



Specifying and Designing Cameras for Computer Vision Applications

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Organization of Talk

- Elements for image capture and formation
- Design example

Elements for Image Formation and Capture

- Optics: delivers a focused image of object onto sensor
- CMOS Image Sensor: converts focused image into raw image bits
 - (Sensor to processor interface: high bandwidth link transports raw image bits from sensor to processor) (OPTIONAL: if functions are in separate chips)
- Image Processor: converts raw image bits into useful image
- System Interface: high bandwidth electrical connection carrying image data

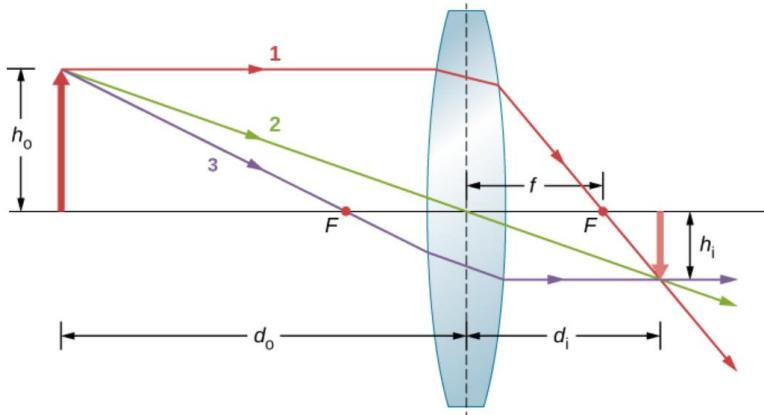
may be
combined

Optics: Focuses Photons onto CMOS Sensor



Optics: Focal Length = f

- The size of an object on sensor:

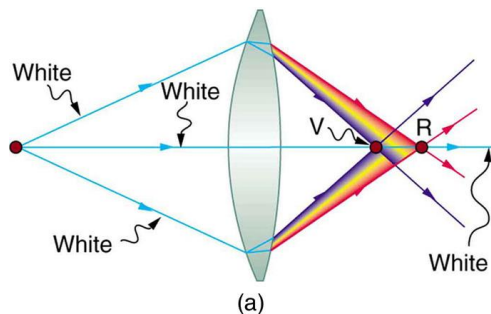


$$d_i = \left(\frac{1}{f} - \frac{1}{d_o} \right)^{-1}$$

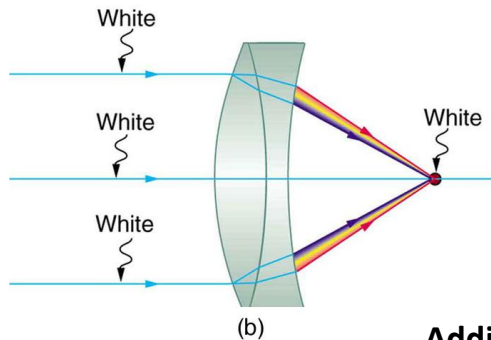
$= \sim f$ for d_o at infinity

$$m \equiv \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

Color Correction



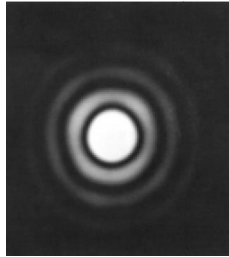
A lens made of a single refractive index material will focus different colors at different places: Degrades image sharpness (chromatic aberration)



Using a second lens made of a different refractive index material can compensate
Typically, one is a high refractive index, and the other is a lower index

Adding Lens Elements Increases Cost

- Focusing:
 - Real optics do not focus a point source to a point
 - Instead, it focuses to a “circle of confusion” or “optical blur”, aka “Airy Pattern”

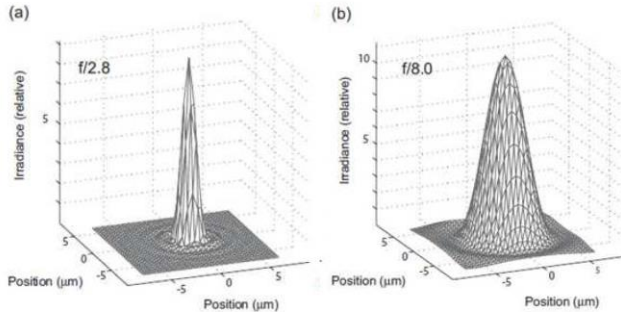


- The diameter of the Airy Pattern depends on F# of optics and wavelength of light
- F# of optics = Focal Length / Aperture diameter

Airy Diameter

Optics and the Airy Disk:

Focal ratio: Sets spot size for diffraction limited optics



Source: Catrysse

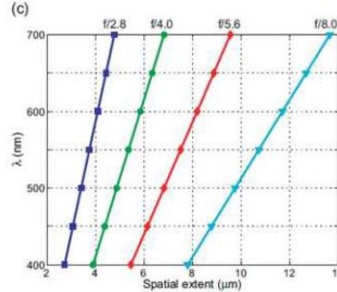


Airy Disk Diameter

~3 microns, f/2.8



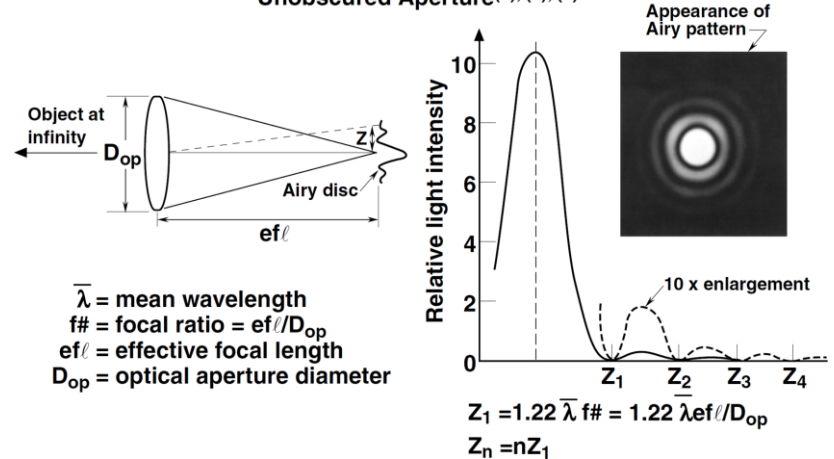
~10 microns, f/8.0



Airy Disk Diameter (microns)

