Transducers

Lecture #6

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Some content has been adapted from a course taught by Prof. Mel Siegel.

Outline of Previous Lecture

- Berkeley Motes
- TinyOS
- nesC

Outline of Today's Lecture

- Basic Terms and Building Blocks
- Sensor Taxonomy
- Some Sensor Principles and Types
- Some Actuator Types

Readings will be on Piazza

Readings

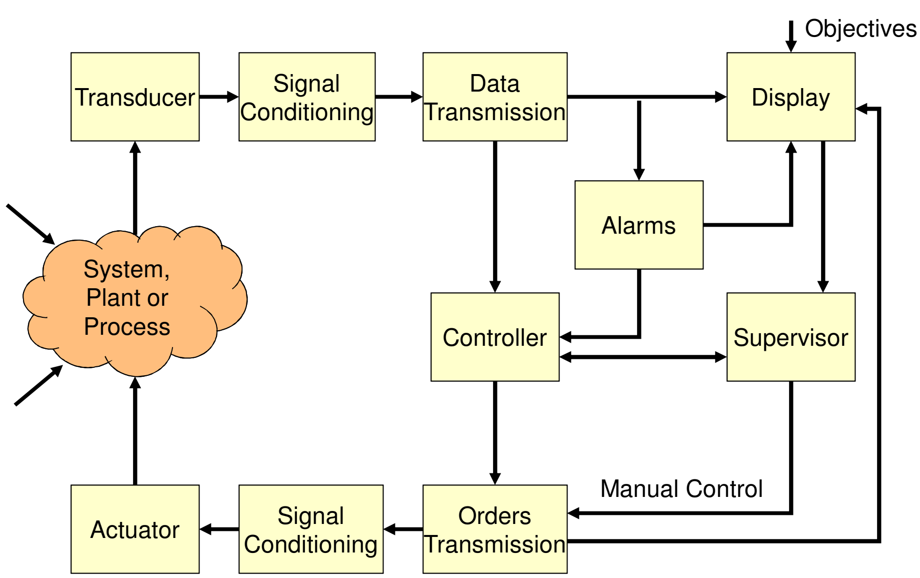
- Required:
  - Sensor Fundamentals
  - Measurement Systems
  - Application Considerations
- Optional:
  - Wireless Sensing
  - Smart Buildings
  - Piezo-Electric Motors
  - *Some Specific Sensors*

All on Piazza

Basic Terms

- Transducer: a device which converts one form of energy to another
- Sensor: a transducer that converts a physical phenomenon into an electrical signal.
  - an interface from the physical world to the computing world.
- Actuator: a transducer that converts an electrical signal to a physical phenomenon
  - an interface from the computing world to the physical world.

A Measurement and Control System

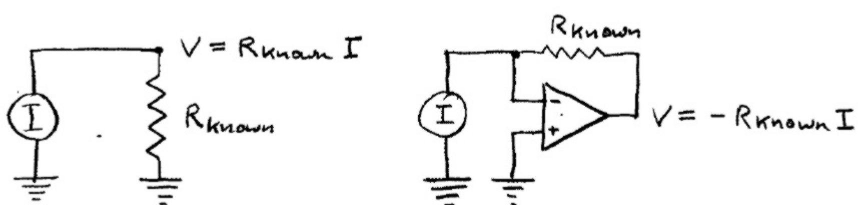


Sensor-to-Signal Interface

- Action of environment on a sensor causes it to generate an electrical signal directly
  - voltage source (V)
  - current (I) or charge (Q) source
- Action of environment on sensor changes an electrical parameter that we can measure
  - resistance changes: V ~ I
  - capacitance changes: $V \sim \int I \, dt$, $I \sim dV/dt$
  - inductance changes: $V \sim dI/dt$, $I \sim \int V \, dt$

Example: Current-to-Voltage Conversion

- *Simple*: $I = V_{measured} / R_{known}$
- *Better*: Use an "op amp"

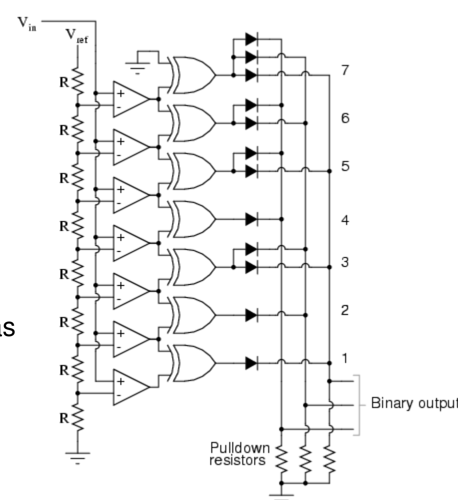


Signal Conditioning

- Filter for expected frequency regime
- Subtract DC offset (“zeroing”)
- Amplify or attenuate signal (“scaling”)
- Linearize relationship between measurand and observed electrical parameter
  - now *usually* done in software after ADC
- ...

