ECE 442/510
Internet of Things and Cyber Physical Systems

Lecture 10: Sensors and Actuators
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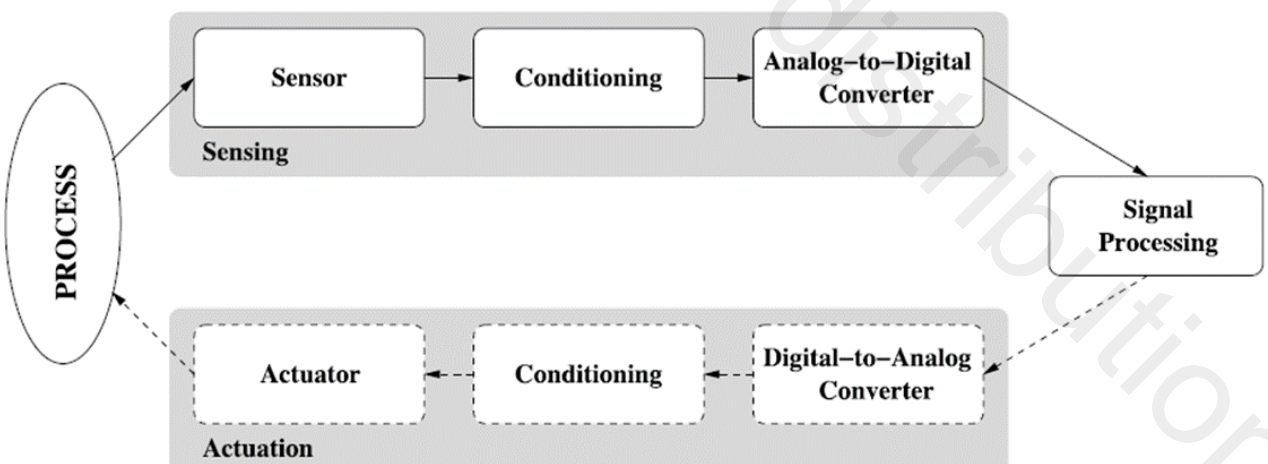
Sensors and Actuators

- **What is a transducer?**
  - A device that converts a primary form of energy into a corresponding signal with a different energy form
  - Energy forms are mechanical, thermal, electromagnetic, optical, chemical, etc.
- **What is a sensor?**
  - A device that measures a physical quantity
  - Sensing physical world – Active source or passive source interact with stimulus energy (A stimulus is anything that can trigger a physical or behavioral change)
- **What is an actuator?**
  - A device that modifies a physical quantity
  - Impacts the characteristics of a physical world



Sensing and Sensors

- **Sensing:** technique to gather information about physical objects or areas
- **Sensor (transducer):** object performing a sensing task; converting one form of energy in the physical world into electrical energy
- **Examples of sensors from human body**
  - Optical information (light) → eyes
  - Acoustic information (sound) → ears
  - Olfactory information (smell) → nose
  - Tactile information (shape, texture) → skin

  We get **tactile information** through sensory receptors located in the skin. The **tactile** system provides us with **information** about touch sensations: pressure, vibration, movement, temperature and pain. The **tactile** sense is made up of two components: the protective (or defensive) system and the discriminative system.

Commonly Detectable Phenomena

- Biological
- Chemical
- Electric
- Electromagnetic
- Heat/Temperature
- Magnetic
- Mechanical motion (displacement, velocity, acceleration, etc.)
- Optical
- Radioactivity

Common Conversion Methods

- Physical
  - thermo-electric, thermo-elastic, thermo-magnetic, thermo-optic
  - photo-electric, photo-elastic, photo-magnetic
  - electro-elastic, electro-magnetic
  - magneto-electric
- Chemical
  - chemical transport, physical transformation, electro-chemical
- Biological
  - biological transformation, physical transformation

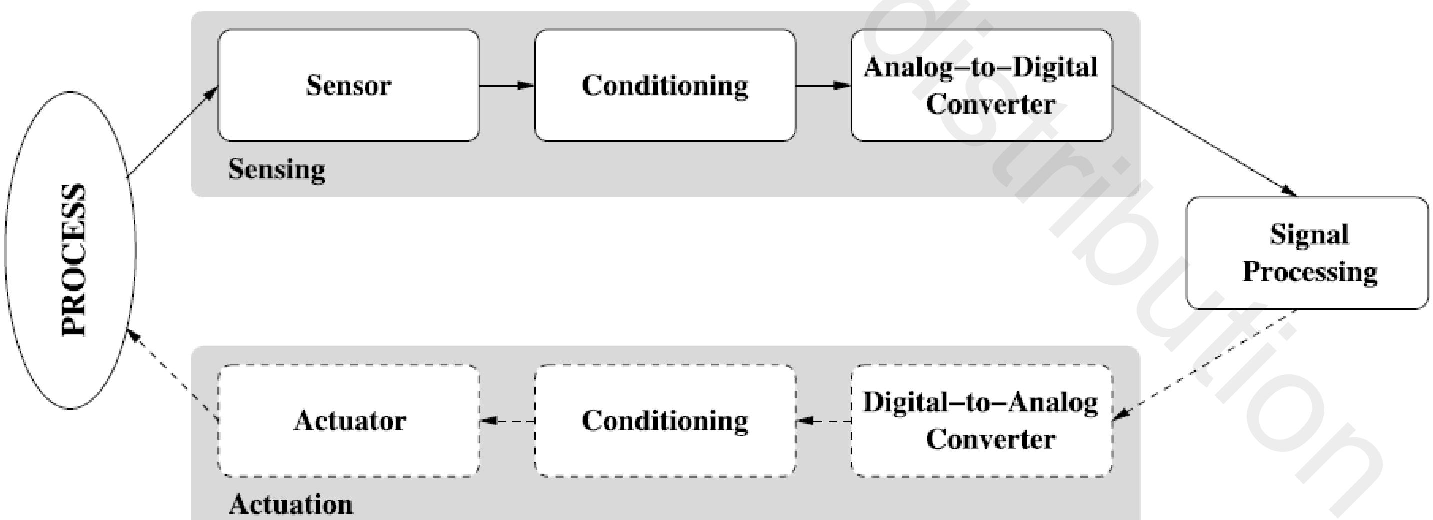
Any change in an organism that alters its general character and mode of life

Common Measured Quantities

Stimulus	Quantity
Acoustic	Wave (amplitude, phase, polarization), Spectrum, Wave Velocity
Biological & Chemical	Fluid Concentrations (Gas/Liquid)
Electric	Charge, Voltage, Current, Electric Field (amplitude, phase, polarization), Conductivity, Permittivity: a measure of resistance that is encountered when forming an electric field in a particular medium (capacitance)
Magnetic	Magnetic Field (amplitude, phase, polarization), Flux, Permeability
Optical	Refractive Index, Reflectivity, Absorption
Thermal	Temperature, Flux, Specific Heat, Thermal Conductivity
Mechanical	Position, Velocity, Acceleration, Force, Strain, Stress, Pressure, Torque

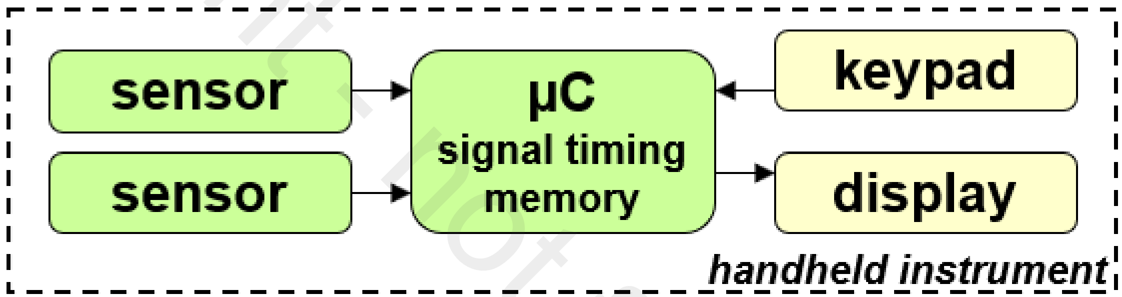
Sensing (Data Acquisition)

