Introduction to Embedded Systems

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Chapter 7: Sensors and Actuators

What is a sensor? An actuator?

A sensor is a device that **measures** a physical quantity
→ Input / “Read from physical world”

An actuator is a device that **modifies** a physical quantity
→ Output / “Write to physical world”

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
- …

Modeling Issues:

- Physical dynamics
- Noise
- Bias
- Sampling
- Interactions
- Faults
- …

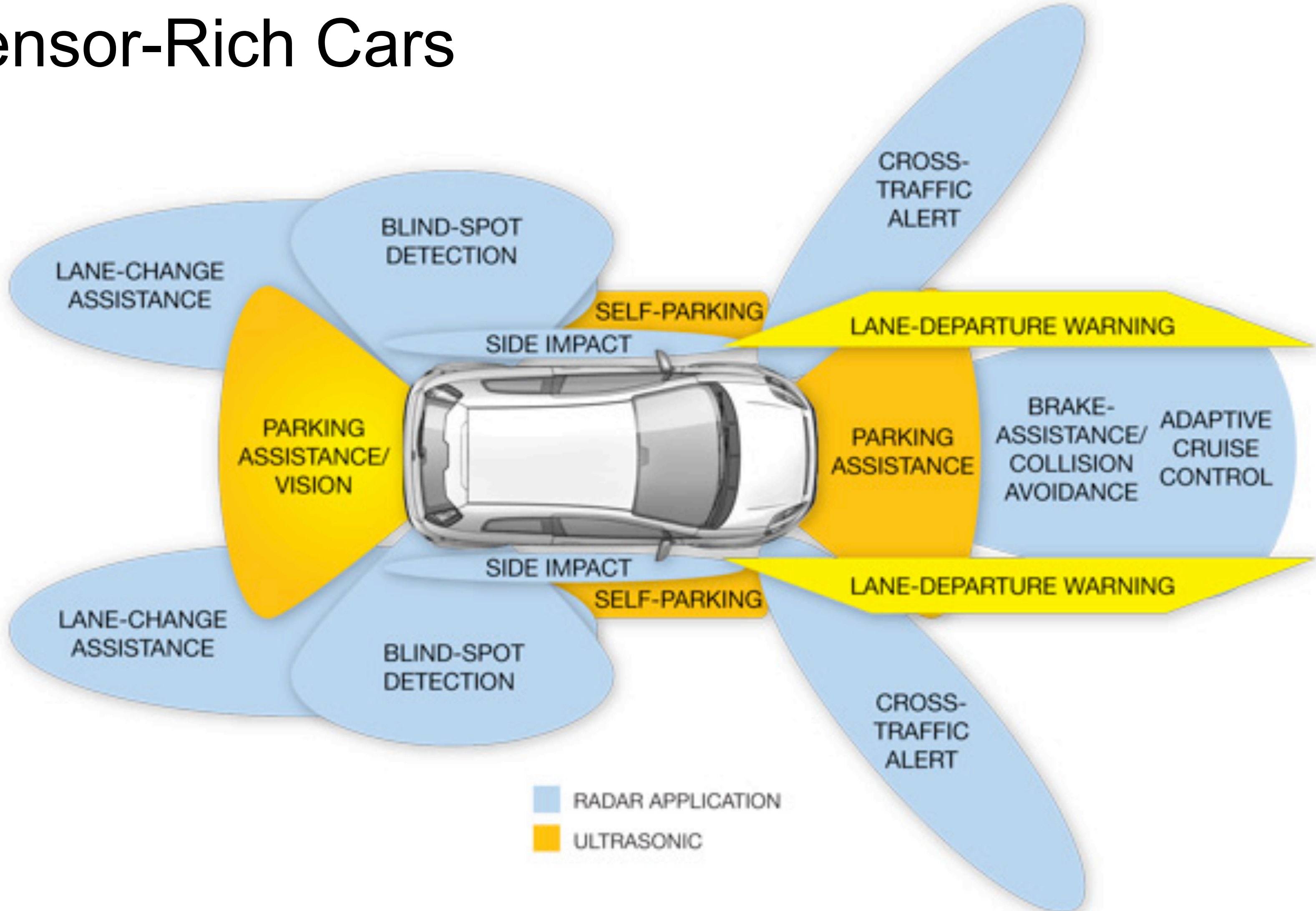
Self-Driving Cars

Berkeley PATH Project Demo,
1999, San Diego.

Google self-driving car 2.0

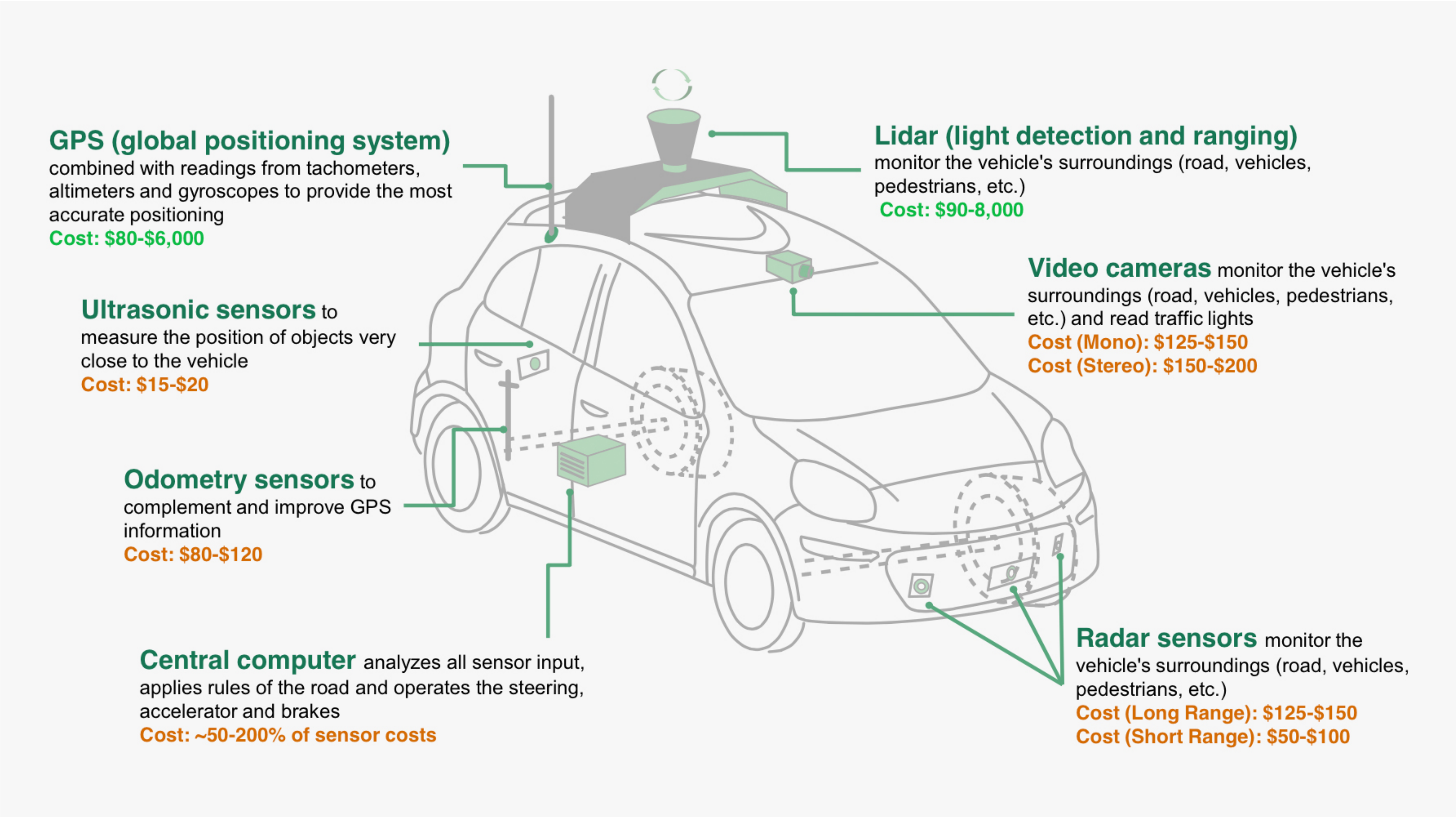
Kingvale Blower
Berkeley PATH Project, March, 2005

