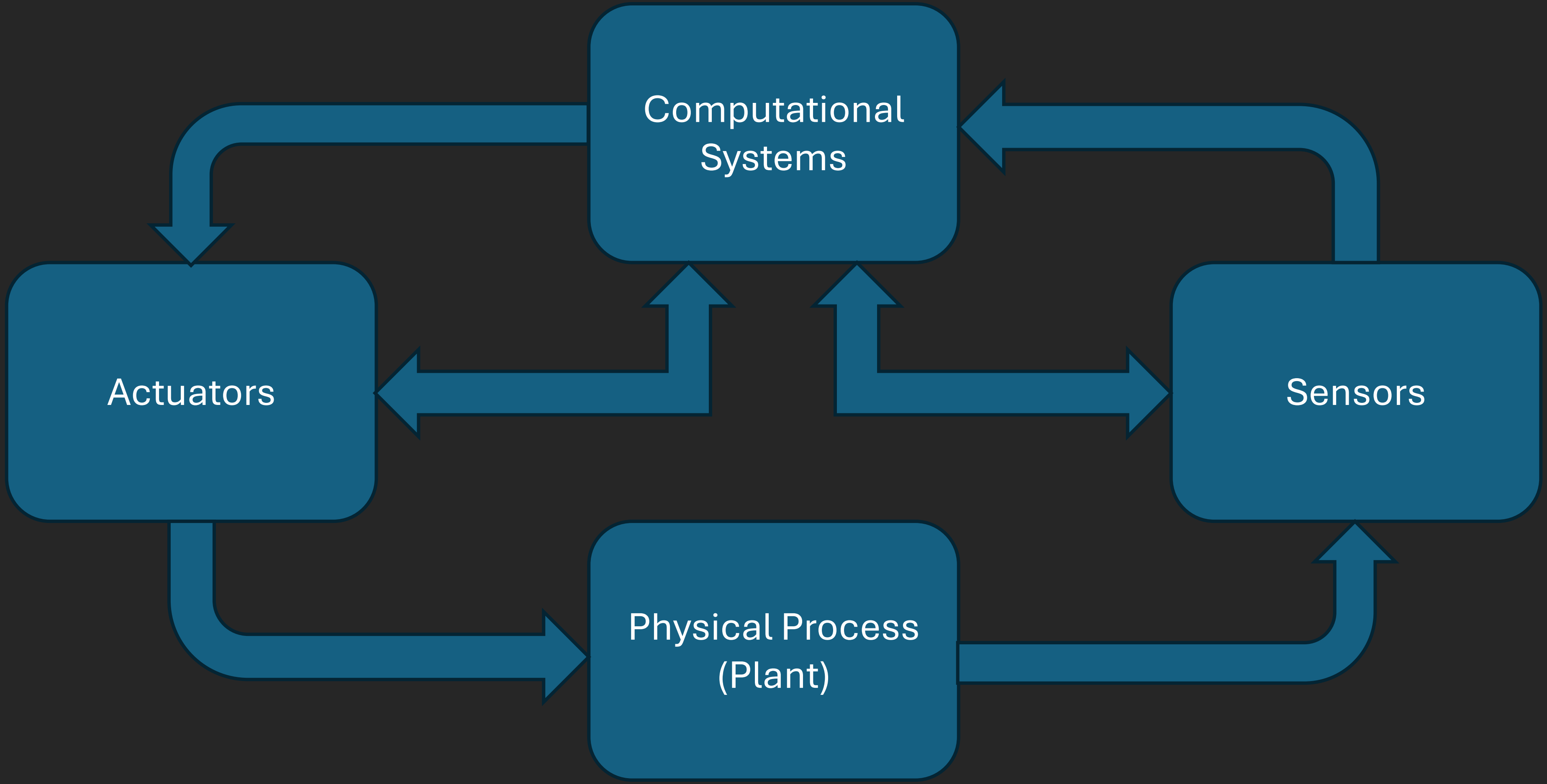
Cyber-Physical Systems

Dr. Jonathan Jaramillo

Sensor Systems

What are Cyber-Physical Systems?



Computational and Physical

- Sensors: A device that detects and measures physical properties from the environment and converts them into electrical signals that can be processed by a digital system.

Sensor Foundations

- Analog to Digital Converter (ADC) – Circuit that converts analog electrical signals into digital values
- Most sensor generate analog electrical signals
  - Temperature sensor, accelerometer, gyroscope
- Some sensors generate digital signals
  - Binary sensors, pulse-based timing sensors

Analog to Digital Converters

Analog to Digital Converters (ADCs)

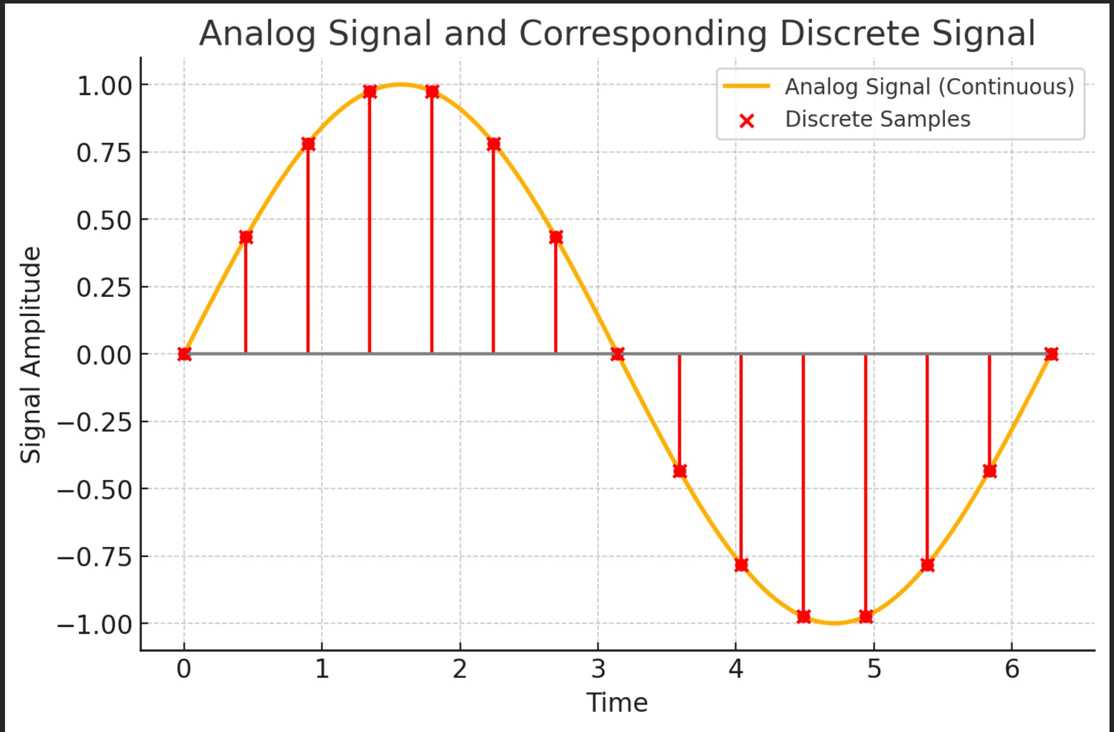
- An electronic device that converts a **continuous analog signal** (such as voltage or current) into a **discrete digital representation.**

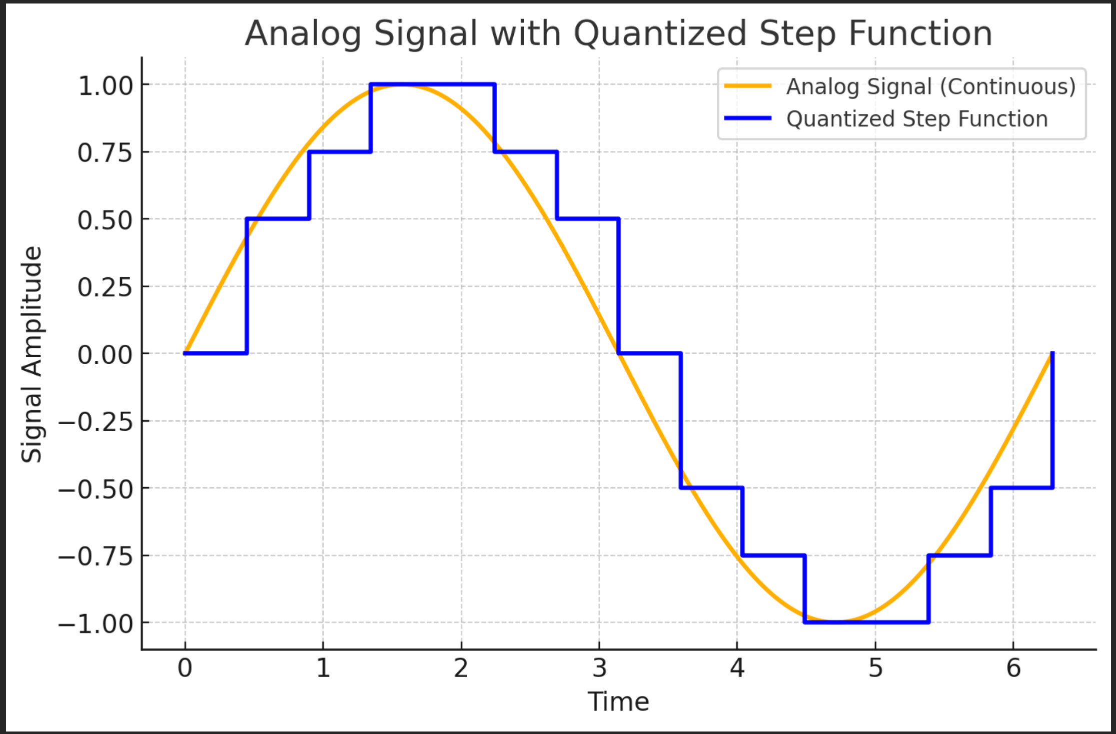
Analog to Digital Converters (ADCs)

- Sampling
  - The ADC takes periodic simples of the analog signal
- Quantization
  - Each sample is assigned a specific digital value based on its amplitude
- Encoding
  - The quantized values are converted into binary

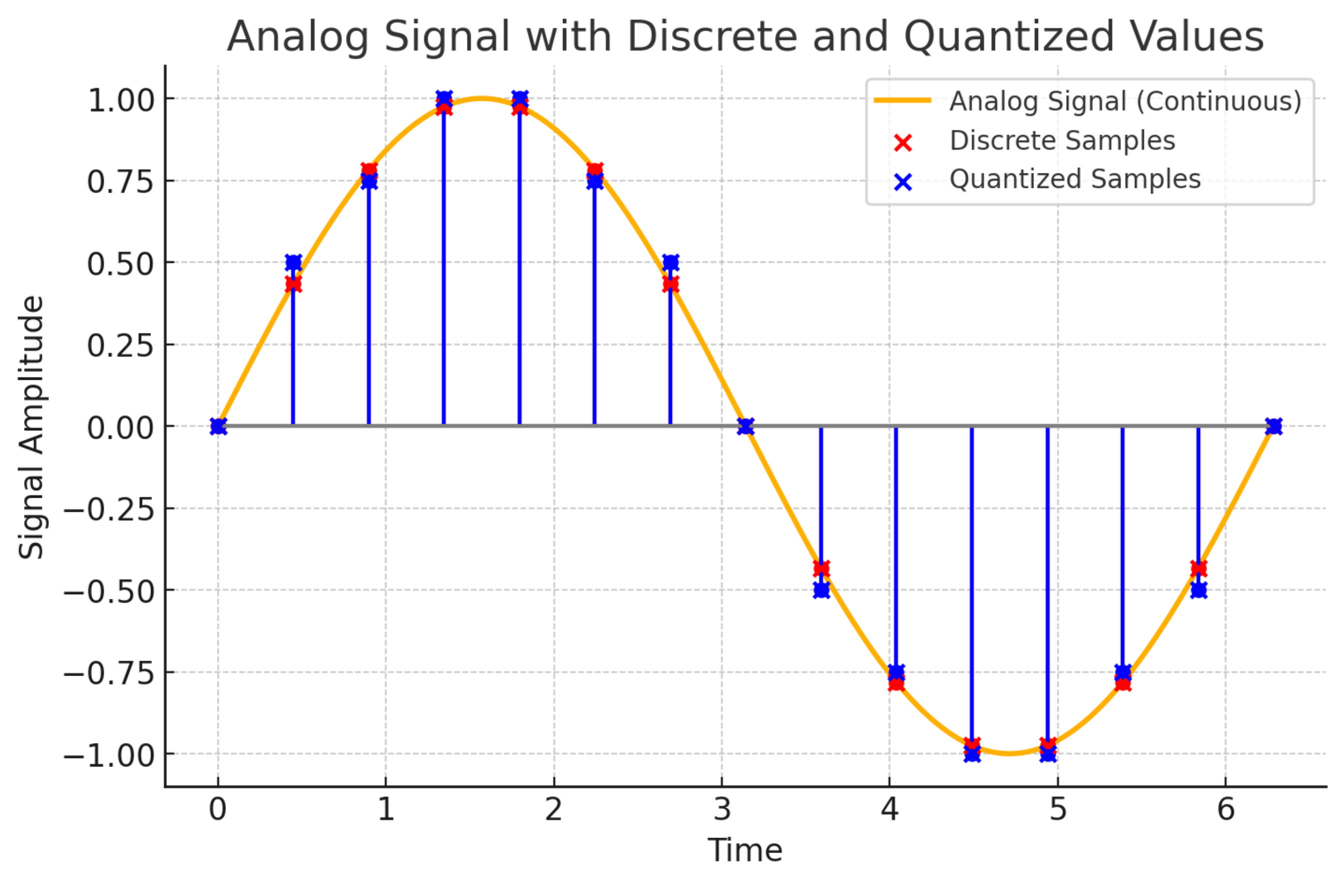
- Analog signals – continuous in time and value domains
- Digital signals – Discrete in time and value domain

Discretization vs Quantization





Discretization vs Quantization

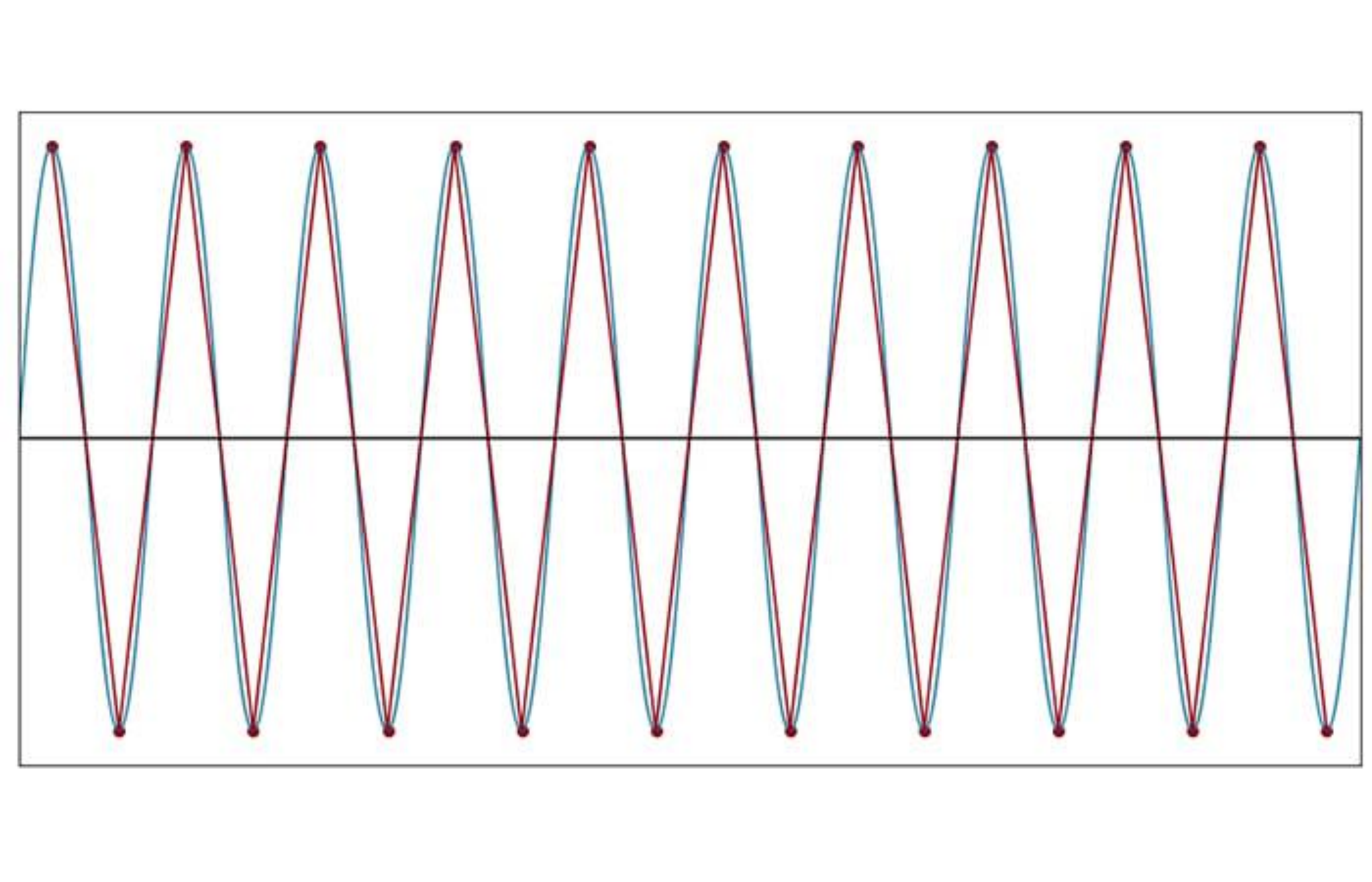


Discretization vs Quantization

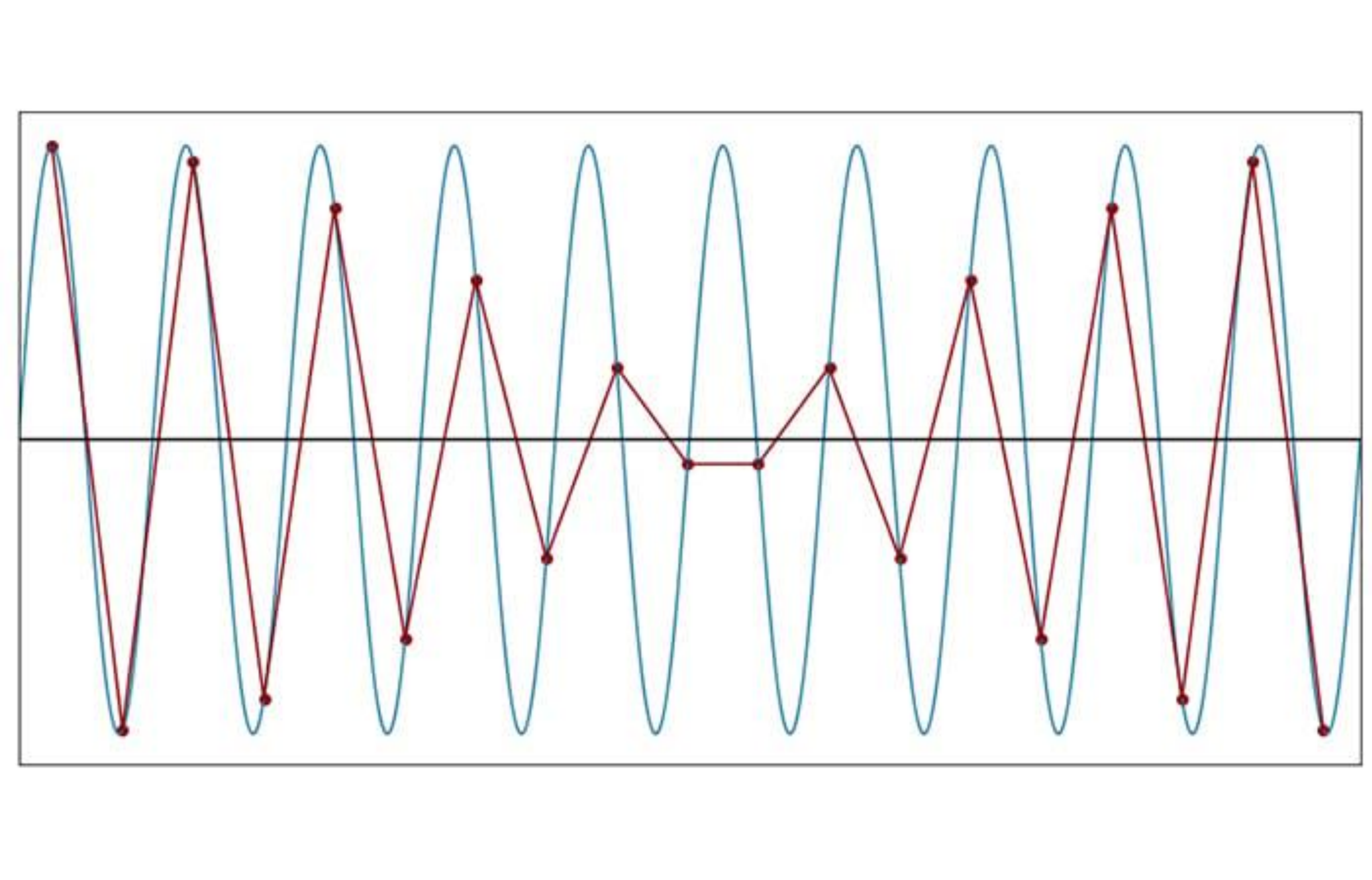
Shannon-Nyquist Theorem

- A continuous signal can be perfectly reconstructed from its discrete samples **if and only if** the signal is sampled at a rate at least twice the highest frequency component present in the signal.

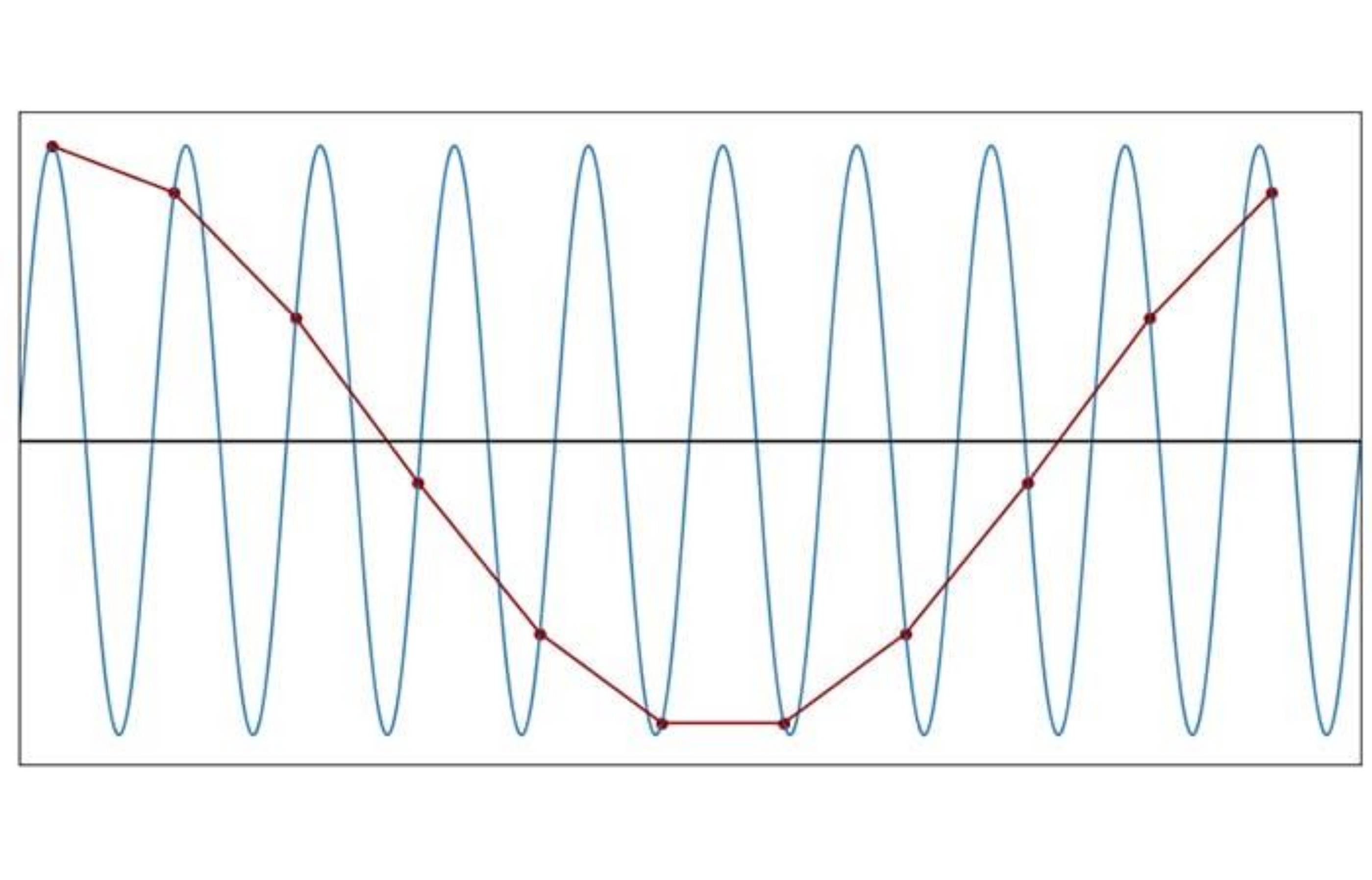
Shannon-Nyquist Theorem



Shannon-Nyquist Theorem



Shannon-Nyquist Theorem



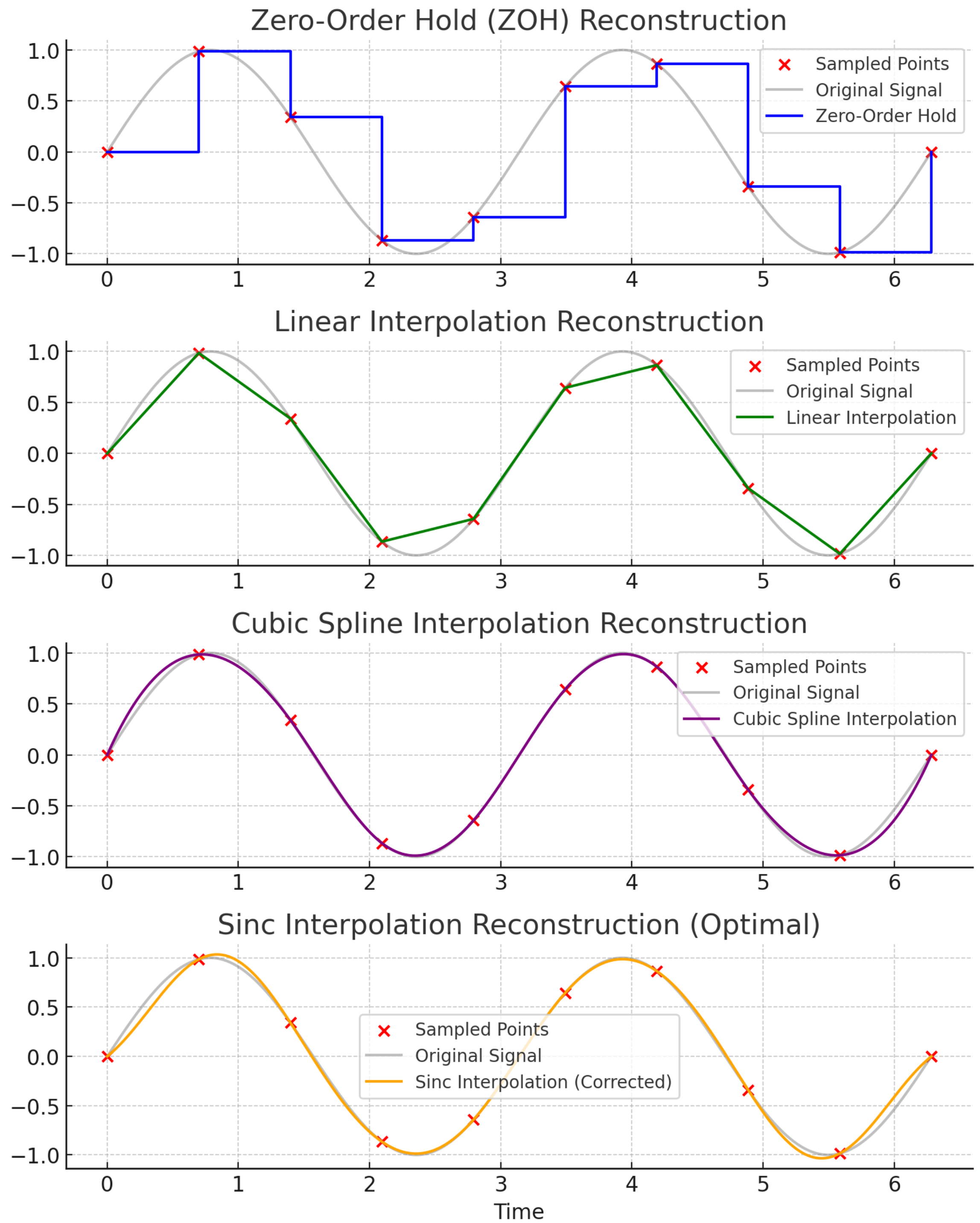
Signal Reconstruction

$$x_{ZOH}(t) = x[n], \quad \text{for } t \in [nT, (n+1)T)$$

$$x_{Linear}(t) = x[n] + \frac{x[n+1] - x[n]}{T}(t - nT), \quad \text{for } t \in [nT, (n+1)T)$$

$$x_{Spline}(t) = a_n + b_n(t - nT) + c_n(t - nT)^2 + d_n(t - nT)^3, \quad \text{for } t \in [nT, (n+1)T)$$

