Lecture 3 : Sensors and Actuators

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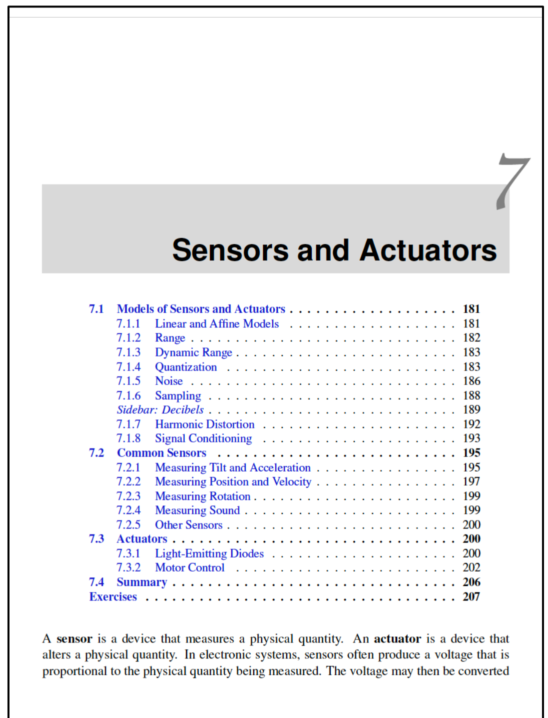
Outline

- What are sensors? Actuators?
- How Accelerometers work
- Affine Model of Sensors
- Bias and Sensitivity
- Faults in Sensors
- Overview of Actuators



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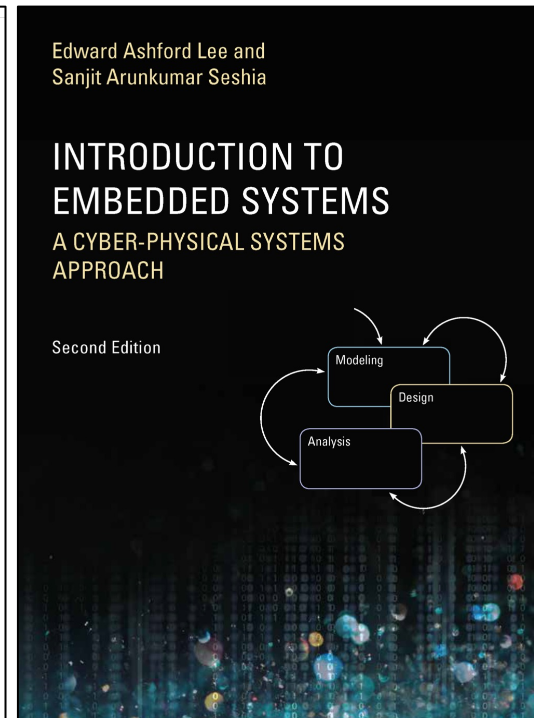
Sensors and Actuators

A **sensor** is a device that measures a physical quantity. An **actuator** is a device that alters a physical quantity. In electronic systems, sensors often produce a voltage that is proportional to the physical quantity being measured. The voltage may then be converted



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”

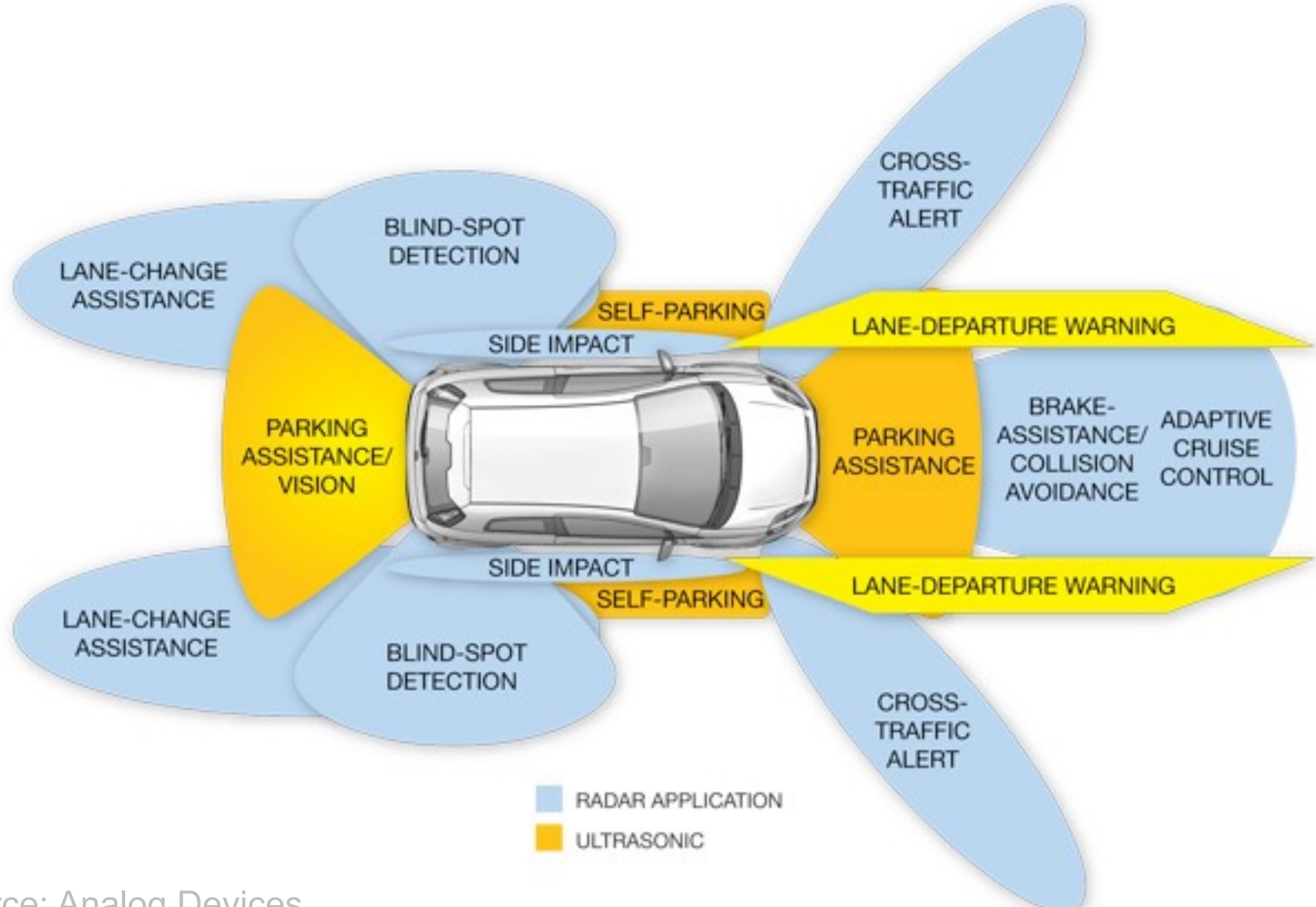
Sensors and Actuators – The Bridge between the Cyber and the Physical

