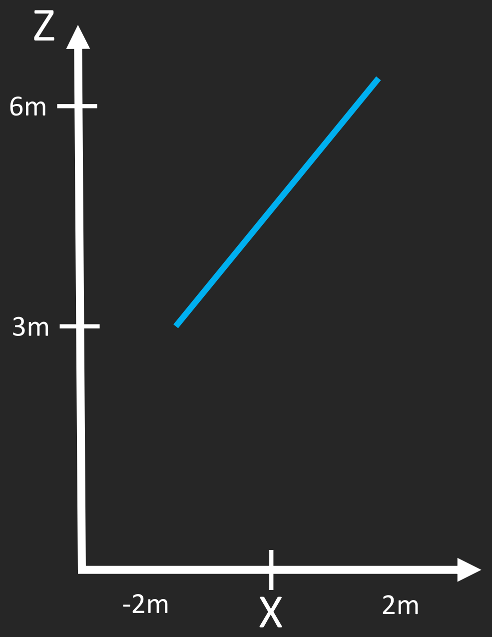


Scene



Imaged Curtain

Tilted curtain outdoors in cloudy day

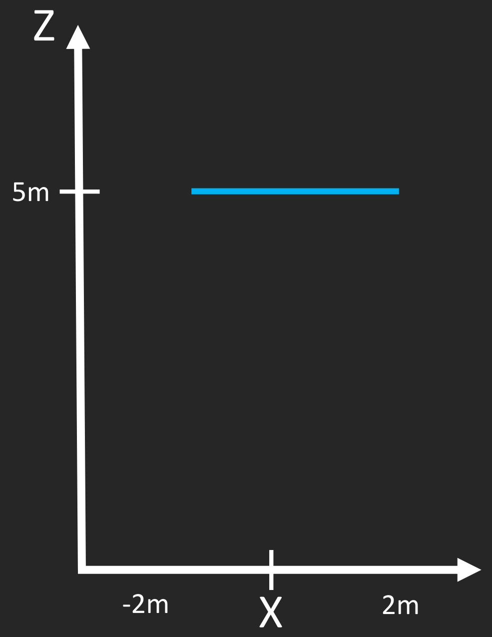


Light Curtain

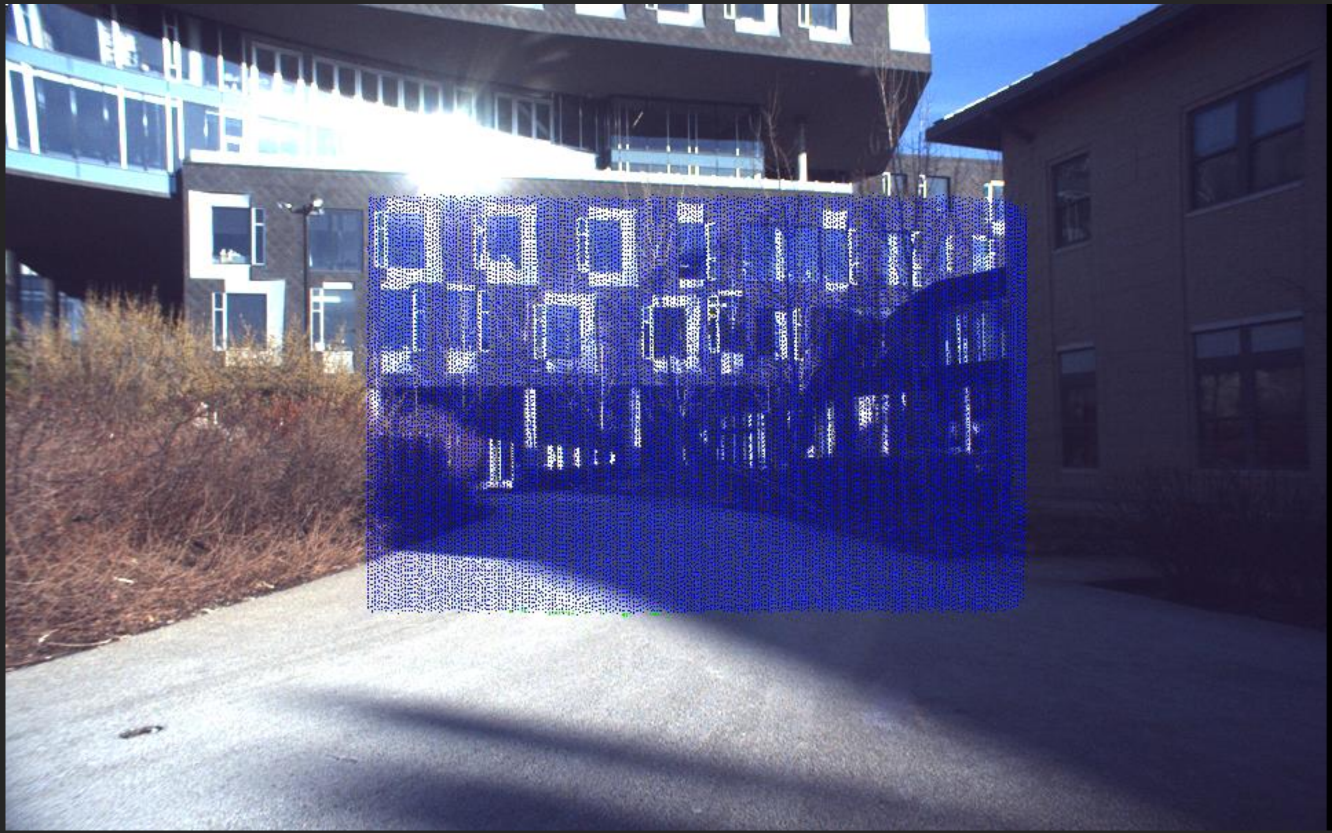
Scene

Imaged Curtain

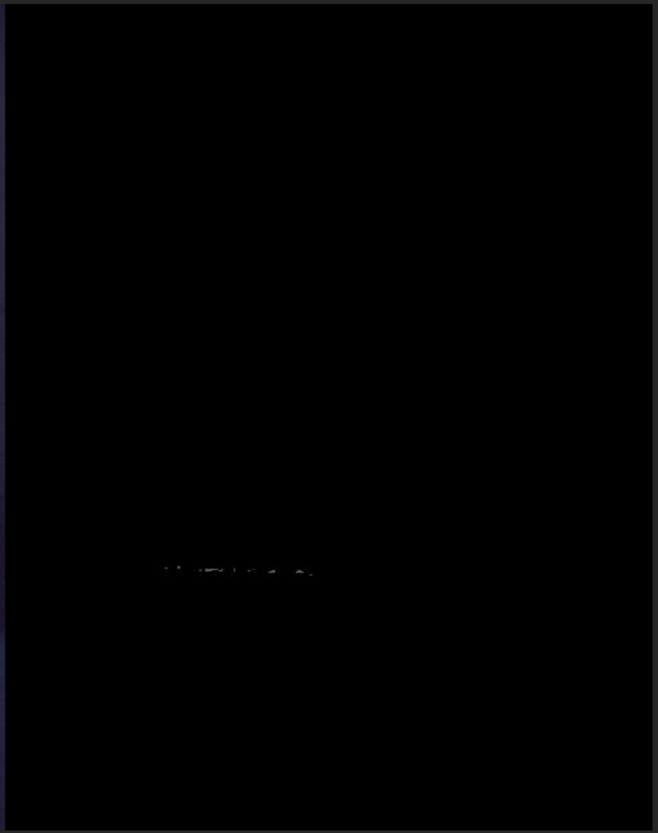
Planar curtain outdoors under strong sunlight