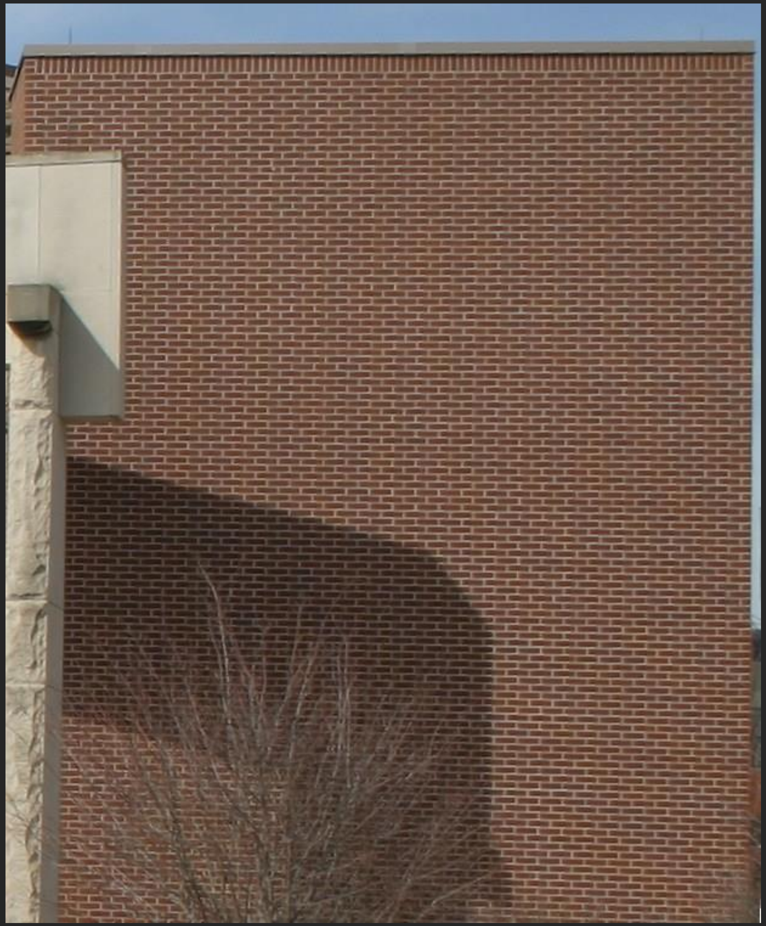
$$x_{Sinc}(t) = \sum_{n=-\infty}^{\infty} x[n] \cdot \text{sinc}\left(\frac{t - nT}{T}\right)$$



Aliasing

- When a continuous signal is under sampled, causing different signals to become indistinguishable, resulting in distorted or misleading reconstructions of the original signal.
- Sampled data may appear to have lower frequency that it actually does.

Aliasing



Wagon Wheel Effect

ADC Features

- Resolution – “Quantization” or the number of bits in the digital output
- Sampling Rate – frequency at which data is converted to digital vales
- Reference Voltage – Value against which analog values are compared
- Input Range – Min and max analog values that can be measured
- Accuracy – How close the ADC’s output can match the analog value

Other Consideration

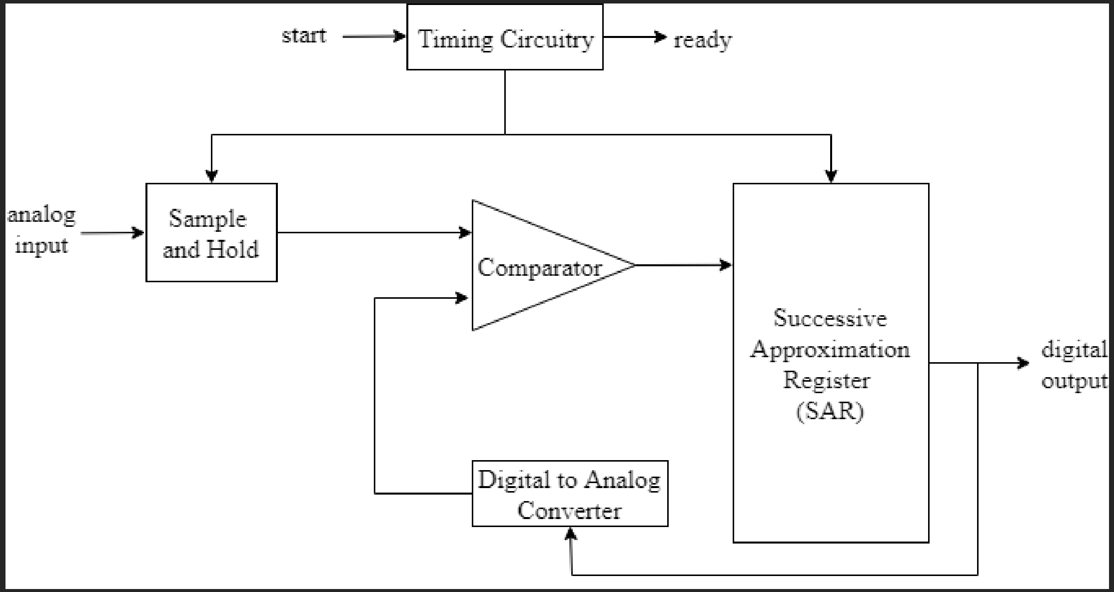
- Signal to noise ratio
  - Temperature, clock timing, shot noise, EMI, power supply
- Settling Time
  - Time it takes ADC’s internal circuits to stabilize after input change
- Power Consumption
- Latency
  - Delay between sampling and obtaining digital output

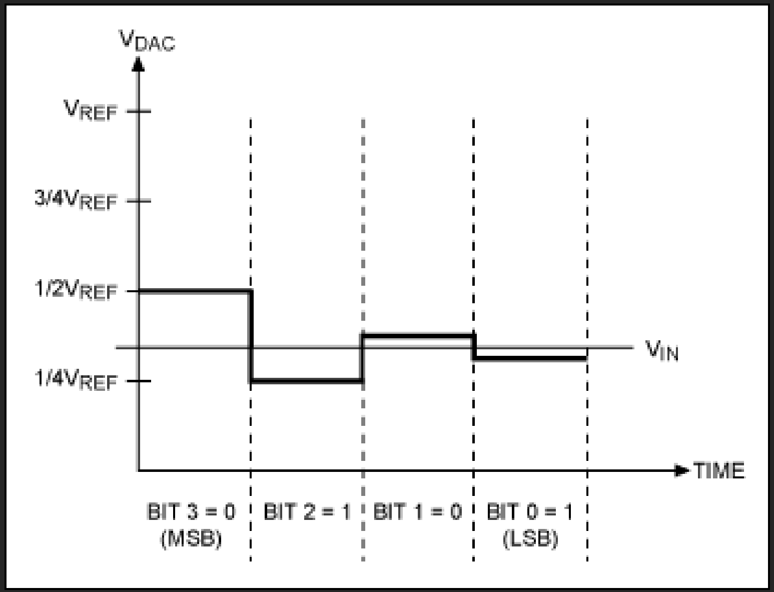
Types of ADCs

- Successive Approximation Registers (SARs)
- Delta-Sigma
- Pipeline
- Dual Slope
- Flash

Successive Approximation Register

- Approximate the analog signal in steps using a binary search algorithm
  - Digital to analog converter compares the register value to the analog signal and flips bits successively until the values match





Successive Approximation Register

- Advantages
  - Moderate to high resolution (usually 8-16 bits)
  - Efficient power consumption (ideal for portable devices)
  - Moderate speed
- Disadvantage
  - Trade off between speed and resolution
- Widely used
  - Embedded systems, automotive, industrial, communication, portable devices

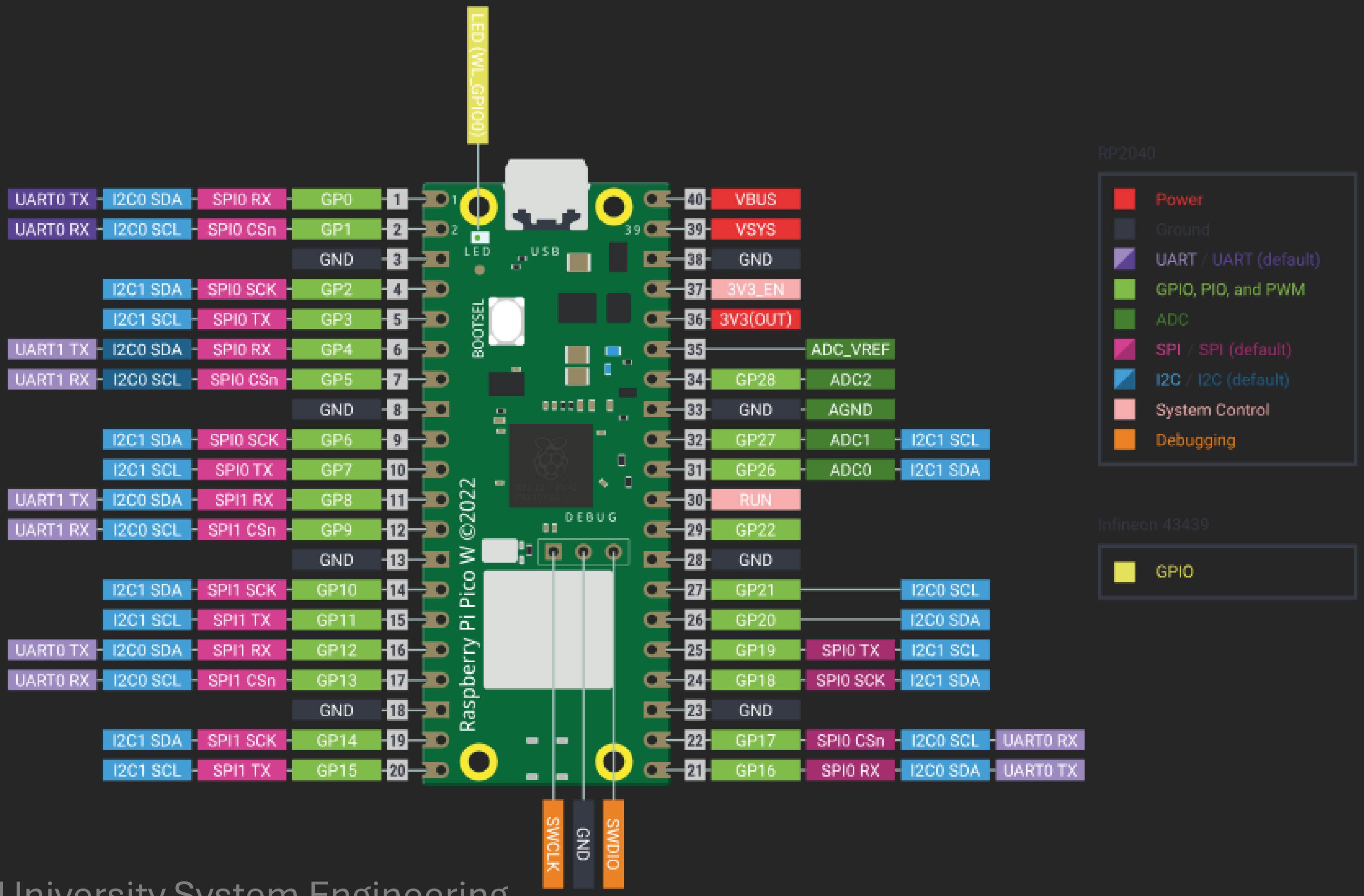
Successive Approximation Register

Resolution (Bits)	Common Sample Rate Range
8-bit SAR ADC	100 kHz – 50 MHz
10-bit SAR ADC	100 kHz – 20 MHz
12-bit SAR ADC	50 kHz – 10 MHz
14-bit SAR ADC	10 kHz – 5 MHz
16-bit SAR ADC	1 kHz – 2 MHz
18-bit SAR ADC	1 kHz – 1 MHz
20-bit SAR ADC	10 Hz – 500 kHz

Successive Approximation Register

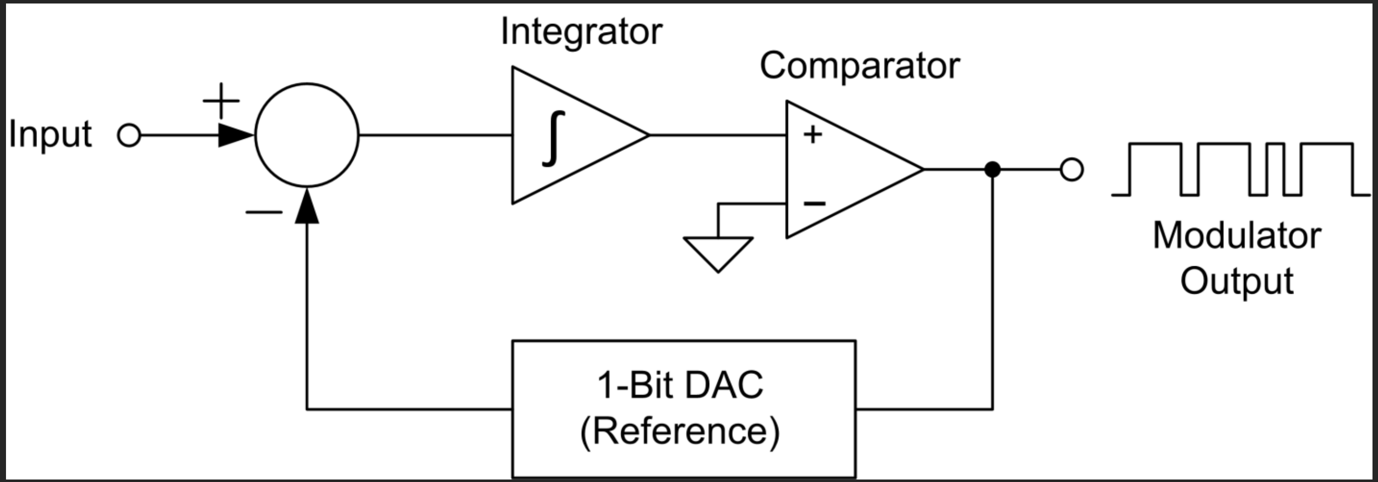
- Raspberry Pi Pico W
- 12-bit SAR
- Range 0-3.3v corresponding to 0-4096 (2^12)
- Sample Rate 500 kHz
- Channels 3 + 1 (internal temperature sensor)

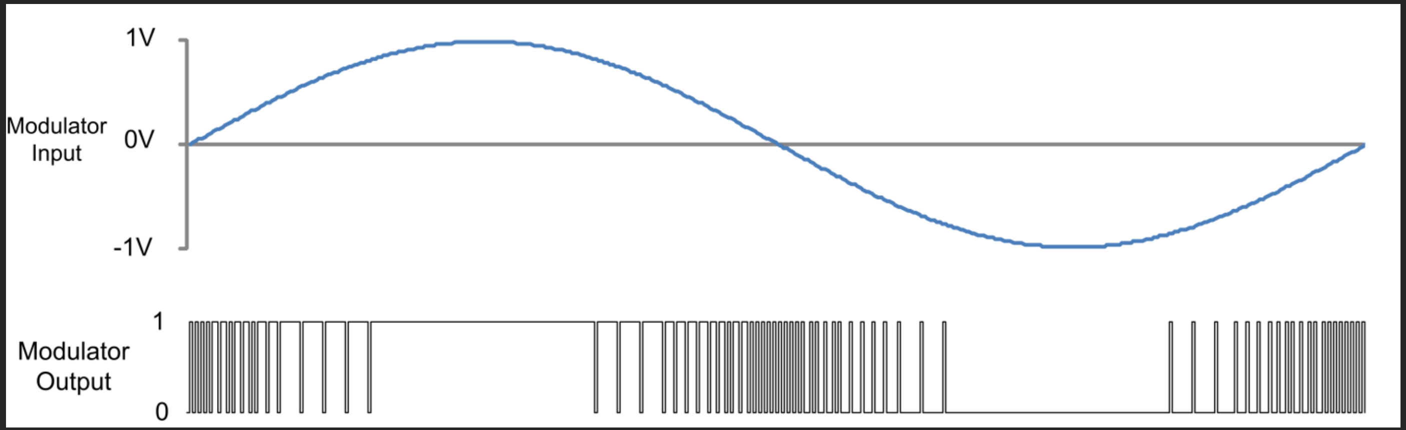
Raspberry Pi Pico W



Delta-Sigma ADC

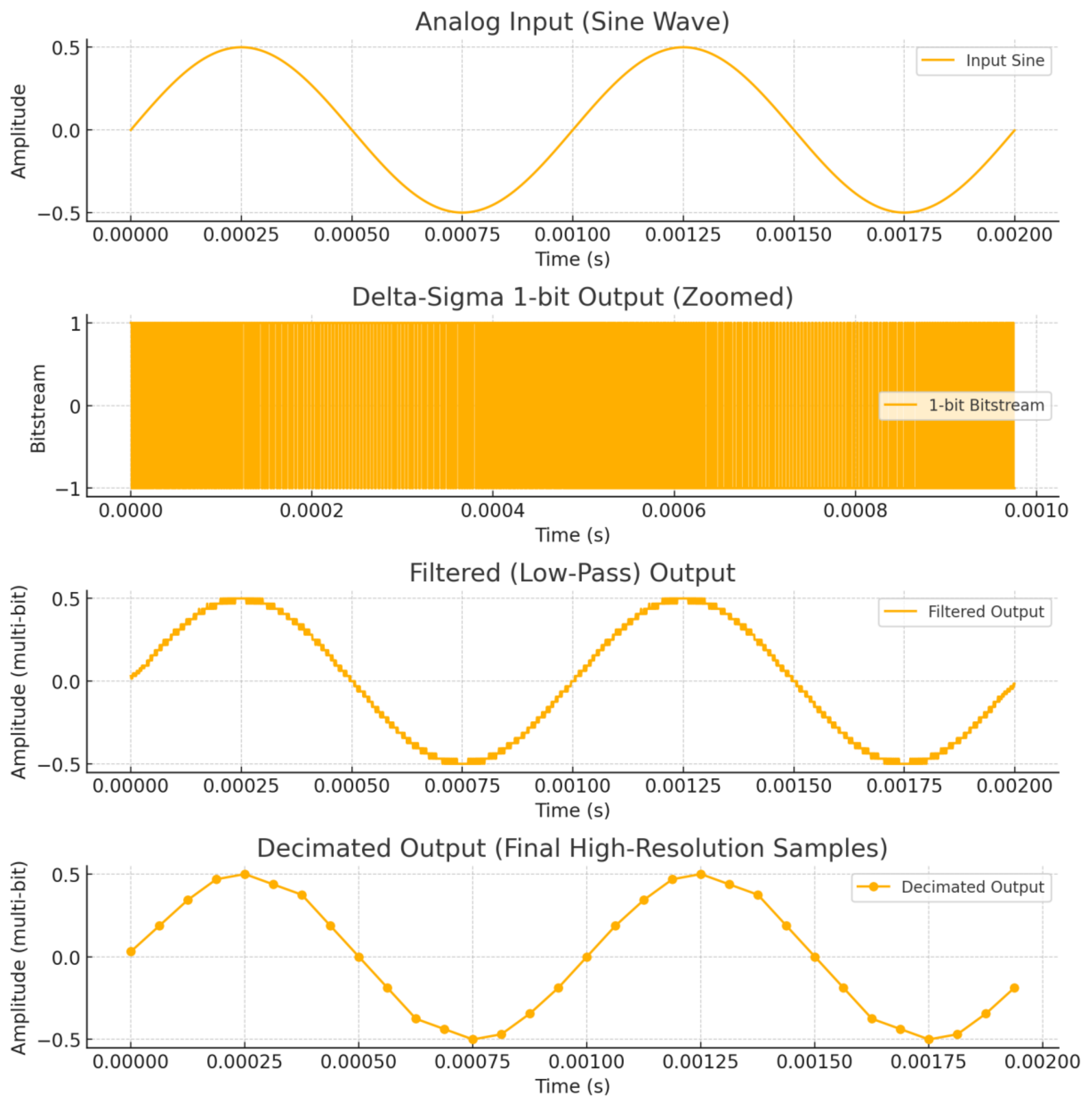
- Bit stream is generated corresponding to the analog input





Delta Sigma ADC

- The bit stream is then passed into a digital low pass filter and decimated

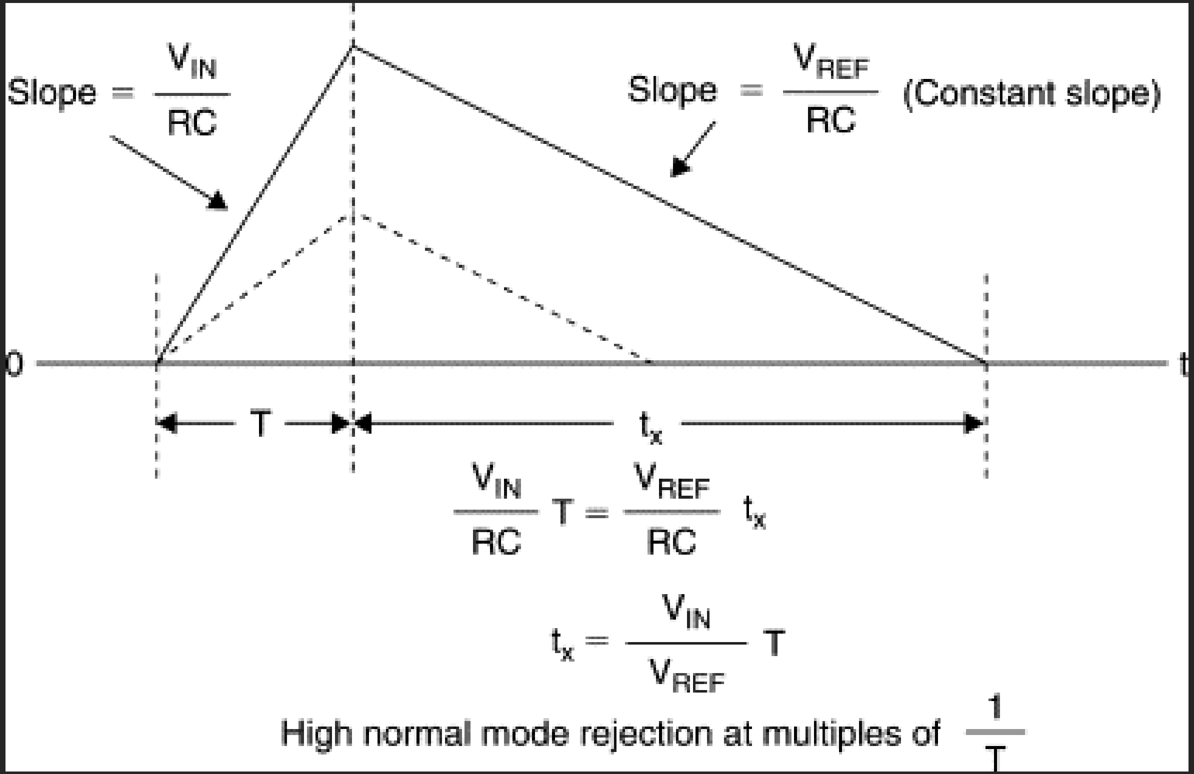


Delta Sigma ADC

- Advantages
  - Very high resolution (up to 24 bits – 16.8 million values)
  - Excellent noise reduction
  - Suitable for precision measurements
- Disadvantage
  - Moderate sampling speeds
- Widely used
  - Precision measurement systems, audio systems

Dual Slope ADC

- The input voltage is integrated over a fixed amount of time (charging).
- The results is de-integrated (discharging) via a known reference voltage back to zero and the time is measured.

