SENSORS AND ACTUATORS

Sistemas Embutidos

[dcc]

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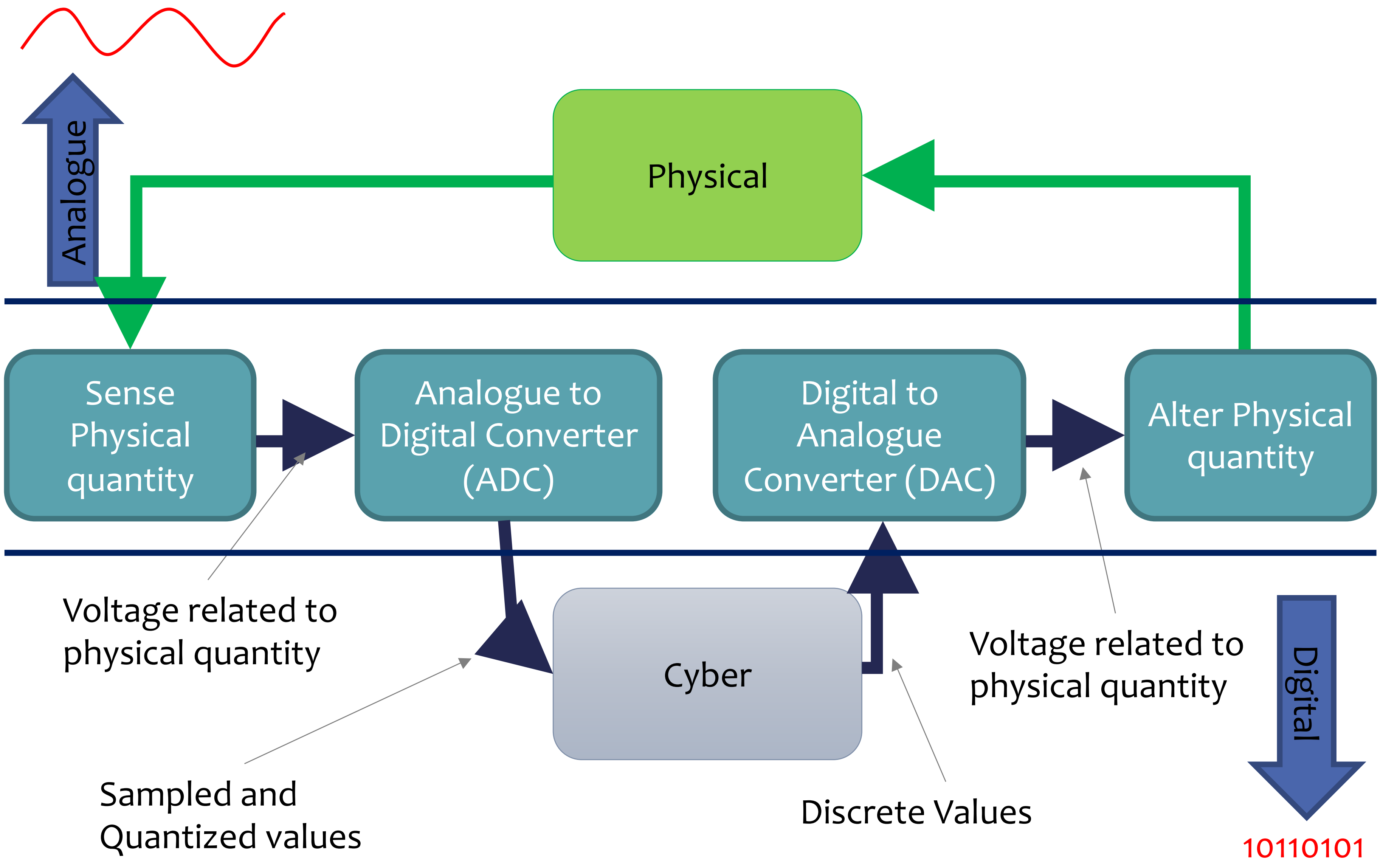
References

- Slides are from Edward A. Lee & Sanjit Seshia, UC Berkeley, EECS 149 Fall 2013
  -

Bridges between physical and cyber worlds



Buzzwords, name trends

- Internet of Things (IoT),
- Industry 4.0, the Industrial Internet also Industrial IoT (IIoT)
- Internet of Everything,
- Smarter Planet,
- TSensors (Trillion Sensors),
- The Fog (like The Cloud, but closer to the ground).
- Machine-to-Machine (M2M),

Linear and affine Models

- Physical quantity: $x(t)$
- Sensor reported: $\mathrm{f}\big(x(t)\big), f\colon\ \mathbb{R} \to \mathbb{R}$

- Linear:

$$\mathrm{f}\big(\mathrm{x}(t)\big) = a \cdot x(t)$$

- Affine:

$$\mathrm{f}\big(\mathrm{x}(t)\big) = a \cdot x(t) + b$$

- $a \in \mathbb{R}$ proportionality constant (sensitivity)
- $b \in \mathbb{R}$ bias constant

Range

- Outside the range affine model is no longer valid

$$f\big(x(t)\big) = \begin{cases} a \cdot x(t) + b & if\ L \leq x(t) \leq H \\ a \cdot H + b & if\ x(t) > H \\ a \cdot L + b & if\ x(t) < L \end{cases}$$

- $L, H \in \mathbb{R}, L < H$
  - *Low and High end of the sensor range*

- Non-linearity

Dynamic Range

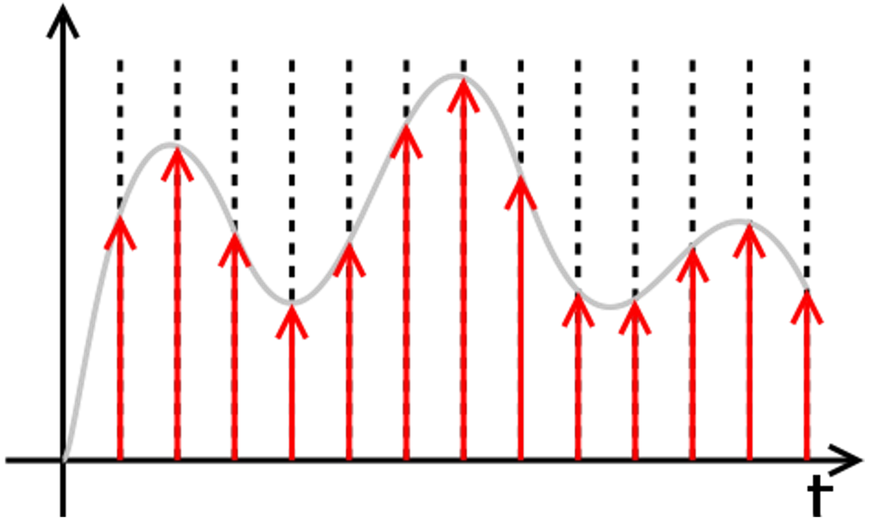
- p: precision of a sensor
  - *the smallest absolute difference between two values of a physical quantity whose sensor readings are distinguishable.*
- The dynamic range $D \in \mathbb{R}_{>0}$ of a digital sensor is the ratio:

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

- Measured in decibels:

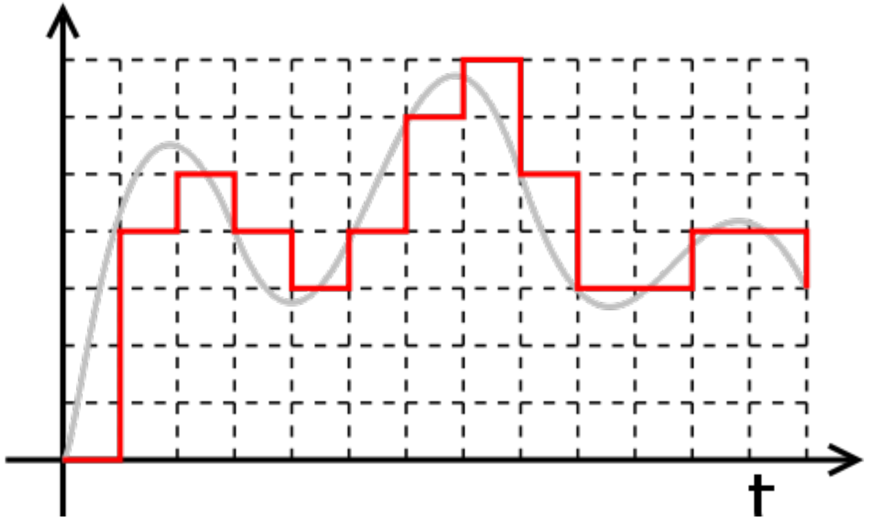
$$D_{dB} = 20 \cdot log_{10}\left(\frac{H - L}{p}\right)$$