Light Curtain

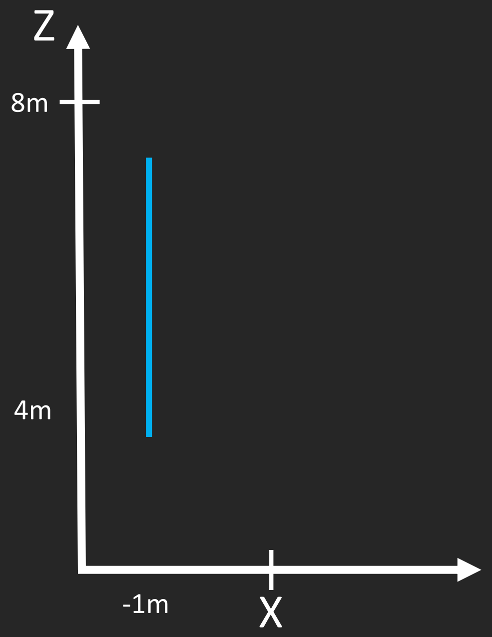


Scene

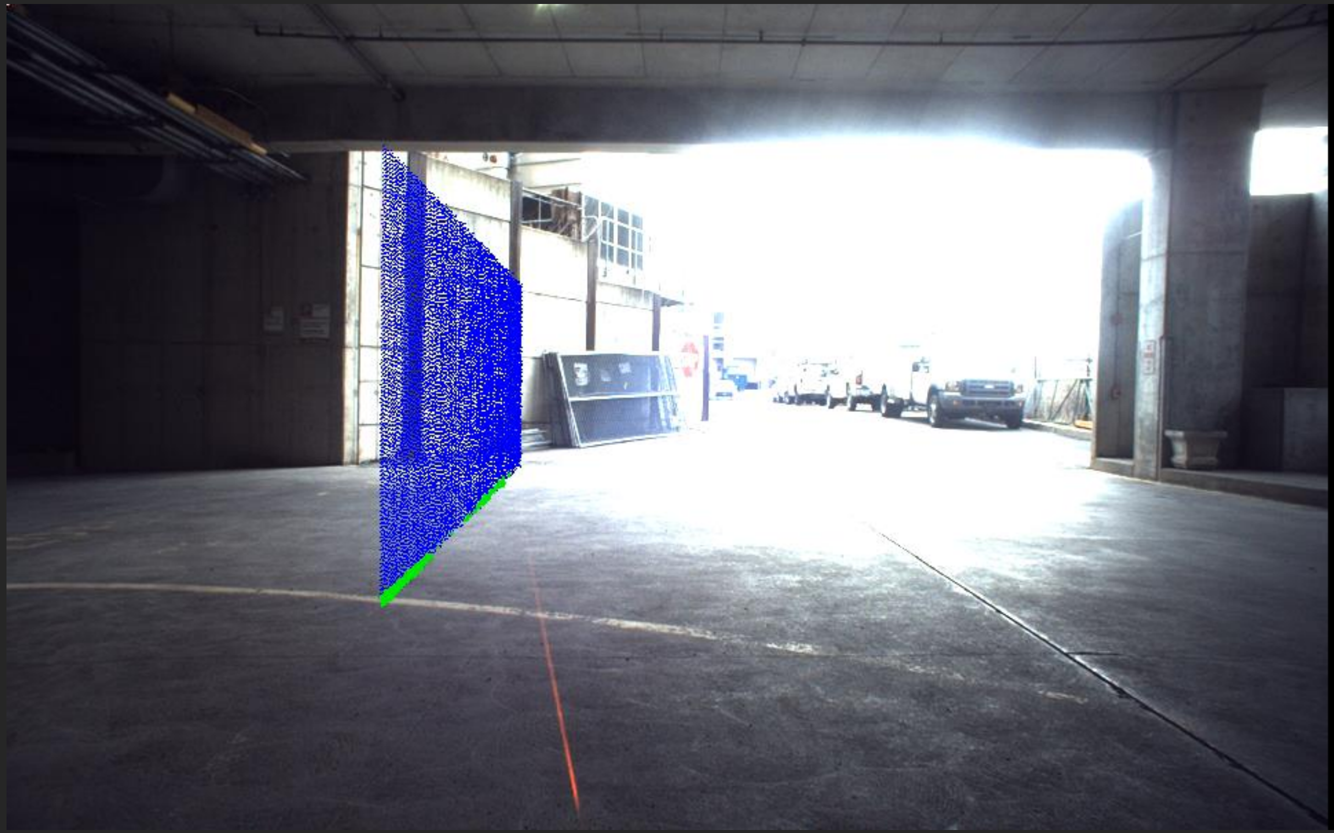


Imaged Curtain

Backup detection – Vertical curtain



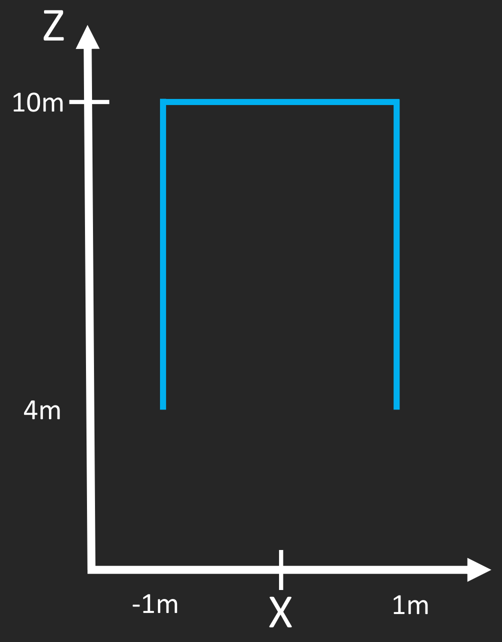
Light Curtain



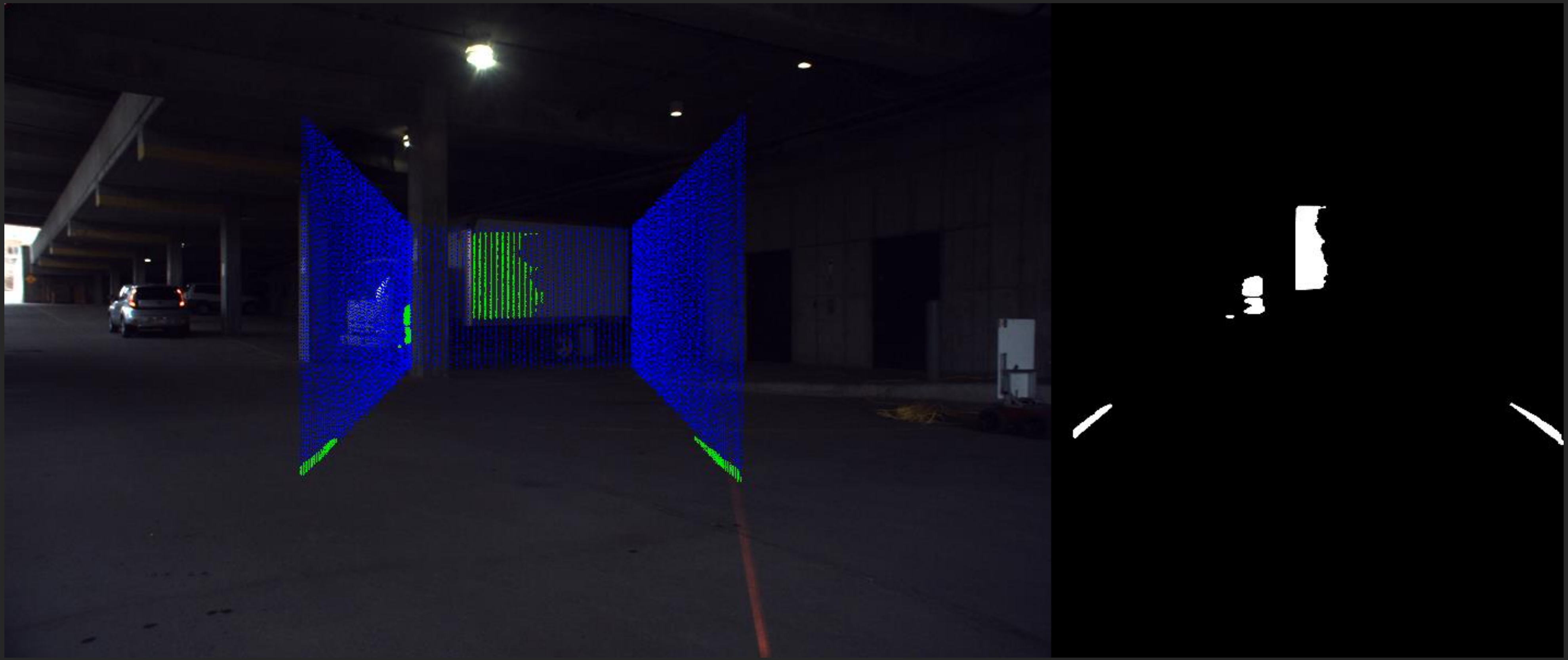
Scene

Imaged Curtain

Π – Curtain for vehicle lane monitoring



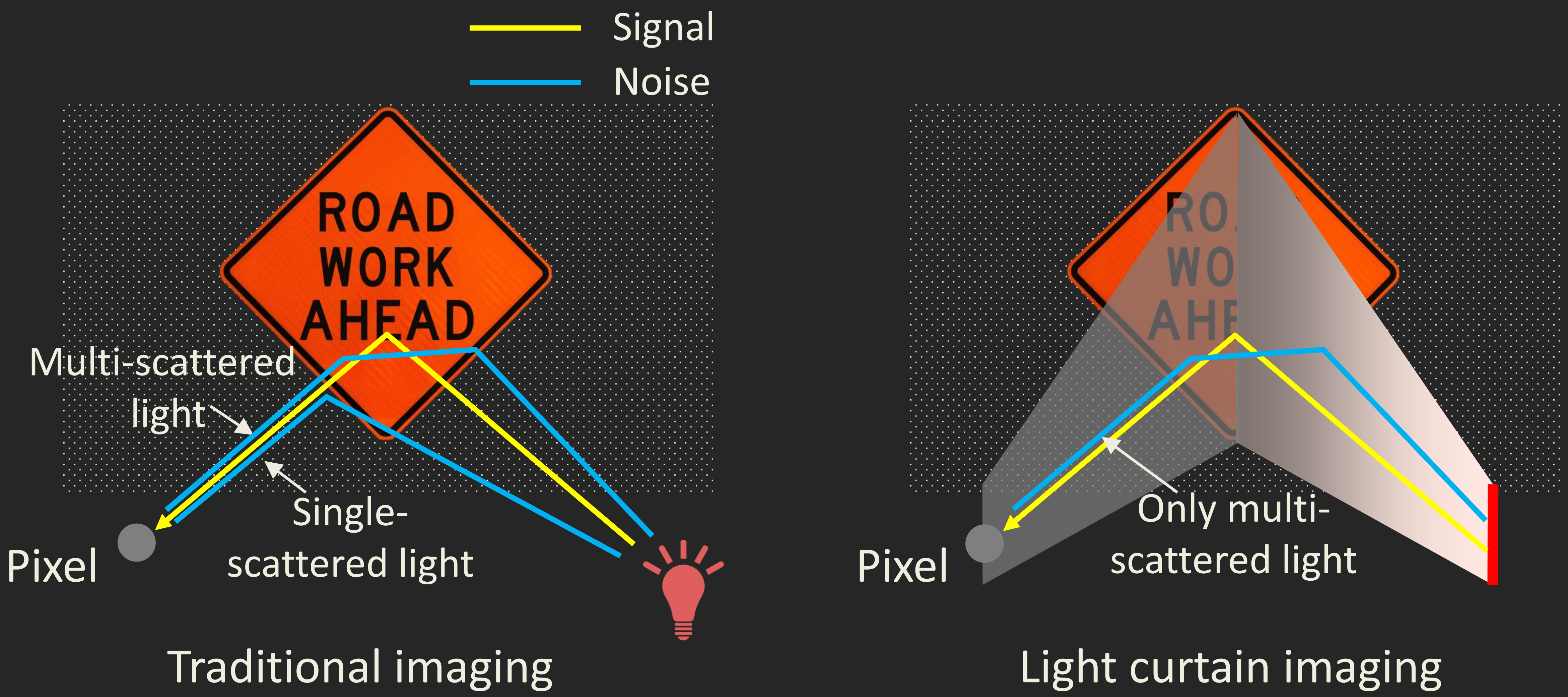
Light Curtain



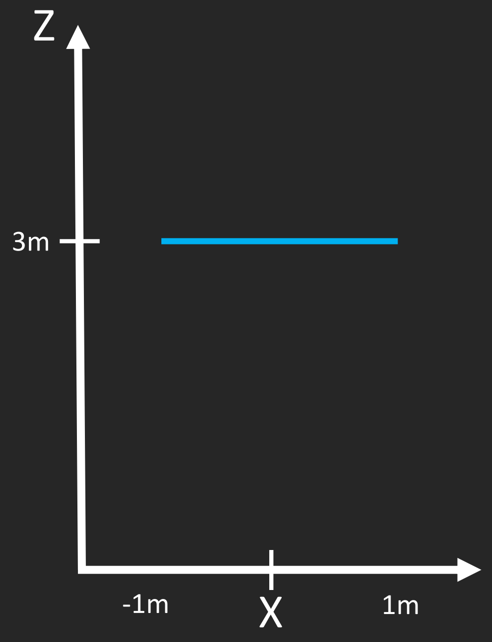
Scene

Imaged Curtain

Scattering media (fog, smoke…)

