Cyber-Physical Systems

Sensors & Actuators

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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”

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

Sensor-Rich Cars

- Source: Analog Devices

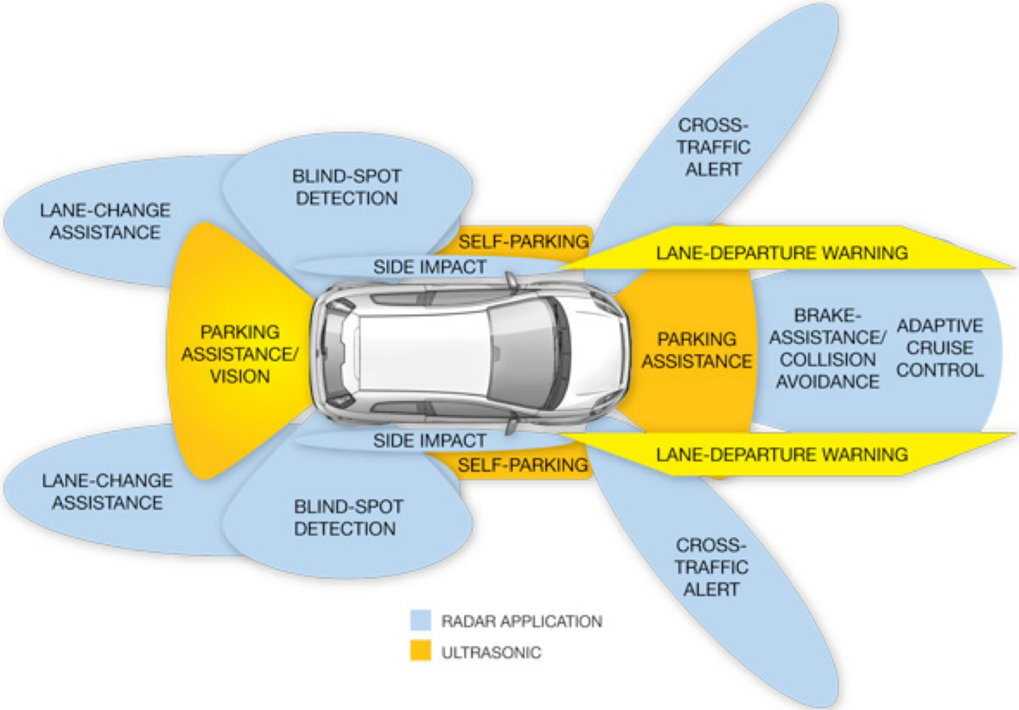
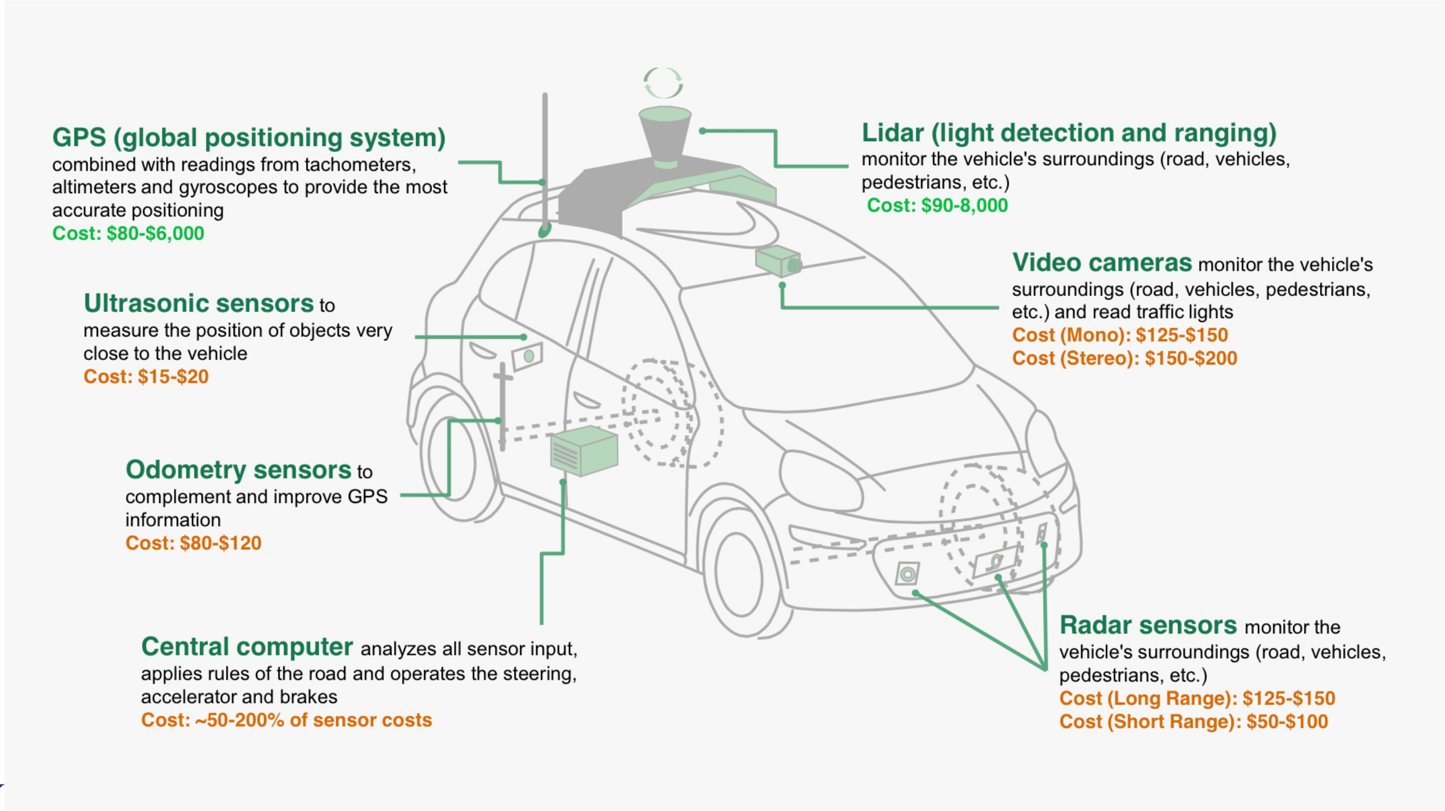


