Lecture 14: Sensors and Actuators

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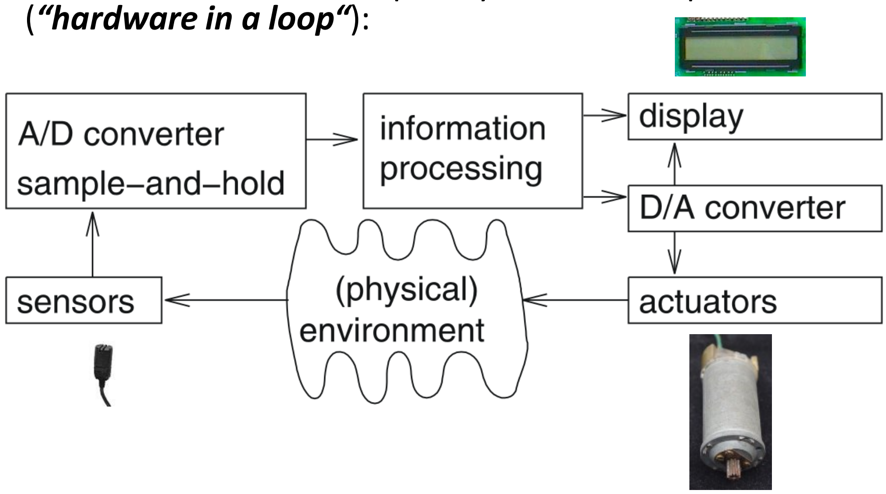
Some Slides from Edward Lee and Peter Marwedel

Review

- IO Hardware and Mechanisms
  - Connecting Cyber and physical worlds: practical issues
  - Interrupts and concurrency
  - Modeling an interrupt controller

CPS & ES Hardware

- CPS & ES hardware is frequently used in a loop (***"hardware in a loop"***):



What is A Sensor? What is An Actuator?

- A sensor is a device that measures a physical quantity
  - Input / "Read from physical world"
- Many physical effects used for constructing sensors
  - law of induction (gen. of voltages in a magnetic field)
  - light-electric effects

- An actuator is a device that modifies a physical quantity
  - Output / "Write to physical world"
- Huge variety of actuators and output devices

Sensors and Actuators – The Bridge between the Cyber and the Physical

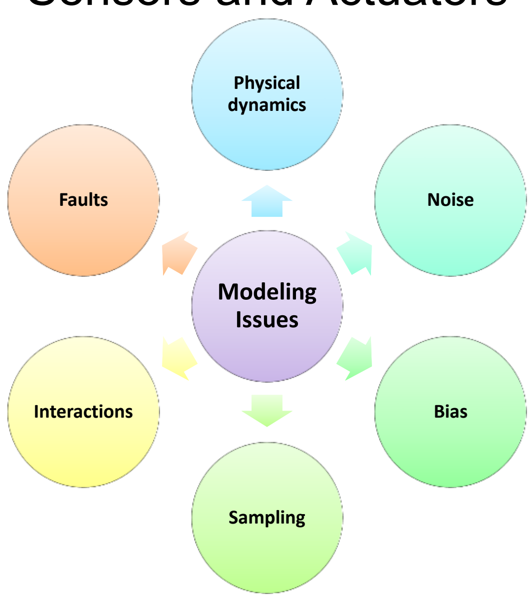
Sensors

- Cameras
- Accelerometers
- Gyroscopes
- Strain gauges
- Microphones
- Magnetometers
- Radar/Lidar
- Chemical sensors
- Pressure sensors
- Switches
- ...

