CHAPTER 4

Smart Imaging

Outline

- 4.1 introduction
- 4.2 Low light imaging
- 4.3 High speed
- 4.4 Wide dynamic range
- 4.5 Demodulation
- 4.6 Three dimensional range finder
- 4.7 Target tracking
- 4.8 Dedicated arrangement of pixel and optics

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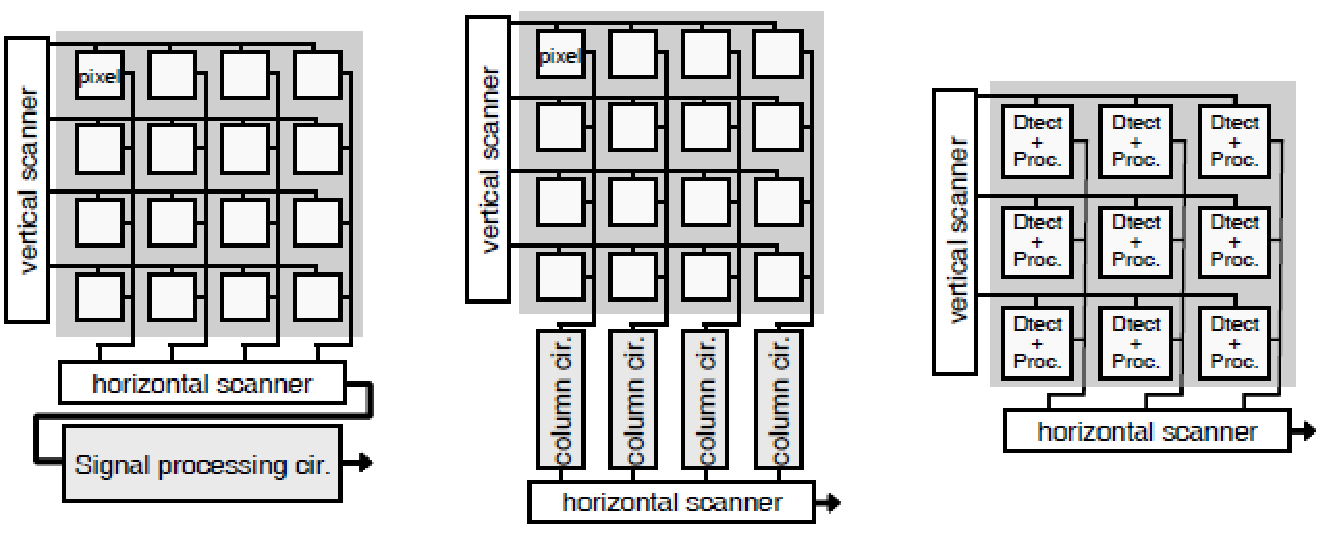
Types of Implementation

- Basic concept of smart CMOS image sensors
  (a) chip-level processing
  (b) column-level processing
  (c) pixel-level processing



(a) (b) (c)

Other Features

- Random access to an arbitrary pixel
- Non-destructive readout or multiple readout

  (Note that the original 4T-APS cannot be applied for non-destructive readout)
- Integration of signal processing circuitry in each pixel and/or each column and/or a chip

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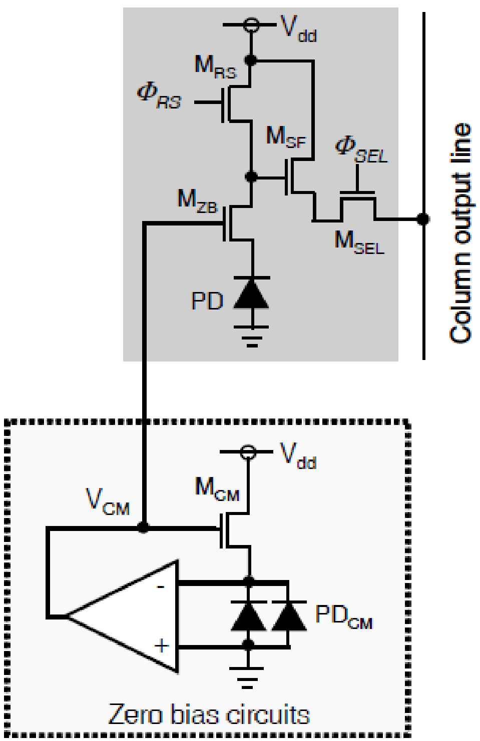
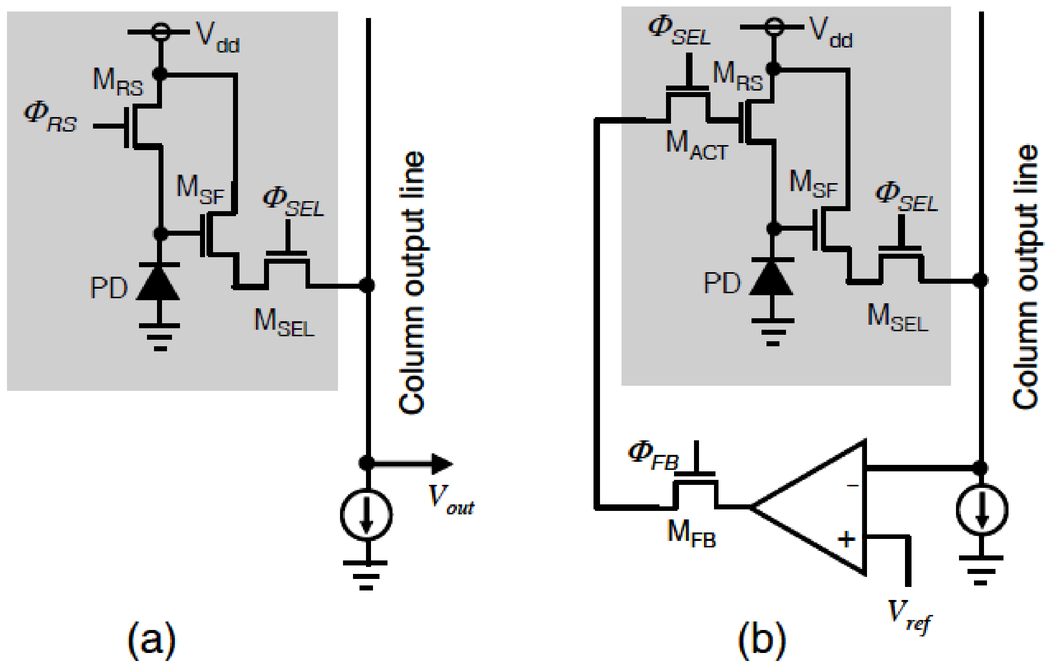
Reducing Dark Current

- Cooling
- Near zero bias circuits for reducing dark current in an APS

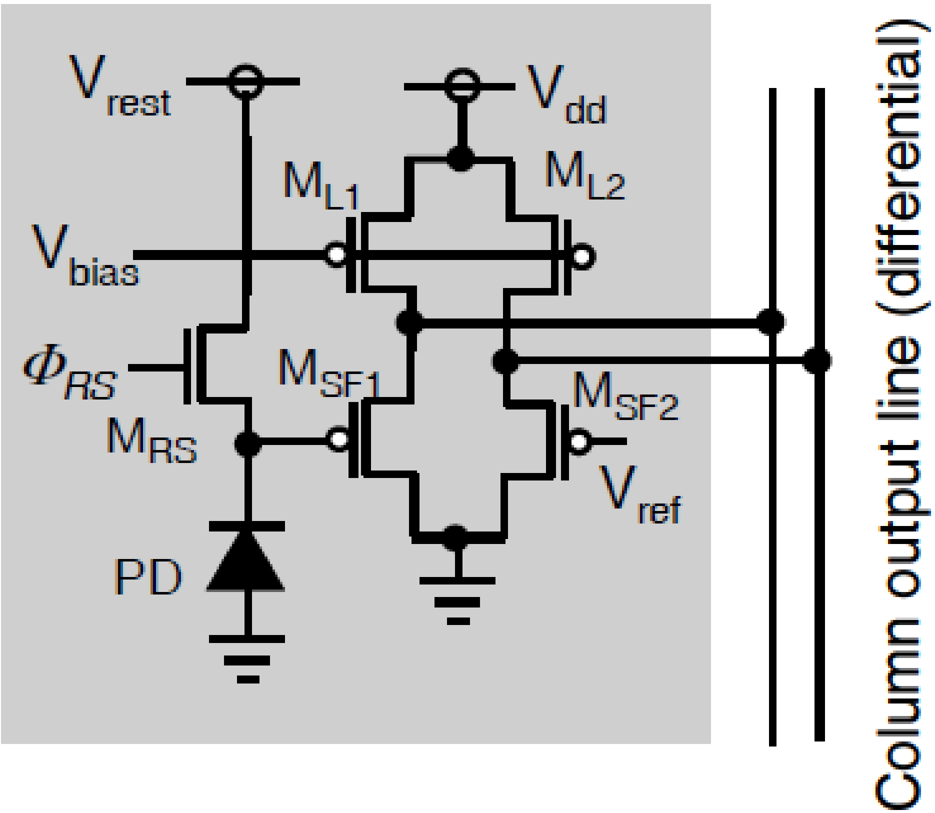


Active Reset

- Active reset circuits
  - (a) conventional 3T-APS
  - (b) 3T-APS with active reset

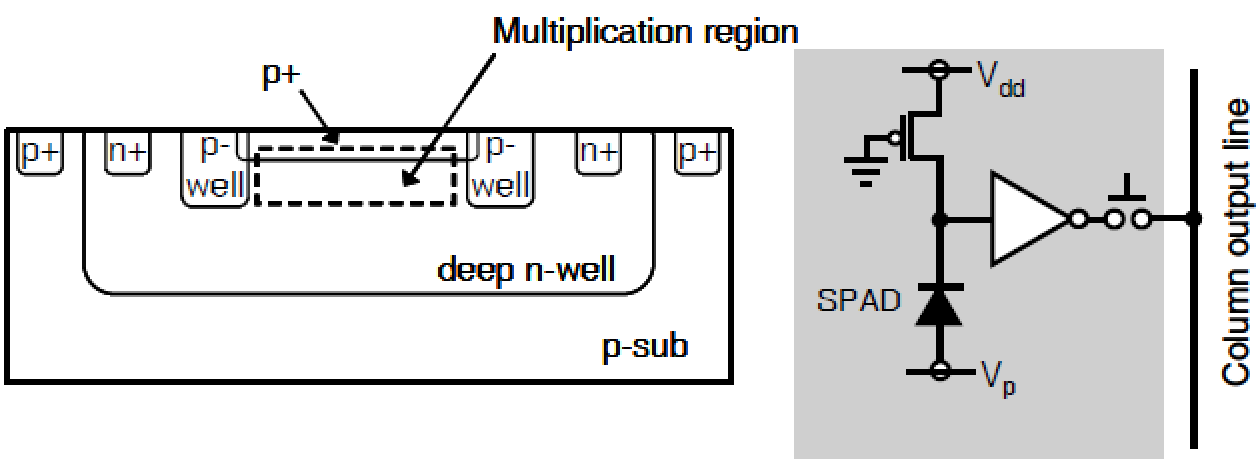


Differential APS



Geiger Mode APD

- SPAD: single photon avalanche diode.
  - Spike-like signal, not analog output
  - Produced pulse count proportional to light intensity



(a) (b)

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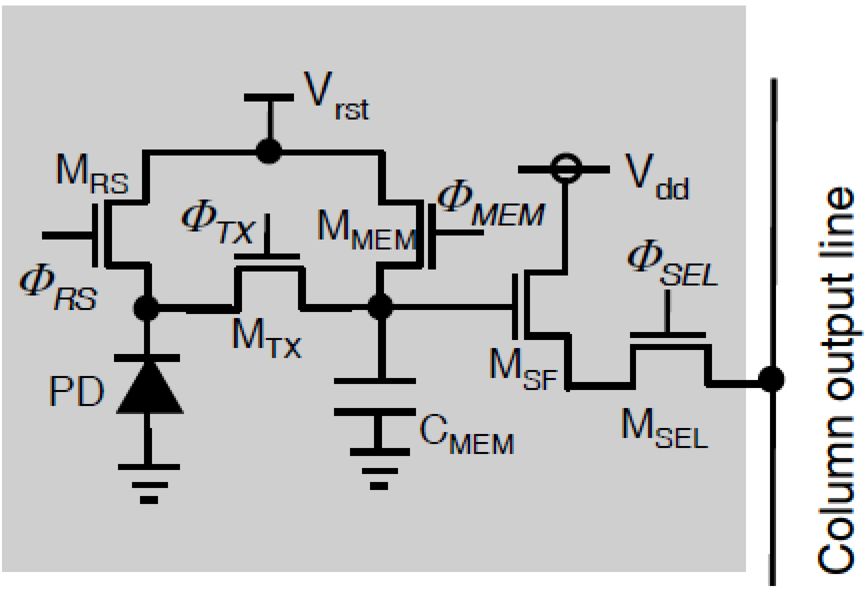
Global Shutter