Sensor-Rich Cars



Source: Analog Devices

Sensor-Rich Cars



Source: Wired Magazine

Kingvale Blower: Technology Overview
Berkeley PATH Project, March, 2003

Magnetometers

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.

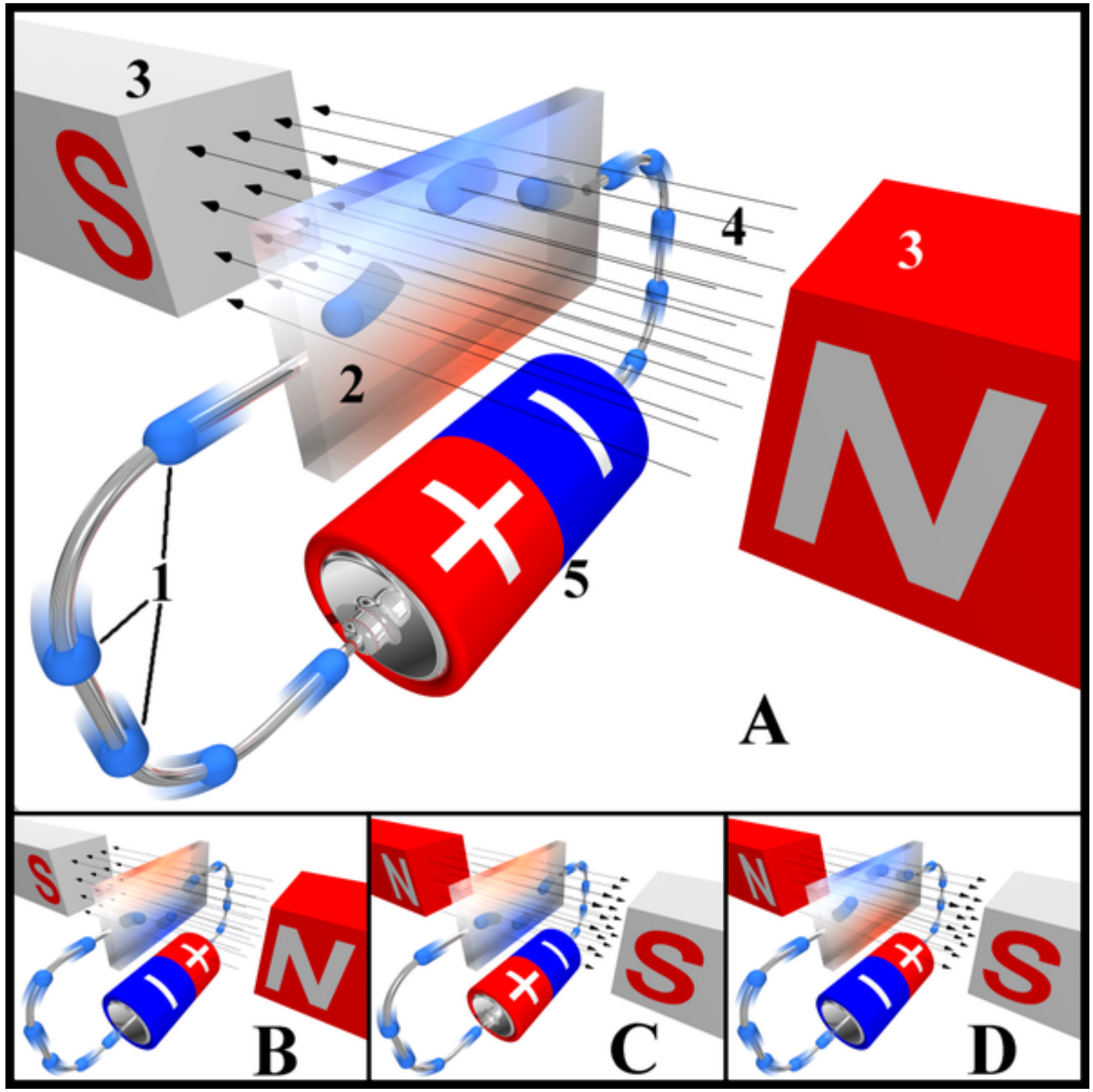
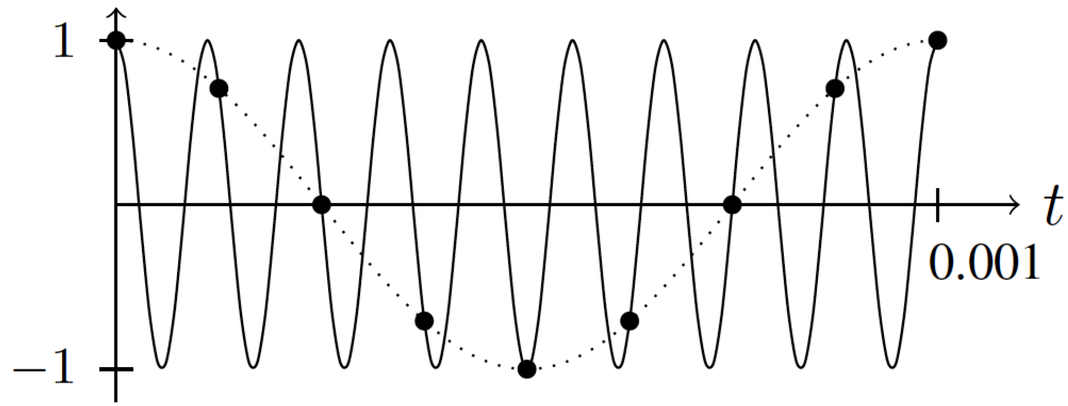


Image source: Wikipedia Commons

Edwin Hall discovered this effect in 1879.

