# When 2D Is Not Enough: An Overview of Optical Depth Sensing Technologies

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Ambarella

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# Ambarella

*AI Vision Processors For Edge Applications*


**2021**
**280+ million**
HD/4K cameras enabled

**2015**
Acquisition of VisLab

**2012**
IPO NASDAQ: AMBA

**2004**
Ambarella founded

## Founded on the premise that video is a unique type of data requiring an optimized SoC architecture

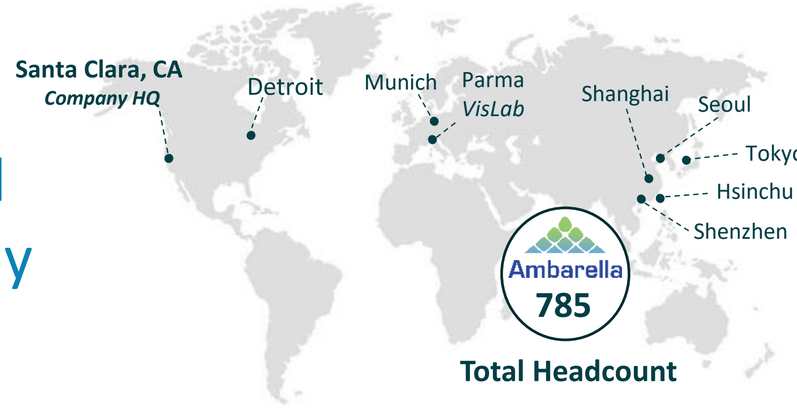
- DNN AI processors integrated with state-of-the-art video processors yield highly optimized computer vision SoCs

## Viewing and sensing SoCs with leading performance and efficiency

- Low-power and high-performance SoCs for IoT and Automotive camera markets

## World-class engineering team

- **>600** software, algorithm, VLSI and image processing engineers globally

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# Outline

- Why Depth?
- Depth Sensing Modalities
- Stereo Camera, Time of Flight, and Structured Light
  - Operating Principles
  - Design considerations: Resolution, Range, Precision, Bright light and Low-light performance
- Review and comparison
- Applications

# Why Depth?

# Why Depth?

Which face is real?


Are all objects flat?

What is in the way?

# Modalities

# Depth Sensing Modalities

Sonar

Radar

Lidar

Stereo camera

Time of Flight module

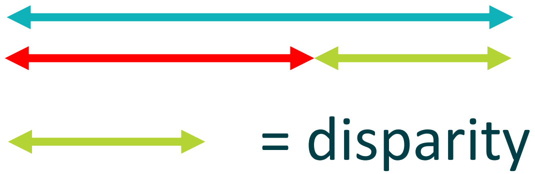
Structured Light module

# Stereo Camera System

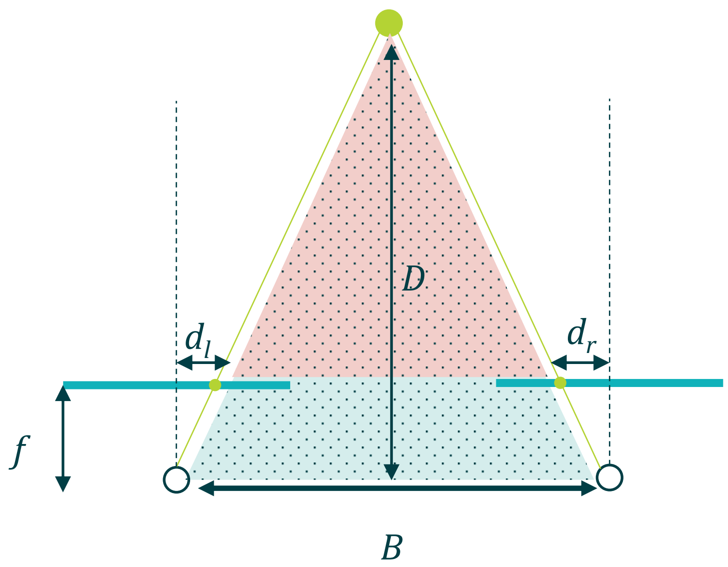
# Operating Principle – Stereo Camera System