- Image lag is critical for frame rate > 1000fps
- 4T-APS is not suitable due to long transfer time
- Hard reset is necessary
- Global shutter



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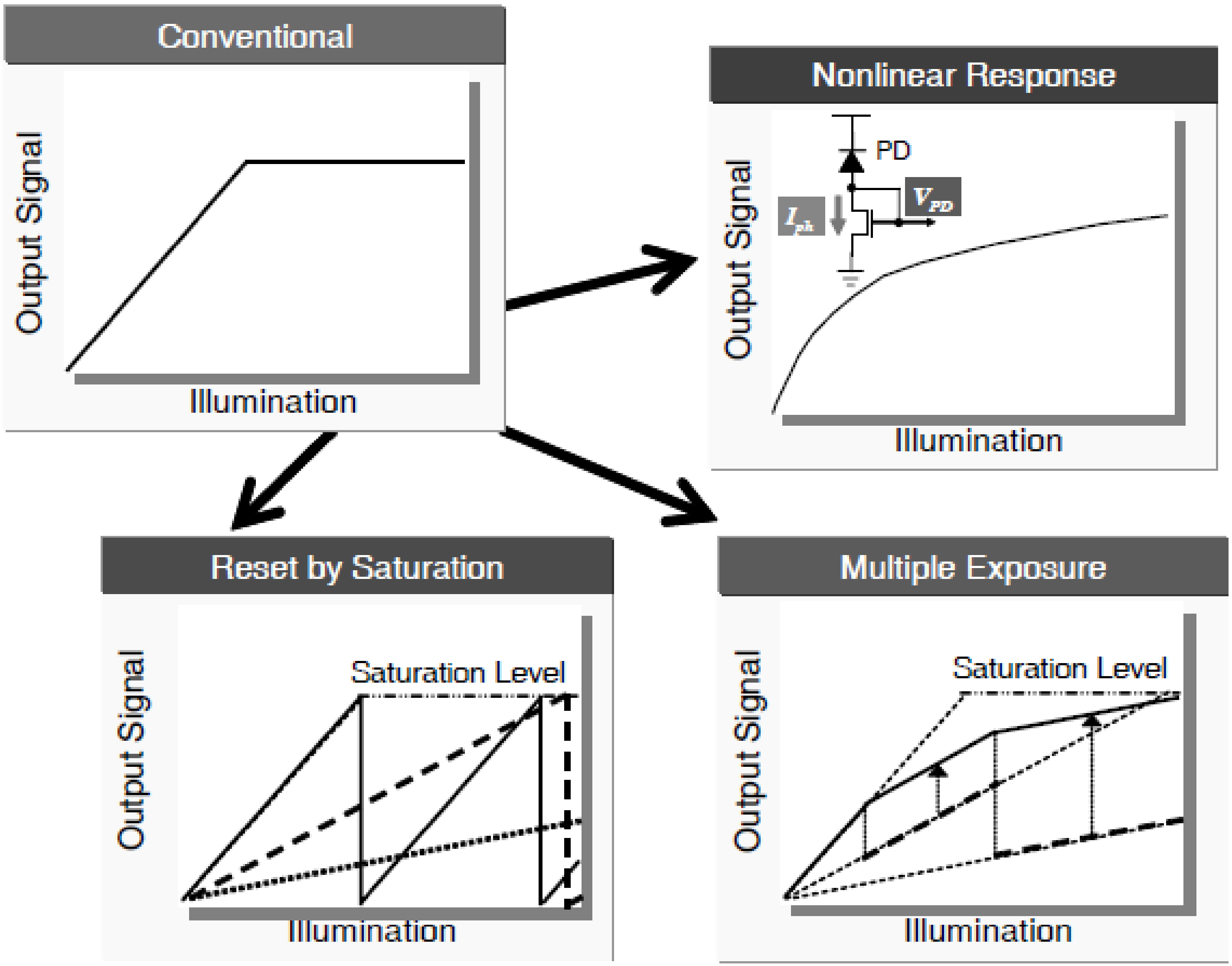
Wide Dynamic Range

- Human eye : 200dB
  - 2 sensing cell : cone & rods
  - Nonlinear response
- Conventional CIS : 60-70dB
- Security/automobile requirement : >100dB
- WDR approaches
  - Nonlinear response
  - Multiple exposure
  - Saturation detection

Enhancing Dynamic Range



Synthesized WDR Image

Smart CMOS Sensors for WDR

Category	Implementation method	Refs.
Dual sensitivity	PG & PD in a pixel	[302, 306, 307]
Nonlinear response	Log sensor	[163–169]
	Log/linear response	[308–310]
	Well capacity adjustment	[298, 311–318]
	Control integration time/gain	[319, 320]
Multiple sampling	Dual sampling	[321–323]
	Multiple sampling with fixed short exposure time	[324, 325]
	Multiple sampling with varying short exposure time	[301]
	Multiple sampling with pixel-level ADC	[140, 184, 186]
Saturation detection	Locally integration time and gain	[326]
	Saturation count	[263, 326–332]
	Pulse width modulation	[179, 263, 333]
	Pulse frequency modulation	[141, 194, 196, 202, 334, 335]
Diffusive brightness	Resistive network	[304, 305]

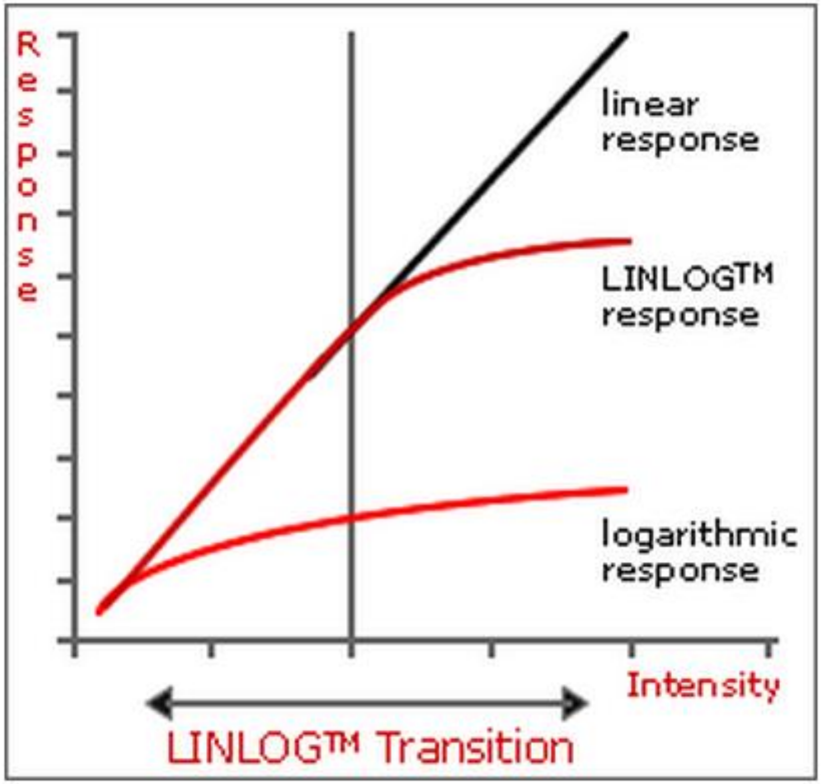
Dual Sensitivity

- Two PD : Higher & lower sensitivity
  - Mimic human eye
- In 4T-APS, FD can be used as lower sensitivity diode.
  - Synchronized high/low illuminated signal capture
  - No timing latency

Log Sensor

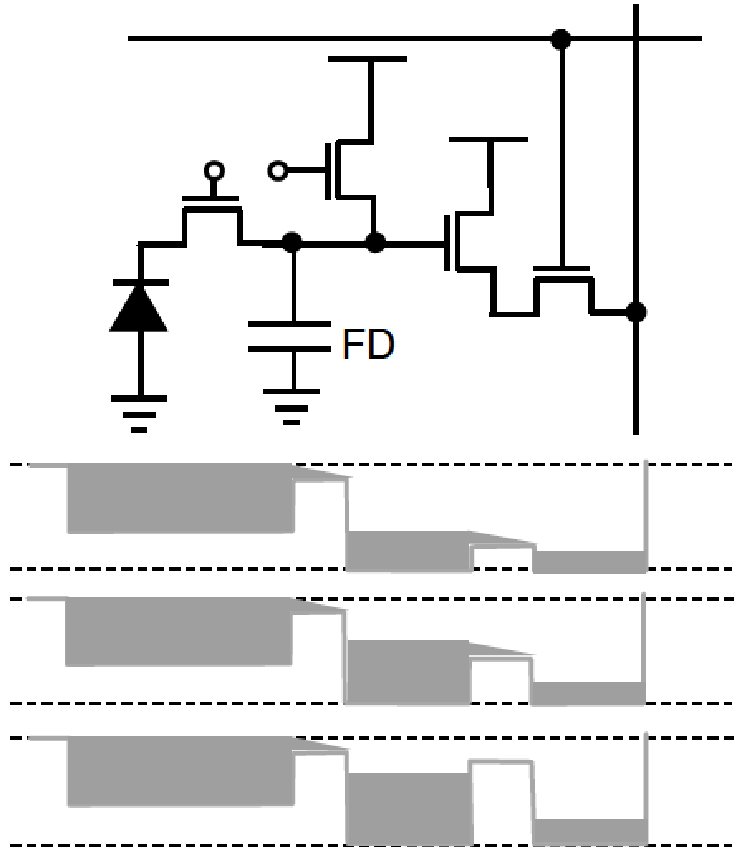
- Nonlinear response
- Small signal at low light
- Slow response
- Fixed pattern noise
- Linear-Log (LinLog) sensor
  - Linear response for low illumination
  - Log response for high illumination
  - Need calibration in the transition region

LinLog Sensor



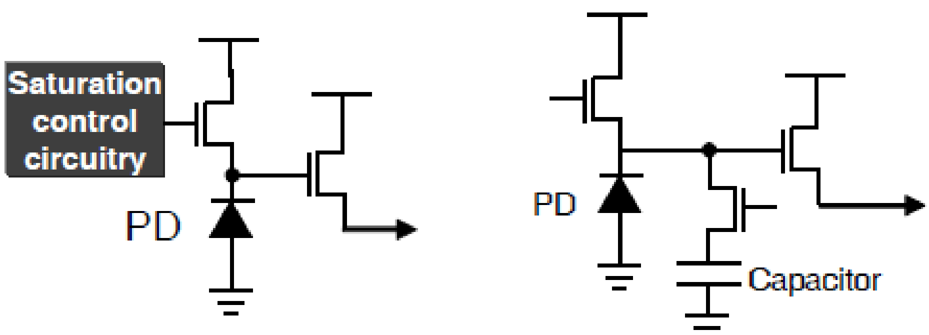
Well-Capacity Adjustment

- Overflow control for high illumination
- Stacked capacitor to increase well capacity (DR)



Reset Control & Extra Cap.