Spatial Impulse Response of an Optical System

The Airy Pattern: Optical Diffraction of a Circular Unobscured Aperture^{(1), (2), (3)}

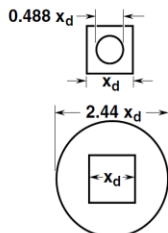


- (1) W. J. Smith, *Modern Optical Engineering*, McGraw-Hill, New York, 1966, pp. 135 – 139.
 (2) J. W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, New York, 1968, pp. 63 – 66.
 (3) M. Born and E. Wolf, *Principles of Optics*, Pergamon Press, 5th Edition, Oxford, 1975, pp. 394 – 398.

Airy Diameter is proportional to f# & wavelength

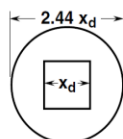
Optimum Pixel and Spot Size Relationship

Q Parameter Determines Optical Blur Sampling Detector Size and Airy Disk vs Q



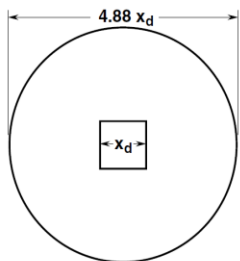
Q = 0.2 EE = 0.904

Increasing Q



Q = 1.0 EE = 0.499

Decreasing EE



Q = 2.0 EE = 0.170

Radius of first zero of airy disk = $1.22 \lambda / D$;
Linear obscuration ratio = 0.20
Fraction of PSF energy with circle of first zero = 0.76

EE = Ensquared energy

Optimum

Optical Q Parameter Definitions

- Optical Q parameter is useful in quantifying spatial sampling of system optical blur
 - Specifies ratio of optical blur diameter to the pixel pitch (or pixel size)

$$Q \equiv \frac{\bar{\lambda} f \#}{x_p} = \frac{\bar{\lambda} e f \ell}{x_p D_{op}} = \frac{2 f_n}{f_{co}}$$

where

$$f \# = \frac{e f \ell}{D_{op}}; f_n = \frac{1}{2 x_p}; f_{co} = \frac{1}{\lambda f \#}$$

- $\beta \equiv$ number of detector widths that fit inside first zero of optical Airy pattern

$\bar{\lambda}$	= center wavelength
f#	= focal ratio
D_{op}	= optical diameter
$e f \ell$	= effective focal length
x_p	= detector pitch distance
x_{det}	= detector width
f_n	= spatial frequency at which Nyquist criteria is met
f_{co}	= optical system spatial cutoff frequency
EE	= ensquared energy

Q	β	f_n / f_{co}	EE	Interpretation
0.5	1.22	0.25	0.88	Optical blur under sampled by 4 ×
1.0	2.44	0.50	0.50	Optical blur under sampled by 2 ×
1.5	3.66	0.75	0.31	Optical blur under sampled by 1.3 ×
2.0	4.88	1.00	0.17	Exact Nyquist sampling of optical blur

Note: High fill factor assumed then: $x_p \approx x_{det}$

Optimum

CMOS Image Sensor: Photons to Bits



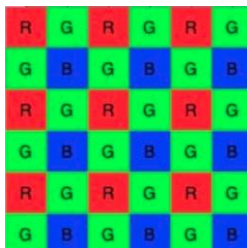
CMOS Image Sensor Main Functions

- Charge Generation from Light
 - Focused light generates photo-electrons in silicon substrate proportional to intensity & time (Einstein's Photoelectric Effect, 1921 Nobel Prize in Physics)
- Charge Collection
 - Charge is generated in an XY grid of depletion regions in silicon substrate ("pixels") formed by semiconductor doping and control gate structures (sensor design / layout)
- Charge Transfer
 - Gate circuitry is clocked to move charge packets to where they can be measured (sensor design/layout)
- Charge Measurement
 - Charge for each pixel is sampled by a switch, stored on a sense capacitor and measured as a voltage on the capacitor (sensor design / layout)
- Analog to Digital Conversion
 - The voltage on the sense capacitor is digitized by on-chip Analog to Digital Converters (ADCs) to create raw digital image data (sensor architecture design / layout: power, pincount & package limits)
- Image Processing (may be incorporated on sensor or done with a separate chip)
 - The raw digital image data is calibrated and processed to make a final image or video stream (sensor die size, cost, system flexibility considerations vs standalone processor chip)

Image Sensor Key Specifications

- Pixel size (affects sensitivity and choice of optics)
- Pixel saturation level (affected by pixel size)
- Number of pixels (FOV & sensor/camera bandwidth affected)
- Sensitivity (pixel architecture, frontside vs back illuminated, microlenses)
- Sensor physical size (affects choice of optics & required size of lens illuminated circle)
- Cost (sensor & lens are usually most costly elements in a camera)