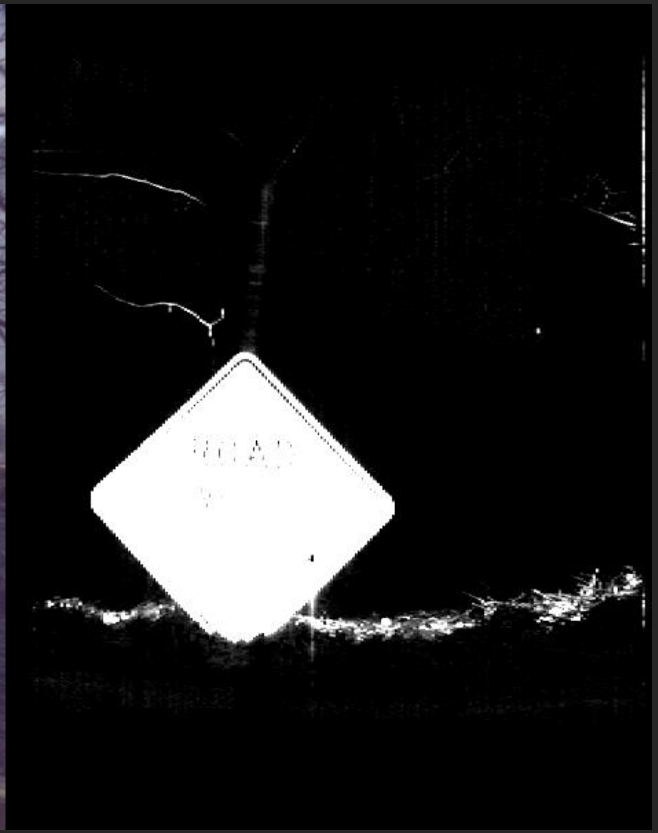


Planar light curtain in smoke



Light Curtain

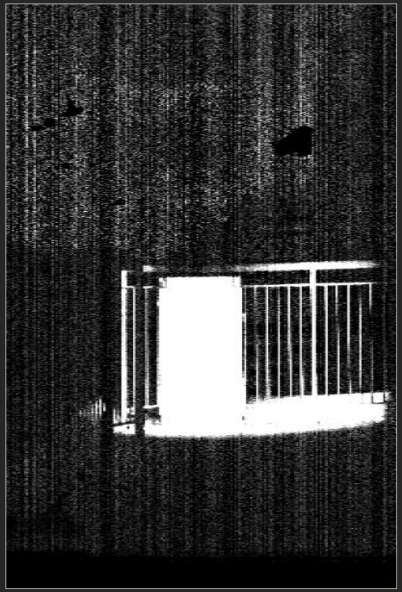
Scene



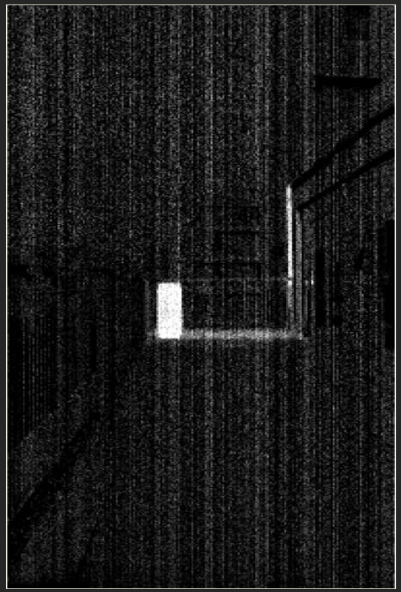
Imaged Curtain

Performance – 100klux

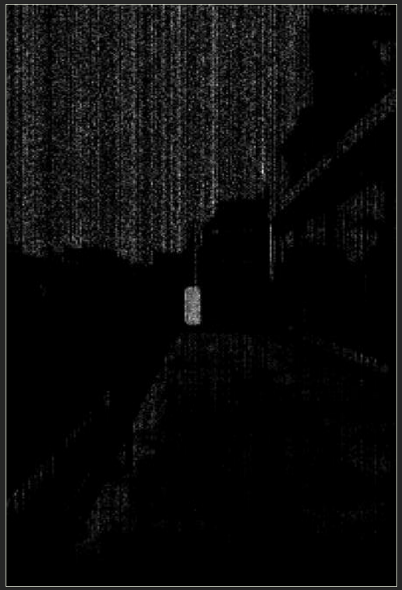
Scene



5m



15m



25m

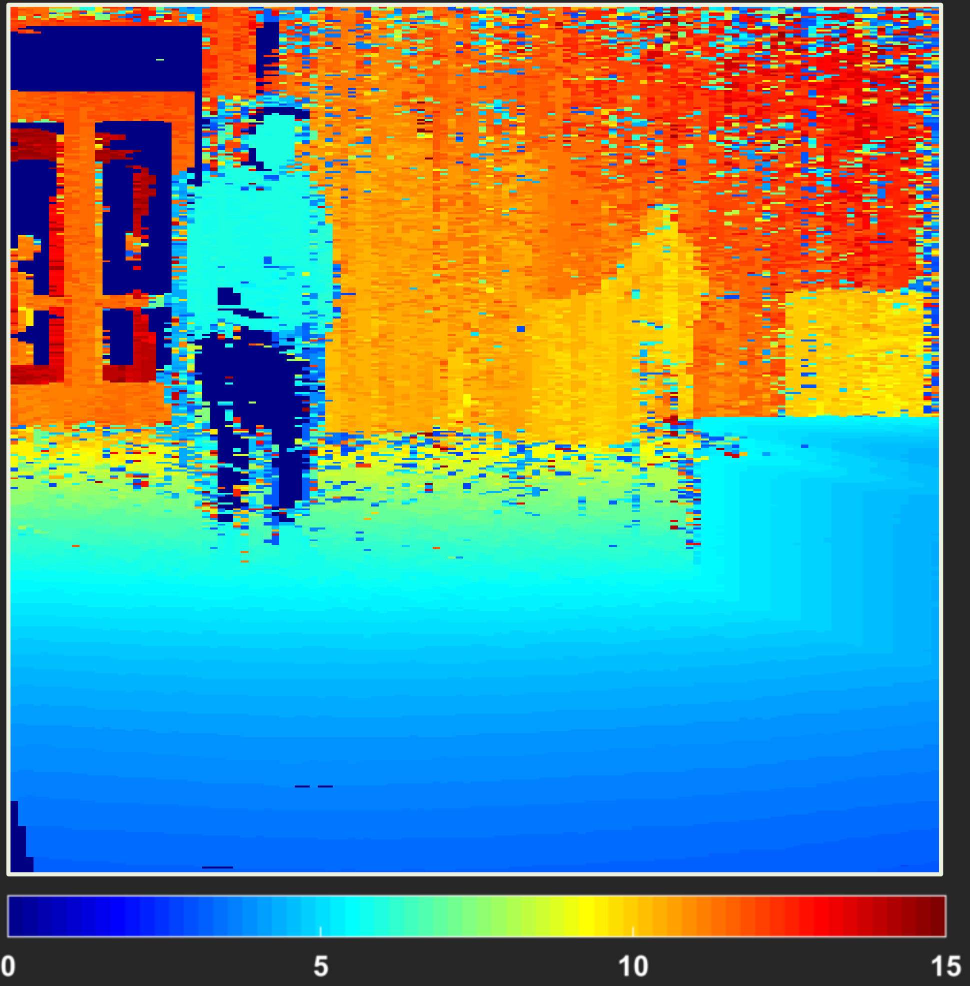
35m

Depth Map under strong sunlight

Scene

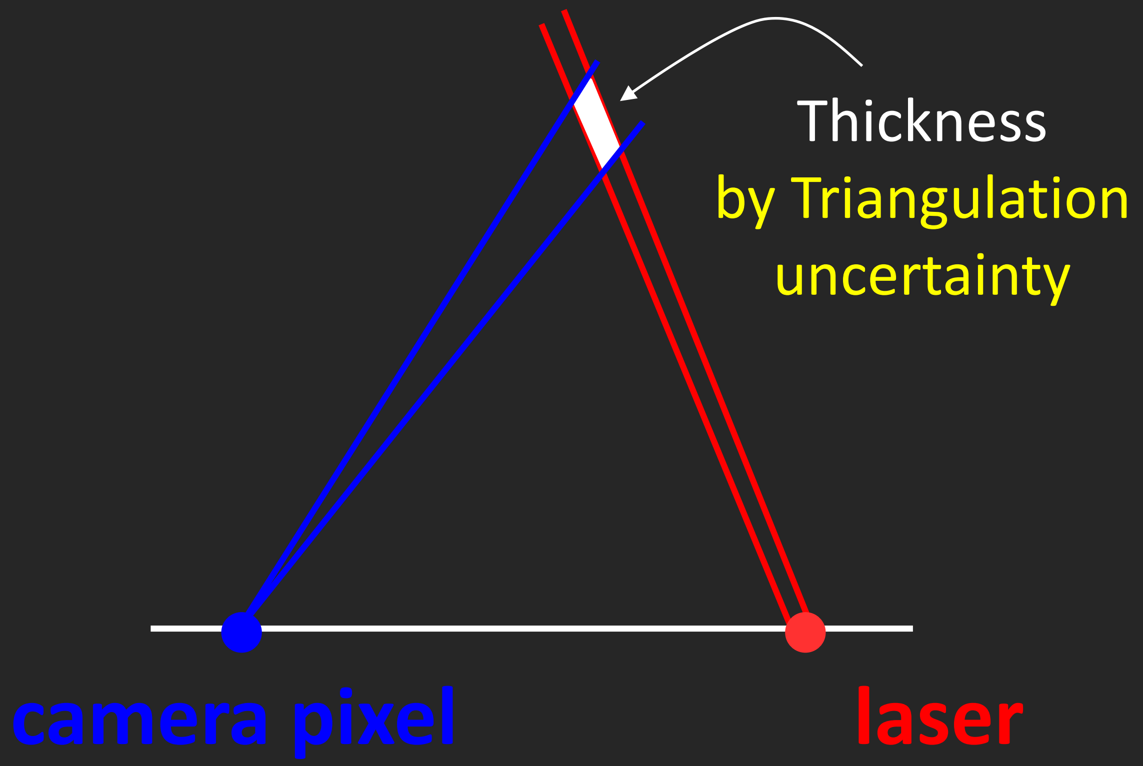
Sunny – 100klux

Depth Map



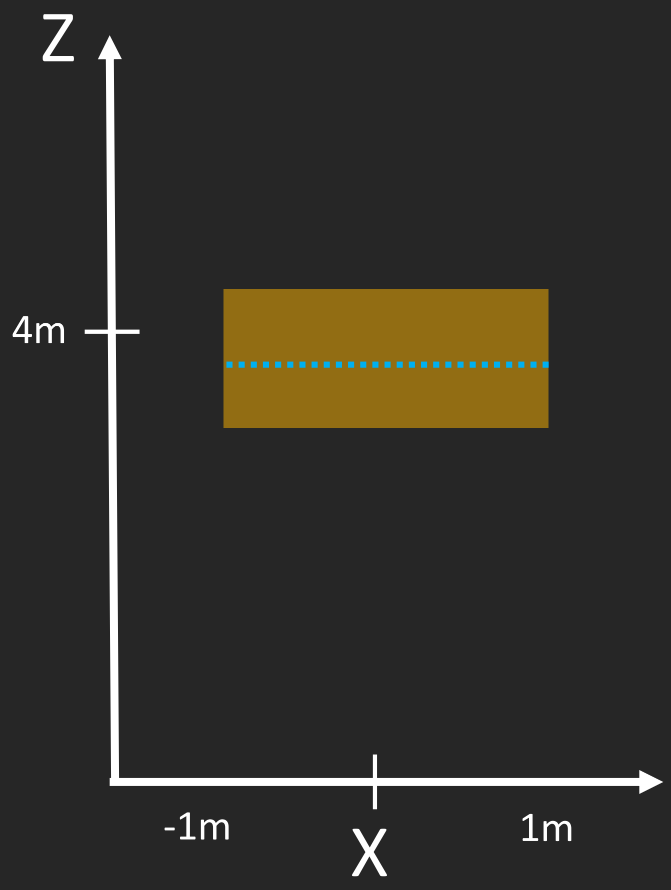
Depth (meters)