- **Sensors** capture phenomena in the physical world (process, system, plant)
- **Signal conditioning** prepare captured signals for further use (amplification, attenuation, filtering of unwanted frequencies, etc.)
- **Analog-to-Digital Conversion (ADC)** translates analog signal into digital signal
- Digital signal is processed, and output is often given (via **digital-analog converter and signal conditioner**) to an actuator (device able to **control the physical world**)

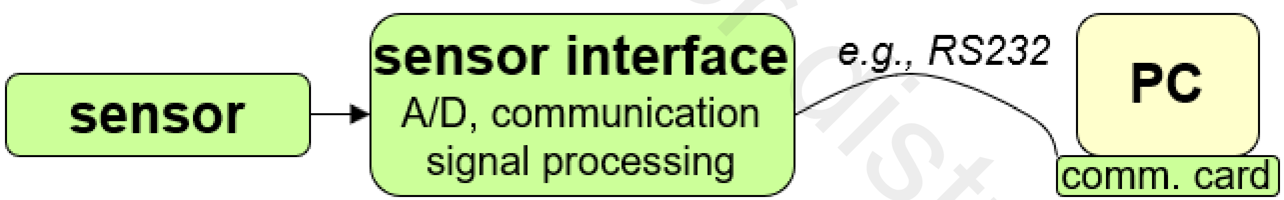


Sensors

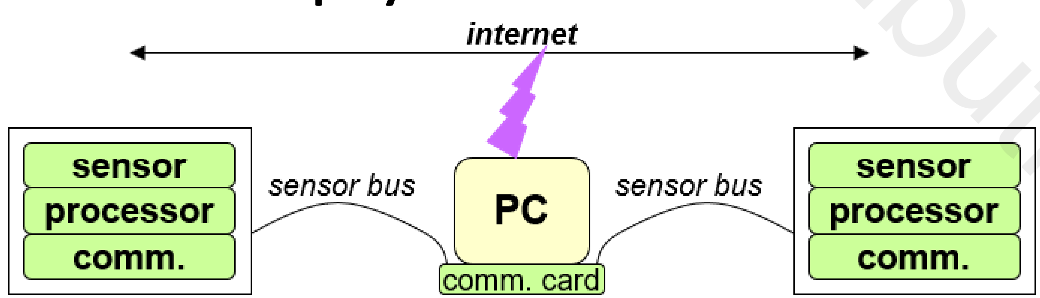
- Components vary with application
  - **Digital sensor with an instrument**



  - **Analog sensor analyzed by a PC**

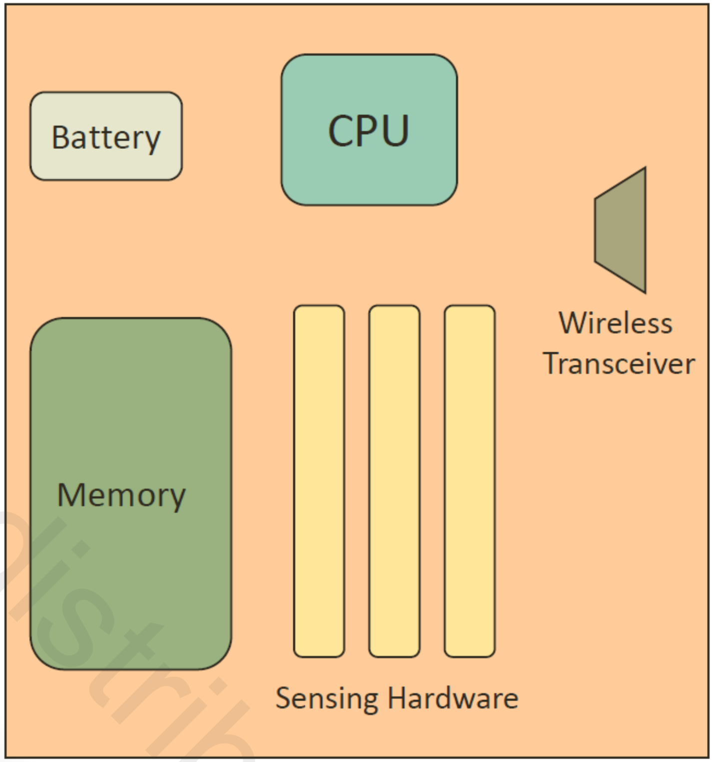


  - **Multiple sensors displayed over Internet**



Sensors – Smart and Connected

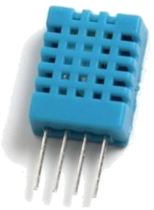
- Enabled by recent advanced in **MEMS (micro-electro-mechanical system)** technology
- **Integrated Wireless Transceiver**
- **Limited in Energy, Computation, Storage, Transmission range, Bandwidth**



