Active Illumination Methods

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Topic: Active Illumination Methods, Module: Reconstruction I

First Principles of Computer Vision

Photometric Stereo Systems

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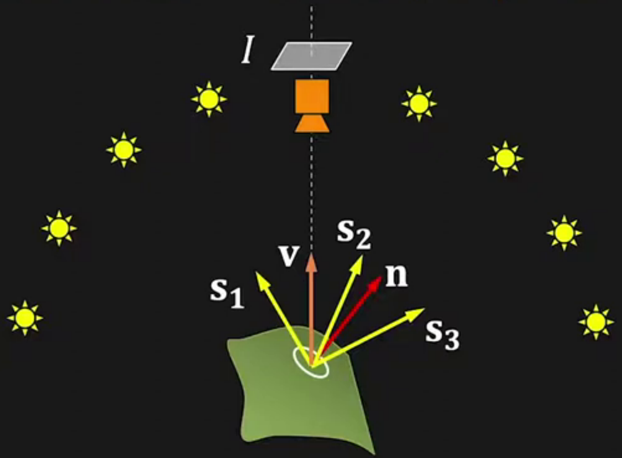
Photometric Sampling

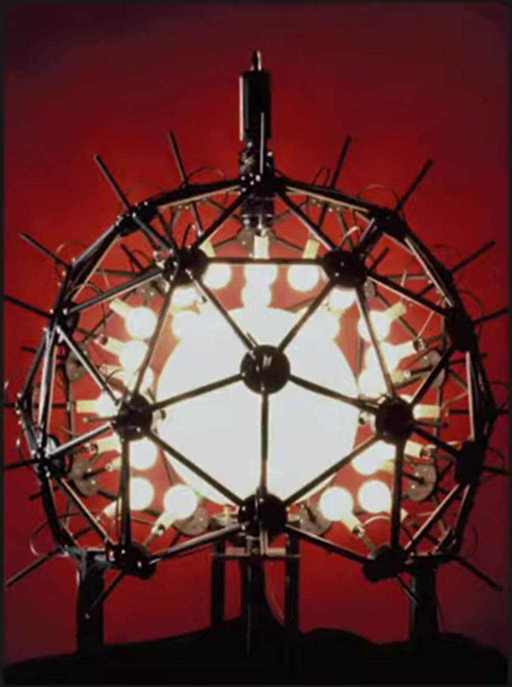
Given: Multiple images of object with known reflectance model with unknown parameters under different known sources.

Find: Surface normals and reflectance parameters.



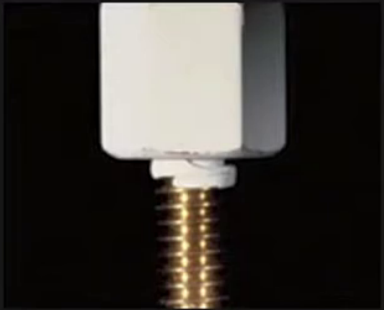
[Nayar 1989]

Photometric Sampling



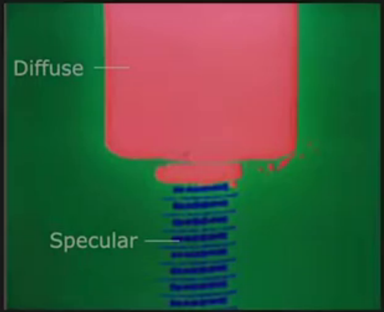
[Nayar 1989]

Recovering Shape and Reflectance



Object

Surface Normals



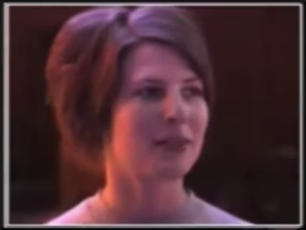
Reflectance

[Nayar 1989]

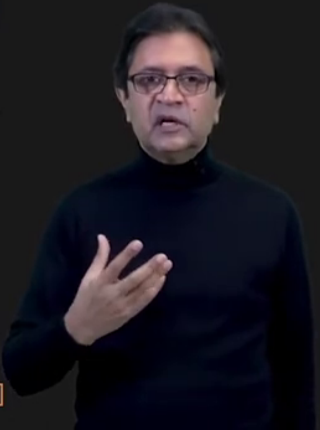
Light Stage

[Wenger 2005]

Relighting



[Wenger 2005]



Real-Time Shape and Reflectance

Surface Normals and Reflectance

[Wenger 2005]

Real-Time Shape and Reflectance

Surface Normals and Reflectance

[Wenger 2005]

Real-Time Shape and Reflectance

Surface Normals and Reflectance

Lighting

Relighting

[Wenger 2005]

Structured Light Range Finding

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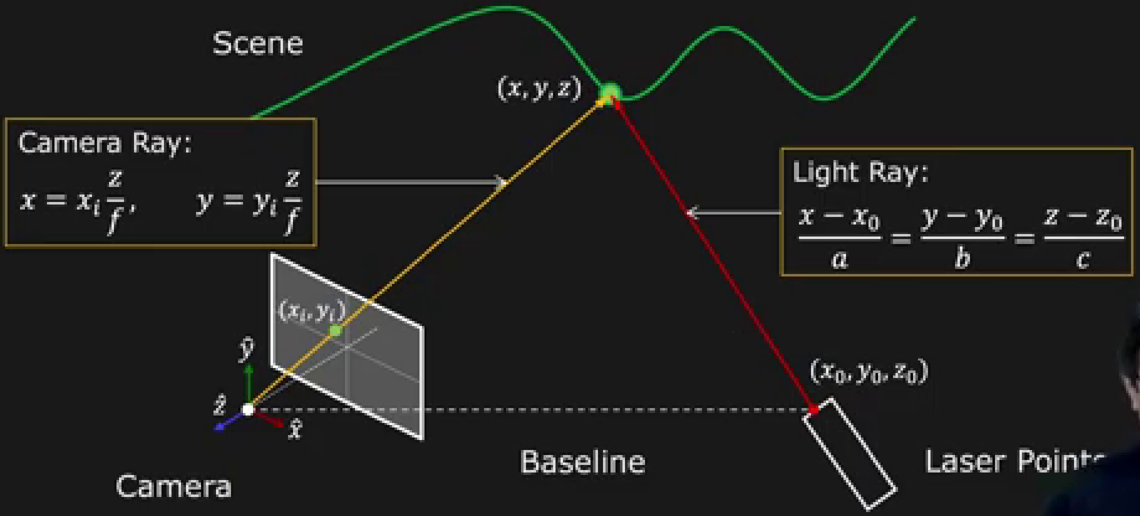
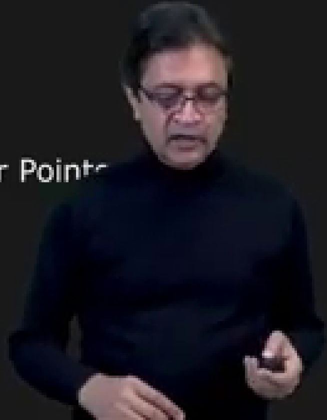
First Principles of Computer Vision

Point Based Range Finding



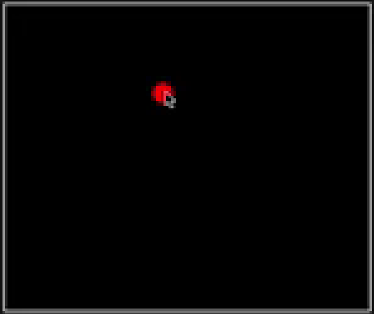
Scene Point (x, y, z)= Camera Ray ∩ Light Ray



Detecting the Illuminated Point

Background Image (I_B)

Captured Image with Pointer (I_P)



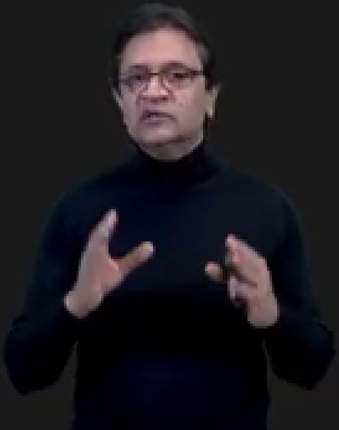
$(I_P - I_B)$

How Many Images?