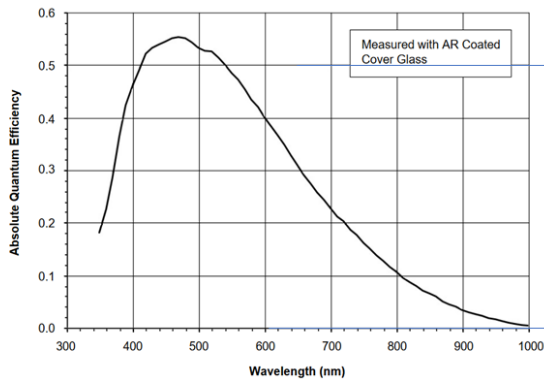
Color Imager: Add Color Filter Array to Mono Sensor's Pixel Array



One Popular Arrangement is the 2x2 “Bayer Pattern”

Quantum Efficiency

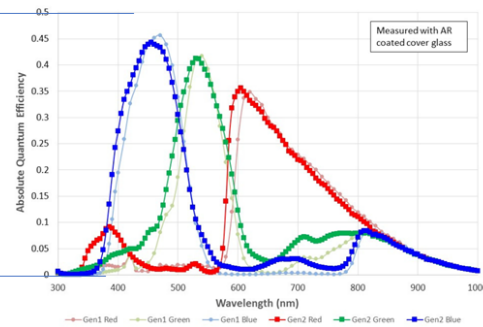
Monochrome with Microlens



Higher light flux:
Sensitive to all visible wavelengths

Monochrome Version

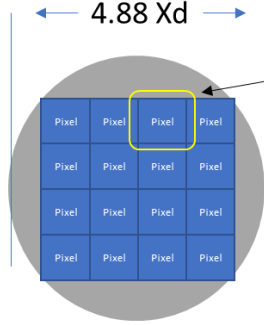
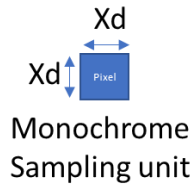
Color (Bayer RGB) with Microlens



Each color masked pixel gets about 1/3 of visible light flux. Lower SNR given same exposure & optics

Color Masked Version

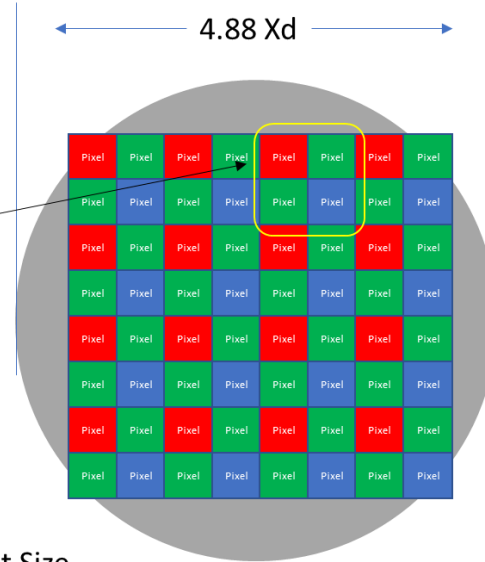
Color Imager: Optimum Spot Size Changes vs Mono for Same Base Pixel Array



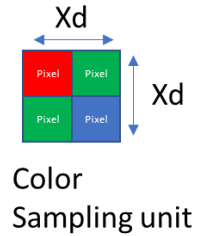
Optimum Spot Size
(monochrome)

Sampling
unit

2x difference in Spot Size
2x difference in F#



Optimum Spot Size
(color)

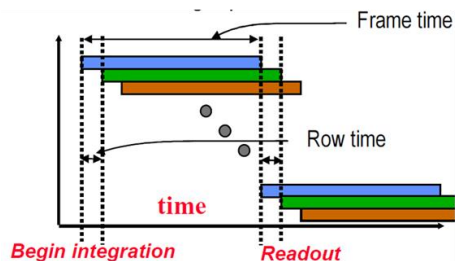


Color
Sampling unit

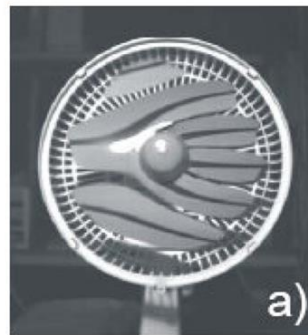
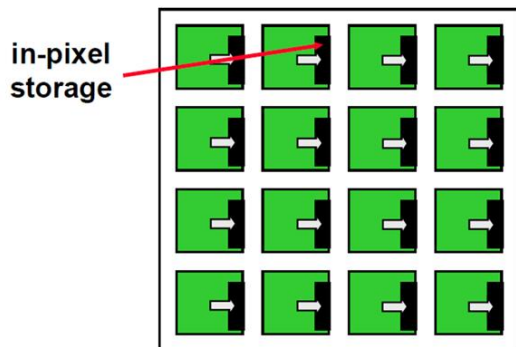
Non-Ideal Characteristics of CMOS Sensors

CMOS Image Shuttering

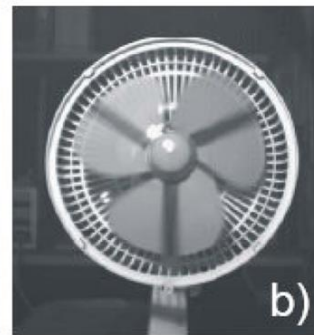
- Standard CMOS “rolling shutter” imparts motion artifacts (focal plane distortion): the start and stop time for each exposed line are offset from one another
- For still images, no problem is observed
- For images with motion strange artifacts can be observed



CMOS Global Snap Shutter Avoids Rolling Shutter Artifacts



Rolling Shutter



Snap Shutter

In-pixel storage of charge in light-shielded structure allows all exposures to start/stop at same time. Charge is dynamically stored inside pixels until read out (line by line readout). High temperature and slow frame aggravate shot noise via thermally generated charge.