Sensors and Actuators

- **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…

Internet of Things – Sensors

			
ECG Sensor	EEG Sensor	EMG Sensor	SpO_2 Pulse Oximeter
			
Blood Pressure	Temperature & Humidity	Air Flow (Breathing)	Accelerometer

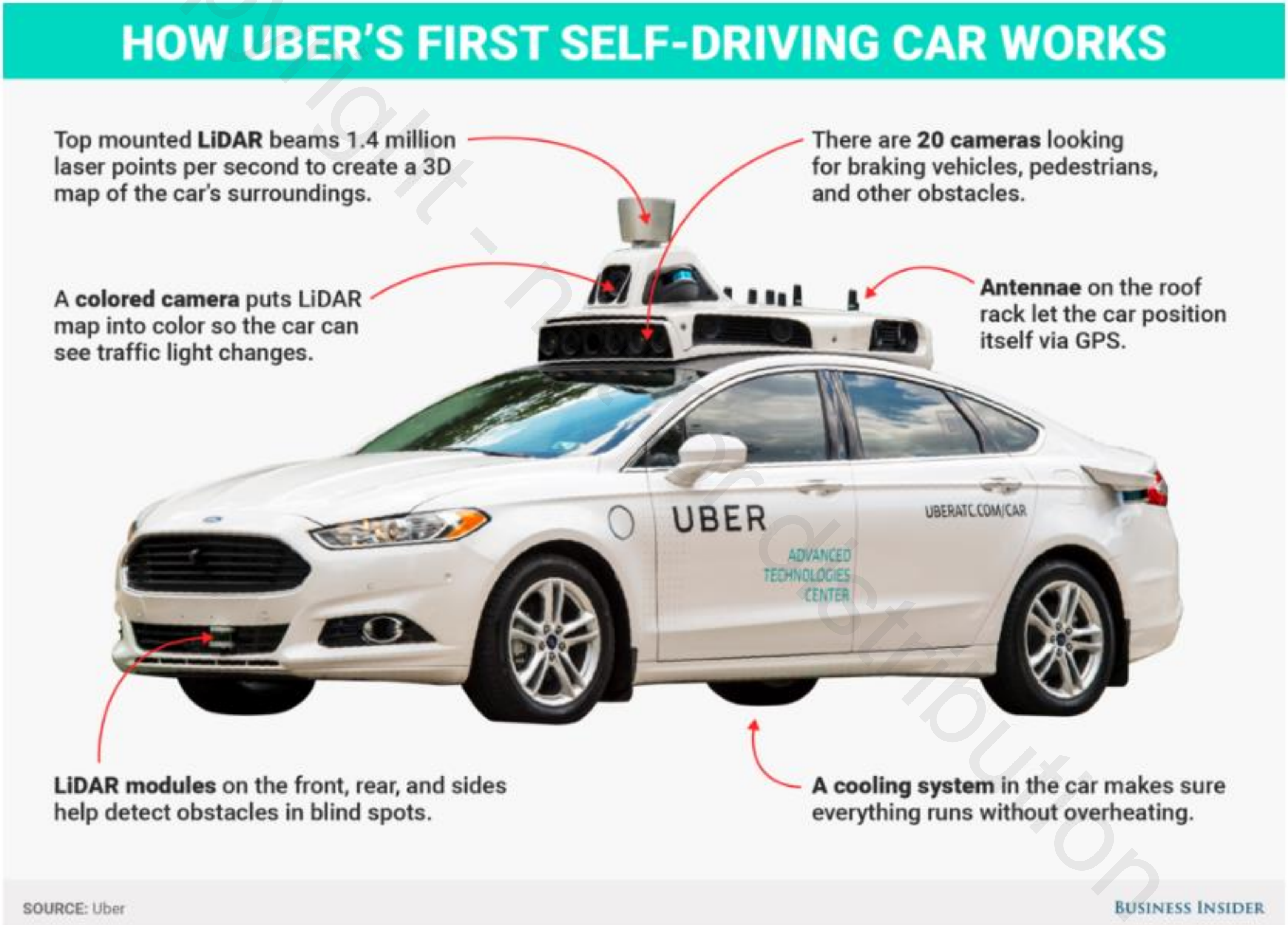
Internet of Things – Sensors

Sensors	Bandwidth	Purpose
Blood Pressure	0.01 – 10 Kbps	Max. and min. of blood pressure
Pulse Rate	0.01 – 10 Kbps	Heart beat rate
Temperature	0.01 – 10 Kbps	On-body/In-body temperature
Respiration	0.01 – 10 Kbps	Chest expansion/contraction
Glucose	0.01 – 10 Kbps	Sugar level in the blood
SpO_2	0.01 – 10 Kbps	Blood oxygen saturation level
EEG	10 – 200 Kbps	Brain wave activities
ECG	10 – 200 Kbps	Electrical activity of heart beats
EMG	10 – 500 Kbps	Electrical activity of the skeletal muscles

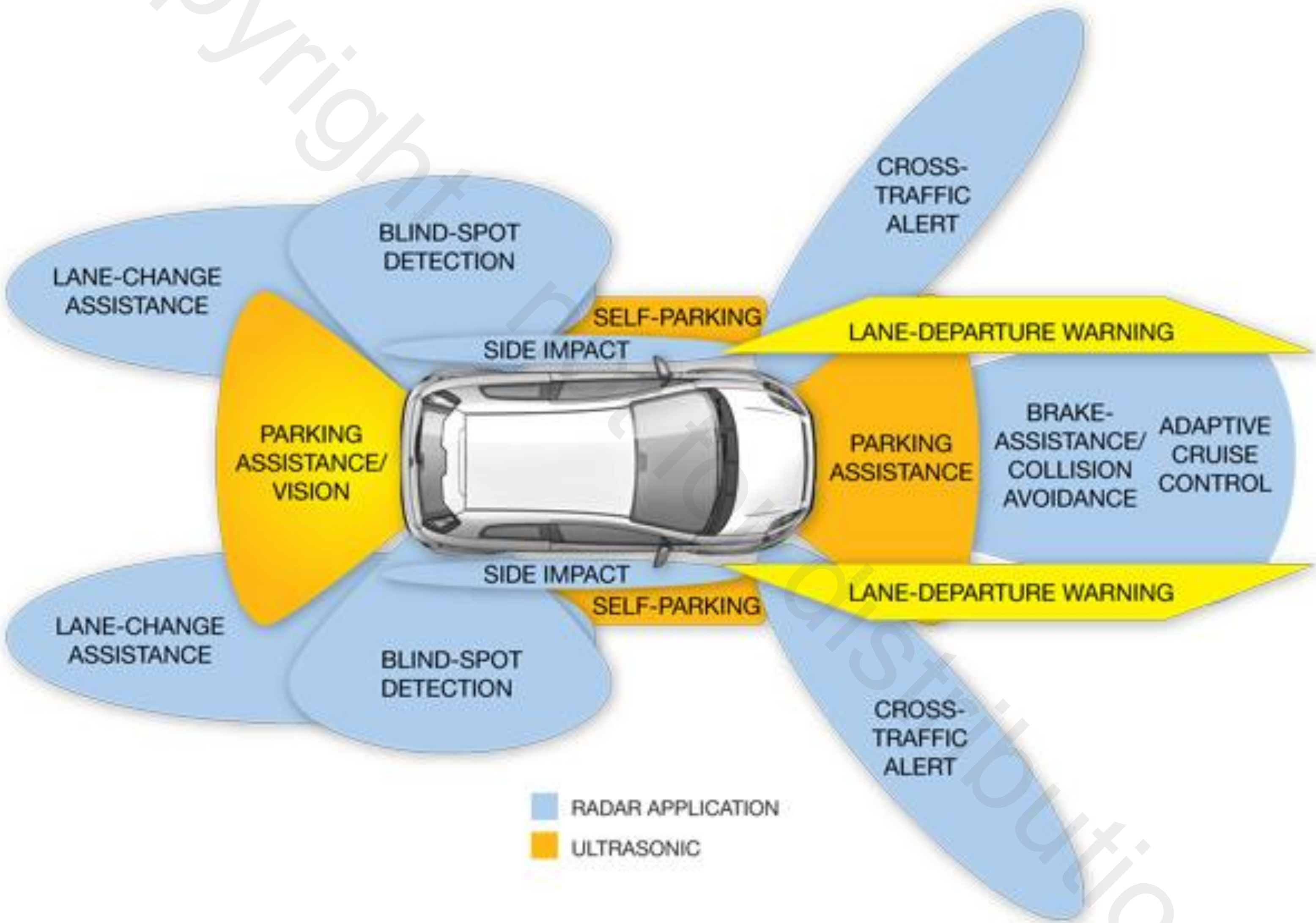
Internet of Things – Sensors

Body Sensors	Bandwidth	Purpose
Accelerometer	0.01 – 10 Kbps	Proper acceleration (G-Force)
Gyroscope	0.01 – 10 Kbps	Object orientation
Barometer	0.01 – 0.1 Kbps	Air pressure of current position
Contactless IR Temperature	0.01 – 0.02 Kbps	Object and ambient temperature
Magnetometer	0.01 – 0.5 Kbps	Direction of the magnetic field
Humidity	0.005 – 0.01 Kbps	Humidity of current position
GPS	0.001 – 0.01 Kbps	Latitude and longitude coordinates