- Different approached for WDR
  - (a) method to control the reset transistor
  - (b) method to use another accumulation capacitor



(a) (b)

Dual Sampling

- Multiple readout scheme for wide dynamic range
  - Long exposure T_l for low-illuminated object
  - Short exposure T_s for high-illuminated object
  - Need synthesis to combine images
  - SNR drop issue

$$I_{\max} \bullet T_s = Q_{\max}, \quad I_{\min} \bullet T_l = Q_{\min}, \quad T_l = T_f - T_s$$

$$DR = 20\log\frac{I_{\max}}{I_{\min}} = 20\log\frac{Q_{\max}T_l}{Q_{\min}T_s} = DR_{org} + 20\log\left(\frac{T_f}{T_s} - 1\right)$$

Multiple Sampling

- Fixed short time exposure
  - T_I=integration time
  - T_f=frame time
  - T_s=short integration time
  - k=number of reading the short time integration (k=1 is Double sampling)

$$T_l = T_f - kT_s.$$

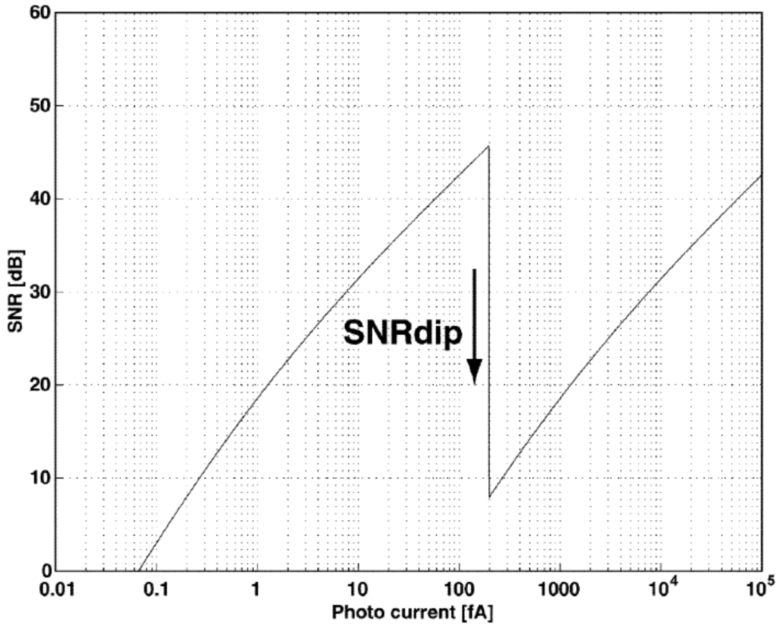
- SNR dip at boundary of exp.

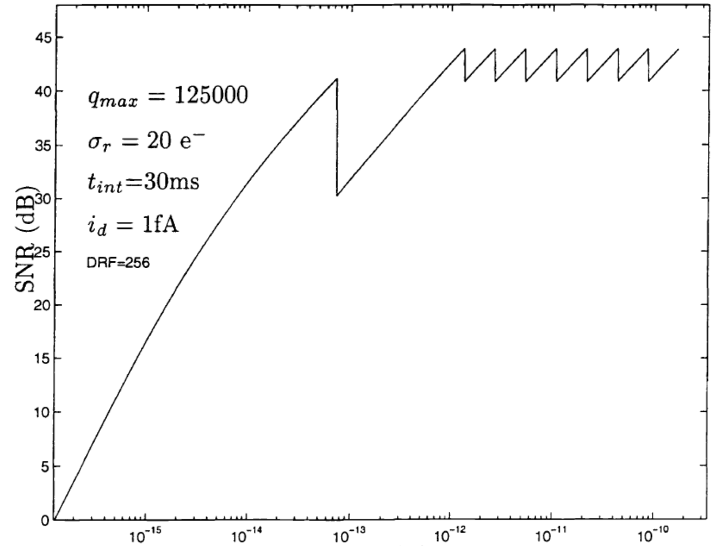
$$\Delta SNR = 10 \log k \frac{T_s}{T_l}.$$

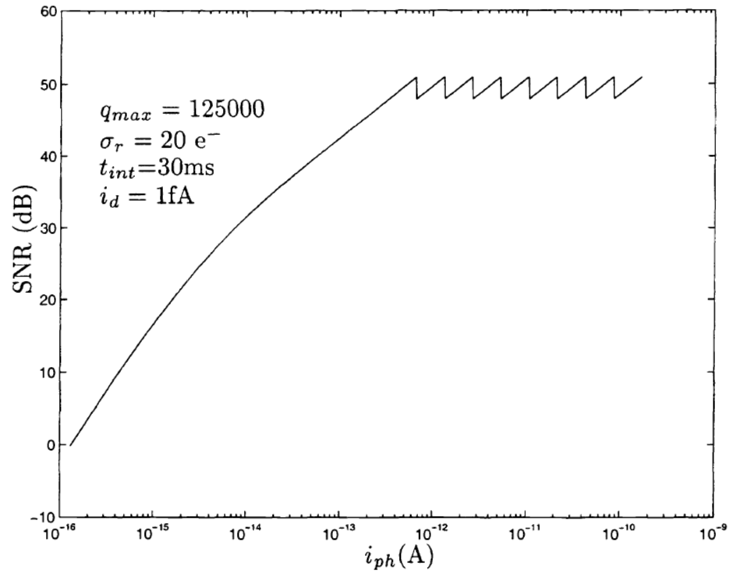
- Dynamic range expansion

$$\Delta DR = 20 \log \left(\frac{T_f}{T_s} - k \right)$$

SNR DIP of Multiple Exposure







$$SNR1 = 20\log\frac{I_{ph}T_l}{\sqrt{I_{ph}T_l}},\quad SNR2 = 20\log\frac{I_{ph}T_s}{\sqrt{I_{ph}T_s}}$$

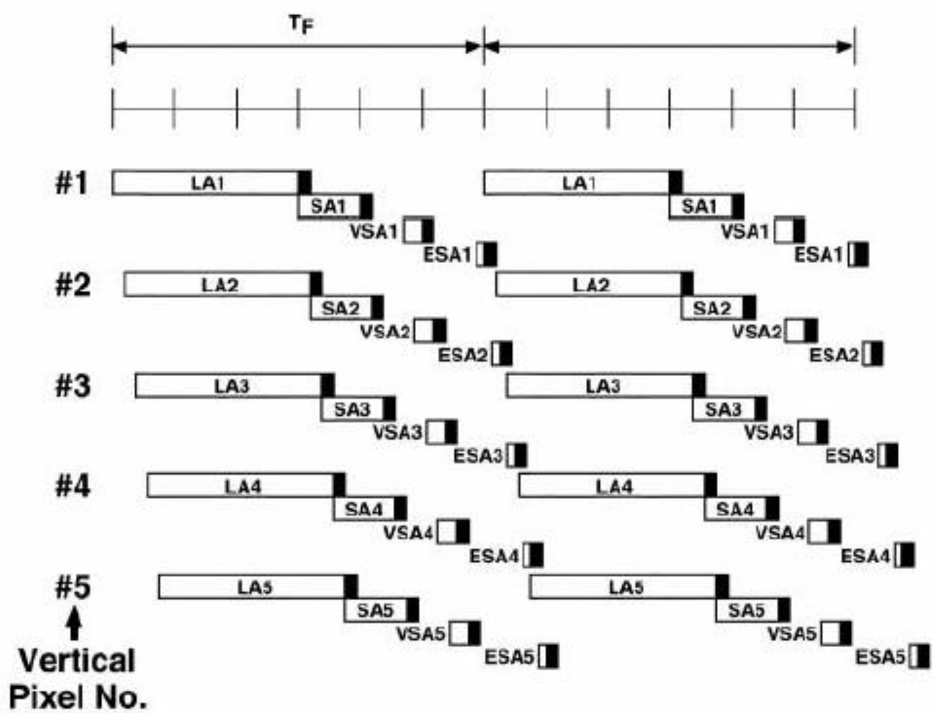
$$SNR_{dip} = SNR1 - SNR2$$

$$= 20\log\sqrt{\frac{T_l}{T_s}} = 10\log\frac{T_l}{T_s}$$

Multiple Sampling(cont'd)

- Varying short exposure times
  - $T_{s,min}$=minimum exposure time.
  - LA: long accumulation
  - SA: short accumulation
  - VSA: very short accumulation
  - ESA: extremely short accumulation
- Optimized SNR dip.

$$\Delta DR = 20\log\frac{T_l}{T_{s,min}}$$



Saturation Detection

- Asynchronized automatic exposure control of each pixel
- Worse reset noise : hard to cancel
- Basic approaches
  - Saturation count
  - Pulse width modulation
  - Pulse frequency modulation

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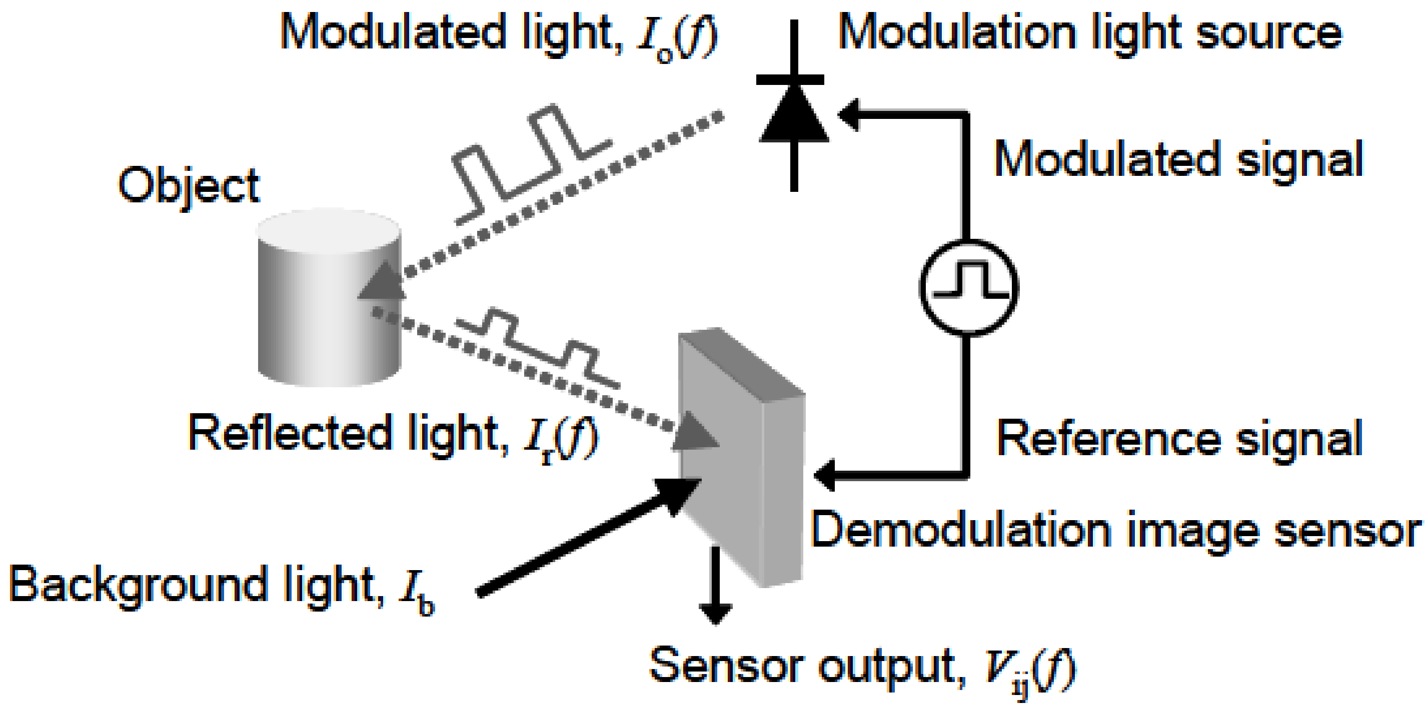
Demodulation Sensor

- Object illuminated by a modulated light
- Demodulate acquired signal from sensor
- High SNR due to static background removal
- Accumulation will erase the modulation info.
- Applications
  - Intelligent transport system
  - Gesture recognition (xBox)
  - Object tracking
  - 3D range finder (time-of-flight)