Left Image

Right Image



# Operating Principle – Stereo Camera System




- Distance inversely proportional to disparity
- Epipolar geometry helps to reduce search space for matching point
- Finding matching point is called correspondence problem

$$\frac{B}{D} = \frac{B - dl - dr}{D - f}$$

$$D = f\frac{B}{d_l - dr}$$

$B$ – baseline (distance between optical center)
$D$ – distance to be measured
$f$ – focal length of lens
$d$ – distance of projected point from optical axis

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# Design Considerations – Stereo Camera Systems

- Systems are flexible and scalable – can accommodate many configurations with appropriate change in sensor resolution, field of view (FoV), and baseline.
- Depth precision decreases with distance – non-linear error model.
- Good performance in bright light conditions. Low-light performance depends on output of image pipeline.
- Challenged on scenes with low texture – improved with active illumination.
- Manufacturing process can be complicated – alignment of optical units is critical during and after manufacture. Improved with periodic calibration or autocalibration software.

# Design Consideration – Stereo Camera Systems

Stereo Left

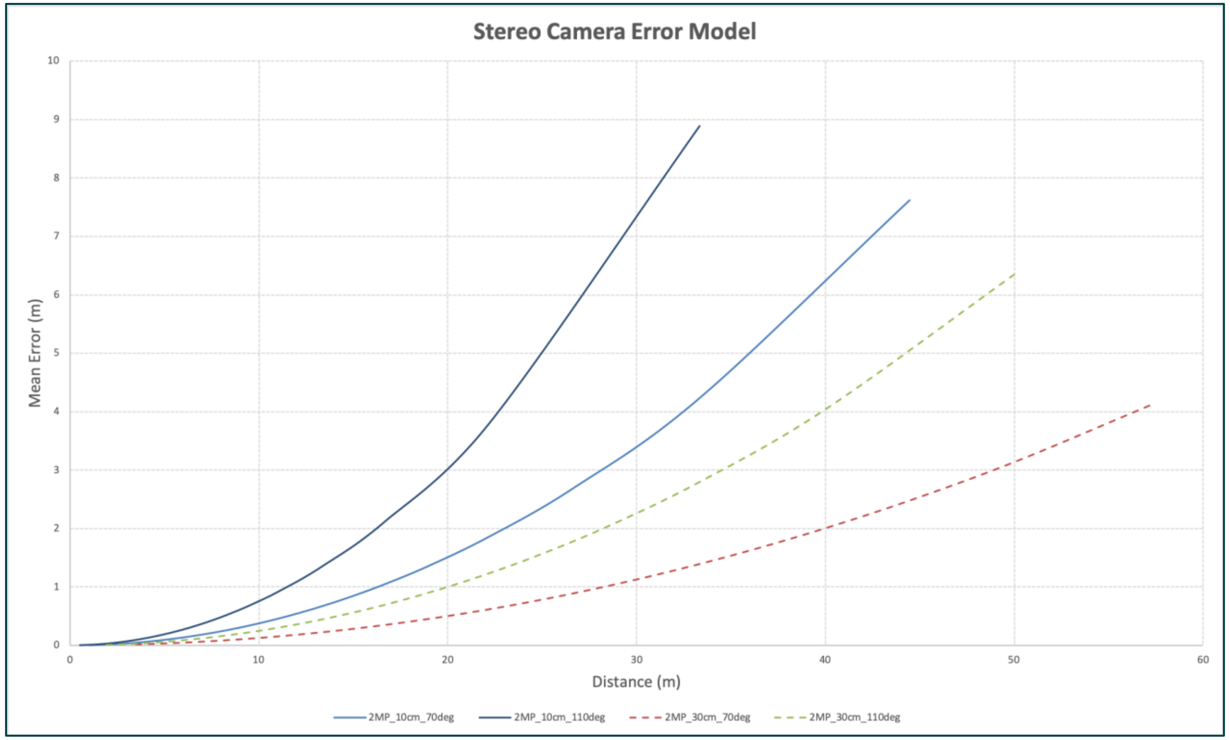
Stereo Right

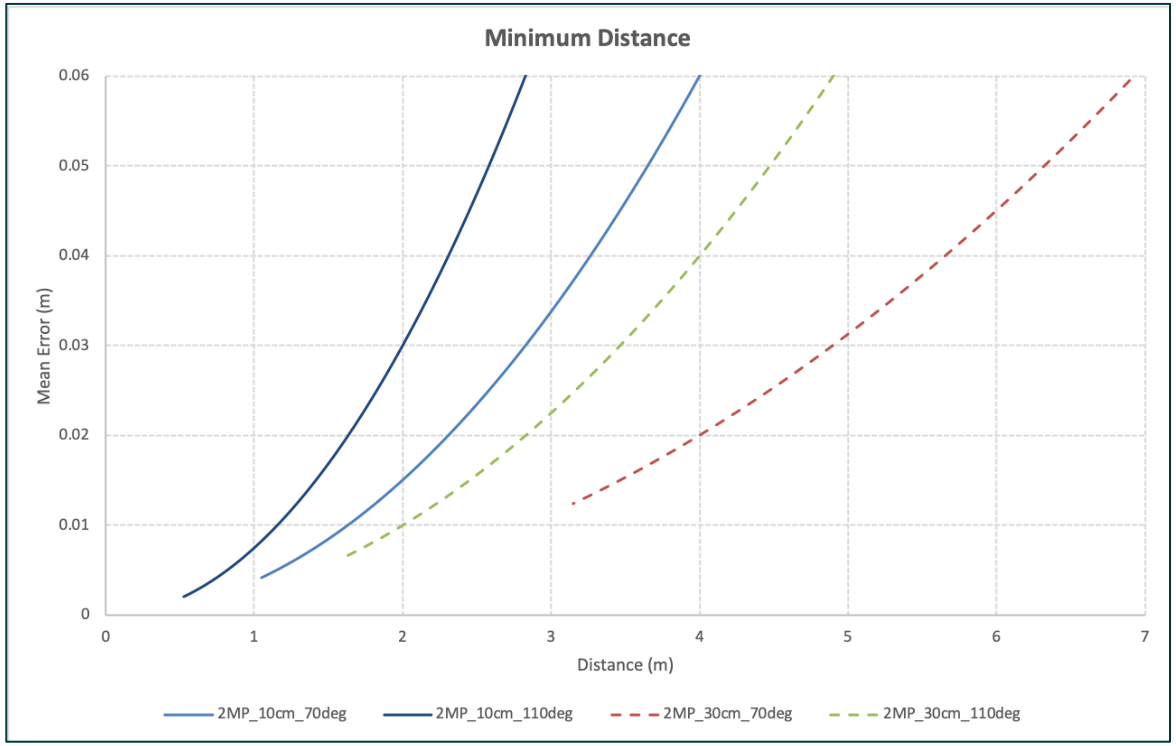
# Performance – Stereo Camera Systems

Stereo Left

Stereo Right

# Design Considerations – Stereo Camera Systems

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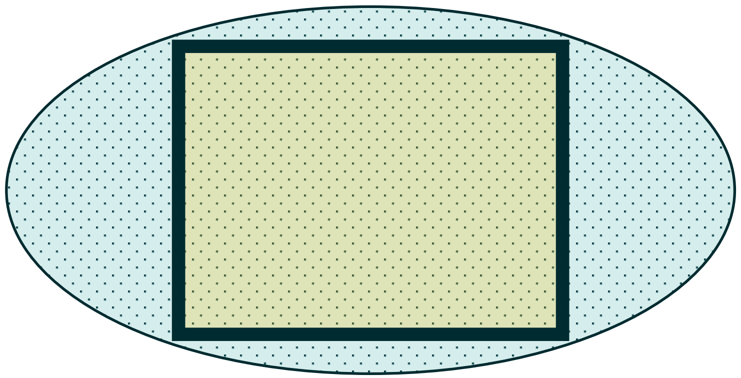
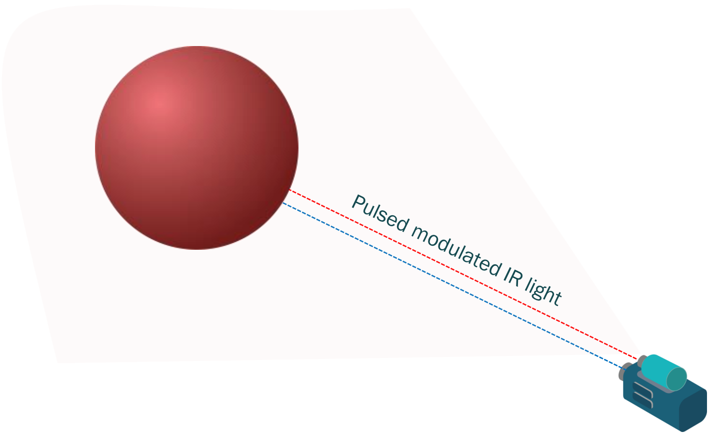
# Time of Flight