Thickness

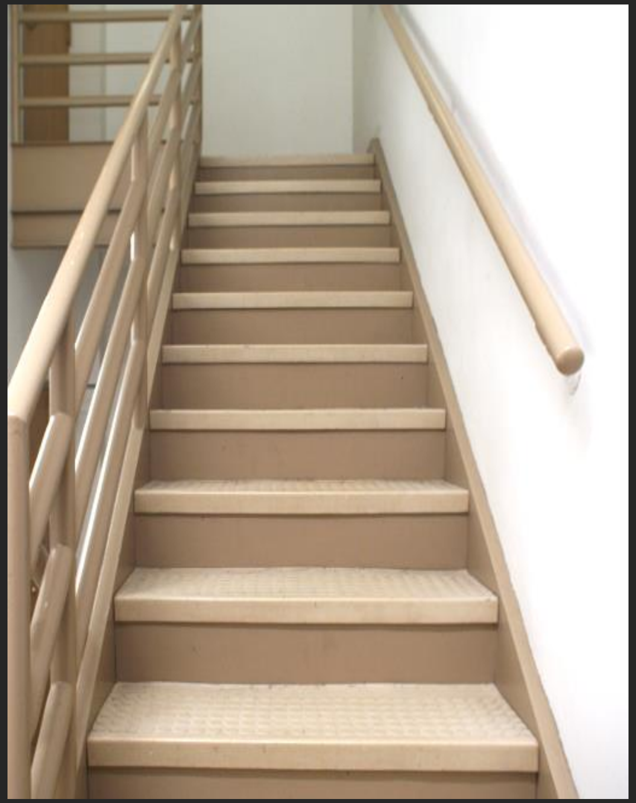


Top view

Thickness



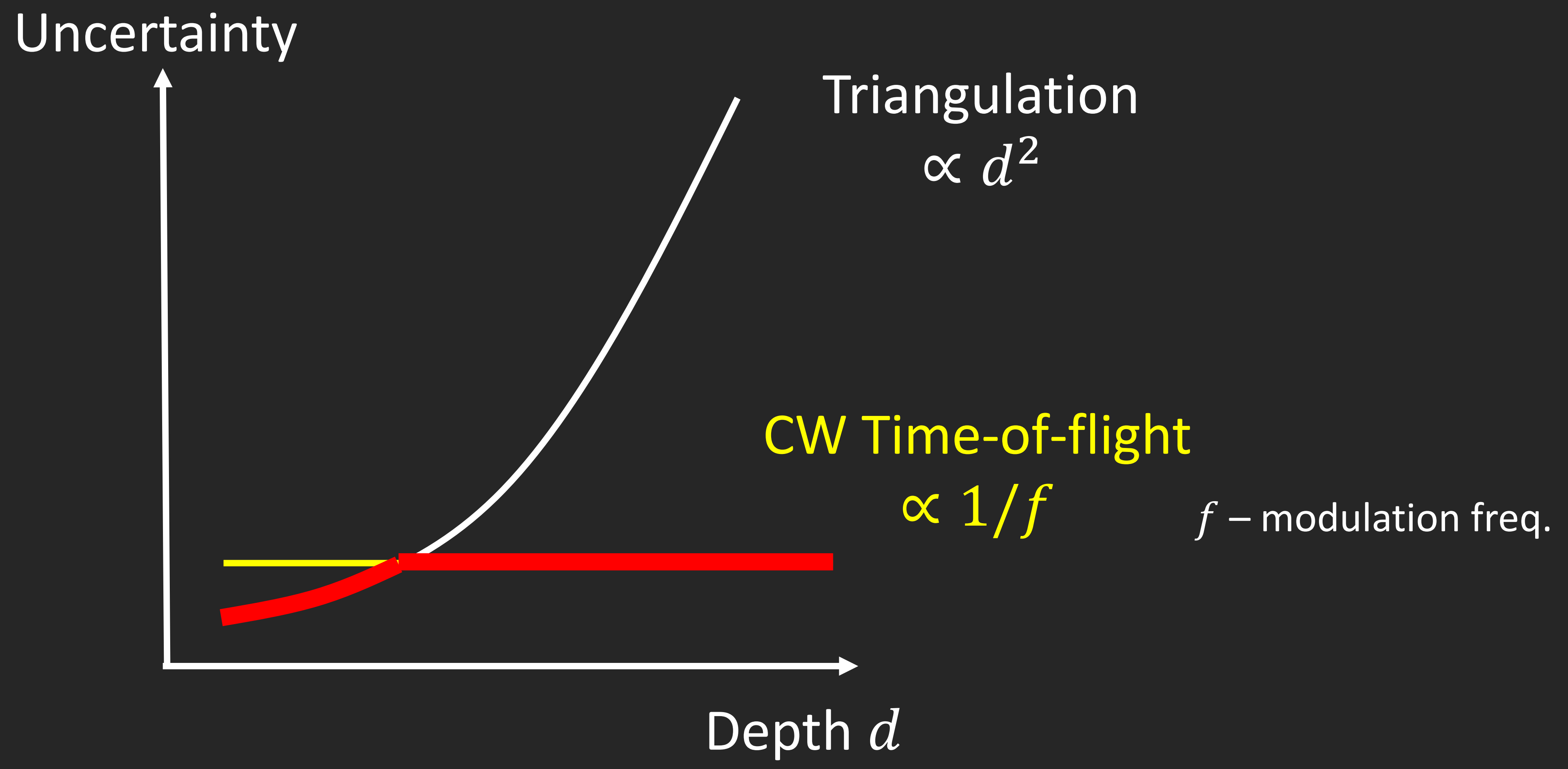
Light curtain
with thickness



Scene

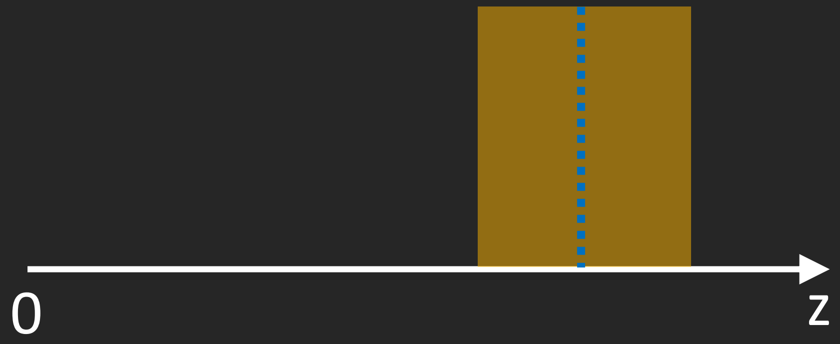
Light curtain data

Thickness



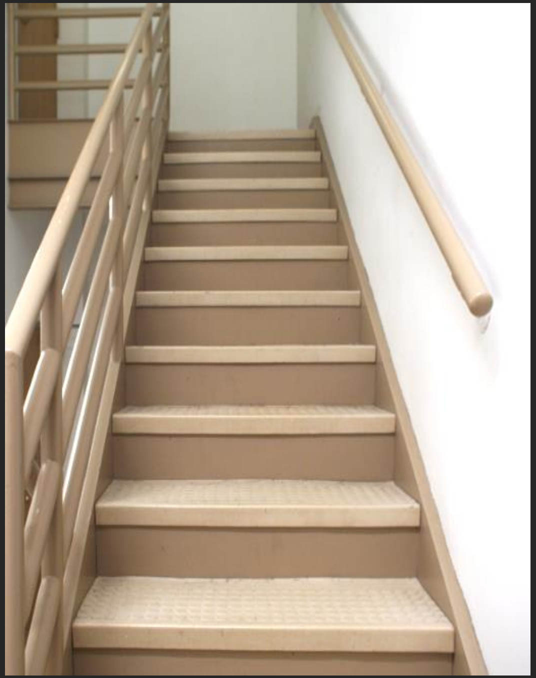
Uncertainty
Triangulation
$\propto d^2$
CW Time-of-flight
$\propto 1/f$
f – modulation freq.
Depth d