Figure 2 Several driver-assistance systems are currently using radar technology to provide blind-spot detection, parking assistance, collision avoidance, and other driver aids (courtesy Analog Devices).

Sensor-Rich Cars

- Source: Wired Magazine



GPS (global positioning system)
combined with readings from tachometers, altimeters and gyroscopes to provide the most accurate positioning
Cost: $80-$6,000

Ultrasonic sensors to measure the position of objects very close to the vehicle
Cost: $15-$20

Odometry sensors to complement and improve GPS information
Cost: $80-$120

Central computer analyzes all sensor input, applies rules of the road and operates the steering, accelerator and brakes
Cost: ~50-200% of sensor costs

Lidar (light detection and ranging)
monitor the vehicle's surroundings (road, vehicles, pedestrians, etc.)
Cost: $90-8,000

Video cameras monitor the vehicle's surroundings (road, vehicles, pedestrians, etc.) and read traffic lights
Cost (Mono): $125-$150
Cost (Stereo): $150-$200

Radar sensors monitor the vehicle's surroundings (road, vehicles, pedestrians, etc.)
Cost (Long Range): $125-$150
Cost (Short Range): $50-$100

Self-Driving Cars

Berkeley PATH Project Demo, 1999, San Diego.

Google self-driving car 2.0

Kingvale Blower

- Berkeley PATH Project, March 2005

Inertial Measurement Units (IMUs)

- Intertial Sensors:
  - Gyroscopes, Accelerometers, Magnetometers
  - gyroscope measures angular velocity in degrees/sec
  - accelerometer measures linear acceleration in m/s^2
  - magnetometer measures magnetic field strength in uT (micro Tesla) or Gauss (1 Gauss = 100 uT)
- Dead Reckoning:
  - Calculate current position based on previous position and change in *estimated* speeds

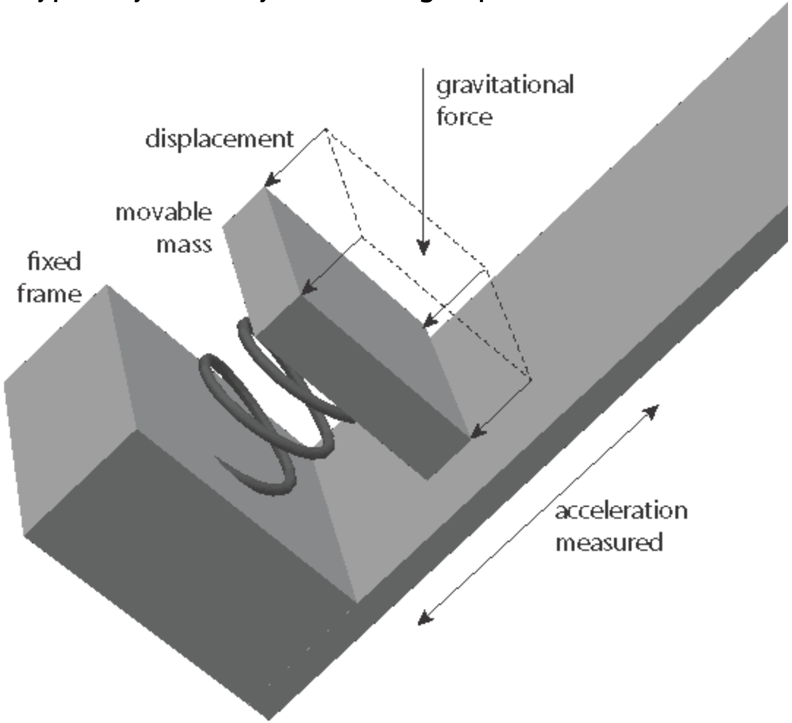
Degrees of Freedom (DoF)