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
- …

Sensor-Rich Cars



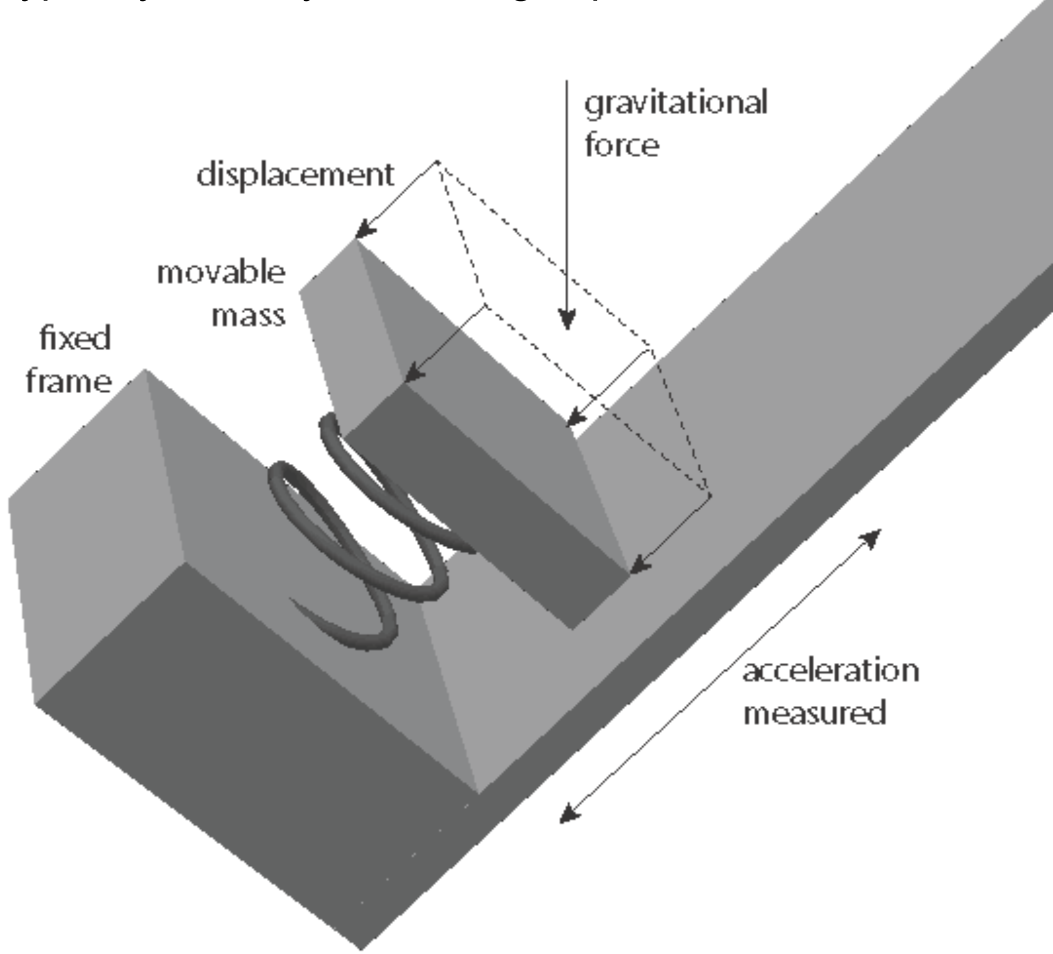
Source: Analog Devices

Accelerometers

Uses:

- Navigation
- Orientation
- Drop detection
- Image stabilisation
- Airbag 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.