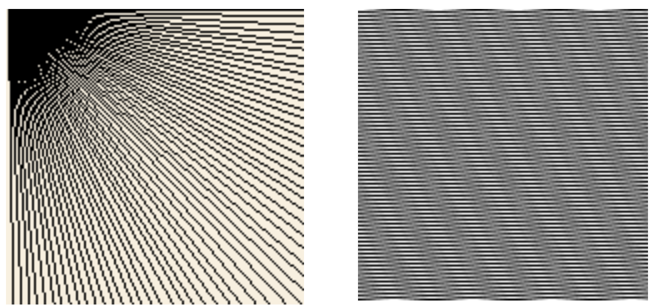
Aliasing



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

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.



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.

Roadmap

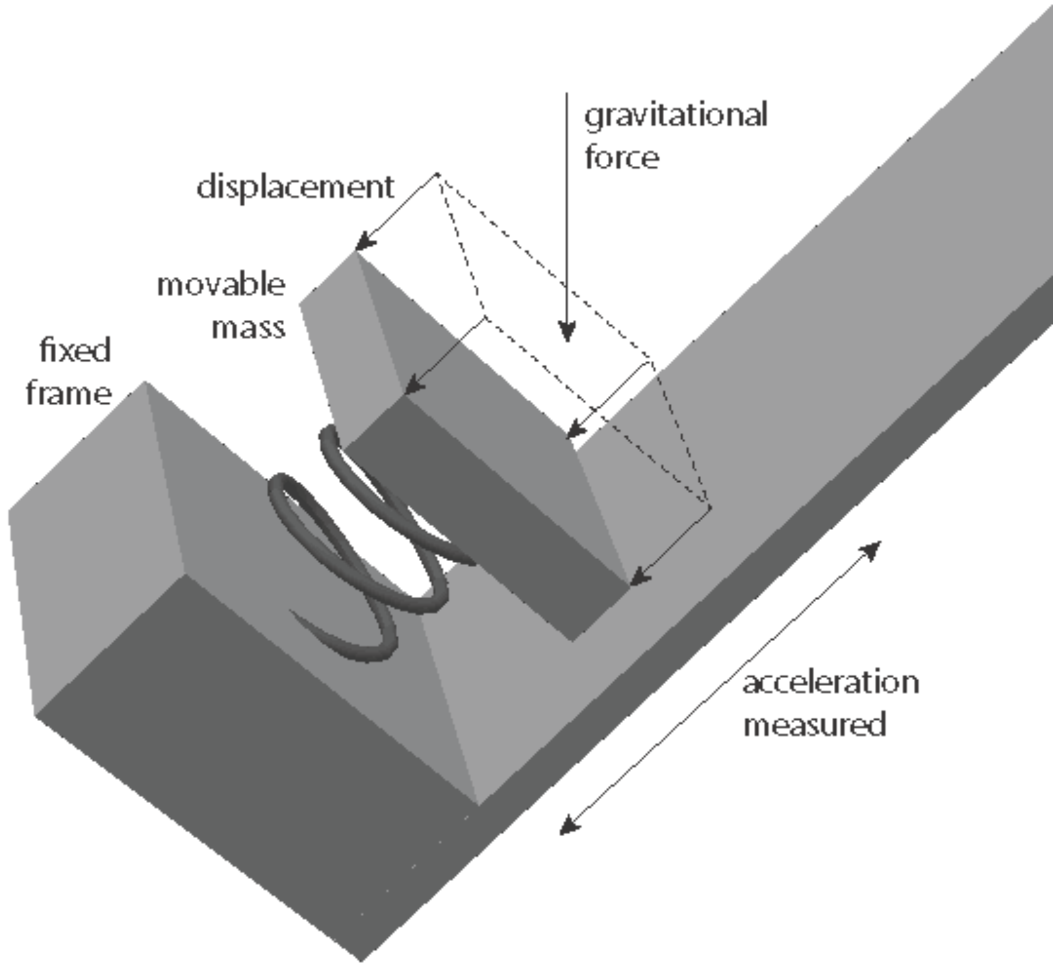
- How Accelerometers work
- Affine Model of Sensors
- Bias and Sensitivity
- Faults in Sensors
- Brief Overview of Actuators

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.

Uses:

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



Spring-Mass-Damper Accelerometer

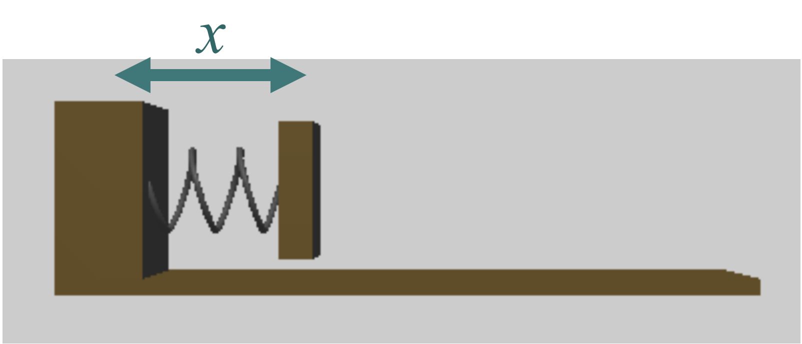
By Newton's second law, F=ma.

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

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

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:

$$F_2(t) = -c\dot{x}(t)$$

Newton's second law:

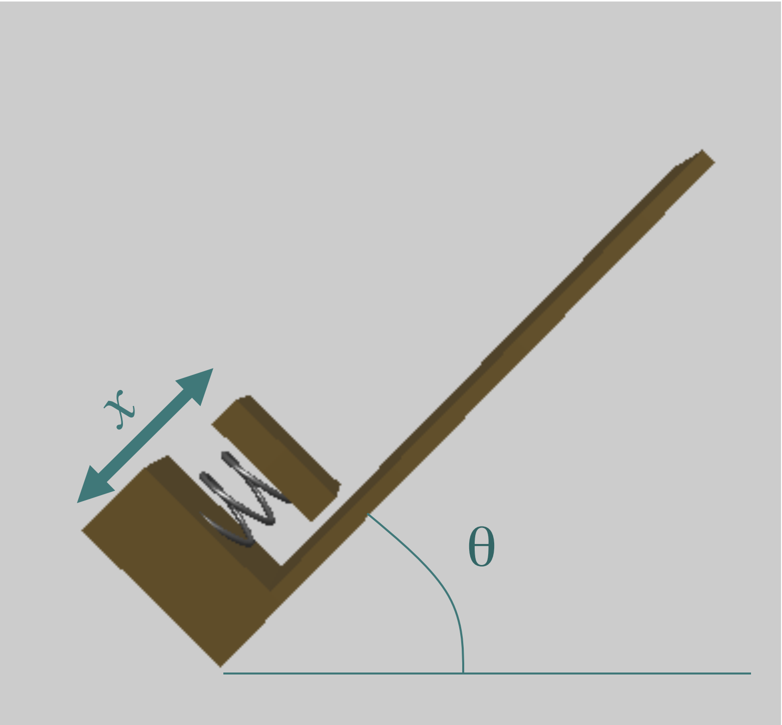
$$F_1(t) + F_2(t) = M\ddot{x}(t)$$

or

$$M\ddot{x}(t) + c\dot{x}(t) + kx(t) = kp.$$

Exercise: Convert to an integral equation with initial conditions.