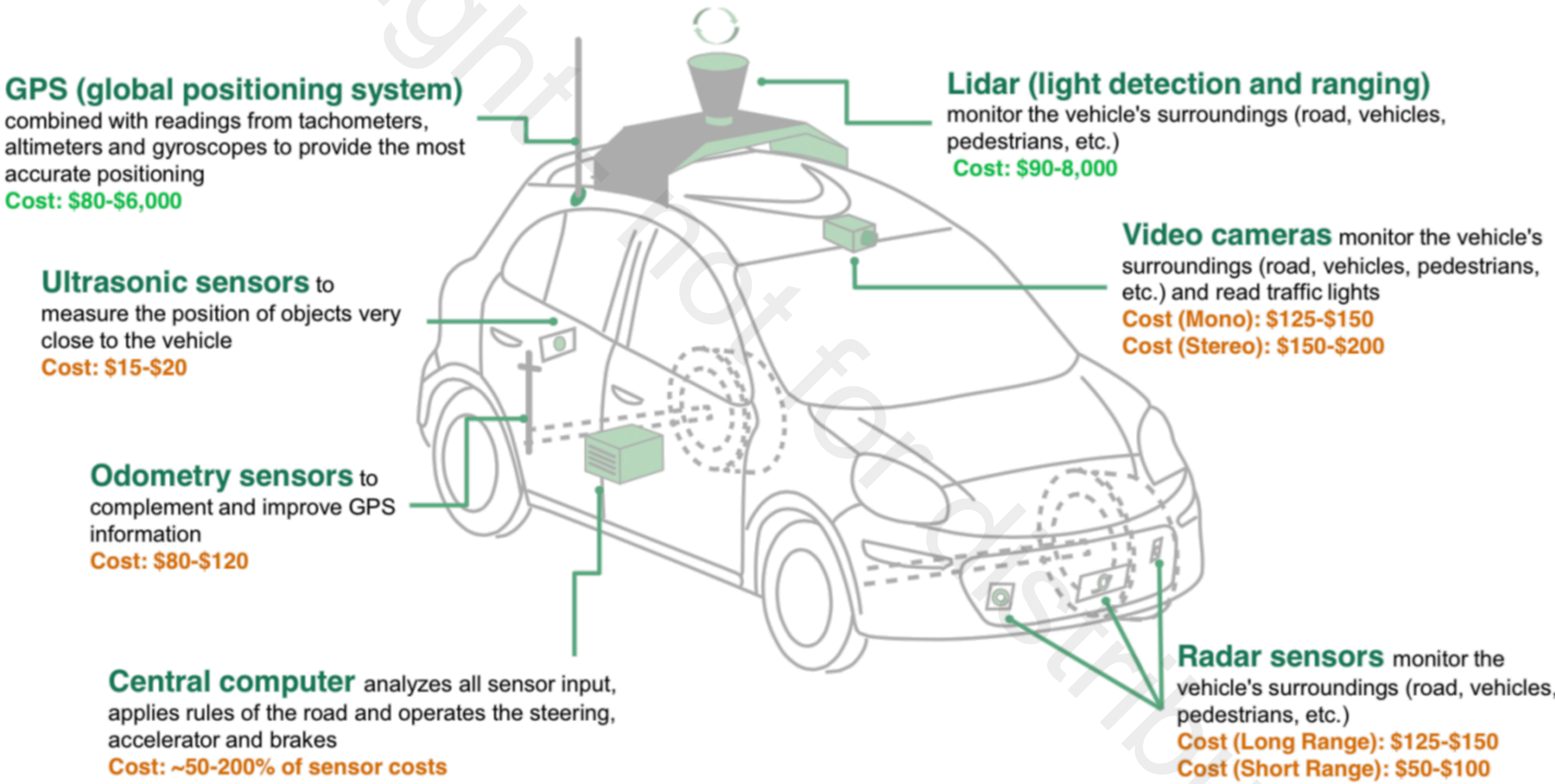
Self-driving Cars



Sensor-rich Cars

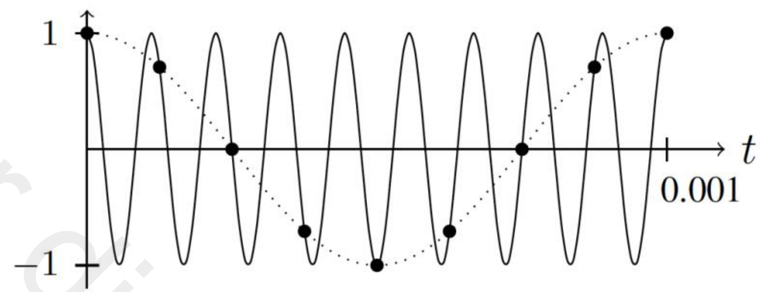


Sensor-rich Cars



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 condition 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

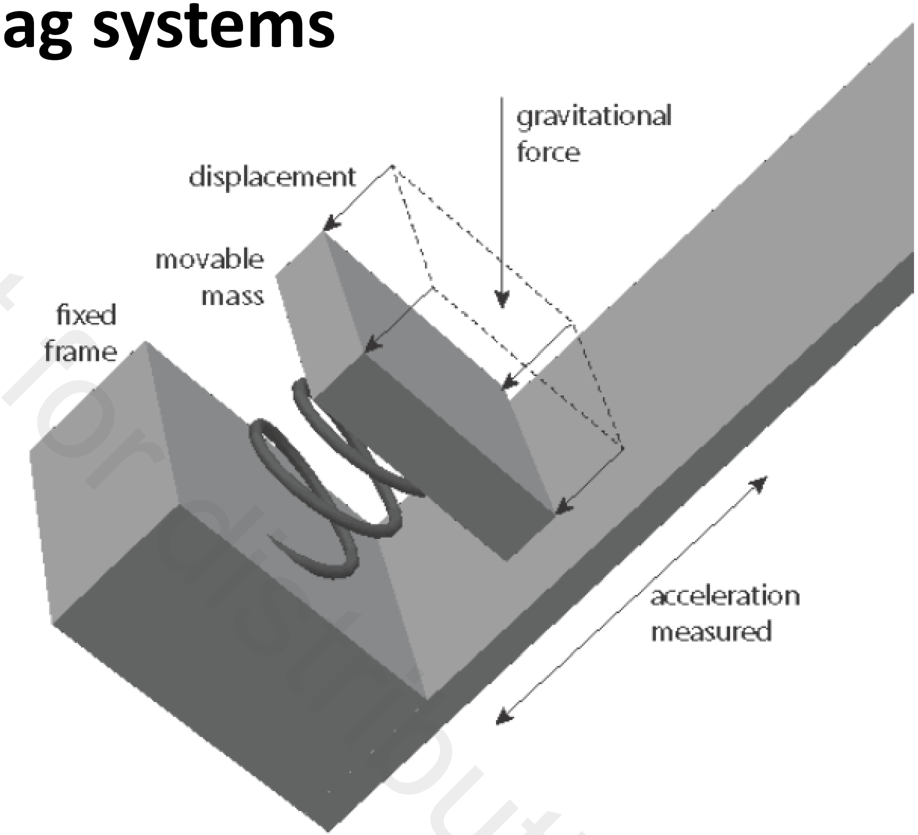


- Digitally sampled images are vulnerable to aliasing as well, where patterns and edges appear as a side effect of sampling

Accelerometers

- **Navigation, orientation, drop detection**
- **Image stabilization, airbag systems**

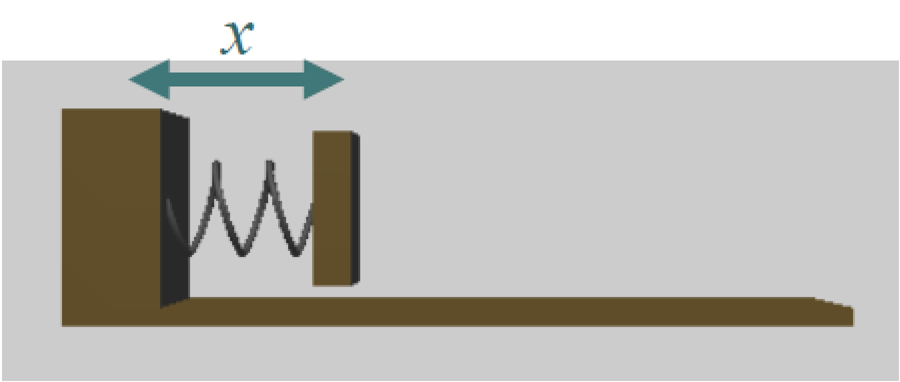
- The most common design measures the distance between a plate fixed to the platform and one attached by a spring and damper. **The measurement is typically done by measuring capacitance.**



Accelerometers (Spring-Mass-Damper)

- By Newton's 2nd law, F=Ma (M: Mass, a: Acceleration)
- F could be the Earth's gravitational force
- The force is balanced by restoring force of the spring

- **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 2nd law:

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

or

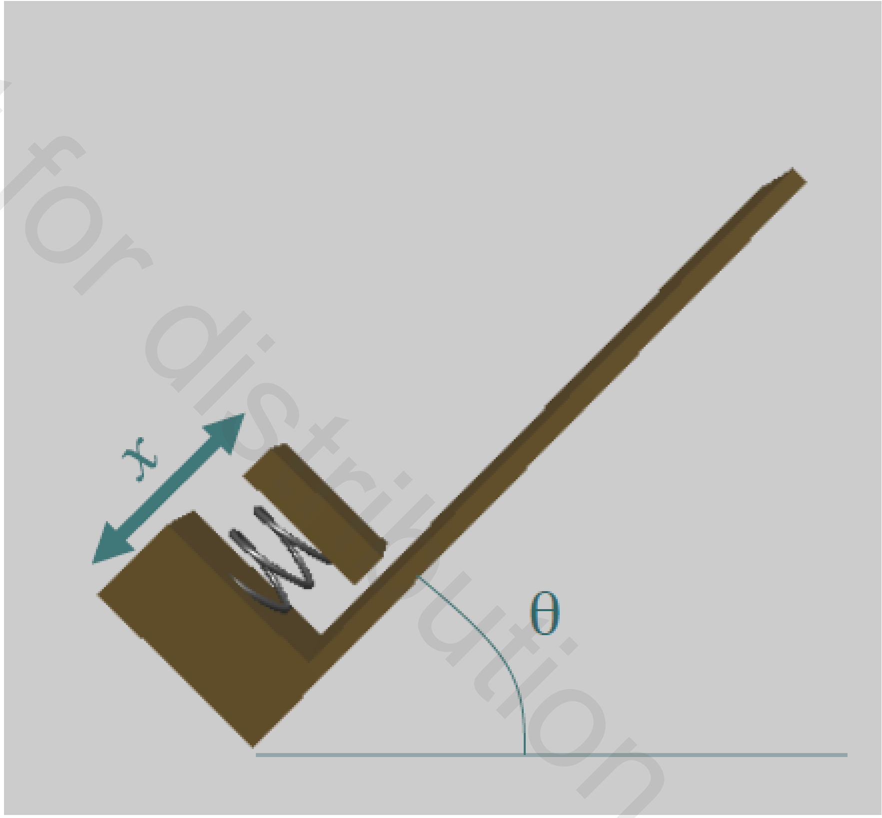
$$M\ddot{x}(t) + c\dot{x}(t) + kx(t) = kp$$