Principles of Demodulation

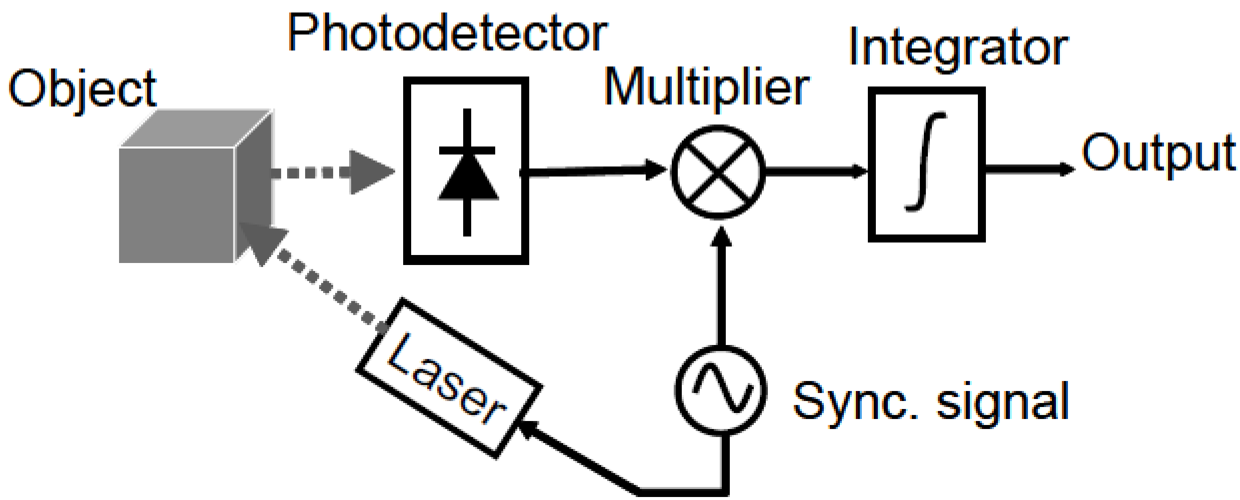
- Concept of a demodulation image sensor



$$V_{out} = \int_{t-T}^{t} (I_r(\tau) + I_b)\, m(\tau)\, d\tau,$$

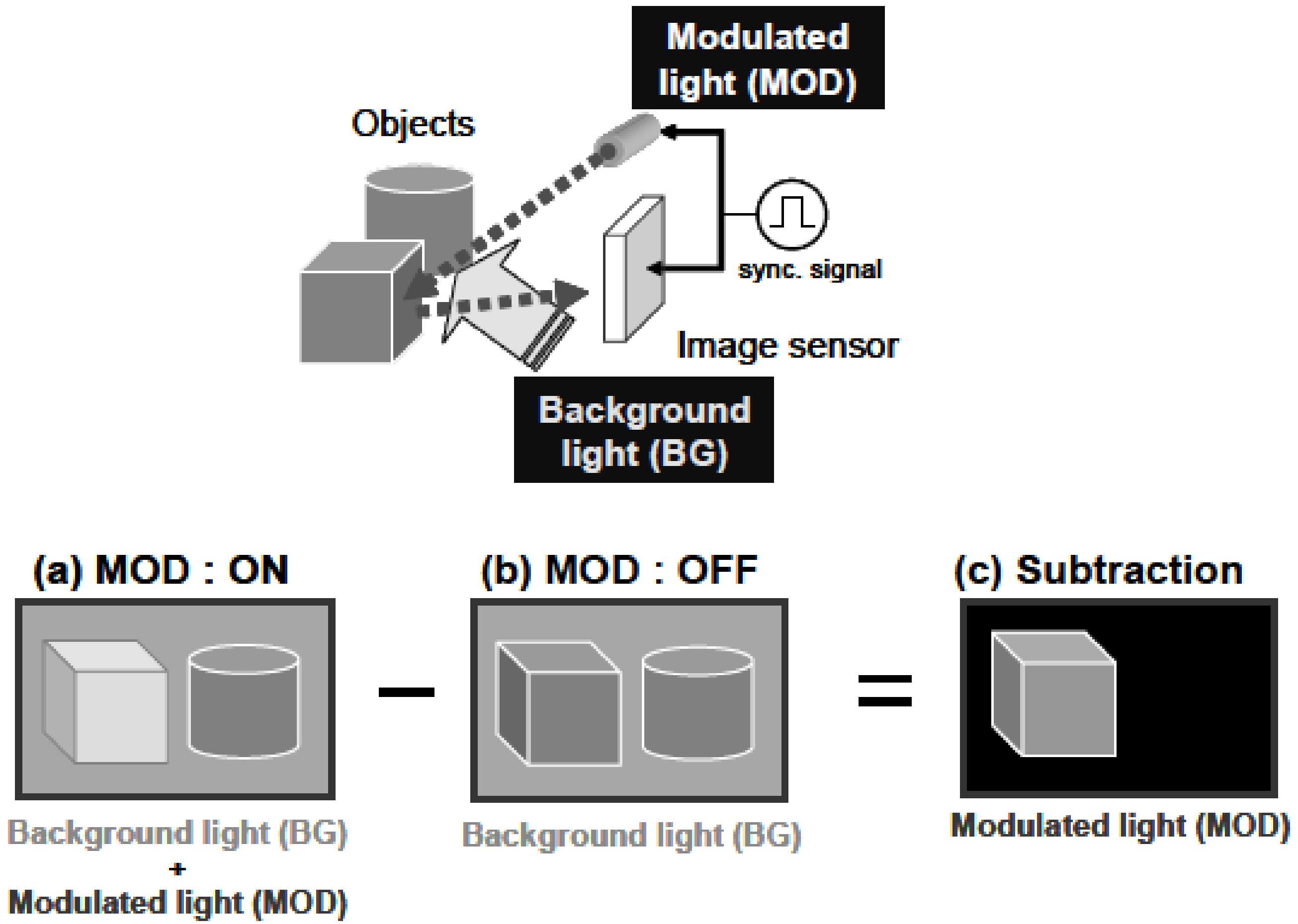
Correlation

- Conceptual illustration of the correlation method



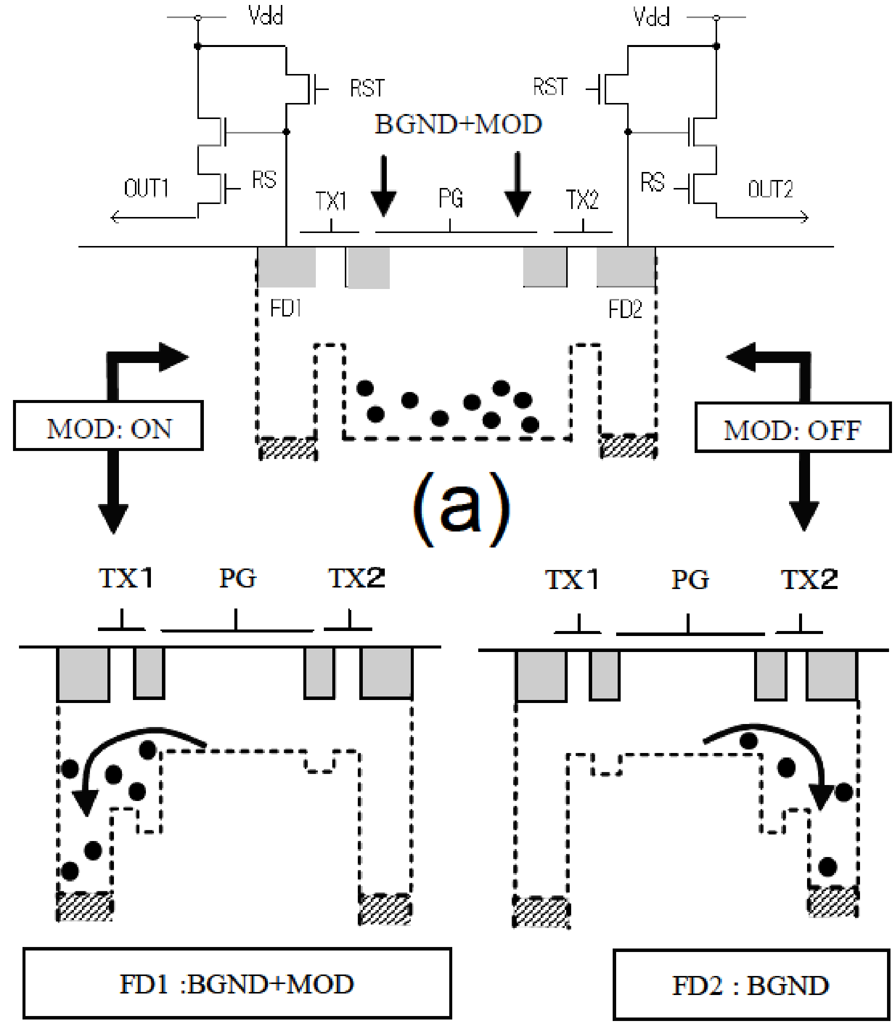
Two Accumulation Regions

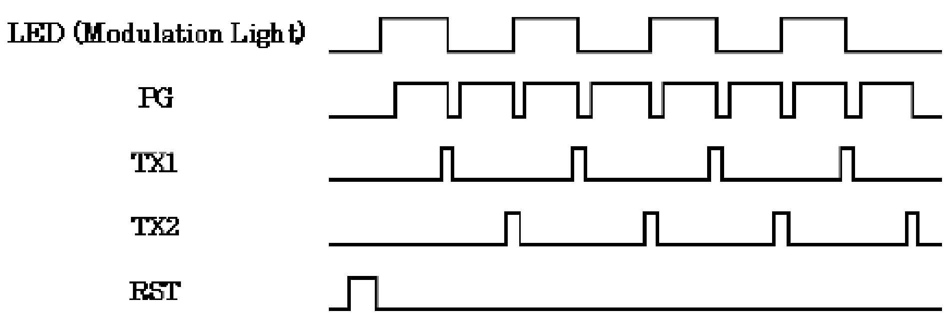
- Concept of the two accumulation regions method



Demodulated CIS Pixel

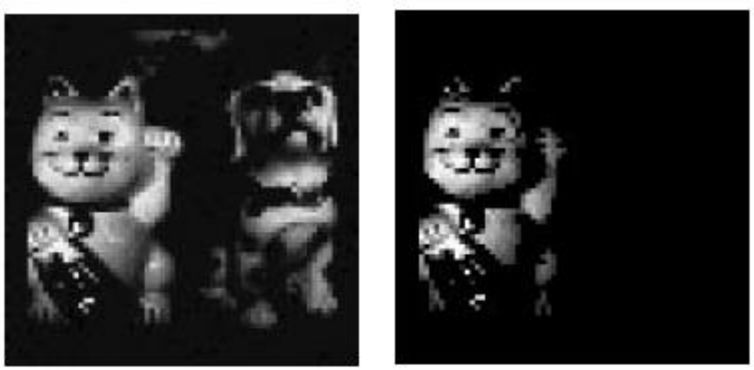
- FD1 : modulation + bgnd
- FD2 : background
- FD1 – FD2 = modulated signal



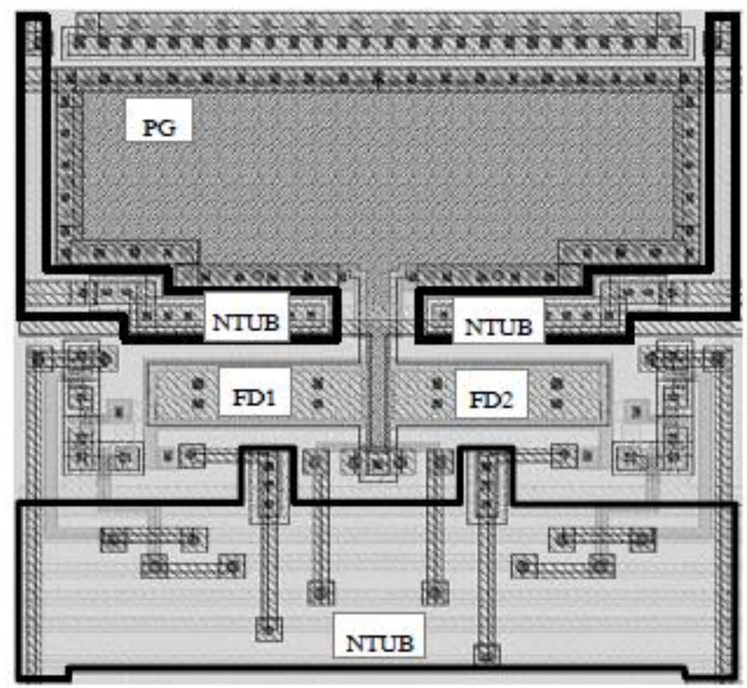


Sample Image

- Cat is illuminated by modulated light only
  - (a) normal image
  - (b) demodulated image

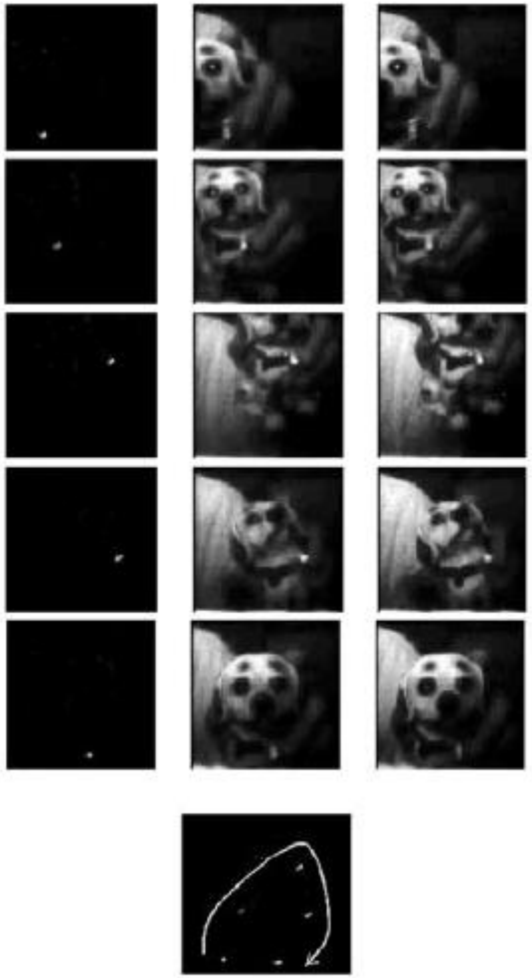


(a) (b)