- Movement of a rigid body in space
- 3 DoF
  - Translational Movement (x, y, z)
  - Rotational Movement (roll, yaw, pitch)
- 6 DoF
  - Combine 3 Translational Movement and 3 Rotational Movement
- 9DoF
  - Sensor Fusion with Magnetometer

Accelerometers

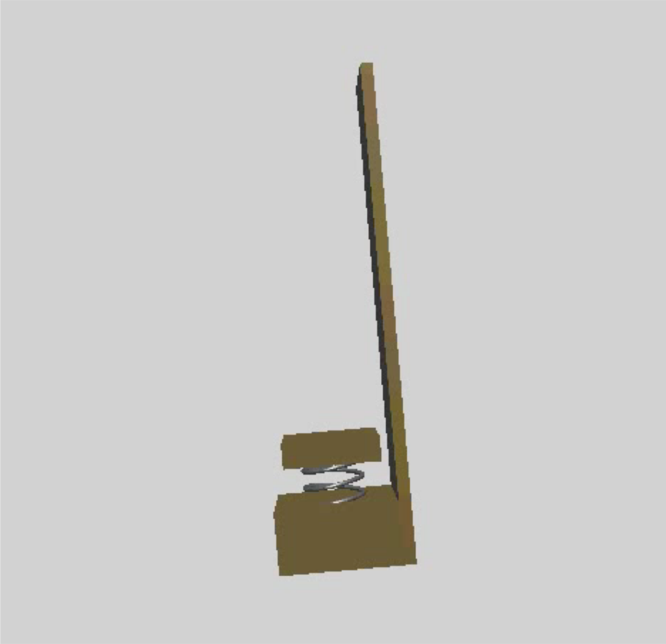
- Uses:
  - Navigation
  - Orientation
  - Drop detection
  - Image stabilization
  - Airbag systems
  - VR/AR systems

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.



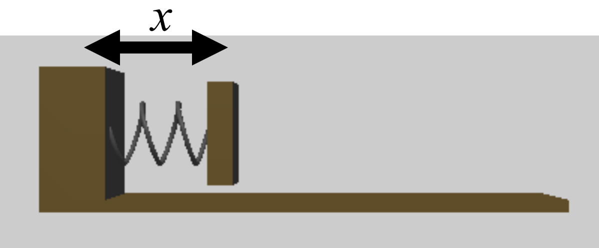
Spring-Mass-Damper Accelerometer

- 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

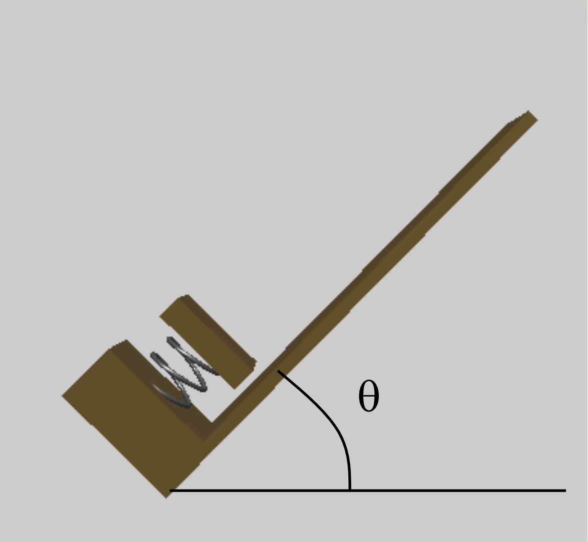
$$M\ddot{x}(t) + c\dot{x}(t) + kx(t) = kp.$$

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

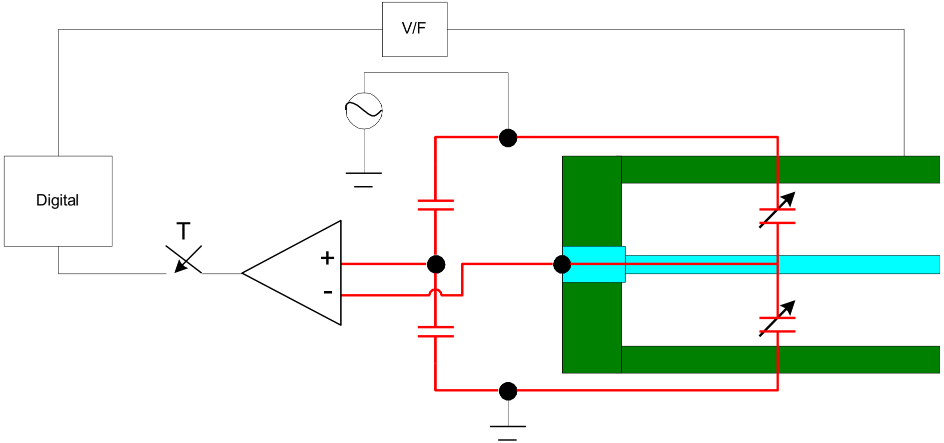
$$p(t) = p(0) + \int_0^t v(\tau) d\tau,$$