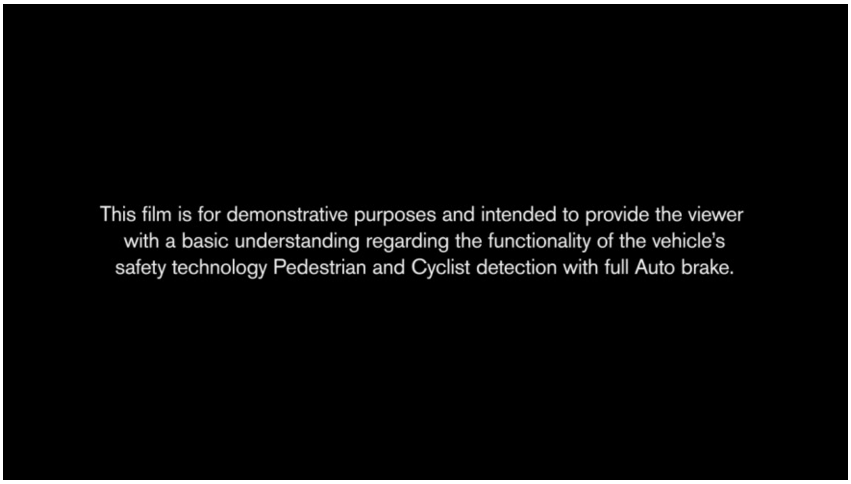
Actuators

- Motor controllers
- Solenoids
- LEDs, lasers
- LCD and plasma displays
- Loudspeakers
- Switches
- Valves
- ...