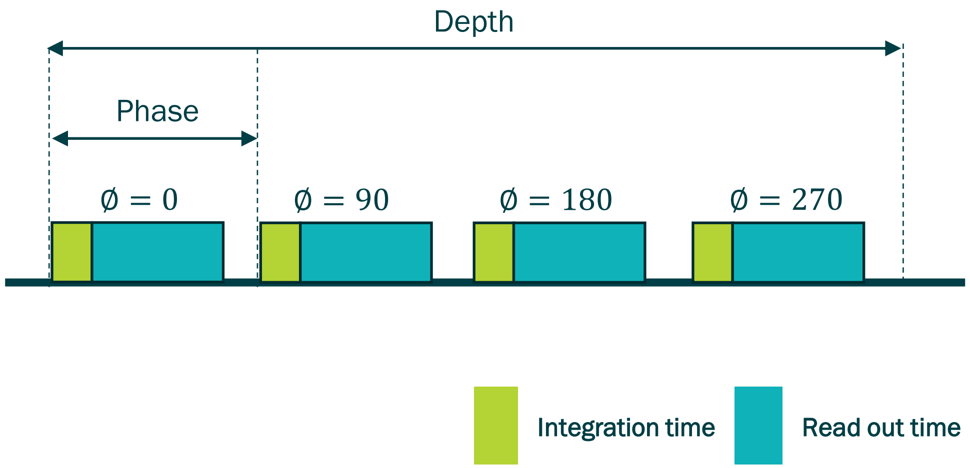
# Operating Principle – Time of Flight

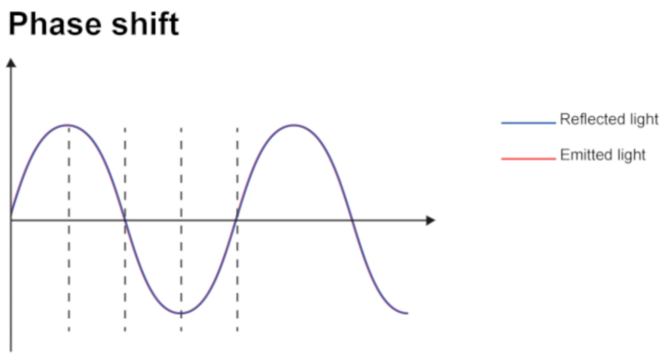
- Two types of ToF sensors: direct ToF and indirect ToF.
- Direct Tof sensors emit a pulse of light and measure the time it takes for the reflection to arrive at the sensor. Pulse strength and duration can be varied to allow long range measurements (up to kms).
- Indirect ToFs also called continuous-wave ToFs emit a pulsed, modulated light signal and measure the phase difference of the reflected signal to derive depth.

# Operating Principle – Time of Flight





# Operating Principle – Time of Flight


Depth


Amplitude

# Design Consideration– Time of Flight

- Depth range depends on modulating frequency of the IR source - maximum measurable distance for given frequency called *unambiguous range*.