Accelerometers (Measure 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 $\boldsymbol{\theta}$**, up to an ambiguity of π



Accelerometers (Difficulties)

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

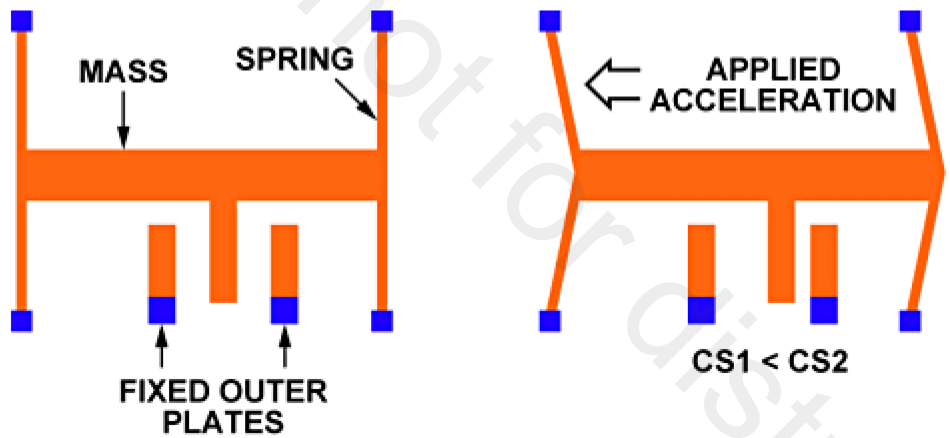
$$p(t) = p(0) + \int_0^t v(\tau)\, d\tau$$

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

- **Position, *p(t)*, is the integral of velocity (*v(t)*), which is the integral of acceleration, *x (t)***
- **Bias in the measurement of acceleration** causes position estimate error to increase quadratically

Accelerometers – MEMS Technology

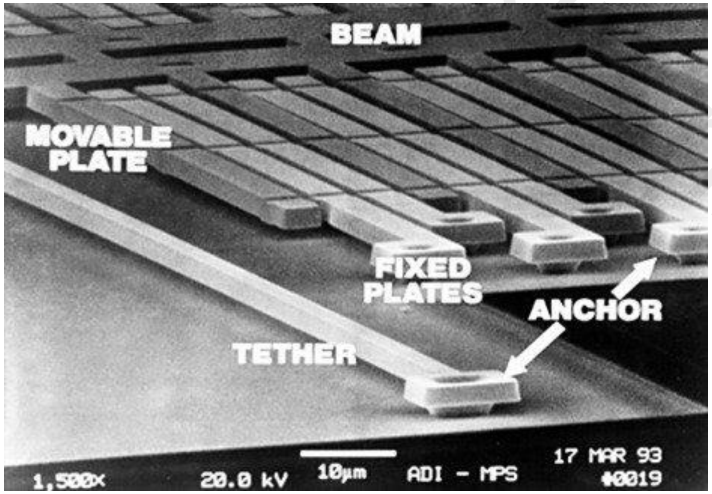
- Moving **beam structure composed of two sets of fingers**: one set is fixed to a solid ground plane on a substrate; the other set is attached to a known mass mounted on springs that can move in response to an applied acceleration



- Applied application changes the capacitance between the fixed and moving beam fingers

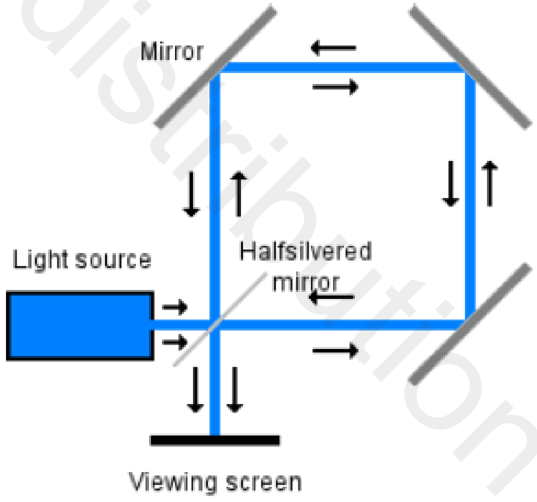
Accelerometers – MEMS Technology

- Single-crystal silicon or polysilicon
- Structures with very different mechanical characteristics can be created, controlled, varied by design that can measure fractions of one g or hundreds of g's with bandwidths as high as 20 kHz
- Characteristics include spring stiffness, mass of the sense element, damping of the structure
- Micrograph of an MEMS accelerometer's structure



Gyroscope (Measuring Orientation Changes)

- 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 of the light travels in one direction is smaller than the distance in the other**
- **This shows up as a change in the interference**



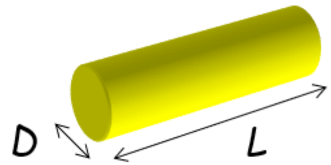
Other Sensors

- **Force, Torque, and Pressure Sensors**
  - Strain gauge dynamometers and piezoelectric type
  - Both are available to measure force and/or torque either in one axis or multiple axes
  - Dynamometers may be limited by their natural frequency
  - Piezoelectric sensors provide high stiffness, high resolution, suitable for dynamic loadings in a wide range of frequencies
- **Flow Sensors**
  - *Venturimeter/orifice plate* restrict the flow and use the pressure difference to determine the flow rate
  - *Pitot tube* pressure probe measures total and static pressures
  - *Rotameter/turbine meters* rotate at a speed proportional to the flow rate

Other Sensors – Strain Gauge

- **Gauge Factor**
  - For a strained thin wire… $\frac{\Delta R}{R} = \frac{\Delta L}{L} - \frac{\Delta A}{A} + \frac{\Delta\rho}{\rho}$
  - $A = \pi(\frac{D}{2})^2$, for circular wire

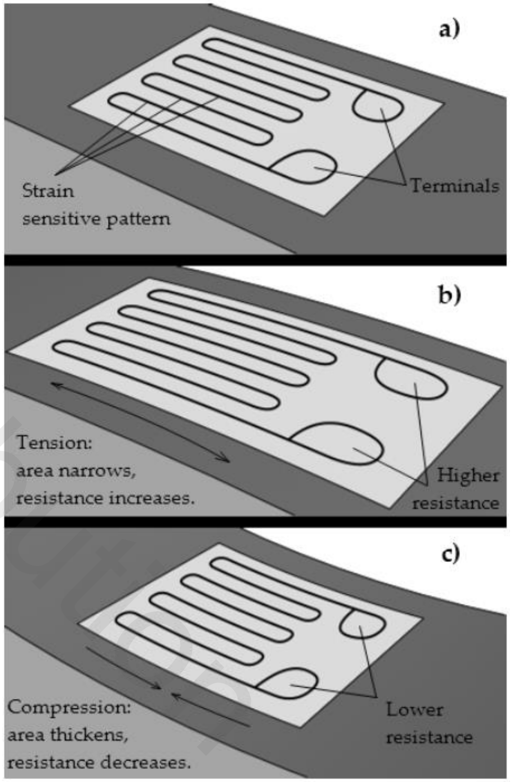
ΔR: change in electrical resistance
R: electrical resistance
$\frac{\Delta L}{L}$ or Ɛ : mechanical strain
ΔL: absolute change in length
L: original length
ρ: Resistivity