Analog-to-Digital Converter (ADC)

- Many different principles
- Often integrated with microcontrollers
  - in some types, e.g., “successive approximation”, the CPU participates in the conversion process
    - Normally, want to avoid this
- All involve trade-offs of speed (conversion time), resolution (number of bits) and cost
- “Flash converter” is the fastest, has the lowest resolution and the highest cost
  - required for video digitization



(One) Classification of Sensors

Criterion	Classes	Example
Power supply	Modulating	Thermistor*
	Generating	Thermocouple**
Output signal	Analog	Potentiometer
	Digital	Position encoder
Operating mode	Deflection	Deflection accelerometer
	Null	Servo-accelerometer

* *Thermistor*: a resistor whose resistance changes with temperature.
** *Thermocouple*: a temperature-sensing element which converts thermal energy directly into electrical energy

Power Supply

- Modulating
  - Also known as Active Sensors
  - They need auxiliary power to perform functionality
  - Sensitivity can be controlled
- Self-Generating
  - Also known as Passive Sensors
  - They derive the power from the input

Operating Mode

- Deflection
  - The measured quantity produces a physical effect
  - Generates an apposing* effect which can be measured
  - Faster
- Null
  - Applies a counter-force
  - To balance the deflection from the null point ("balance" condition)
  - Can be more accurate but slow

**Appose (v): to place in proximity; juxtapose*

Another Classification (cont'd)

A better classification would be the Physical Property which we are measuring…

- Temperature
- Pressure
- Humidity
- Light
- Microphone
- Motion detector
- Chemical detector
- Image Sensor
- Flow and level sensor
- … … …

Electrical Phenomena

- Resistive
- Capacitive
- Inductive
- Piezo-electric

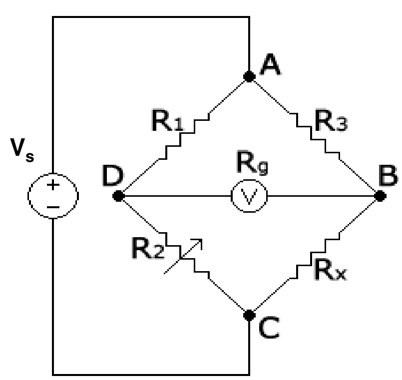
Resistance-based Devices

- Resistance of the material depends on the length, area and resistivity as:

$$R = \frac{L \cdot \rho}{A}$$

- If any one of the terms changes, it affects resistance
- The most common circuit used to measure the change in resistance is a Wheatstone bridge
- The output voltage is related to the source voltage as:

$$V = \left(\frac{R_x}{R_3 + R_x} - \frac{R_2}{R_1 + R_2} \right) V_s$$



Capacitive Devices

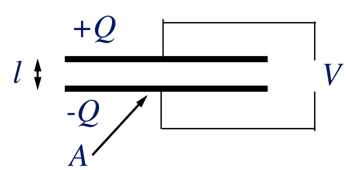
- A "Mousepad" or "touchpad" is now ubiquitous, reliable and stable
- Same geometrical factors as resistive sensors (but remember that capacitance is defined "upside down"):

$$V = L\, dI/dt + R\, I + Q/C$$

- Actual approach is to measure distortion in "stray" capacitance
- Many geometries including some with "finger-like" curvatures

$\mu_0 = 4\pi\ 10^{-7}$ henry/m, $\varepsilon_0 = \mu_0/c^2 = 8.85\ 10^{-12}$ farad/m

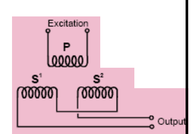
- "small capacitor" is ~ 100 pF (p = pico = 10^{-12})

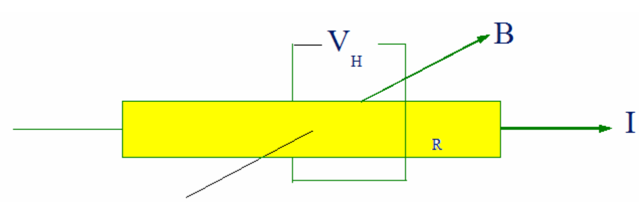


V volts $= \varepsilon$ farad/m $A\ m^2 / l\ m$

Magnetic and Inductive Effects

- Many prototypes, multi-generation developments
- Inductive devices are more-or-less miniature LVDTs
  - Linear Variable Displacement Transducer: a displacement-measuring instrument
- Magnetic effects, e.g., magneto-resistance plausible
  - recent development of "giant" and "colossal" magneto-resistance materials may hold some promise
- Some slip-sensing potential with dipoles oriented *within* surface
- Hall effect sensors may be the most plausible, as Hall effect switches are in common use in computer keyboards, etc.

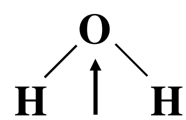




Hall effect: voltage due to deflection of current's charge carriers

Piezo- and Pyro-electric Devices

- Piezo- (pressure) and pyro- (heat) electricity are always coupled
  - due to separation of electrical charges in the material's crystalline arrangement
  - electric dipoles at the molecular level (e.g., H_2O)
  - high voltage poling to macroscopically align dipoles
  - "electrets" made by poling various waxy mixtures
- Pressure → voltage (sensor)
  Voltage → deformation (actuator)
- Due to leakage, effect is transient
  - to stabilize, leakage is intentionally increased, making device respond effectively to *dP/dt*
- High voltage + high input impedance → tiny current (hard to measure, slow to measure)



