Sensors

CSE 6367: Computer Vision

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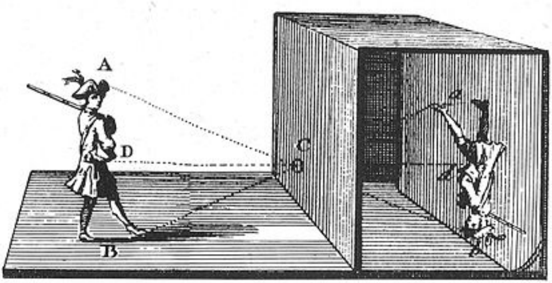
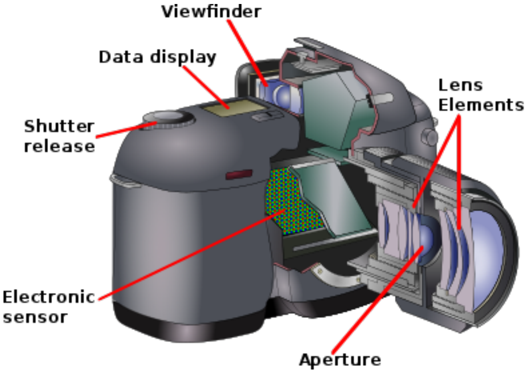
- Sensor data can be used in numerous applications (robotics/machine vision, factory automation, autonomous vehicles, etc.)
- The predominate sensor is the 2D digital camera, however low-cost 3D sensors have become increasingly available

The Pinhole Camera



The Digital Camera



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- After starting from one or more light sources, reflecting off one or more surfaces and passing through the camera's optics (lenses), light finally reaches the imaging sensor
- How are the photons arriving at the sensor converted into the digital (R,G,B) values that we observed when looking at a digital image?

The Digital Camera

- Light falling on an imaging sensor is picked up by an **active sensing area**, integrated for the duration of the exposure (expressed as the shutter speed in a fraction of a second, e.g. $\frac{1}{125}, \frac{1}{60}, \frac{1}{30}$), and then passed to a set of **sense amplifiers**

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- The two main sensors used in digital still and video cameras today are **charge-coupled device** (CCD) and **complementary metal oxide on silicon** (CMOS)

Charge-Coupled Device (CCD)

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- Then, during a *transfer* phase, the charges are transferred from well to well ("bucket brigade") until they are deposited at the sense amplifiers
- The sense amplifiers amplify the signal and pass it to an analog-to-digital converter (ADC)

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- Today, CMOS is used in most digital cameras

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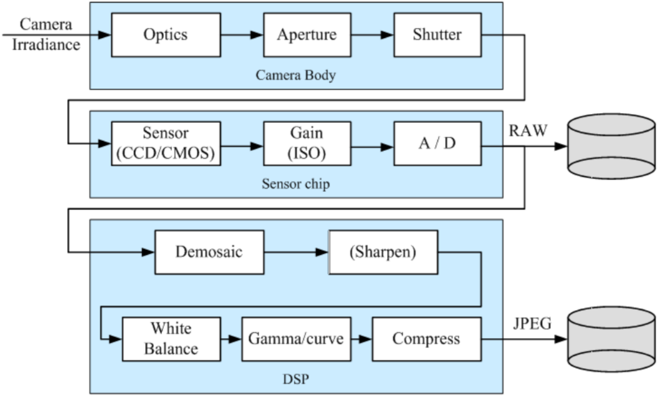
- Many of these performance parameters can be read from the EXIF flags embedded in a digital image while others can be obtained from the camera manufacturers' specification sheets or from camera review or calibration websites

Image Sensing Pipeline



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- Usually, a high shutter speed (less motion blur) makes subsequent analysis of the image easier

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- However, a smaller pitch means that each sensor has a smaller area and cannot accumulate as many photons; this makes it not as **light sensitive** and more prone to noise

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- However, this must be balanced with the need to place additional electronics between the active sense areas

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- When overall device size is not important, having a larger chip size is preferable since each sensor cell can be more photo-sensitive
- However, larger chips are more expensive to produce not only because fewer chips can be packed into each wafer, but also because the probability of a chip defect increases linearly with the chip area

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- In newer digital cameras, the user has some additional control over this gain through the **ISO setting** (typically expressed in ISO standard units such as 100, 200, or 400)

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- It is possible to estimate the **noise level function** (NLF) for a given image which predicts the overall noise variance at a given pixel as a function of its brightness

ADC Resolution

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- For most cameras, the number of bits quoted (e.g. 8 bits for compressed JPEG images) exceeds the actual number of usable bits

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- These operations include: color filter array (CFA) demosaicing, white point setting, mapping of the luminance values through a gamma function to increase the perceived dynamic range of the signal, etc.