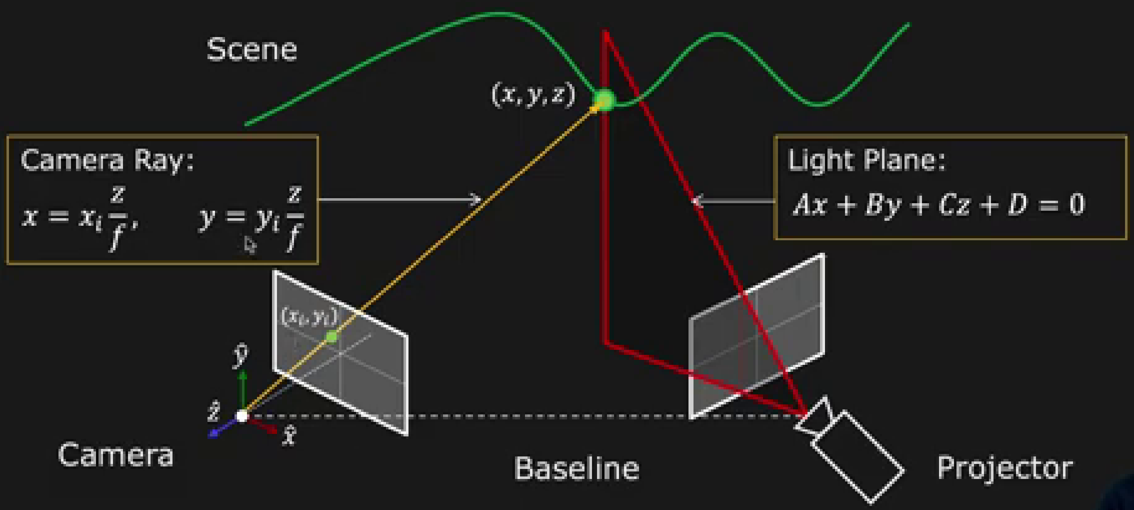
One image per pixel

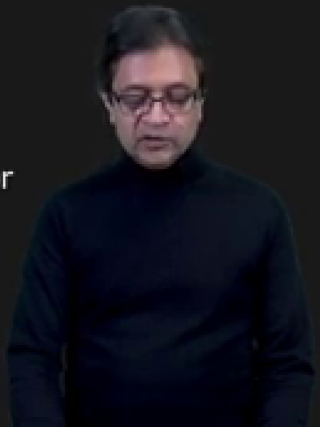
For 640x480 image: >300,000 images!

At 30 frames per second (fps): ~3 hours!



Light Stripe Based Range Finding

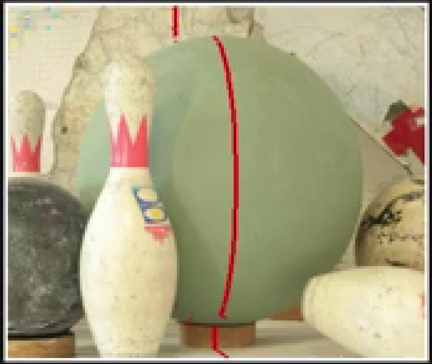




Scene Point (x, y, z)= Camera Ray ∩ Light Plane

$$\boxed{z = \frac{-Df}{Ax_i + By_i + Cf}}$$

How Many Images?



What camera sees

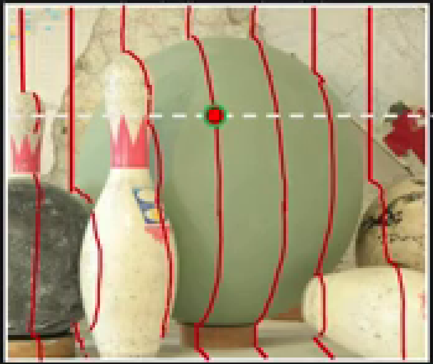
What projector "sees"

One image per column

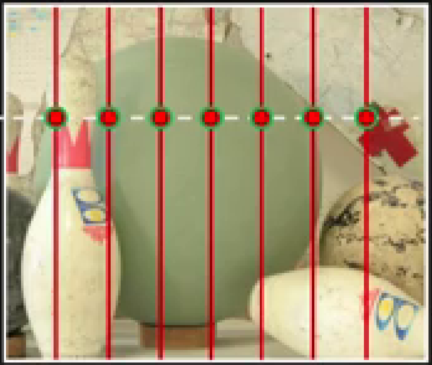
For 640x480 image: still 640 images!

At 30 fps: ~21s

Can we do Multiple Stripes at Once?



What camera sees

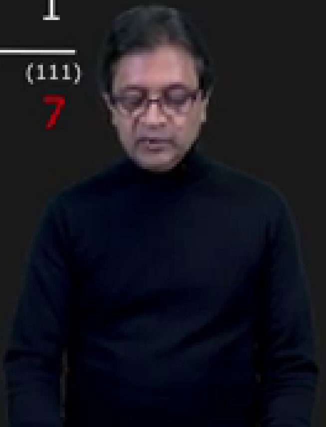


What projector "sees"

Ambiguous!

Binary Coded Structured Light

Bit 1	0	0	0	1	1	1	1
Bit 2	0	1	1	0	0	1	1
Bit 3	1	0	1	0	1	0	1
(Binary)	(001)	(010)	(011)	(100)	(101)	(110)	(111)
Stripe Numbers	1	2	3	4	5	6	7



[Posdamer 1981]

Binary Coded Structured Light

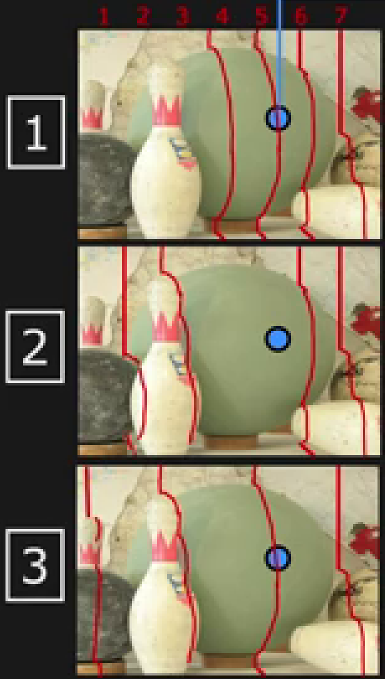


Image		Projection Pattern						
1	Bit 1	0	0	0	1	1	1	1
2	Bit 2	0	1	1	0	0	1	1
3	Bit 3	1	0	1	0	1	0	1
(Binary)		(001)	(010)	(011)	(100)	(101)	(110)	(111)
Stripe Numbers		1	2	3	4	5	6	7