Quantization



Sampling

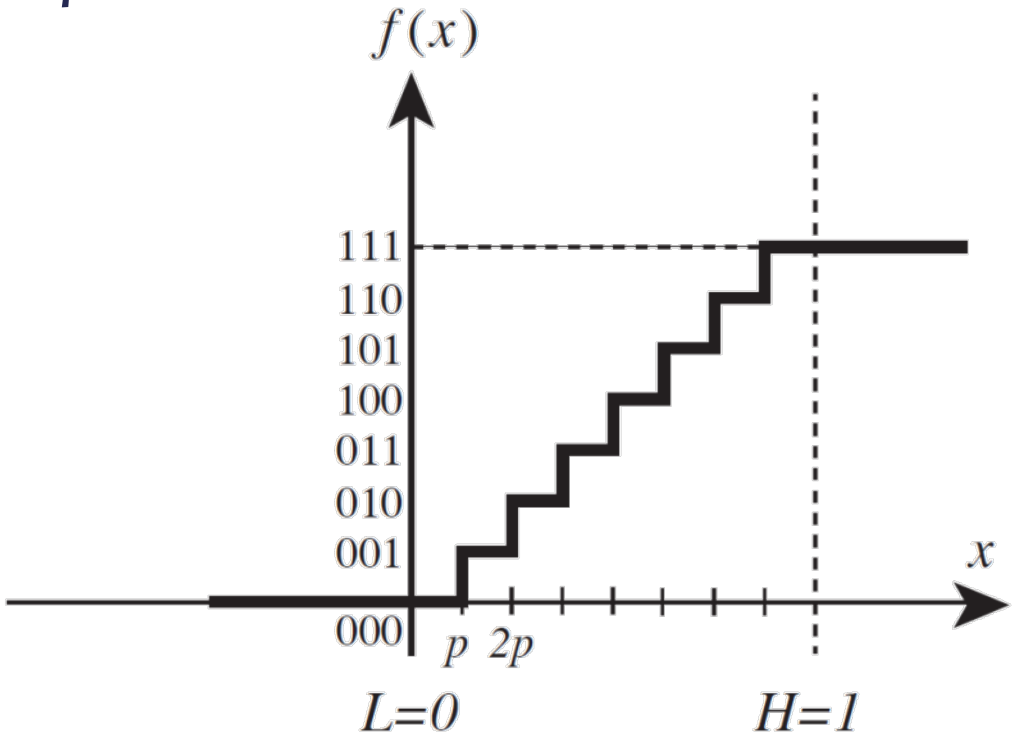
Images from Wikipedia



Quantization at the sampling times

Quantization II

- Digital sensor represents in n bits the physical quantity
  - 2^n *different values can be represented*



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

$$= 20 \cdot log_{10}(2^n)$$
$$= 20 \cdot n \cdot log_{10}(2)$$
$$\approx 6 \cdot n \text{ dB}$$

Noise

- Additive model:

$$f\big(x(t)\big) = x(t) + n(t)$$

- $n(t)$, noise signal
- $SNR_{dB} = 20 \cdot log_{10}\left(\frac{X}{N}\right)$
  - *Signal to noise ratio*

Noise & Signal Conditioning

- Parseval's theorem relates energy (or power) in a signal in time and frequency domains. For a finite energy signal x, the energy is:

$$\int_{-\infty}^{\infty}\left(x(t)\right)^2 dt = \frac{1}{2\pi}\int_{-\infty}^{\infty}|X(\omega)|^2 d\omega$$

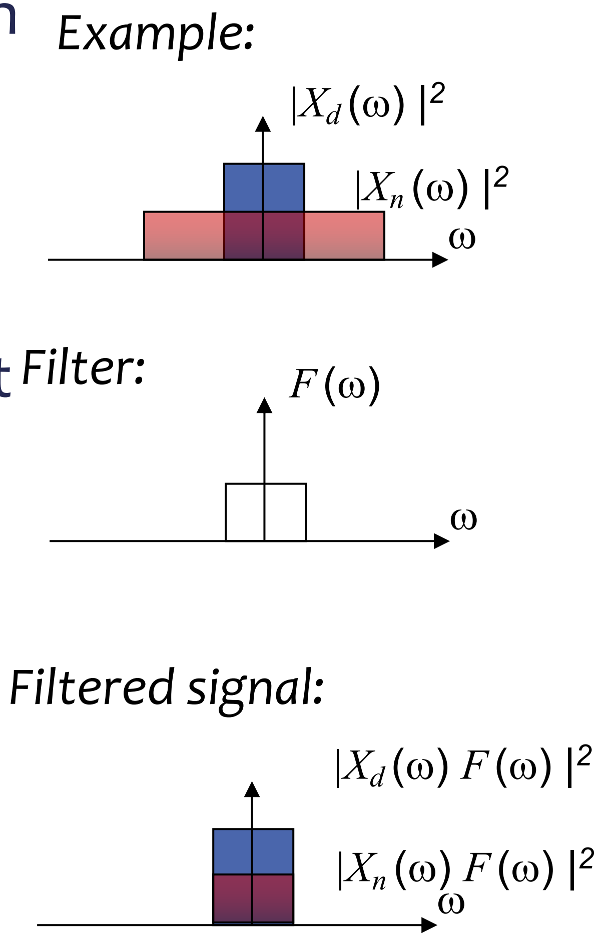
- Where X is the Fourier transform. If there is a desired part x_d and an undesired part (noise) x_n,

$$x(t) = x_d(t) + x_n(t)$$

- Then

$$X(\omega) = X_d(\omega) + X_n(\omega)$$

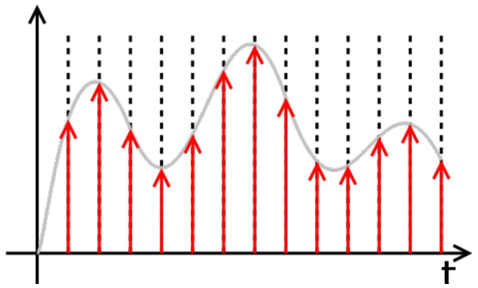
- If x_d is a narrowband signal and x_n is a broadband signal, then signal to noise ratio (SNR) can be greatly improved by filtering.



Sampling

- $\forall\, n \in \mathbb{Z},\ \ s(n) = f\big(x(nT)\big)$
  - T: *sampling interval*

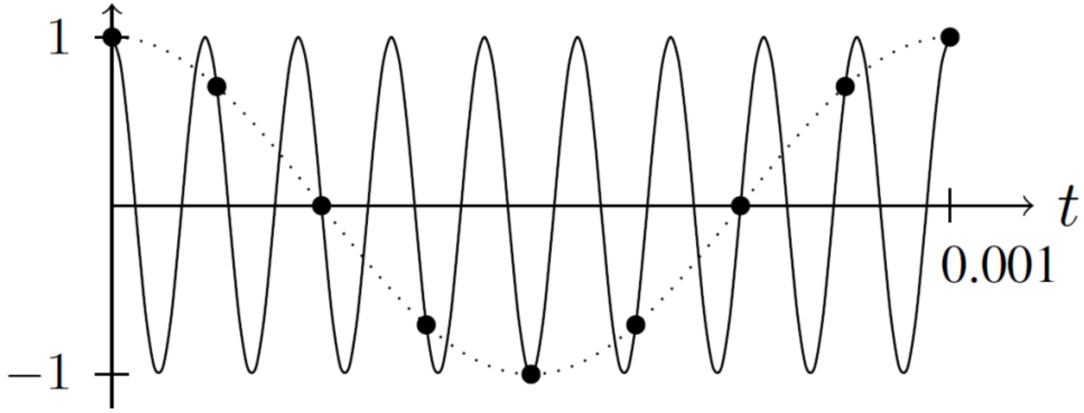
- Faster sampling ➔ more cost to provide more bits
  - *With filtering/signal conditioning can reduce noise*
  - *faster ADCs typically produce fewer bits ➔ higher quantization error or smaller range*



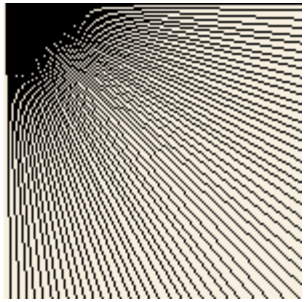
Aliasing

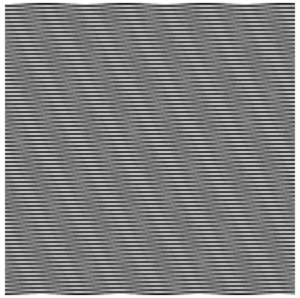
- Sampled data is vulnerable to aliasing, where high frequency components masquerade as low frequency components.