Practical Piezo-Electric Materials

- Quartz (cut along particular crystal axes to maximize piezo- and minimize pyro- effects):
  - the effect is small but very stable
- Various ceramics, e.g., ZnO, PZT - Lead Zirconate Titanate (piezoelectric ceramic material)
  - Esp. by deposition on micro- and mini- fabricated devices
    - SAW (surface acoustic wave) devices
    - MEMS devices are also possible
- Plastics (e.g., polyvinylidene difluoride PDVF aka PVF_2)
  - (apparently) enormous quantities are used in submarine sonar transducers

Magnitude of Piezo-Electric Effect

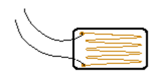
- Easy to get tens of volts but need high input impedance instrument
- Can get very high voltages (enough to spark across ~ 1 mm) in response to impact
  - buy yourself a “flintless” butane lighter

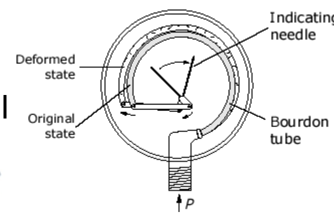
Flint (n): A massive hard dark quartz that produces a spark when struck by steel

Pressure Sensors

Pressure Sensing: Principle and Types

- Transduces pressure into electrical quantity
- Pressure exerts force which can be converted to electrical voltage using various methods
- Types
  - Strain gauges →
  - Capacitive diaphragms
  - Piezo-resistive or Silicon cell
  - Bourdon tubes →
  - Glass feed-through with silicon cell

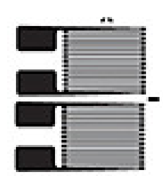


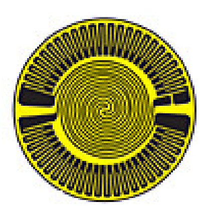


"blowout"

Pressure Sensor Types (1 of 2)

- Strain Gauges
  - Based on the variation of resistance of a conductor or semiconductor when mechanical stress is applied
  - Made of alloys like constantan, nichrome and also semiconductors
  - Can be bonded or un-bonded
- Capacitive diaphragms
  - Diaphragm acts as one plate of capacitor
  - The stress changes the space between capacitor plates
  - Can be made of strain gauge or other metal

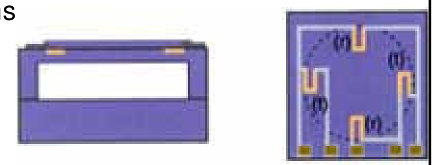




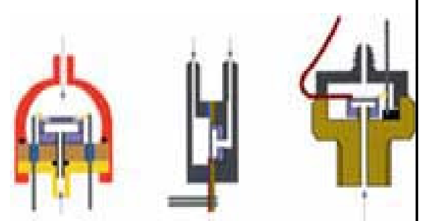
Diaphragm: thin membrane

Pressure Sensor Types (2 of 2)

- Piezo-resistive or Silicon Cell
  - Micromachined silicon diaphragms
  - Piezo-resistive strain gauges diffused into it
  - Very sensitive to pressure



- Tubes and Feed-Through Glass
  - Glass feed-through and silicon cell-mounted on plastic housing
  - Based on the pressure difference



Humidity Sensors

Humidity Sensing: Principle and Types

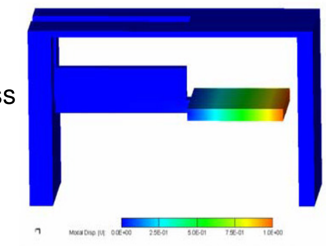
- Humidity is defined as the water vapor content in the air (or other gases)
- Measured as
  - Absolute Humidity
    - Ratio of the mass of water vapor to the volume of air or gas
  - Relative Humidity or RH
    - The ratio of the moisture content of air compared to the saturated moisture level at the same temperature or pressure
  - Dew Point
    - Temperature and pressure at which gas begins to condense into liquids (like water vapor in air showing up as dew drops)

Humidity Sensor Types (1 of 2)

- Capacitive RH sensor
  - Change in dielectric constant is directly proportional to the relative humidity in the environment
  - Very low temperature effect
  - 0.2-0.5 pF change in capacitance for 1% RH change
- Resistive Humidity Sensors
  - Measure the impedance change
  - Inverse exponential relationship to humidity
  - Mostly used are conductive polymer, salt etc.
  - Ceramic-coated to avoid condensation effect

Humidity Sensor Types (2 of 2)

- Thermal Conductivity Humidity Sensors
  - Measure absolute humidity
  - Calculate the difference between dry air and air containing water vapor
  - One thermistor sealed in dry nitrogen and another exposed to the environment
  - Difference in current proportional to humidity
- MEMS-based Humidity sensor
  - Polymide-coated cantilever beam
  - Provided with movable electrode
  - Absorption causes increase in beam mass
  - Deflection causes capacitance change