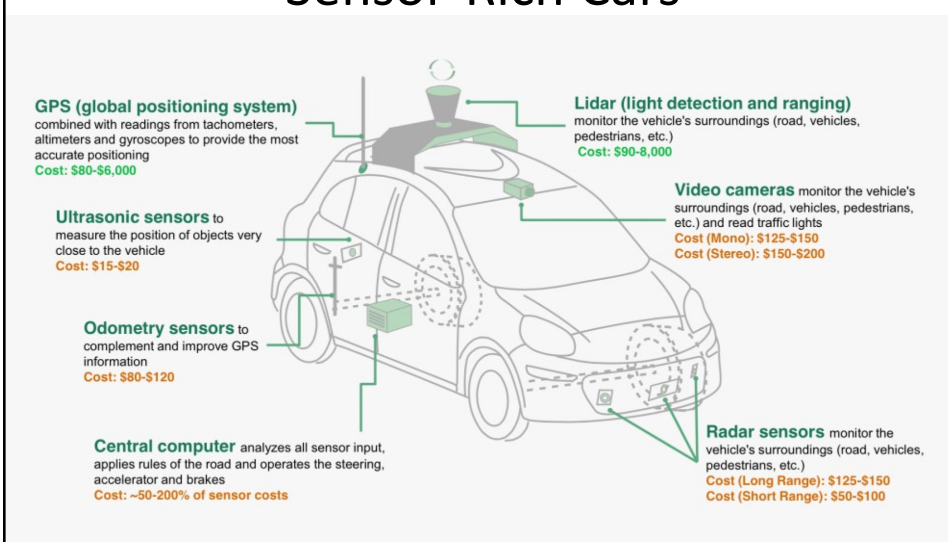
Sensors and Actuators



Safe Cars

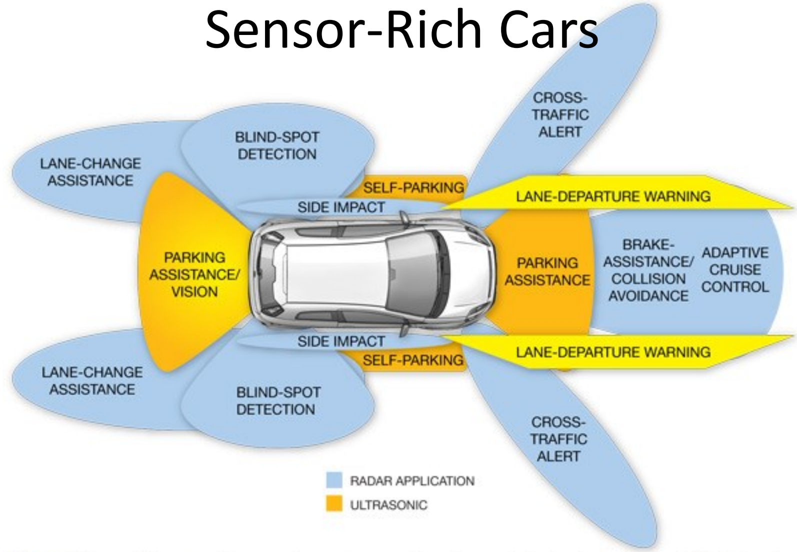


Sensor-Rich Cars



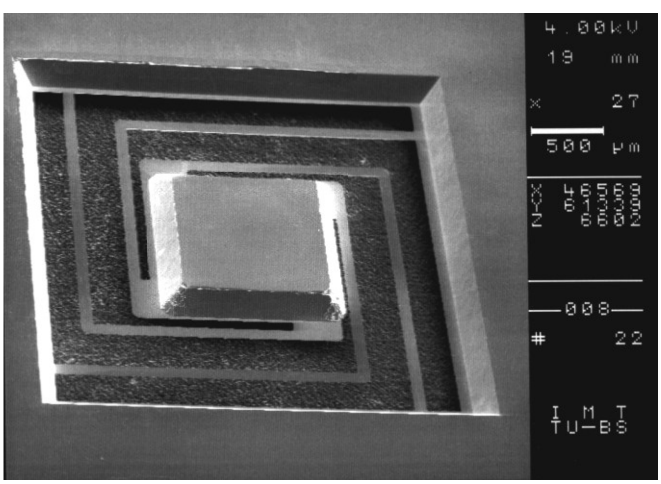
- Source: Wired Magazine

Sensor-Rich Cars



- Source: Analog Devices

Example: Acceleration Sensor



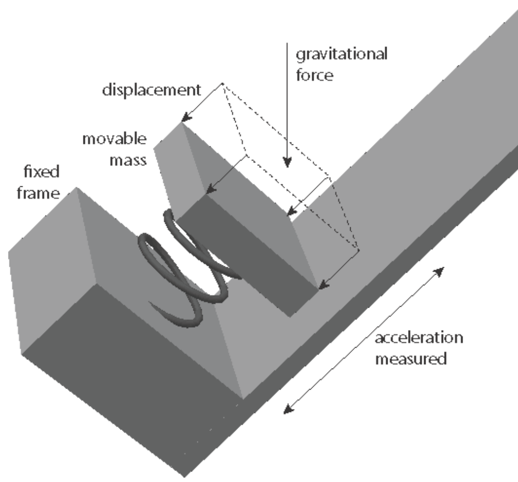
- Courtesy & ©: S. Bütgenbach, TU Braunschweig

Accelerometers

The most common design measures the distance between a plate fixed to the platform and one attached by a spring and damper. The measurement is typically done by measuring capacitance.

Usages:

- Navigation
- Orientation
- Drop detection
- Image stabilization
- Airbag systems



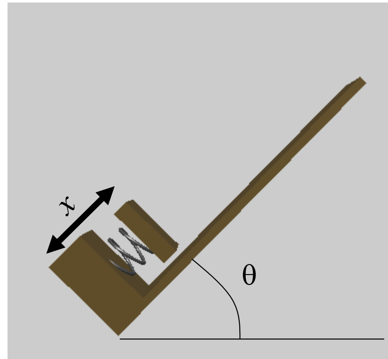
Spring-Mass-Damper Accelerometer

By Newton’s second law, F=ma.

For example, F could be the Earth’s gravitational force.

The force is balanced by the restoring force of the spring.

Measuring tilt



Component of gravitational force in the direction of the accelerometer axis must equal the spring force:

$$Mg\sin(\theta) = k(p - x(t))$$

Given a measurement of x, you can solve for θ, up to an ambiguity of π.

Difficulties Using Accelerometers

- Separating tilt from acceleration
- Vibration
- Nonlinearities in the spring or damper
- Integrating twice to get position: Drift

$$p(t) = p(0) + \int_0^t v(\tau)d\tau,$$

$$v(t) = v(0) + \int_0^t x(\tau)d\tau.$$

- Position is the integral of velocity, which is the integral of acceleration.
- Bias in the measurement of acceleration causes position estimate error to increase quadratically.

Inertial Navigation Systems

Dead reckoning plus GPS.