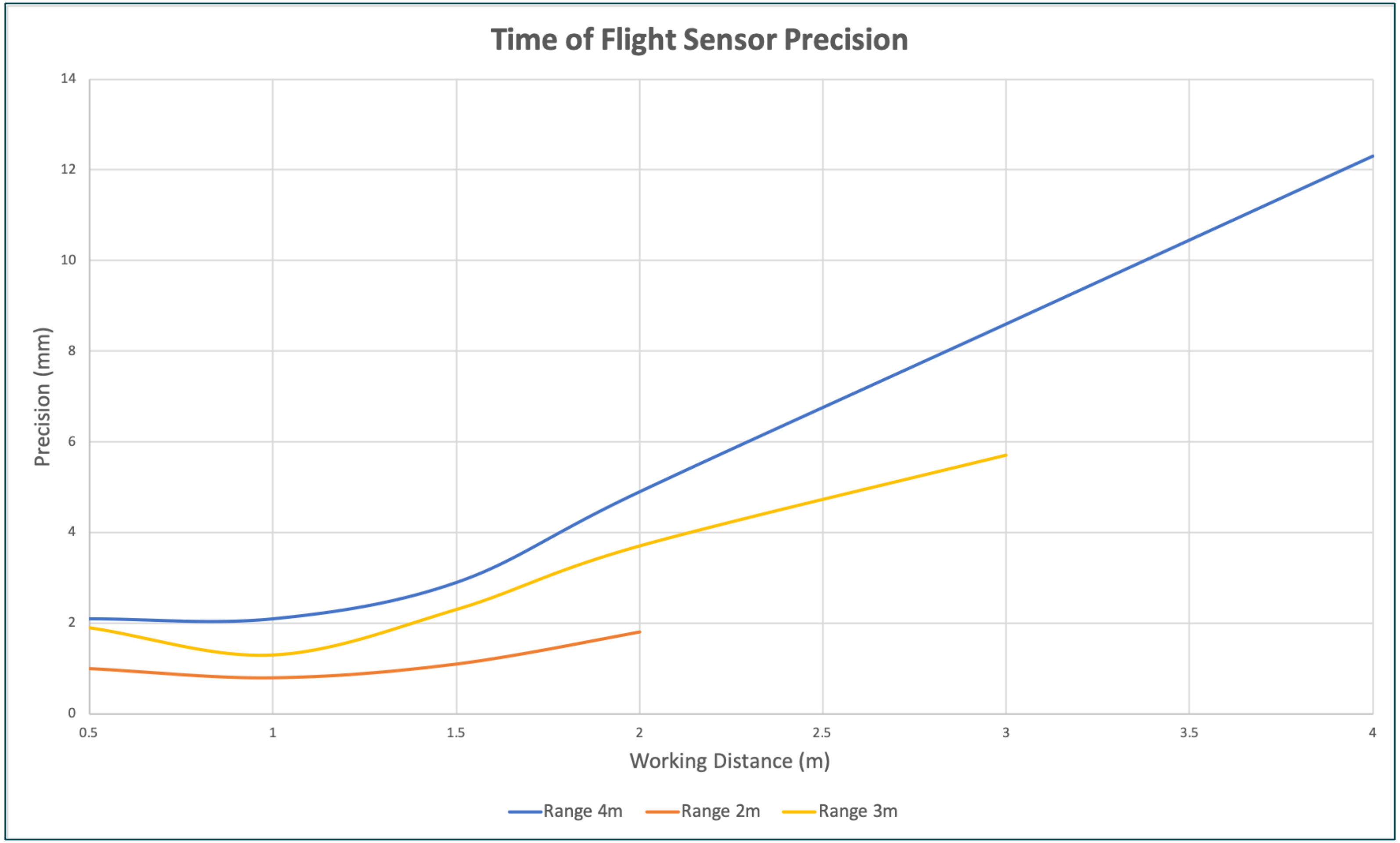
| Modulating Frequency (MHz) | Unambiguous Range (m) |
|---|---|
| 20 | 7.5 |
| 50 | 3 |
| 75 | 2 |
| 100 | 1.5 |

- LEDs can be used up to 30MHz. VCSELs (vertical-cavity surface-emitting laser) can be used if higher modulating frequencies are required (up to 100MHz).

# Design Considerations – Time of Flight

- Comparatively low resolution (VGA current max) but unaffected by scene texture
- Dense depth information where field of view and field of illumination overlap
- Range limited by modulating frequency of illuminator. Depth precision decreases with distance for a given modulating frequency.
- Good performance in low-light conditions. Sunlight affects bright light performance – improved when using 940 nm IR illuminator.
- Scattered reflections and cross talk can impact depth measurement.
- Integration time impacts number of fps but can handle motion.
- Combining multiple systems can be challenging – can be separated by frequency.