Rangefinder Sensors

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- These methods include laser, radar, sonar, light detection and ranging (LIDAR), and ultrasonic

2D Laser Scanner

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- A laser scanner operates on the time of flight principle by sending out a laser pulse in a narrow beam and measuring the time taken by the pulse to be reflected off the surrounding objects and returned to the device

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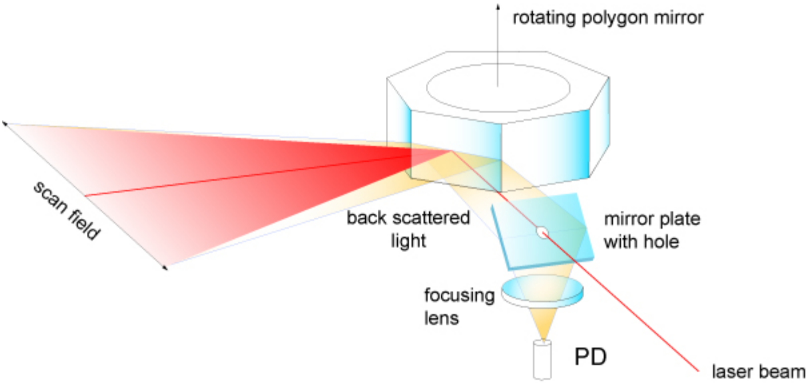

3D Sensors

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- There are two types of such sensors:
  - **Time-of-flight** (ToF) sensors measure depth by estimating the time delay from light emission to light detection
  - **Structured-light** sensors combine the projection of a light pattern with a standard 2D camera and that measure depth by triangulation

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- ToF sensor systems use either **pulsed-modulation** or **continuous wave modulation**

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- The arrival time must be detected very precisely
- To do this, very short light pulses with fast rise and fall times along with high optical power (lasers or laser diodes) are used

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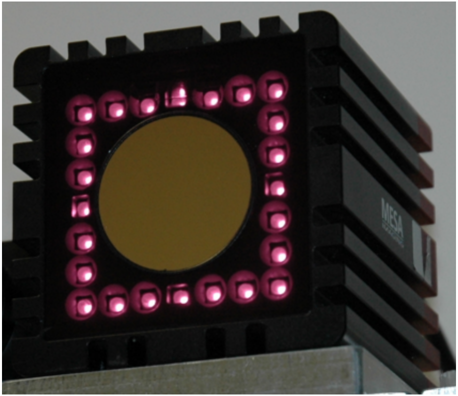
- Different shapes of signals are possible e.g. sinusoidal, square waves
- Cross-correlation between the received and sent signals allows phase estimation which is directly related to distance if the modulation frequency is known

Time-of-Flight Sensor



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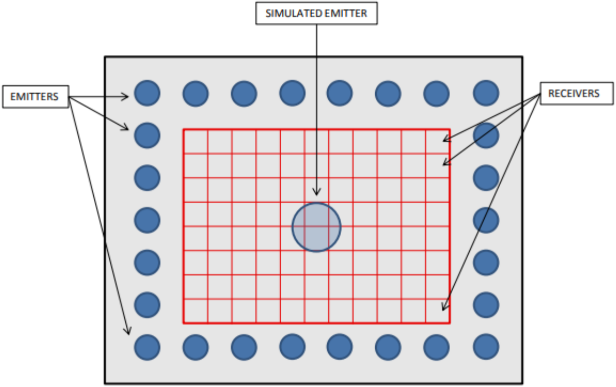

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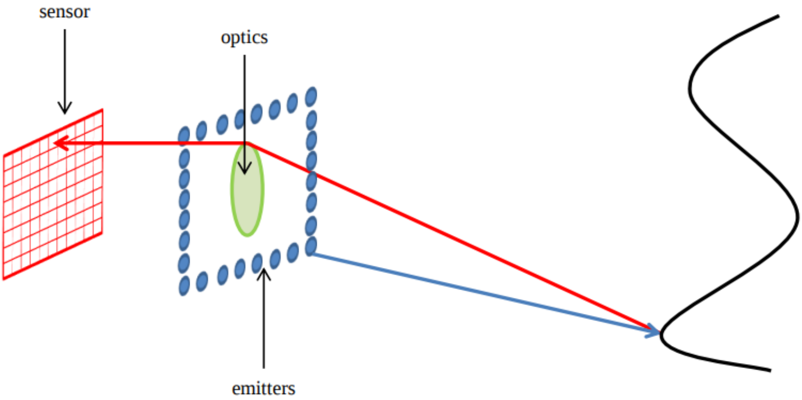