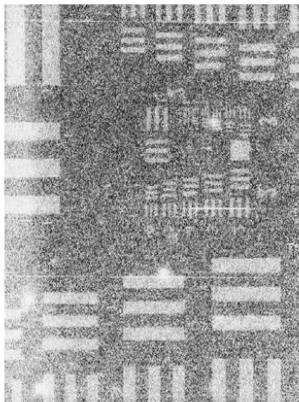
Dynamic Range and Saturation vs Pixel Size

- As pixel size shrinks, the charge capacity of the pixel is reduced leading to a reduction of dynamic range
- For a single exposure, the dynamic range is equal to:
$$\text{Dynamic Range} = \text{DR} = \text{Saturation level} / \text{readout noise}$$
- Typical pair of images with different exposure showing light and dark saturated regions (“histogram clipping”)



(in an image, what is the brightest bright region and dimmest dark region that can be simultaneously captured?)

Noise Sources: Dark, Offset, Lag, Reset & RTN

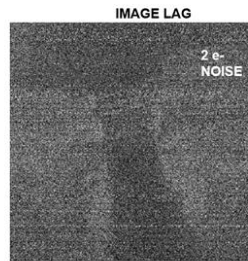


Degraded by Dark Signal

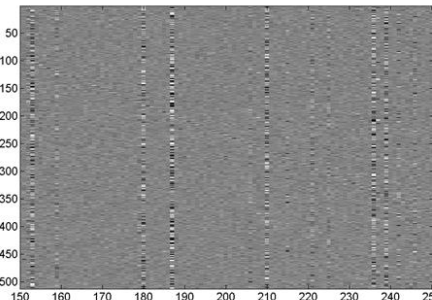
PPD IMAGE LAG



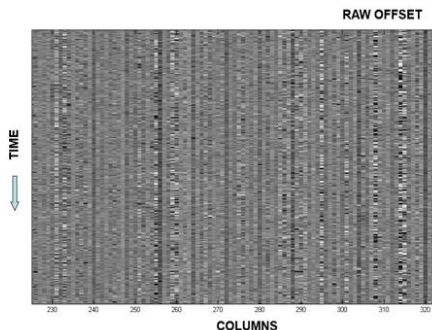
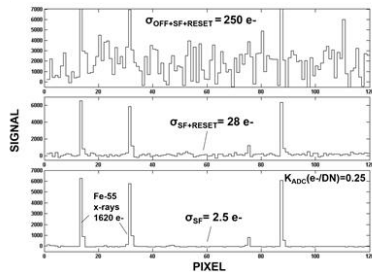
IMAGE



CMOS OFFSET FPN



RTN (Random Telegraph Noise)

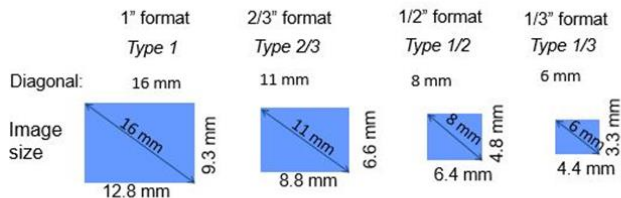


Sensor Formats, Pixel Counts and Interface Bandwidth

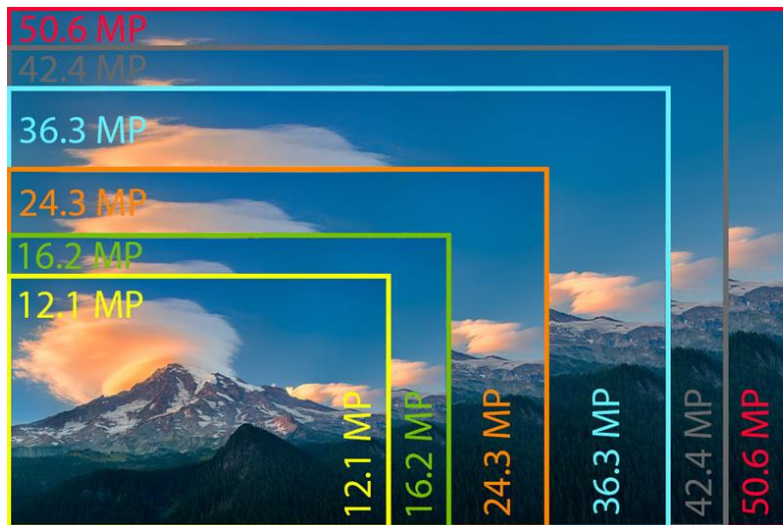
Common Sensor Formats and Pixel Resolution

SENSOR SIZES & FILM FORMATS

Measurements are in mm width x height
 "D" = Diagonal in mm of sensor or film area (same as diameter of image circle needed to cover it)
 Number of Pixels on horizontal axis represented in Ks (HD = 1920 x 1080)