Combine with time-of-fight sensor

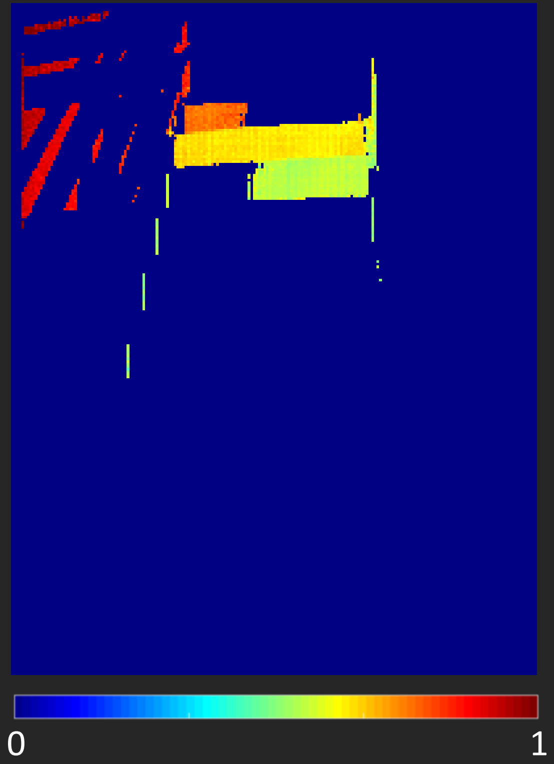


Combine with time-of-fight sensor

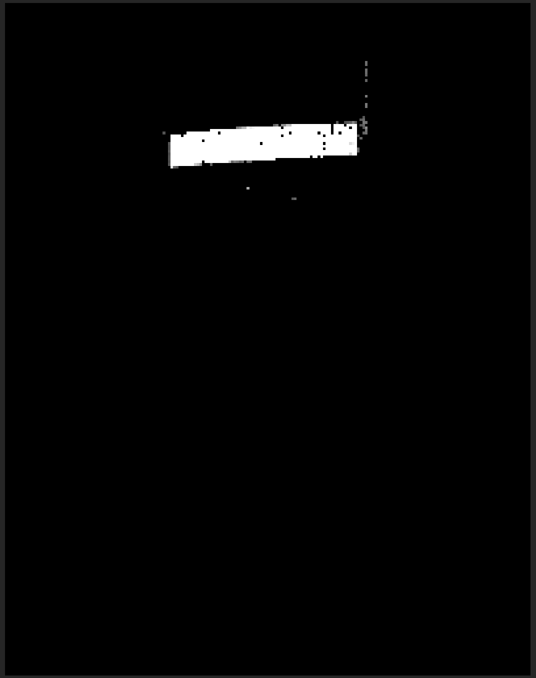
Combine with time-of-fight sensor



By triangulation



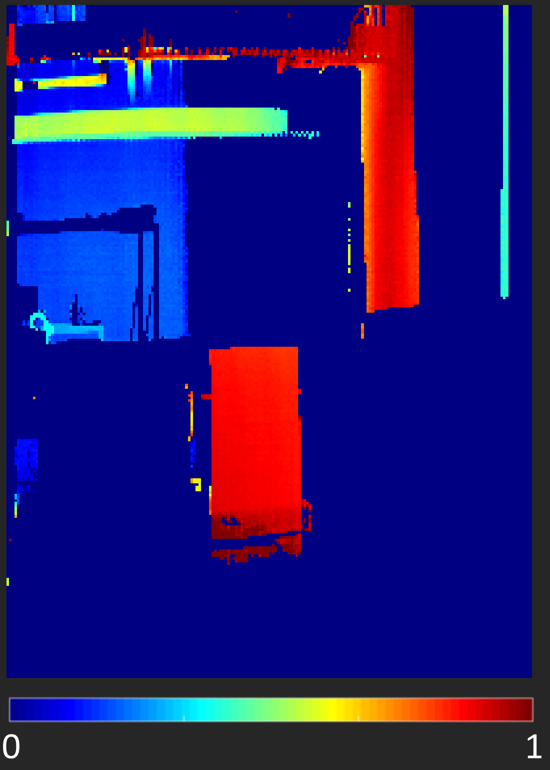
Phase



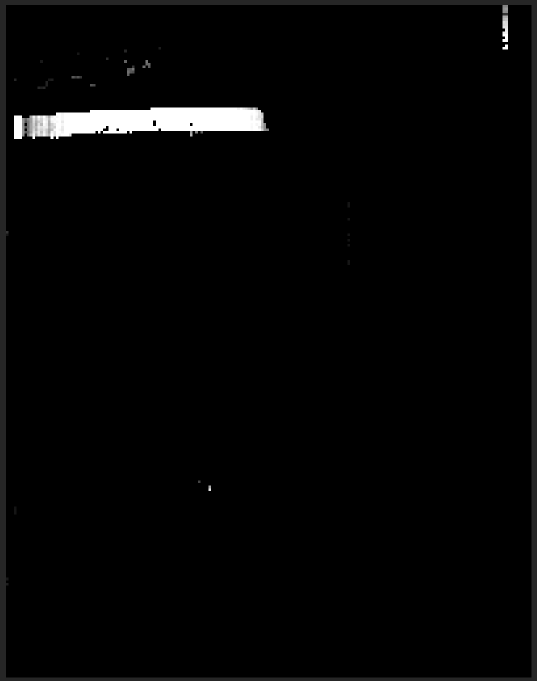
Triangulation + Phase

Combine with time-of-fight sensor

By triangulation

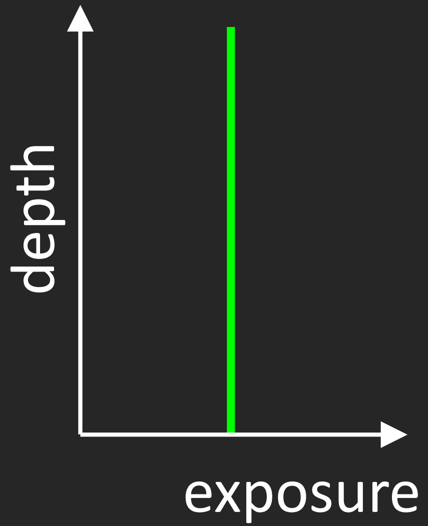


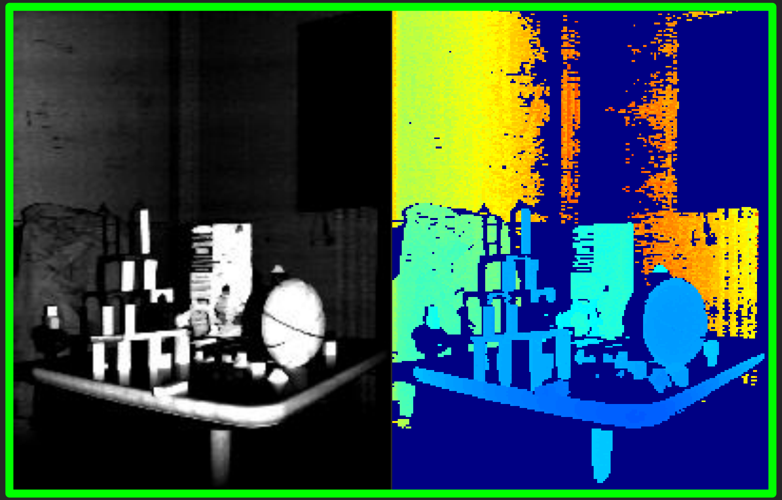
Phase with wrapping



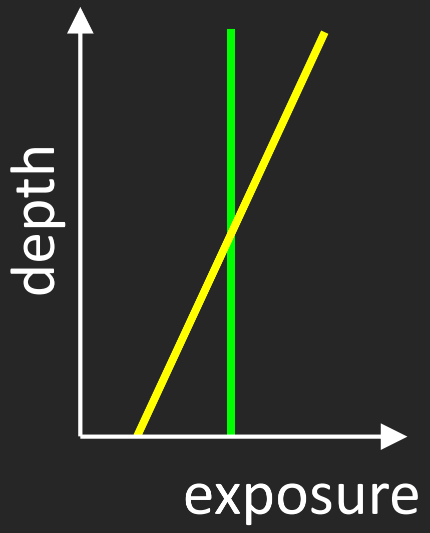
Triangulation + Phase

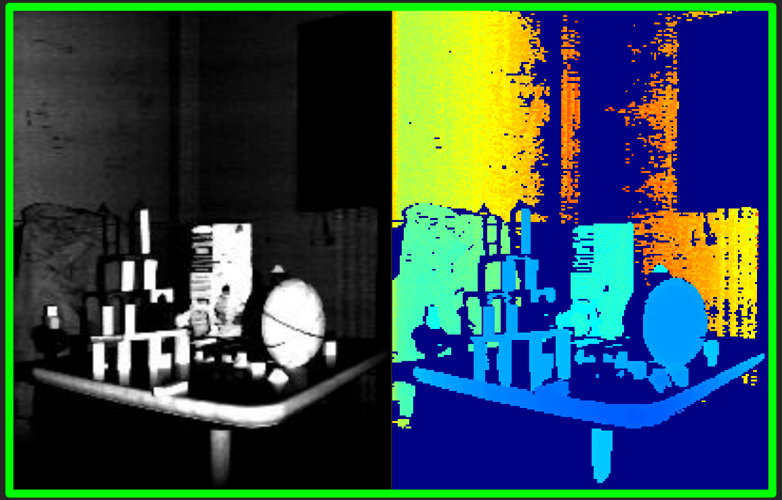
Light fall-off

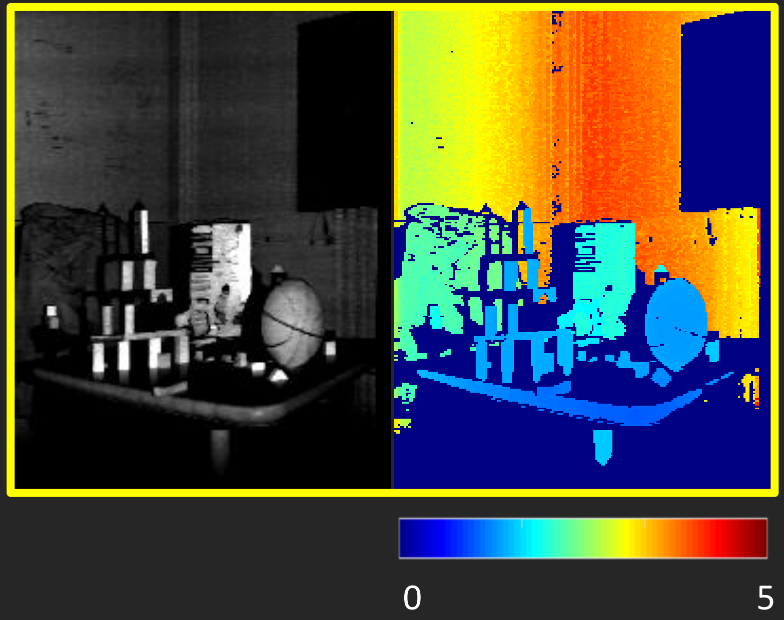




Depth-adaptive energy



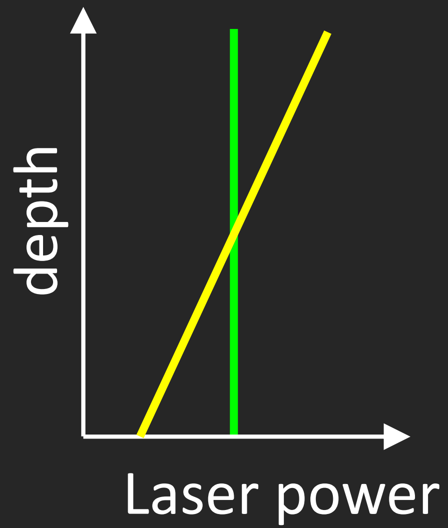


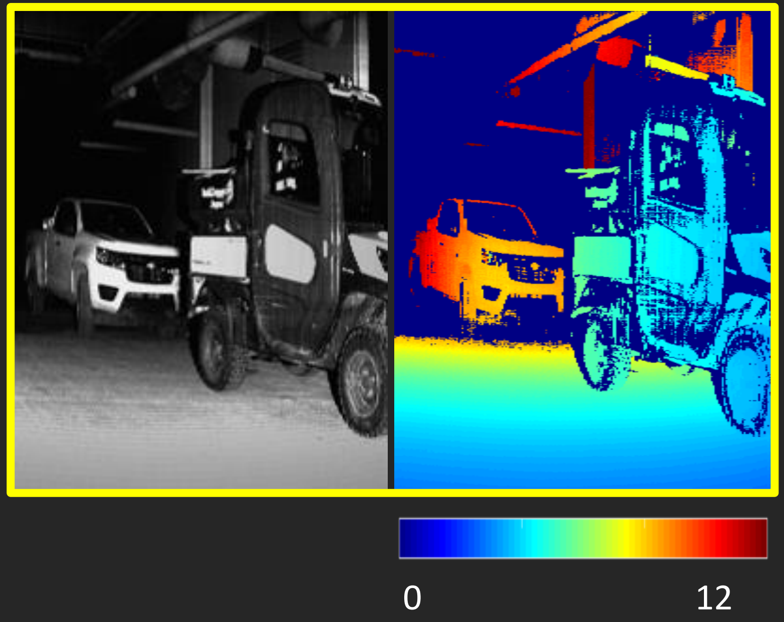


Constant

Depth-adaptive