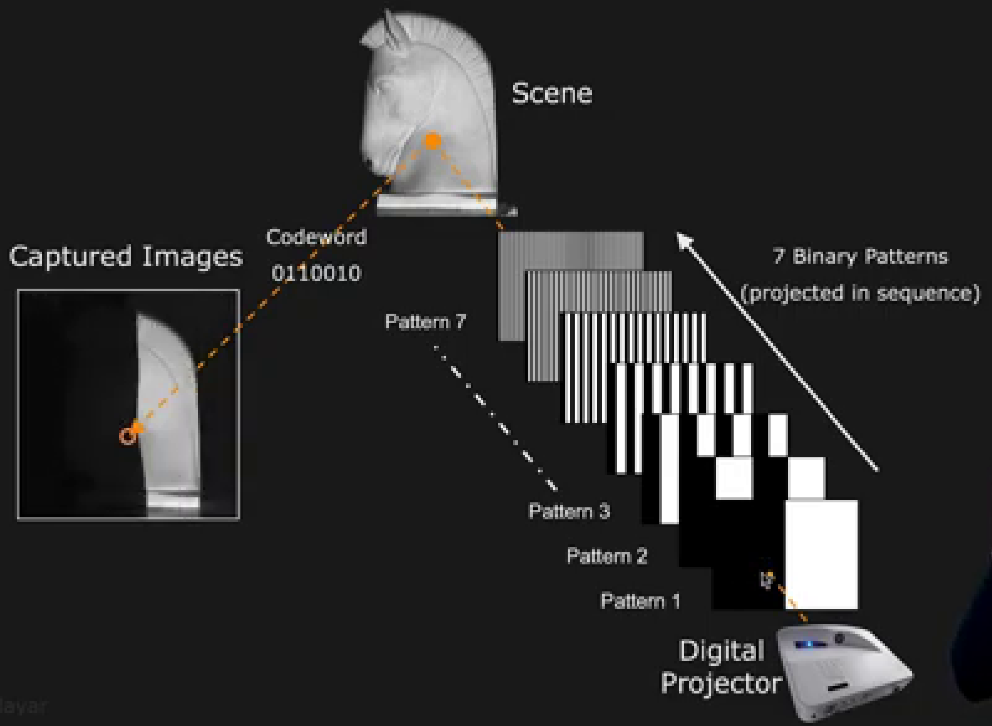
7 stripes in 3 images!

In general, we can do
$2^n - 1$ stripes in n Images

Note: (000) is not an option. Hence, the

[Posdamer 1981]

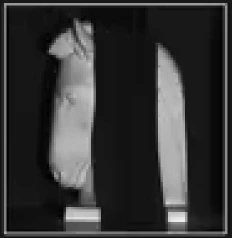
Binary Coded Structured Light: Example



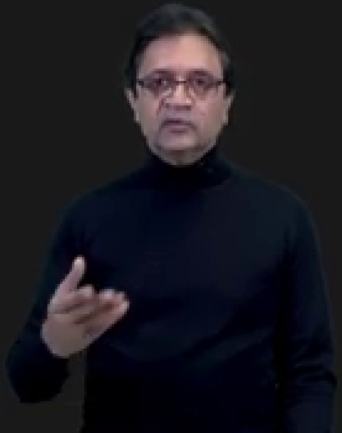
Binary Coded Structured Light: Example

Scene

Captured Images



3D Reconstruction

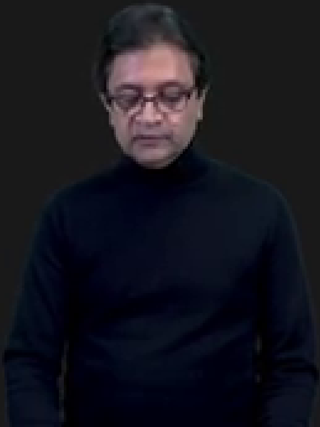


Gray Coding to Reduce Errors

Image	Projection Pattern						
1	0	0	0	1	1	1	1
2	0	1	1	1	1	0	0
3	1	1	0	0	1	1	0
(in binary)	(001)	(010)	(011)	(100)	(101)	(110)	(111)
Stripe Number	1	2	3	4	5	6	7
Gray Code	(001)	(011)	(010)	(110)	(111)	(101)	(100)

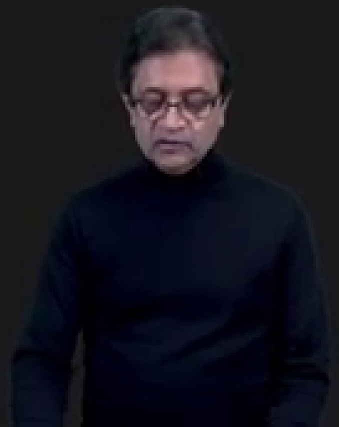
We can have a maximum of 6 errors!

[Inokuchi 1984]



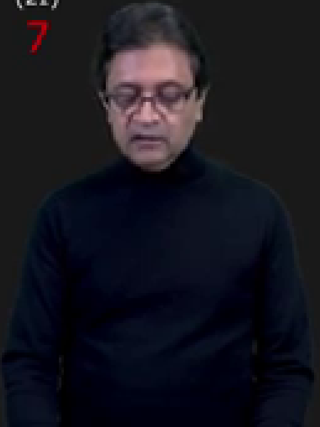
k-ary Methods

Coding	Base	Values
Binary	2	0, 1 (Off, On)
Ternary	3	0, 1, 2 (R, G, B), (Off, ½On, On)
k-ary	k	0, 1, 2,… k-1



Color Coding with R, G, B

	R	R	G	G	G	B	B
	G	B	R	G	B	R	G
(Ternary)	(01)	(02)	(10)	(11)	(12)	(20)	(21)
Stripe Numbers	1	2	3	4	5	6	7



[Caspi 1998]

Color Coding with R, G, B

1

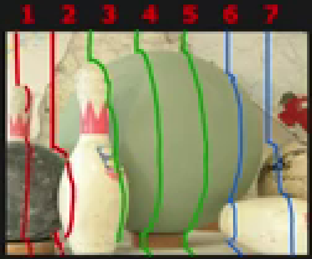
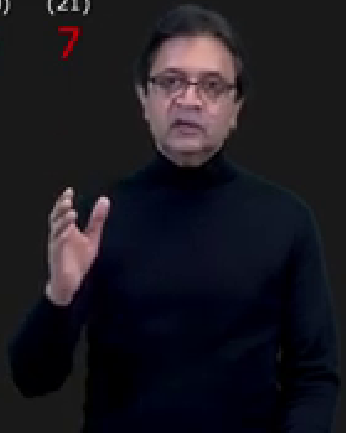


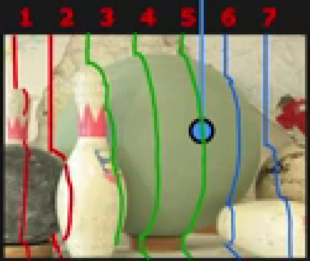
Image	Projection Pattern						
1	R	R	G	G	G	B	B
	G	B	R	G	B	R	G
(Ternary)	(01)	(02)	(10)	(11)	(12)	(20)	(21)
Stripe Numbers	1	2	3	4	5	6	7



[Caspi 1998]