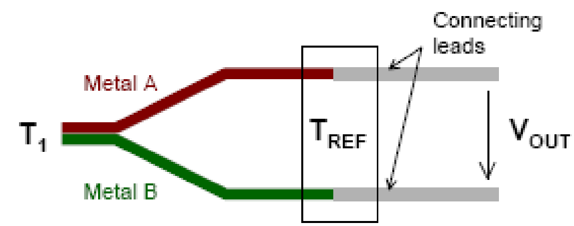
- **Poisson's ratio**
  - μ relates change in diameter D to change in length L
  - $\frac{\Delta D}{D} = -\mu \frac{\Delta L}{L}$
  - Thus, $\frac{\Delta R}{R} = (1+2\mu)\frac{\Delta L}{L} + \frac{\Delta\rho}{\rho}$

dimensional effect piezoresistive effect

- **Gauge Factor (G)**
  - Used to compare strain-gauge materials
  - $G = \frac{\Delta R/R}{\Delta L/L} = (1+2\mu) + \frac{\Delta\rho/\rho}{\Delta L/L}$

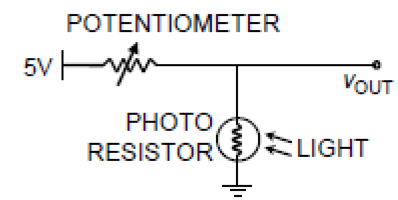


Other Sensors

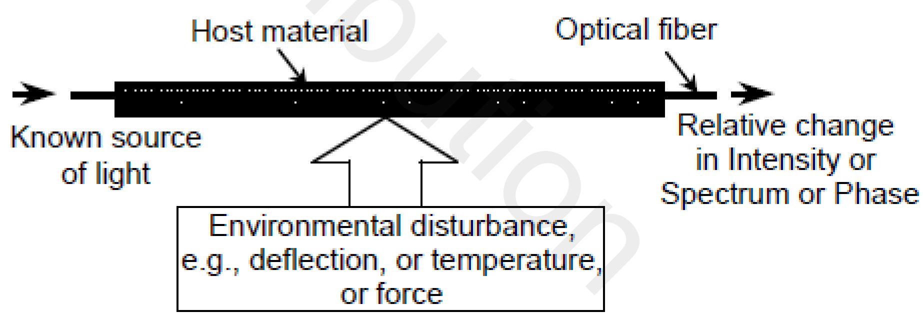


- **Temperature Sensors**
  - ***Thermocouples*** consist of two dissimilar metal wires joined at the ends to create the sensing junction, temperature shows up as a voltage difference. (versatile, inexpensive, wide range)
  - ***Thermistors*** are semiconductors devices whose resistance changes as the temperature changes. (high sensitivity, limited range)
  - ***Infrared type*** sensors use the radiation heat to sense the temperature from a distance
- **Proximity Sensors**
  - ***Inductance type*** consist of a coil wound around a soft iron core, and inductance changes when a ferrous object is close by
  - ***Capacitance types*** are similar to inductance except the proximity of an object changes the gap and affects the capacitance.
  - ***Photoelectric*** *sensors* detects voltage level changes when proximity of a moving object interrupts the light beam
  - **Hall effect sensor** is a transducer that varies its output voltage in response to a magnetic field. **Hall effect sensors** are used for proximity switching, positioning, speed detection, and current **sensing** applications.

Other Sensors



- **Light Sensors**
  - ***Photoresistors***, made of cadmium sulfide whose resistance is maximum when the sensor is in dark
  - When exposed to light, its resistance drops in proportion to the intensity of light.
- **Smart Material Sensors**
  - ***Optic fibers, piezoelectric, and magnetostrictive*** materials (**The inverse magnetostrictive effect** (also known as **magnetoelastic effect** or **Villari effect**) is the name given to the change of the magnetic susceptibility of a material when subjected to a mechanical stress)
  - **Optic fibers used to sense strain, liquid level, force and temperature with very high resolution**
    - economical for use as *in situ* distributed sensors on large areas
    - Found in **smart structure applic**ations (**damage sensors, vibration sensors, cure-monitoring sensor**



Other Sensors

- **Micro- and Nanosensors**
  - **MEMS** (Microelectromechanical systems) are the miniaturized version of conventional microsensors with **improved performance** and **reduced cost**
  - Fiberscope of approximately 0.2mm in diameter for inspecting flaws inside tubes
  - Microtactile sensor uses laser light to detect contacts between a catheter and inner wall of blood vessels during insertion

Sensors - Selection Criteria

- **Range** – Difference between the max. and min. value of the sensed parameter
- **Resolution** – The smallest change the sensor can differentiate
- **Accuracy** – Difference between the measured value and the true value
- **Precision** – Ability to reproduce repeatedly with a given accuracy
- **Sensitivity** – Ratio of change in output to a unit change of the input
- **Zero offset** – A non-zero value output for no input
- **Response time** – The time lag between the input and output
- **Bandwidth** – Frequency at which the output magnitude drops by 3 dB
- **Resonance** – The frequency at which the output magnitude peak occurs
- **Operating temperature** – The range in which the sensor performs as specified
- **Deadband** – The range of input for which there is no output
- **Signal-to-noise ratio (SNR)** – Ratio between the magnitudes of the signal and the noise at the output

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

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.

Sensor Fault Example: QANTAS Flight 72

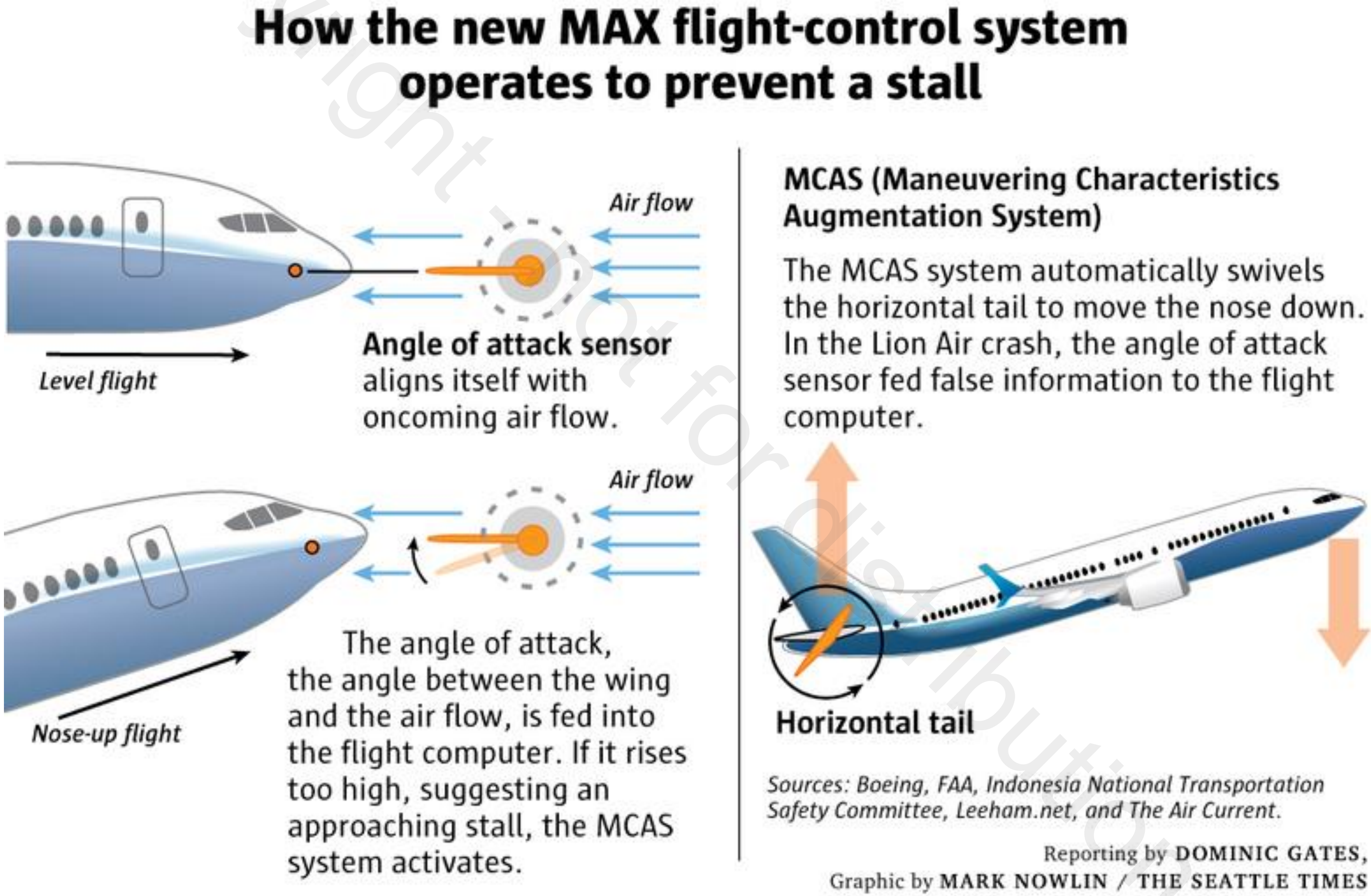
An Airbus A330 enroute from Singapore to Perth on 7 October 2008