- Careful modeling of the signal sources and analog signal conditioning or digital oversampling are necessary to counter the effect.



A high frequency sinusoid sampled at a low rate looks just like a low frequency sinusoid.





Digitally sampled images are vulnerable to aliasing as well, where patterns and edges appear as a side effect of the sampling. Optical blurring of the image prior to sampling avoids aliasing, since blurring is spatial low-pass filtering.

Nyquist-Shannon sampling theorem.

- Samples at rate $R = 1/T$ uniquely define a continuous-time signal that is a sum of sinusoidal components with frequencies less than $R/2$
  - *T is the period of sampling*

➔ ***Sample at twice the most rapid expected variation***

- Example: telephony
  - *Speech does not require frequencies $\leq 4\ KHz$*
  - *Sample at 8 KHz*

Harmonic distortion

- Sensitivity of the sensor or actuator is not constant and depends on the magnitude of the signal.
- Second harmonic distortion is a dependence on the square of the physical quantity.

$$\mathrm{f}\big(\mathrm{x}(t)\big) = a \cdot x(t) + b + d_2 \cdot \big(x(t)\big)^2$$

- d_2: amount of second harmonic distortion

This affects extracting velocity from accelerometer data

EXAMPLES OF DEVICES

(Extra – not for exam)

Bridges between physical and cyber worlds

- Cameras
- Accelerometers
- Rate gyros
- Strain gauges
- Microphones
- Magnetometers
- Radar/Lidar
- Chemical sensors
- Pressure sensors
- Switches
- …

Sensors

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

Actuators

Modelling Issues:

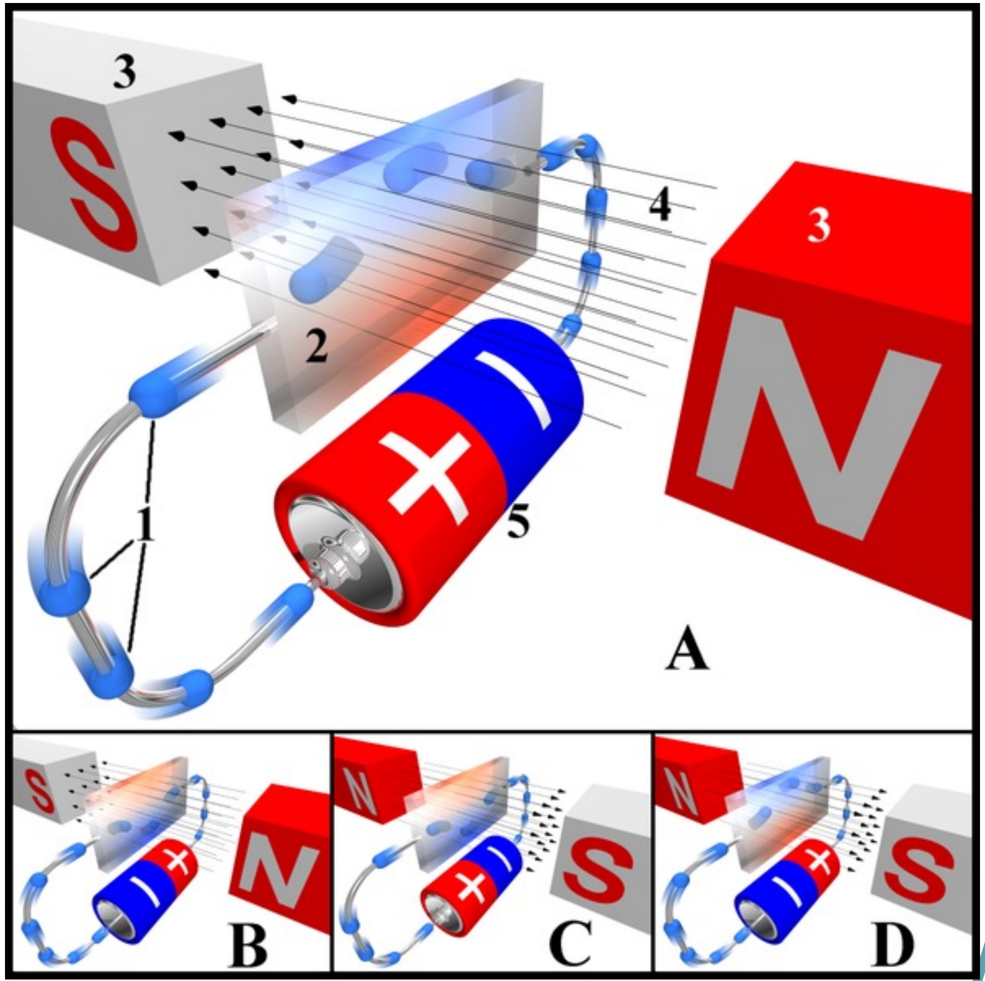
- Physical dynamics
- Noise
- Bias
- Sampling
- Interactions

Magnetometers

Edwin Hall discovered this effect in 1879.

- A very common type is the Hall Effect magnetometer.
- Charge particles (electrons, 1) flow through a conductor (2) serving as a Hall sensor. Magnets (3) induce a magnetic field (4) that causes the charged particles to accumulate on one side of the Hall sensor, inducing a measurable voltage difference from top to bottom.
- The four drawings at the right illustrate electron paths under different current and magnetic field polarities.

Image source: Wikipedia Commons

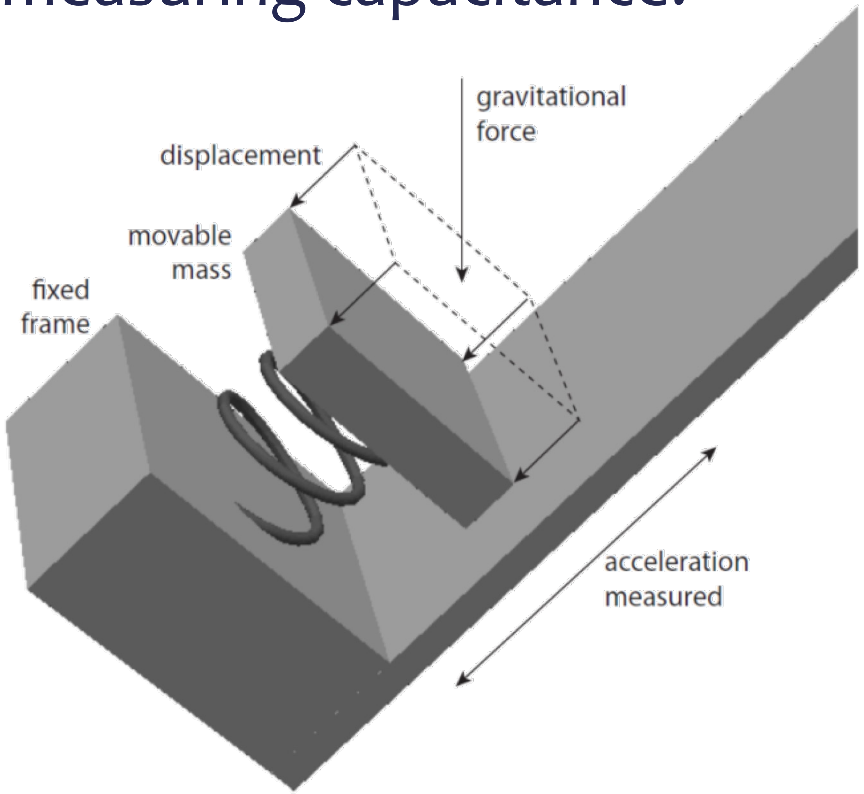


Accelerometers

- 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.