Color Coding with R, G, B

1



2

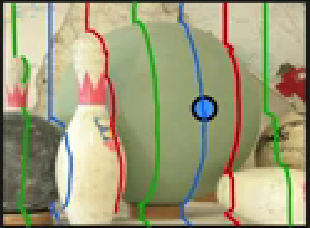
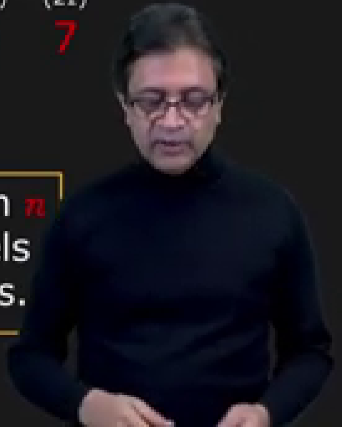


Image	Projection Pattern						
1	R	R	G	G	G	B	B
2	G	B	R	G	B	R	G
(Ternary)	(01)	(02)	(10)	(11)	(12)	(20)	(21)
Stripe Numbers	1	2	3	4	5	6	7

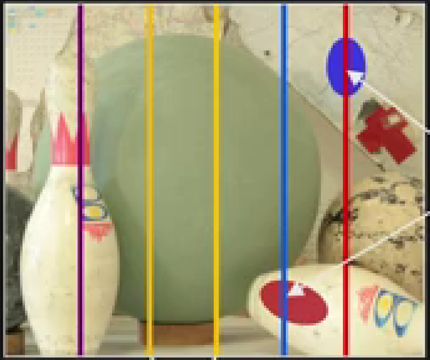
Only 2 images needed!

With k levels, we get k^n stripes in n images. When one of the levels is 0 (OFF), we get k^n-1 stripes.

[Caspi 1998]



Color Structured Light: Remarks



- Similar colors hard to distinguish
- Some colors not reflected by some scene point

Phase Shifting Method

Shree K. Nayar

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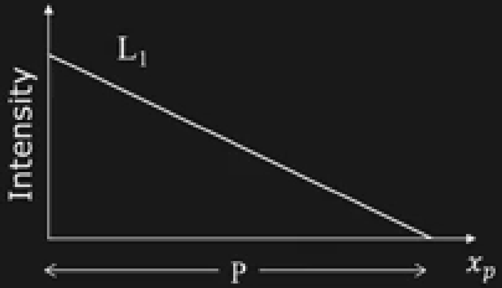
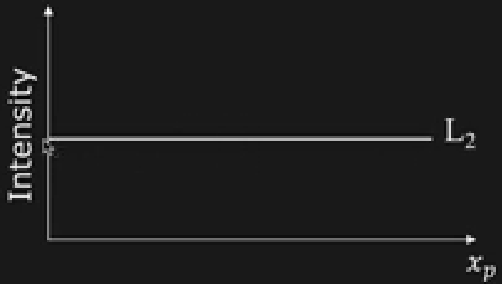
First Principles of Computer Vision

Intensity Ratio Method

Projection Pattern

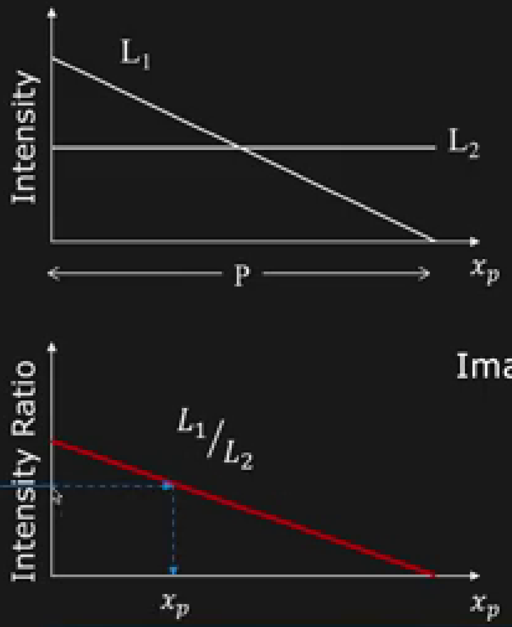




Captured Image

[Carrihill 1985]

Finding Correspondence



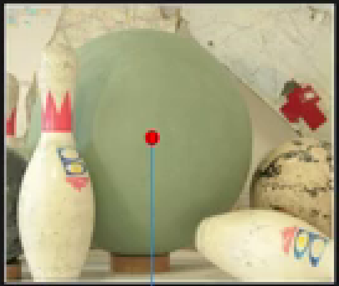


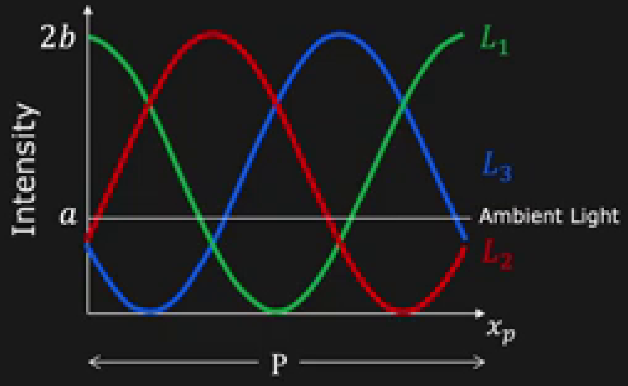
Image Intensities:

$$I_1 = \rho \cdot L_1$$

$$I_2 = \rho \cdot L_2$$

Phase Shift Method

Projected Pattern



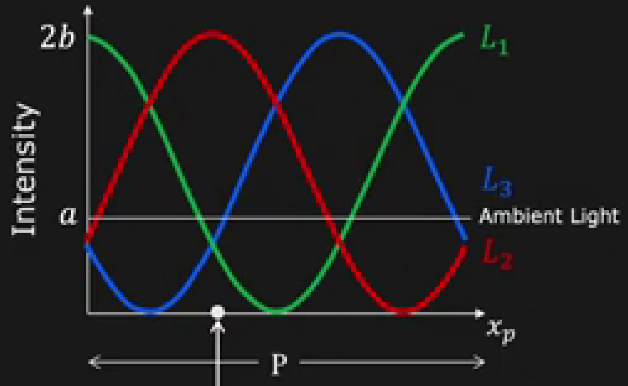
Captured Image

$$L_3(x_p) = a + b + b\cos\left(\frac{2\pi x_p}{P} + \frac{2\pi}{3}\right)$$

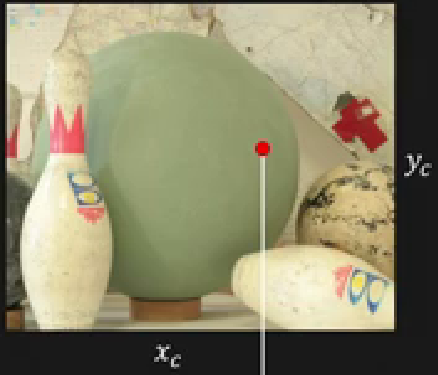
$$I_3(x_c, y_c) = \rho a + \rho b + \rho b\cos\left(\frac{2\pi x_p}{P} + \frac{2\pi}{3}\right)$$

Finding Correspondence

Projected Pattern



Captured Image

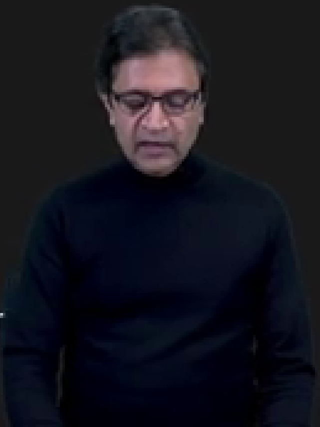


$$\boxed{x_p = \frac{P}{2\pi}\tan^{-1}\left(\sqrt{3}\,\frac{I_2 - I_3}{2I_1 - I_2 - I_3}\right)}$$