Tracking

- Demonstration of marker tracking
  - Left column: modulated pattern extracted by the sensor
  - Middle column: modulated and background signal
  - Right column: output from only the background light
  - Bottom figure: the moving trace of the marker



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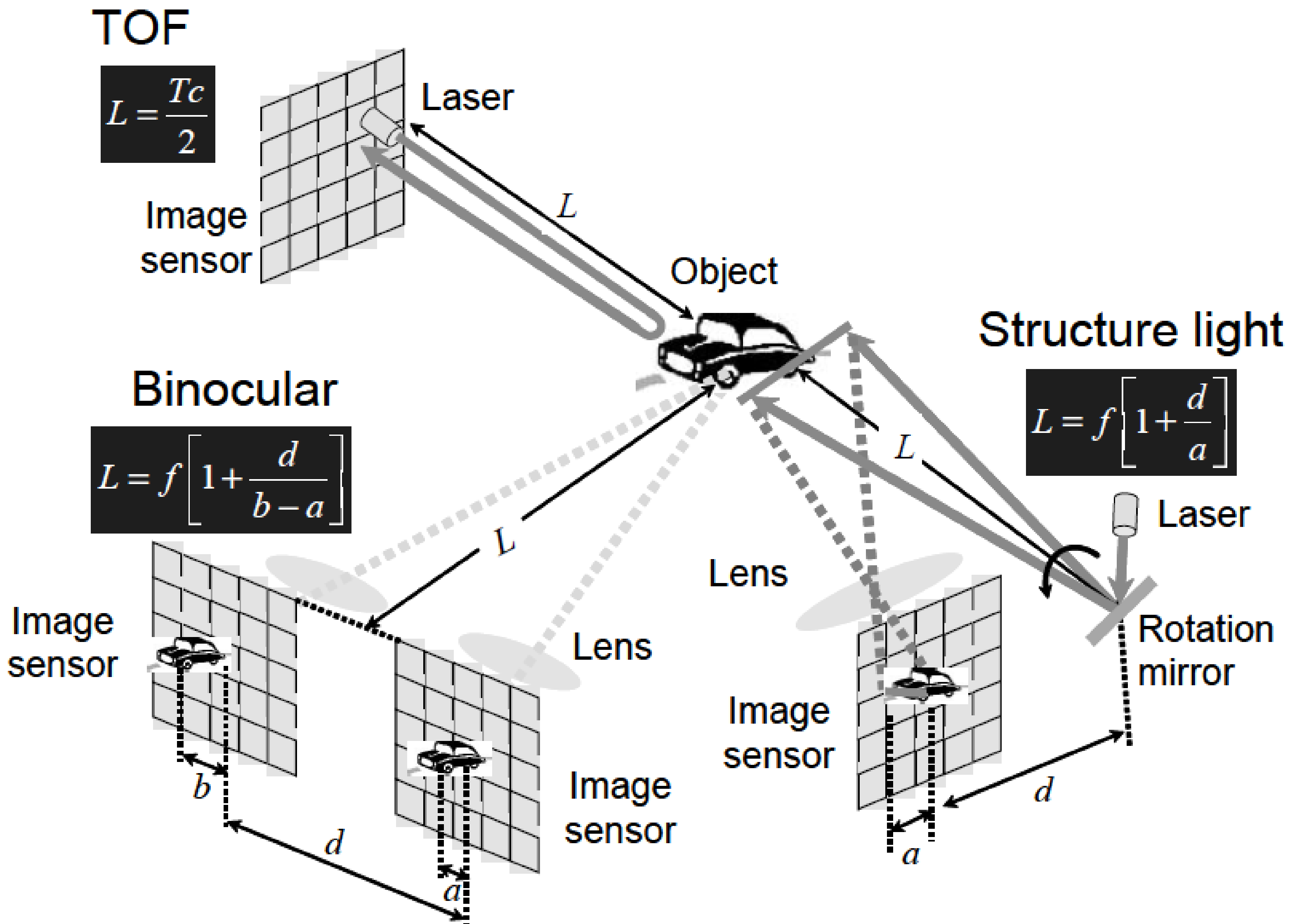
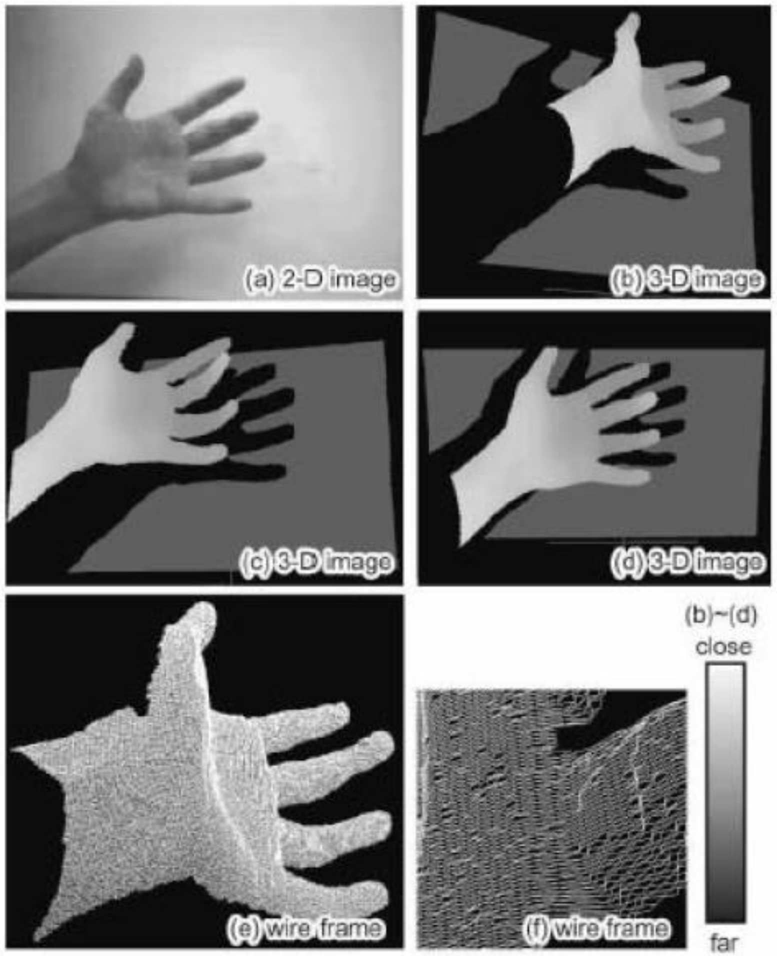
3D Range Finder



Common 3D Imaging Tech.

- Time-of-flight (TOF)
  - Direct
  - Indirect
- Triangular
  - Binocular
  - Structure light
- Light-intensity



3D Range Finders Methods

Smart CMOS sensors for 3D range finders

Category	Implementation method	Affiliation and Refs.
Direct TOF	APD array	ETH [97, 98], MIT [357]
Indirect TOF	Pulse	ITC-irst [358, 359], Fraunhofer [360, 361], Sizuoka U. [362]
	Sinusoidal	PMD [340, 341, 363, 364], C-SEM [353, 365], Canesta [366], JPL [367]
Triangulation	Binocular	Shizuoka U. [368], Tokyo S-ci. U. [369] Johns Hopkins U. [370, 371]
	Structured light	Carnegie Mellon U. [87, 372] U. Tokyo [350, 356, 373, 374], SONY [157], [375], Osaka EC. U. [342]
Others	Light intensity (Depth of intensity)	Toshiba [376]

Time of Flight (TOF)

- Measure distance by round-trip time of flight
  - L = Distance
  - T = round-trip time
  - C = speed of light

$$L = \frac{Tc}{2},$$

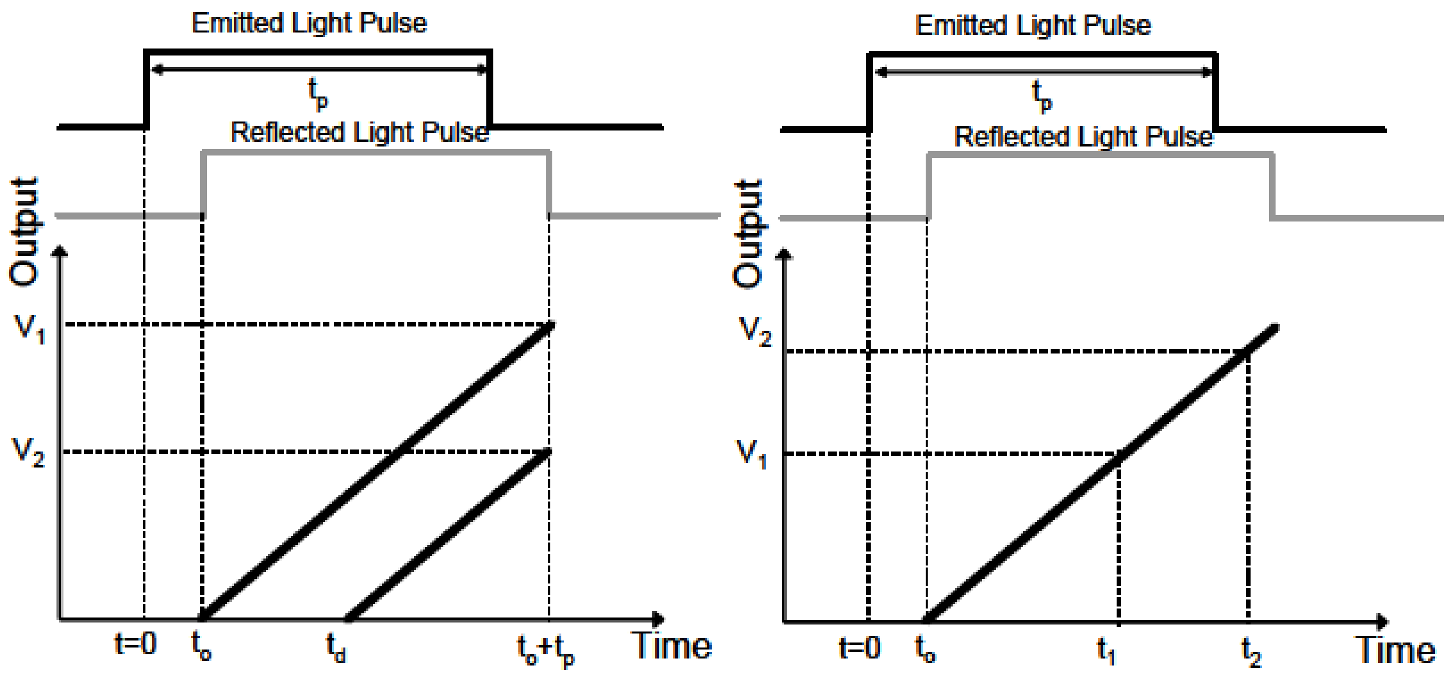
- Simple system

Direct TOF

- Measure round-trip time directly
- Require high speed photodetector and high speed precision timing circuit.
  - L = 3m, T = 10 psec
  - Suitable sensor : APD
- Wide measuring distance range : m ~ km
- Need averaging to improve accuracy