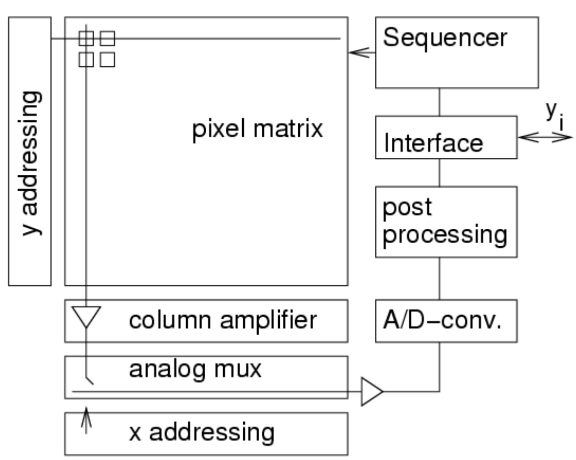
Combinations of:
- GPS (for initialization and periodic correction).
- Three axis gyroscope measures orientation.
- Three axis accelerometer, double integrated for position after correction for orientation.

Typical drift for systems used in aircraft have to be:
- 0.6 nautical miles per hour
- tenths of a degree per hour

Good enough? It depends on the application!

Example: CMOS image sensors

Based on standard production process for CMOS chips, allows integration with other components.



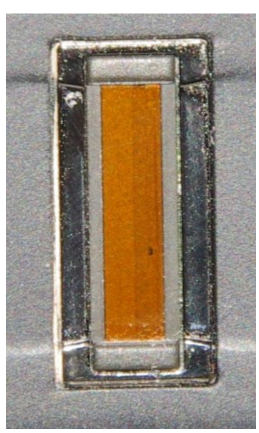
Comparison CCD/CMOS sensors

Property	**CCD**	**CMOS**
Technology optimized for	Optics	VLSI technology
Technology	Special	Standard
Smart sensors	No, no logic on chip	Logic elements on chip
Access	Serial	Random
Size	Limited	Can be large
Power consumption	Low	Larger
Video mode	Possibly too slow	ok
Applications	Situation is changing over the years	

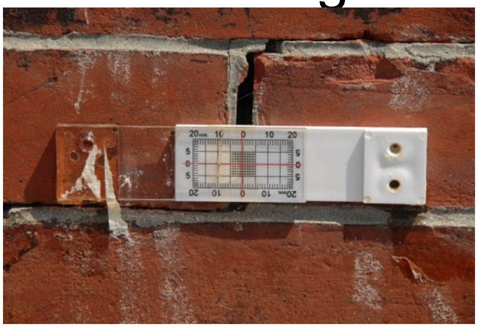
See also B. Diericks: CMOS image sensor concepts. Photonics West 2000 Short course (Web)

Example: Biometrical Sensors

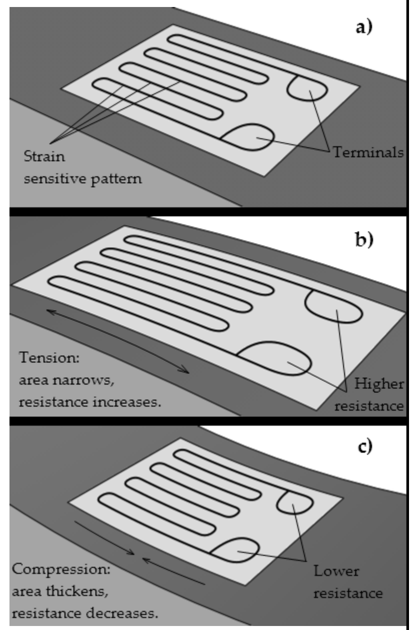
e.g.: Fingerprint sensor



Strain Gauges



Mechanical strain gauge used to measure the growth of a crack in a masonry foundation. This one is installed on the Hudson-Athens Lighthouse. Photo by Roy Smith, used with permission.



Images from the Wikipedia Commons

Models of Sensors and Actuators

- Linear and affine models
- Range
- Dynamic range
- Quantization
- Noise
- Sampling
- Harmonic distortion

Sensor Calibration (Same for Actuators)

- Assume a physical quantity $x(t)$ is reported by the sensor to have value $f(x(t))$
- f is linear if there exists a proportionality constant $a \in R$ such that

$$f(x(t)) = ax(t)$$

- f is affine if there exists a proportionality constant $a \in R$ and a bias $b \in R$ such that

$$f(x(t)) = \underbrace{a}_{\text{Sensitivity}}x(t) + \underbrace{b}_{\text{Bias}}$$