Structured Light for Depth Recovery

Method	Number of Images
Point based Structured Light	NM
Line based Structured Light	N
Binary Coded Structured Light	$\lceil \log_2(N+1) \rceil$
k-ary (Color) Coded Structured Light	$\lceil \log_k(N+1) \rceil$
Intensity Ratio Method	2
Phase Shifting Method	3

$[N, M]$: Camera Image Size, k: Number of colors, $\lceil x \rceil$: Smallest integer



Structured Light for Depth Recovery

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Binary Coded Structured Light	$\lceil \log_2(N+1) \rceil$
k-ary (Color) Coded Structured Light	$\lceil \log_k(N+1) \rceil$
Intensity Ratio Method	2
Phase Shifting Method	3

$[N, M]$: Camera Image Size, k: Number of colors, $\lceil x \rceil$: Smallest integer

Structured Light Systems

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First Principles of Computer Vision

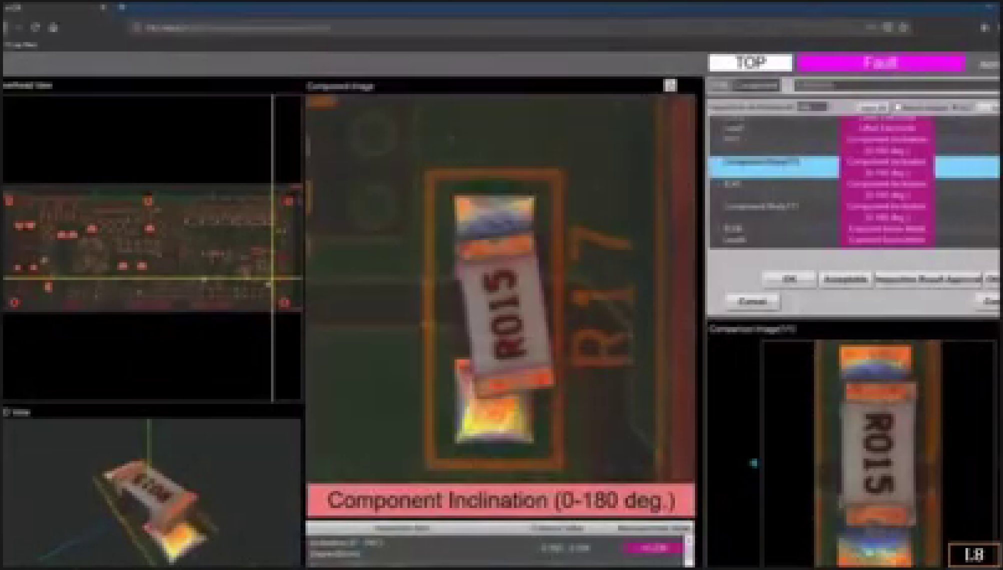
3D Visual Inspection System

Courtesy of Omron Corporation

3D Visual Inspection System

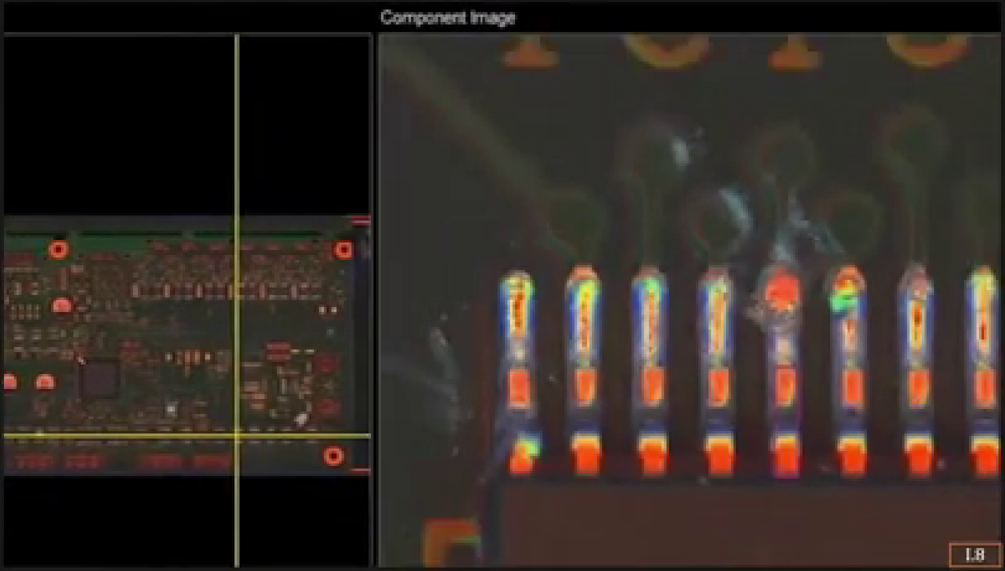
Courtesy of Omron Corporation

3D Visual Inspection System



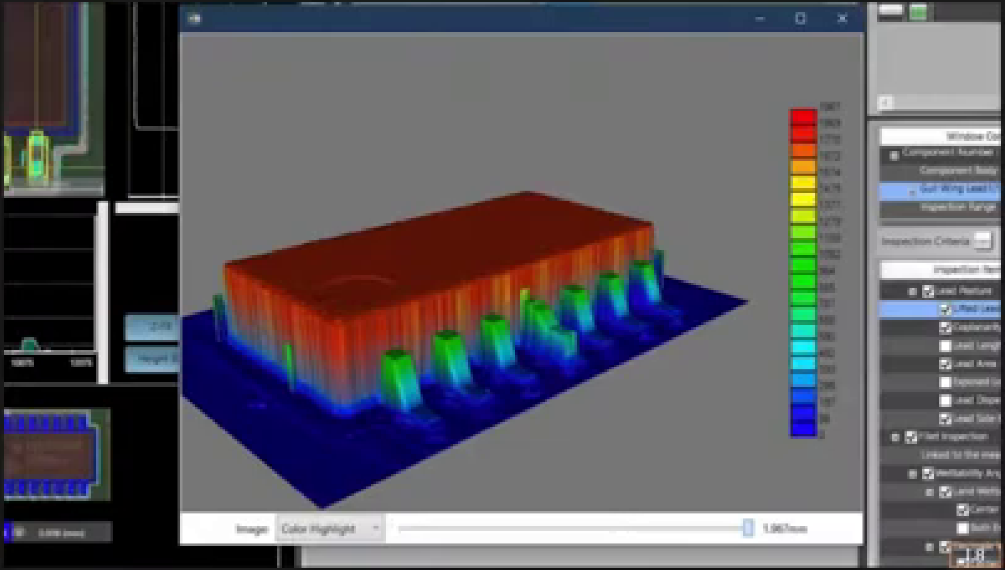
Courtesy of Omron Corporation

3D Visual Inspection System