Indirect TOF

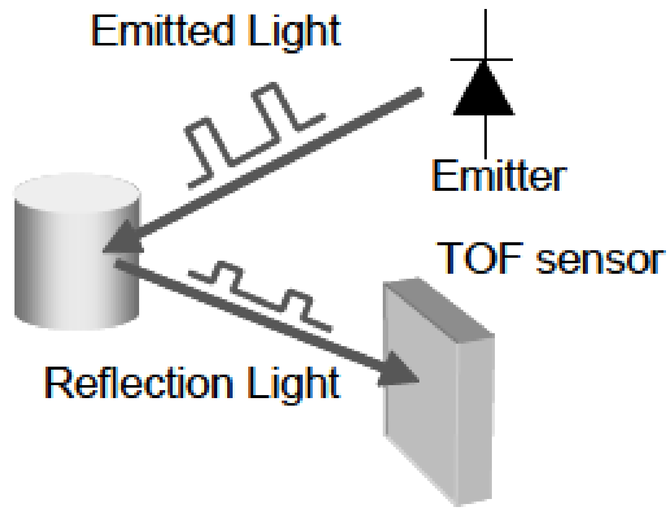
- 2 same duration (t_p) pulse with delay t_d
- 2 different duration pulse (t_1 & t_2) with 0 delay

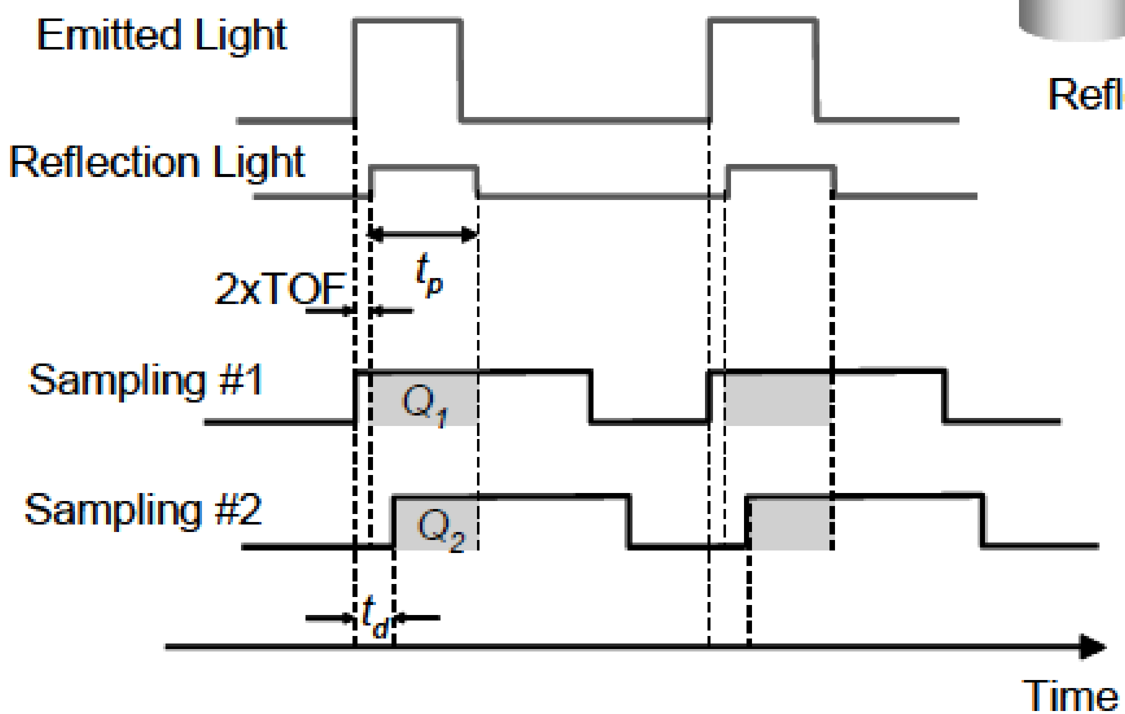


$$L = \frac{c}{2}\left[t_p\left(\frac{V_2}{V_1} - 1\right) + t_d\right]$$

$$L = \frac{1}{2}c\left(\frac{V_2 t_1 - V_1 t_2}{V_2 - V_1}\right)$$

Indirect TOF with delayed pulses





$$t_d - 2\times\mathrm{TOF} = t_p \frac{Q_1 - Q_2}{Q_1}$$

$$\mathrm{TOF} = \frac{L}{c}$$

$$\therefore L = \frac{c}{2}\left[t_p\left(\frac{Q_2}{Q_1}-1\right)+t_d\right]$$

Indirect TOF(cont'd)

- Operation principle of indirect TOF with sinusoidal emission light

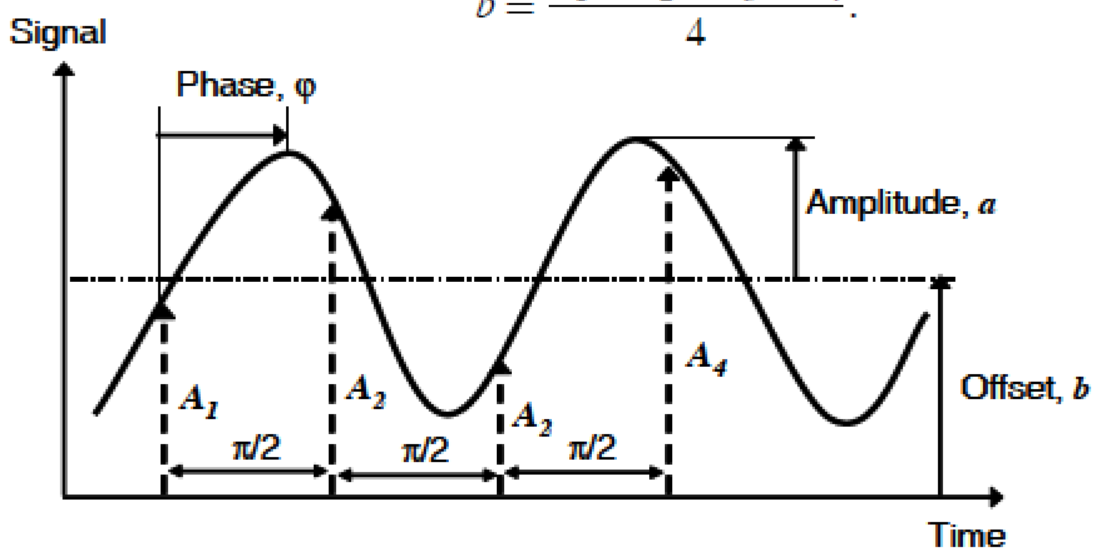
$$A_1 = a\sin\phi + b,$$
$$A_2 = a\sin(\phi + \pi/2) + b,$$
$$A_3 = a\sin(\phi + \pi) + b,$$
$$A_4 = a\sin(\phi + 3\pi/2) + b.$$

$$\phi = \arctan\left(\frac{A_1 - A_3}{A_2 - A_4}\right).$$

$$a = \frac{\sqrt{(A_1 - A_3)^2 + (A_2 - A_4)^2}}{2}.$$

$$L = \frac{c\phi}{4\pi f_{mod}},$$

$$b = \frac{A_1 + A_2 + A_3 + A_4}{4}.$$



Triangulation

- Measure distance by triangular geometrical arrangement
  - Passive : Binocular (stereo vision) method
  - Active: Structure light method

Binocular Method

- No light source
- Two sensor with identical FOV
  - Complicated system accuracy requirement
- Single sensor with pattern optical-block layer

Structure Light Method

- Require structure light source
  - Require scanning system
  - Require special optics system
- Background cancellation
  - Need to suppress ambient light against the structured light

Depth Key

- Measure distance by focus depth
- Measure distance by reflected intensity
  - Affected by reflectance of the object

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Target tracking

- Object extraction
  - Modulation techniques
  - Structure light
- Centroid finding with frame difference
  - Maximum detection
  - Projection
  - Resistive network
  - Digital processing

Target Tracking Summary

Smart CMOS sensors for target tracking

Method	Preprocess	Tech. (μm)	Pixel #	Pixel size (μm)	Speed	Power consum.	Ref.
MaxDet.	WTA & 1D-RN	2	24×24	62×62	7 kpix/s		[383]
MaxDet.	1D-RN & comparator	0.6	11×11	190×210	50 μs (sim.)		[384]
Projection	Current sum	2	256×256	35×26	10 ms		[173]
Projection	Edge detect	2	Fovea 9×9, periphery 19×17	Fovea 150×150, periphery 300×300	10 lpix/s	15 mW	[385]
Projection	Binarization	0.18	80×80	12×12	1000 fps	30 mW	[386]
Projection	Charge sum	0.6	512×512	20×20	1620 fps	75 mW	[387]
2D-RN		0.25	100×100 (hex.)	87×75.34	$\sim$7 μs	36.3 mW	[45]
CNN		0.18	48×48	85×85	500 μs, $\sim$725 MIPS/mW	243 μW	[388]
Digital process.	ADC	0.5	64×64	80×80	1 kHz	112 mW	[61]

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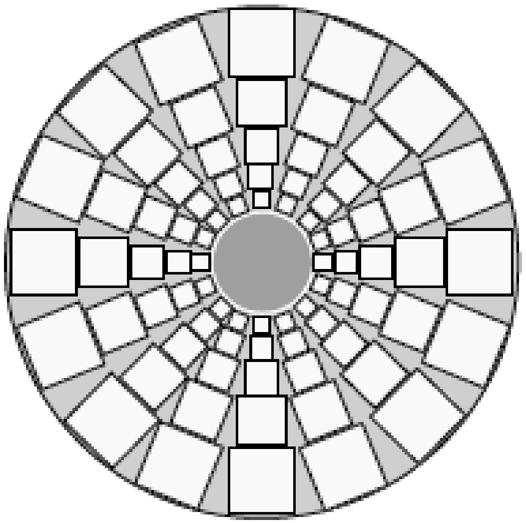
Non-orthogonal Arrangement

- Pixel arrangement of a foveate image sensor
  - the pixel size increases by square root
  - the pixel pitch logarithmically decreases
  - the circle area of the center shows the control circuits

$$r = \sqrt{x^2 + y^2}$$
$$\theta = \arctan\left(\frac{y}{x}\right).$$

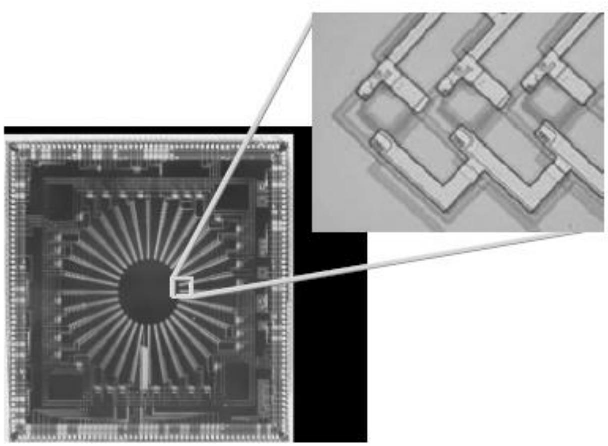


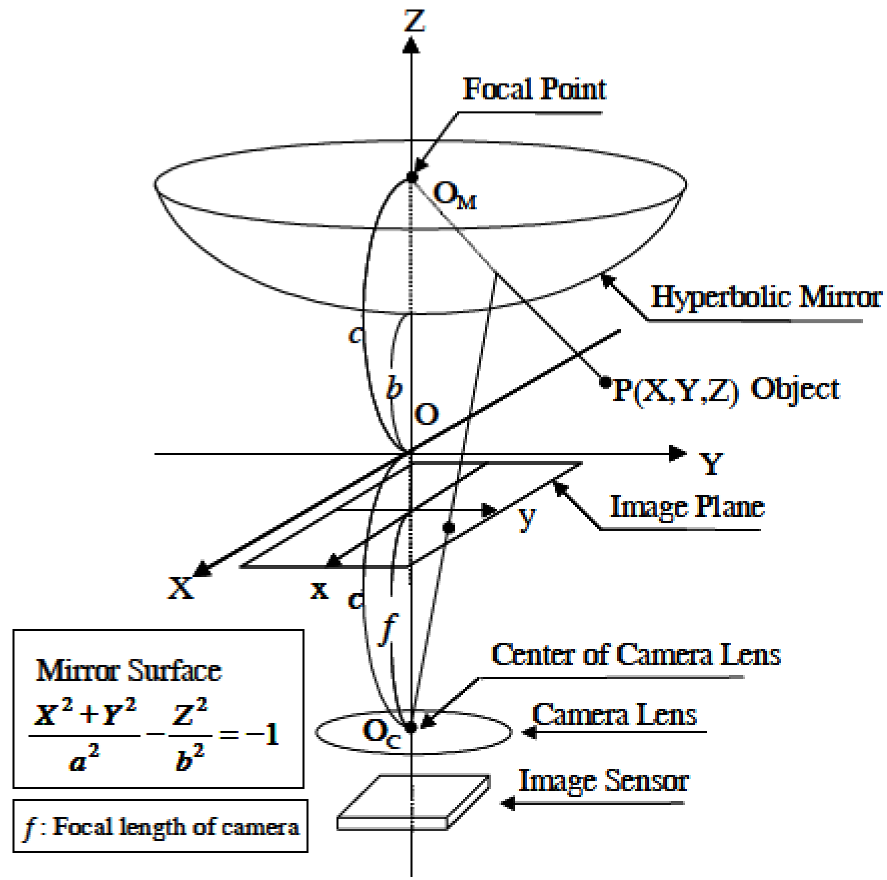
Non-orthogonal Arrangement

- Configuration of a Hyper omni vision (HOVI) system

$$x = \frac{X f \left(b^2 - c^2\right)}{\left(b^2 + c^2\right) Z - 2bd\sqrt{X^2 + Y^2 + Z^2}},$$