Temperature Sensors

Temperature Sensing: Principle & Types

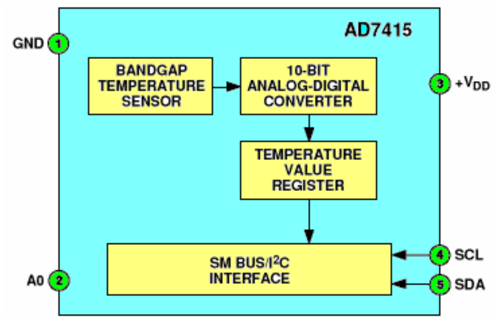
- A temperature sensor detects a change in a physical parameter such as resistance or output voltage that corresponds to a temperature change.
- Type of Sensing
  - Contact
    - Sensor is in direct physical contact with the object to be sensed
    - To monitor solids, liquids, gases over a wide range
  - Non-contact
    - Interprets the radiant energy of a heat source to energy in electromagnetic spectrum
    - Monitor non-reflective solids and liquids

Contact sensing

- Thermocouples
- Thermistors
- Resistance Temperature Detectors (RTD)
- Semiconductor Temperature sensors
- Liquid-in-Glass Thermometers
- Bi-metallic Thermometers

Non-Contact sensing

- Radiation Thermometers
  - Infrared Thermal Imaging
  - Scanners
  - Spot Radiometers
- Thermal Imagers
- Ratio Thermometers



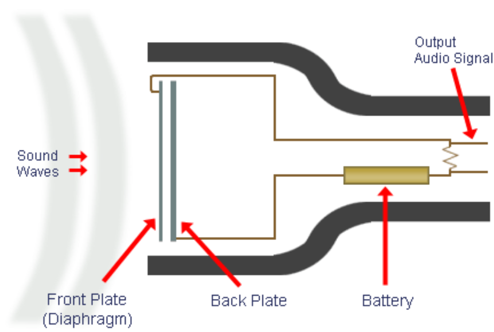
Microphone

Microphone Sensing: Principle

- A **microphone** is an acoustic-to-electric transducer that converts sound into an electrical signal.
- Microphones capture sound waves with a thin, flexible diaphragm. The vibrations of this element are then converted by various methods into an electrical signal that is an analogue of the original sound.
- Most microphones in use today use electromagnetic generation (dynamic microphones), capacitance change (condenser microphones) or piezo-electric generation to produce the signal from mechanical vibration.

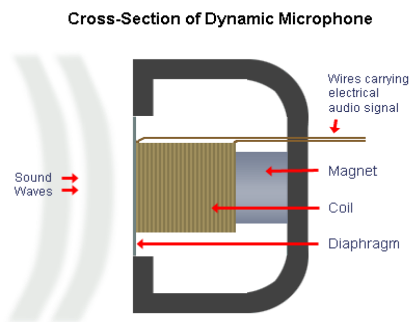
Condenser (or Capacitor) Microphones

- In a condenser microphone, the diaphragm acts as one plate of a capacitor, and the vibrations produce changes in the distance between the plates.
- Since the plates are biased with a fixed charge (Q), the voltage maintained across the capacitor plates changes with the vibrations in the air.



Dynamic Microphones

- In a dynamic microphone, a small movable induction coil, positioned in the magnetic field of a permanent magnet, is attached to the diaphragm.
- When sound enters through the windscreen of the microphone, the sound wave vibrations move the diaphragm.
- When the diaphragm vibrates, the coil moves in the magnetic field, producing a varying current in the coil through electromagnetic induction.



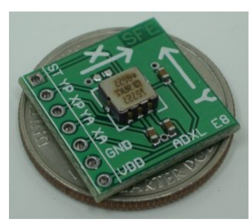
Microphone Types (cont'd)

- Carbon Microphone
  - It consists of two metal plates separated by carbon granules
  - When sound waves strike this plate, the pressure on the granules changes
    - this in turn changes the electrical resistance between the plates.
- Piezo Microphone
  - A piezo microphone uses the phenomenon of piezo-electricity
  - It is widely used to amplify acoustic instruments for live performance
    - to record sounds in unusual environments
- Ribbon microphones
  - Corrugated metal ribbon is suspended in a magnetic field.
  - The ribbon is electrically connected to the microphone's output
  - Vibration within the magnetic field generates the electrical signal by electromagnetic induction.

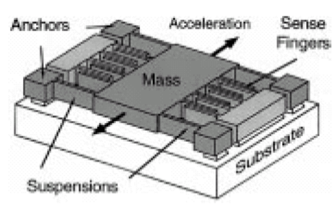
Accelerometer

Accelerometer Sensor: MEMS

- Types
  - Piezo-resistive
    - Proof mass suspended with piezo-resistive beams
      - Simple structure, fabrication, and readout (low impedance output)
      - Large temp. sensitivity, smaller overall sensitivity than capacitance devices
  - Capacitive
    - Acceleration is measured by the capacitance between a fixed plate and plate on the proof mass.
      - Stable (temperature, drift)
      - Can be susceptible to EMI.
- Cost: < $10.