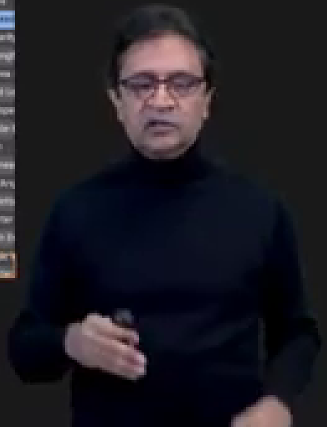


Courtesy of Omron Corporation

3D Visual Inspection System



Courtesy of Omron Corporation



Digital Michelangelo Project

480 individually aimed scans

2 billion polygons

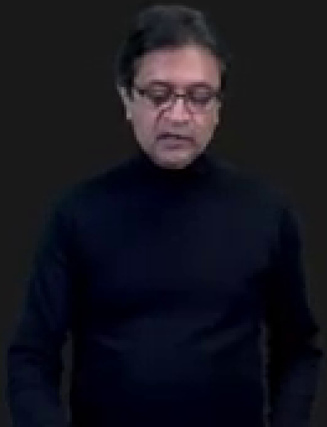
7,000 color images

32 gigabytes of data

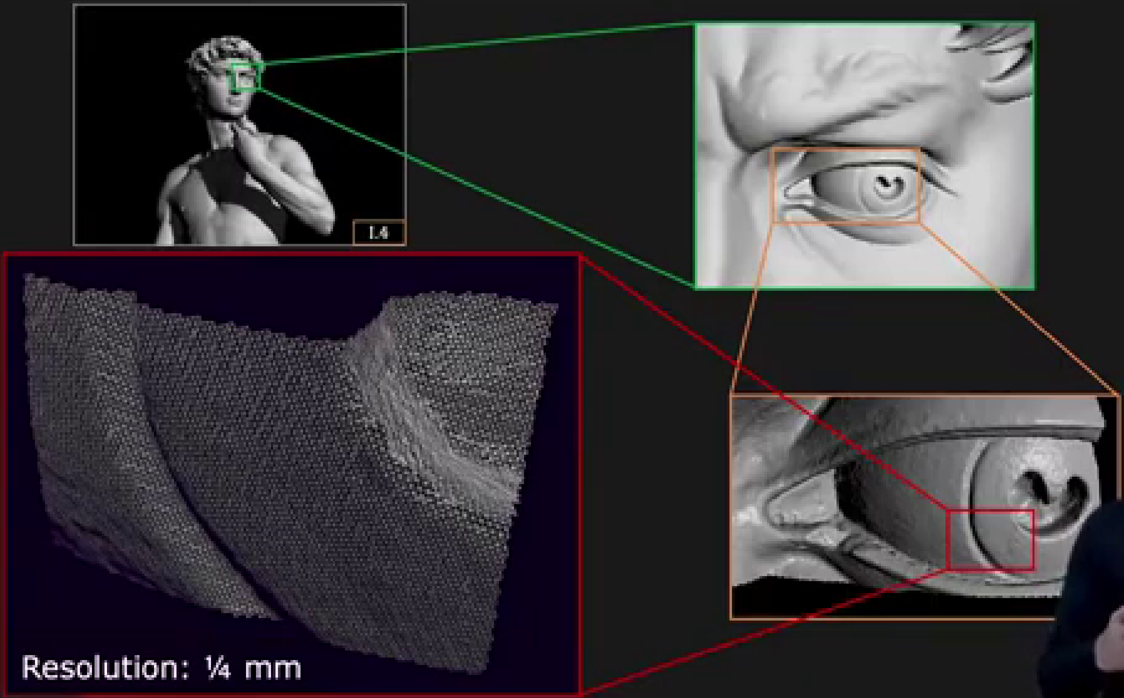
30 nights of scanning

22 people

[Levoy 2000]



Virtual "David"



Great Buddha Project

Great Buddha, Nara

Digital Model

[Ikeuchi 2007]

Performance Capture with Light Stage

[Guo 2019]

Performance Capture with Light Stage

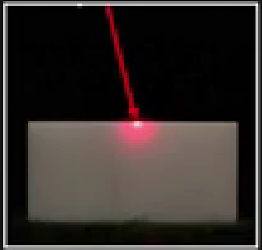
[Guo 2019]

Performance Capture with Light Stage

[Guo 2019]

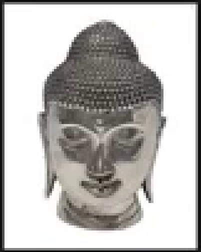
Unsolved Problems

Optically uncooperative materials

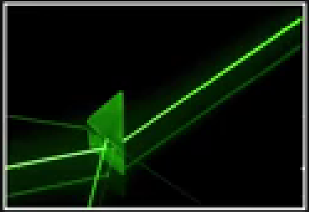


Scattering surface
(marble)

Scattering environment
(underwater)

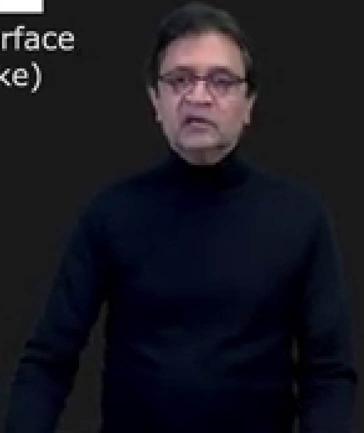


Specular surface
(mirror-like)



Transparent surface
(glass)

Fuzzy
(hair)



Time of Flight Method

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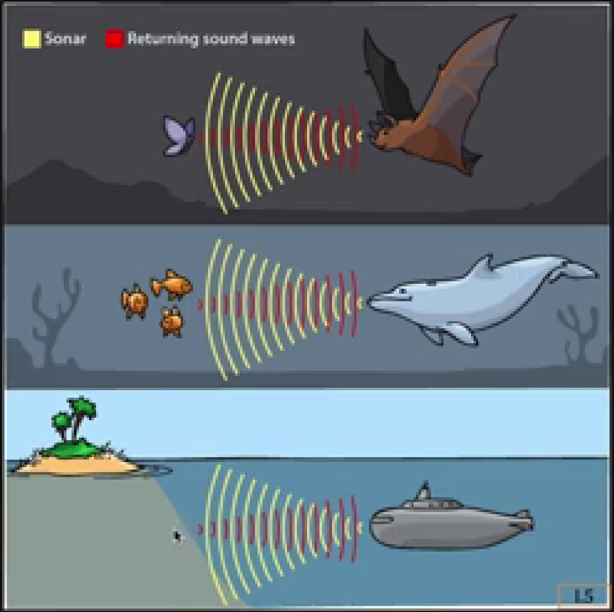
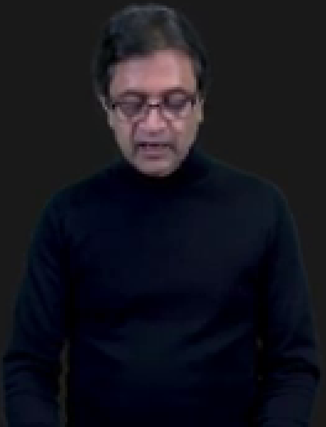
First Principles of Computer Vision