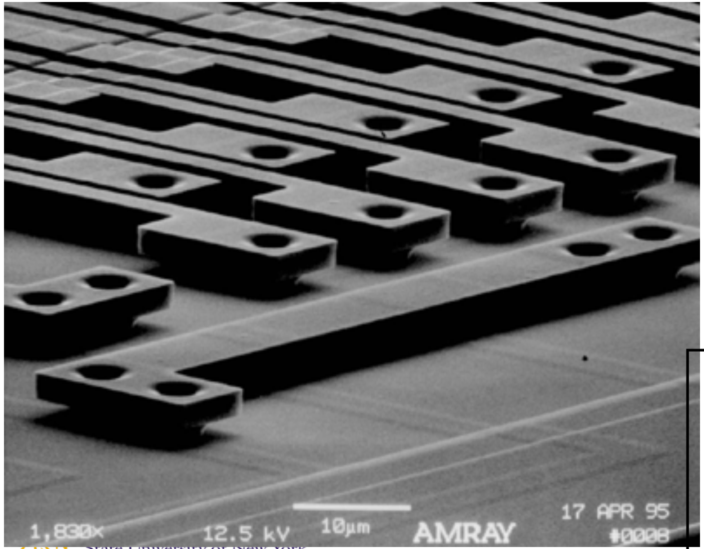
$$v(t) = v(0) + \int_0^t x(\tau) d\tau.$$

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

Feedback improves accuracy and dynamic range

- 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.



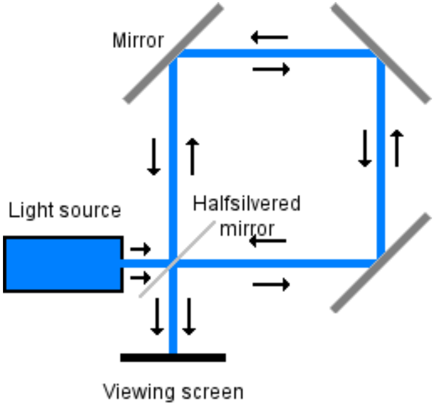


M. A. Lemkin, "Micro Accelerometer Design with Digital Feedback Control",

Ph.D. dissertation, EECS, University of California, Berkeley, Fall 1997

Measuring Changes in Orientation: Gyroscopes

- MEMS Gyros: microelectromechanical systems using small resonating structures
- Optical Gyros:
  - 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.



Magnetometers

- 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.