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- Structured light is the process of projecting a known pattern (often grids or horizontal bars) on to a scene
- By measuring the deformation of the pattern upon striking the surface of an object the depth information can be calculated

Structured-Light Sensor

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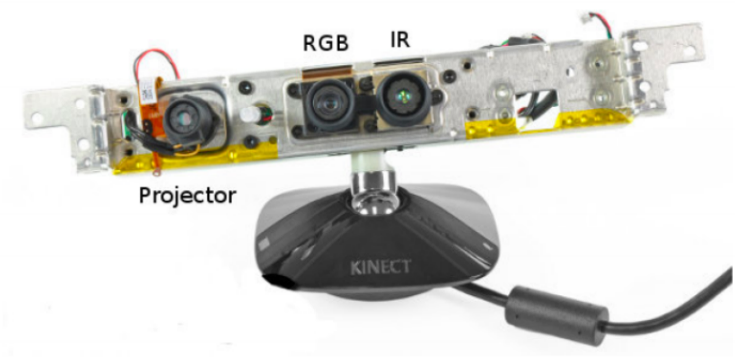
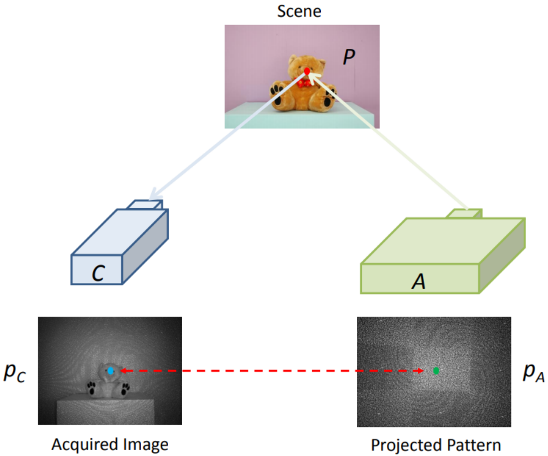
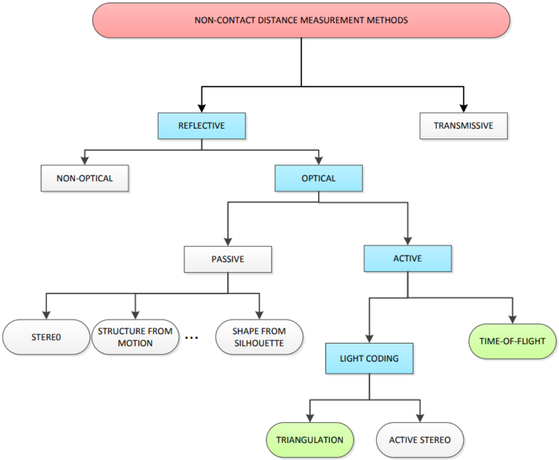


Matricial Active Triangulation



Recap: Distance Measurement Methods



Sampling and Aliasing

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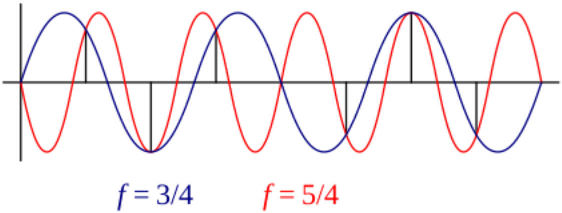
- What happens when a field of light impinging on the image sensor falls onto the active sense areas of the imaging chip?
- The photons arriving at each active cell are integrated and then digitized
- However, if the fill factor on the chip is small and the signal is not otherwise band-limited, then visually unpleasing **aliasing** can occur

Aliasing of a 1D Signal



- The blue sine wave at $f = 3/4$ and the red sine wave at $f = 5/4$ have the same digital samples when sampled at $f = 2$, i.e. they are **aliased**

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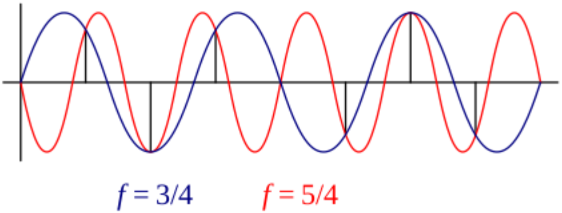

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- Why is this a bad effect?