Range and Dynamic Range

- Sensors/actuators normally have an operating range (L,H)
  - Outside of that they will saturate
- An affine function model is augmented:

$$f(x(t)) = \begin{cases} ax(t)+b & \text{if } L \leq x(t) \leq H \\ aH+b & \text{if } x(t) > H \\ aL+b & \text{if } x(t) < L, \end{cases}$$

Example: Look at ADXL330 accelerometer datasheet

- The precision p of a digital sensor: smallest absolute difference between two values of a physical quantity whose sensor readings are distinguishable.
- Dynamic range:

$$D = \frac{H-L}{p}$$

In decibels:

$$D_{dB} = 20\log_{10}\left(\frac{H-L}{p}\right)$$

Analog Devices ADXL330 Data Sheet

SPECIFICATIONS

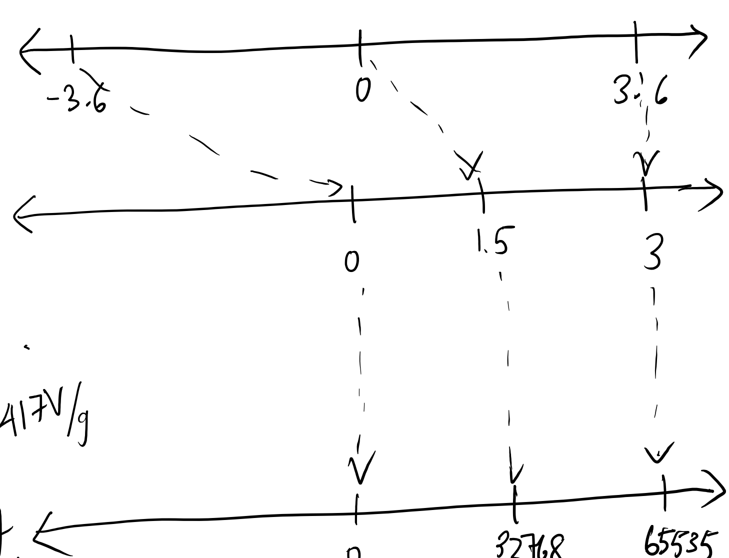
$T_A = 25°C$, $V_S = 3$ V, $C_X = C_Y = C_Z = 0.1$ μF, acceleration = 0 *g*, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

Table 1.

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		*g*
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Inter-Axis Alignment Error			±0.1		Degrees
Cross Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	$V_S = 3$ V	270	300	330	mV/*g*
Sensitivity Change Due to Temperature[3]	$V_S = 3$ V		±0.015		%/°C
ZERO *g* BIAS LEVEL (RATIOMETRIC)	Each axis				
0 *g* Voltage at X_{OUT}, Y_{OUT}, Z_{OUT}	$V_S = 3$ V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		mg/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			280		μg/√Hz rms
Noise Density Z_{OUT}			350		μg/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency			5.5		kHz

Acc
x (g)

Voltage readout (V)
F(x)



$F(x) = ax + b$

$b = 1.5$

$a = \frac{1.5}{3.6} = 0.417 V/g$

ADC - 16 bit

$[0, 3V] \to [0, 2^{16} - 1]$

Quantization

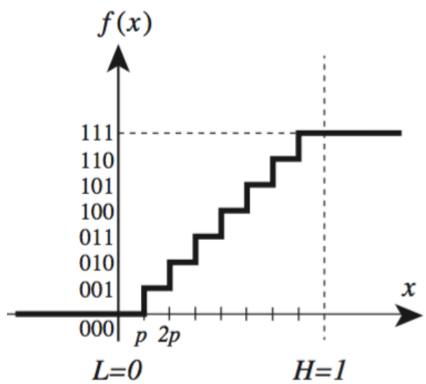
- An *n*-bit digital sensor picks one of 2^n values for a physical quantity.
- Precision:

$$p = \frac{(H - L)}{2^n}$$

- Dynamic range:

$$D_{dB} = 20\log_{10}\left(\frac{H-L}{p}\right) 20\log_{10}(2^n)$$
$$= 20n\log_{10}(2) \approx 6n\ dB$$

- 6 decibels of dynamic range per bit



f: sensor distortion function

Noise

- Undesired part of the signal

  f(x(t)) = x(t) + n(t)