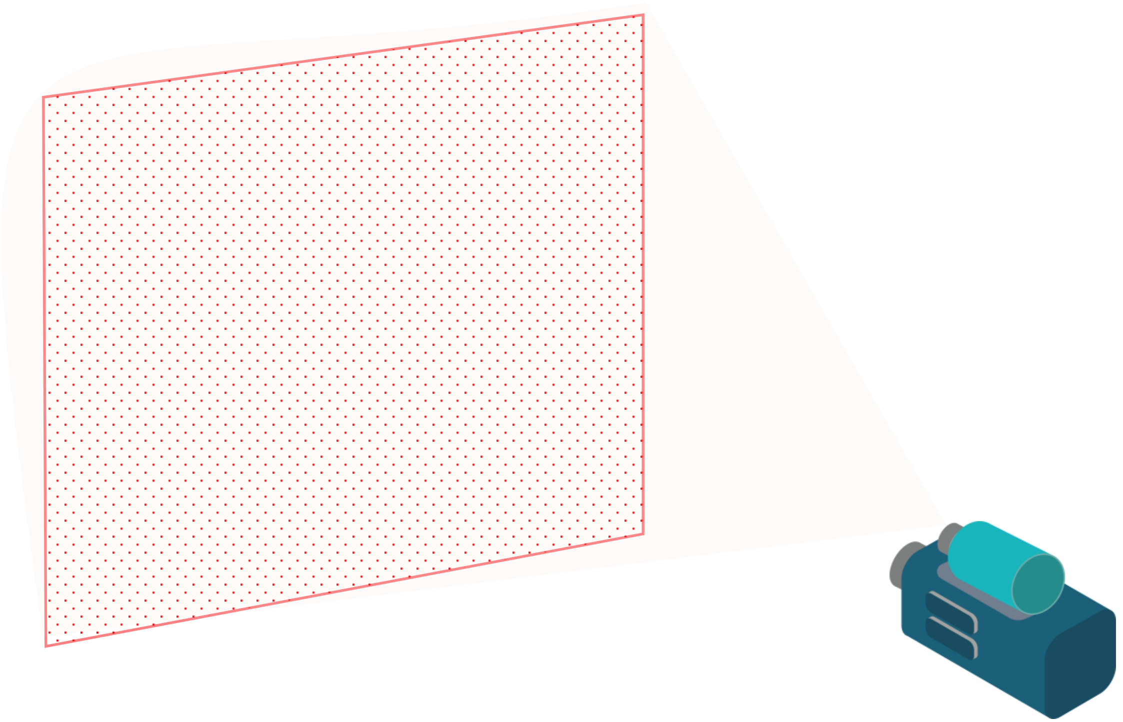
# Design Considerations – Time of Flight




* Data from vendor module

# Structured Light

# Operating Principle – Structured Light



- Light source plus a pattern generator project a random pattern.
- When image plane moves pattern shifts depending on object distance.
- Reflected pattern correlated against a reference stored on the system.
- Depth depends on disparity between the reference and reflected pattern.

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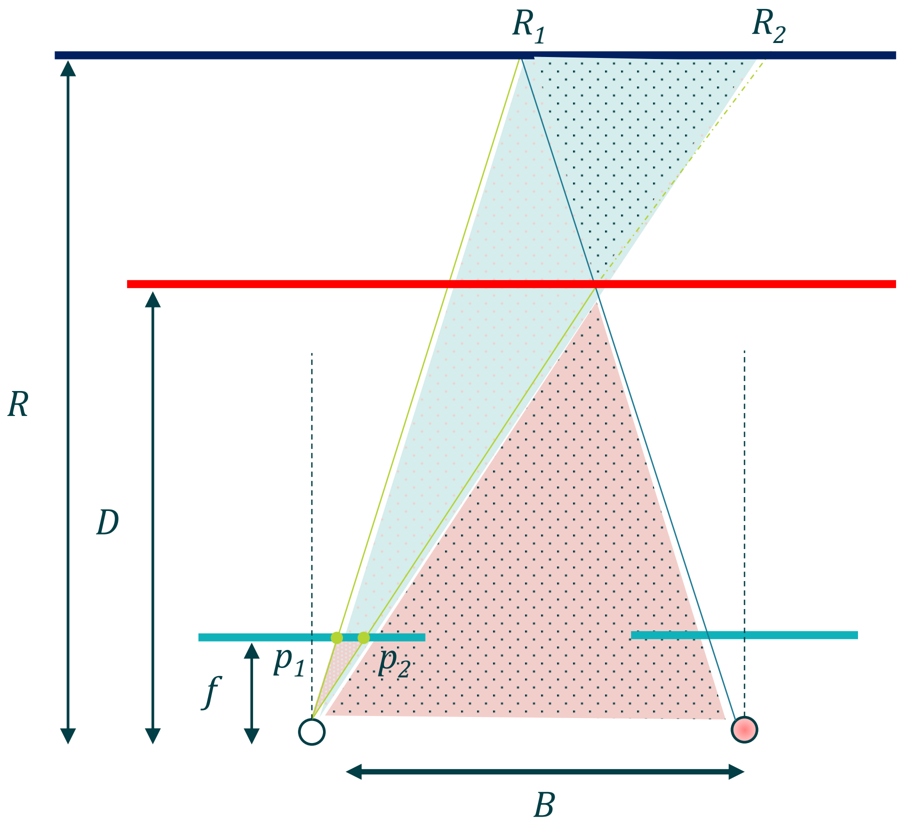
# Operating Principle – Structured Light