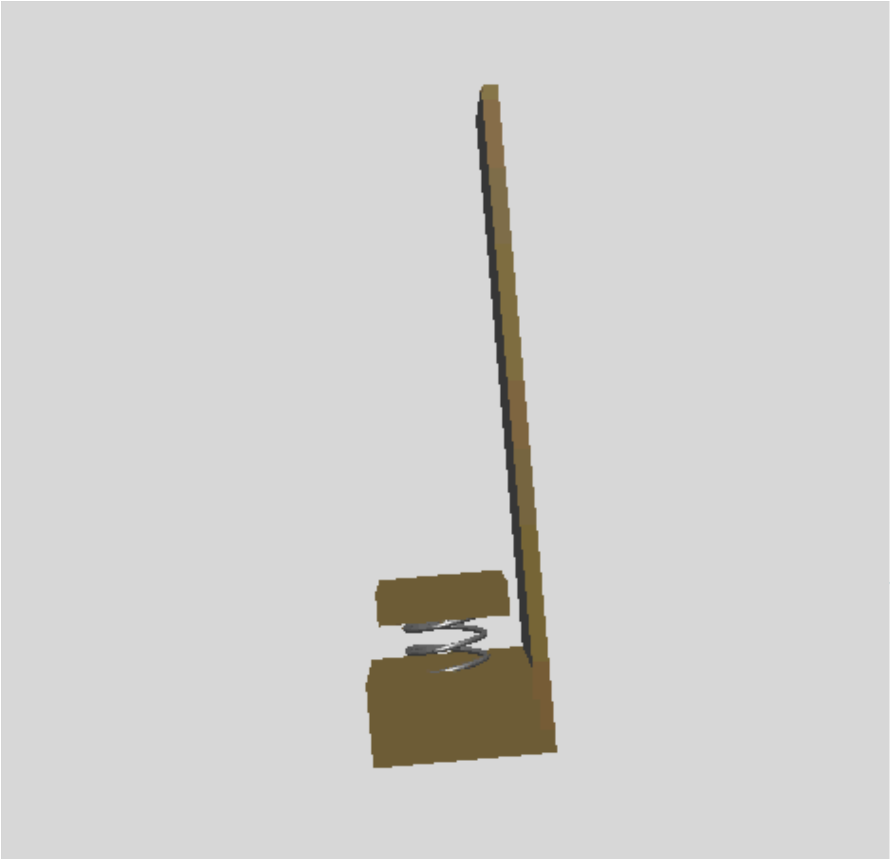
Used for:

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



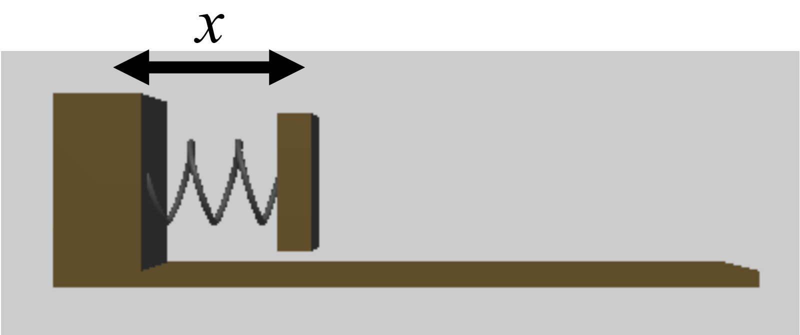
Spring-Mass-Damper Accelerometer

- By Newton's second law, $F = m \cdot a$
- F could be the Earth's gravitational force.
- The force is balanced by the restoring force of the spring.



Spring-Mass-Damper System

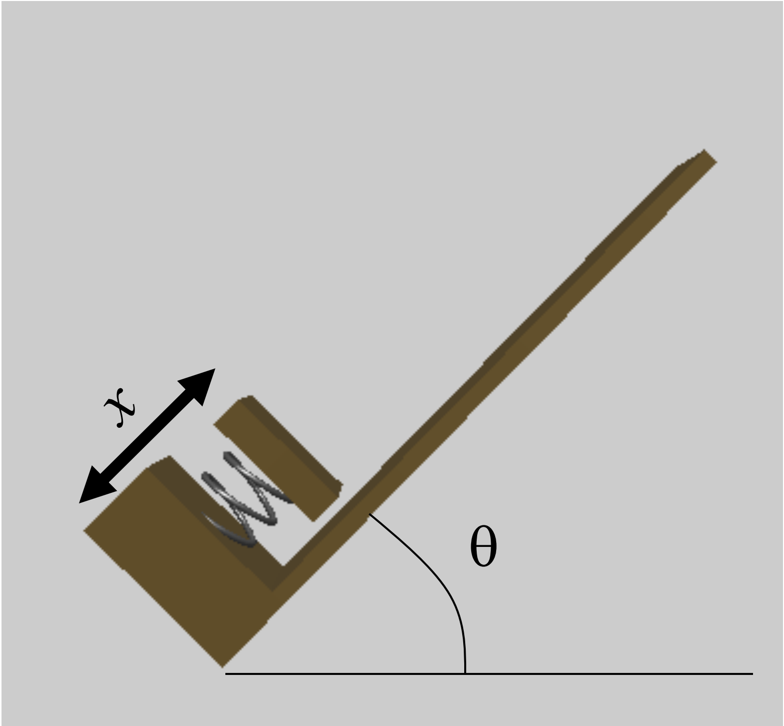
- Mass: M
- Spring constant: k
- Spring rest position: p
- Position of mass: x
- Viscous damping constant: c



- Force due to spring extension
  $$F_1(t) = k(p - x(t))$$
- Force due to viscous damping
  $$F_2(t) = -c \cdot \dot{x}(t)$$
- Newton's second law
  $$F_1(t) + F_2(t) = M \cdot \ddot{x}(t)$$
- Or
  $$M \cdot \ddot{x}(t) + c \cdot \dot{x}(t) + k \cdot x(t) = k \cdot p$$

Measuring tilt

- Component of gravitational force in the directions of the accelerometer axis must equal the spring force (no damping)
$$M \cdot g \cdot sin(\theta) = k(p - x(t))$$
- Given a measure of x, you can solve for θ, up to an ambiguity of π



Difficulties Using Accelerometers

- Separating tilt from acceleration
- Integrating twice to get position: implies a Drift error
  - *Position of object to track:* $p(\mathrm{t})$

$$p(\mathrm{t}) = p(0) + \int v(\tau)d\tau$$

$$v\,(\mathrm{t}) = v(0) + \int a(\tau)d\tau$$

  - *But from affine model:*

Acceleration measured by sensor

Real acceleration

$$a(\mathrm{t}) = k \cdot \hat{a}(t) + b$$

$$p(\mathrm{t}) = p(0) + \int \left[v(0) + \int \left[k \cdot \hat{a}(\tau) + b\right] d\tau\right] d\tau$$

$$= p(0) + t \cdot v(0) + t^2 \cdot b + k \cdot \int \int \hat{a}(\tau)d\tau d\tau$$