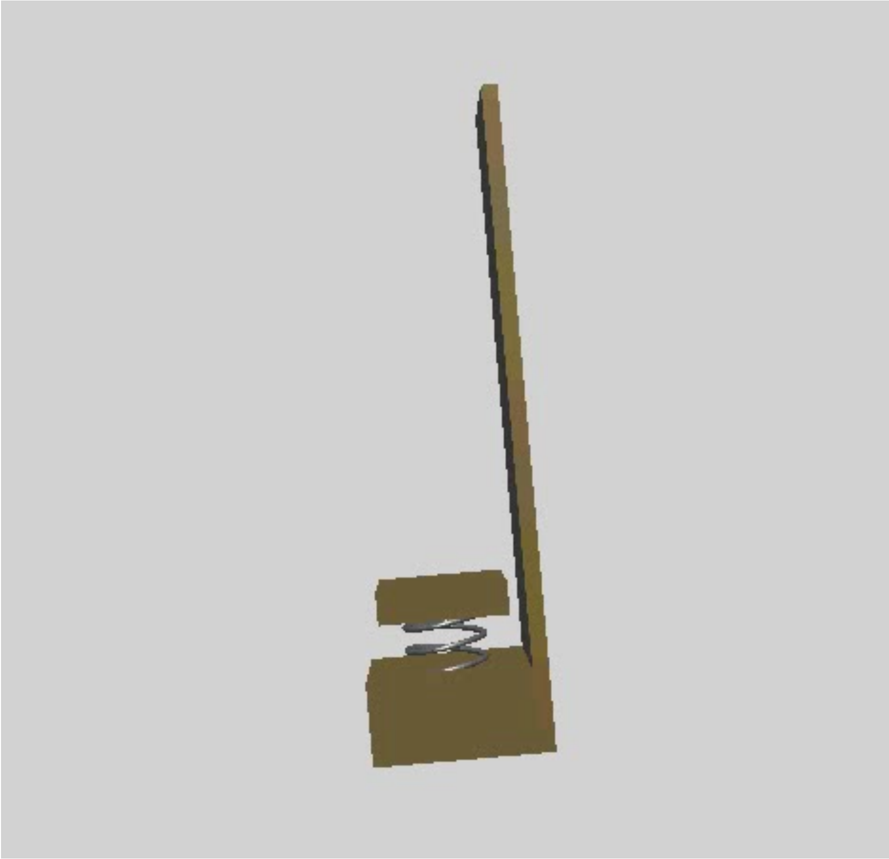


Spring-Mass-Damper Accelerometer

- By Newton's second law, F=ma.

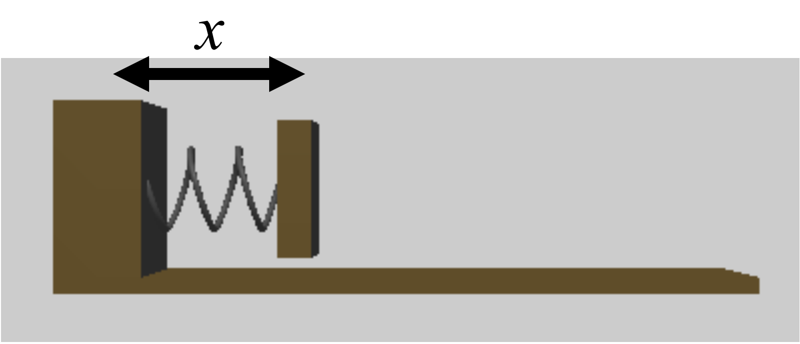
- For example, F could be the Earth's gravitational force.

- 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:

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

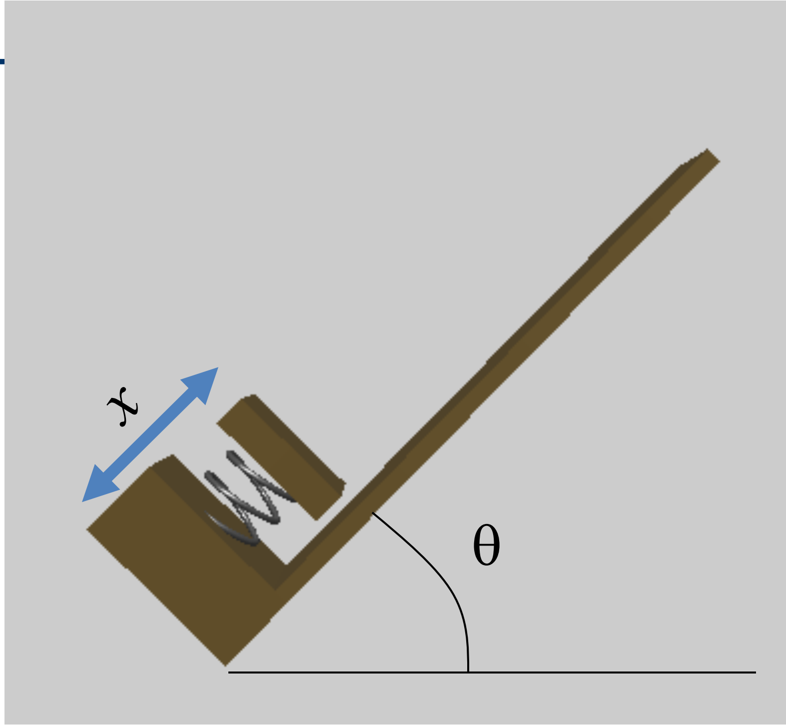
Newton's second law:

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

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

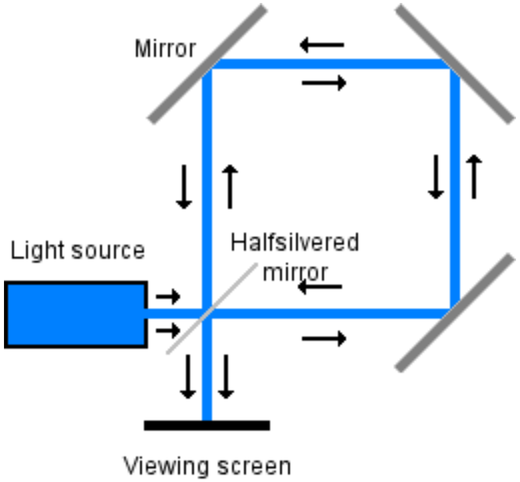
- Separating tilt from acceleration
- Vibration
- Nonlinearities in the spring or damper
- Integrating twice to get position: Drift

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

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

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

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 initialisation 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

Affine sensor model

A sensor measures a physical quantity $x(t)$, e.g. temperature.

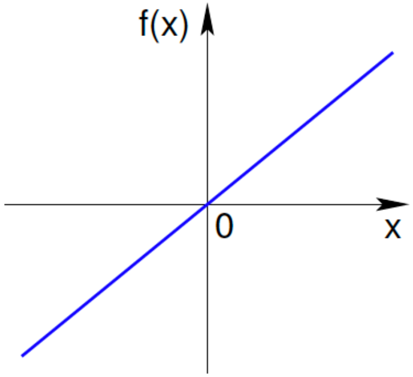
The sensor reports quantity $f(x(t))$, often a voltage.

Function $f\colon \mathbb{R} \to \mathbb{R}$ maps a real physical quantity $x(t)$ to a real physical quantity $f(x(t))$.

A linear function $f\colon \mathbb{R} \to \mathbb{R}$ has the form

$$f(x) \;=\; ax$$

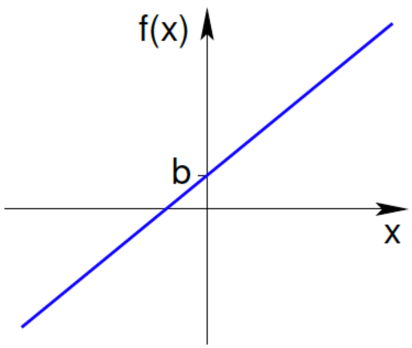
for some constant $a \in \mathbb{R}$.



If the straight line $f(x)$ does not pass through the origin, i.e. $f(0) \neq 0$, then

$$f(x) = ax + b\,, \quad b \neq 0$$

is an affine function with bias $b \in \mathbb{R}$.



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]					

Example

acceleration (g)

x

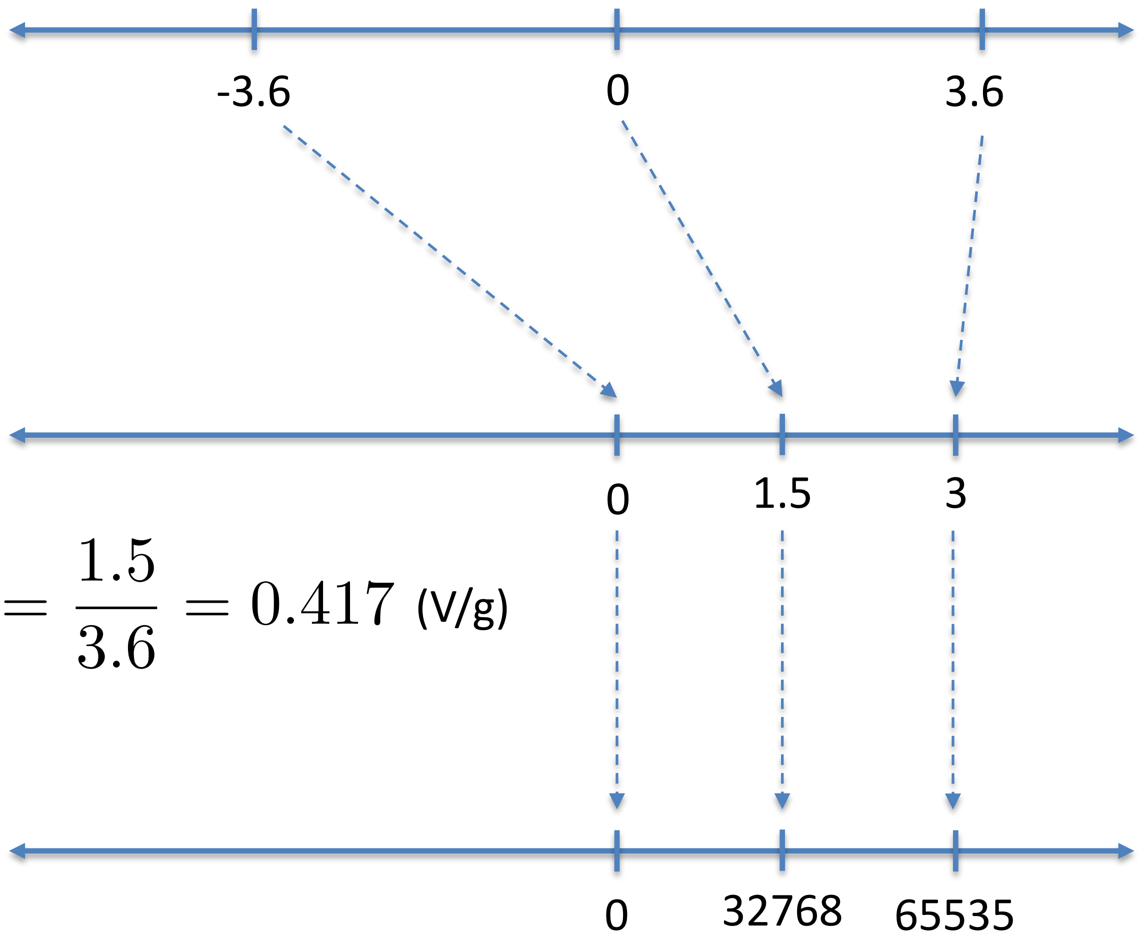
voltage (V)