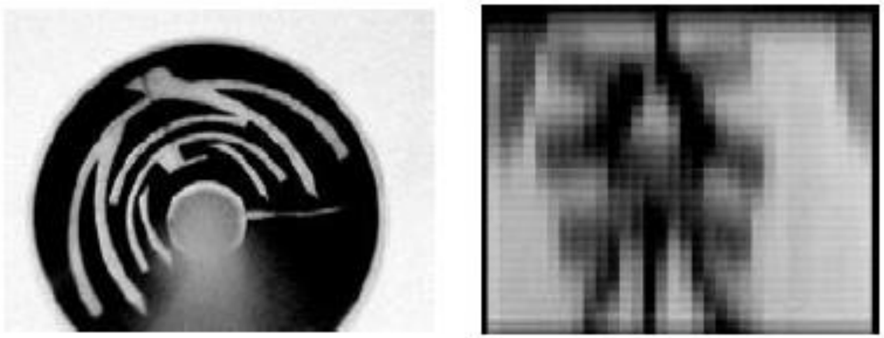
$$x = \frac{Y f \left(b^2 - c^2\right)}{\left(b^2 + c^2\right) Z - 2bd\sqrt{X^2 + Y^2 + Z^2}}.$$





Non-orthogonal Arrangement(cont'd)

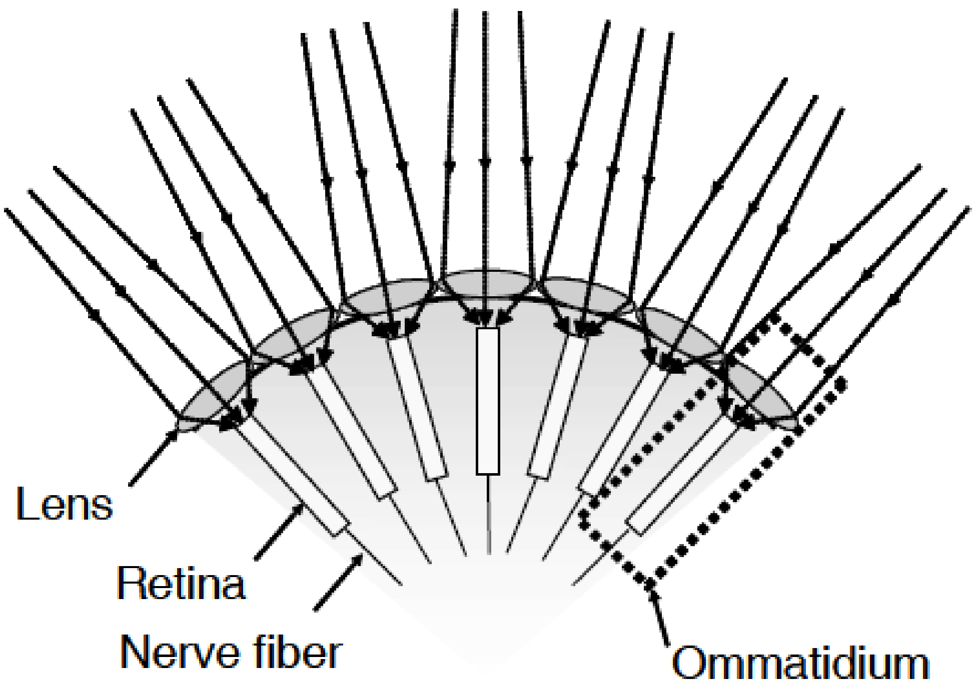
- HOVI's images (a Japanese character)
  - (a) output of conventional HOVI system
  - (b) output of foveate sensor



(a) (b)

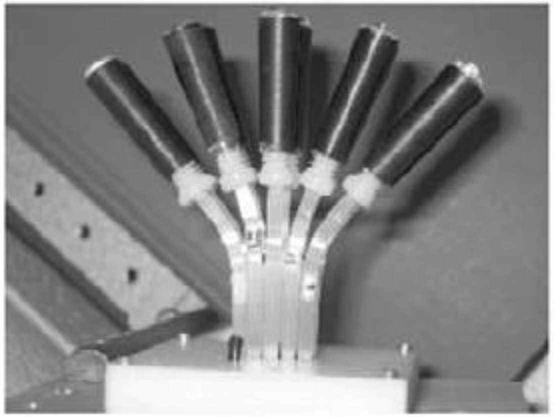
Dedicated Optics

- Concept of an apposition compound eye system



Dedicated Optics(cont'd)

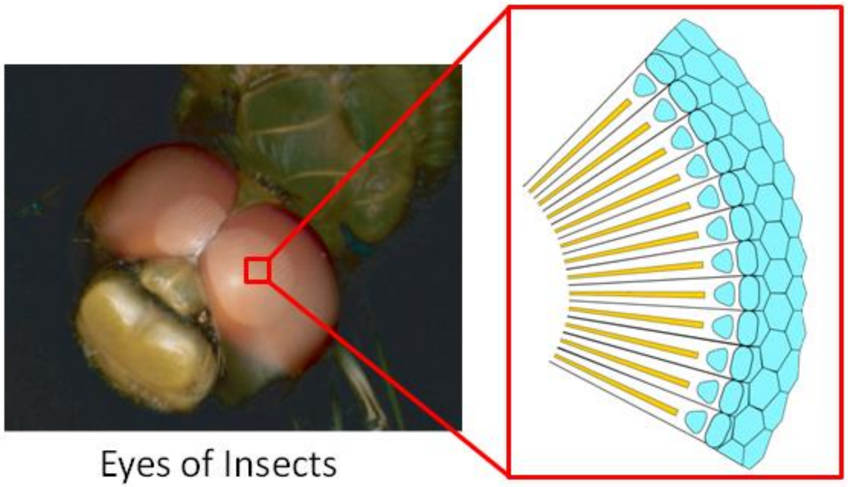
- Photographs of the prototype of DragonflEye
  - (a) close up of eyelet bundle
  - (b) total system



(a)

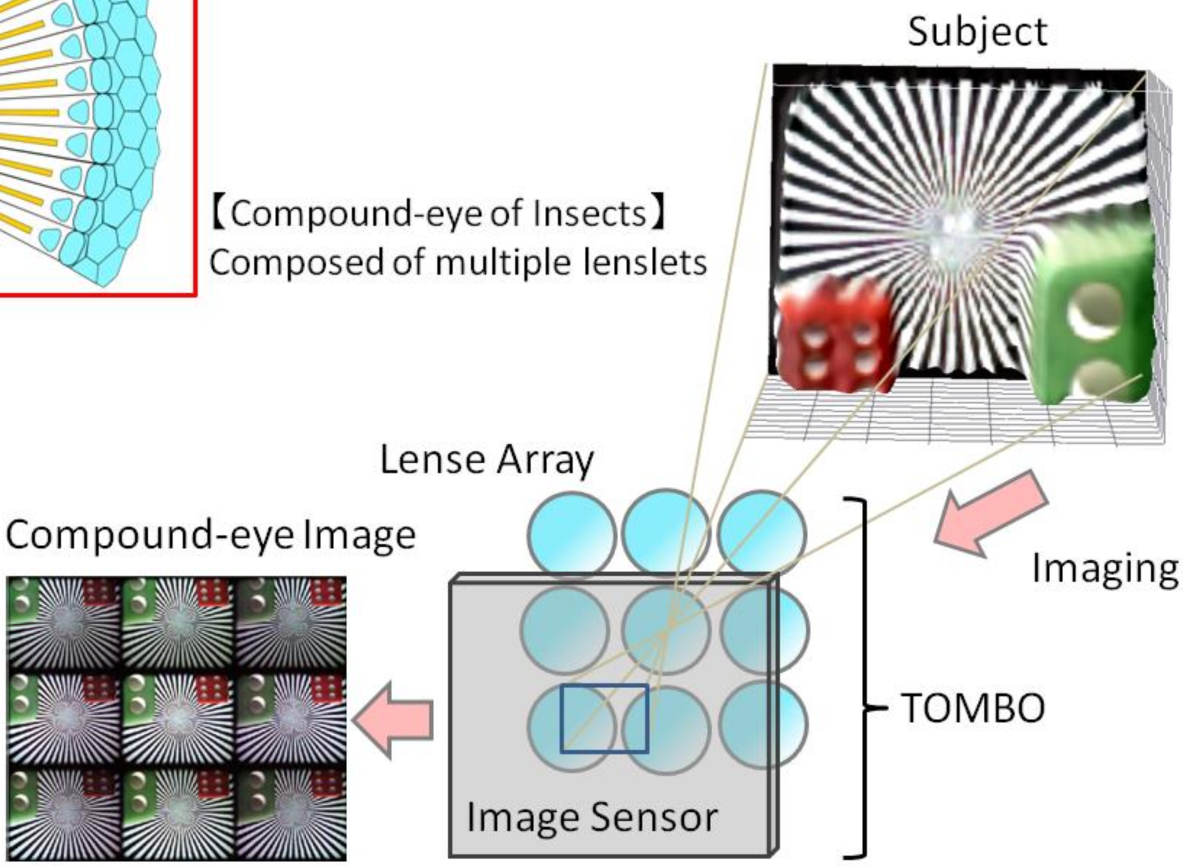
(b)