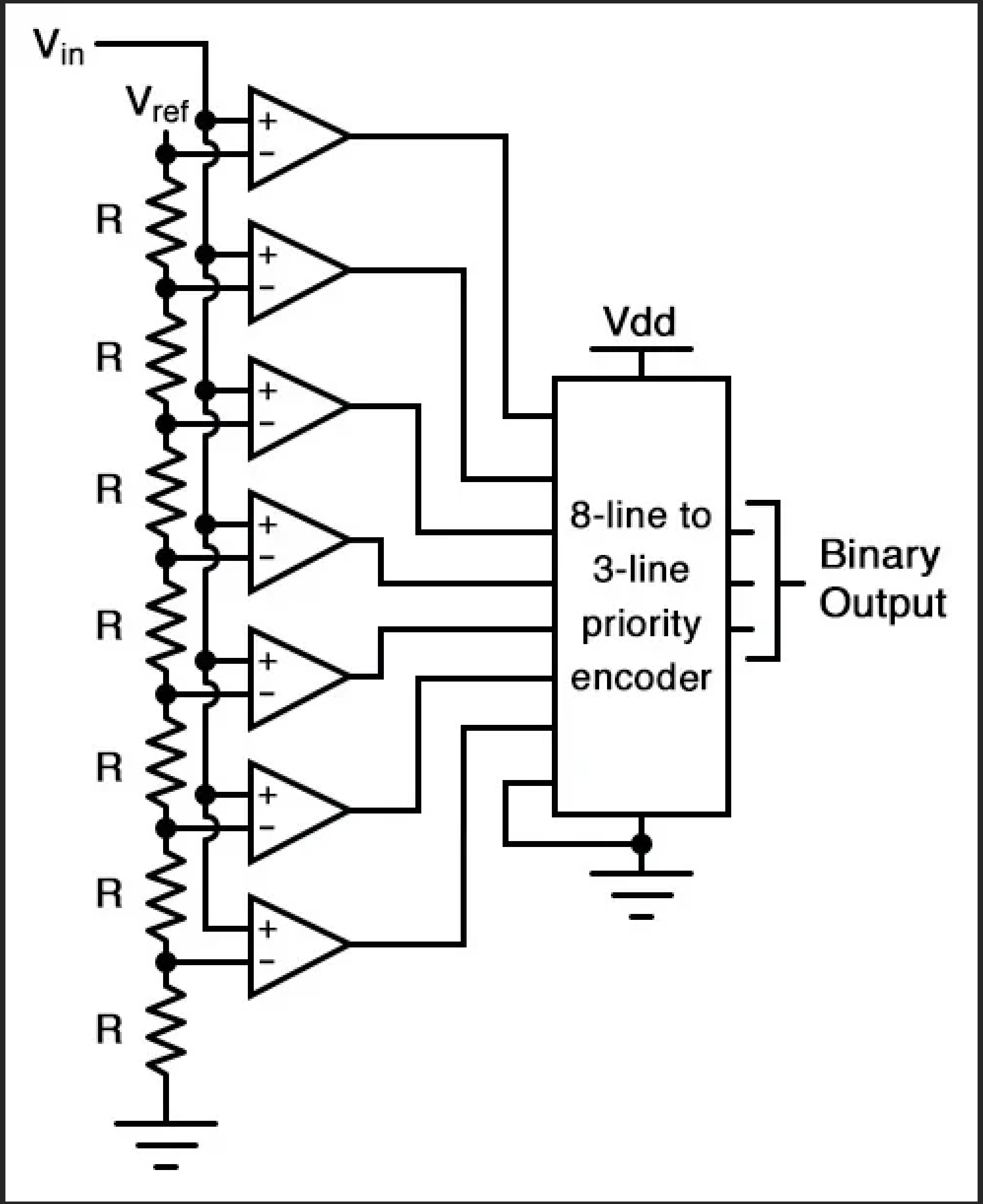


Dual Slope ADC

- Advantages
  - High noise immunity (particularly due to AC interference)
  - Very accurate and stable
  - Low power consumption
- Disadvantage
  - Slow
- Widely used
  - Digital multi-meters, precision instruments

Flash ADC

- Input is fed into an array of comparators, each connected to a specific reference voltage.
- Reference voltages are generated using a resistor ladder generating a “thermometer code”
- The thermometer code is converted to binary in a single clock cycle



Flash ADC

- Advantages
  - Extremely fast, fastest conversion speed among ADC types
  - No latency
- Disadvantage
  - High power consumption
  - Significant die area due to large number of comparators ($2^n - 1$)
  - Low resolution (typically 4-8 bits)
- Widely used
  - Radar, RF communication, oscilloscopes

ADCs Comparisons

ADC Type	**Resolution**	**Speed**	**Power Consumption**	**Complexity**	**Accuracy**	**Noise Immunity**	**Applications**
SAR	Medium to High (8-18 bits)	Medium (Up to 10 MHz)	Low to Medium	Medium	High	Medium	General-purpose ADCs, Microcontrollers, Data Acquisition
Delta-Sigma	Very High (16-24 bits)	Slow (Few kHz to 1 MHz)	Medium to High	High	Very High	Excellent	Audio, Precision Measurements, High-Resolution Sensors
Dual-Slope	Very High (16-24 bits)	Very Slow (Few Hz to kHz)	Low	Low	Very High	Excellent	Digital Multimeters, Precision Weighing Scales
Flash	Low to Medium (4-10 bits)	Very Fast (Up to GHz)	Very High	Very High	Low	Poor	High-Speed Signal Processing, Radar, Oscilloscopes

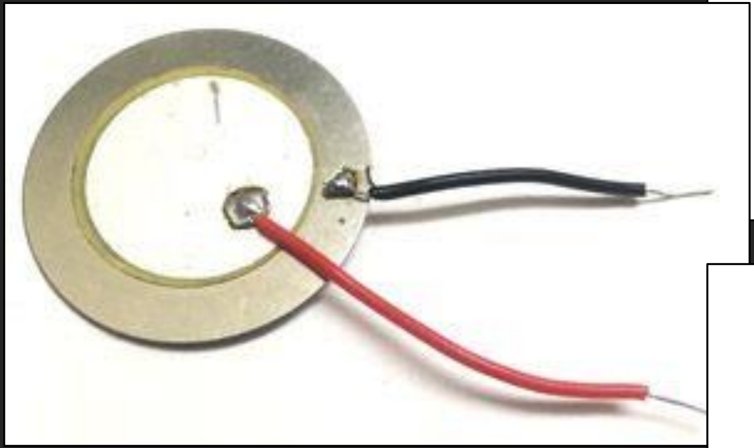
Sensor Fundamentals

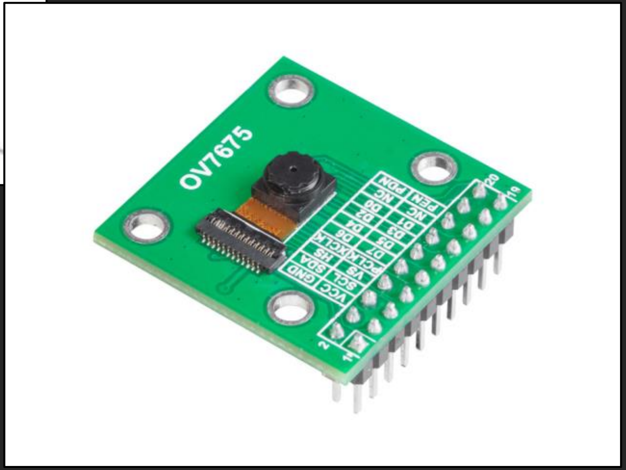
Categories

- Passive
  - Detect and measure energy originating from the environment.
- Active
  - Require emission of power to sense the environment
- Analog
  - Produce a continuous output signal that is directly proportional to the measured quantity
- Digital
  - Output discrete signals, often binary values

Passive Sensors

- Thermocouples
- Photodiodes
- Piezoelectric Sensors
- Cameras

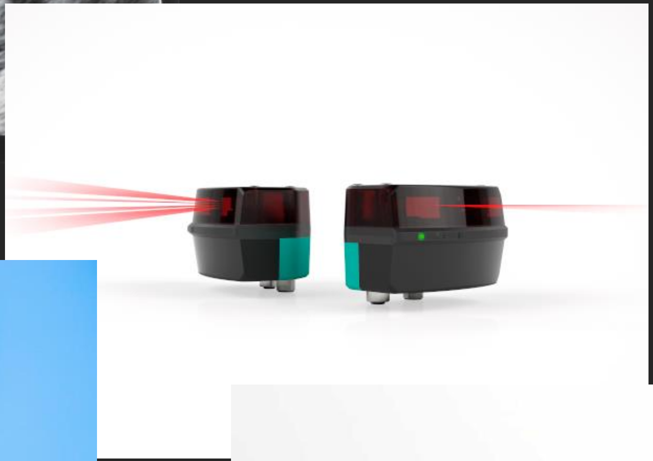




Passive Control System

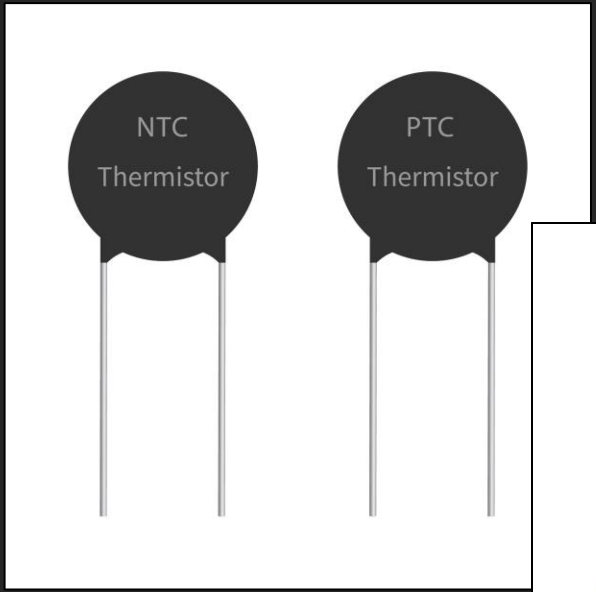
Active Sensors

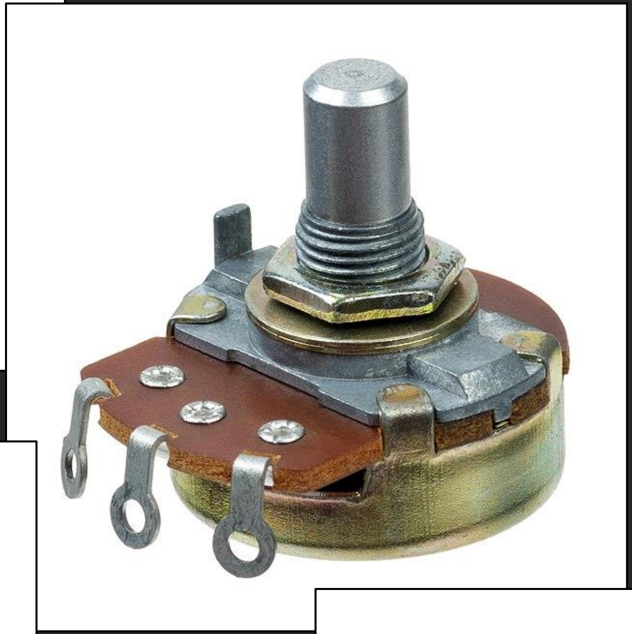
- Ultrasound
- LiDAR
- RaDAR
- Optical Encoder

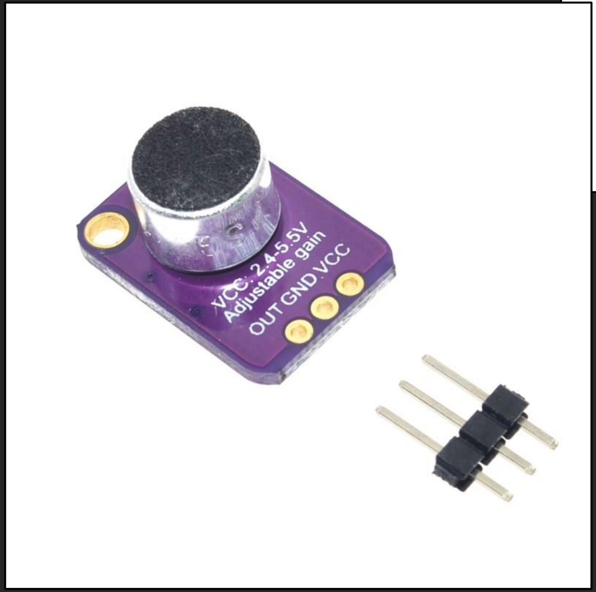


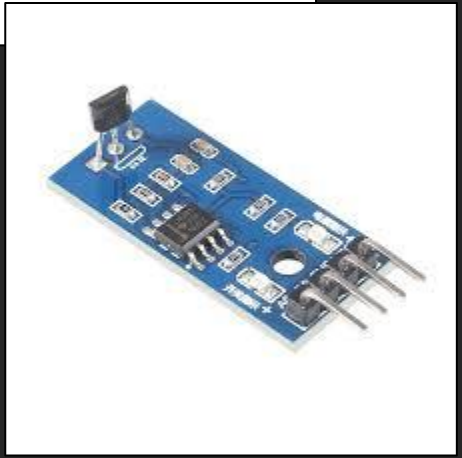
Analog Sensors

- Thermistor
- Potentiometer
- Microphone
- Hall Effect Sensor



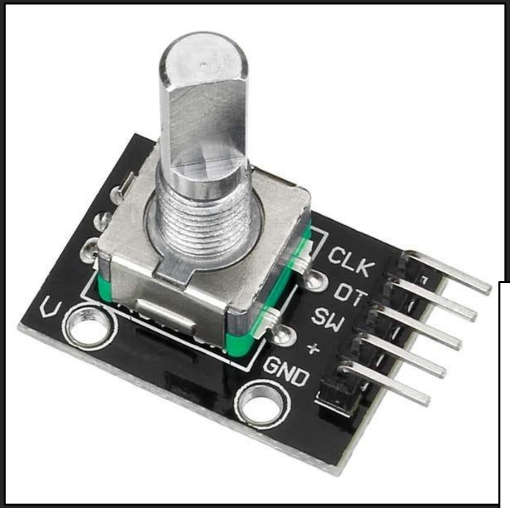


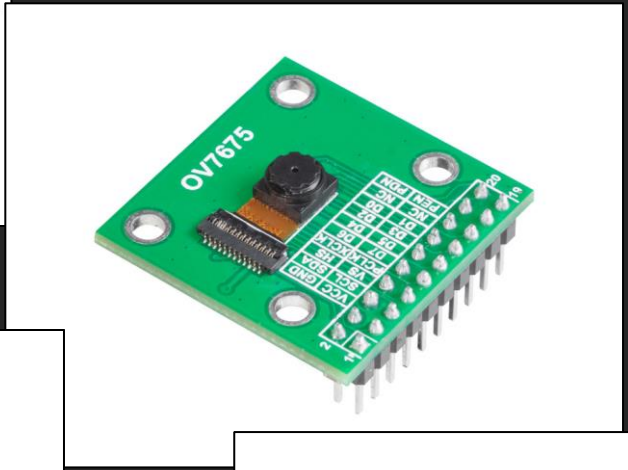


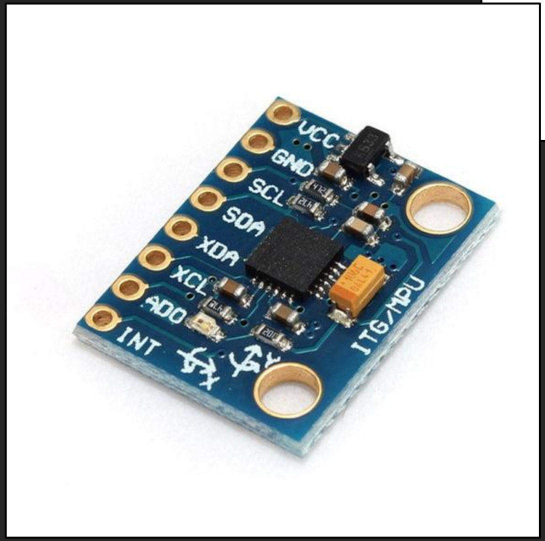


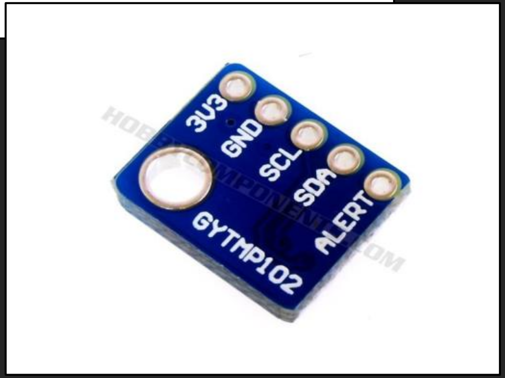
Digital Sensors

- Encoder
- Digital Camera
- IMU
- Digital Temperature Sensor









Sensor Characteristics

Sensitivity

- Refers to how much the sensor output changes per unit change in the input
- Typically expressed as a ratio
- Example:
  - Thermocouple: Type-K thermocouple has a sensitivity of 41 uV/C
  - Accelerometer: MEMS unit has a sensitivity of 100mV/g
- Relevance:
  - Higher sensitivity improves precision
  - Impacts choice of ADC

Sensitivity - Example

TEXAS INSTRUMENTS

TMP61

SBOS921F – DECEMBER 2018 – REVISED NOVEMBER 2023

TMP61 ±1% 10-kΩ Linear Thermistor With 0402 and 0603 Package Options

1 Features

- Silicon-based thermistor with a positive temperature coefficient (PTC)
- Linear resistance change across temperature
- 10-kΩ nominal resistance at 25°C (R25)
  - ±1% maximum (0°C to 70°C)
- Wide operating temperature of –40°C to +150 °C
- Consistent sensitivity across temperature
  - 6400 ppm/°C TCR (25°C)
  - 0.2% typical TCR tolerance across temperature range
- Fast thermal response time of 0.6 s (DEC)
- Long lifetime and robust performance
  - Built-in fail-safe in case of short-circuit failures
  - 0.5% typical long term sensor drift

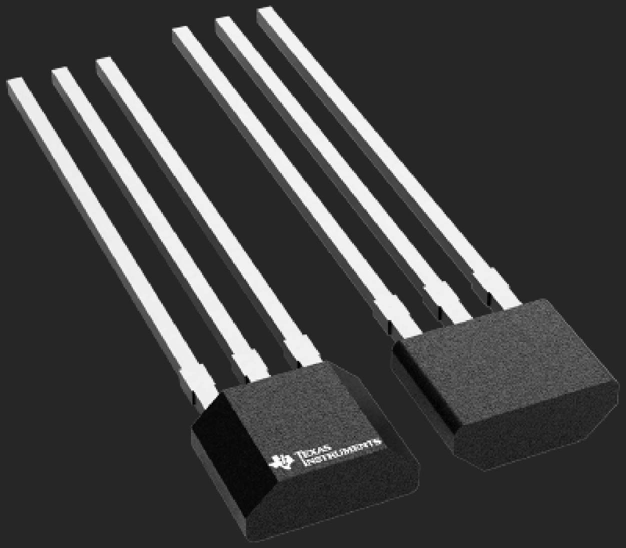
2 Applications

3 Description

Get started today with the Thermistor Design Tool, offering complete resistance vs temperature table (R-T table) computation, other helpful methods to derive temperature and example C-code.

The TMP61 linear thermistor offers linearity and consistent sensitivity across temperature to enable simple and accurate methods for temperature conversion. The low power consumption and a small thermal mass of the device minimize self-heating.

With built-in fail-safe behaviors at high temperatures and powerful immunity to environmental variation, these devices are designed for a long lifetime of high performance. The small size of the TMP6 series also allows for close placement to heat sources and quick response times.



Resolution

- Smallest change in the input that the sensor can detect
- Typically depends on the ADC, related to LSB
- Example:
  - Digital Temp Sensor: 0.0078C
  - Optical Encoder: 1000 pulses per revolution
- Relevance:
  - Affects precision of control
  - Poor perception

Resolution - Example

TEXAS INSTRUMENTS

TMP117

SNOSD82D – JUNE 2018 – REVISED SEPTEMBER 2022

TMP117 High-Accuracy, Low-Power, Digital Temperature Sensor With SMBus™- and I²C-Compatible Interface

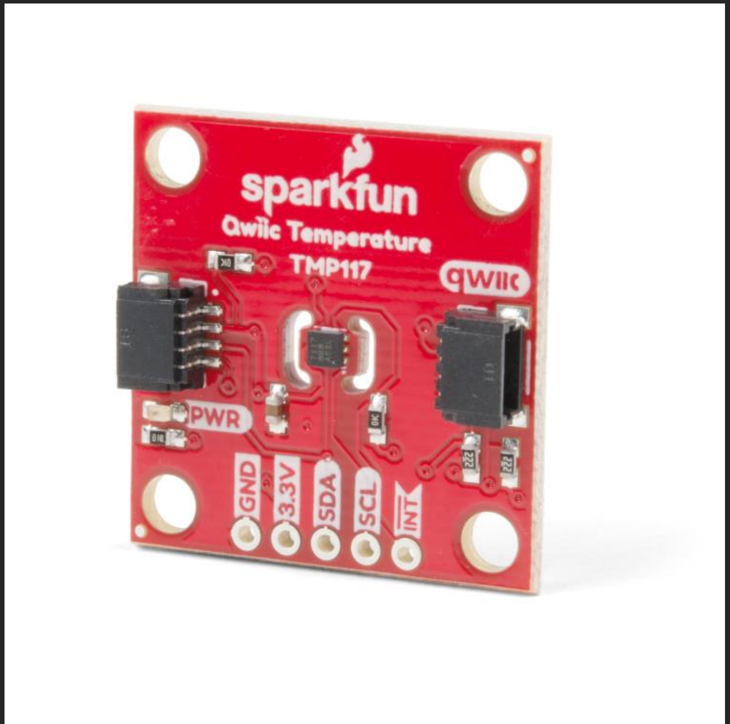
1 Features

- TMP117 high-accuracy temperature sensor
  - ±0.1 °C (maximum) from –20 °C to 50 °C
  - ±0.15 °C (maximum) from –40 °C to 70 °C
  - ±0.2 °C (maximum) from –40 °C to 100 °C
  - ±0.25 °C (maximum) from –55 °C to 125 °C
  - ±0.3 °C (maximum) from –55 °C to 150 °C
- Operating temperature range: –55 °C to 150 °C
- Low power consumption:
  - 3.5-µA, 1-Hz conversion cycle
  - 150-nA shutdown current
- Supply range:
  - 1.7 V to 5.5 V from –55 °C to 70 °C
  - 1.8 V to 5.5 V from –55 °C to 150 °C
- 16-bit resolution: 0.0078°C (1 LSB)
- Programmable temperature alert limits
- Selectable averaging
- Digital offset for system correction

3 Description

The TMP117 is a high-precision digital temperature sensor. It is designed to meet ASTM E1112 and ISO 80601 requirements for electronic patient thermometers. The TMP117 provides a 16-bit temperature result with a resolution of 0.0078 °C and an accuracy of up to ±0.1 °C across the temperature range of –20 °C to 50 °C with no calibration. The TMP117 has in interface that is I²C- and SMBus™-compatible, programmable alert functionality, and the device can support up to four devices on a single bus. Integrated EEPROM is included for device programming with an additional 48-bits memory available for general use.

The low power consumption of the TMP117 minimizes the impact of self-heating on measurement accuracy. The TMP117 operates from 1.7 V to 5.5 V and typically consumes 3.5 µA.



Accuracy

- How close the sensor's measurement is to the true value
- Affected by noise, drive, and environmental conditions
- Example:
  - Digital Barometer: +- 1hPa
  - Industrial Load Cell: +- 0.05% of full scale
- Relevance:
  - Impact criticality of the system
  - Poor perception

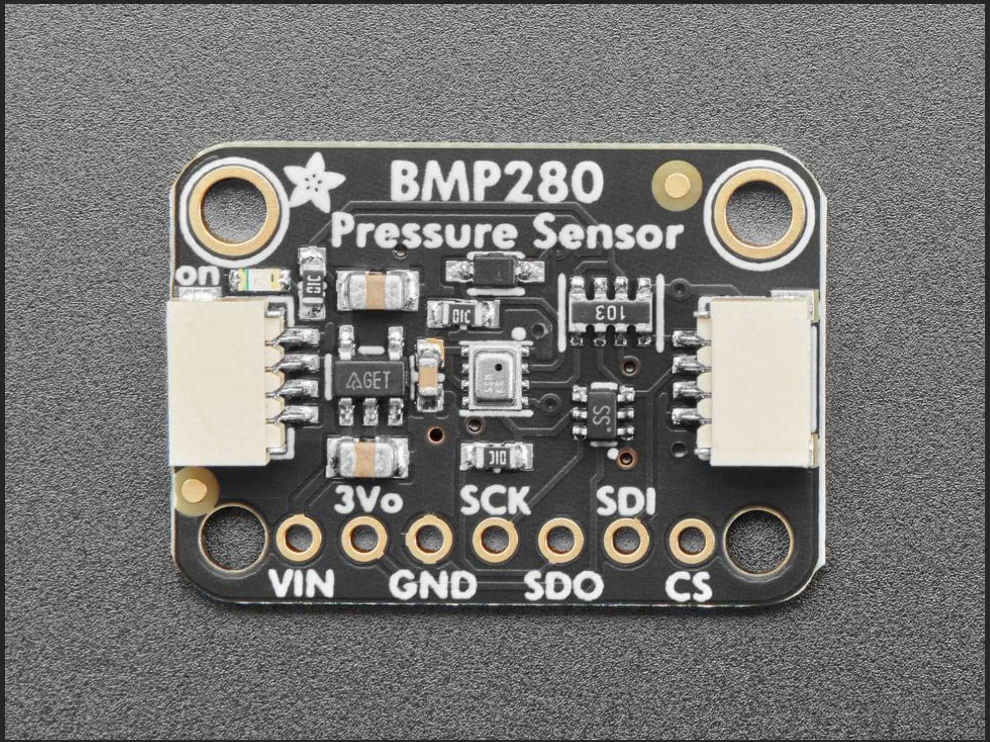
Accuracy - Example

BMP280

Digital Pressure Sensor

Key parameters

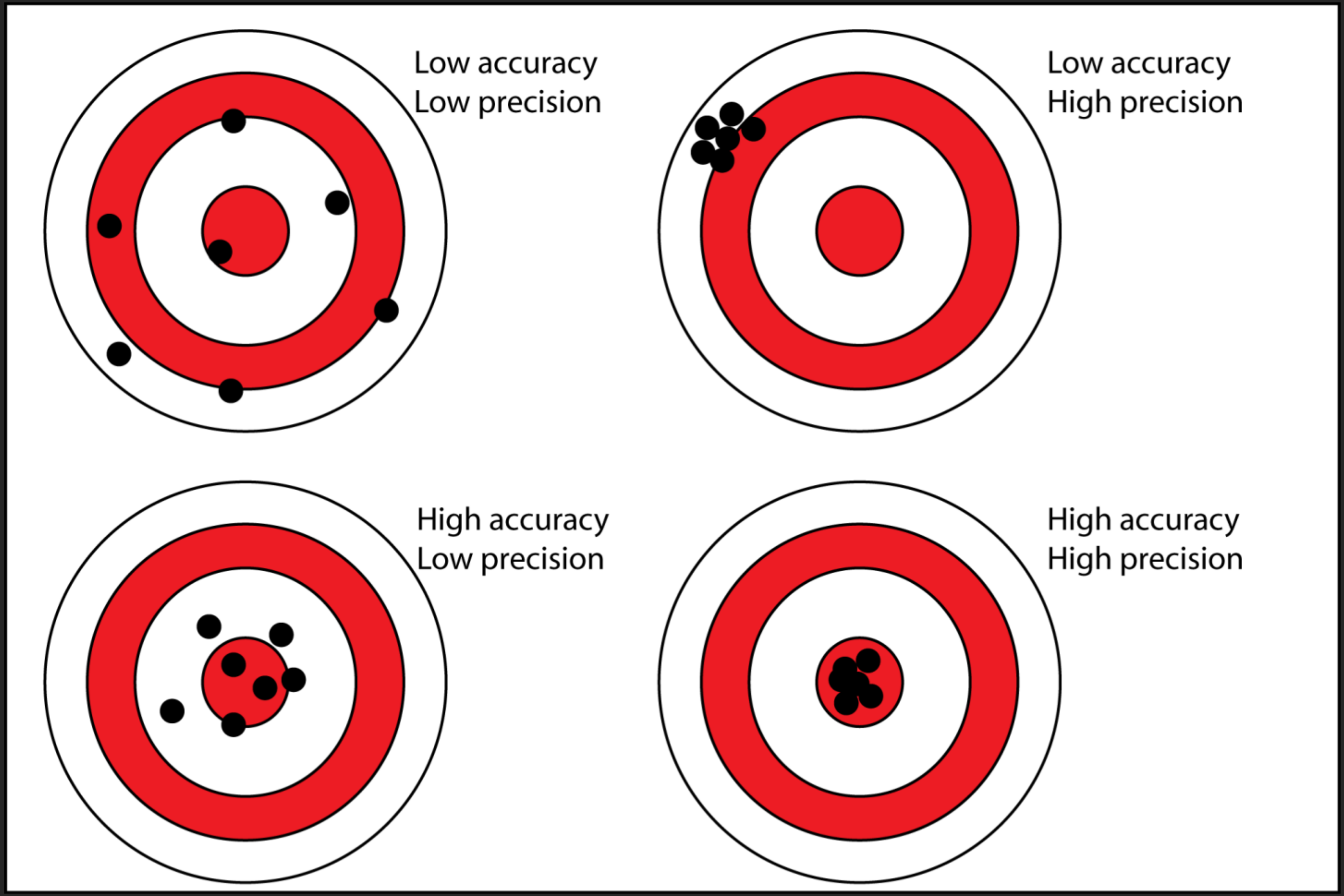
- Pressure range — 300 … 1100 hPa (equiv. to +9000…-500 m above/below sea level)
- Package — 8-pin LGA metal-lid; Footprint : 2.0 × 2.5 mm², height: 0.95 mm
- Relative accuracy (950 … 1050hPa @25°C) — ±0.12 hPa, equiv. to ±1 m
- Absolute accuracy (950 …1050 hPa, 0 …+40 °C) — typ. ±1 hPa
- Temperature coefficient offset (25 … 40°C @900hPa) — 1.5 Pa/K, equiv. to 12.6 cm/K
- Digital interfaces — I²C (up to 3.4 MHz); SPI (3 and 4 wire, up to 10 MHz)
- Current consumption — 2.7µA @ 1 Hz sampling rate
- Temperature range — -40 … +85 °C
- RoHS compliant, halogen-free
- MSL 1