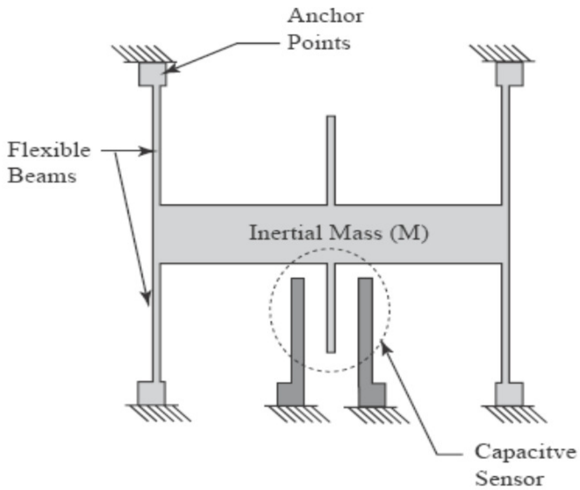
2-axis Analog Devices Breakout Board



Capacitive Inertial MEMS Sensor

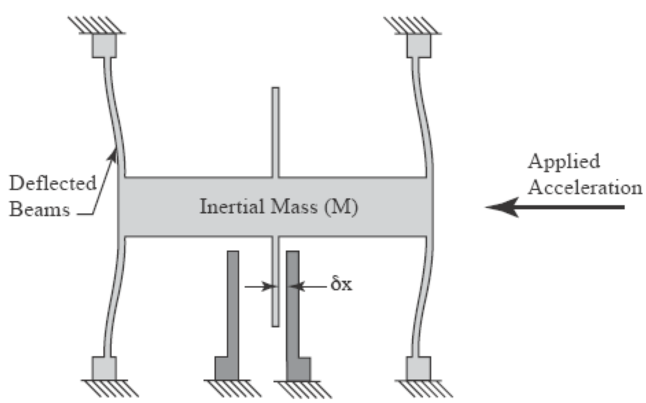
Electrical & Computer ENGINEERING 18-748: Wireless Sensor Networks Carnegie Mellon

Accelerometer: Inner Working (1 of 2)



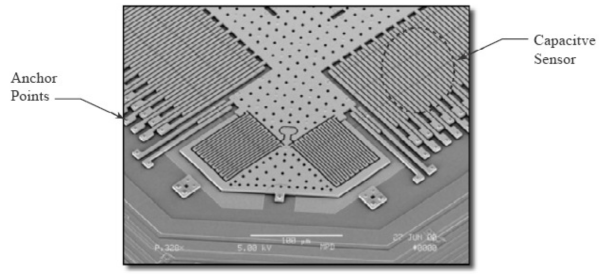
It consists of beams and capacitive sensor with some anchor points

Accelerometer: Inner Working (2 of 2)



On applying the acceleration, the beams deflect and cause the change in capacitance.

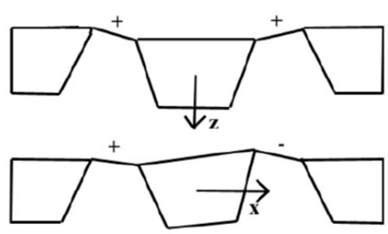
A Snapshot of an Accelerometer



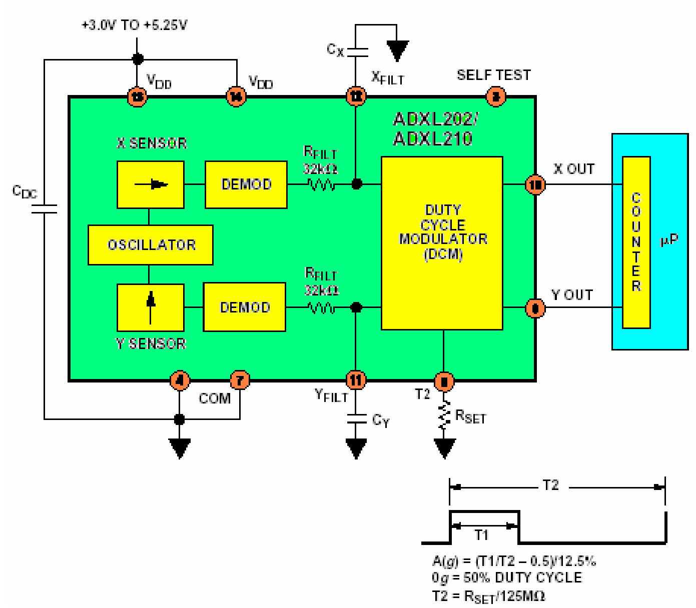
2-Axis Accelerometer, [Analog Devices]

Piezoelectric Accelerometer

- The principle is to sense the force *F* created by a seismic mass *m* under an acceleration *a*:
  $$F = ma$$
- This force is transformed into a bending moment applied on a piezo-electric bimorph.
- The seismic mass displacement is sensed by two piezoelectric bridges
- Z-axis acceleration is distinguished from x-axis by a differential measurement between these two sensors.