Depth-adaptive energy





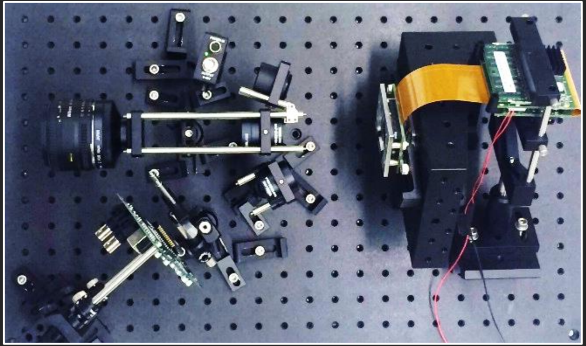
Constant

Depth-adaptive

Summary of TriLC device

- The depth of interest is pre-specified, so the device can be optimized accordingly
  - Cost, energy, computation - low
  - Workable under sunlight, in thick smoke/fog – ‘high’
  - Flexible: shape, thickness
  - Fast

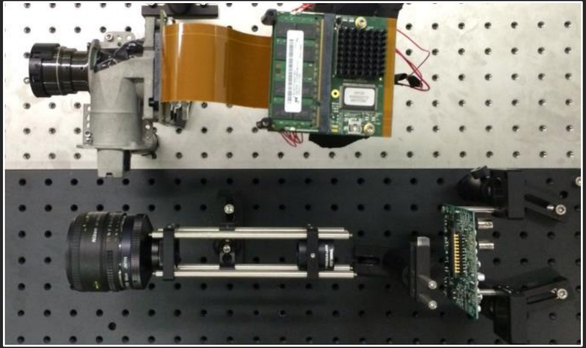
- *‘Limitation’: only depth of interest*



LiSens

2D imaging architecture

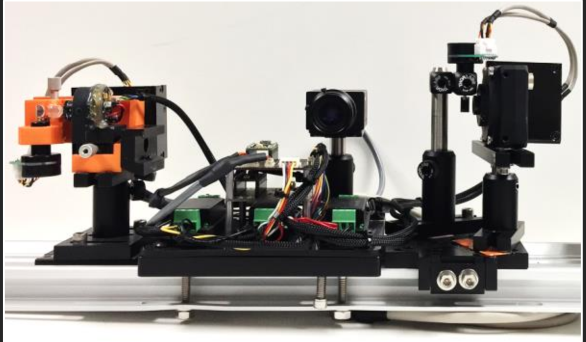
Jian Wang, Mohit Gupta, and Aswin C. Sankaranarayanan. "LiSens-A scalable architecture for video compressive sensing." ICCP 2015.



DualSL

3D scanning architecture

Jian Wang, Aswin C. Sankaranarayanan, Mohit Gupta, and Srinivasa G. Narasimhan. "Dual structured light 3d using a 1d sensor." ECCV 2016.