Time of Flight



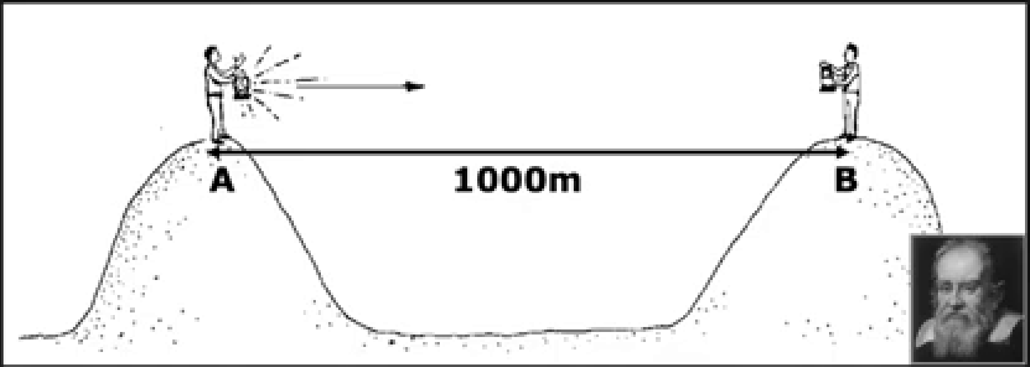
Echolocation

Measuring Time of Flight of Sound Waves



Time of Flight of Light

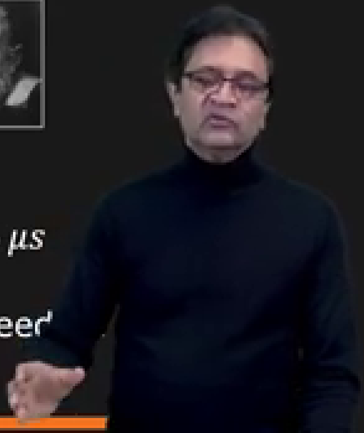
Does light travel or exist instantaneously?



Galileo's experiment (early 1600s)

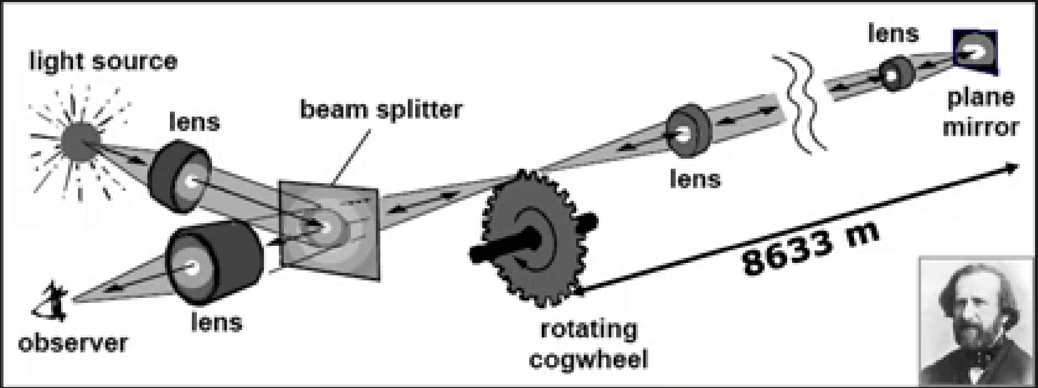
Time for light to travel back and forth: $t_{A \to B \to A} = \frac{2000}{3e^8} \cong 6.6\,\mu s$

Much faster than human reflexes for experiment to have succeed



HISTORY

Time of Flight of Light

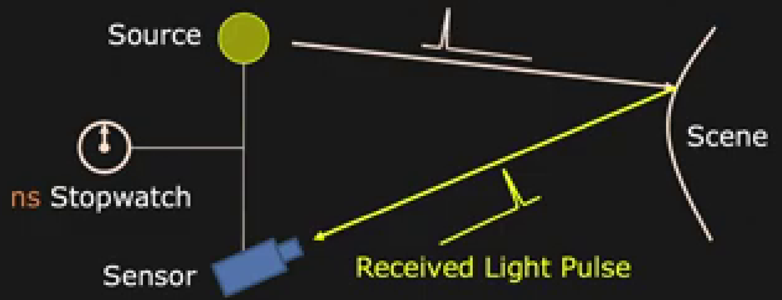


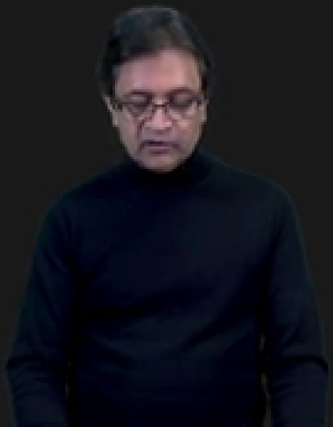
Fizeau's experiment (1849)