Circuit

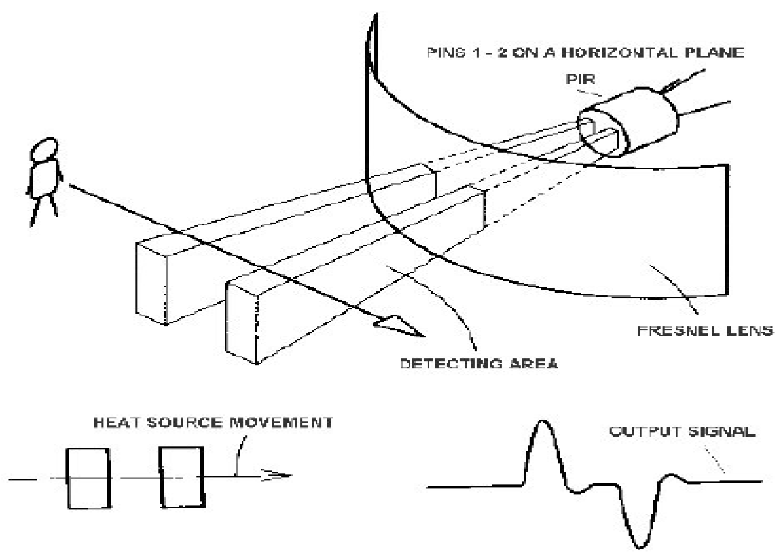


Motion Detector

Motion Detector: Types

- Photo Sensor
  - Beam of light crossing the room near the door, and a photo sensor on the other side of the room. When the beam breaks, the photo sensor detects the change in the amount of light and rings a bell (or opens garage doors).
- Microwave- Or Ultrasonic-based
  - Burst of microwave radio energy and waits for the reflected energy to bounce back.
  - When a person moves into the field of microwave energy, it changes the amount of reflected energy or the time it takes for the reflection to arrive.
  - The same thing can be done with ultrasonic sound waves, bouncing them off a target and waiting for the echo.

Pyro-electric Infrared Motion Detector



Pyro-electric Infrared Motion Detector

- Humans, having a skin temperature of about 34º C (93º F), radiate infrared energy with a wavelength between 9 and 10 micrometers. Therefore, the sensors are typically sensitive in the range of 8 to 12 micrometers.
  - Lambda [microns] = 2900 / T [deg K]
- The infrared light bumps electrons off a substrate, and these electrons can be detected and amplified into a signal.
- When a person walks by, the amount of infrared energy in the field of view changes rapidly and is easily detected. An electronics package attached to the sensor is looking for a fairly ***rapid change*** in the amount of infrared energy it is seeing.
- There is a single or sometimes two sensors inside looking for changes in infrared energy.

Light and Image sensing

Light Sensing: Principles

- Photo-chemistry
  - Light renders silver halide grains in film "emulsion" "developable"
- Thermal physics
  - Heating effect of incident light heats a sensor that basically measures temperature
- Photo-physics
  - Interaction of light with matter frees electrons or promotes them from valence to conduction band

Photoelectric Effect

- Light absorbed by metal surfaces causes current to be ejected from them
  - for visible light, it is necessary to use alkali metals (typically cesium) in a vacuum
- Light absorbed by semiconductors causes their conductivity to increase (i.e., causes their resistivity to decrease)
  - depending on device structure and measuring approach, signal may be seen as photocurrent, photovoltage, or photoconductance

Photoelectric Effect: History

- Well-understood empirically by ~1900:
  - photocurrent proportional to light intensity
  - "*stopping potential*" inversely proportional to the wavelength of light employed
  - Generally, the more chemically reactive the photocathode metal, the longer the maximum wavelength that will cause photoemission
- Explained by Einstein in 1905 based on the quantum hypothesis of Planck:

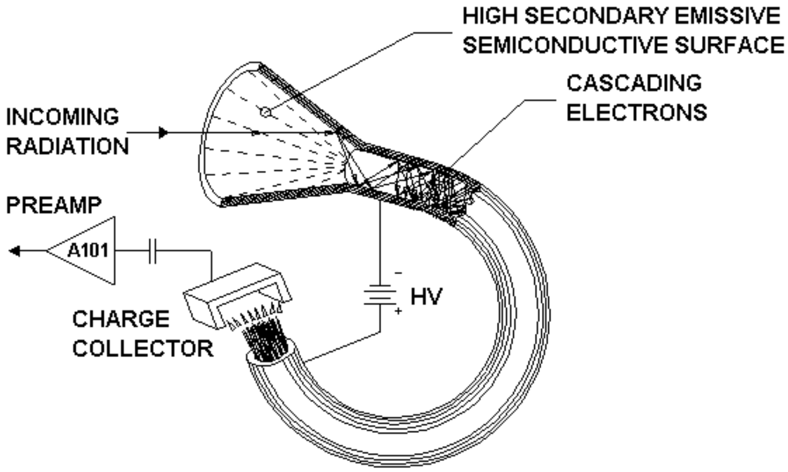
$$E = h\nu$$

E is the energy of a photon, *h* is Planck's constant (6.626E-34Js), and ν (Greek letter nu) is the photon's frequency.