Precision

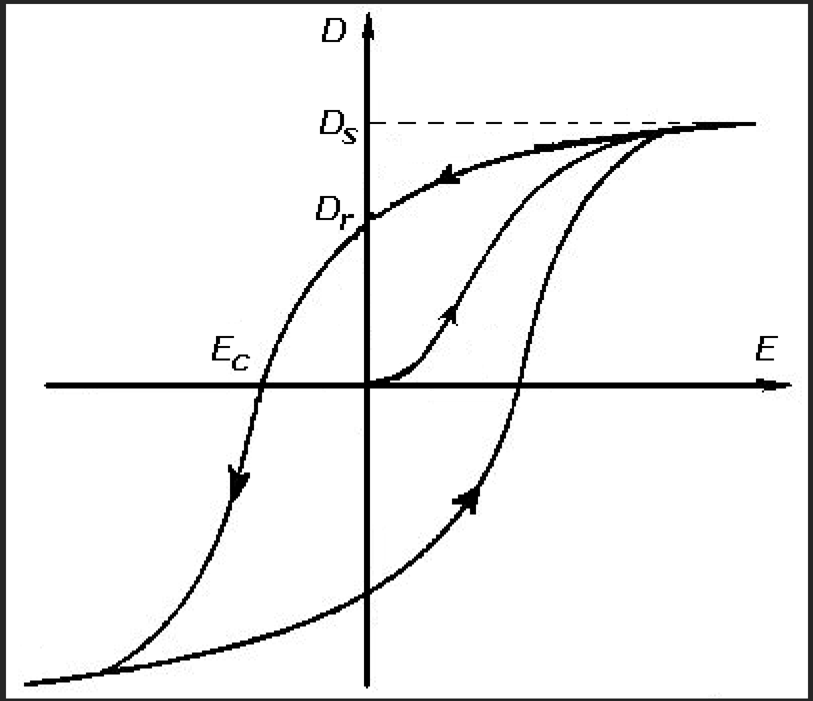
- How repeatable a sensor reading is
- Example:
  - Gyroscopes: have a bias that changes very slowly
- Relevance:
  - Impacts the frequency of calibration

Precision Vs Accuracy



Other Factors

- Linearity
- Drift
- Response Time
- Hysteresis
  - Sensor will give different outputs depending on whether the value is increasing or decreasing

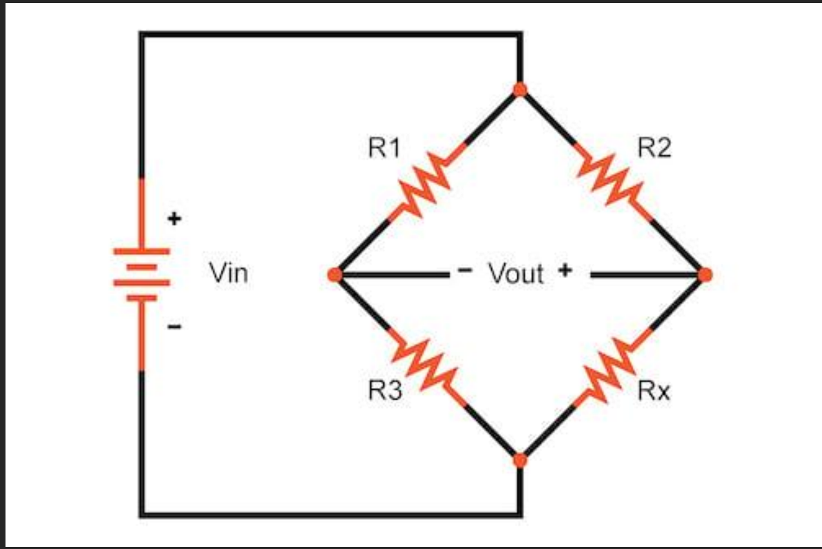


Sensing Technologies

Resistive Sensors

- Resistance is governed by Ohms Law
  - $V = IR$
- External stimulant changes resistance

Measuring Resistance



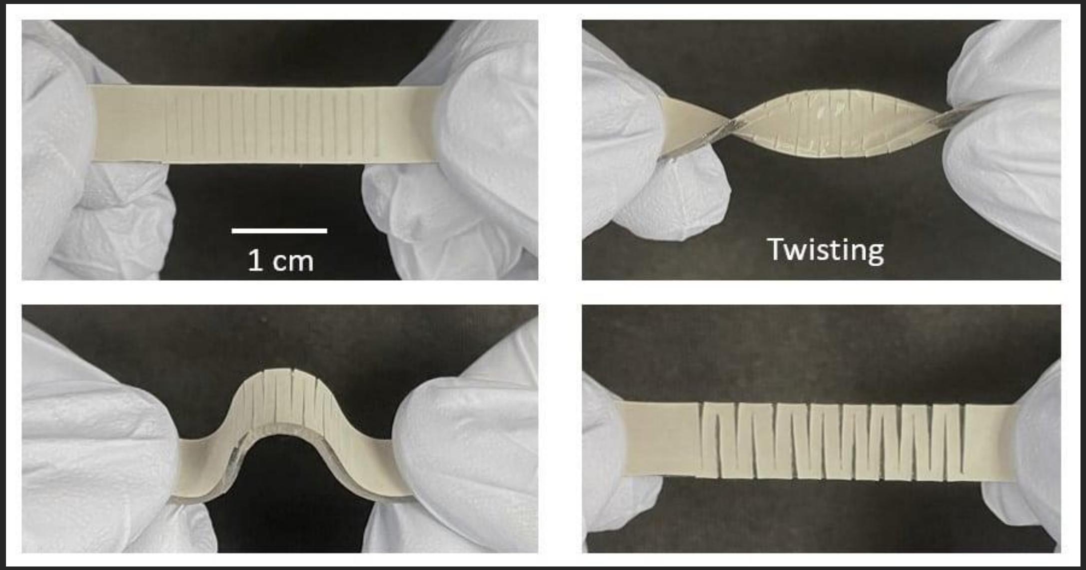
- Ohm Meter
  - Apply a known voltage and measure current
  - Simple, quick, limited by contact resistance and test lead quality
- Wheatstone Bridge
  - 3 variable resistors are tuned to balance current flow
  - High accuracy and sensitivity, ideal for small changes, requires stable power
- Current-Voltage Method
  - Known current is pushed through resistor and voltage is measured
  - Accurate, requires precision current supply, sensitive to noise

Importance to CPS

- Simple and cost effective
- Versatile – strain, pressures, temperature
- Robust – many resistive sensors have a long lifespan
- Compatible – easily interfaced with ADS and microcontrollers
- Challenges
  - Drift and hysteresis
  - Environmental sensitivity
  - Linearity issues

Strain Gauge

- Thin Wire or foil that changes resistance when deformed
- Structural health monitoring, industrial wight systems, biomedical



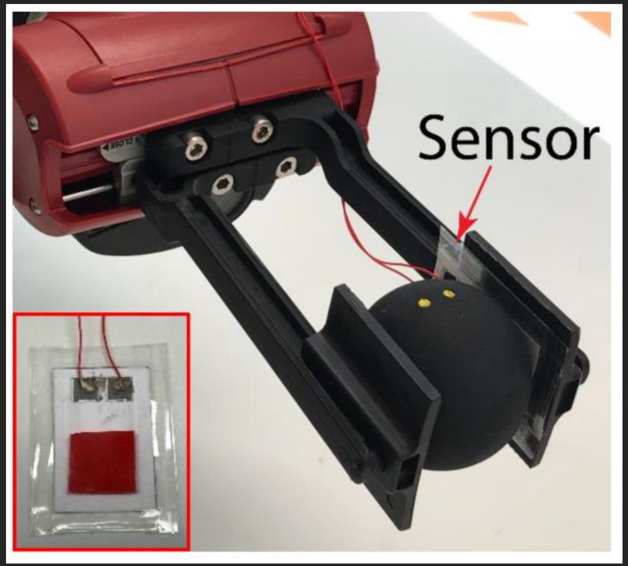
Thermistor (NTC/PTC)

- Resistance changes depending on temperature
- HVAC systems, battery temperature regulators, overheat protection

Resistive Force and Pressure Sensor

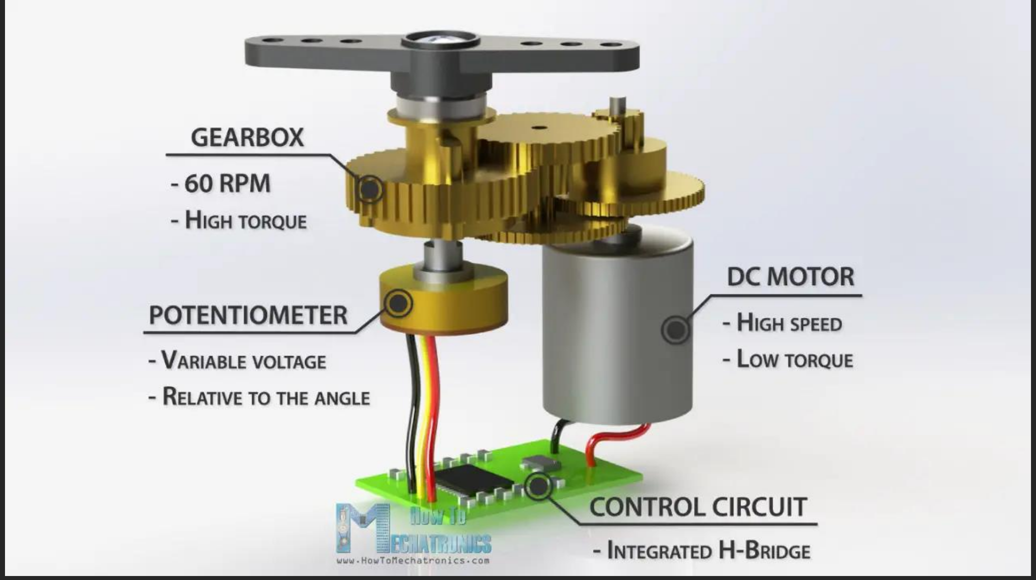
- Force-sensitive resistors are polymer film that change resistance under pressure
- Robotics (gripping), electronic prosthetics, touch interfaces





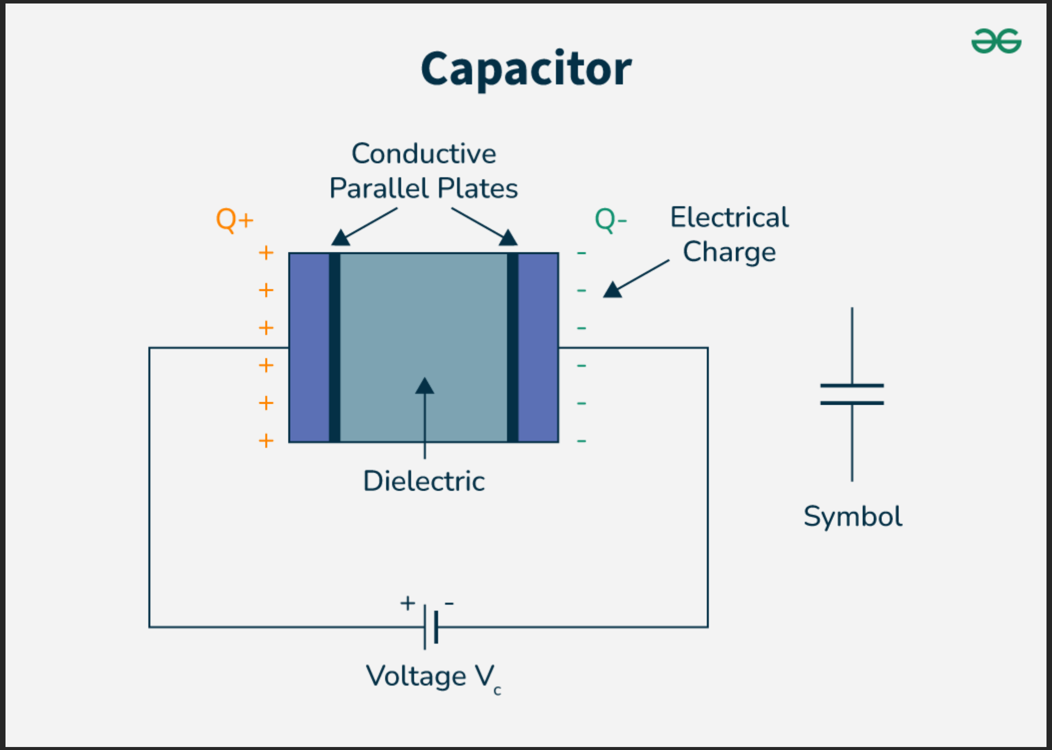
Potentiometers

- A variable resistor with a moveable wiper that changes resistance based on position
- Servo feedback, position tracking , volume control



Capacitive Sensors

- Capacitance is the ability of a system to store charge
- $C = \frac{\varepsilon A}{d}$
- C = Capacitance
- ε = Permittivity of the material
- A = Area of the plates
- d = Distance between the plates



Measuring Resistance

- Charge-Discharge Method
  - Charge at known rate and discharge is measured over time
  - Used in capacitive touch sensors, can be implemented on microcontroller
- Frequency-Based Methods
  - Time constant: $\tau = RC$ or Oscillator: $f = \frac{1}{2\pi\sqrt{LC}}$
  - Used in proximity sensors
- Capacitive Wheatstone Bridge
  - Similar to resistive bridge but with capacitors

Importance to CPS

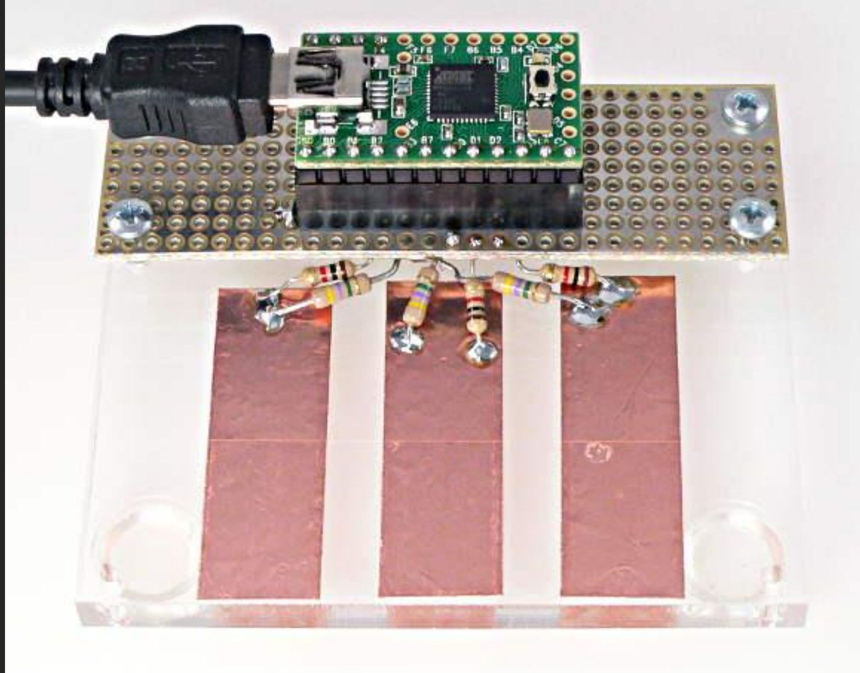
- Very high sensitivity
- Non-contact measurement – reduced wear
- Low power consumption
- Wide application range
- Challenges
  - Nonlinear response
  - Environmental sensitivity
  - Parasitic capacitance

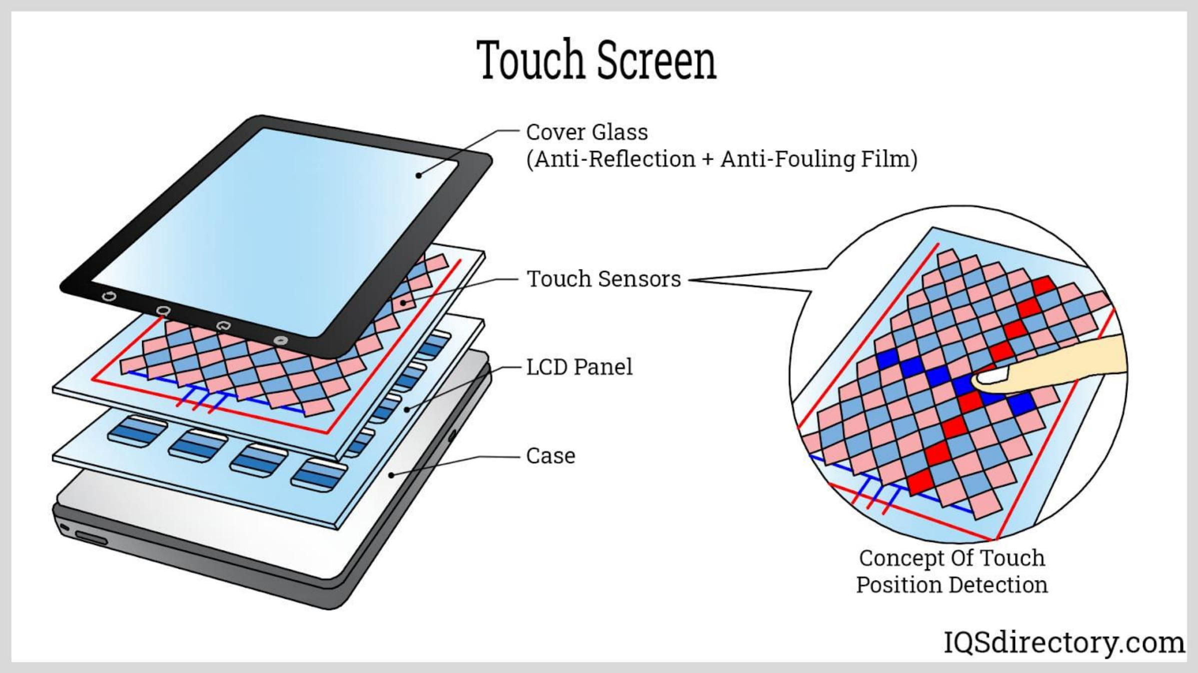
Proximity Sensors

- Measures changes in capacitance from nearby conductive objects
- Touch free gesture control, security systems, industrial automation

Touch Sensors

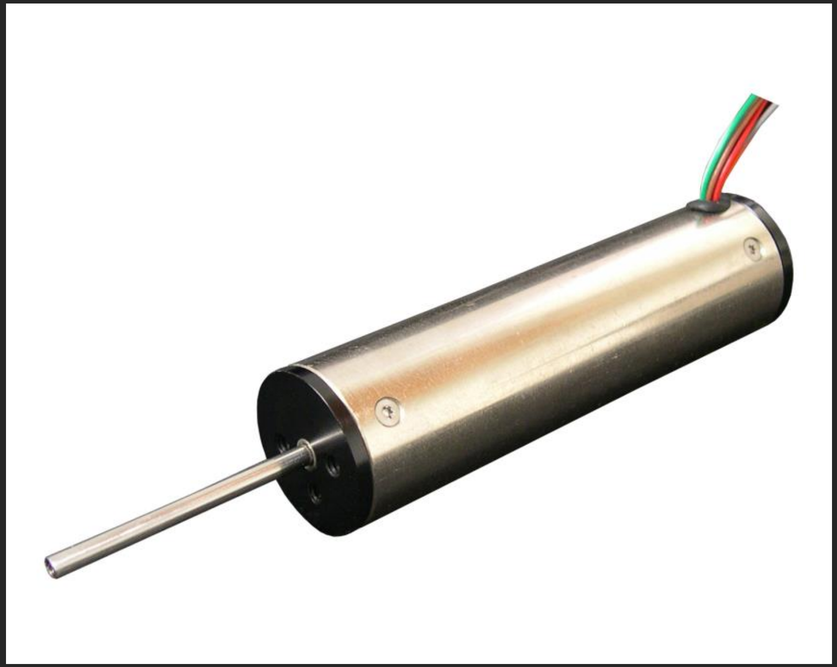
- Uses the body's natural capacitance to detect touch
- Smartphones, wearable devices, automotive control panels





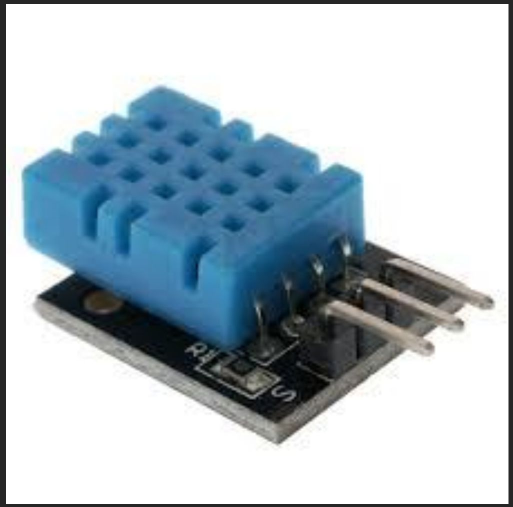
Displacement Sensors

- Measures small movements between plates
- Robotics, MEMS, microphones



Humidity and Moisture Sensors

- Moisture changes the permittivity of the air or soil changing the capacitance
- HVAC systems, soil moisture sensors, medical devices



Inductive Sensors

- Induction is the ability of a system to hold energy in the form of electrical current in coils of wire.
  - Coil – wire wound into a loop that current is passed through
  - Oscillator circuit – generates alternating magnetic field around the coil
  - Target – A metallic object disrupts the field
  - Detection circuit – measures changes in inductance or energy loss

Inductance

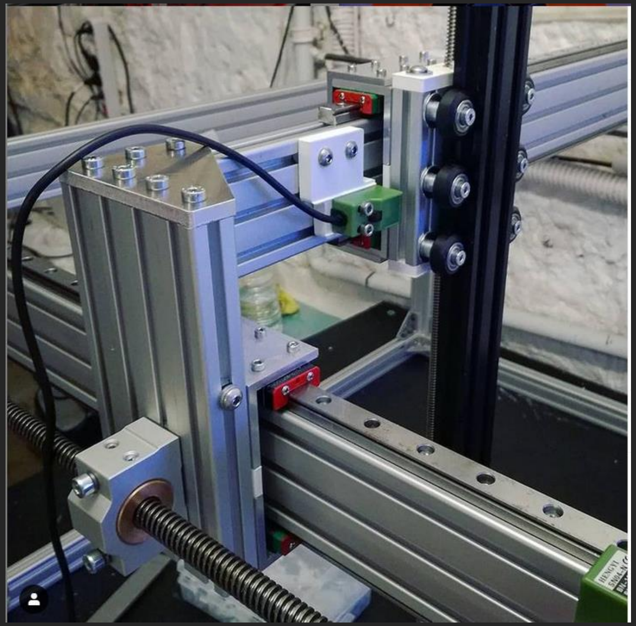
- $L = \frac{N^2 \mu A}{l}$
- L = Inductance
- N = Number of turns in coil
- μ = Magnetic permeability of core
- A = Cross sectional area of the coil
- l = Length of the coil

Importance to CPS

- Non-contact operation – no mechanical wear
- Highly reliable in harsh conditions – dirt, dust, temperatures
- Fast response times – ideal for real time performance
- Long lifespan compared to mechanical switches
- Challenges
  - Only works with metal objects
  - Limited sensing range

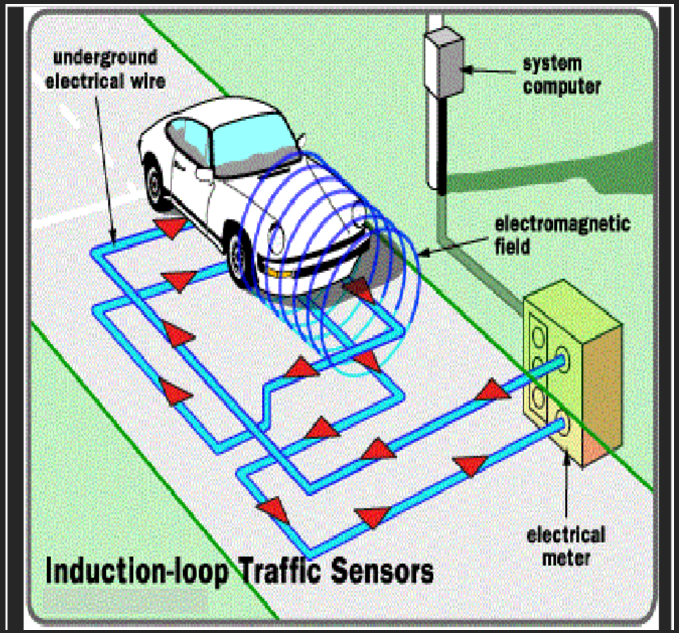
Inductive Proximity Sensors

- Metical objects change the magnetic permeability of the system
- Robotics, industrial conveyer belts, factory automation



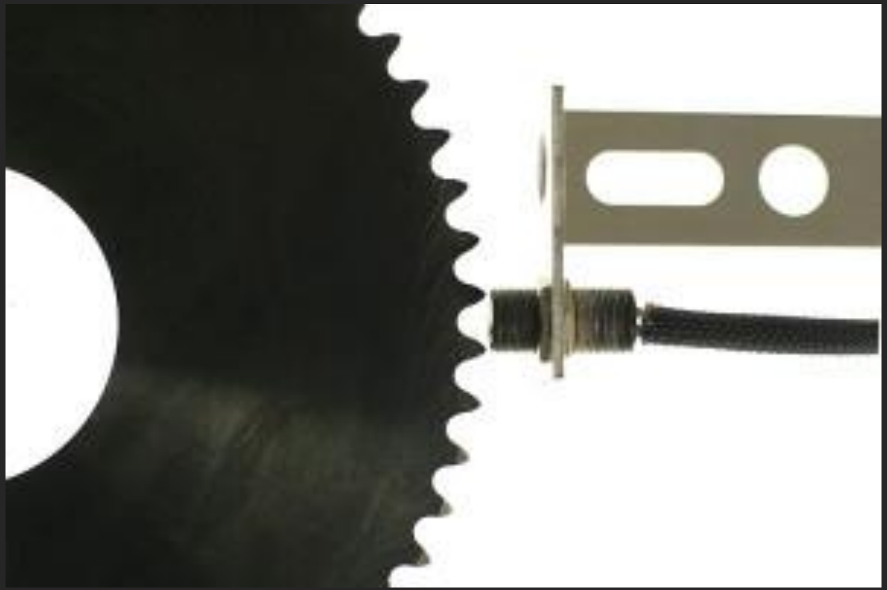
Inductive Loop Sensors

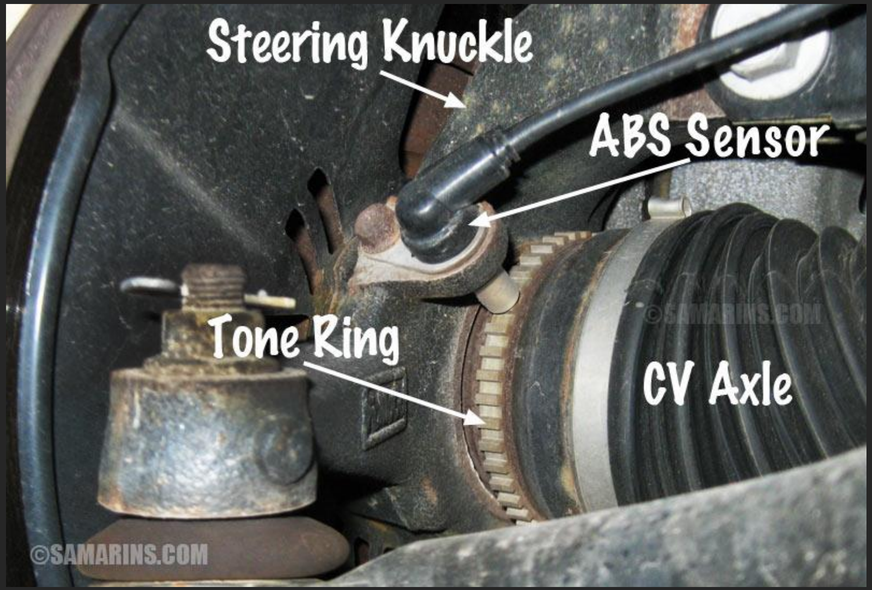
- A large inductive coil detects the presence of metallic objects by measuring eddy current changes
- Traffic light control, parking lot occupancy,



Inductive Gear Tooth Sensor

- Measures the presence of a rotating metal gear
- Robotics, industrial motors, vehicle ABS systems





Piezoelectric Sensors

- Operate based on the “piezoelectric effect”, where certain crystalline materials generate electric charge when subject to mechanical stress.
- Quartz, lead zirconate titanate, barium titanate, polyvinylidene fluoride
- Linear model: $Q = d \cdot F$
- Generated charge is converted to voltage signal using charge amplifiers or high impedance voltage measurement circuits.