Compound Eye



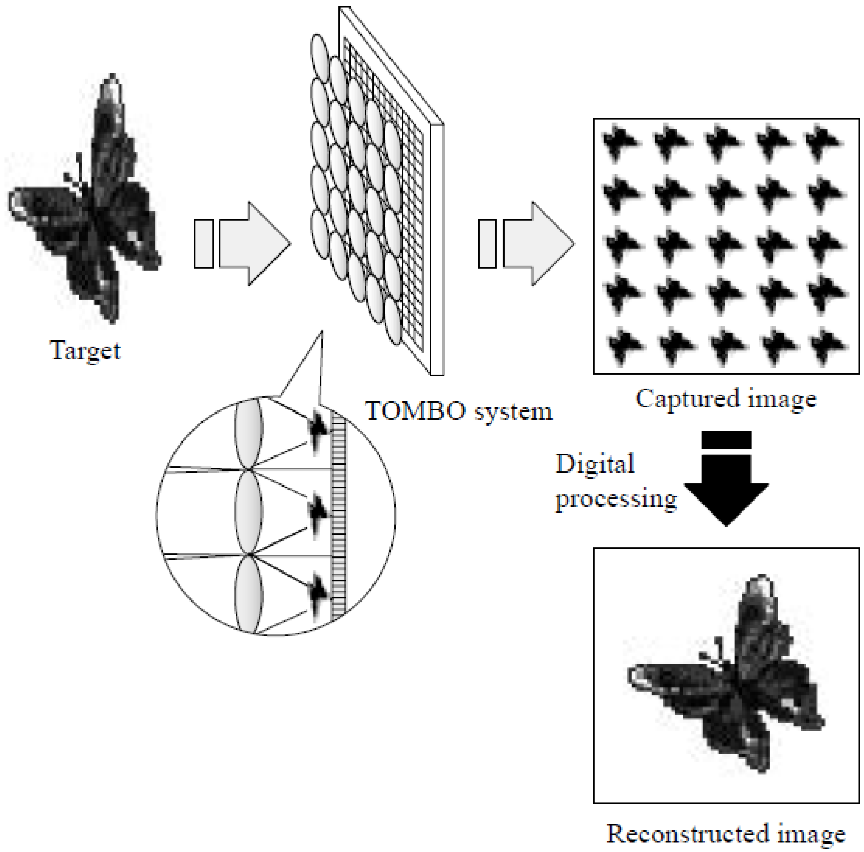
Eyes of Insects

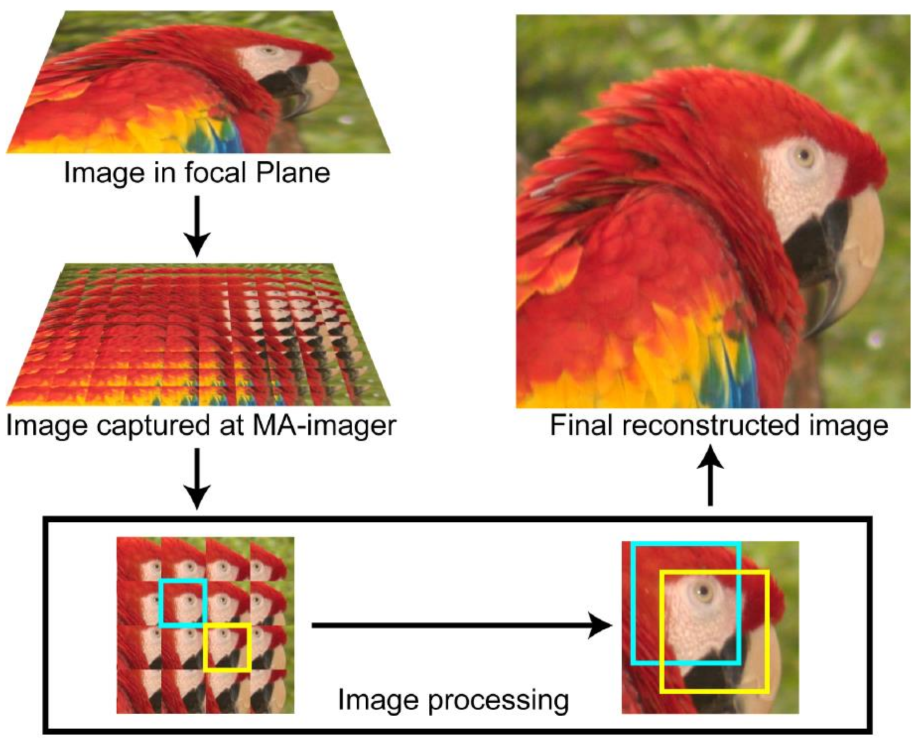
【Compound-eye of Insects】
Composed of multiple lenslets



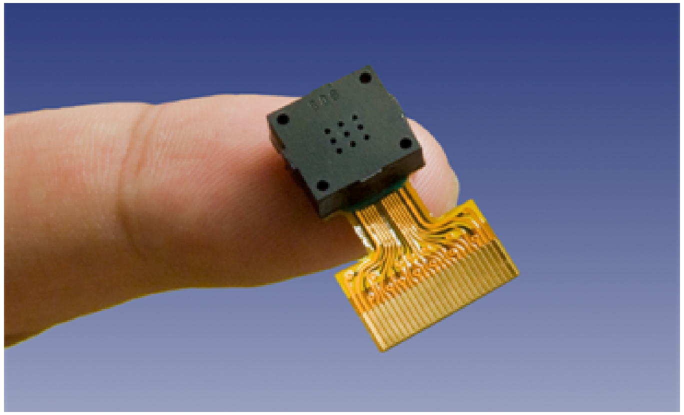
Dedicated optics(cont'd)

- Concept of TOMBO system

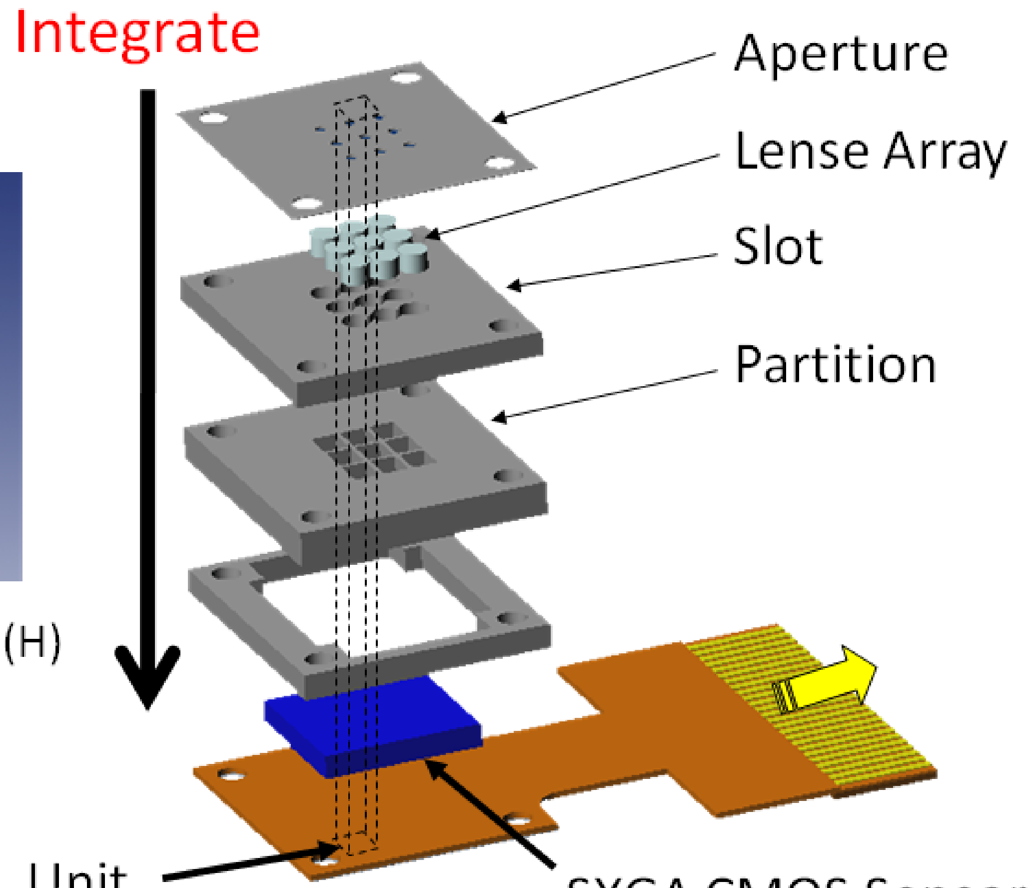




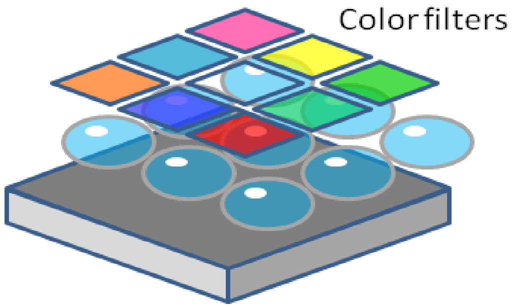
Structure of TOMBO



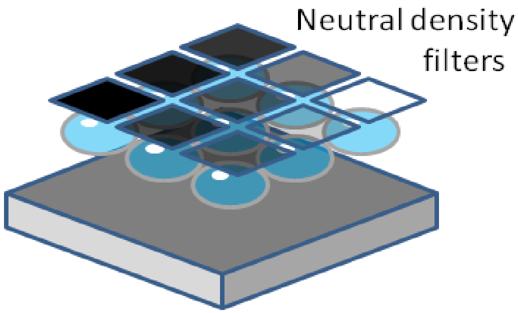
9.6mm(W) × 9.0mm(D) × 3.4mm(H)



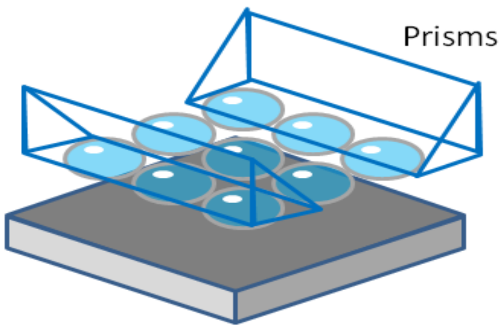
Functional Imager of TOMBO



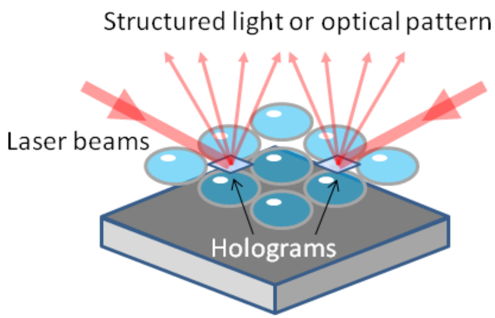
Multi-spectral imaging



High dynamic-range imaging

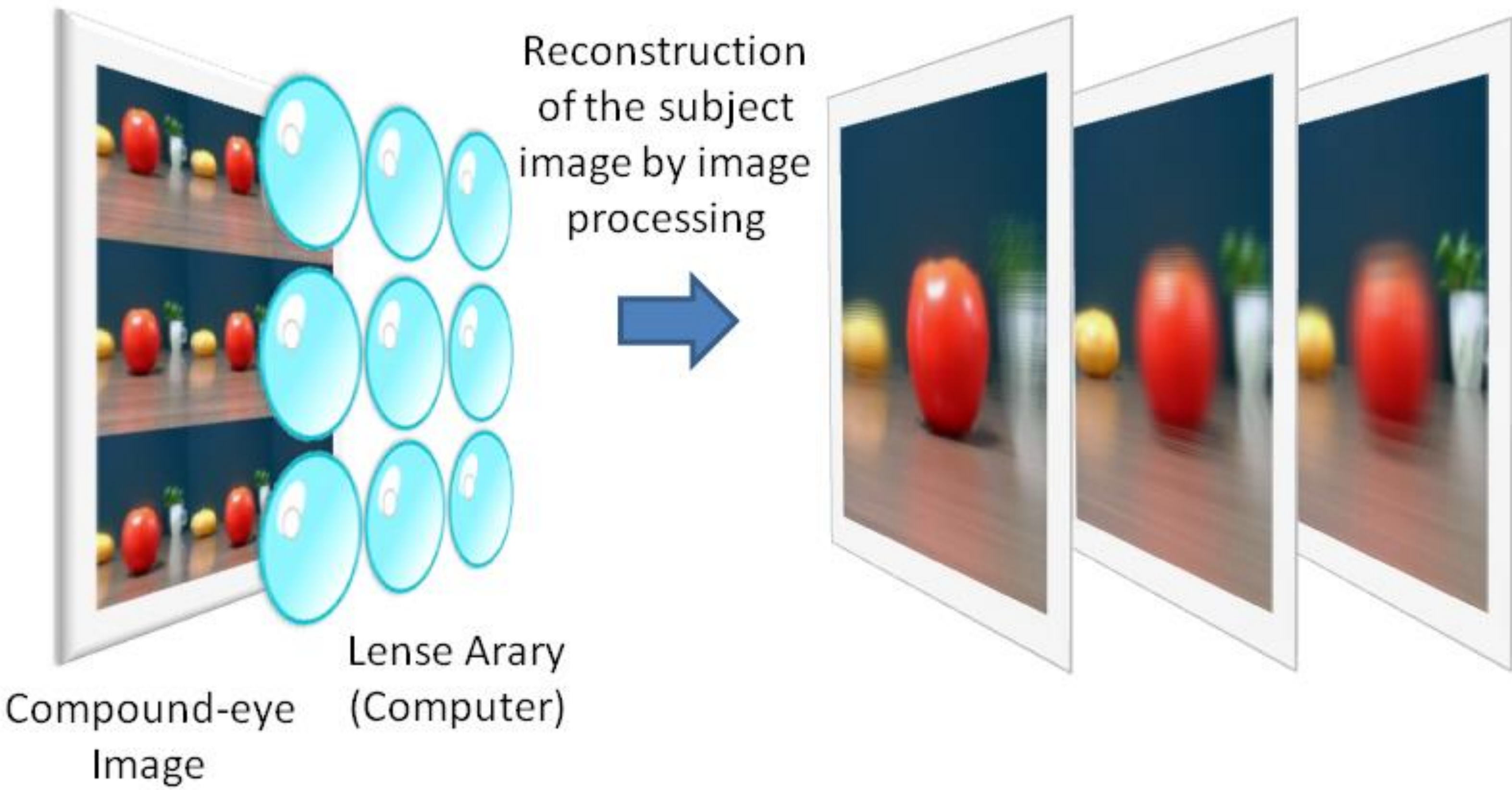


Wide field-of-view imaging



Integration of micro projectors

Re-Focusing



Reconstruction of the subject image by image processing
Compound-eye Image
Lense Arary (Computer)