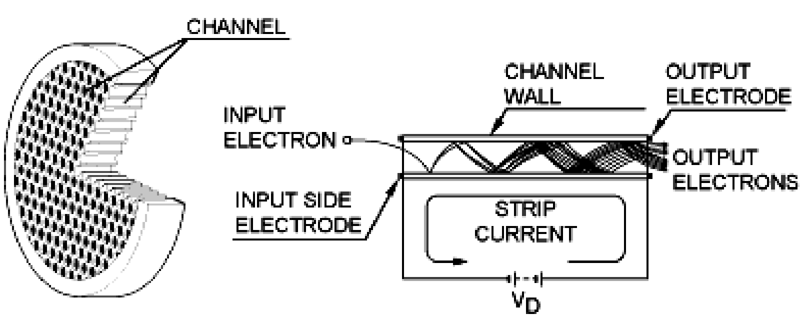
Electrons & Photons → Light Sensing

- Optical power = photons/second * energy/photon
- Electron current created is proportional to photons/second received
- For any given material (copper, silicon, etc.), there is a well-defined minimum energy/photon that can eject any electrons at all
  - minimum photon energy ⇔ maximum wavelength
  - minimum photon energy == "work function" (WF)
- maximum electron energy is $h\nu$ – WF
  - electron energy can be less (due to resistive loss)
  - WF is generally smaller for more reactive materials

Continuous Channel Multiplier



Microchannel Imaging Plate



Evolution of Image Sensors

- Photographic film (silver halide + minor others)
- Photoelectric effect + electron beam scanning
- Semiconductor screens + electron beam scanning
- *(+ hybrid technologies, e.g., image intensifiers)*
- Semiconductor technologies
  - CCD (“charge coupled device”)
  - CMOS (“complementary metal oxide semiconductor”)
    - *old*: raw memory chips
    - *new*: “camera on a chip”
  - special purpose, emerging, or evolving
    - CID (“charge injection device”)

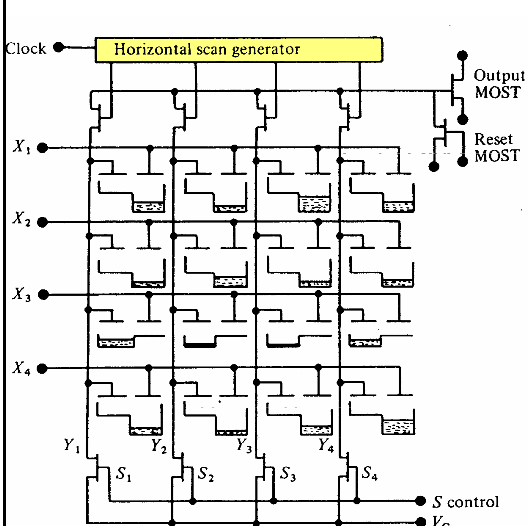
Pixel Size, Signal, & Signal-to-Noise

- Charge accumulates at a rate proportional to the light intensity incident per unit area of pixel
- Capacitance is proportional to pixel area

  → For a given light intensity, exposure time, and cell depth, the **signal voltage** (accumulated charge / cell capacitance) is **independent of cell area**
- But, the **signal-to-noise ratio improves** with larger accumulated charge, hence **with cell area**

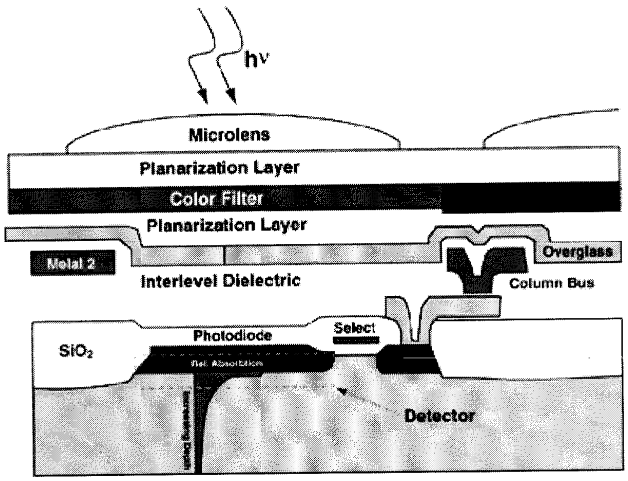
Modern Image Sensors

CID: Charge Injection Device



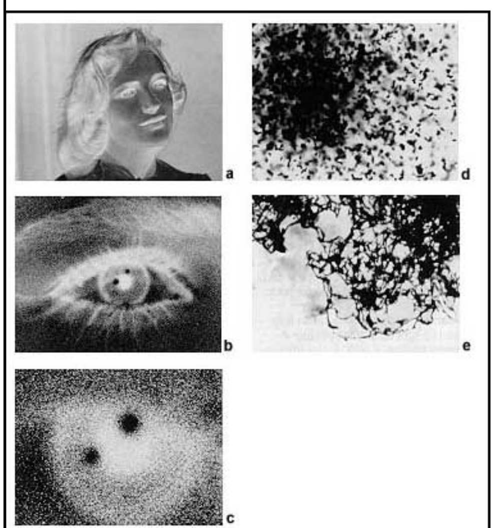
- CCDs: inherently serial readout - no way to address an individual pixel
- Could realize better dynamic range, electronic zooming, etc., if could address individual pixels
- CID has been a promising “around the corner” possibility for ~20 years

CMOS Image Sensors



- Uses same technology as standard memory chips
- Economical: uses highly-tuned high-volume production
- Allows high degree of integration between imaging and image processing