Sensor Resolution: Image Scale & FOV Impact on Images



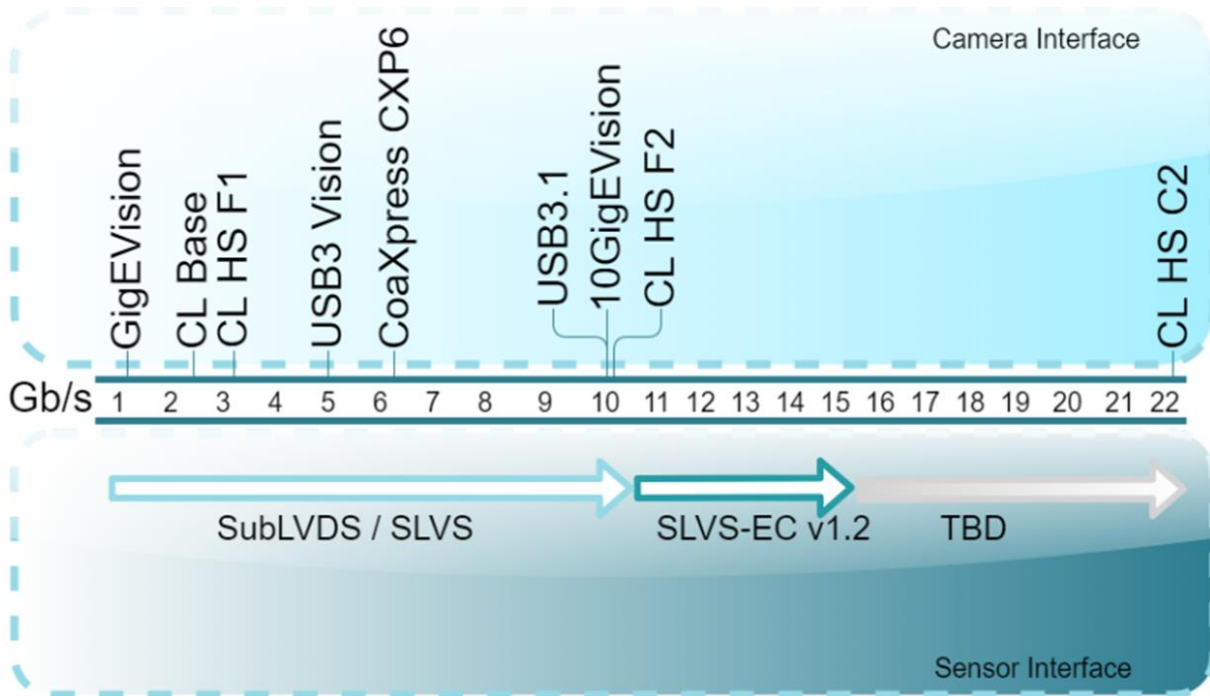
Same FOV, different Image scale



Same Image scale, different FOV

Sensor Link & Camera Network Bandwidth Standards For Higher Resolution/Frame Rate Video Cameras

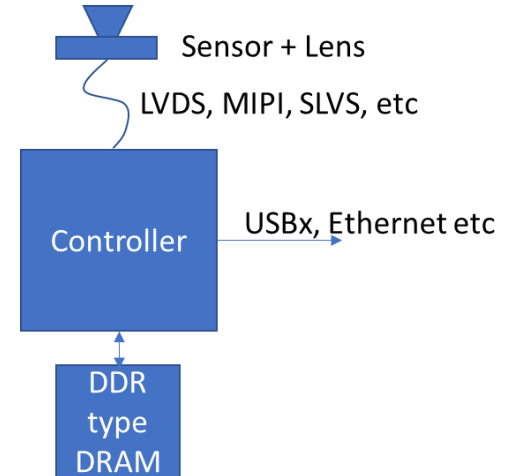
Pixel Count (Mpixels)	Bits/pixel	Frame Rate (F/s)	Sensor Link Bandwidth (Gbits/sec)
1	36	60	2.11
2	36	60	4.22
4	36	60	8.44
8	36	60	16.88
12	36	60	25.31
16	36	60	33.75



DRAM Memory Frame Buffers used to resolve bandwidth delta between camera and sensor interface bandwidths & protocol packetization

Memory Frame Buffer: Resolves Data Rate Difference Between Sensor & Camera Interfaces

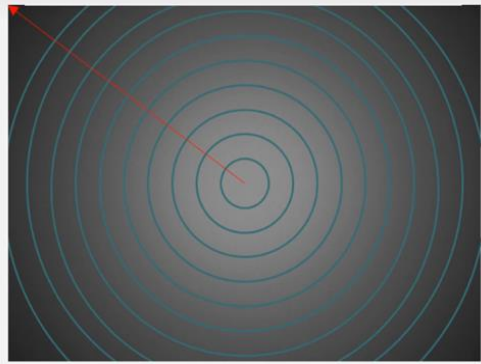
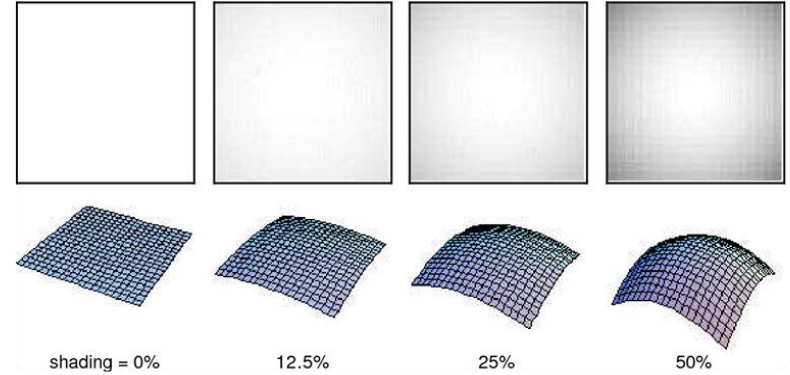
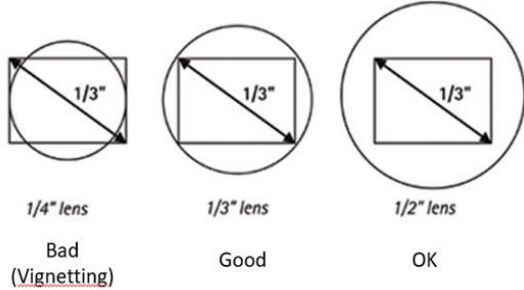
Pixel Count (Mpixels)	Bits/pixel	Frame Rate (F/s)	Bits for one frame (Mbits)	Write + Read bandwidth for Frame Buffer (Gbytes/sec)	x16 DDR Memory Bus Clock (MHz)	x32 DDR Memory Bus Clock (MHz)
1	36	60	36	0.53	131.84	65.92
2	36	60	72	1.05	263.67	131.84
4	36	60	144	2.11	527.34	263.67
8	36	60	288	4.22	1054.69	527.34
12	36	60	432	6.33	1582.03	791.02
16	36	60	576	8.44	2109.38	1054.69



Can't drop pixels or frames. "Within the time of one incoming video frame, at a minimum, the memory must store it and read it out to the camera interface".