Importance to CPS

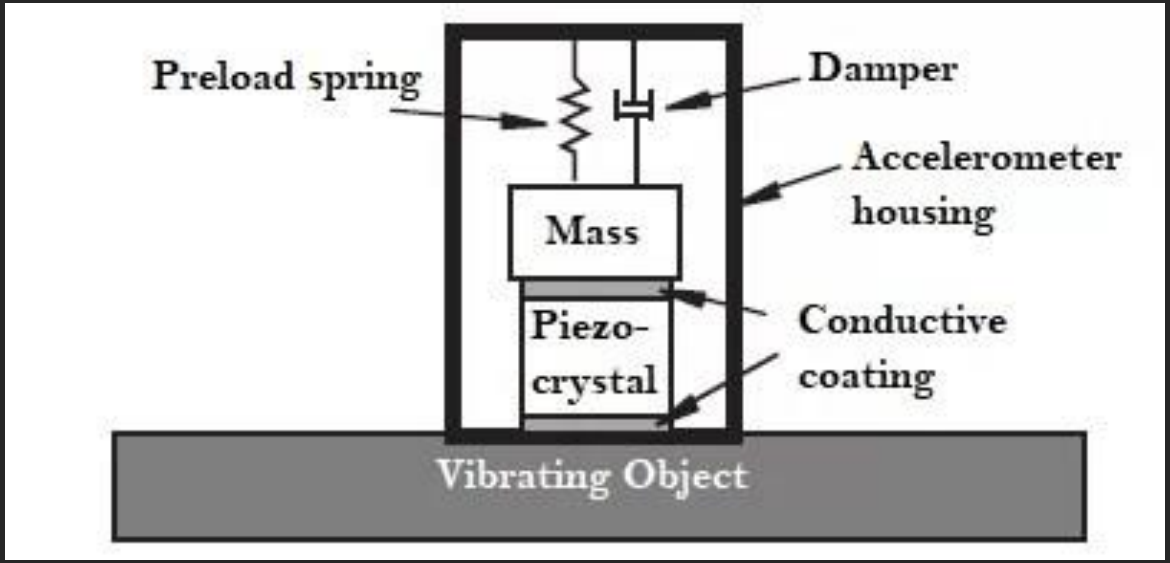
- High speed, high frequency sensing
- Impact and force measurement
- Acoustic wave detection
- Energy harvesting for self powered wireless sensors

Piezoelectric Force and Pressure Sensors

- Converts mechanical force into electrical signal
- Robotics, medicine, automotive (airbags), aerospace (airpressure)

Piezoelectric Accelerometer

- By attaching a known mass to a piezoelectric force sensor, you create an accelerometer
- Vibration monitoring in aerospace and manufacturing



Piezoelectric Microphones

- Vibrational forces on piezoelectric sensor can pick up a wide range of frequencies
- Microphones, sonar, seismic activity, instruments

Piezoelectric Energy Harvesters

- The charge is collected and processed using rectifiers and storage circuits (batteries and capacitors).
- Wearables and transportation systems

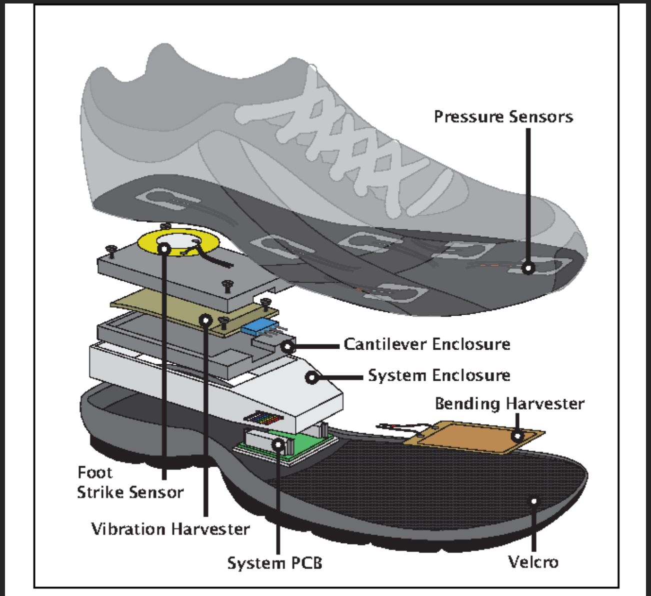
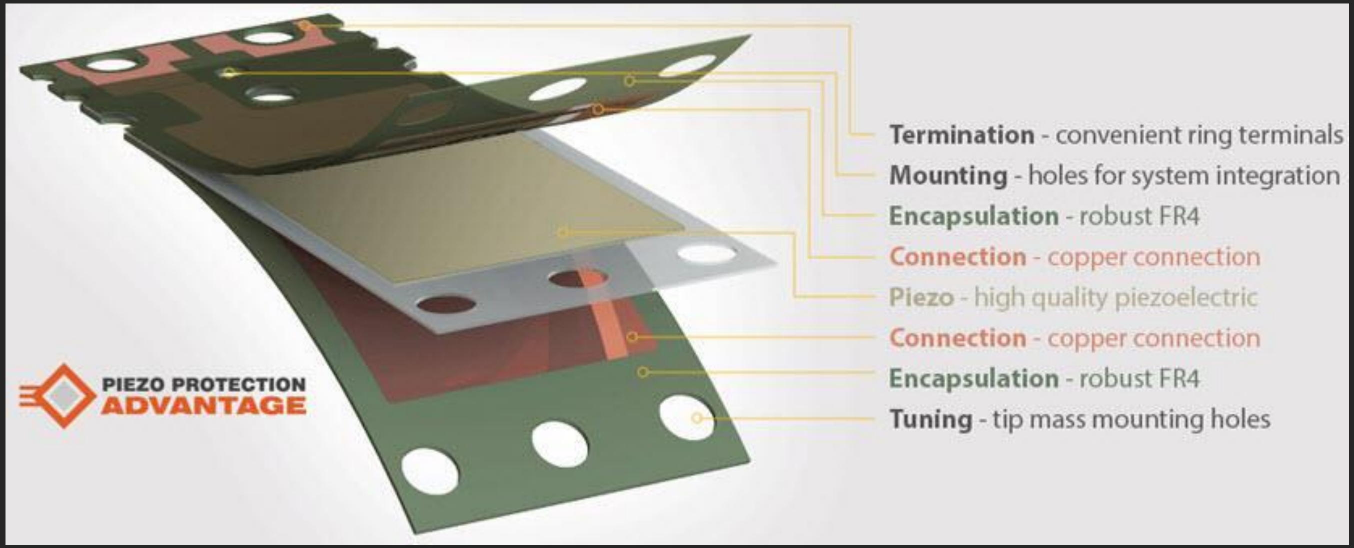


Fig. 1. Expanded view of the shoe system and all integrated components.

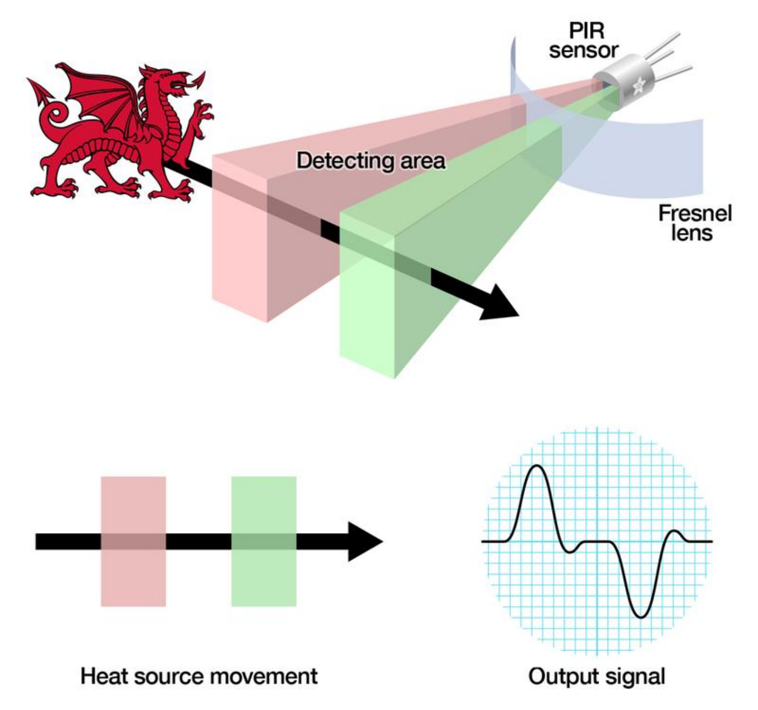


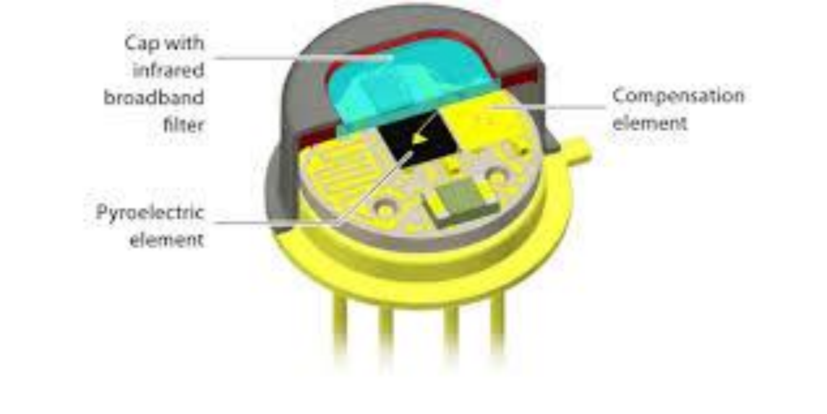
Infrared Sensing

- Relies on electromagnetic radiation in the infrared spectrum (700nm-1mm)
  - Near-IR (.7-1.4um) – fiberoptic communication and night vision
  - Mid-IR (1.4-8um) – thermal imaging and remote sensing
  - Far-IR (8-1000um) – passive heat detection and climate monitoring

Passive Infrared Sensing

- Detect changes in IR radiation from moving objects
- Composed of two pyroelectric sensors



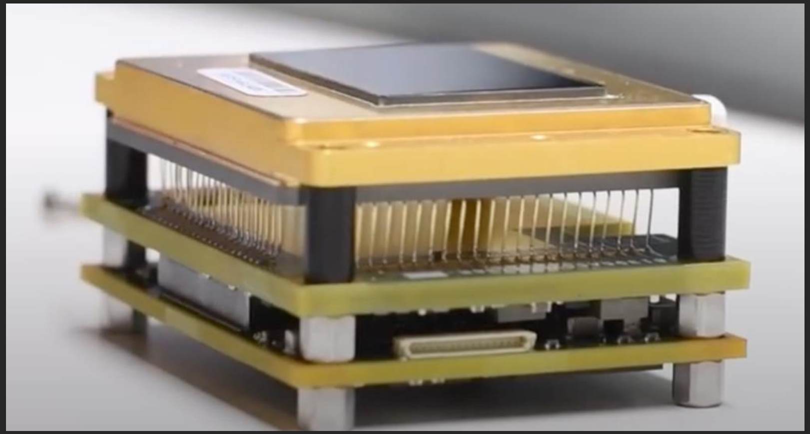


Passive Infrared Sensing

- Advantages
  - Low power and low cost
  - Reliable for motion detection
- Limitations
  - Can't detect stationary objects
  - Requires line of sight
- Automatic light, doors, occupancy detection

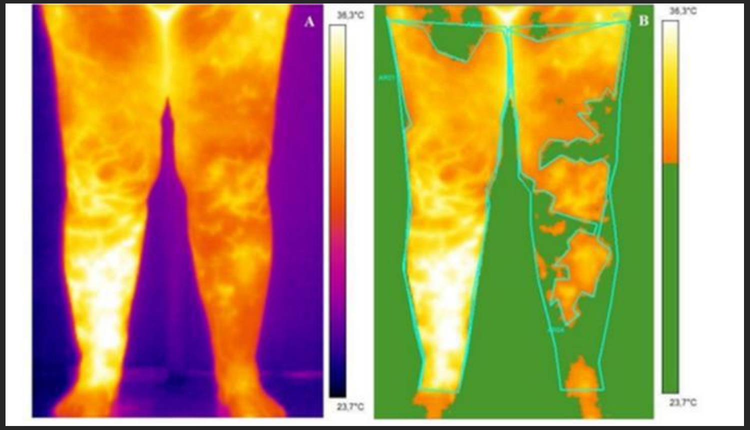
Thermal Infrared Sensing (Thermography)

- Uses infrared cameras to detect emitted heat patterns
- Cryogenic Sensors – Use cooled detectors
  - Highly expensive and used for military, aerospace, scientific applications
- Microbolometers – detect IR radiation passively
  - More affordable and used commercially, medical devices, industry



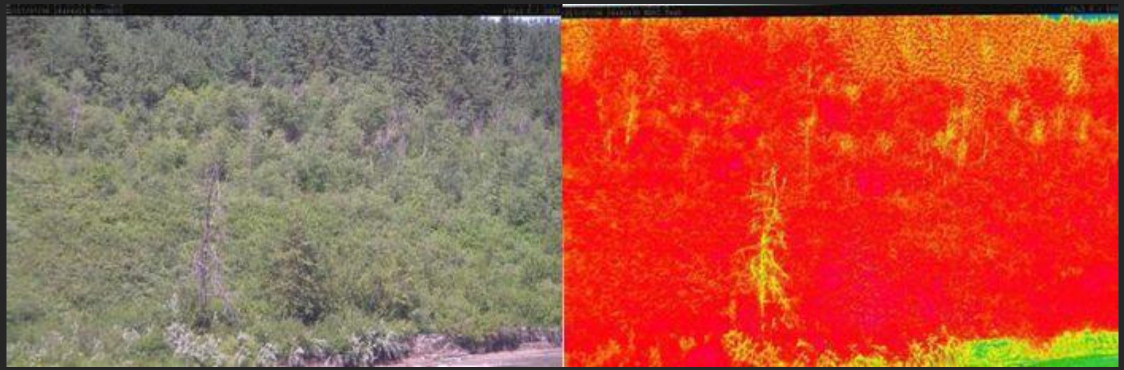
Thermal Infrared Sensing Applications

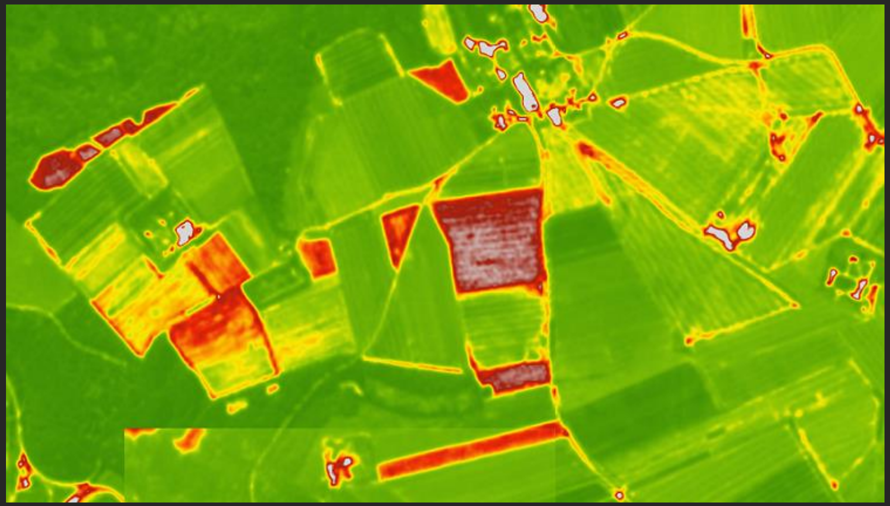
- Industrial and Manufacturing
  - Overheating detection in electrical systems
  - Monitor mechanical wear
- Building and Smart Infrastructure
  - Energy efficiency audits
  - Leaky pipes
- Medical
  - Fever, inflammation, breast cancer detection
  - Vascular disorders



Normalized Difference Vegetative Index

- $NDVI = \frac{(NIR-RED)}{(NIR+RED)}$
- NIR = Near-Infrared (~850nm)
  - Strongly reflected by plant chlorophyll
- RED = Red light (~650nm)
  - Strongly absorbed by plants for photosynthesis
- Healthy vegetation – NDVI close to 1
- Stressed or sparce vegetation – NDVI closer to 0
- Bare soil or non-vegetation – NDVI near -1



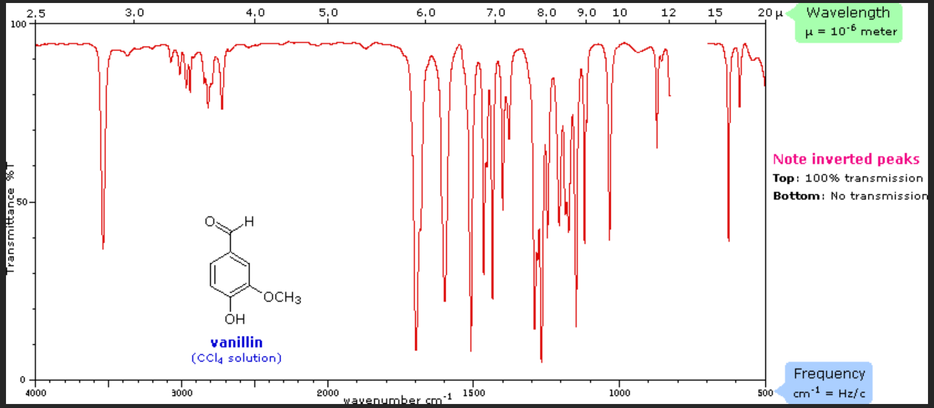


Active IR Sensor

- Shines IR light and measures reflectance
- Use for obstacle avoidance in robotics, optical encoders, and gesture recognition (paper towel dispensers)

Infrared Spectroscopy

- Uses IR absorption to identify chemical composition
- Application
  - Gas sensing
  - Food quality
  - Biomedical diagnostics



Ultrasonic Sensors

- Ultrasonic sound waves are typically 20-200kHz
- Time-of-flight
  - $Distance = \frac{\text{Speed of Sound} \cdot Time\ Delay}{2}$
- Doppler Effect
  - $\Delta f = \frac{2 f_0 v}{c}$

Ultrasonic Transducers

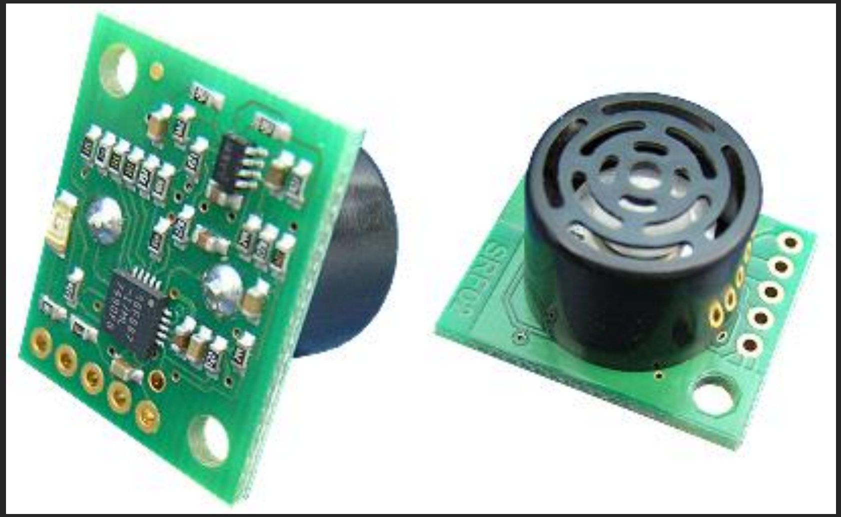
- A transducer is a device that convers electrical energy to sound waves and vice versa.
- Types of transducers
  - Piezoelectric – most common and most versatile
  - Capacitive – primarily used in MEMS sensors
  - Magnetic – traditional speaker mechanism

Importance to CPS

- Advantages
  - Works in air, liquids, and solids
  - Non-contact sensing – ideal to delicate objects
  - Works day night – unlike cameras, no light is required
  - Low cost compared to light-based methods
- Limitations
  - Cannot detect soft surfaces well
  - Limited range compared to light-based methods
  - Affected by air temperature and humidity

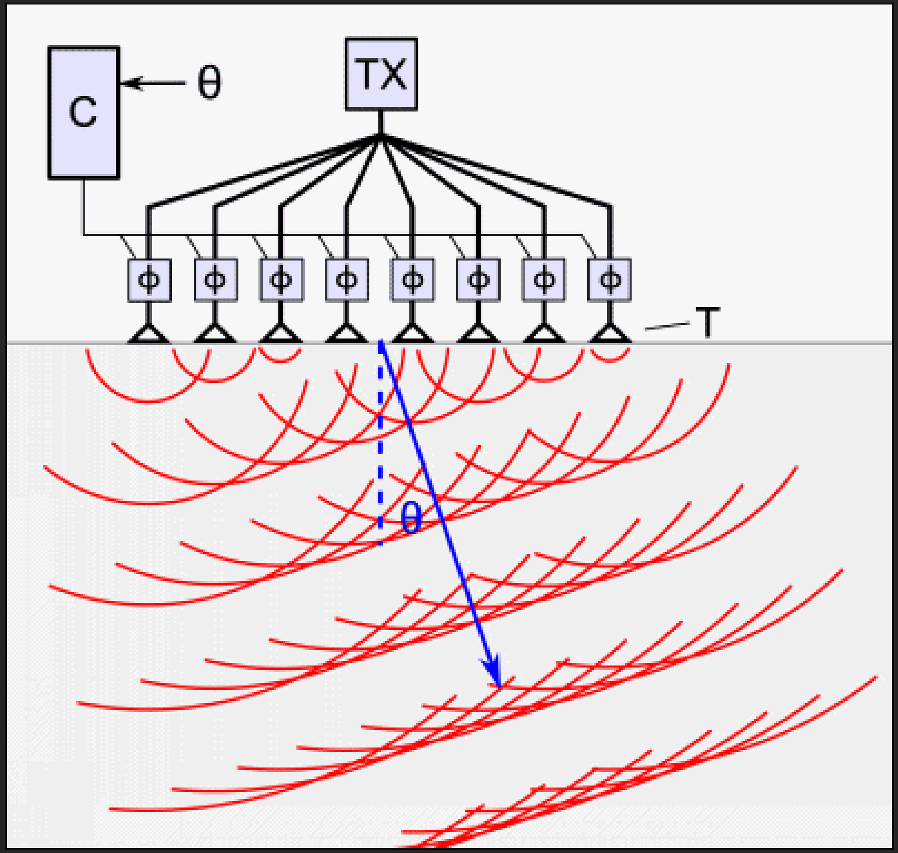
Ultrasonic Distance Sensors (Sonar)

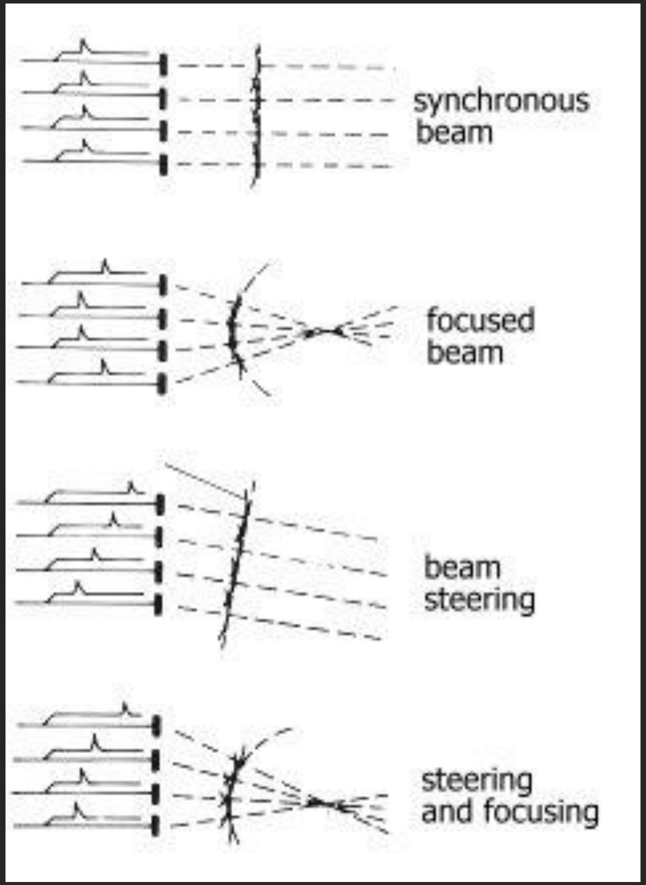
- Measure distance using sound reflection
  - Robot navigation, proximity sensing, liquid level sensing
- Signal Processing
  - Threshold detection
  - Echo Filtering
  - Temperature compensation
- Transducer
  - Single transducer
  - Double transducer