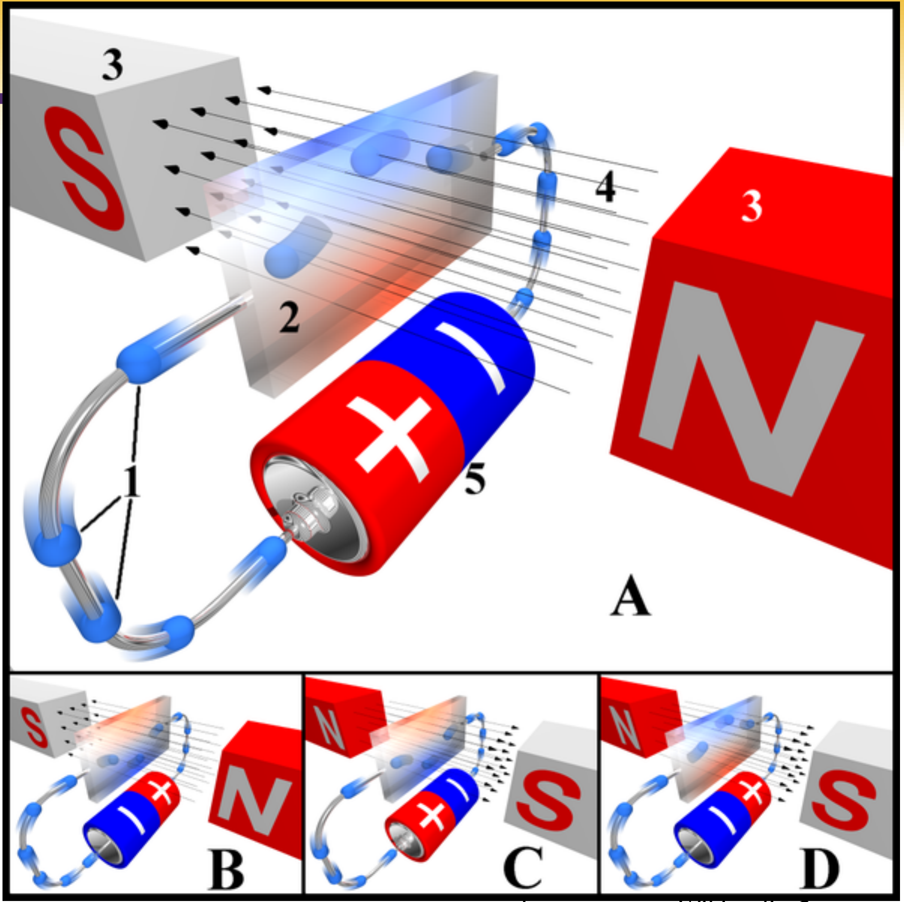


Image source: Wikipedia Commons

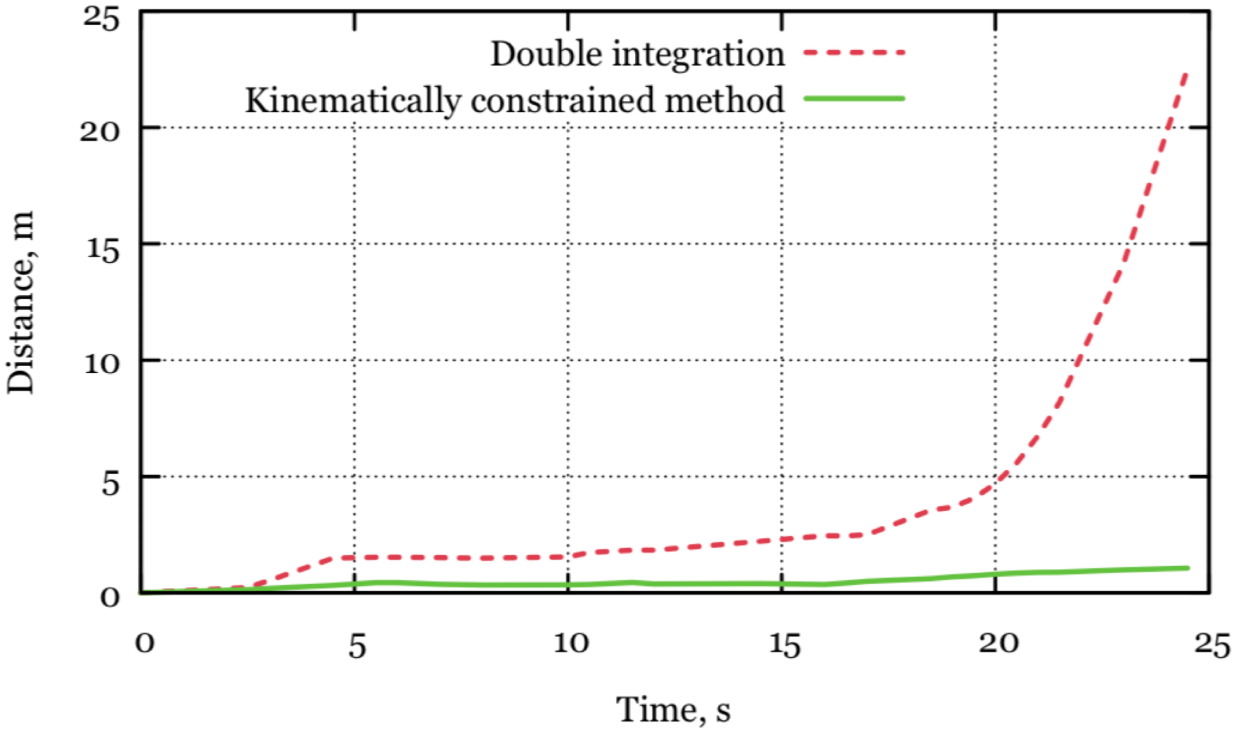
Edwin Hall discovered this effect in 1879.

Inertial Navigation Systems

- 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!

How often to calibrate?