~2x sensor bandwidth needed for Frame Buffer at a minimum.

Lens Fitment, Shading and Correction



Light intensity roll-off can be algorithmically corrected in the image signal processor

“Lens Shading Correction”

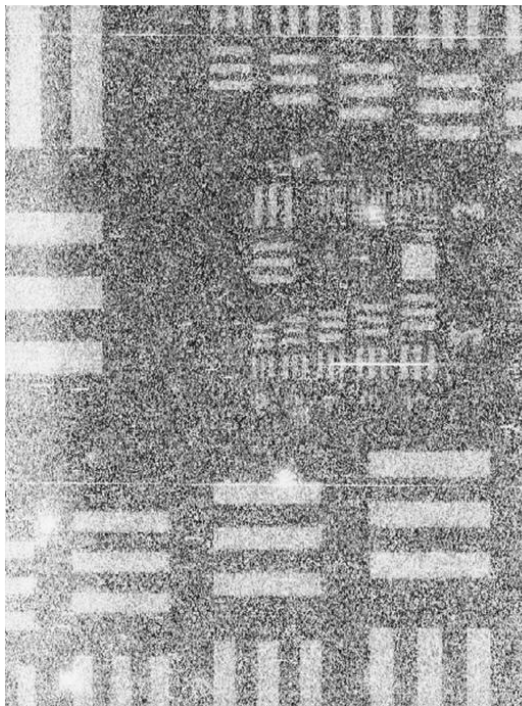


Image Signal Processing

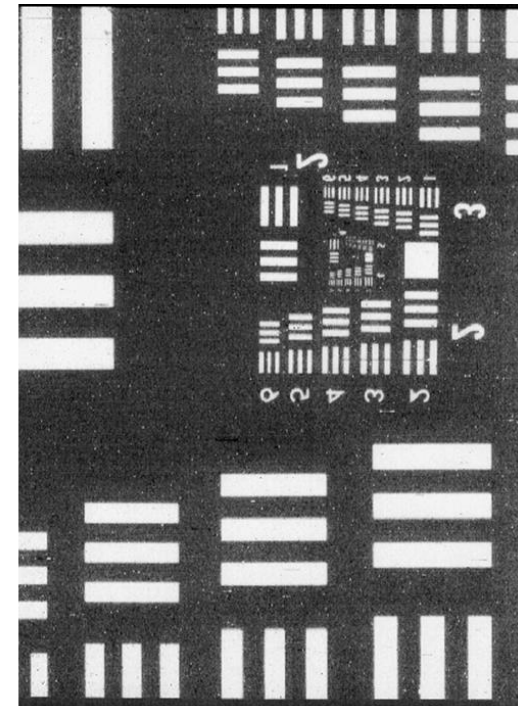


Dark Noise (thermally generated charge)

High temperature and long exposures of dim targets are prone to dark signal noise degradation



Possible to “despike” image via signal processing (subtract a dark frame of same exposure parameters)



High Dynamic Range via Image Fusion

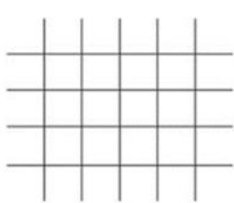


Final Result

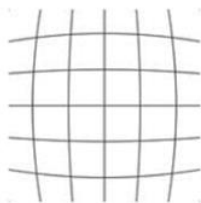
Signal Processing can be used to algorithmically combine a sequence of images taken in rapid succession, each with a different exposure length, to increase the overall dynamic range of a composite image

Lens Distortion & Distortion Correction

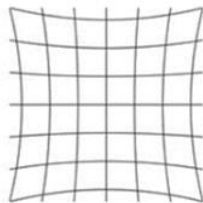
How an input grid looks in images with different distortion types



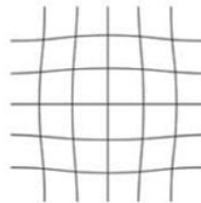
No Distortion



Barrel Distortion



Pincushion Distortion

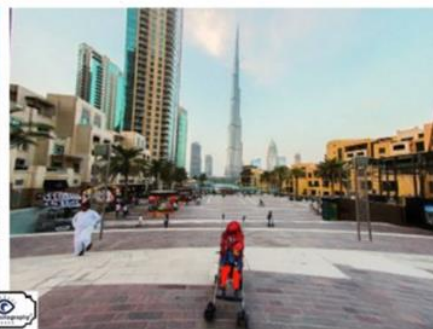


Mustache Distortion

www.apriorit.com



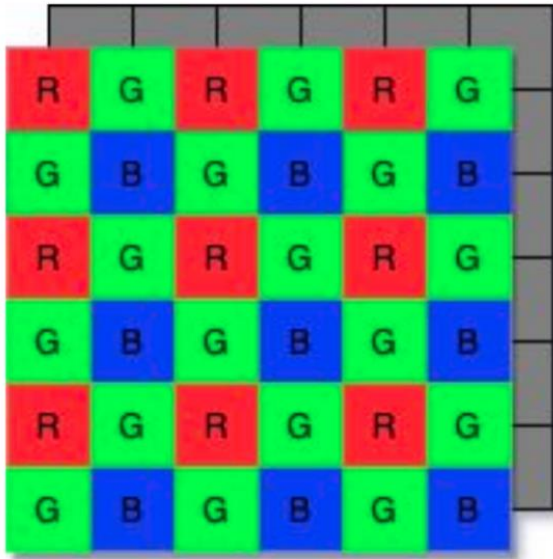
Original Photo



Corrected photo

The image signal processor can correct lens distortion using a model of the distorted frame