Measuring tilt



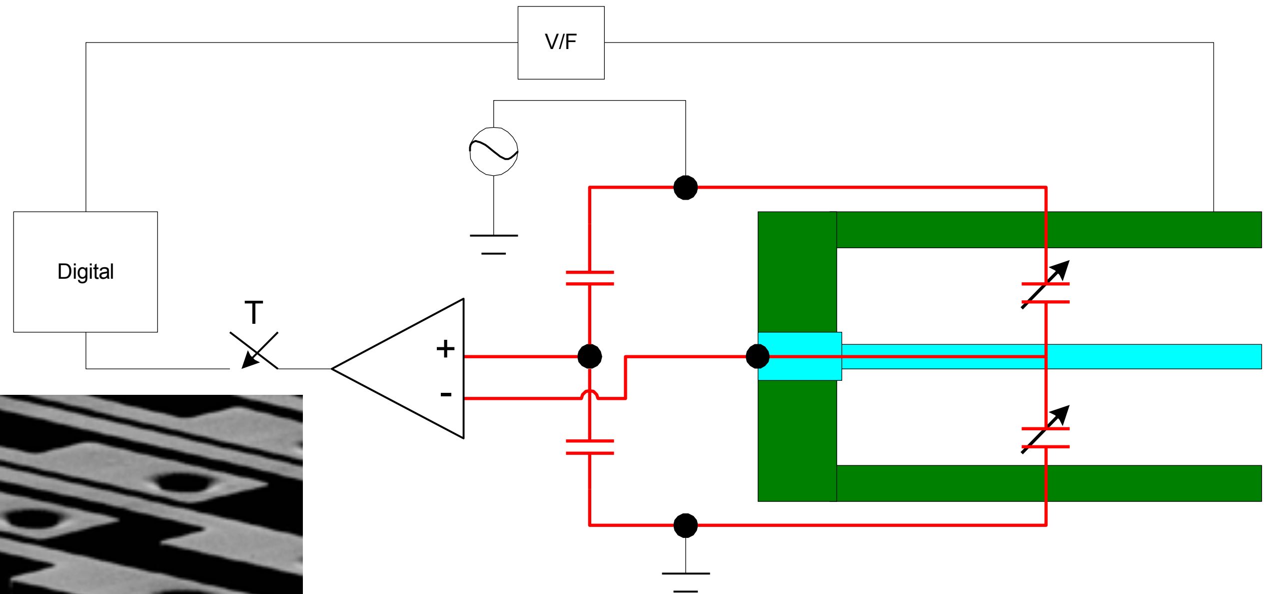
Component of gravitational force in the direction of the accelerometer axis must equal the spring force:

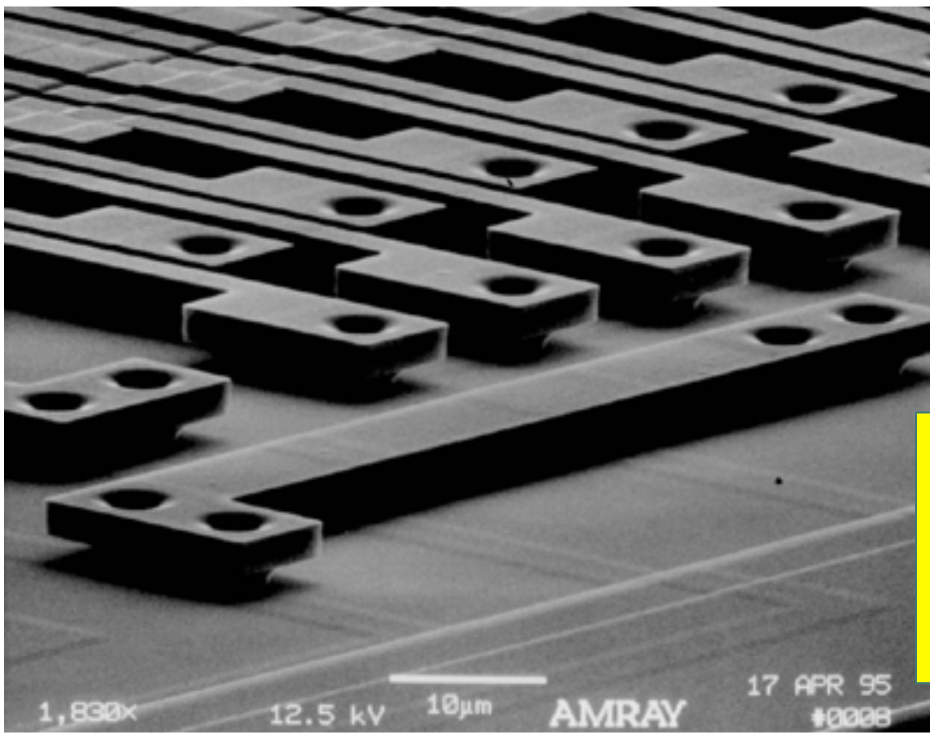
$$Mg\sin(\theta) = k(p - x(t))$$

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

Feedback dramatically improves accuracy and dynamic range of microaccelerometers.

The Berkeley Sensor and Actuator Center (BSAC) created the first silicon microaccelerometers, 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

Difficulties Using Accelerometers

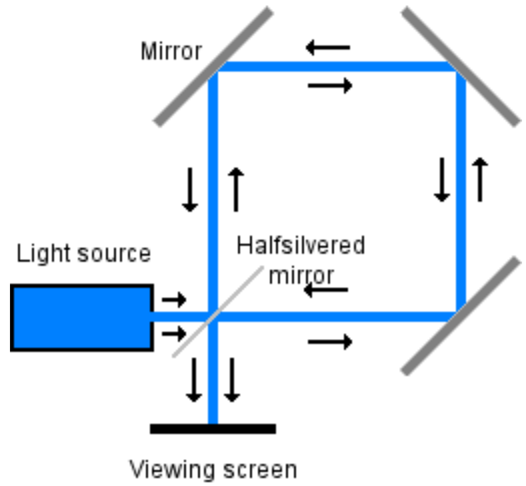
- Separating tilt from acceleration
- Vibration
- Nonlinearities in the spring or damper
- Integrating twice to get position: Drift

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

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

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

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

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!