Photographic Film

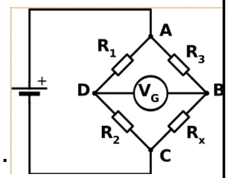


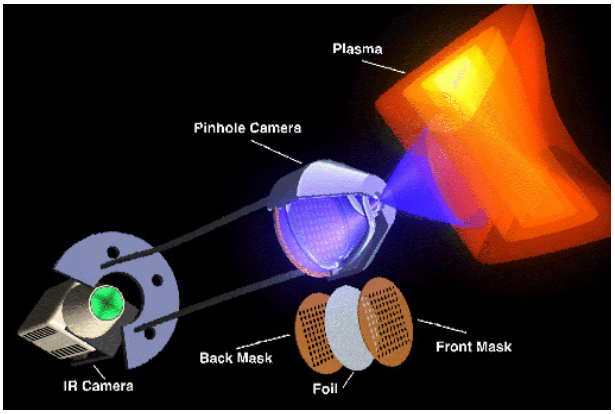
(a) A 2.5X enlargement of a negative shows no apparent graininess.
(b) At 20X, some graininess shows.
(c) When a segment of the negative is inspected at 60X, the individual silver grains start to become distinguishable.
(d) With 400X magnification, the discrete grains are easily seen. The apparent "clumping" of silver grains is actually caused by overlap of grains at different depths when viewed in two-dimensional projection.
(e) The makeup of individual grains takes different forms. This filamentary silver, enlarged by an electron microscope, appears as a single opaque grain at low magnification.

Thermal Physics (bolometry)

Usually just a simple temperature-sensitive resistor in a Wheatstone Bridge circuit

– they can get very fancy, as in this NASA camera ...





Note that one does not need the IR camera ... one could measure the local resistivity of the foil, or replace the foil with an array of thermocouples, RTDs, etc

RTD: Resistance Temperature Detector

Bolometry: the measurement of minute amounts of radiant energy, especially infrared spectra.

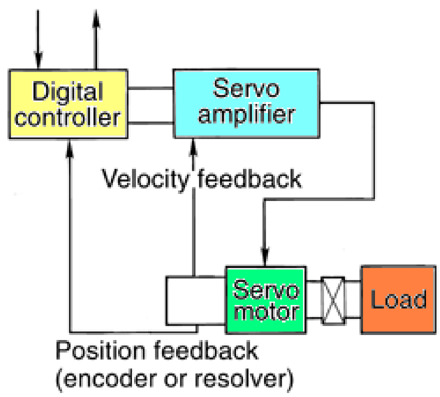
Actuators

Actuator: Principle and Types

- A control system is incomplete without an actuator
  - A mechanism by which something can be put into automatic action
- Types
  - Electric
  - Hydraulic
  - Mechanical
  - Pneumatic
  - Servo
  - Piezoelectric
  - Electro-active Polymers

Actuator: Servo Mechanism

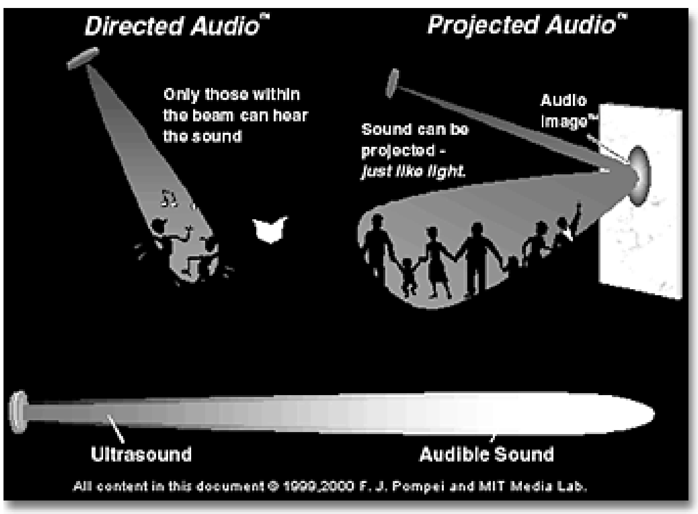
- Provides a mechanical control on electrical input
- Feedback control to provide position accuracy
- Controls the electric input to the motor
- Provides the angular motion
- Available in various sizes
- Piezoelectric motor reduces size



Ultrasound Speakers

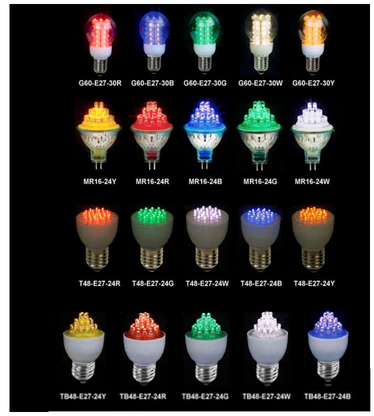
- Ultrasound is highly directional because of its relatively short wavelength
- Audible sound can be produced by inter-modulation of ultrasound beam in air
  - This is because at high intensity (above 125 dB), air stops behaving linearly
- Controlling the phase of nearby ultrasound beams can create audible sounds
  - But interference can affect the audio quality

Application



Light Emitting Diode (LED)

- Widely used nowadays in almost all applications
  - Housing
  - Automotive lights
  - Street lights
  - Focus lights
- Voltage when applied in the forward direction emits light
- Flowing of the electrons to lower energy level releases energy
- Consumes very little energy and gives off very little heat
- Color depends on the type of semiconductor material and not on filters
- Has long life (about 10 years)
- Dies with fatigue rather than sudden death



Questions?