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

$$b = 1.5 \text{ (V)} \qquad a = \frac{1.5}{3.6} = 0.417 \text{ (V/g)}$$

ADC – 16 bits

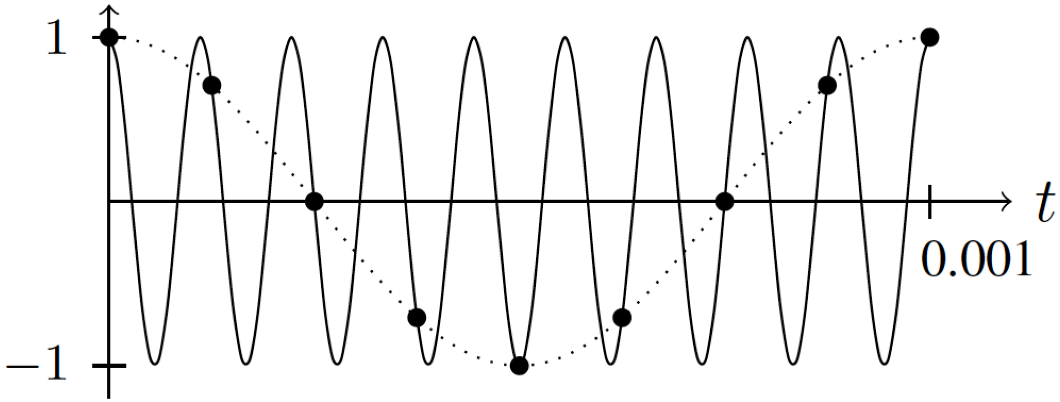
$$[0, 3] \rightarrow [0, 2^{16} - 1]$$



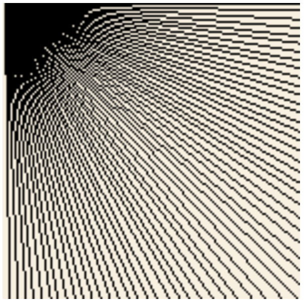
Aliasing: The Effect of Undersampling

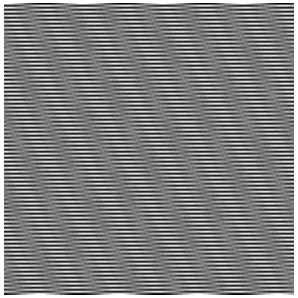
Sampled data is vulnerable to *aliasing*, where high frequency components masquerade as low frequency components.

Careful modelling 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.





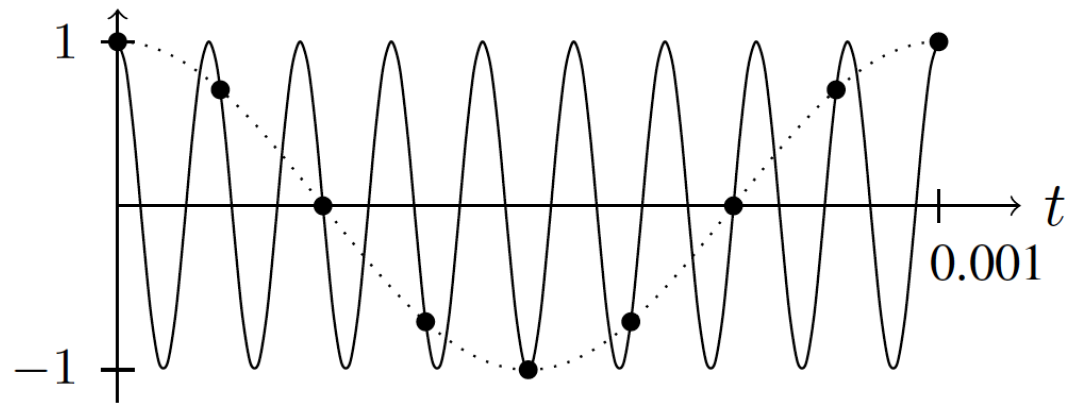
Digitally sampled images are vulnerable to aliasing as well, where patterns and edges appear as a side effect of the sampling. Optical blurring of the image prior to sampling avoids aliasing, since blurring is spatial low-pass filtering.

Aliasing: The Effect of Undersampling

Aliasing is complex (Sec 7.3 of Signal & Systems, Oppenheim, et al.)