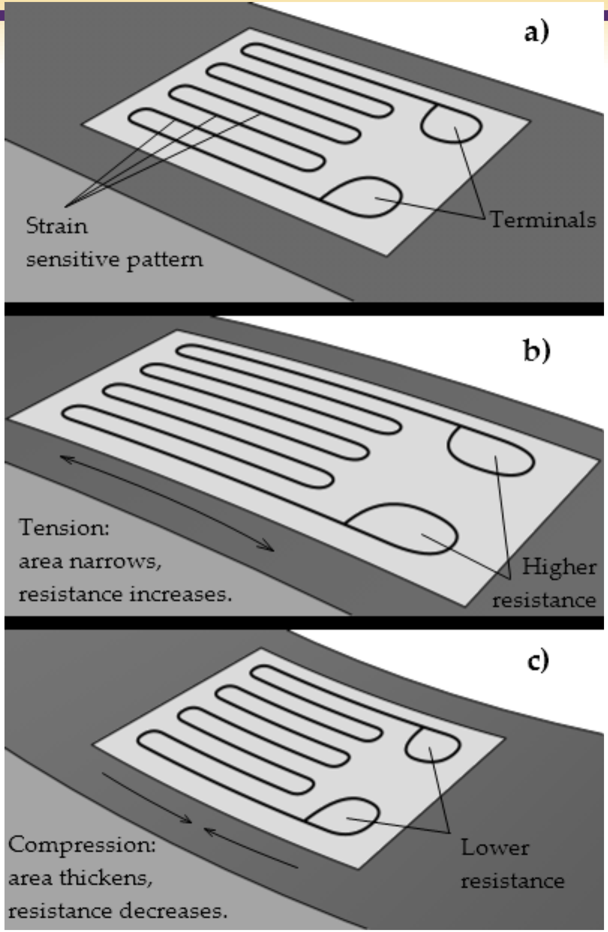
Minimizing Error



Head Tracking for the Oculus Rift, 2014

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.



Images from the 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
- Sampling
  - Aliasing
  - Missed events
- Noise
  - Analog signal conditioning
  - Digital filtering
  - Introduces latency
- Failures
  - Redundancy (sensor fusion problem)
  - Attacks (e.g. Stuxnet attack)

Sensor Calibration

- Linear and Affine Functions

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

$$f\big(x(t)\big) = ax(t) + b$$

- Affine Sensor Model

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

- Sensitivity (a), Bias (b) and Noise (n)
  - Sensitivity specifies the degree to which the measurement changes when the physical quantity changes

Range and Dynamic Range

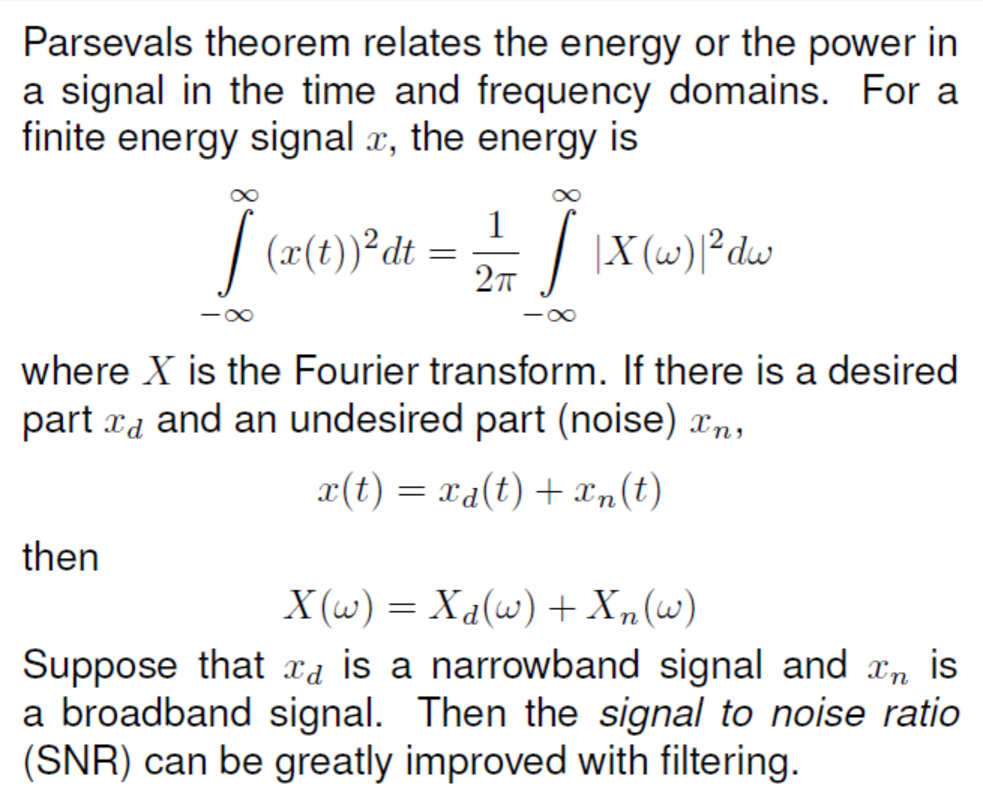
- Range

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

- Dynamic Range

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

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

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

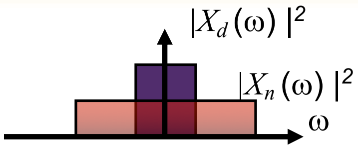
where X is the Fourier transform. If there is a desired part x_d and an undesired part (noise) x_n,