Minimum Sampling Rate

- Shannon's sampling theorem shows that the minimum sampling rate required to reconstruct a signal from its samples must be at least twice the highest frequency

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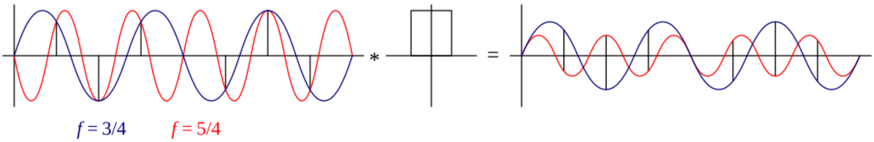
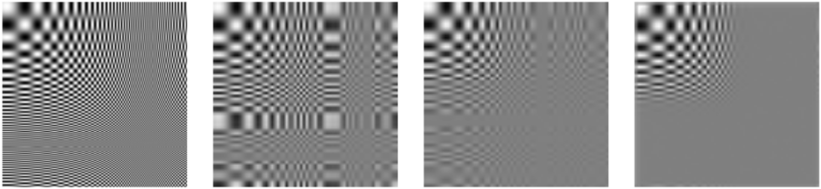
- The maximum frequency in a signal is known as the **Nyquist frequency** and the inverse of the minimum sampling frequency, $r_s = 1/f_s$, is known as the **Nyquist rate**

Filtering of a 1D Signal



- Even after convolution with a 100% fill factor box filter the two signals, while no longer of the same magnitude, are still aliased in the sense that the sampled red signal looks like an inverted lower magnitude version of the blue signal

Aliasing of a 2D Signal



(a) (b) (c) (d)

- (a) original full-resolution image; (b) downsampled 4 x with a 25% fill factor box filter; (c) downsampled 4 x with a 100% fill factor box filter; (d) downsampled 4 x with a high-quality 9-tap filter

Predicting the Amount of Aliasing

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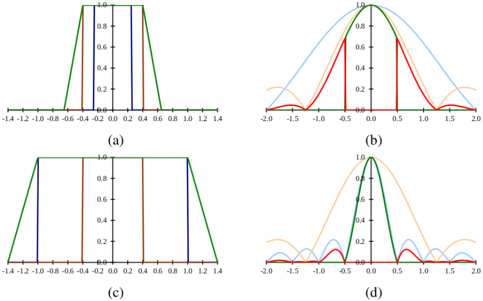
- The best way to predict the amount of aliasing an imaging system will produce is to estimate the **point spread function** (PSF) which represents the response of a particular pixel sensor to an ideal point light source
- If we know the blur function of the lens and the fill factor (sensor area shape and spacing) for the imaging chip, then we can convolve these to obtain the PSF

Sample Point Spread Functions



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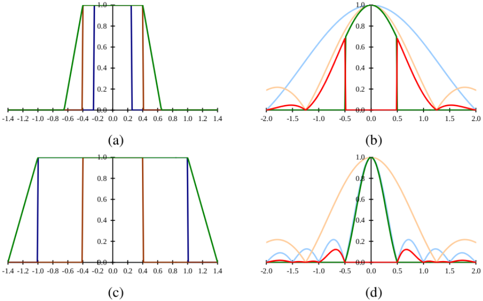

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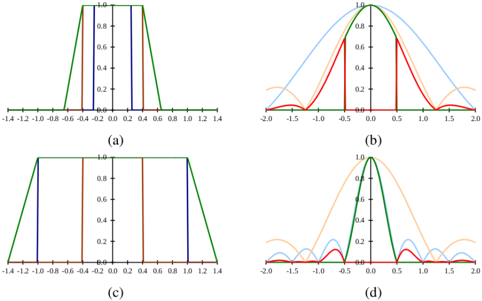

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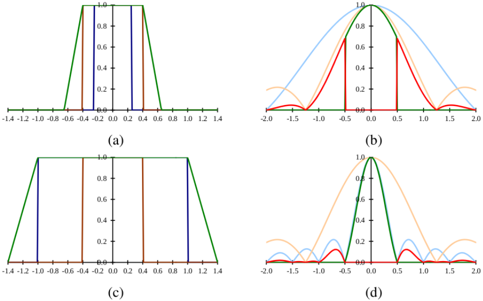

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- The Fourier response of the PSF is shown in (b) and (d)

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- 3D sensors are becoming increasingly popular as a low-cost alternative to complicated stereo vision systems
- Aliasing effects both the quality of the image and the ability to reconstruct the original signal