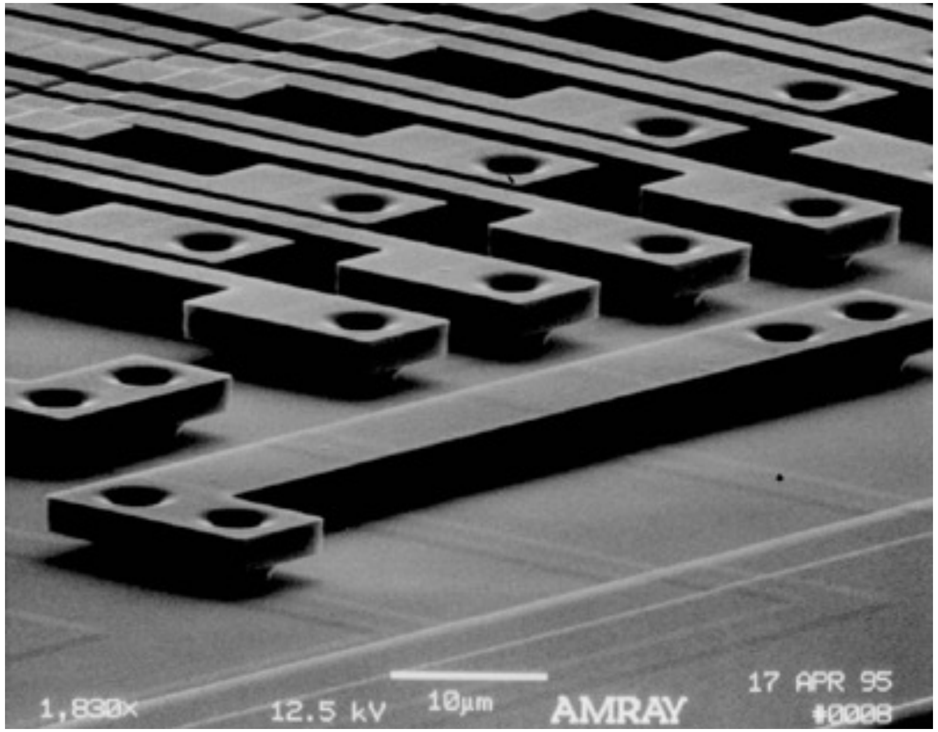
Difficulties Using Accelerometers (2)

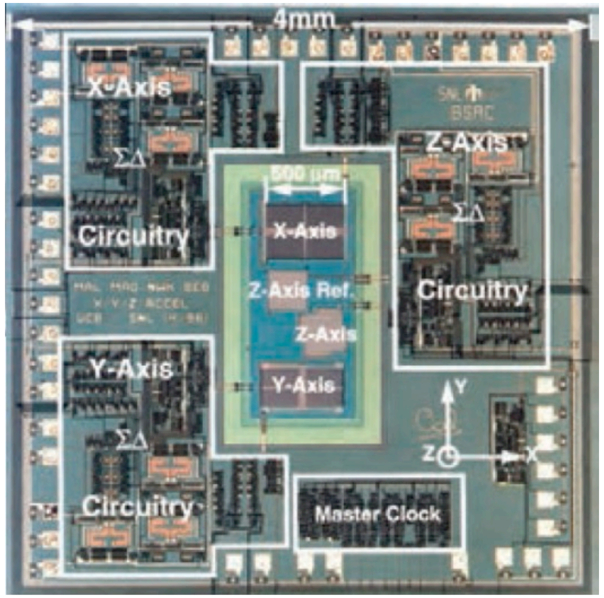
$$p(t) = p(0) + t \cdot v(0) + t^2 \cdot b + k \cdot \int \int \hat{a}(\tau) d\tau d\tau$$

- *Bias (b) will give error proportional to* t^2
  - Drift
  - And the 2nd harmonic is not in the equation ➔increase error
- Vibration
- Nonlinearities in the spring or damper

Feedback dramatically improves accuracy and dynamic range of micro-accelerometers.

- The Berkeley Sensor and Actuator Center (BSAC) created the first silicon micro-accelerometers, MEMS devices now used in airbag systems, computer games, disk drives (drop sensors), etc.

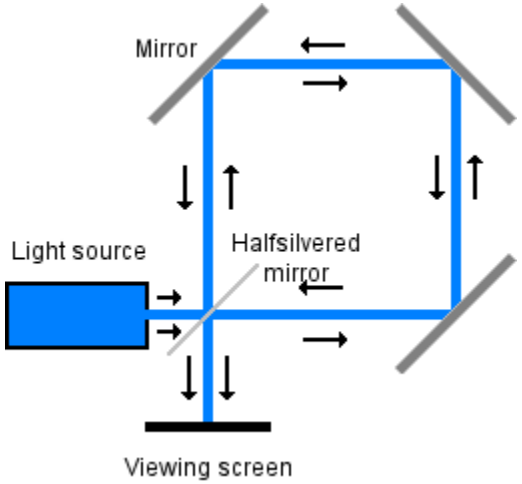




M. A. Lemkin, "Micro Accelerometer Design with Digital Feedback Control", Ph.D. dissertation, EECS, University of California, Berkeley, Fall 1997

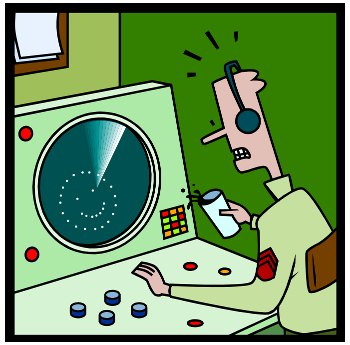
Measuring Changes in Orientation: Gyroscopes

- Optical gyros: Leverage the Sagnac effect, where a laser light is sent around a loop in opposite directions and the interference is measured. When the loop is rotating, the distance the light travels in one direction is smaller than the distance in the other. This shows up as a change in the interference.



Images from the Wikipedia Commons

Inertial Navigation Systems



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

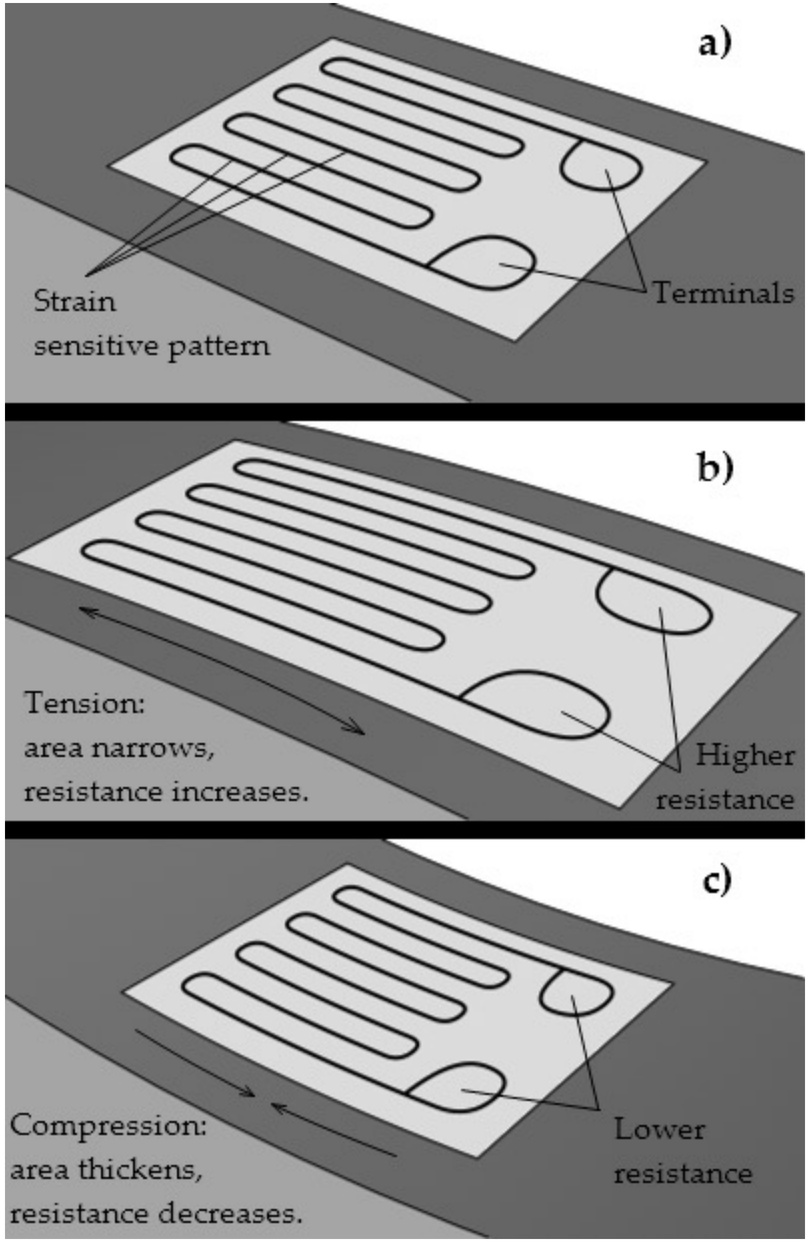
- Typical drift for systems used in aircraft have to be:
  - *0.6 nautical miles per hour*
  - *tenths of a degree per hour*

- Good enough? It depends on the application!