TriLC

Robust proximity sensor

Jian Wang, Joe Bartels, William Whittaker, Aswin C. Sankaranarayanan, and Srinivasa G. Narasimhan. "Programmable Triangulation Light Curtains." ECCV 2018.

High spatial temporal resolution with line sensors

Conclusion remarks

- Traditional methods
  - Passive imaging in non-visible wavebands
  - Active imaging in strong ambient light and global light
  - Point detector based: cheap, robust but too slow
  - 2D sensor based: fast but costly, not reliable

- This thesis: High resolution 2D imaging and 3D scanning with line sensors
  - Cheap, robust and fast
  - LiSens: 2D imaging architecture
  - DualSL: 3D scanning architecture
  - TriLC: robust proximity sensor and see-thru-smoke imager

Thanks the committee

- Vijayakumar Bhagavatula
- Mohit Gupta
- Aswin Sankaranarayanan (advisor)
- Srinivasa Narasimhan (advisor)

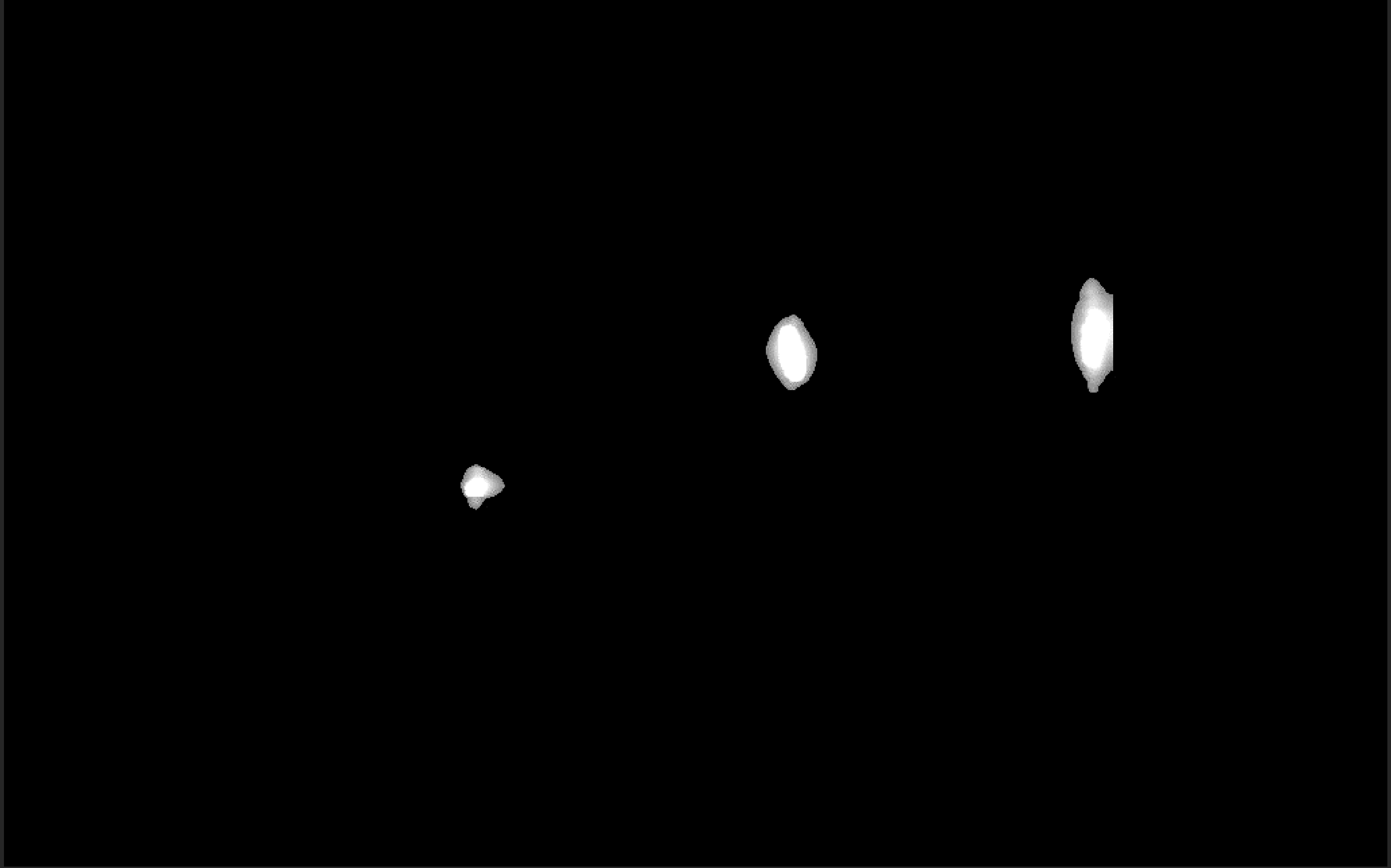
Future work

- TriLC with multiple line lasers
  - Eye-safety distance is same as light curtain usage distance
  - Interference problem is solved
- Triangulation gating + temporal gating for seeing through scattering media
  - Spatial cue and temporal cue
- Outdoor real-time photometric stereo
  - One rolling-shutter camera and two aligned line light and the Sun
- Incorporating machine learning
  - LiSens with fast reconstruction
  - DualSL with less patterns
  - TriLC with adaptively assigning lines

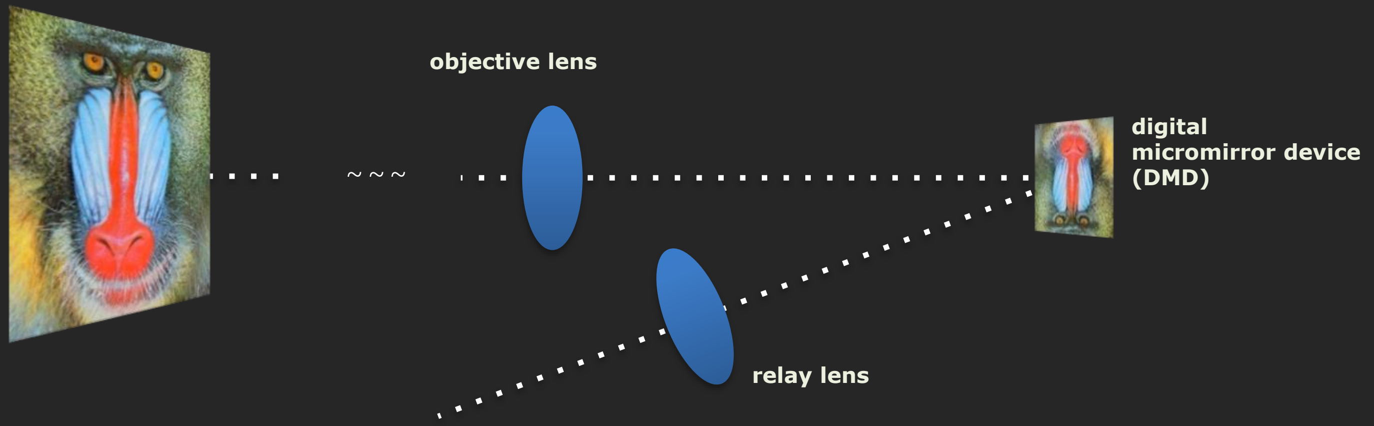
LiSens

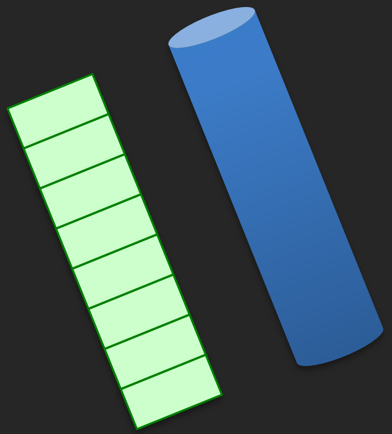
Laser dots movement

1024 x 768 pixels
104 fps
70x compression

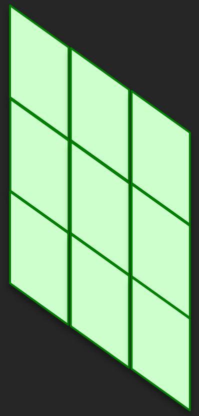


Line sensor vs. low-res 2D sensor array





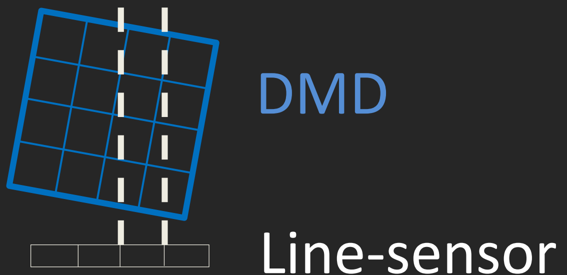
vs.