- Started pitching violently, unrestrained passengers hit the ceiling, 12 serious injuries (counting as an accident)
- Three Angle of Attack (AOA) sensors on the plane
- Want to get a consensus good value
- Have to deal with inaccuracies, different positions, gusts/spikes, failures.

A330 AOA Sensor Processing

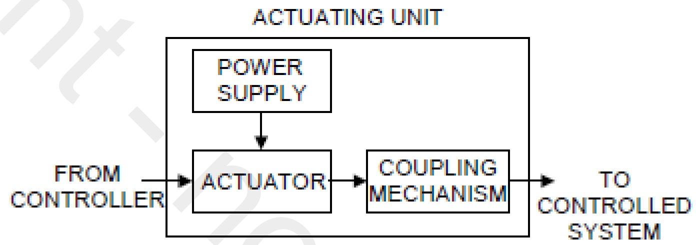
- Sampled at 20 Hz
- Compared each sensor to the median of the three
- If difference is larger than some threshold for more than 1 second, flag as faulty and ignore for remainder of flight
- Assuming all three are OK, use mean of #1 and #2 sensors (since they are on different sides)
- If difference between #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

Boeing 737 MAX 8



Actuators

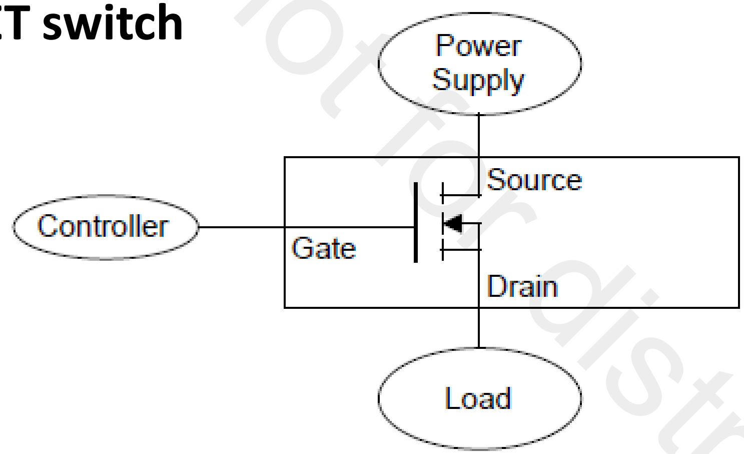
- **Accepts a control command and produces a change in the physical system by generating force, motion, heat, flow, etc.**



- **Coupling mechanism acts as the interface between the actuator and the physical system**
  - Rack and pinion, gear drive, belt drive, lead screw, nut, piston, linkages
- **Can be classified on the type of energy**
  - electrical, electromechanical, electromagnetic, hydraulic, pneumatic
- **Can be classified as binary and contin**uous based on the number of stable-state outputs
  - relay, stepper motor

Actuators

- **Electrical Actuators**
  - Electrical switches for most of the on-off type control action
  - Switching devices accept a low energy level command signal from the controller (**Diodes, transistors, TRIAC, MOSFET, relays**) and switch on or off electrical devices (motors, valves, heating elements, etc.)
  - e.g., **MOSFET switch**



  - Gate terminal receives low energy control signal from the controller
  - Controller makes or breaks the connection between the power supply and the actuator load

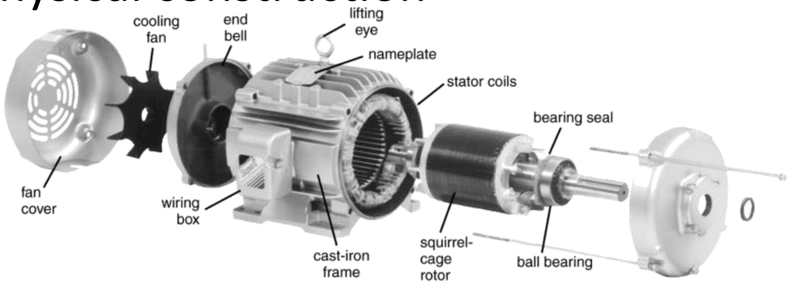
Actuators

- **Electromechanical Actuators**
  - **Most common electromechanical actuator is a <u>motor</u>**
  - **Converts electrical energy to mechanical energy/motion**
  - **DC motors, AC motors, stepper motors**
- **DC Motors**
  - Operate on DC voltage, varying the voltage can easily control the speed
  - Thousands of horsepower motors (rolling mills)
  - Fractional horsepower motors (automobiles' starter motors, fan motors, windshield wiper motors, etc.)
  - Governing equation of DC motor motion:
  - $\boldsymbol{T = J\frac{d\omega}{dt} + T_L + T_{loss}}$

T: torque
J: total inertia
ω: angular mechanical speed of the rotor
T_L: torque applied to the motor shaft
T_{loss}: internal mechanical losses (friction)

Actuators

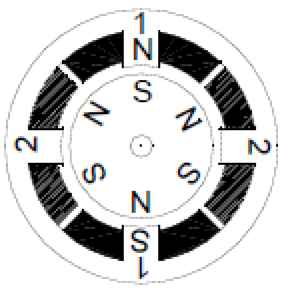
- **AC Motors**
  - Most popular (using standard AC power)
  - No brushes and commutators → less expensive than DC motor
  - Can be further classified as *induction motors, synchronous motors, universal motors* according to their physical construction
- **Induction Motors**
  - Simple, rugged, maintenance free
  - Three-phase induction motor
    - Used in large-horsepower applications (pump drives, steel mill drives, hoist drives, vehicle drives)
  - Two-phase servomotor
    - Used extensively in position control system
  - Single-phase induction motors
    - Used in household appliance



Actuators

- **Stepper Motor**
  - Discrete (incremental) positioning device that moves one step at a time for each pulse command input
  - Used widely in industrial control applications
  - **Mostly used in fractional horsepower applications**

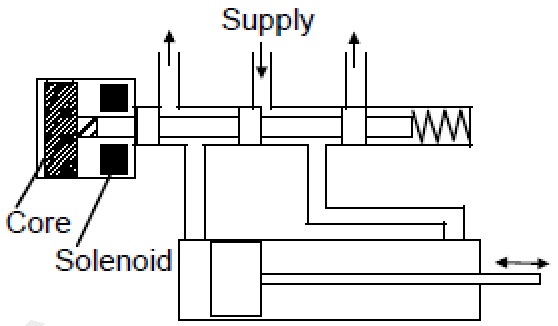
- **Unipolar Stepper Motor**
  - Winding-1 is between the top and bottom stator pole
  - Winding-2 is between the left and right motor poles
  - Rotor is a permanent magnet with six poles resulting in a single step angle
  - With appropriate excitation of winding-1, the top stator pole becomes a north pole and the bottom stator pole becomes a south pole, attracts the rotor
  - With de-energized winding-1 and energized winding-2, the rotor will turn.
  - By exciting the two windings in sequence, the motor can be made to rotate at a desired speed continuously