A useful rule of thumb is provided by Nyquist-Shannon sampling theorem.

If you sample a signal with highest frequency *R*/2, then sampling at a rate at least *R* results in samples that uniquely represent the signal.



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

Informal Version of the Sampling Theorem:

A set of samples at rate R=1/T uniquely define a continuous times signal that is a sum of sinusoidal components with frequencies less than R/2 .

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,

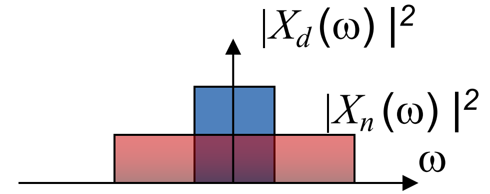
$$x(t) = x_d(t) + x_n(t)$$

then

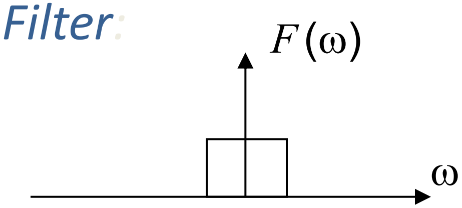
$$X(\omega) = X_d(\omega) + X_n(\omega)$$

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.

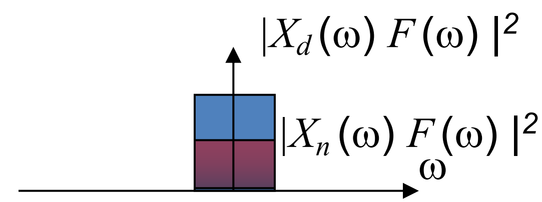
•*Example:*



Filter:



Filtered signal:



A full treatment of this requires random processes.

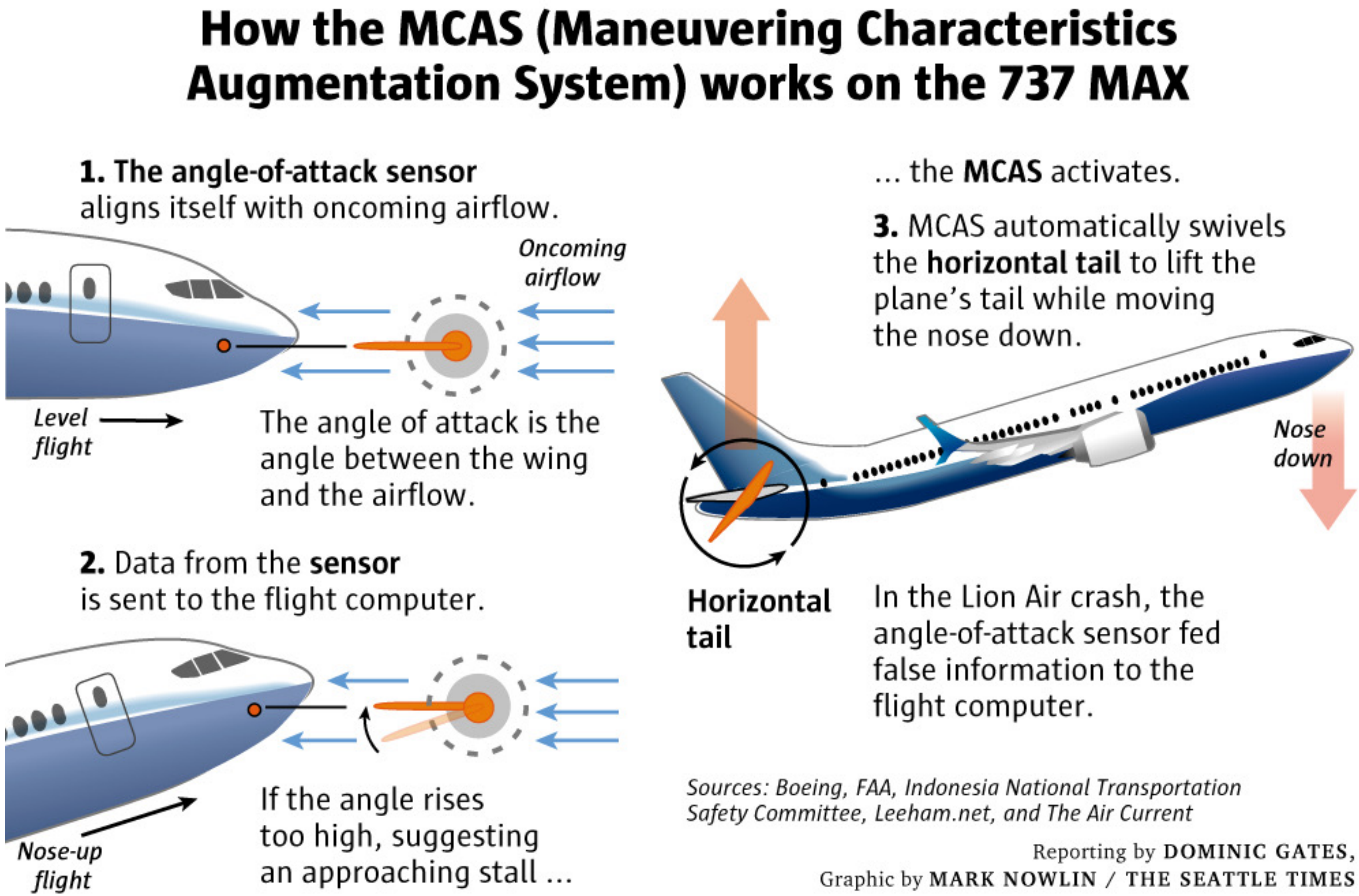
Faults and Errors in Sensors

- 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: in general a hard problem. Active research being done.
- One approach is to use redundancy