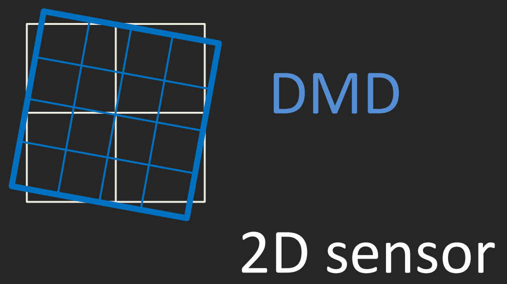


line sensor

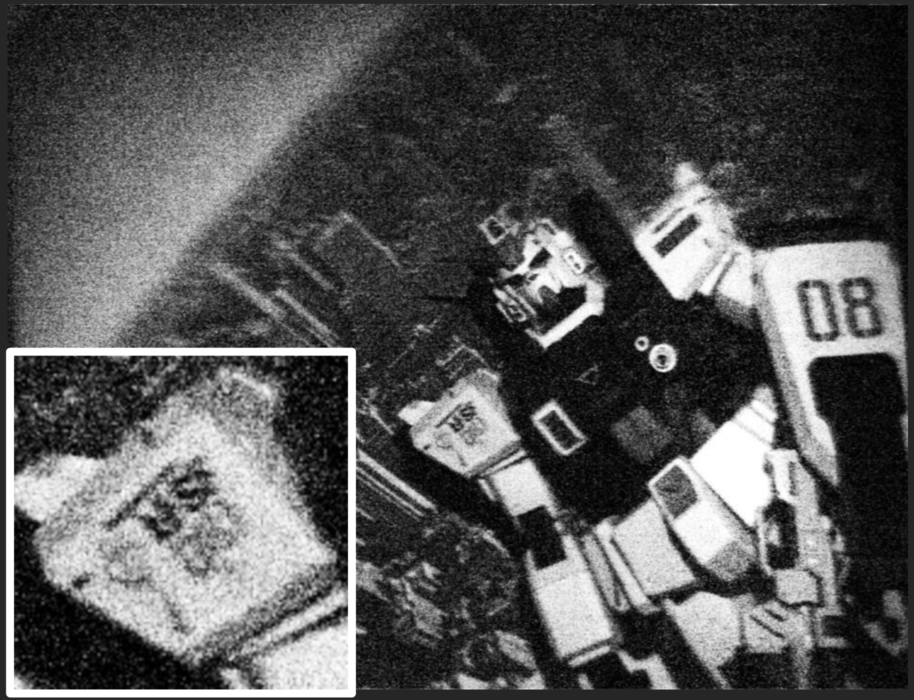
2D sensor

If misalignment…

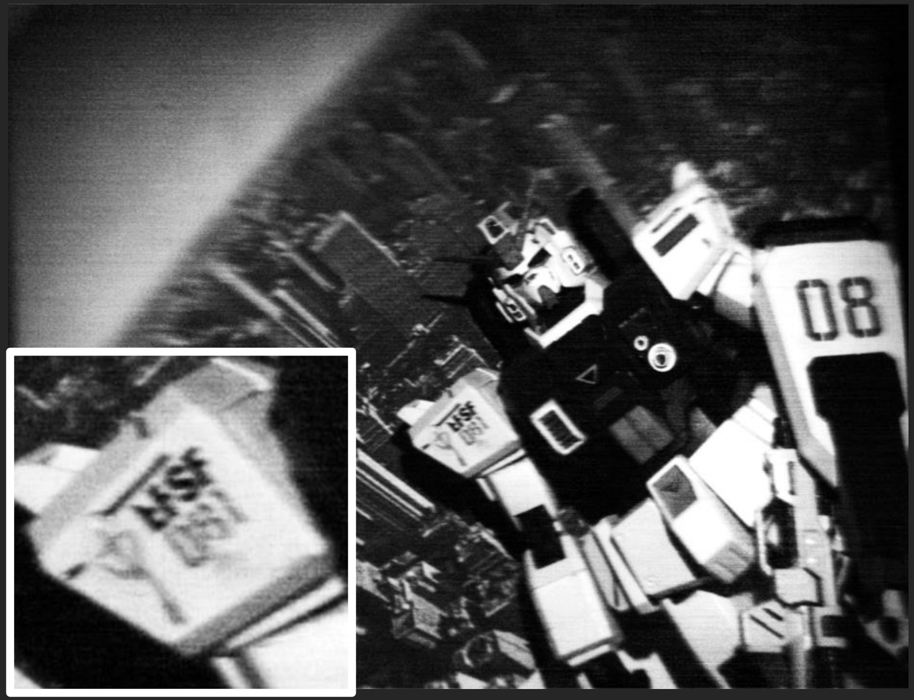




Frame transfer
No light loss during readout

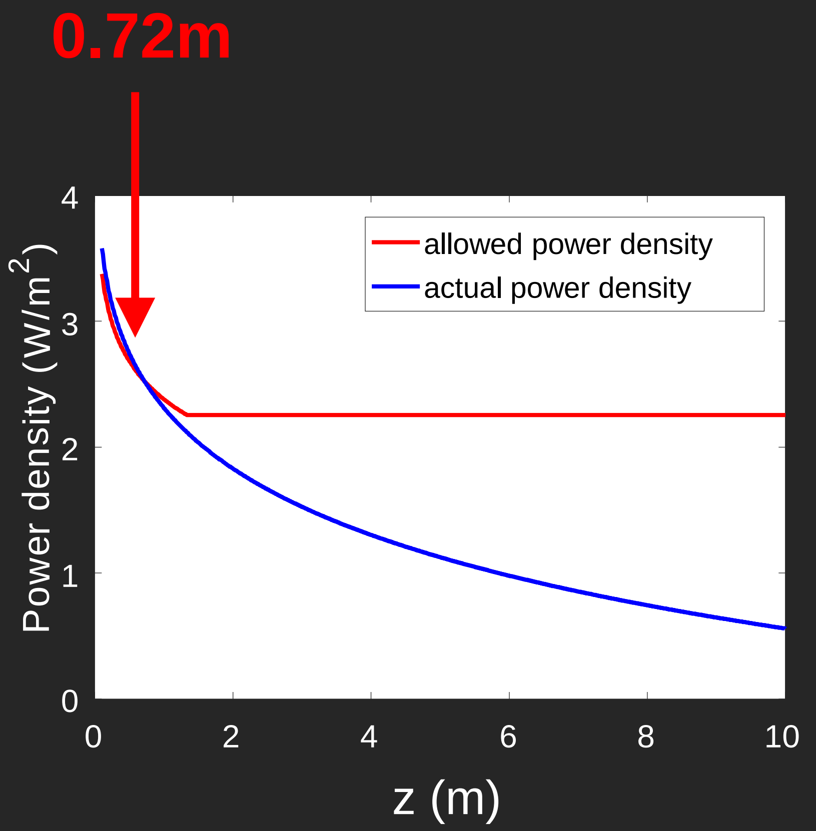


Sequential
exposure and readout
Without frame transfer

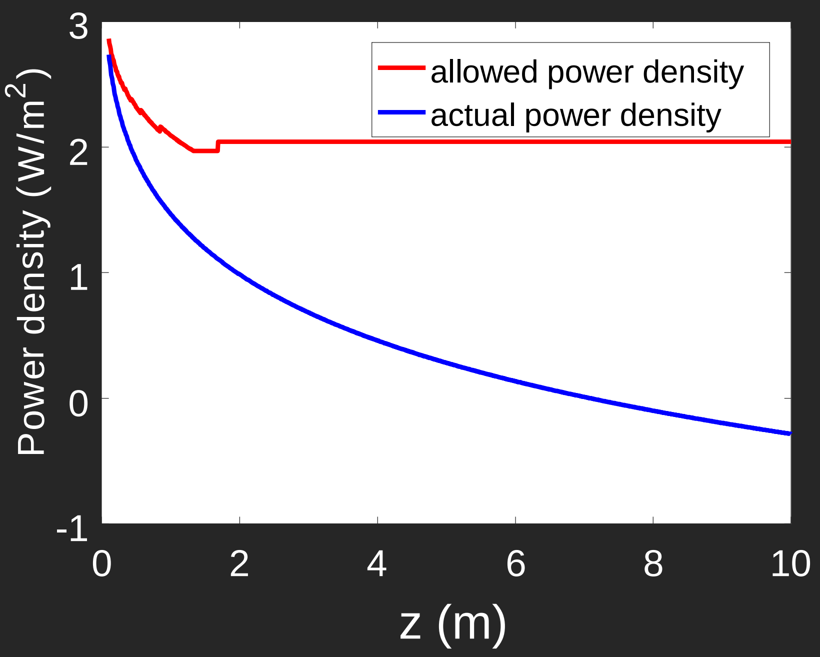


Simultaneous
exposure and readout
With frame transfer

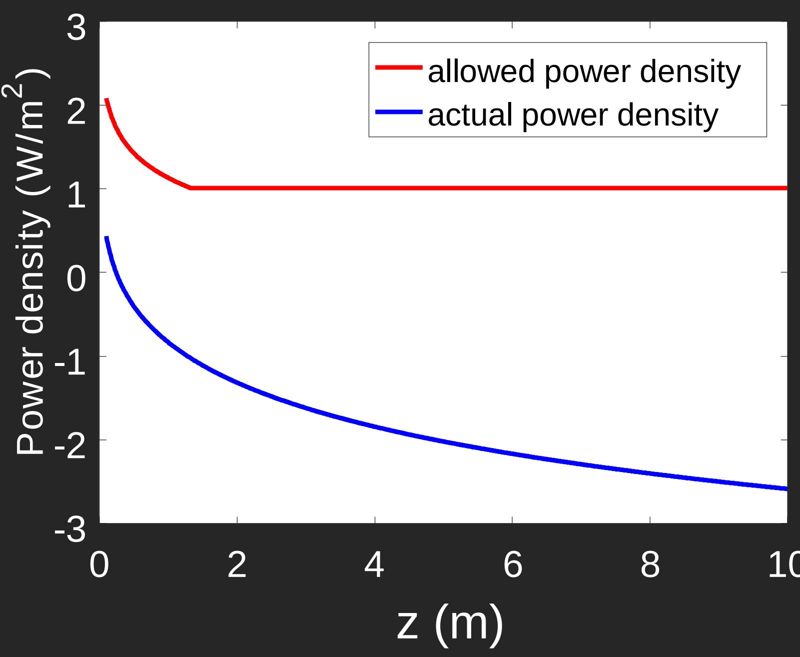
Laser Safety



Single pulse test



Consecutive rows test



Long time run (8 hrs) test