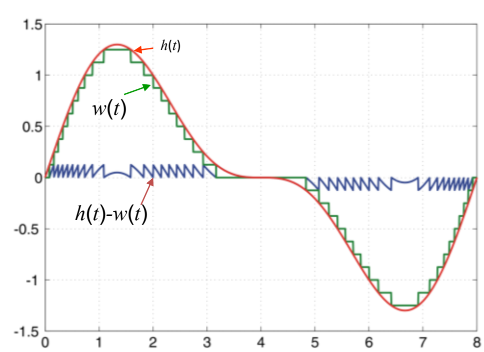
- Root mean square (RMS) of the noise

$$N = \lim_{T\to\infty}\sqrt{\frac{1}{2T}\int_{-T}^{T}(n(\tau))^2 d\tau}.$$

- Signal to noise ratio (SNR, in decibels)

$$SNR_{dB} = 20\log_{10}\left(\frac{X}{N}\right)$$

- Quantization noise:

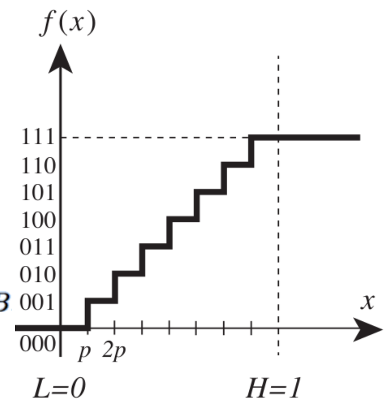


Example: Quantization Noise of a 3-bit Digital Sensor

$$X = \sqrt{\int_0^1 x^2 dx} = \frac{1}{\sqrt{3}}$$

$$N = \sqrt{\int_{-1/8}^{0} 8n^2 dn} = \sqrt{\frac{1}{3 \cdot 64}} = \frac{1}{8\sqrt{3}}$$

$$SNR_{dB} = 20\log_{10}\left(\frac{X}{N}\right) = 20\log_{10}(8) \approx 18dB$$

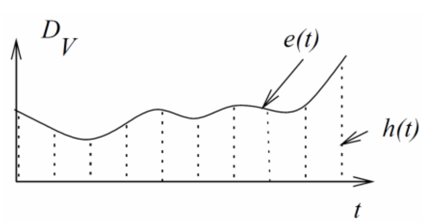


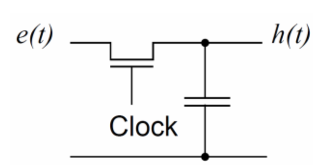
Sampling

- Discretizing a continuous-time physical quantity
- For uniform signal sampling with sampling interval *T*

  $\forall n \in Z, \; s(n) = f(x(nT))$

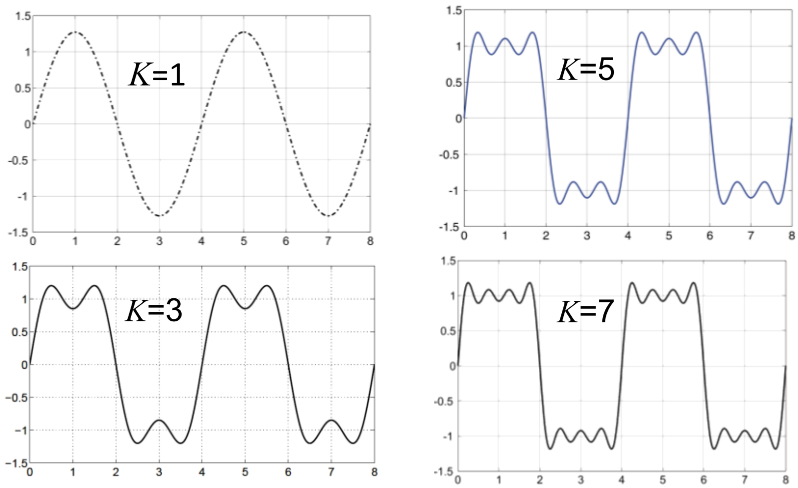
What is a good *T*?