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

Boeing 737 MAX Incidents (Lion Air, Ethiopian Air, 2019)



Boeing 737 MAX Incidents (Lion Air, Ethiopian Air, 2019)

- If the system gets triggered erroneously—and the plane dives for no reason—a pilot can pull back on the control column to lift the nose up again.
- But every time a pilot straightens the plane out, the MCAS resets: the system can be triggered again…
- The pilot and the MCAS repeated a tug-of-war cycle 21 times.
- Like all 737s, the MAX actually has two “angle of attack” sensors.
- The MCAS was designed to take a reading from only one of them.

Design Issues with Sensors

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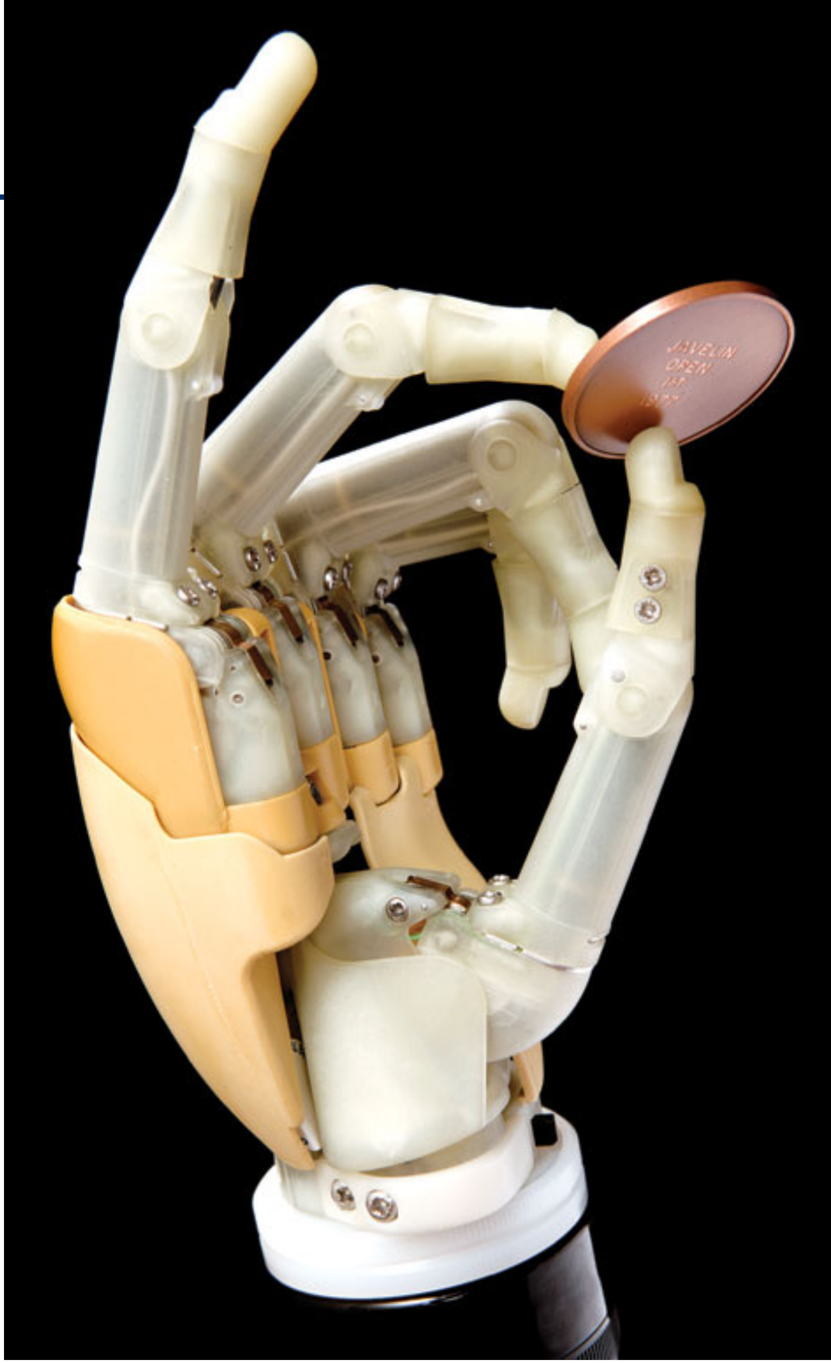
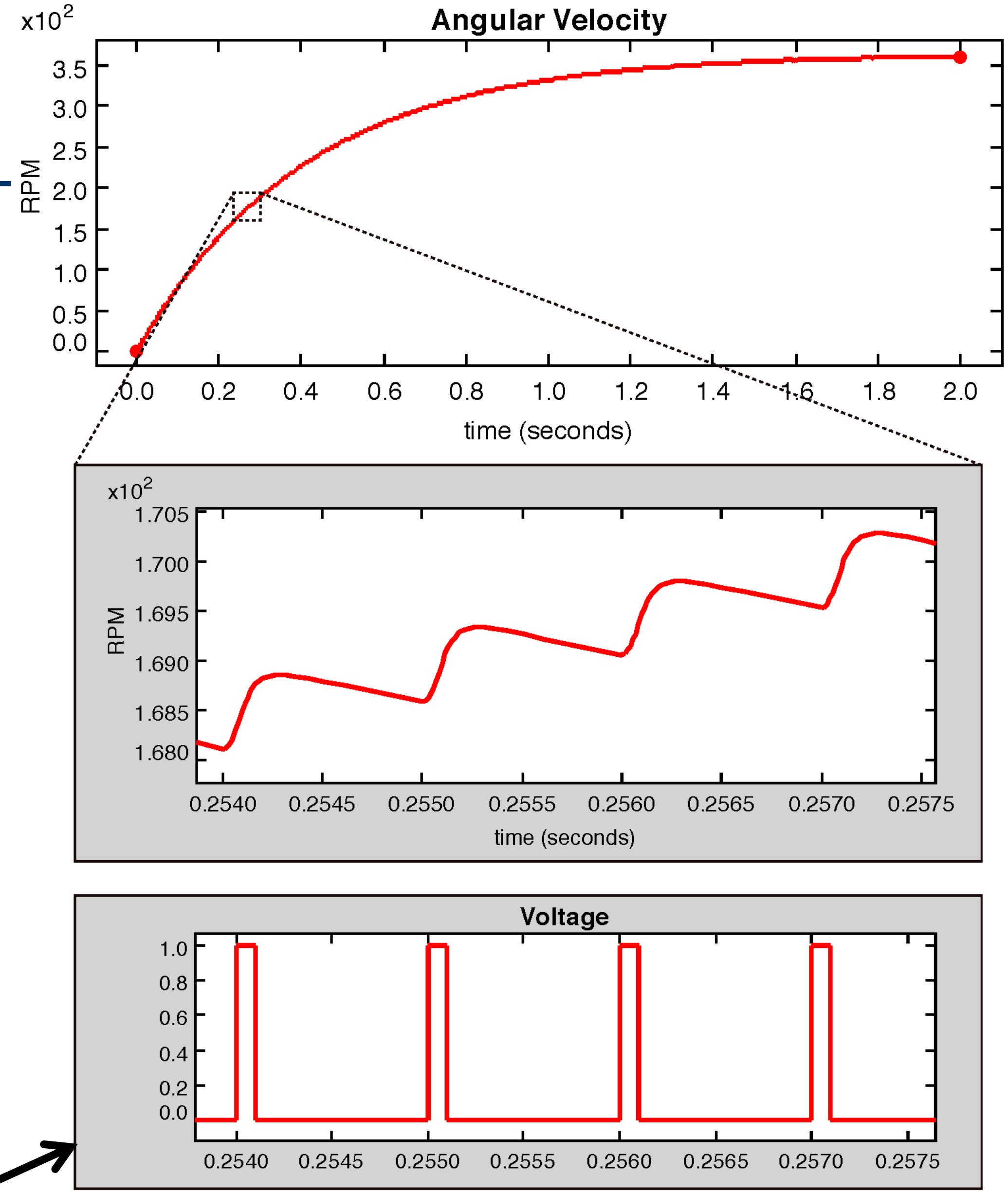
Motor Controllers