Browser of the future? (courtesy of Ras Bodik, UCB)

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 Wikipedia Commons

Design Issues with Sensors

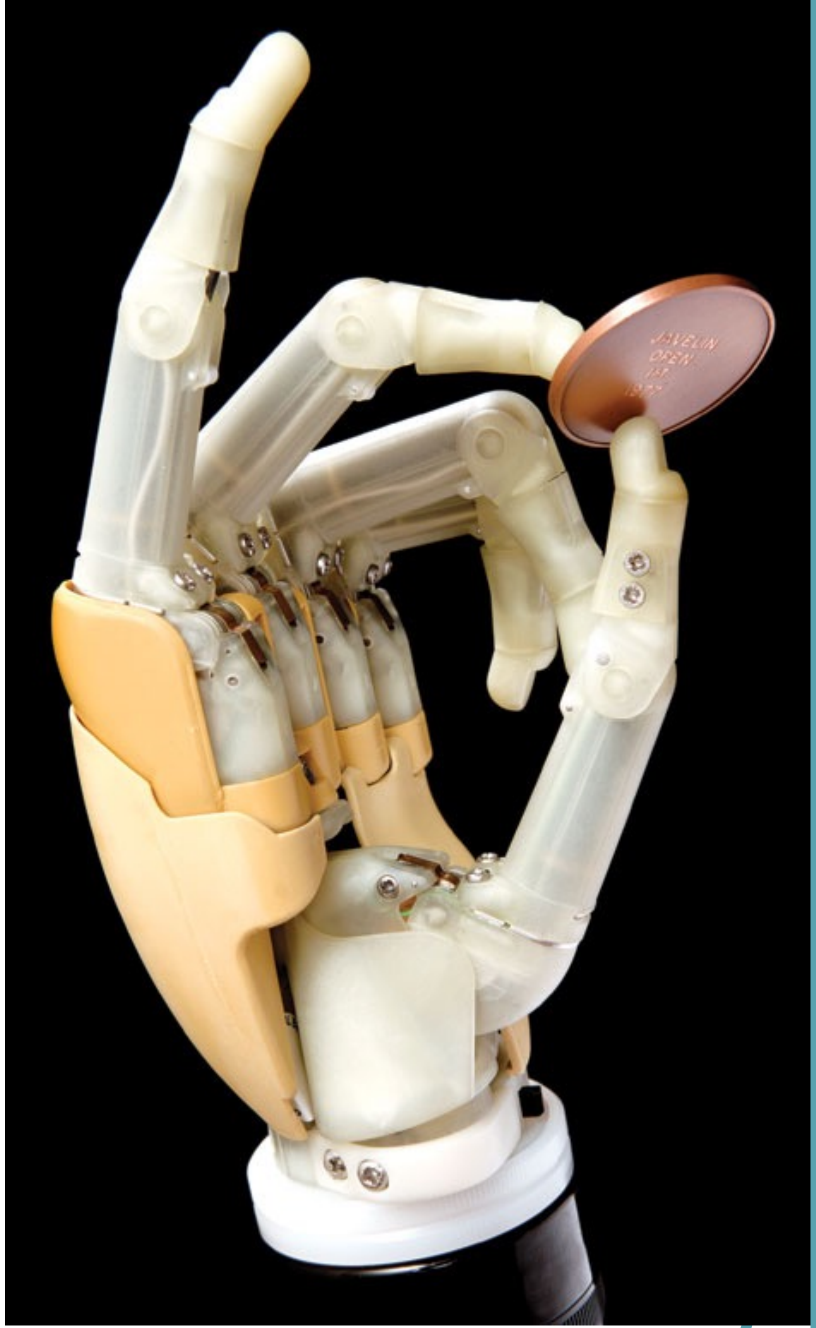
- Calibration
  - *Relating measurements to the physical phenomenon*
  - *Can dramatically increase manufacturing costs*
- Nonlinearity
  - *Measurements may not be proportional to physical phenomenon*
  - *Correction may be required*
  - *Feedback can be used to keep operating point in the linear region*

Design Issues with Sensors (continued)

- Sampling
  - *Aliasing*
  - *Missed events*
- Noise
  - *Analog signal conditioning*
  - *Digital filtering*
  - *Introduces latency*

Motor Controllers

Photo by Touch Bionics



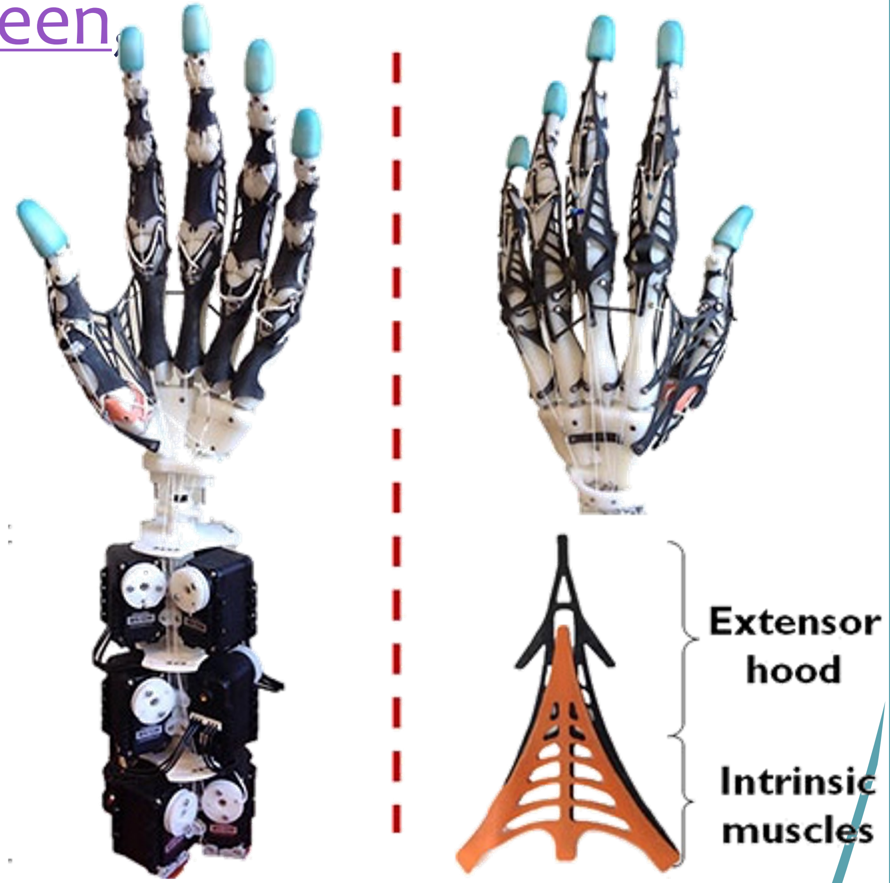
- It's got an embedded computer, a rechargeable battery, and five small dc motors. It costed US $18 500 (2007). And it can do things most other prosthetic hands just can't, like grabbing a paper cup without crushing it, turning a key in a lock, and pressing buttons on a cellphone. The fingers of Touch Bionics' iLIMB Hand are controlled by the nerve impulses of the user's arm, and they operate independently, adapting to the shape of whatever they're grasping. The hand can also do superhuman tricks, like holding a very hot plate or gripping an object tirelessly for days. says Touch Bionics CEO Stuart Mead. IEEE Spectrum, Oct. 2007.