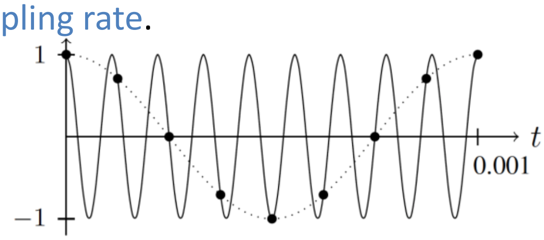
Approximation of a Square Wave

$$e'_K(t) = \sum_{k=1,3,5,..}^{K} \frac{4}{\pi k} \sin\left(\frac{2\pi\, t}{p_k}\right)$$ with $\forall k$: $p_k = p_1/k$, $p_1=4$



Aliasing

- A high frequency sinusoid sampled at a low rate looks just like a low frequency sinusoid
- Nyquist criterion (sampling theory)
  - Aliasing can be avoided if we restrict the frequencies of the incoming signal to less than half of the sampling rate.



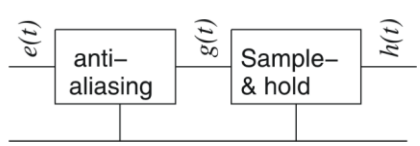
Aliasing in Computer Graphics

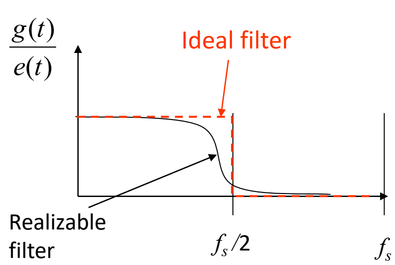
Sub-sampled, no filtering

http://en.wikipedia.org/wiki/Image:
Moire_pattern_of_bricks_small.jpg

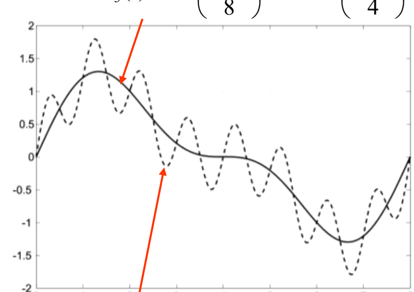
Anti-Aliasing Filter

- A filter is needed to remove high frequencies





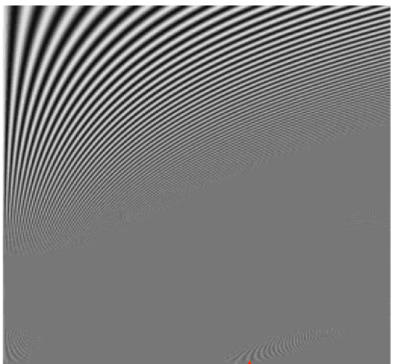
$$e_3(t) = \sin\left(\frac{2\pi t}{8}\right) + 0.5\sin\left(\frac{2\pi t}{4}\right)$$



$$e_4(t) = \sin\left(\frac{2\pi t}{8}\right) + 0.5\sin\left(\frac{2\pi t}{4}\right) + 0.5\sin\left(\frac{2\pi t}{1}\right)$$

Aliasing in Computer Graphics

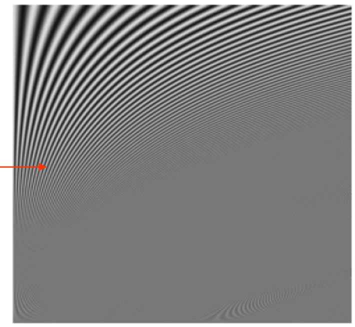
- Original (pdf screen copy)



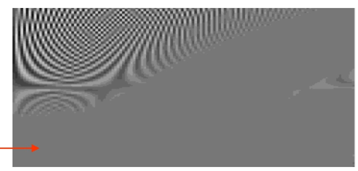
http://www.niirs10.com/Resources/Reference Documents/Accuracy in Digital Image Processing.pdf