$$\frac{f}{p_2 - p_1} = \frac{R}{R_2 - R_1}$$

$$\frac{D}{B} = \frac{R - D}{R_2 - R_1}$$

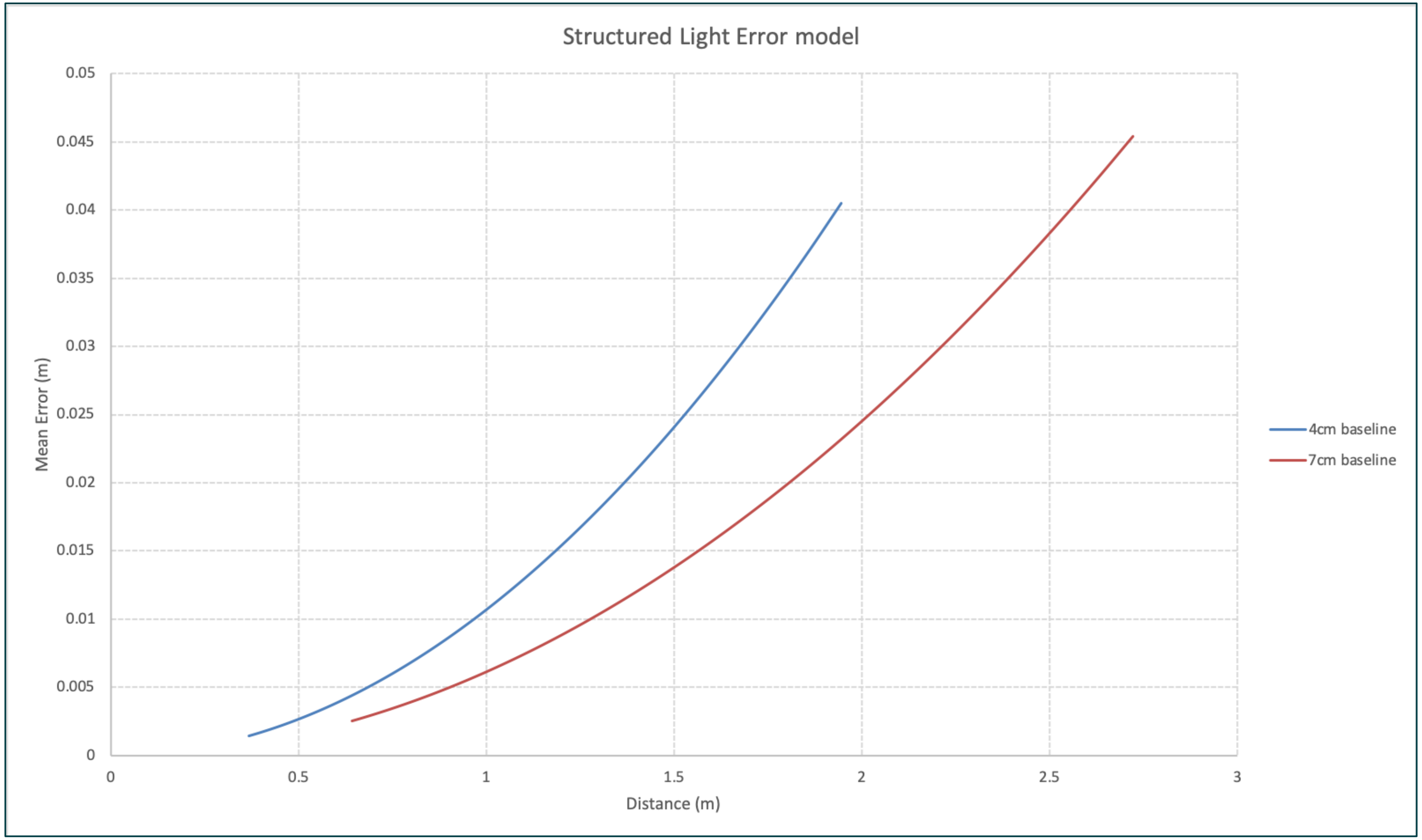
$$D = \frac{RBf}{R(p_2 - p_1) + Bf}$$

$B$ – baseline (distance between optical center)
$f$ – focal length of lens
$R$ – distance to reference plane
$D$ – distance to be measured
$R_n$ – Point on reference plane
$p_n$ – projected points on image plane