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)

Sensor Calibration

Affine Sensor Model

Bias and Sensitivity

Example: Look at ADXL330 accelerometer datasheet

x — Phy Qty $\quad x : \mathbb{R}$

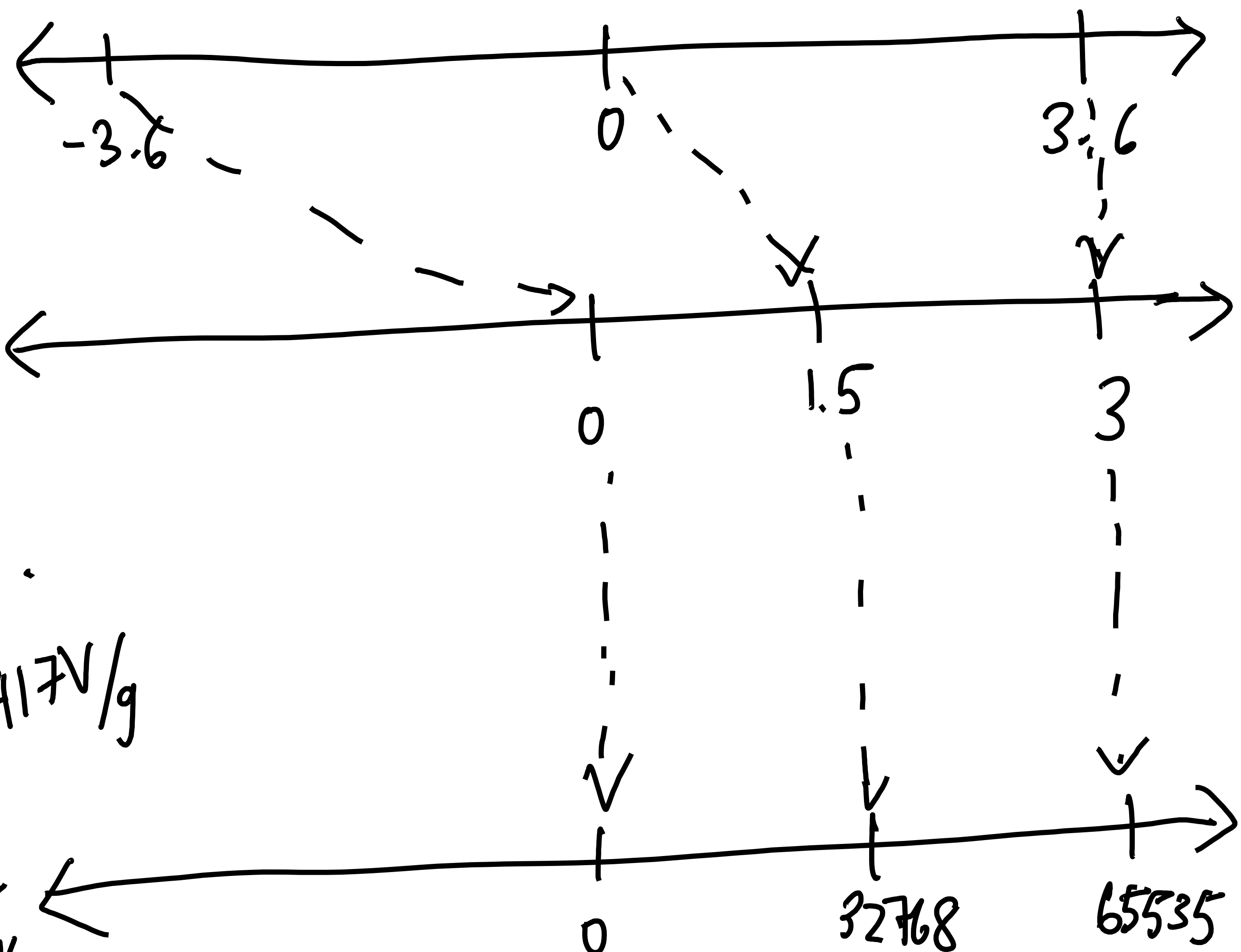
Sensor $\quad F : \mathbb{R} \to \mathbb{R}$

affine

$$F(x) = ax + b$$

bias

$$\frac{dF(x)}{dx} = a = \text{sensitivity}$$



F(x)

$F(x) = ax + b$.

$b = 1.5$

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

ADC - 16 bit

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

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		m*g*/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			280		µ*g*/√Hz rms
Noise Density Z_{OUT}			350		µ*g*/√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
SELF TEST[6]					

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Faults in Sensors

Sensors are physical devices

Like all physical devices, they suffer wear and tear, and can have manufacturing defects

Cannot assume that *all* sensors on a system will work correctly at *all* times

Solution: Use redundancy

→ However, must be careful *how* you use it!

Violent Pitching of Qantas Flight 72 (VH-QPA)

An Airbus A330 en-route from Singapore to Perth on 7 October 2008

- Started pitching violently, unrestrained passengers hit the ceiling, 12 serious injuries, so counts it as an accident.
- Three Angle Of Attack (AOA) sensors, one on left (#1), two on right (#2, #3) of nose.
- Have to deal with inaccuracies, different positions, gusts/spikes, failures.

[Rushby, 2002]

A330 AOA Sensor Processing

- Sampled at 20Hz
- Compare each sensor to the median of the three
- If difference is larger than some threshold for more than 1 second, flag as faulty and ignore for remainder of flight
- Assuming all three are OK, use mean of #1 and #2 (because they are on different sides)
- If the difference between #1 or #2 and the median is larger than some (presumably smaller) threshold, use previous *average* value for 1.2 seconds
- Failure scenario: two spikes in #1, first shorter than 1 second, second still present 1.2 seconds after detection of first
- Result: flight control computers commanding a nose-down aircraft movement, which resulted in the aircraft pitching down to a maximum of about 8.5 degrees

[Rushby, 2002]

How to deal with Sensor Errors

Difficult Problem, still research to be done

Possible approach: Intelligent sensor communicates an **interval**, not a point value

- Width of interval indicates confidence, health of sensor

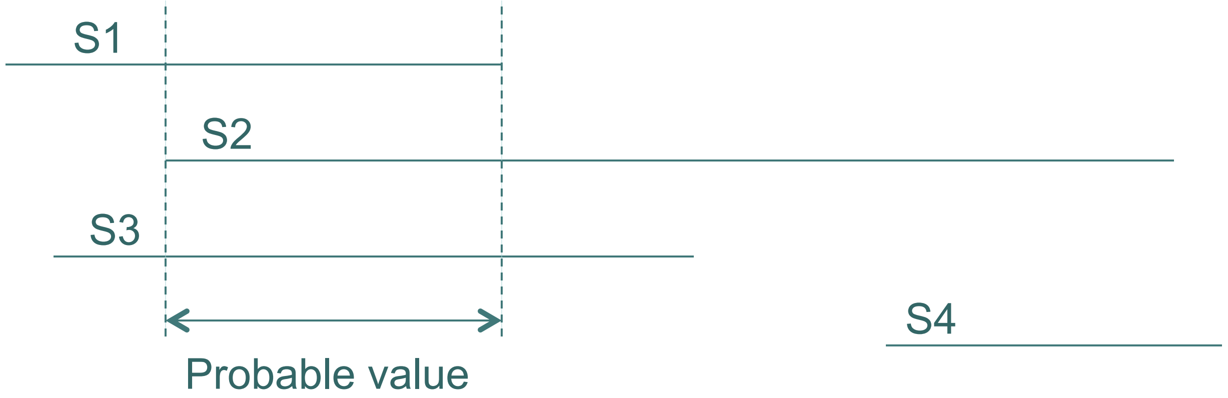
[Rushby, 2002]