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

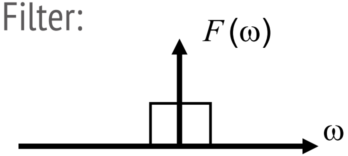
then

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

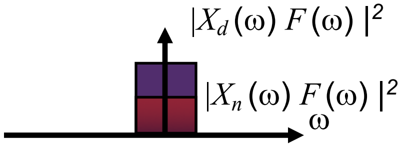
Suppose that x_d is a narrowband signal and x_n is a broadband signal. Then the *signal to noise ratio* (SNR) can be greatly improved with filtering.



Filter:



Filtered signal:



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]

Model of a Motor

- Electrical Model:

Back electromagnetic force constant

Angular velocity

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

- 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

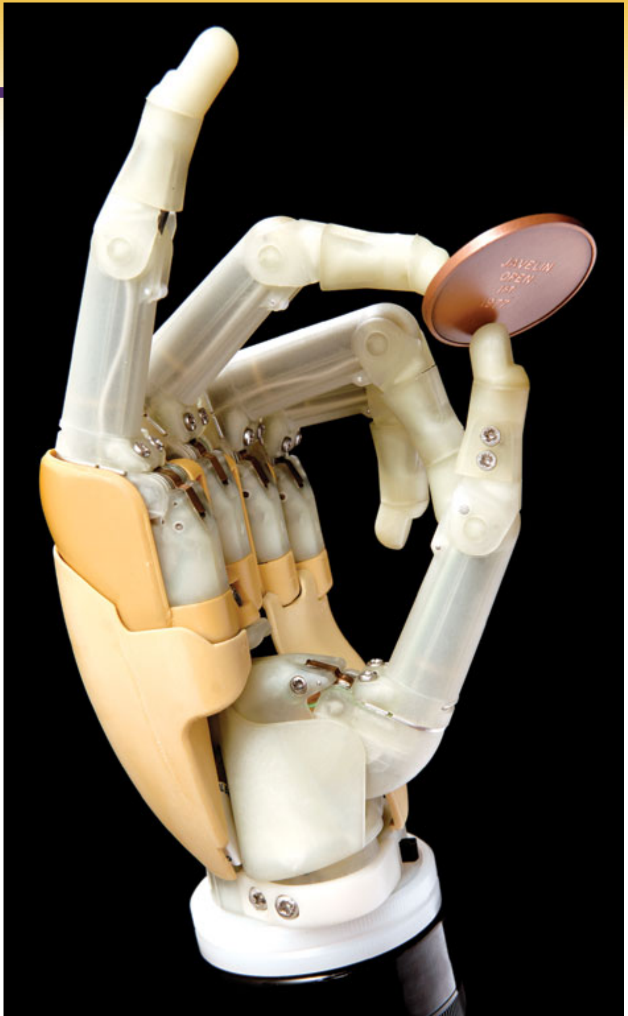
Friction

Load torque

Motor Controllers

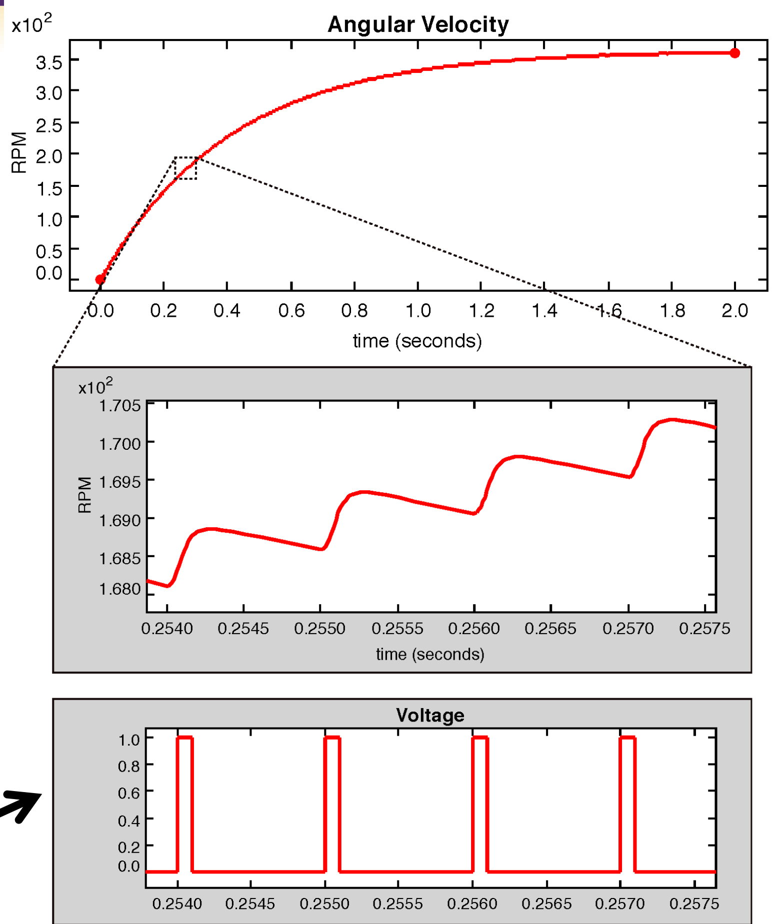
- Bionic hand from Touch Bionics costs $18,500, has and five DC motors, can grab a paper cup without crushing it, and turn a key in a lock. It is controlled by nerve impulses of the user's arm, combined with autonomous control to adapt to the shape of whatever it is grasping.