Transducer Array

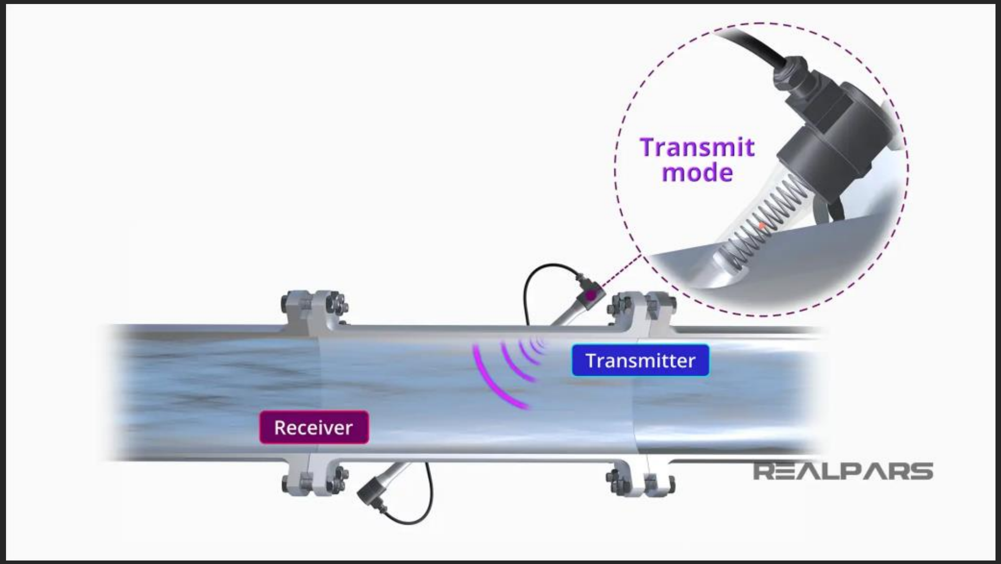
- $\theta = \sin^{-1}\left(\frac{\lambda \Delta t}{d}\right)$
- High precision and special resolution
- Adaptable
- Computationally expensive





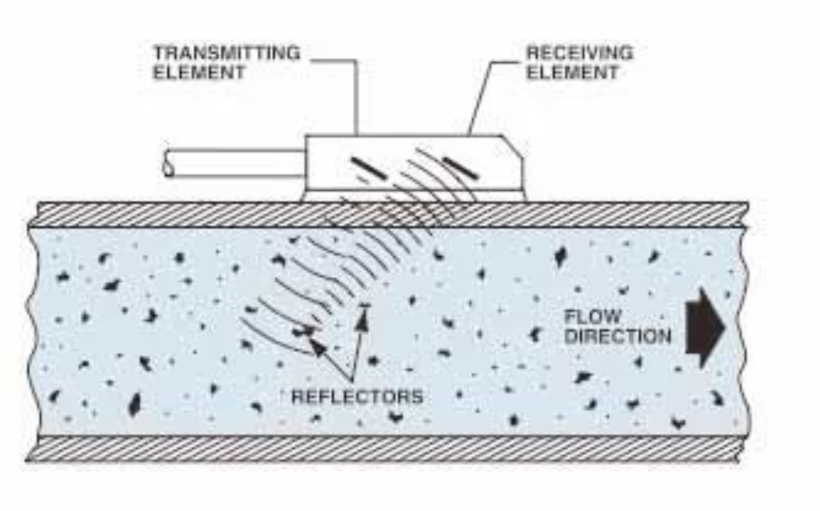
Transit-time Ultrasonic Flow Meter

- One transducer sends a pulse upstream
- A second transducer sends a pulse downstream
- Difference in transit time is proportional to fluid
- Small pipes – same side transducers
  - $v = \frac{c}{2} \cdot \frac{\Delta t}{t_1 t_2}$
- Large pipes – opposite side transducers
  - $v = \frac{c^2 \Delta t}{2L}$
  - $v = \frac{D}{2\cos(\theta)} \cdot \frac{\Delta t}{t_1 t_2}$



Doppler Ultrasonic Flow Meter

- Uses a single transducer to send ultrasonic waves into the fluid
- Working principle
  - The wave reflects off particles or bubble in the liquid
  - Doppler shift if proportional to the fluid velocity
  - $v = \frac{c \cdot \Delta f}{2 f_0 \cos(\theta)}$



Ultrasonic Flow Meters

- Transit-time Ultrasonic Flow Meters
  - Water distribution systems
  - HVAC systems
  - Industrial flow monitoring
  - Motion sensing
- Doppler Ultrasonic Flow Meters
  - Wastewater flow monitoring (particles required)
  - Blood flow measurement
  - Industrial slurry and mixed-phase fluid monitoring
  - Motion sensing

Ultrasonic Imaging (Echograph)

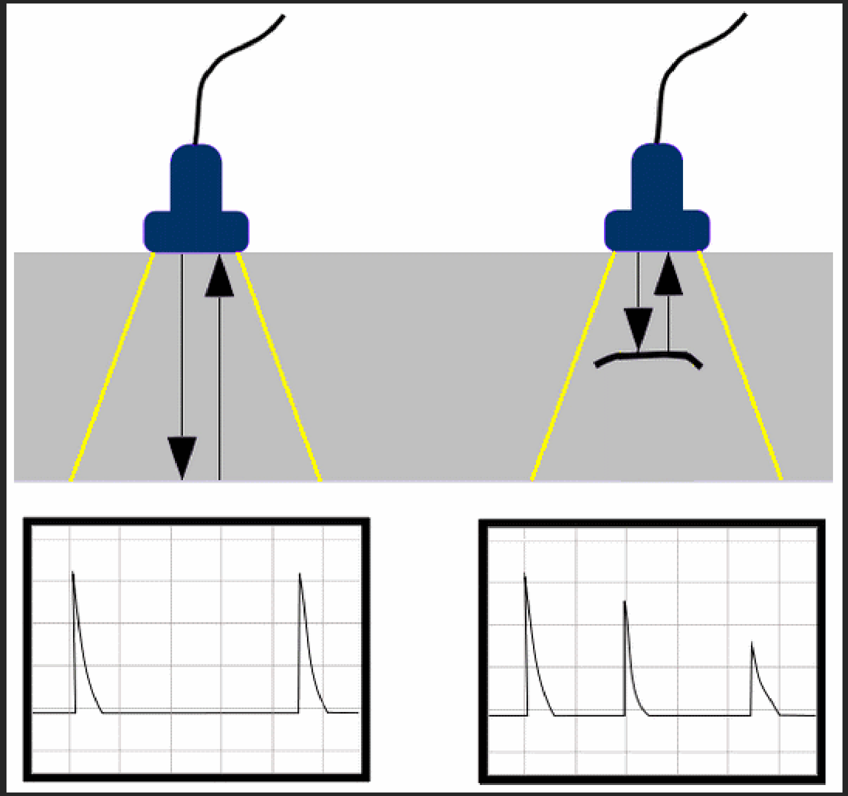
- Wave Frequency: 1-15MHz
  - Higher frequencies – better resolution, shallower penetration
  - Lower frequencies – better penetration, lower resolution
- Pulse Repetition Frequency (PRF): 1-10kHz
  - Higher frequencies – faster imaging, may cause range ambiguity
  - Lower frequencies – better depth resolution, slower frame rate
- Advantages
  - Significantly Cheaper than alternative methods
  - No radiation
- Disadvantages – can’t penetrate bone or air

Ultrasonic Imaging (Echograph)

- Brightness Mode (B-Mode)
  - 2D imaging based on amplitude of return signal
- Doppler Ultrasound
  - Used to evaluate heart function and blood flow
- 3D and 4D Imaging
  - Amplitude and time-of-flight to create 3D images
- Elastography – tissue stiffness
- Contrast-Enhanced – uses microbubble contrast agents
- Ultrasound Therapy – breaks down tissue

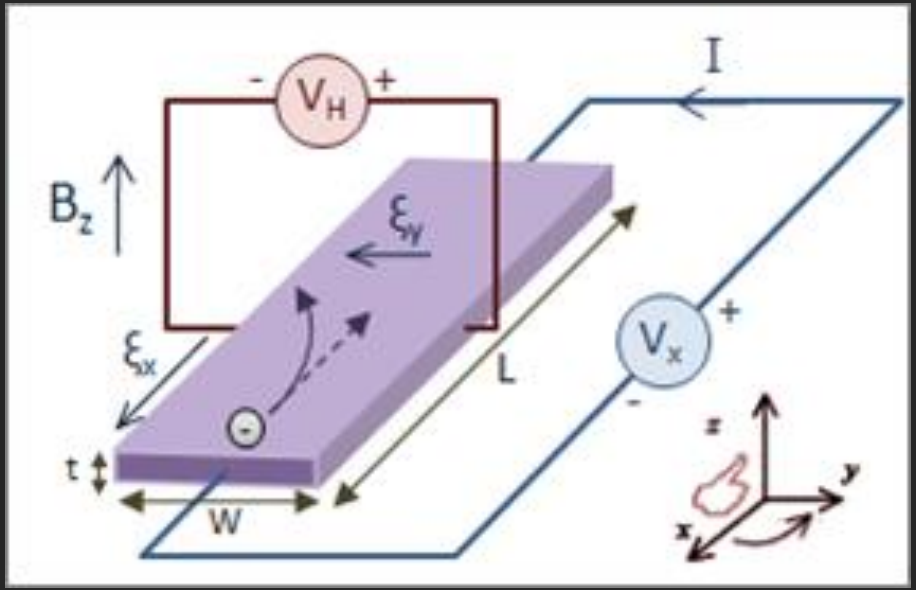
Non-Destructive Testing (NDT – Ultrasound)

- Flaws in structural materials cause boundaries that reflect a portion of the sound wave
- Pulse Echo Method
  - Uses single transducer
- Through-Transmission Method
  - Uses two transducers
- Applications
  - Railways, bridges, buildings, aircraft, turbine blade, pipes, 3D printing



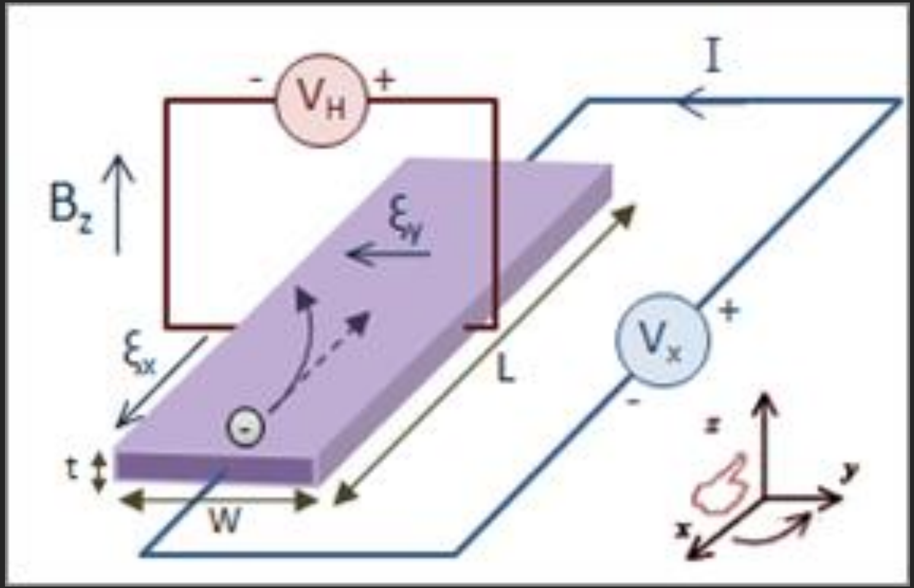
Hall Effect Sensor

- The Hall effect is a fundamental physical phenomenon that describes the generation of a voltage perpendicular to both the current and the magnetic field in a conductor.
- When a magnetic field is applied perpendicular to a current carrying conductor, charge carriers experience the Lorentz force, causing them to accumulate on the side of the conductor.



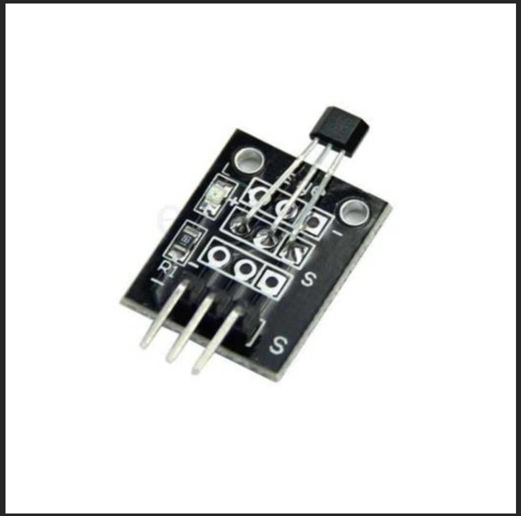
Hall Effect Sensor

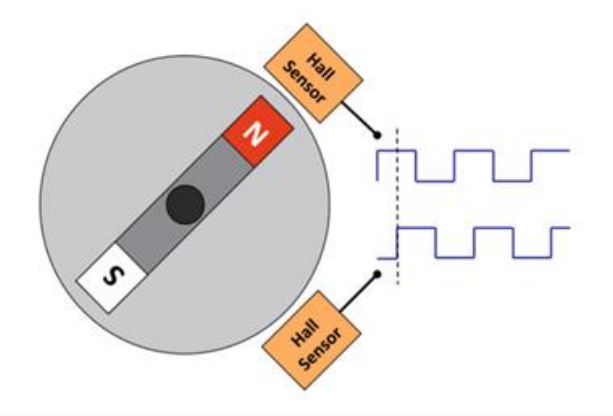
- $V_H = \frac{B \cdot I}{q \cdot n \cdot d}$
- V_H = Hall Voltage
- B = Magnetic flux density
- I = Current
- q = Charge of an electron
- n = Charge carrier density (electrons/m^3)
- d = Thickness of Hall element

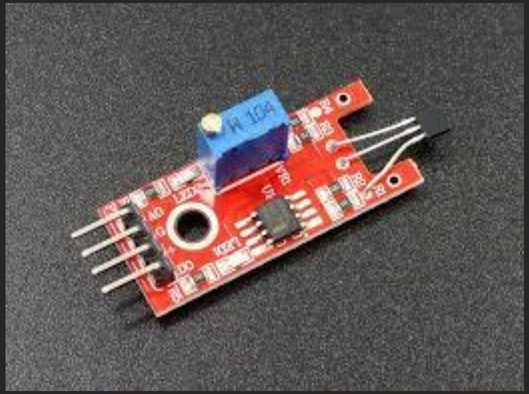


Hall Effect Sensor in CPS

- Analog Hall effect sensors
- Digital Hall effect sensors
- Encoders
- Current sensor

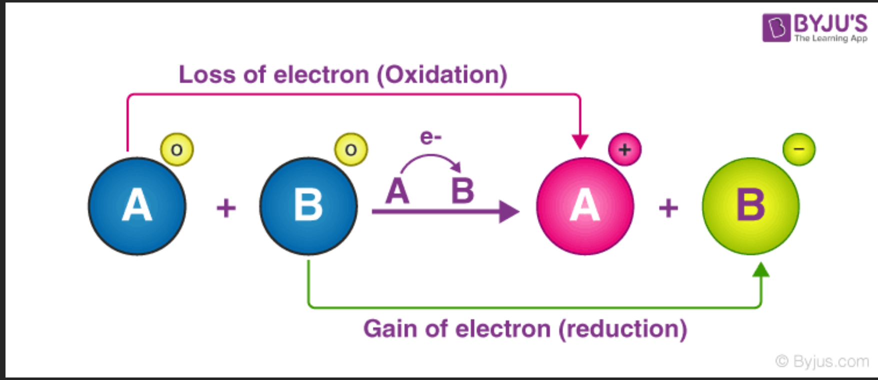






Electrochemical Sensors

- Electrochemical sensors facilitate a redox reaction at an electrode surface, creating an electrical signal.
- Redox reaction
  - Oxidation – substance loses an electron
  - Reduction – substance gains an electron
- When the number of electronics in the reaction aren't equal, they can be 'provided' or 'collected' by the sensor electrode.



Electrochemical Sensor Example

- Carbon monoxide (CO) sensor
  - $CO + H_2O \longrightarrow CO_2 + 2H^+ + 2e^-$
  - CO oxidizes at the electrode, releasing two electrons
  - The electrode collects the electrons, generating a measurable current
- Oxygen (O_2) sensor
  - $O + 4e^- + 4H^+ \longrightarrow 2H_2O$
  - O_2 is reduced at the electrode, accepting four electrons
  - The electrode provides the electrons, generating a measurable current

Measuring Electrochemical Sensors

- Current-based Sensing
  - A constant voltage is provided and electron flow (current) is measured
- Voltage-based Sensors
  - No external voltage is applied
  - $V = \frac{RT}{nF} \ln\left(\frac{Ox}{Red}\right)$

- V = Measured voltage
- R = Gas constant
- T = Temperature
- n = Number of electron
- F = Faraday's constant
- Ox = Concentration of oxidized
- Red = Concentration of reduction

Chemicals

- Oxygen (O_2) - Medical oxygen sensors, combustion monitoring
- Carbon Monoxide (CO) - Air quality monitoring, gas safety
- Hydrogen (H_2) - Hydrogen fuel cell monitoring
- Sulfur Dioxide (SO_2) - Industrial pollution monitoring
- Nitrogen Oxides (NO, NO_2) - Automotive emissions, environmental monitoring
- Chlorine (Cl_2) - Water treatment, industrial gas safety
- Ozone (O_3) - Air quality monitoring, sanitation
- Ammonia (NH_3) - Industrial and agricultural monitoring
- Hydrogen Sulfide (H_2S) - Sewer gas detection, industrial safety
- Volatile Organic Compounds (VOCs) - Air quality, chemical exposure monitoring

Ions

- pH (H^+ ions) - Water quality, medical diagnostics
- Sodium (Na^+) - Blood sodium monitoring, food industry
- Potassium (K^+) - Cardiac monitoring, agricultural soil testing
- Chloride (Cl^-) - Salinity monitoring, sweat analysis
- Calcium (Ca^{2+}) - Water hardness testing
- Fluoride (F^-) - Drinking water monitoring, toothpaste quality control
- Nitrate (NO_3^-) - Agricultural runoff detection, environmental monitoring
- Lead (Pb^{2+}) - Heavy metal pollution analysis
- Mercury (Hg^{2+}) - Toxic metal detection in food & water
- Copper (Cu^{2+}) - Corrosion analysis, industrial effluent monitoring

Biomolecules

- Enzymatic reactions, antigen-antibody reaction, DNA hybridization
- Glucose - Diabetes monitoring (glucose meters)
- Lactate - Exercise physiology, sepsis detection
- Cholesterol - Cardiac health monitoring
- Uric Acid - Kidney function monitoring
- Proteins (Antibodies/Antigens) - Pathogen detection
- Neurotransmitters (Dopamine, Serotonin) - Neurological research, mental health studies

Organic Compounds

- Redox or enzymatic catalysis
- Ethanol (Alcohol) - Breathalyzers, fermentation monitoring
- Methanol - Fuel cell technology
- Formaldehyde - Industrial safety, air quality control
- Hydroquinone (Antioxidants) - Pharmaceutical analysis
- Ascorbic Acid (Vitamin C) - Food quality testing, nutritional research

Industrial and Environmental Pollutants

- Heavy Metals (Pb, Hg, Cd, As)
  - Industrial wastewater monitoring, environmental safety
- Nitrates (NO_3^-), Phosphates (PO_4^{3-})
  - Agricultural runoff control, eutrophication prevention
- Peroxide-based Disinfectants
  - Food & beverage sterilization monitoring
- Pesticides (Organophosphates, Carbamates)
  - Agricultural and food safety

Detecting One Chemical at a Time

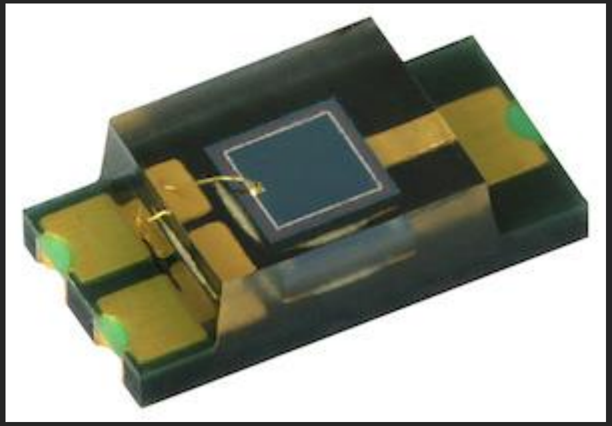
- Choice of electrode material
  - Platinum, gold, carbon-based electrodes
- Use of enzyme-based recognition
  - Enzyme-modified electrodes targe one analyte
- Selective Membranes & Ion-Selective Electrodes (ISEs)
  - Membranes only allow specific ion to reach the electrode
- Applied Potential Control (for Amperometric Sensors)
  - Different voltages allow different redox reactions to occur

Electrochemical Sensors

Photodiodes

- A p-n junction semiconductor that generates a current when exposed to light
- Photovoltaic mode (zero bias)
  - Generates output voltage proportional to light intensity
  - Solar power, energy harvesting, optical receivers
- Photoconductive mode (acts like a variable resistor)
  - Reverse voltage is applied to increase response speed
  - Highspeed optical communication and light meters

Photodiodes

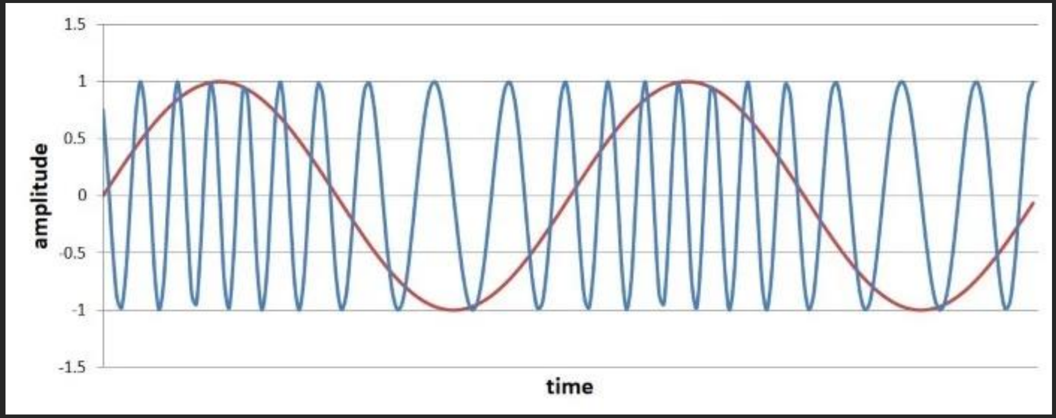


Phototransistors

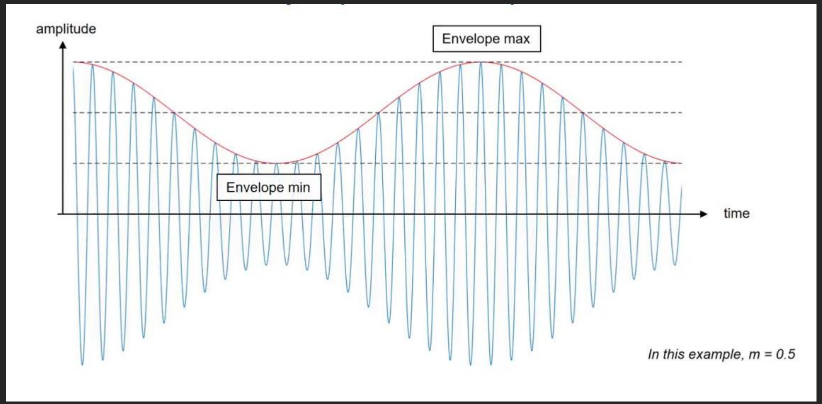
- Light sensitive transistor where light acts as a base current
- Higher sensitivity than photodiodes
- Can operate in on/off mode or linear response
- Light sensitive “switch”

Light Detection and Ranging (LiDAR)

- Time of flight mechanism
  - Laser emits a pulse towards a target
  - Light reflects back from the surface
  - The sensor measures the time delay



- Frequency Modulated Continuous wave
  - A modulated (usually frequency) light signal is produced
  - The phase of the returning signal is measured
  - The phase difference indicates distance to target

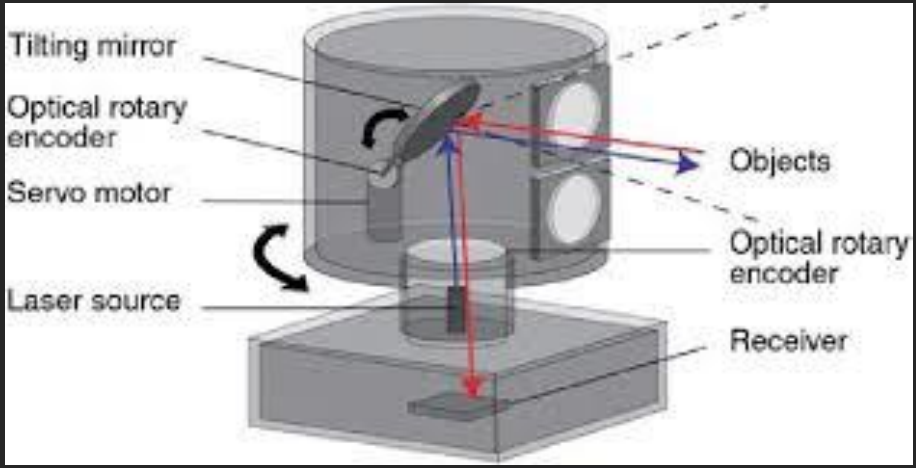


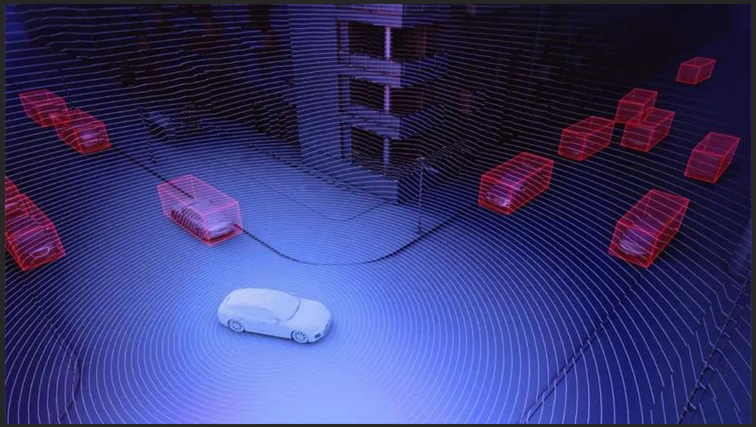
Light Detection and Ranging (LiDAR)

- Time of flight mechanism
  - Works over longer distances
  - High accuracy (~cm)
- Frequency Modulated Continuous wave
  - Measures distance and velocity (Doppler effect)
  - Higher sensitivity

Mechanical LiDAR

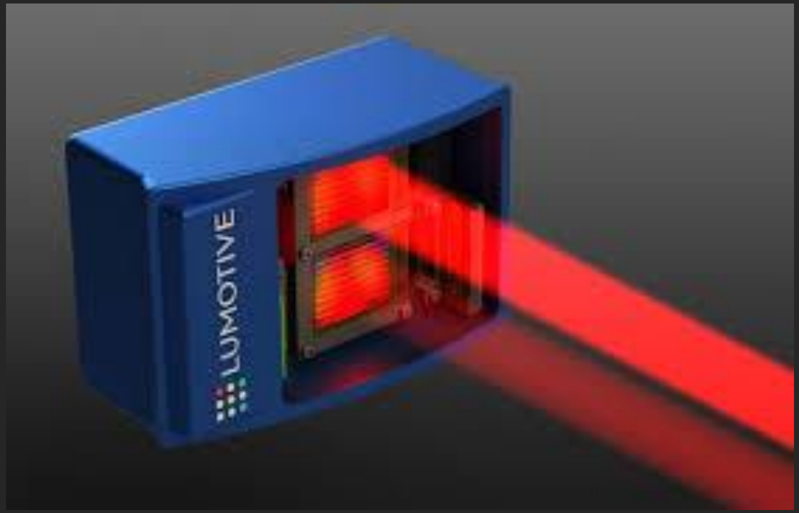
- Spinning mirror that rotates 360 degrees
- Advantages
  - Up to 300m range
  - Wide field of view
- Disadvantages
  - Moving mechanical parts have higher risk of failure
  - Slower collection speed
  - Resolution depends on scanning speed
  - Expensive
- Automotive, robotics, surveying