Sensor Fusion: Marzullo's Algorithm

- Axiom: if sensor is non-faulty, its interval contains the true value
- Observation: true value must be in overlap of non-faulty intervals
- Consensus (fused) Interval to tolerate f faults in n: Choose interval that contains all overlaps of $n - f$; i.e., from least value contained in $n - f$ intervals to largest value contained in $n - f$

[Rushby, 2002]

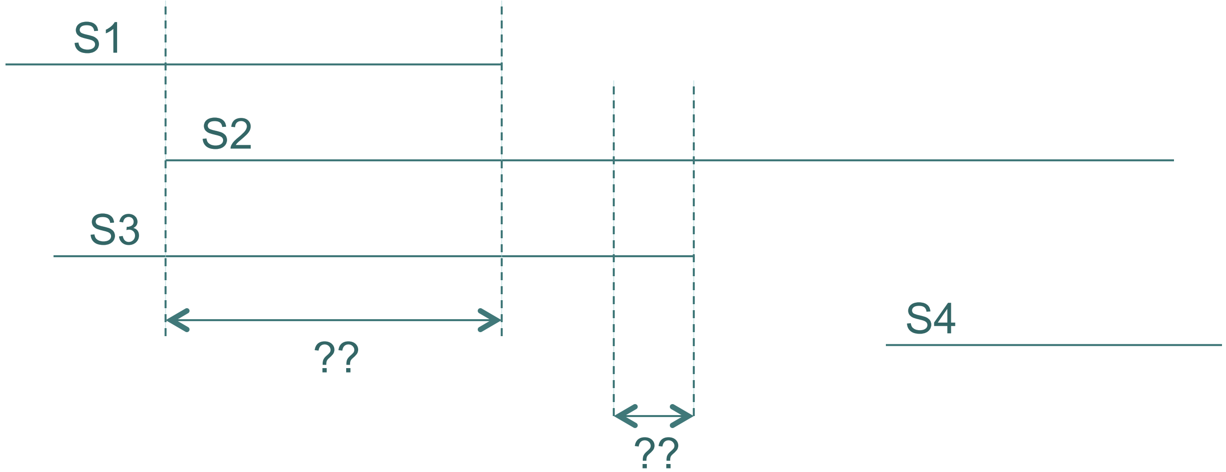
Example: Four sensors, at most one faulty



- Interval reports range of possible values.
- Of S1 and S4, one must be faulty.
- Of S3 and S4, one must be faulty.
- Therefore, S4 is faulty.
- Sound estimate is the overlap of the remaining three.

[Rushby, 2002]

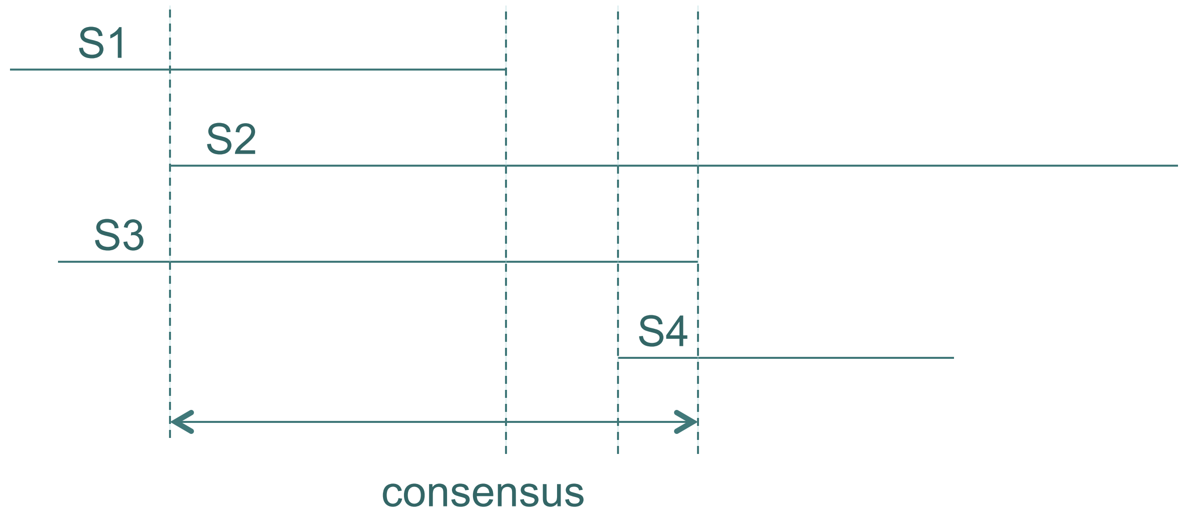
Example: Four sensors, at most one faulty



- Suppose S4's reading moves to the left
- Which interval should we pick?

[Rushby, 2002]

Example: Four sensors, at most one faulty



- Marzullo's algorithm picks the smallest interval that is sure to contain the true value, under the assumption that at most one sensor failed.
- But this yields big discontinuities. Jumps!

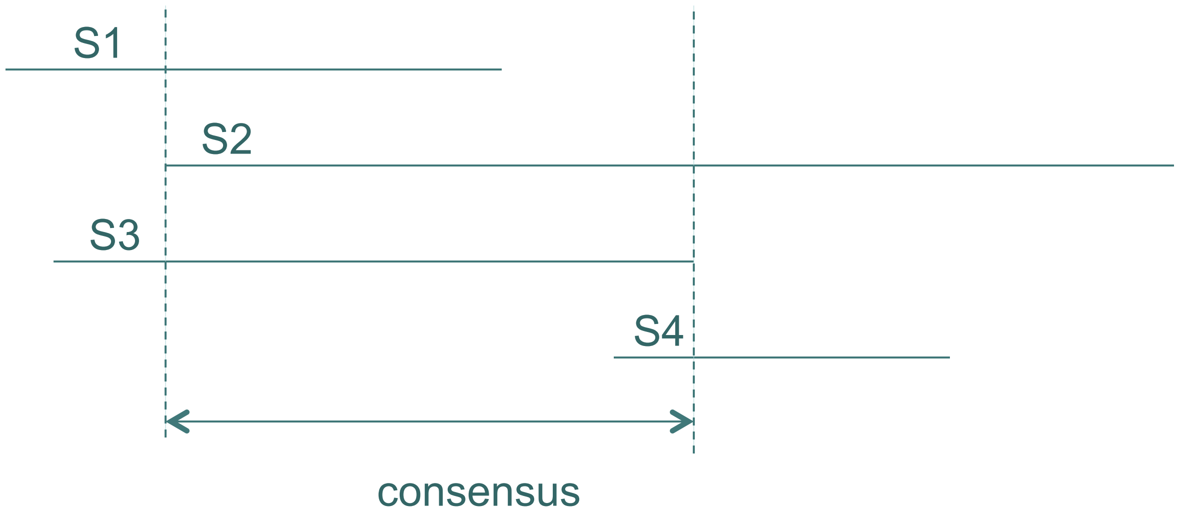
[Rushby, 2002]

Schmid and Schossmaier's Fusion Method

- Recall: n sensors, at most f faulty
- Choose interval from f+1st largest lower bound to f+1st smallest upper bound
- Optimal among selections that satisfy continuity conditions.