Impact of rasterization

Filtered & sub-sampled



Sub-sampled, no filtering



Harmonic Distortion

- A form of nonlinearity that occurs even within the operating range of sensors and actuators
  - sensitivity is not constant and depends on the magnitude of the signal
- Modeled by powers of the physical quantity
  - Second harmonic distortion is a dependence on the square of the physical quantity

$$f(x(t)) = ax(t) + b + d_2(x(t))^2$$

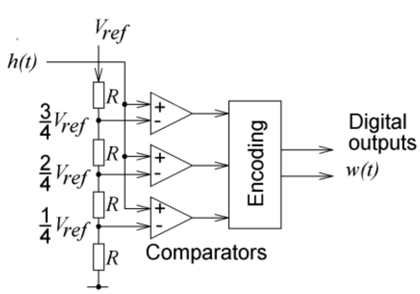
- The importance of harmonic distortion *depends on the application*

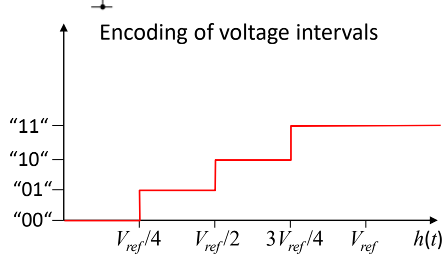
Signal Conditioning

- Use frequency selective filtering to remove noise and harmonic distortion
- Relies on Fourier theory to filter-out undesired frequencies
- Example: An accelerometer measures orientation plus vibration of a slowly-rotating object
  - Solution: Filter-out high-frequency vibration

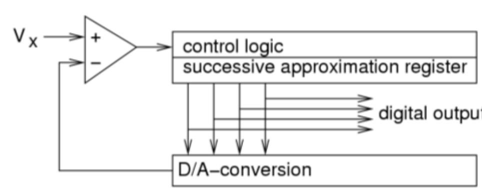
A/D Converters

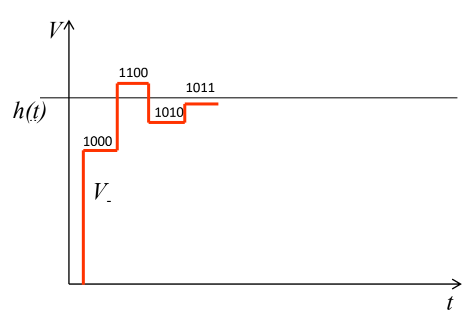
Flash



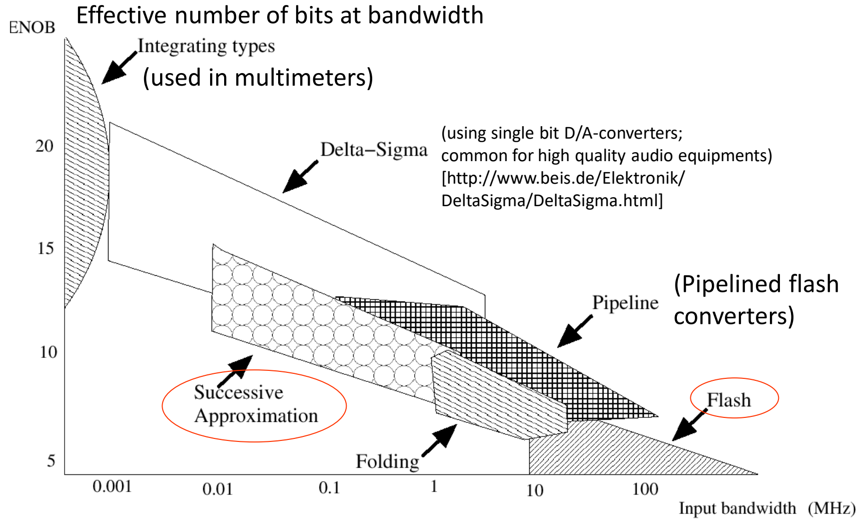


Successive Approximation





Application Areas for Different A/D Converters



[Gielen et al., DAC 2003]

Design Issues with Sensors

Calibration
- Relating measurements to the physical phenomenon
- Can dramatically increase manufacturing costs

Nonlinearity
- Measurements may not be proportional to physical phenomenon
- Correction may be required
- Feedback can be used to keep operating point in the linear region

Sampling
- Aliasing
- Missed events

Noise
- Analog signal conditioning
- Digital filtering
- Introduces latency

Failures
- Redundancy (sensor fusion problem)
- Attacks (e.g. Stuxnet attack)

Next Lecture

- Examples of Sensors
- Read chapter 3 of Pan & Zhu