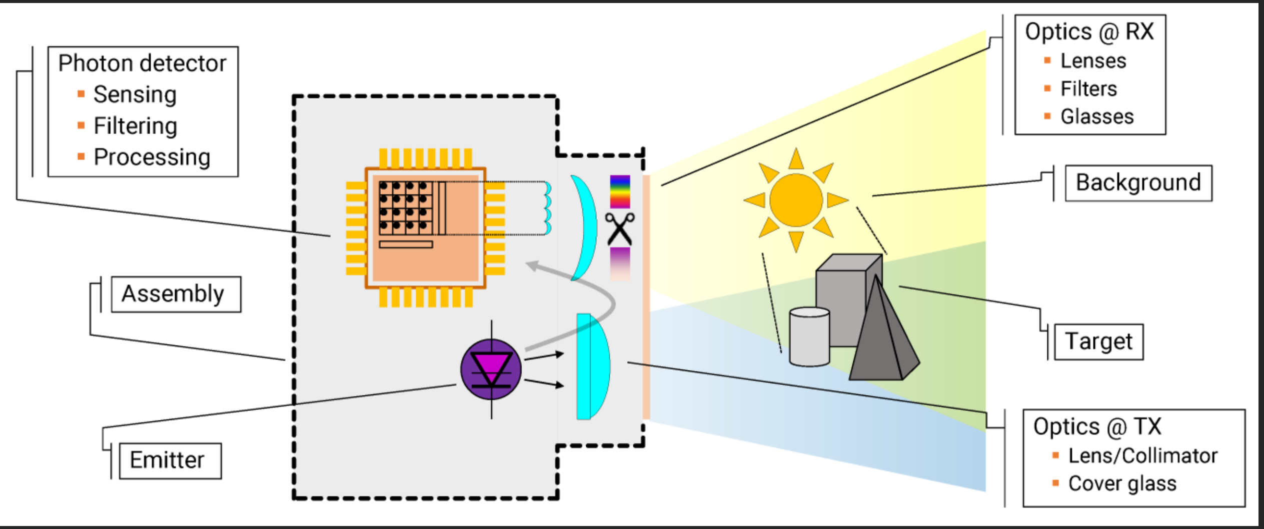
Solid State LiDAR

- Uses optical phase array or MEMs mirrors to direct laser
- Advantages
  - No moving parts
  - Faster than mechanical
  - Lower power consumption
- Disadvantage
  - Lower range (200m)
  - Smaller field of view (120 degrees)
- Automotive, robotics, surveillance

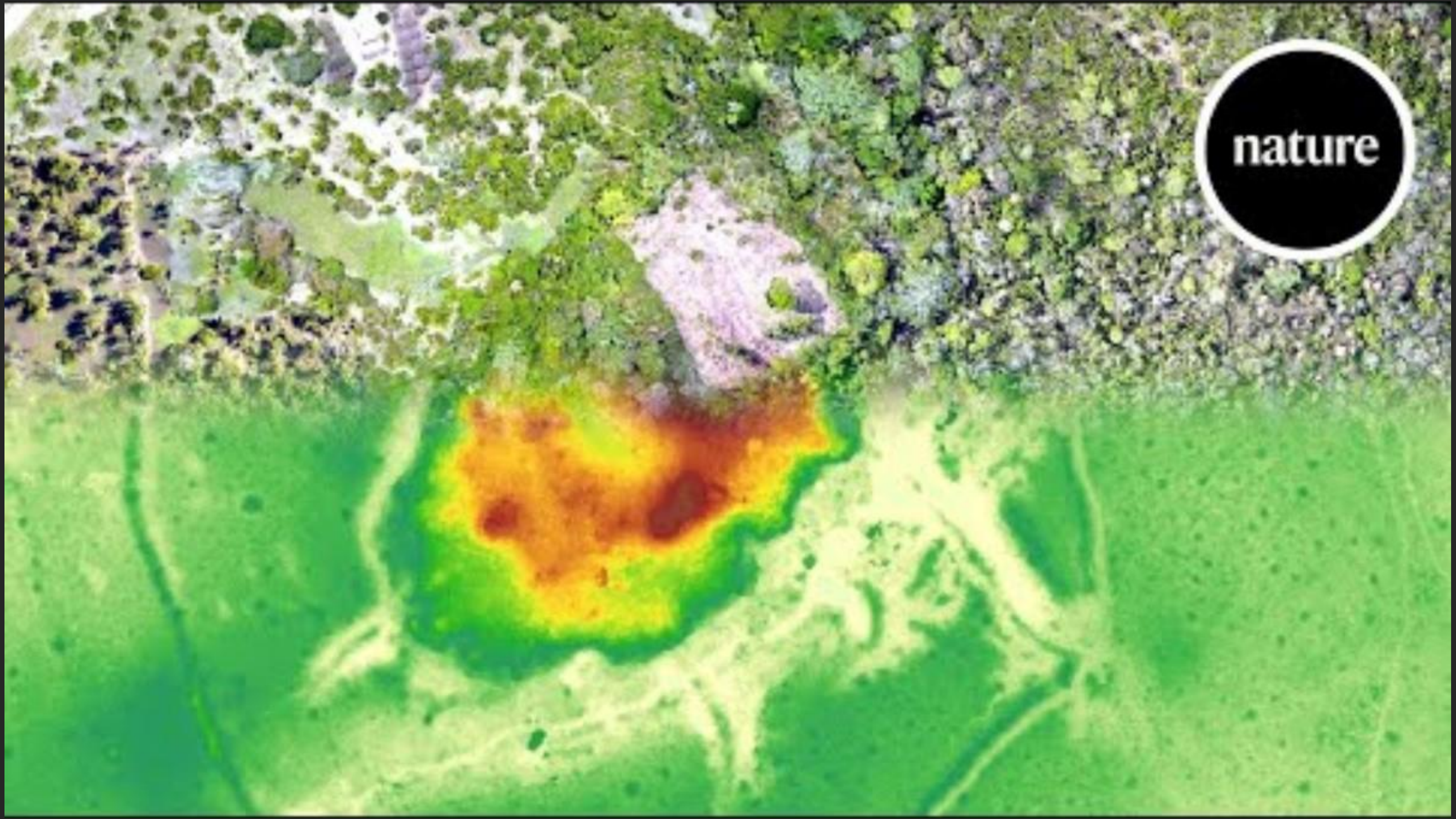


Flash LiDAR

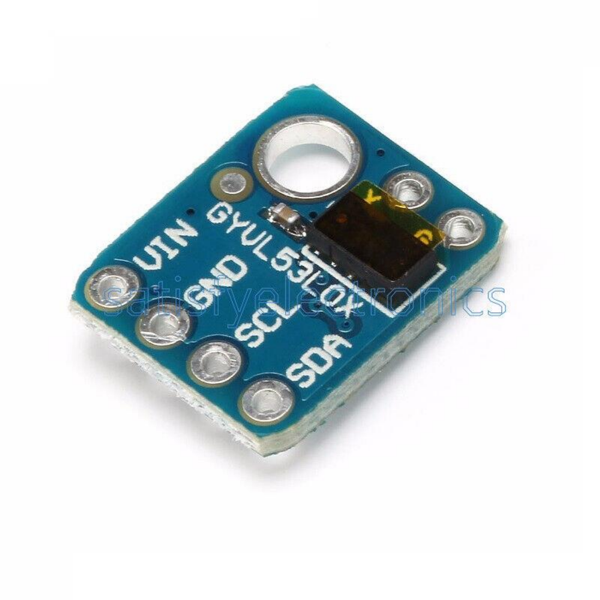
- Illuminates the entire area at once and uses a camera-like mechanism to capture a 3D picture
- Advantages
  - Very fast
  - Compact
- Disadvantages
  - Limited range (50m)
  - Low resolution
  - High sensitivity to noise
- Smartphone devices, autonomous drones, industrial automation



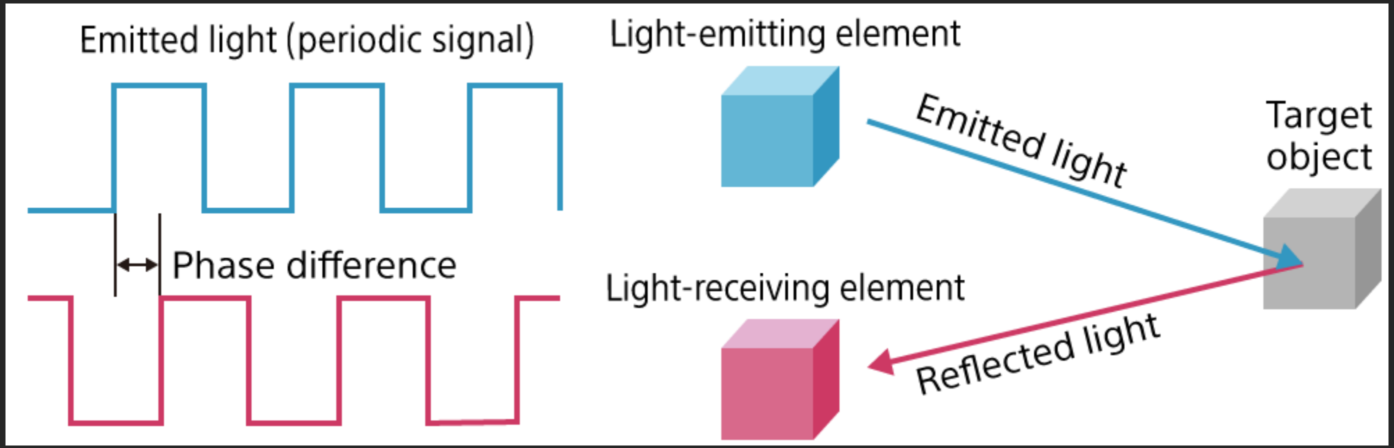
LiDAR



Time-of-Flight Sensor

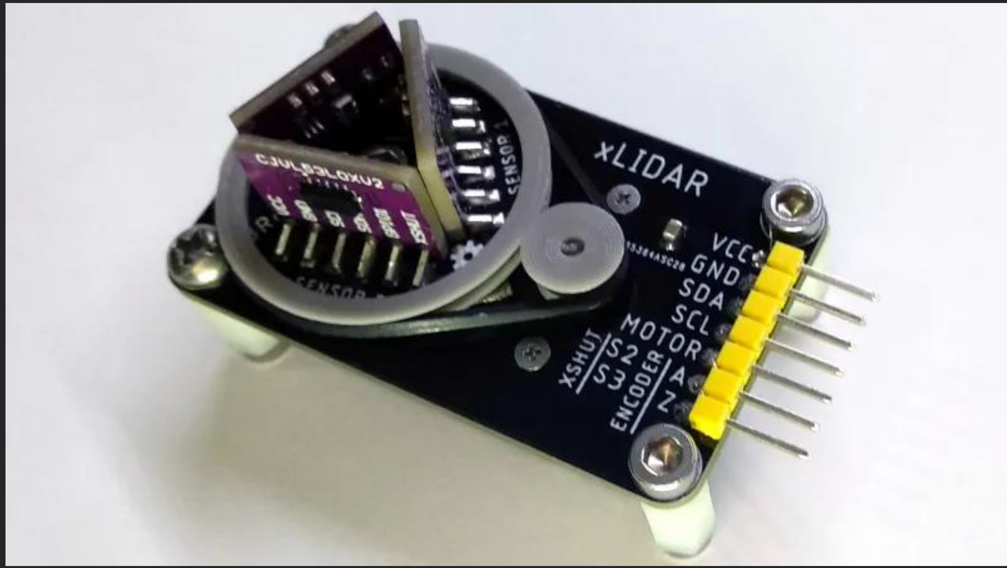


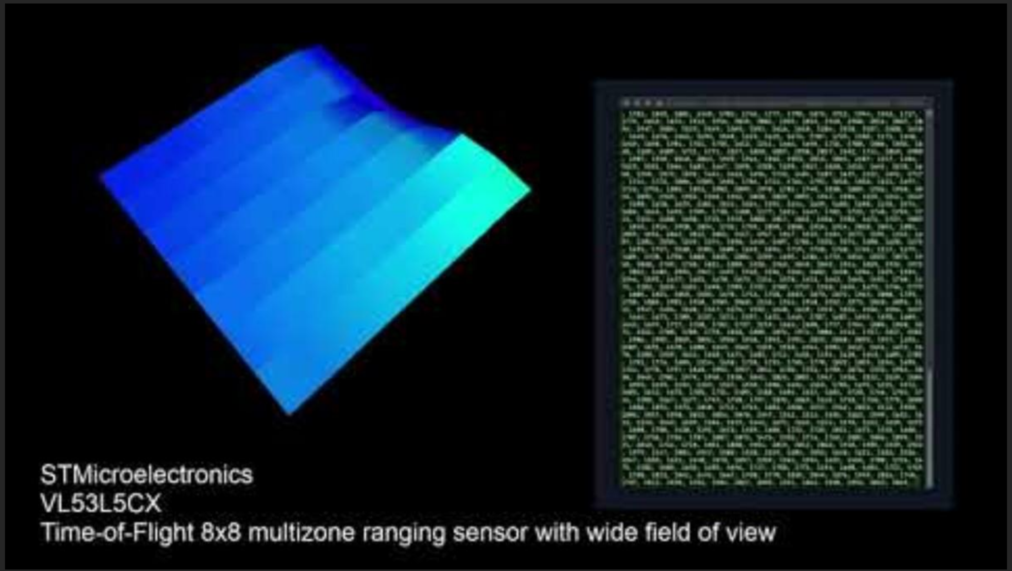
- “Mini”, solid-state LiDAR sensor
- Direct Time-of-flight sensors
  - Precise timing to measure exact delay
  - Single-photon detection – using photomultiplier tube
- Indirect Time-of-flight sensor
  - Amplitude modulation (sinusoidal or square)
  - Measures phase lag



Time-of-flight Sensor

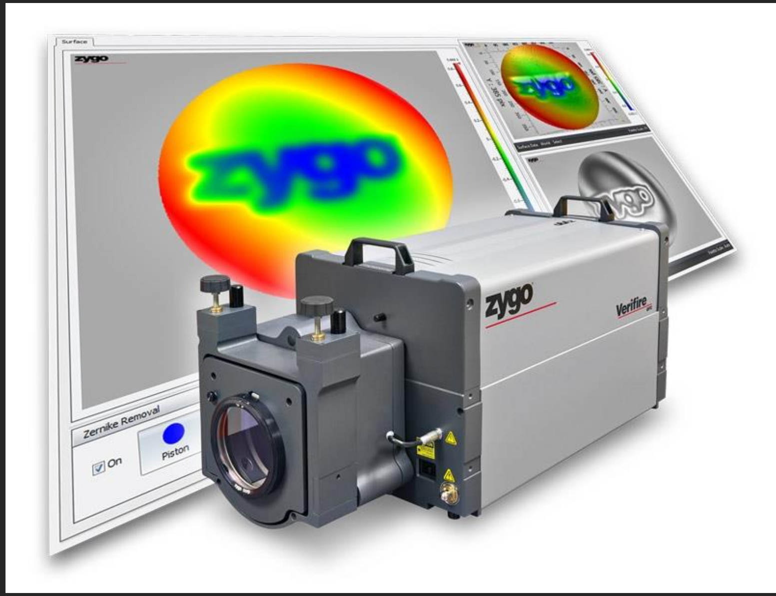
- Tend to be shorter range (1-10m)
- Point sensors or array (8x8 pixels)
- Low cost (less than $30)



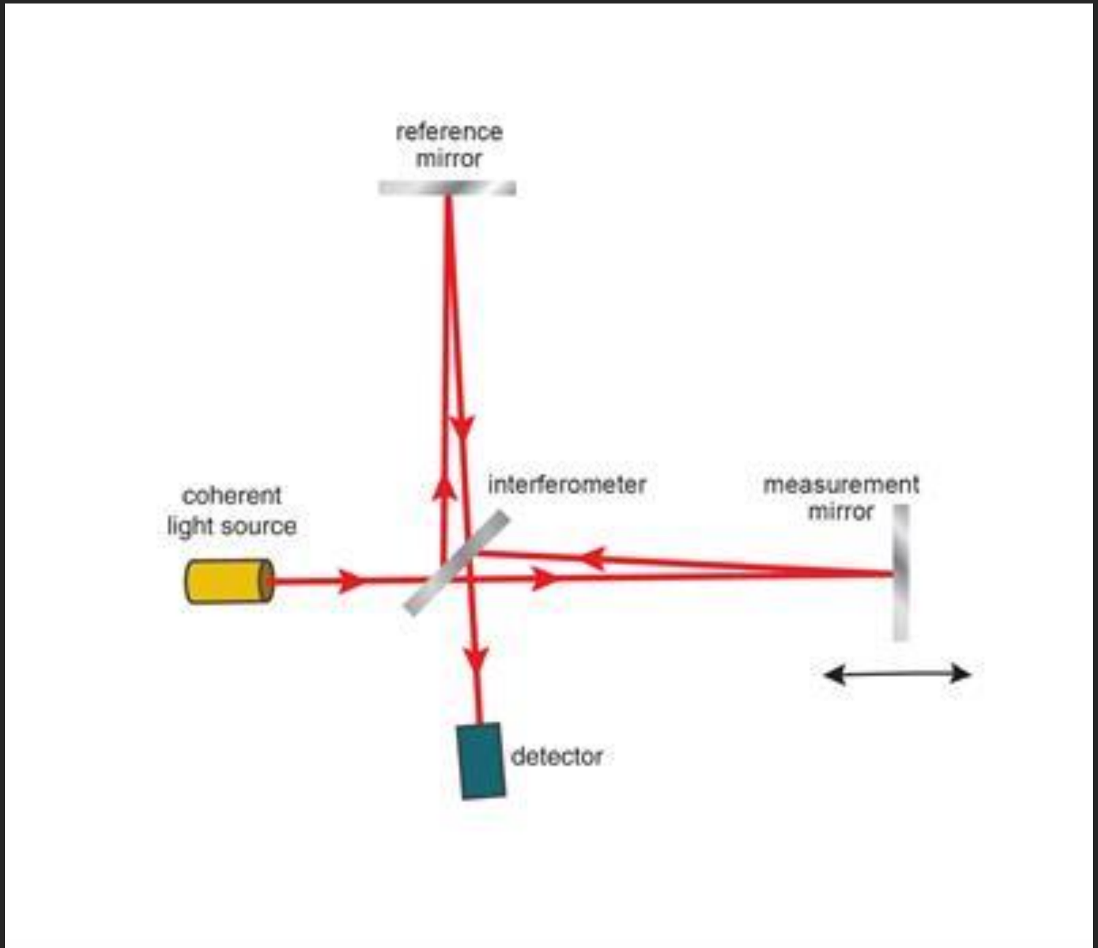


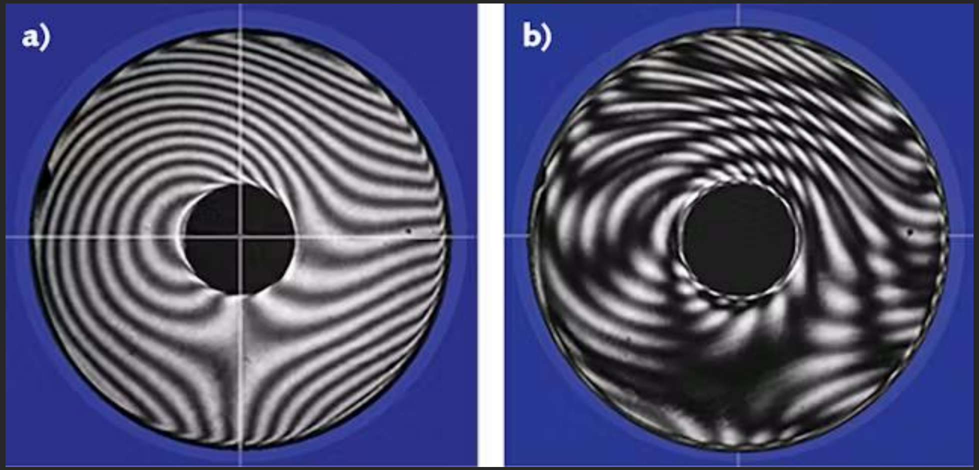
Laser Interferometry

- Extremely high precision measurement
- Industrial Automation & Precision Manufacturing
  - Surface alignment
  - Thickness measurements
  - Displacement
  - Calibration
- Domains
  - Aerospace, semiconductors, high-end optics



Laser Interferometry



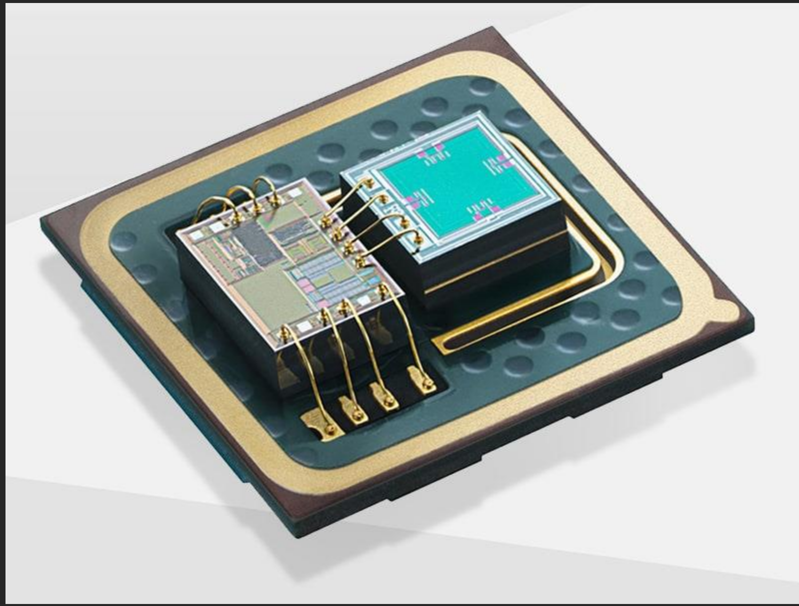


Applications of Laser Interferometry

- Calibration of CNC machines, robotic arms, industrial tools
- Quality control for semiconductor wafers, glass, metal
- Optical component alignment

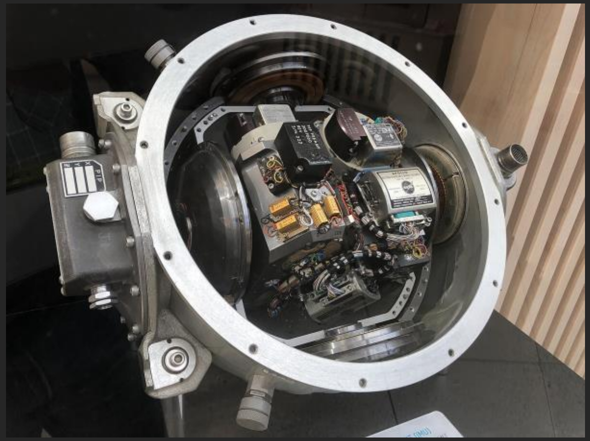
Microelectromechanical (MEM) Sensors

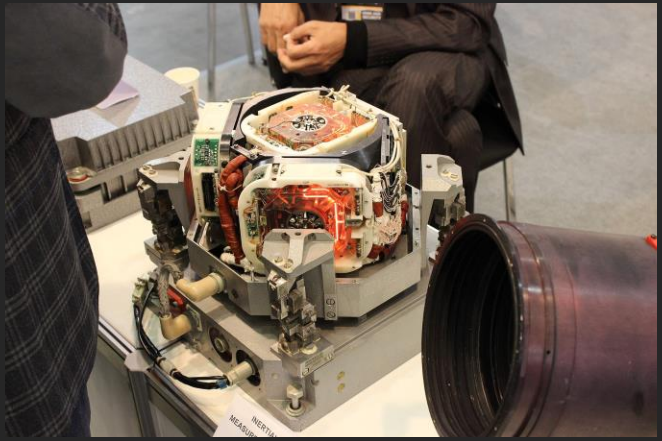
- Miniaturized sensing device that integrates electrical and mechanical components at the micro-scale
- Manufactured using semiconductor fabrication techniques
- Characteristics
  - Size: Microns to millimeters
  - Low-power
  - Functionality: motion, pressure, temperature, light, magnetic, chemical

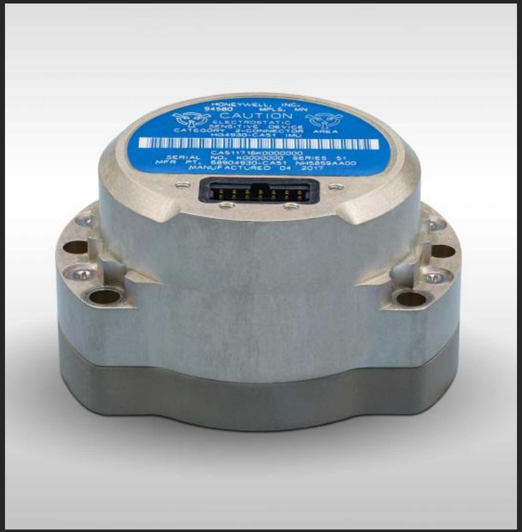


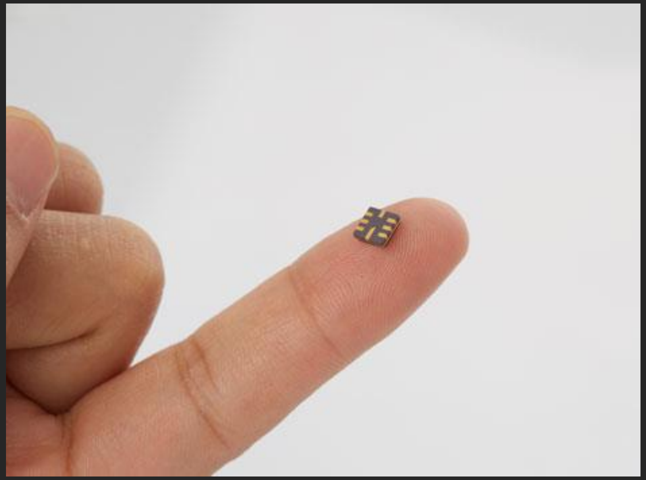
MEMS Sensing Modes

- Capacitive
- Piezoelectric
- Piezoresistive
- Thermosensitive
- Optical
- Hall Effect
- Electrochemical