See How the i-Limb works, from TouchBionics

Robotic Hands

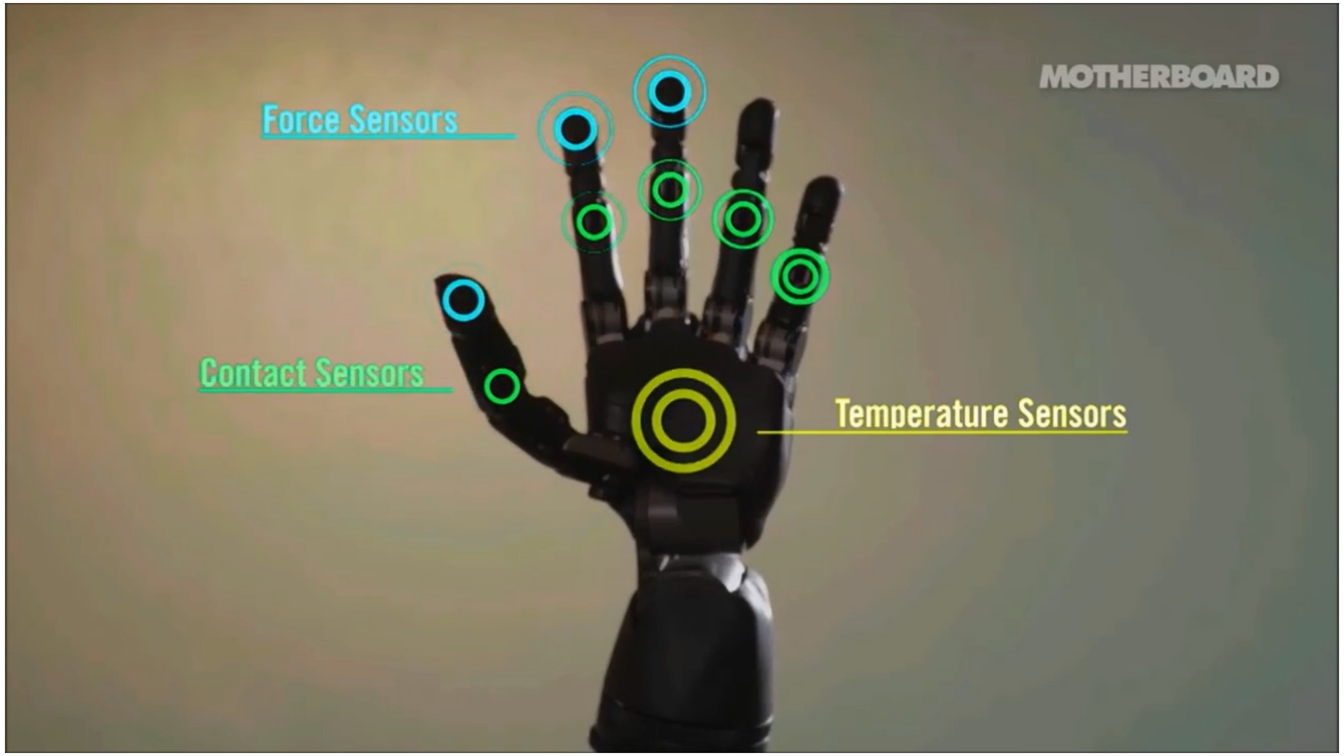
- From IEEE Spectrum, [This Is the Most Amazing Biomimetic Anthropomorphic Robot Hand We've Ever Seen](), By Evan Ackerman

  "Joint ligaments (which stabilize joints and control their range of motion) are made of high strength Spectra strings, with laser-cut rubber sheets replacing the soft tissues that add joint compliance. Extensor and flexor tendons (for straightening and bending fingers) are also made of Spectra, with more laser-cut rubber sheets for the tendon sheathing and extensor hood, which is a complex webbed multi-layered structure that wraps around the fingers to help manage flexibility and torque. The final part to UW's hand are the muscles, which are made up of an array of 10 Dynamixel servos, whose cable routing closely mimics the carpal tunnel of a human hand."



Bionic Arm sensor and actuator

- Research by Advanced Physics Lab (APL) from John Hopkins Univ.
- See full video.



Cameras

- Computer-controlled digital cameras
- Digital video cameras
- Specialized cameras
  - *infrared*
  - *ultra fast/high resolution*
  - *motion trackers*

Pirates of the Caribbean: the Curse of the Black Pearl (2003, Disney) pioneered the use of motion trackers coupled with computer-generated graphics.

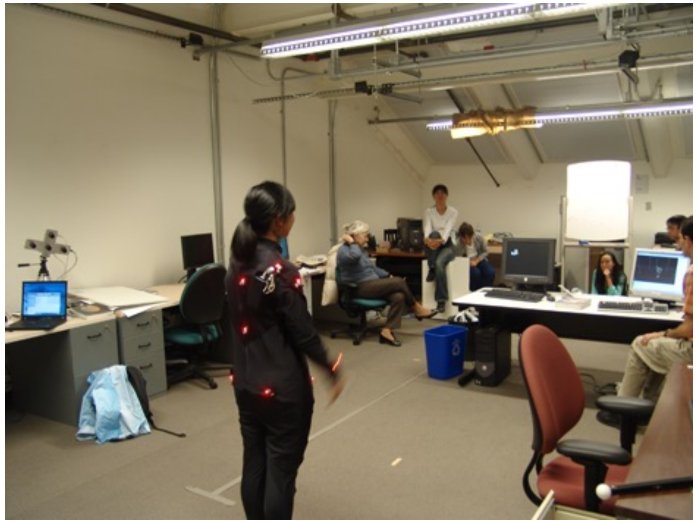
At the right: the transformation of Geoffrey Rush
Photo Credit: Industrial Light & Magic.

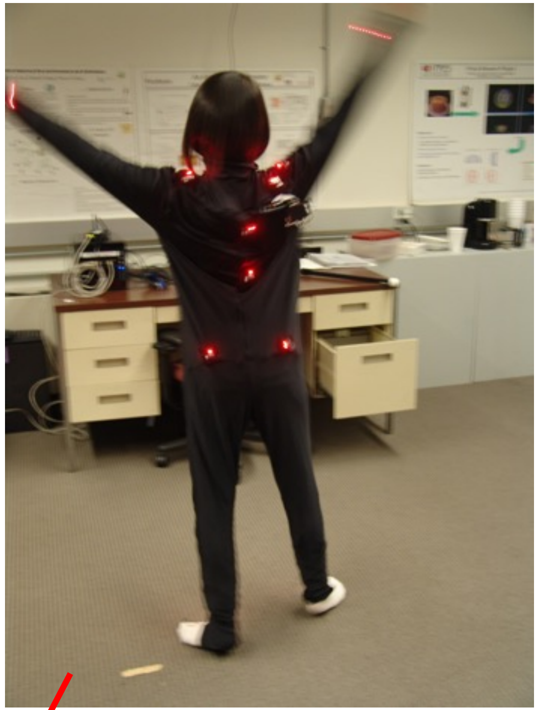
A Motion-Tracker Facility in Hearst Mining Building

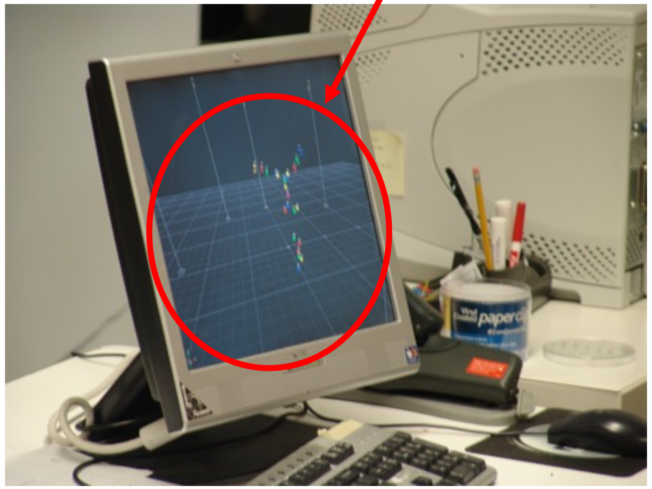
- Prof. Ruzena Bajcsy (EECS) maintains a facility that tracks motion of infrared LEDs in 3-D space.

PHASESPACE
MOTION CAPTURE

http://www.phasespace.com

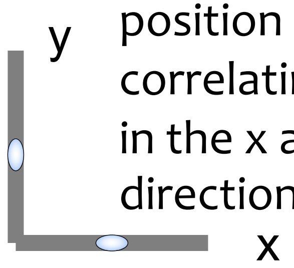




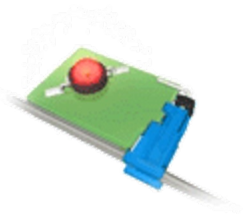


Overview of PhaseSpace Motion Tracker Technology

Impulse camera detecting peaks on two linear sensors with 3600 pixels each, arranged in a straight line, each with 60 degree field of view.