[Rushby, 2002]

Example: Four sensors, at most one faulty

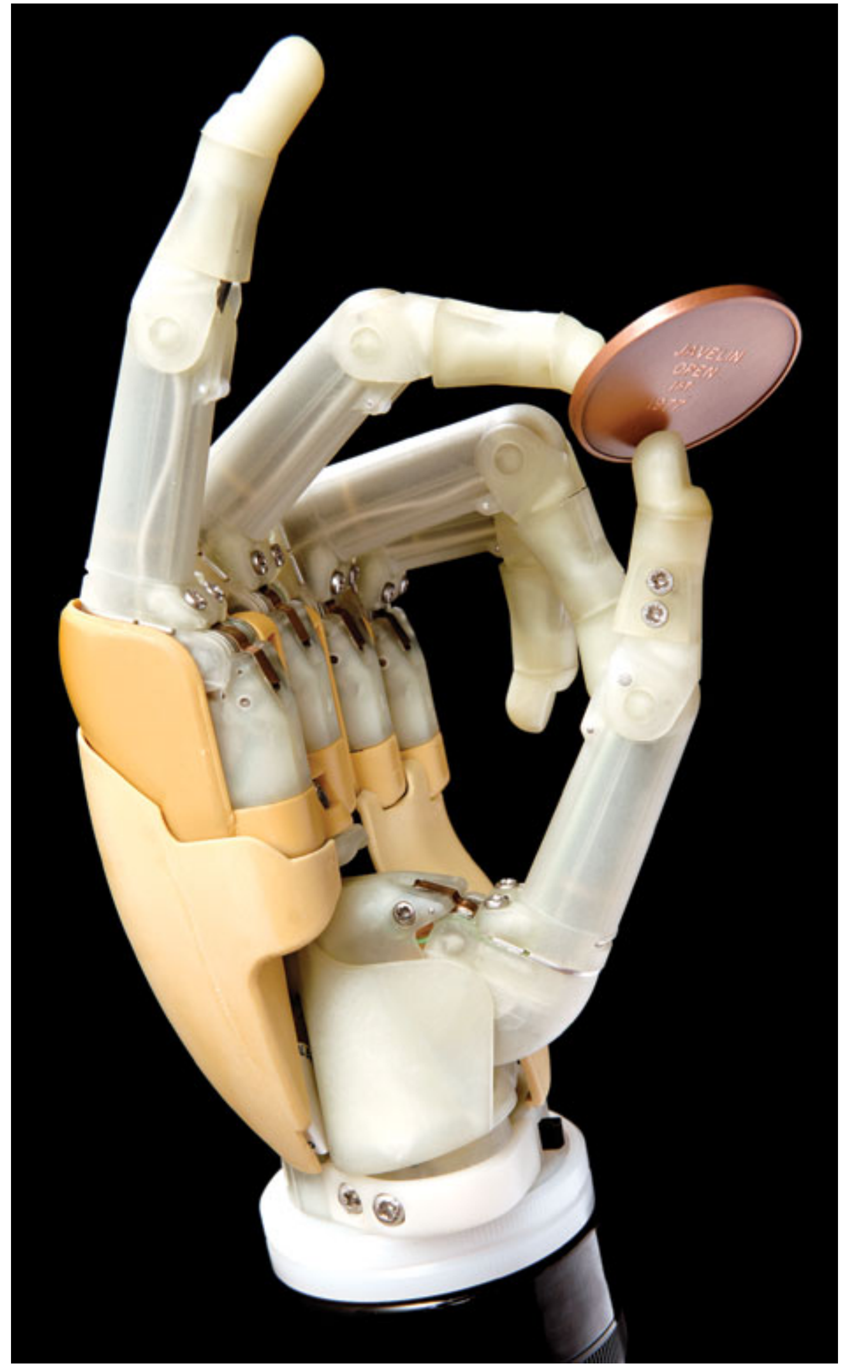


- Assuming at most one faulty, Schmid and Schossmaier's method choose the interval between:
  - Second largest lower bound
  - Second smallest upper bound
  - This preserves continuity, but not soundness

[Rushby, 2002]