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%

How to deal with Sensor Errors

- Difficult Problem, still research to be done

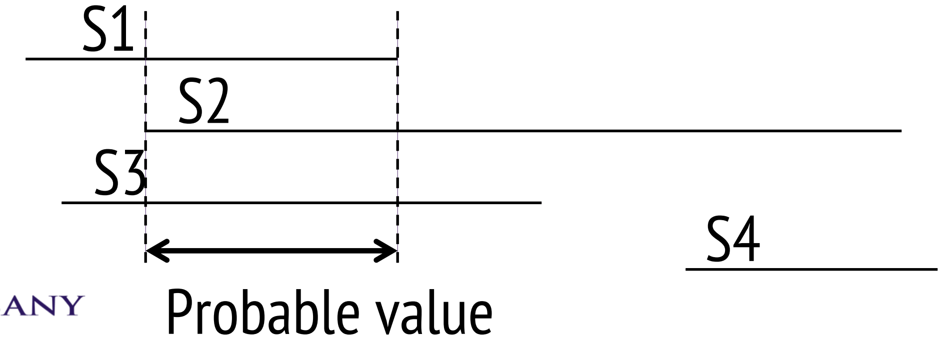
- Possible approach: Intelligent sensor communicates an interval, not a point value
  - Width of interval indicates confidence, health of sensor

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

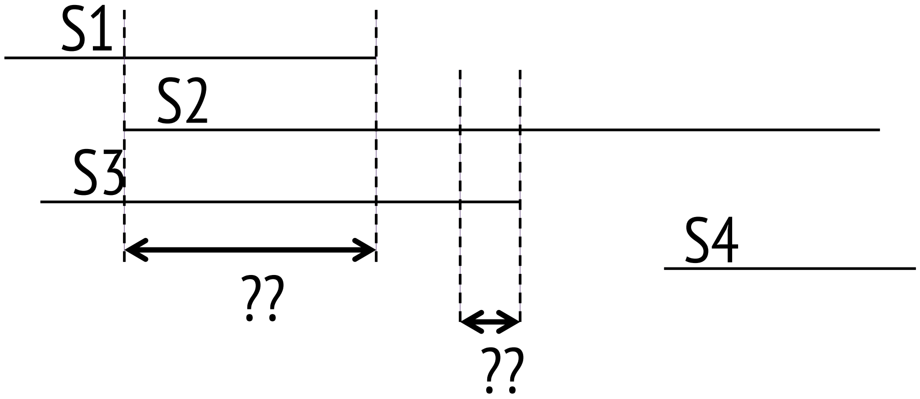
Example: Four sensors, at most one faulty

- 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.



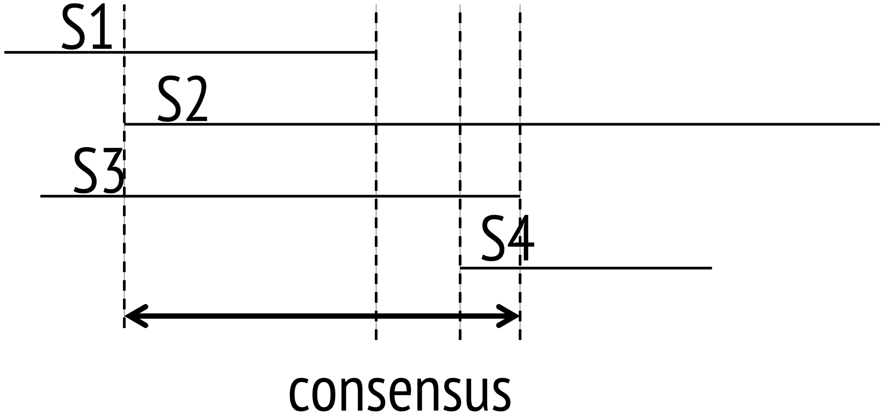
Example: Four sensors, at most one faulty

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



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!



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.

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