Calculation of marker position by correlating the peaks in the x and y directions.

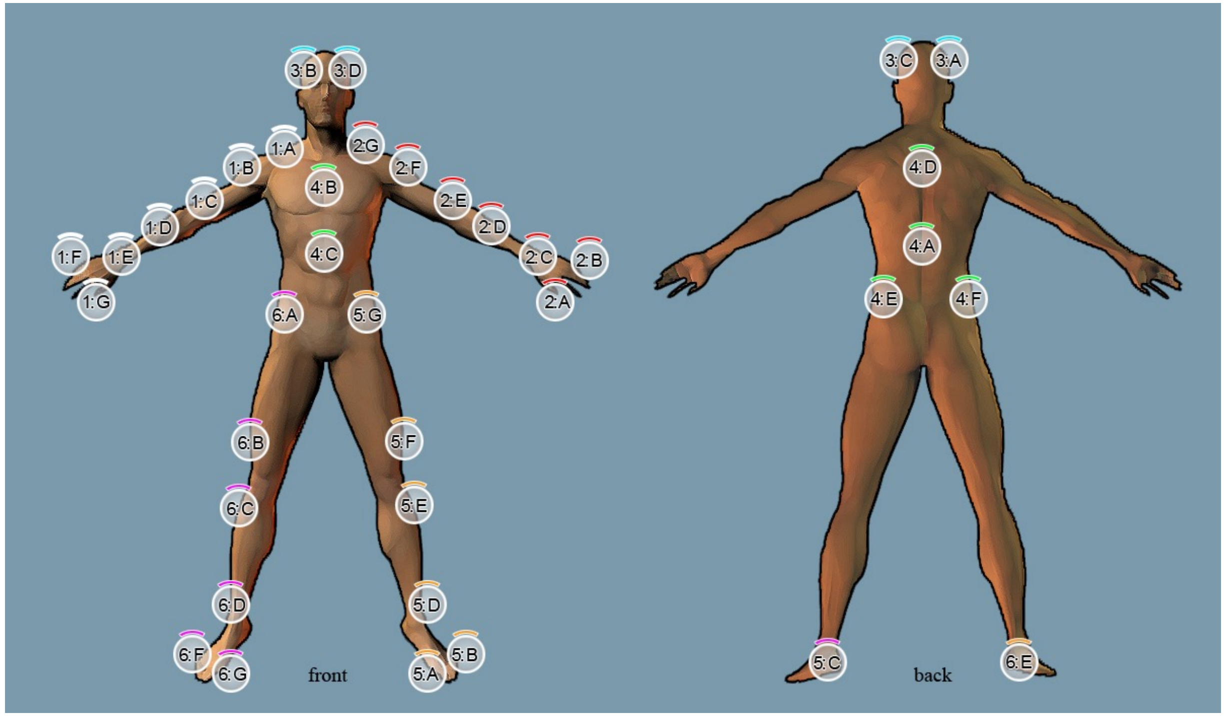


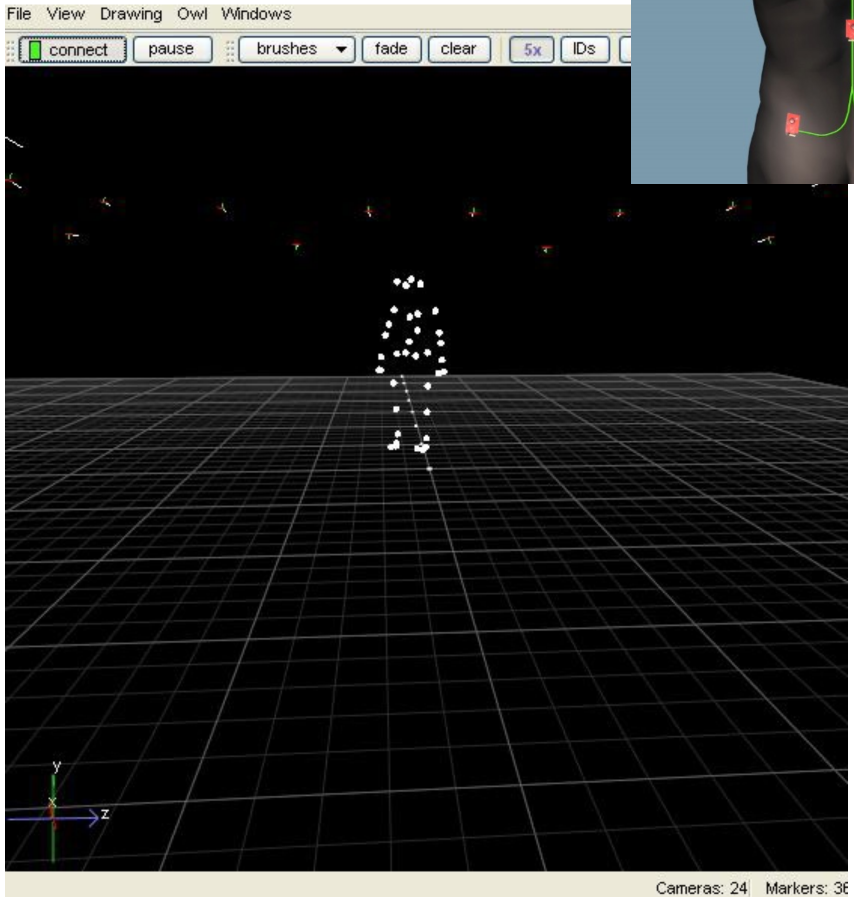
Up to 72 infra-red markers, where each has a unique flashing frequency so that the detector can distinguish them.

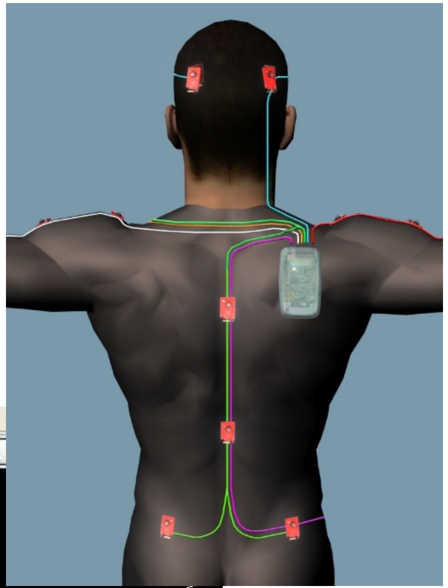
Up to 24 cameras can surround the scene

Motion Suit

- Up to 38 IR markers on the suit
- Wireless control by the server







Motion Capture using accel

Xsens - MVN

Bluetooth 2.0

Full body configuration	17 MTx inertial trackers
Lower body configuration	7 MTx inertial trackers
Upper body configuration	11 MTx inertial trackers
Extra prop / backup tracker	1 MTx inertial tracker

Interface	Wireless or high-speed RS-232/USB
Wireless range radius (typical):	
Outdoor	150 meters (492 ft.)
Indoor open space	150 meters (492 ft.)
Indoor office	50 meters (164 ft.)

Internal update rates	1000, 120, 100, 80, 60 Hz
Export frame rates	240, 120, 100, 60, 50, 30, 25, 24 Hz

Data rate
- 39 MB/min @ 60 Hz
- 52 MB/min @ 80 Hz
- 66 MB/min @ 100 Hz
- 79 MB/min @ 120 Hz

From XSens MVN page

MTx inertial trackers

From XSens leaflets, new products have different characteristics

- 3D orientation accuracy: <0.5 deg
- Resolution: 0.05 deg
- Accelerometer range: ± 180 m/s^2 (18 g)
- Gyroscope range: 1200 deg/s

- MVN Human model
  - *MVN uses a 23 segment biomechanical model with 22 joints.*
  - *Each joint is specified by statistical parameters for 6DOF joint laxity.*
  - *An advanced spine and shoulder model is used that computes the kinematics of the spine and shoulder blades*

Summary

- Models
  - *range*
- Sampling, quantization, SNR
- Examples of sensors and actuators