Unipolar Stepper Motor

Actuators

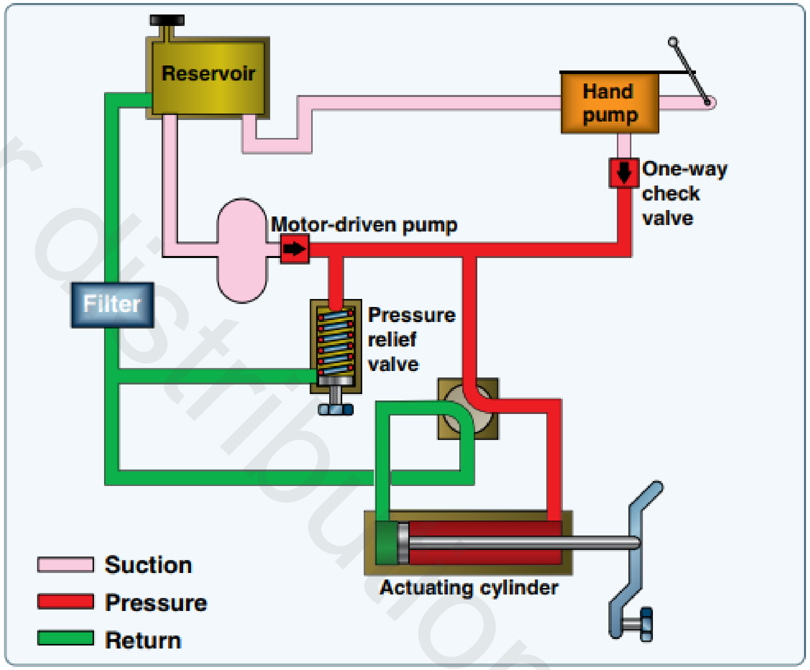
- **Electromagnetic Actuators**
  - Solenoid is the most common electromagnetic actuator
- **DC Solenoid Actuator**
  - Consists of a soft iron core enclosed within a current carrying coil
  - When coil is energized, a magnetic field is established the provides the force to push/pull the iron core
  - Due to the spring force, the soft iron core is pushed to the extreme left position
  - When the solenoid is excited, the soft iron core will move to the right extreme position
  - Thus, providing the electromagnetic actuation



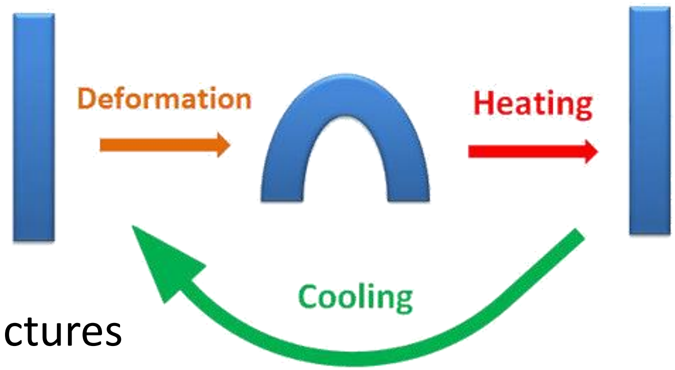
Solenoid operated directional control valve

Actuators

- **Hydraulic and Pneumatic Actuators**
  - Rotary motors, linear piston/cylinder, control valves
  - Ideally suited for generating very large forces coupled with large motion
- **Pneumatic Actuators**
  - Use air under pressure that is most suitable for low to medium force, short stroke, and high-speed applications
- **Hydraulic Actuators**
  - Use pressurized oil that is incompressible
  - Can produce very large forces coupled with large motion in a cost-effective manner. Very complex and need frequent maintenance



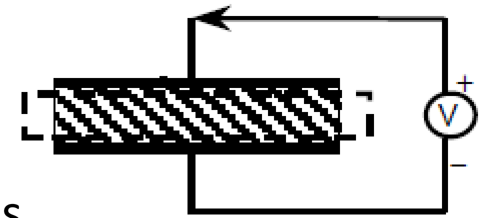
Actuators

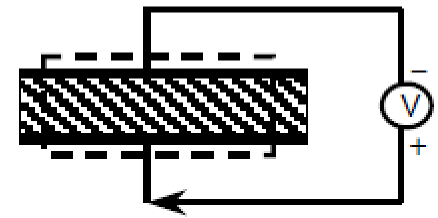


- **Smart Material Actuators**
  - Typically become part of the load bearing structures
  - shape memory alloys, piezoelectric (PZT), magnetostrictive, electrorheological fluids, ion exchange polymers
- **Shape Memory Alloys (SMA)**
  - **Shape-memory alloy** (**SMA**, **smart metal**, **memory metal**, **memory alloy**, **muscle wire**, **smart alloy**) is an alloy that "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated. This material is a lightweight, solid-state alternative to conventional actuators such as hydraulic, pneumatic, and motor-based systems. Shape-memory alloys have applications in robotics and automotive, aerospace and biomedical industries.
  - alloys of nickel and titanium that undergo phase transformation when subjected to a thermal field
  - can recover from strains up to 10% via stress- or temperature-induced crystalline transformation between high temperature austenite and low temperature martensite phases
  - SMA actuator is a wire actuator made from SMA, designed to contract/extend like real muscles

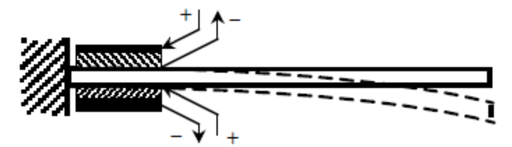
Actuators

- **PZT Actuators**
  - Piezocrystals with top and bottom conducting films
  - When an electric voltage is applied across the two conducting films, the crystal expands in the transverse direction (dotted lines)
  - When the voltage polarity is reversed, the crystal contracts thereby providing bidirectional actuation



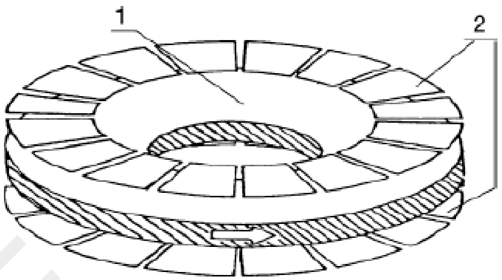


- **Vibration of beam using piezoelectric actuator**
  - Two piezoelectric patches are excited with opposite polarity to create transverse vibration in the cantilever beam
  - provide high bandwidth (0-10KHz) with small displacement
  - Compact and ideally suited for micro and nano actuation



Actuators

- **Micro- and Nanoactuators (MEMS)**
  - Tiny mobile devices being developed utilizing the standard microelectronics processes with the integration of semiconductors and machines micromechanical elements
  - Any device produced by assembling extremely small functional parts of around 1-15mm
- **Electrostatic Motors**
  - Electrostatic force is dominant, unlike the conventional motors (an electrostatic motor is based on the attraction and repulsion of electric charge)
  - Electrostatic forces are well suited as an actuating force for smaller micromechanical systems
  - Rotor is an annular disk with uniform permittivity and conductivity
  - A voltage is applied to the two conducting parallel plates separated by an insulation layer
  - Rotor rotates with a constant velocity between the two coplanar concentric arrays of stator electrodes



Electrostatic motor: 1-rotor, 2-stator electrodes.

Actuators - Selection Criteria

- **Continuous power output** – The maximum force/torque attainable continuously without exceeding the temperature limits
- **Range of motion** – The range of linear/rotary motion
- **Resolution** – The minimum increment of force/torque attainable
- **Accuracy** – Linearity of the relationship between the input and output
- **Peak force/torque** – The force/torque at which the actuator stalls
- **Heat dissipation** – Maximum wattage of heat dissipation in continuous operation
- **Speed characteristics** – Force/torque versus speed relationship
- **No load speed** – Typical operating speed/velocity with no external load
- **Frequency response** – The range of frequency over which the output follows the input faithfully, applicable to linear actuators
- **Power requirement** – Type of power (AC/DC), number of phases, voltage level and current capacity

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