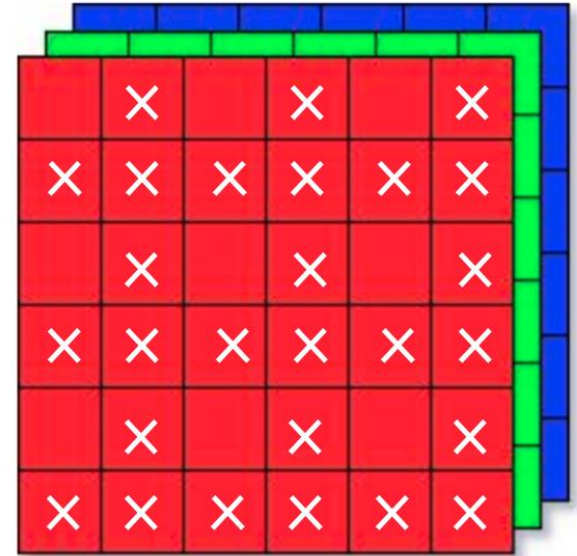
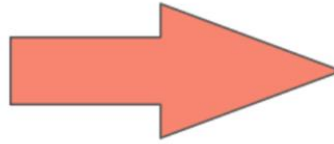
Color Image Sensor: Demosaicing



Bayer Image

Algorithmically “predict”
missing data (“X”s)

In each color plane (R, G, B)



Color Image

Example Design Parameter Calculations

Primary Design Parameters for Imaging System

Start With A Specification, go through loop

Iterate as needed

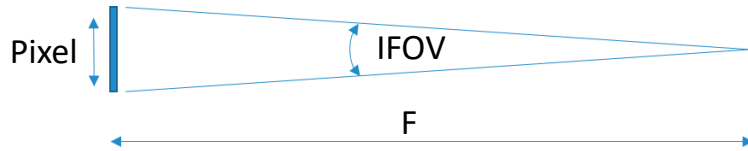
- What IFOV is appropriate for target at maximum range?
- What HFOV?
- What VFOV?
- What lens focal length/focal ratio?
- What pixel size?
- What speed objects will be in video?
 - Range/speed at range or angular velocity?
- How much tearing top to bottom is acceptable #pixels/frame?
- How much smearing is tolerable (# of pixels/exposure)?
- Which sensor (# pixels, qe, max frame rate)?
- Calculate minimum frame rate
- Calculate maximum exposure time
- Is time sufficient to attain target SNR?

Image Scale for Target at Range

- How many pixels should cover the smallest object of interest at the longest range?
 - To detect the object: assume a 2 x 2 cluster of pixels are needed
 - To identify the object perhaps at least 10 x 10 pixels? Better if 100 x 100: depends on nature of the object and how good of an ID you wish
- Assume we want at least 2 x 2 pixels to cover a 110 mm target at 100 meters away. What Pixel IFOV do we need?

Image Scale: Instantaneous FOV (IFOV)

What is the IFOV (“angular resolution”) of one pixel?



$IFOV = \sim \text{Pixel}/F$ (for small IFOV angular values measured in radians, watch for unit consistency)

Ex: Pixel = 4.4 microns/pixel (4.4 e-3 mm/pixel), f = 8 mm, find IFOV

$IFOV \sim 4.4 \text{ e-3 (mm/pixel)}/8 \text{ mm} = \mathbf{0.550 \text{ milliradians/pixel}}$

Basic IFOV, Field of View Calculations (IFOV = instantaneous field of view for one pixel)

From Trigonometry:

$$0.5 * \text{Target} / \text{Range} = \text{Tangent} (1/2 * \text{Target Spread})$$

$$\text{Target Spread} = 2 * \text{Arctan} (0.5 * \text{Target} / \text{Range})$$

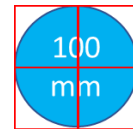
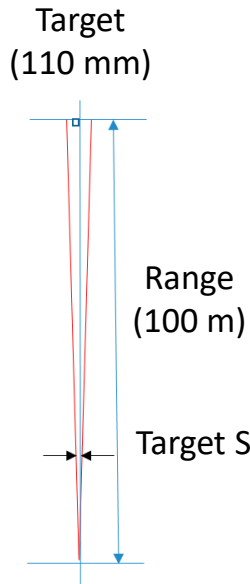
$$\text{Target Spread} = 2 * \text{Arctan} (0.5 * 110 \text{ mm} / 100 \text{ m})$$

$$\text{Target Spread} = 1.1 \text{ milliradian}$$

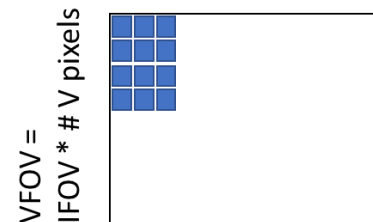
But for small angles the tangent of the angle \approx angle (in radians)

For two pixels to cover:

$$\text{Required Maximum Pixel IFOV} = 0.5 * \text{Target Spread} = 0.55 \text{ milliradian}$$



$$\text{HFOV} = \text{IFOV} * \# \text{ H pixels}$$



Rolling Shutter/Progressive Scan Artifacts

Design Specification Question:

How many pixels of shift (tear), top to bottom, are OK?

DSQ: What is the maximum projected horizontal or vertical velocity of moving objects (pixels/second) at range of interest?



Example Frame Rate Calculations

Maximum tolerable top to bottom shift: Assume 10 pixels

Maximum X velocity: Assume 500 pixels/sec

Time for 10 pixels: $10 \text{ pixels} / 500 \text{ pixels/sec} = 0.02 \text{ sec}$

Slowest frame rate = $1/0.02 \text{ sec} = 50 \text{ frames/sec}$

What object motion velocity is expected at range with lens attached (pixels/sec)?