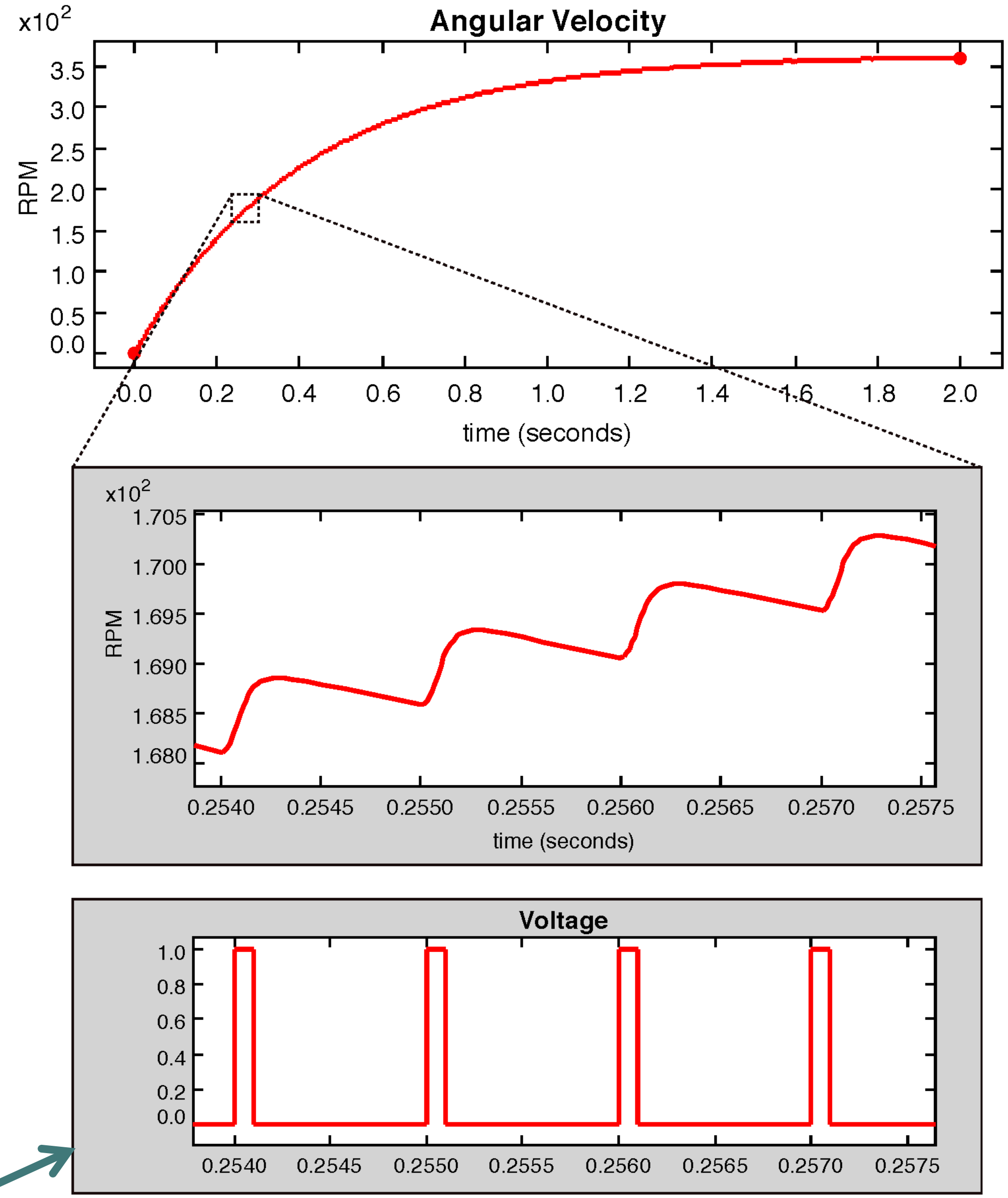
Motor Controllers

Bionic hand from Touch Bionics costs $18,500, has and five DC motors, can grab a paper cup without crushing it, and turn a key in a lock. It is controlled by nerve impulses of the user's arm, combined with autonomous control to adapt to the shape of whatever it is grasping. Source: IEEE Spectrum, Oct. 2007.



Pulse-Width Modulation (PWM)

Delivering power to actuators can be challenging. If the device tolerates rapid on-off controls ("bang-bang" control), then delivering power becomes much easier.



Duty cycle around 10%

Model of a Motor

Back electromagnetic force constant

Angular velocity

Electrical Model:

$$v(t) = Ri(t) + L\frac{di(t)}{dt} + k_b\omega(t)$$

Mechanical Model (angular version of Newton's second law):

$$I\frac{d\omega(t)}{dt} = k_T i(t) - \eta\omega(t) - \tau(t)$$

Moment of inertia

Torque constant

Friction

Load torque

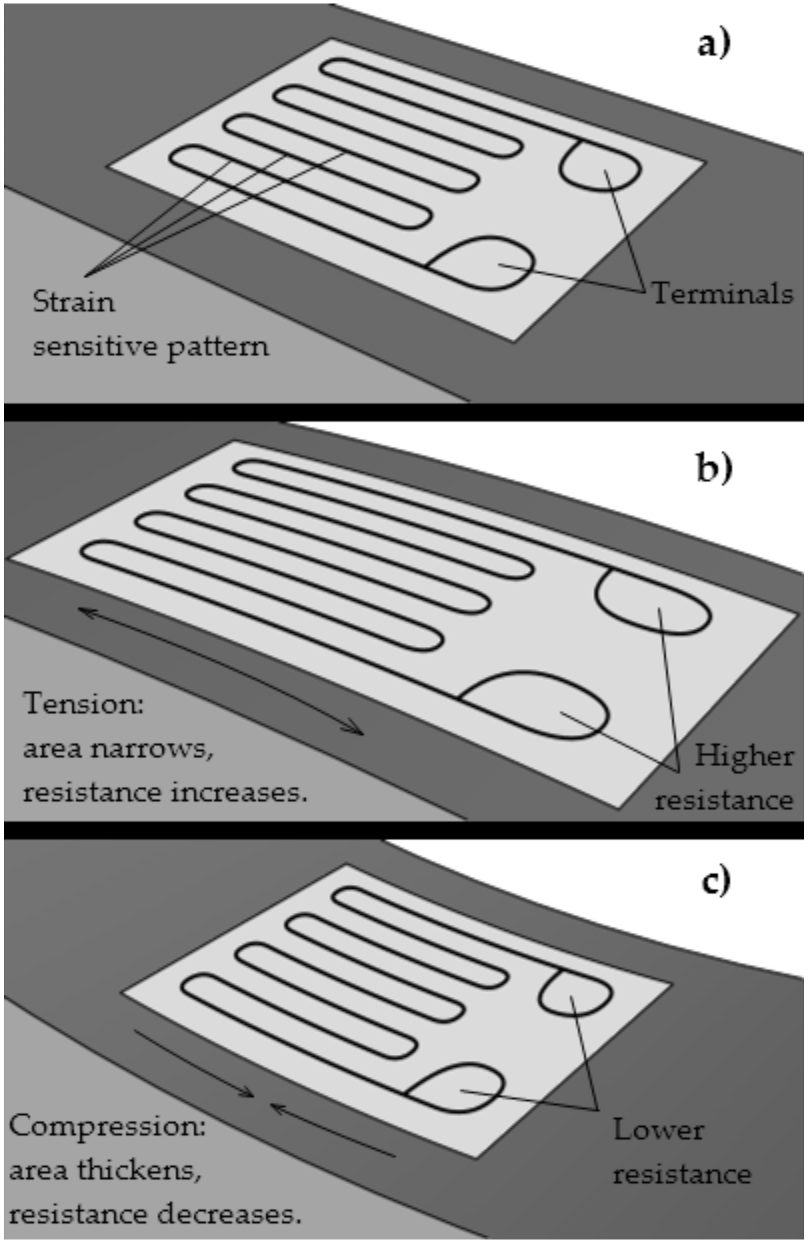
Summary for Lecture

- Overview of Sensors and Actuators
- How Accelerometers work
- Affine Model of Sensors
- Bias and Sensitivity
- Faults in Sensors
- Brief Overview of Actuators

Extra Slides Follow

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

Noise & Signal Conditioning

Parsevals theorem relates the energy or the power in a signal in the time and frequency domains. For a finite energy signal x, the energy is

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

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

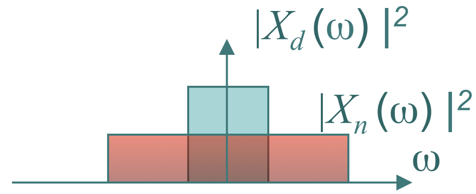
$$x(t) = x_d(t) + x_n(t)$$

then

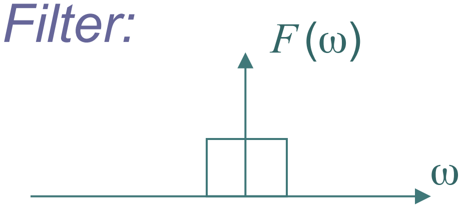
$$X(\omega) = X_d(\omega) + X_n(\omega)$$

Suppose that x_d is a narrowband signal and x_n is a broadband signal. Then the *signal to noise ratio* (SNR) can be greatly improved with filtering.

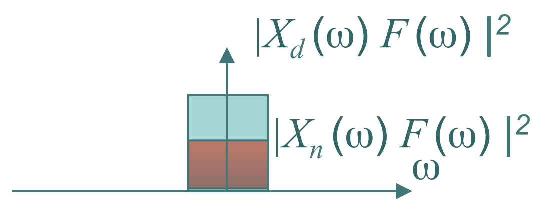
Example:



Filter:



Filtered signal:



A full treatement of this requires random processes.

References

John Rushby, "Formal Verification of Marzullo's Sensor Fusion Interval," CSL Technical Report, January 2002, SRI International, Menlo Park, CA.

http://www.csl.sri.com/users/rushby/papers/sensors.pdf