$$c_{computed} = 3.153 \times 10^8 m/s$$

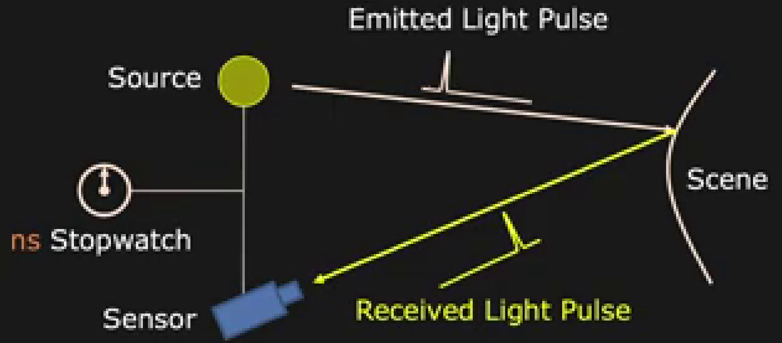
$$c_{actual} = 2.998 \times 10^8 m/s$$

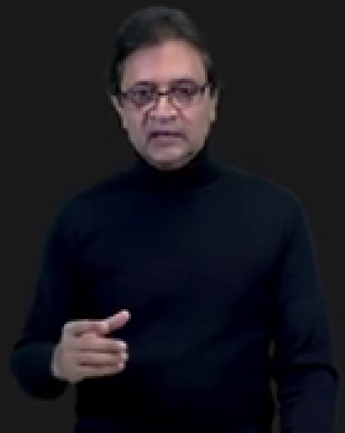
Time of Flight: Pulse Modulation



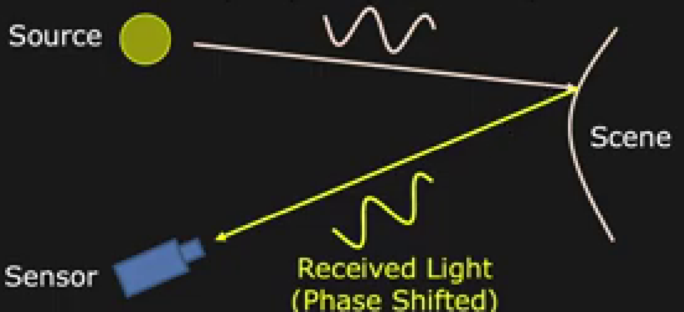


Time of Flight: Pulse Modulation

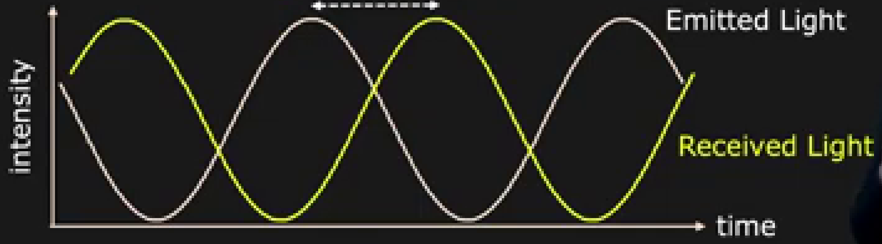




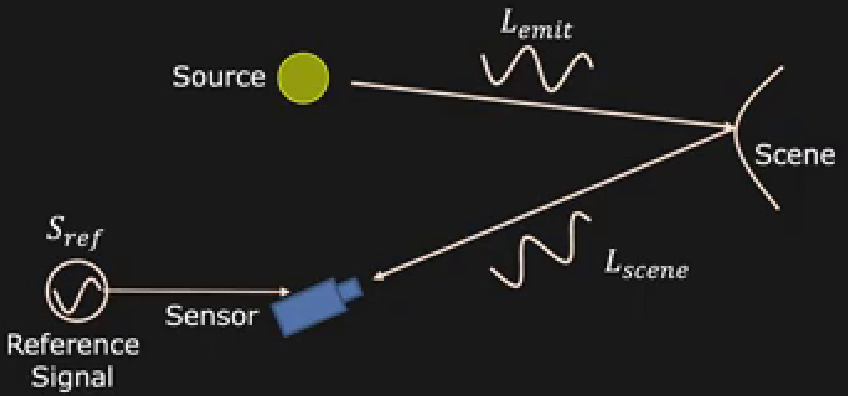
Time of Flight: Continuous Modulation



Depth ∝ Phase shift



Phase Measurement By Correlation



Emitted Light: $L_{emit} = \cos(\omega t)$

Received Light: $L_{scene} = O + A\cos(\omega t - \varphi)$

Reference Signal: $S_{ref} = \cos(\omega t - \delta)$

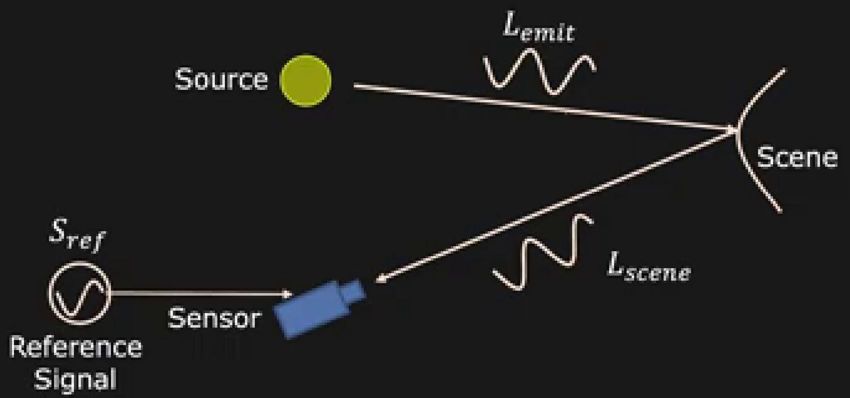
O: ambient light

φ: phase shift

A: albedo

δ: reference p

Phase Measurement By Correlation



Measured Intensity: $I(\delta_i) = \int L_{scene}(t) \times S_{ref}(t, \delta_i) dt$

Simplifying: $I(\delta_i) = P + Q \cos(\delta_i - \varphi)$

Computing Depth From Phase

$$I(\delta_i) = P + Q\cos(\delta_i - \varphi)$$

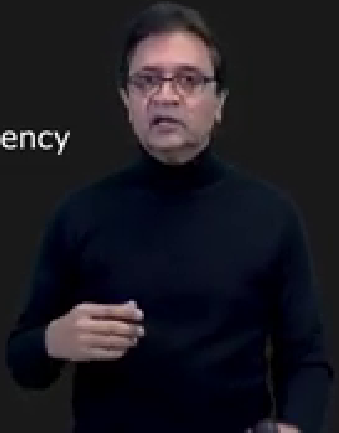
Three measurements $I(\delta_1)$, $I(\delta_2)$, $I(\delta_3)$ are sufficient for computing phase φ.

Depth of scene point:

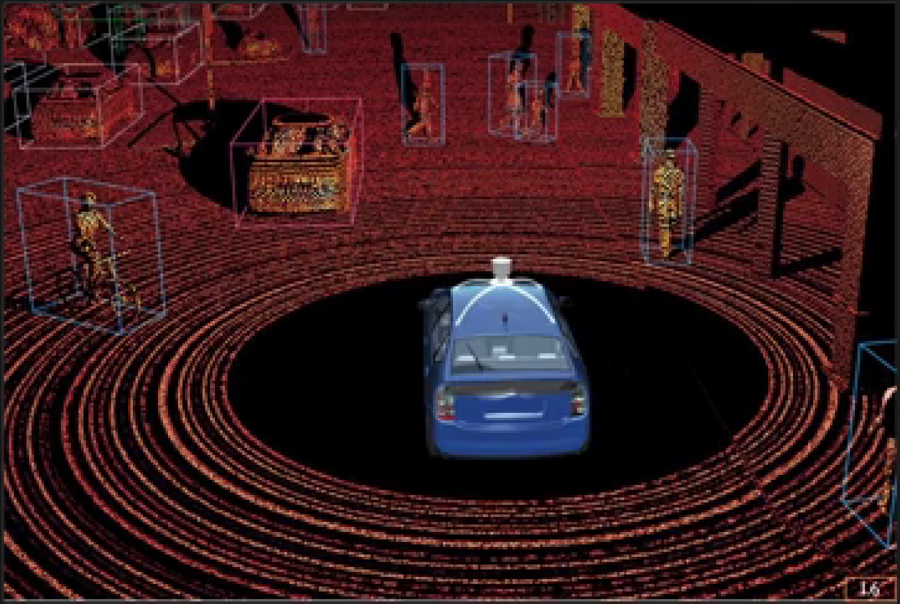
$$\boxed{d = c\frac{\varphi}{4\pi f}}$$

c: speed of light
φ: phase shift
$f = {}^{\omega}/_{2\pi}$: modulation frequency

Example: If $\varphi = \pi, f = 30MHz,$ then $d = 2.5m$.

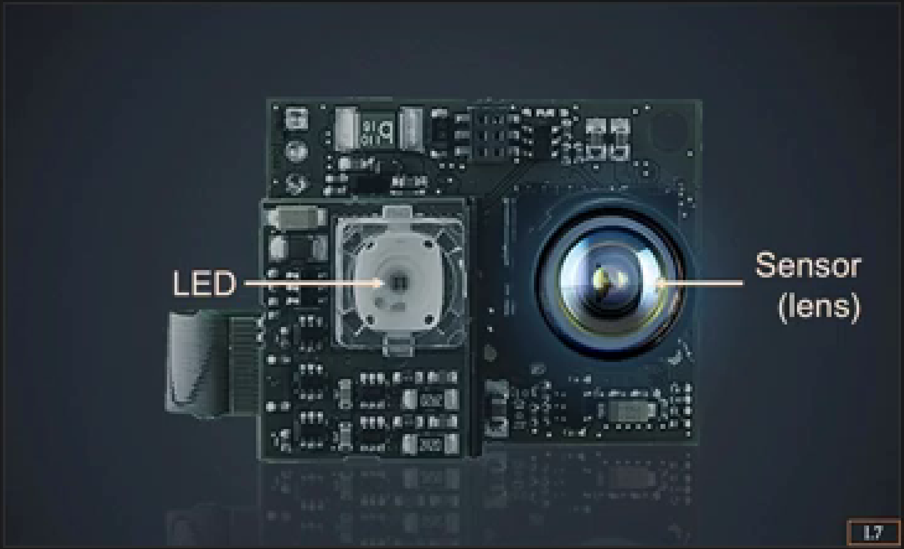


Time-of-Flight Result: Example



Google Self-Driving Car Project

Time of Flight: 3D Camera



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