What is minimum frame rate for video to meet maximum distortion limit?

Pixel Size Calculation

Assume horizontal motion of 500 pixels/sec at 100 meter range

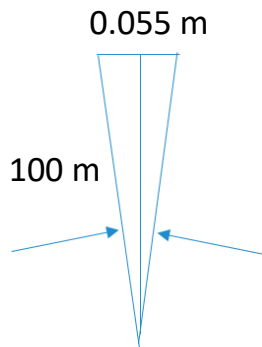
Assume 8 mm focal length

What is minimum pixel size to not exceed 500 pixels/sec horizontal motion?

$$100 \text{ km/hr} * 1 \text{ hr}/3600 \text{ sec} = 27.77 \text{ meters/sec} = 500 \text{ pixels / sec}$$

$$\text{At 100 meter range, 1 pixel} = 27.77/500 \text{ (meters/pixel)} = 0.055 \text{ meters/pixel}$$

Bus traveling at 100 km/hr at 100 meter range



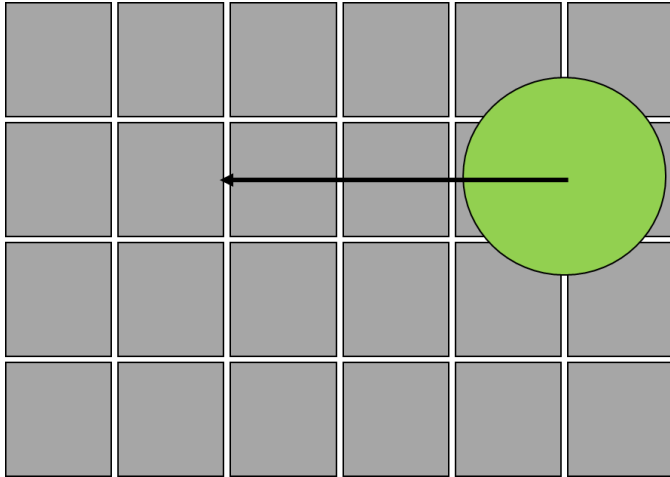
$$\text{Minimum IFOV} = 2 * \text{Arctan} (0.5 * \text{pixel coverage} / \text{range})$$

Minimum IFOV = 0.55 milliradians/pixel

$$2 * \text{Arctan} (0.5 * \text{Pixel size} / 8 \text{ mm}) = 0.00055 \text{ radians/pixel}$$

$$\text{Pixel size} = 16 \text{ mm} * \text{Tangent} (0.5 * 0.00055) = 4.4 \text{ microns (smallest size pixel)}$$

Motion Blur, Pixel Smear (generic photography issue)



Over how many pixels does the spot travel while the exposure occurs?

How much “motion blur” is acceptable?

How many milliradians per pixel is the IFOV?

How many pixels/second is the spot traveling?

How long is the exposure?
(probably main design parameter to adjust)



Motion Blur Calculations

(snap shutter)

Example:

Range = 100 meters

Speed at range = 10 meters/sec

10 mm focal length

2 micron pixel

What is max exposure time to limit smear to two pixels?

$IFOV = 2 * \text{Arctan} (1e-3 * 0.5 * 2 / 10) = 0.2 \text{ milliradians/pixel}$

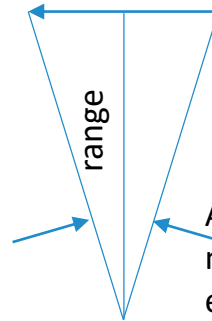
With a 2 pixel smear, we can tolerate 0.4 milliradians motion during exposure

Object velocity at range: $2 * \text{arctan} ((5 \text{ meters/sec}) / 100 \text{ meters}) = 100 \text{ milliradians/sec}$

We can tolerate 0.4 milliradians smear so max exposure time is:

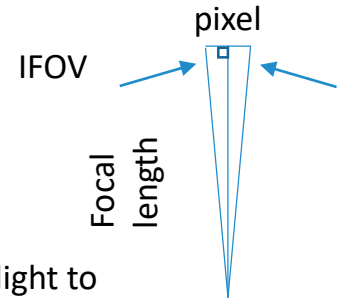
$0.4 \text{ milliradians} / 100 \text{ milliradians/sec} = \mathbf{4 \text{ milliseconds or } 250 \text{ frames/sec minimum frame rate}}$

Distance traveled during one exposure @ range



Angle swept by target motion during one exposure

$IFOV = 2 * \text{Arctan} (0.5 * \text{pixel size} / \text{focal length})$



Do you have enough light to get decent SNR at that speed?

Can you tolerate more smear to improve SNR?

Wrap Up: Key Discussion Points

- Discussed:
 - Image formation/optics & focusing a real lens (physical optics)
 - Optimum pixel size for monochrome vs color sensors vs optics used
 - CMOS image sensor operational basics: Transforming photons to digital images
 - Dynamic range and noise
 - Optical distortion, Motion artifacts & Shuttering tradeoffs
- Example design flow: image scale, pixel size, frame rate, motion blur tolerance

Camera Electronics Design Information:

<https://etron.com/rpc-dram-document/>

(see “Designing a 4K Video Camera” video)

Short Course on CMOS & CCD Image Sensors: Technology, Applications and Camera Design Methodology

[https://drive.google.com/file/d/1RlmY86vpYfgeEFq2JqBfrzGdRxjoG_bb/view?usp=drive link](https://drive.google.com/file/d/1RlmY86vpYfgeEFq2JqBfrzGdRxjoG_bb/view?usp=drive_link)





CMOS Image Sensors: Technology & Camera Design Introduction

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