Bionic hand from Touch Bionics costs $30,000, and has 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

- 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

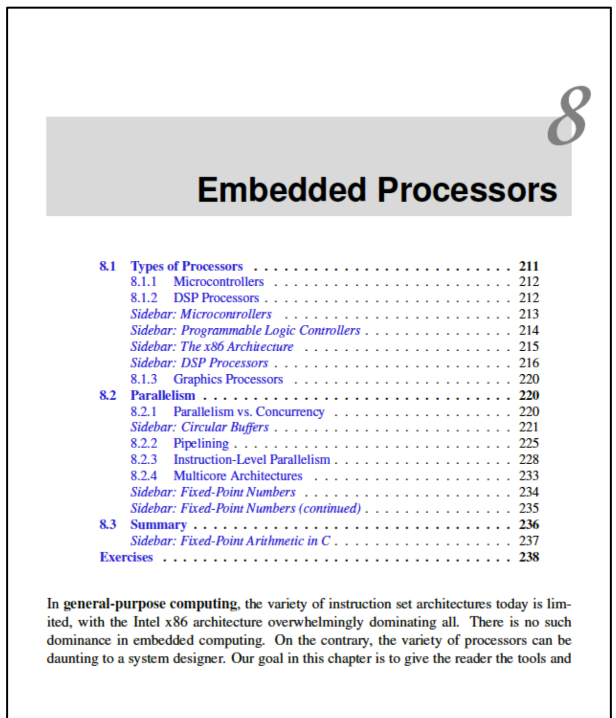
Torque constant

Friction

Load torque

Things to do …

- Download the textbook and read Chapter 8
- Sign up to a group in your workshop class
- MUST do HSW Quiz to attend on-campus workshop
- Read over Workshop 1 and do the pre-workshop work



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Embedded Processors

In **general-purpose computing**, the variety of instruction set architectures today is limited, with the Intel x86 architecture overwhelmingly dominating all. There is no such dominance in embedded computing. On the contrary, the variety of processors can be daunting to a system designer. Our goal in this chapter is to give the reader the tools and