# System Considerations – Structured Light

- Moderately flexible – sensor resolution, baseline, and pattern density can be varied for different applications.
- Depth precision decreases with distance.
- Good performance in low-light conditions. Lower performance when sunlight is present – improved when using 940 nm IR illuminator.
- Spatial resolution higher than time of flight sensors but depth density depends on projector pattern.
- Frame rate depends on sensor and depth processing speed.

# System Considerations – Structured Light



# Comparison

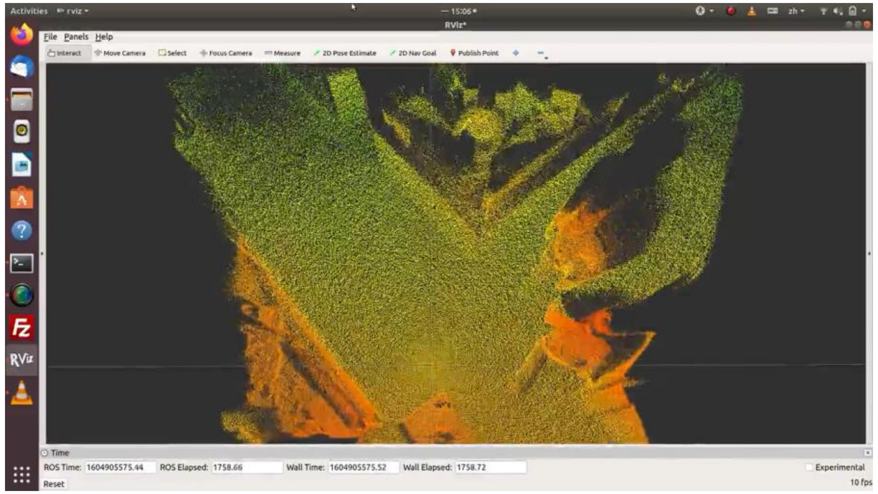
# Comparison

| | Stereo | Time of Flight | Structured Light |
|---|---|---|---|
| Depth Range | Short to long range | Low to mid range | Low to mid range |
| Depth Precision | mm to cm | mm to cm | mm to cm |
| Depth Resolution | High – can detect finer features or objects further away | Up to VGA | Pattern dependent |
| Active emitter | Optional | Required | Required |
| Bright light performance | Good | Fair – improved with 940 nm IR | Fair – improved with 940 nm IR |
| Low-light performance | Depends on ISP | Good | Good |
| Cost | High | Low | Mid |

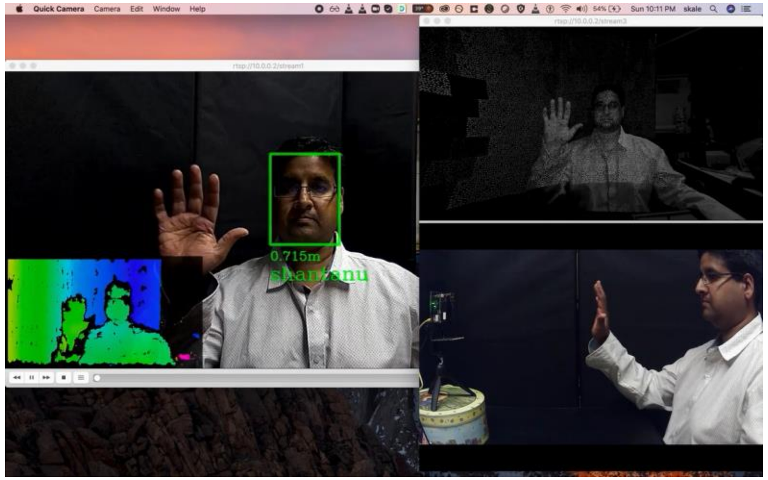
# Applications

# Applications


Long-range stereo for autonomous driving



ToF for occupancy sensing



Structured light for access control

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# Thank You