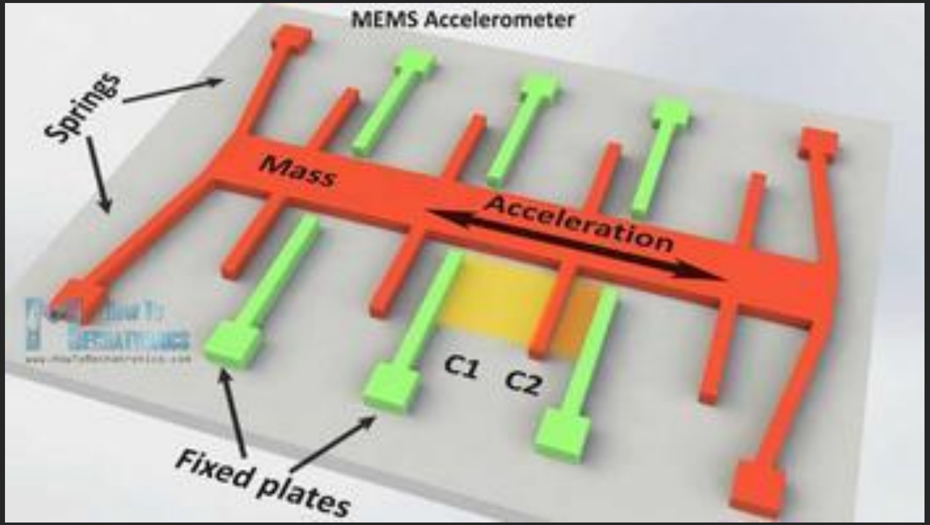


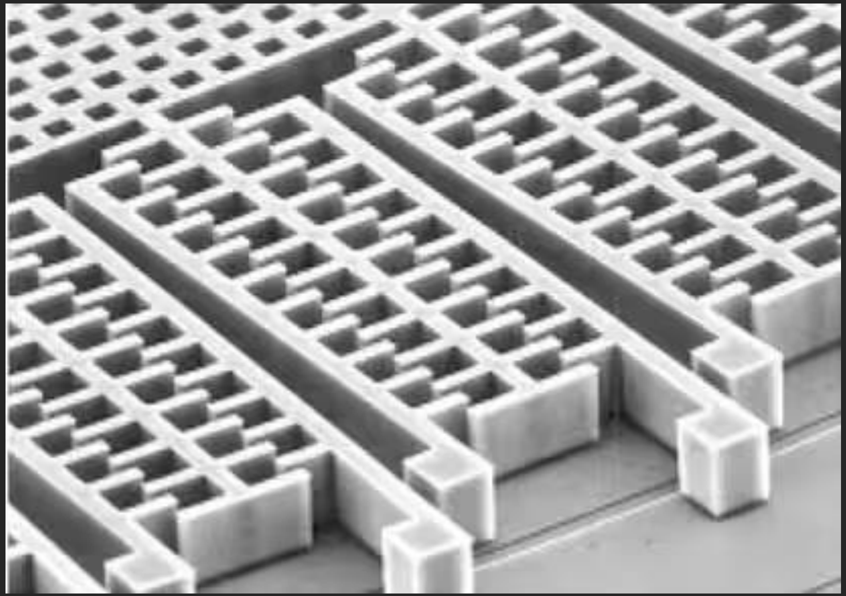




MEMS Accelerometer

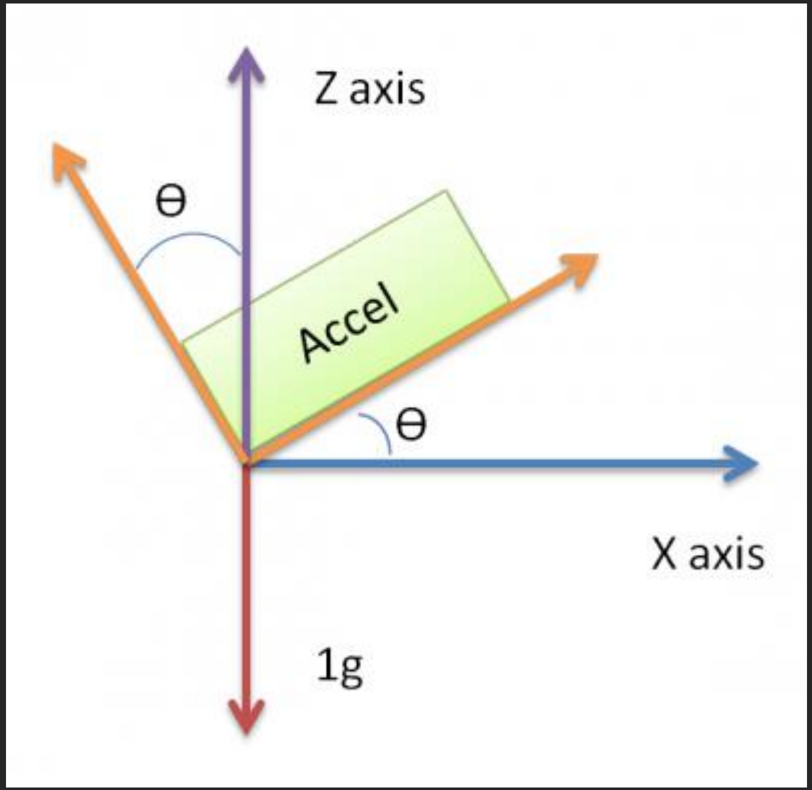
- Proof Mass – tiny mass that move when accelerated
- Suspension System (spring) – holds proof in place
- Sensing Mechanism – converts displacement to electricity
  - Capacitive, piezoelectric, piezoresistive



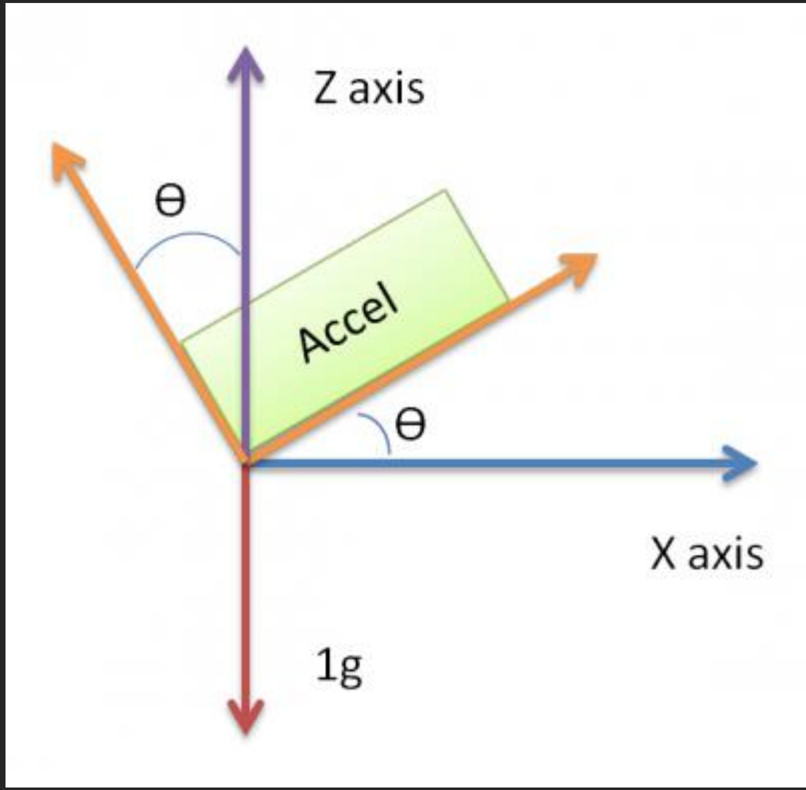


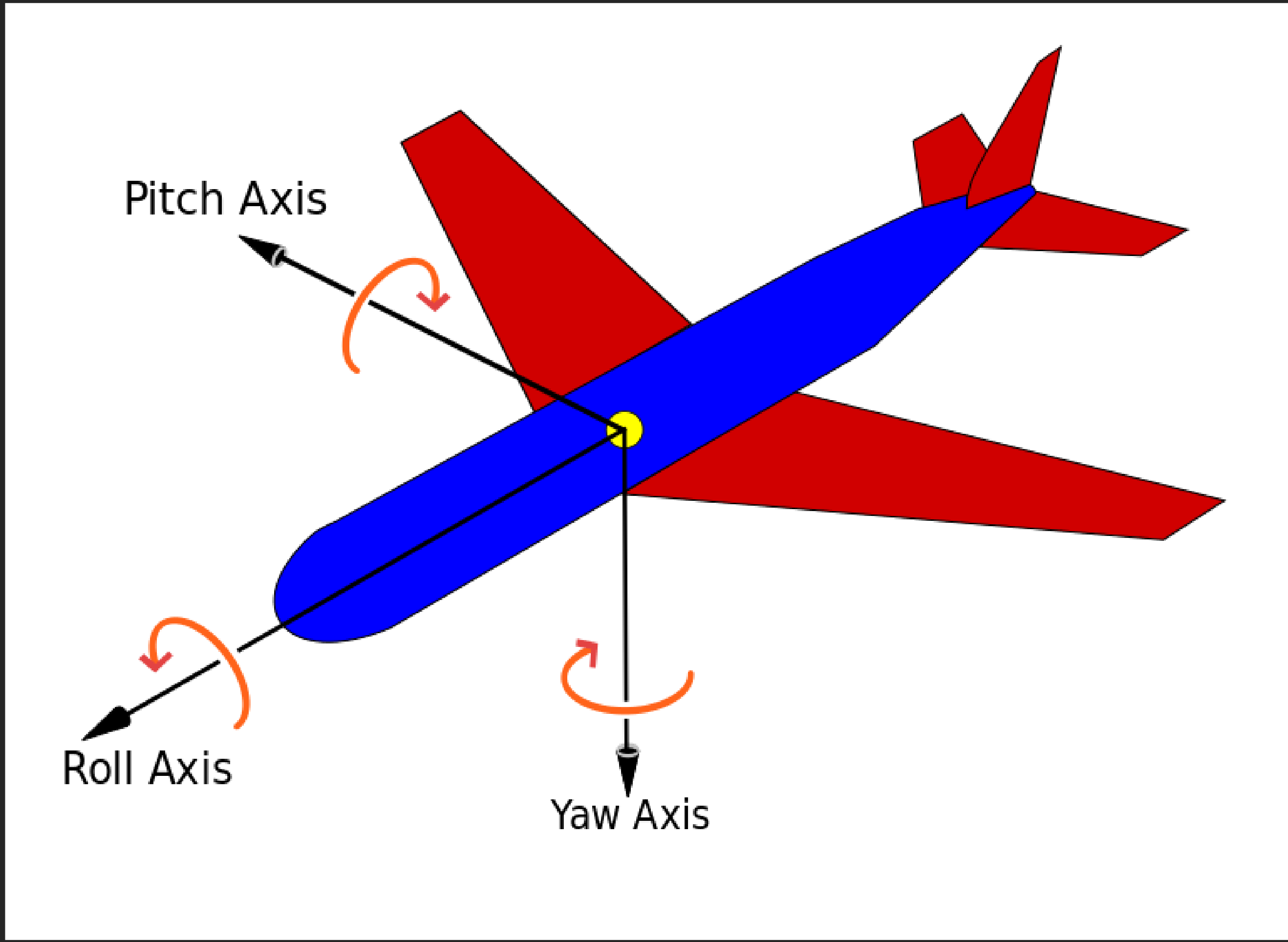
MEMS Accelerometer

- Linear Acceleration – due to motion
  - Velocity – integration
  - Position – double integration
- Gravitational Force – always down
  - Gravity vector is projected into new axis
  - Trigonometry



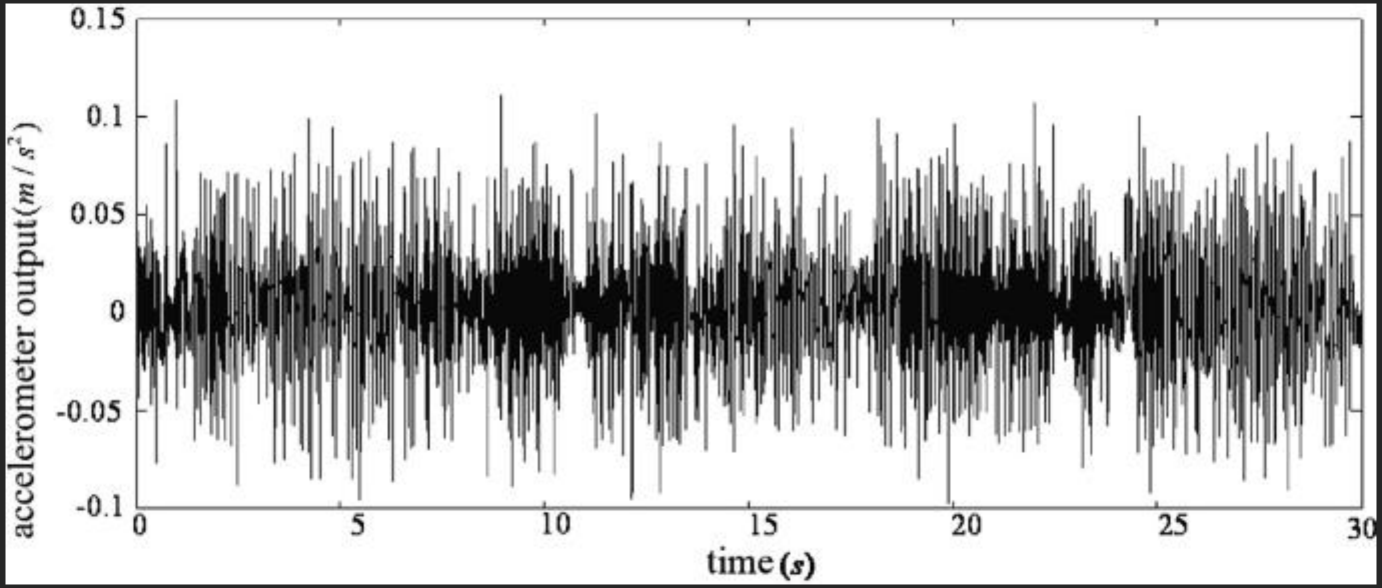
MEMS Accelerometer





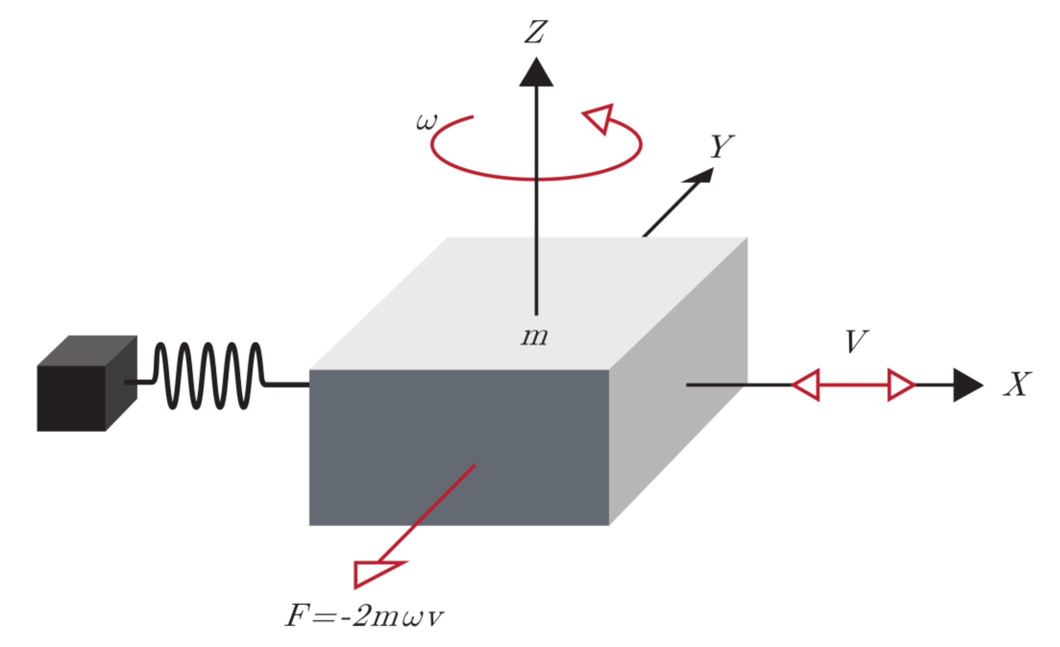
MEMS Accelerometer

- Noise
  - Thermal noise
  - Resonate frequency
  - Poor mechanical design
  - Electrical noise



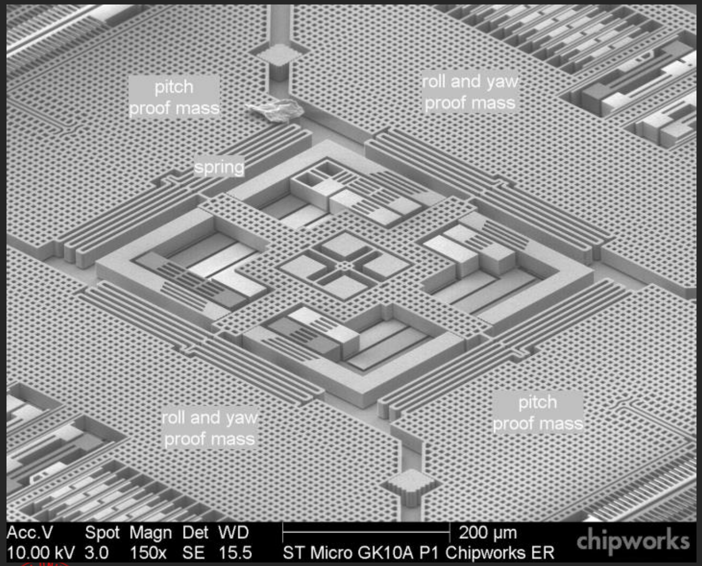
MEMS Gyroscope

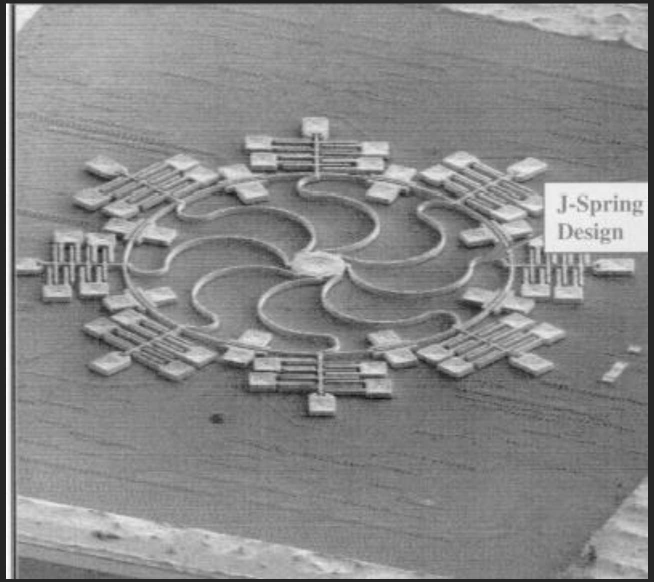
- Measure Angular Speed
  - Angular position - integration
- Vibrating Proof Mass – oscillates back and forth
- Coriolis Effect: $F_c = -2m(\Omega \times v)$
- Sensing Mechanism
  - Capacitive, piezoelectric/resistive

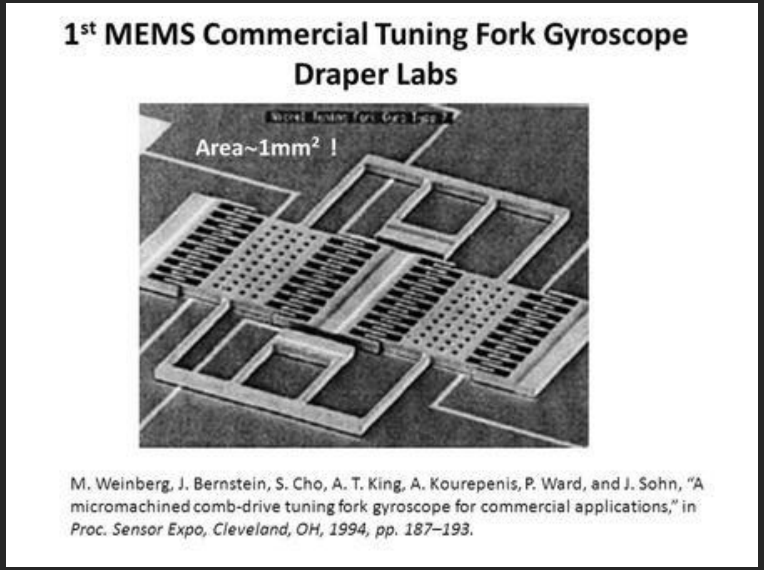


MEMS Gyroscope

- Vibrating structure
- Ring
- Tuning fork

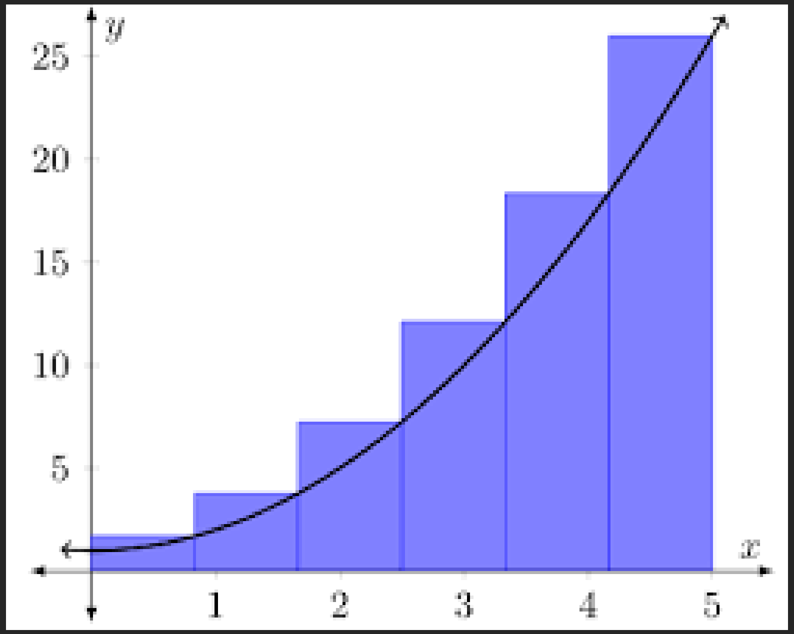






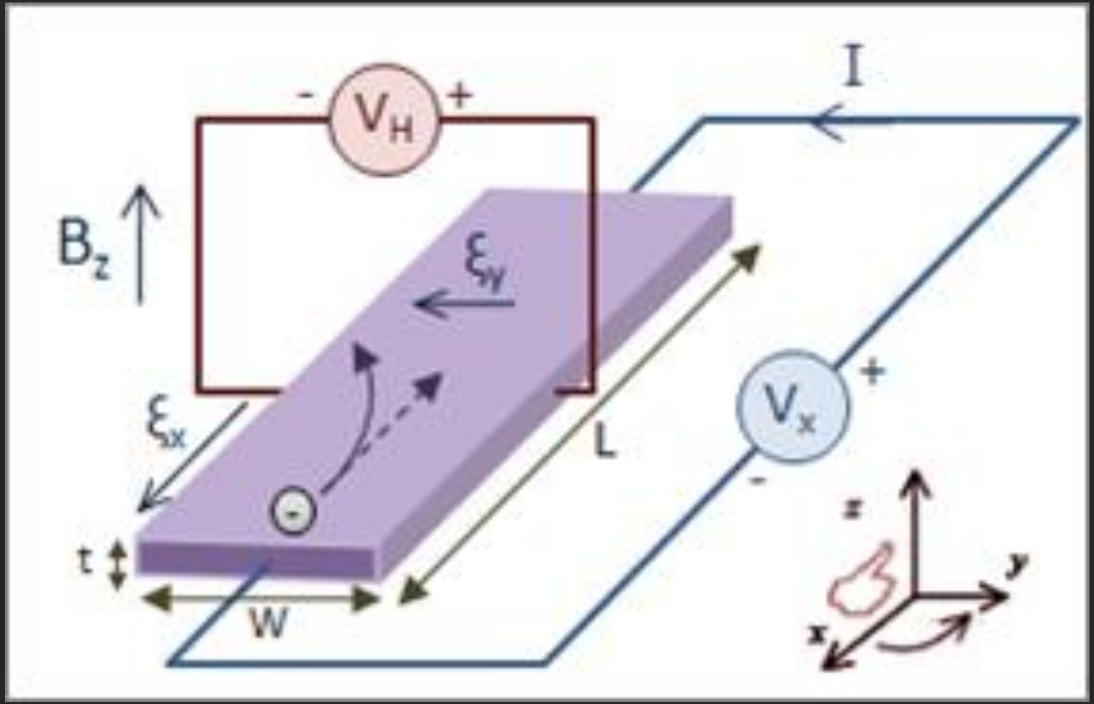
MEMS Gyroscope – Angular Position

- Angular position can be determined from angular speed
  - angular_position += angular_speed * dt
- MEMS gyroscopes have a non-zero average when stationary (drift)
  - Changes slowly with time and temperature
- Discretization error – from integration
- Solutions
  - Integrate quickly
  - Calibrate



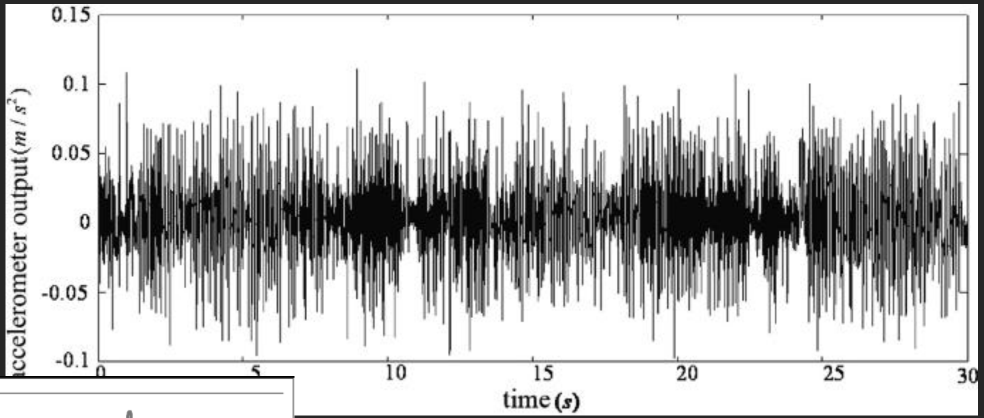
MEMS Magnetometer

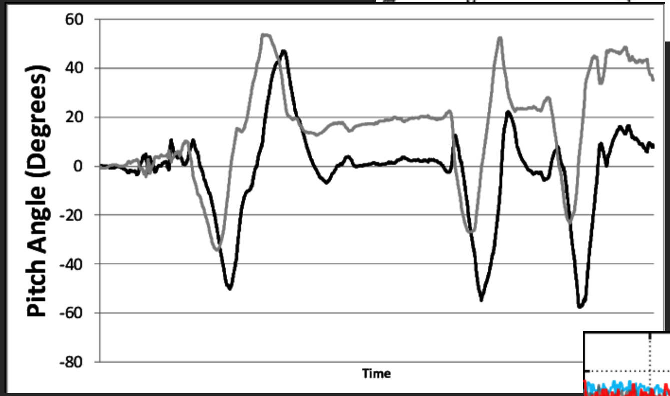
- Senses magnetic field strength
- Modes
  - Hall Effect (most common)
  - Magneto resistive
  - Lorentz Force
- Very noisy
- Susceptible to electric motors

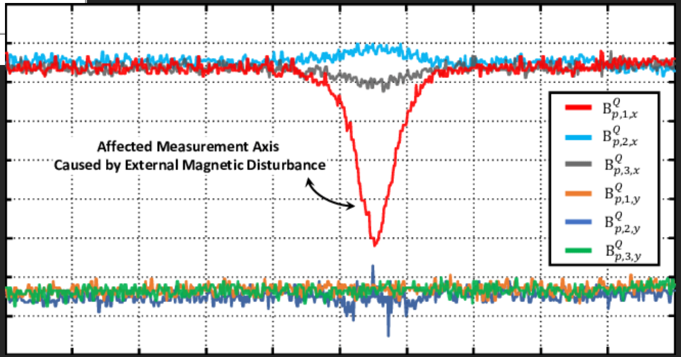


Inertial Measurement Unit

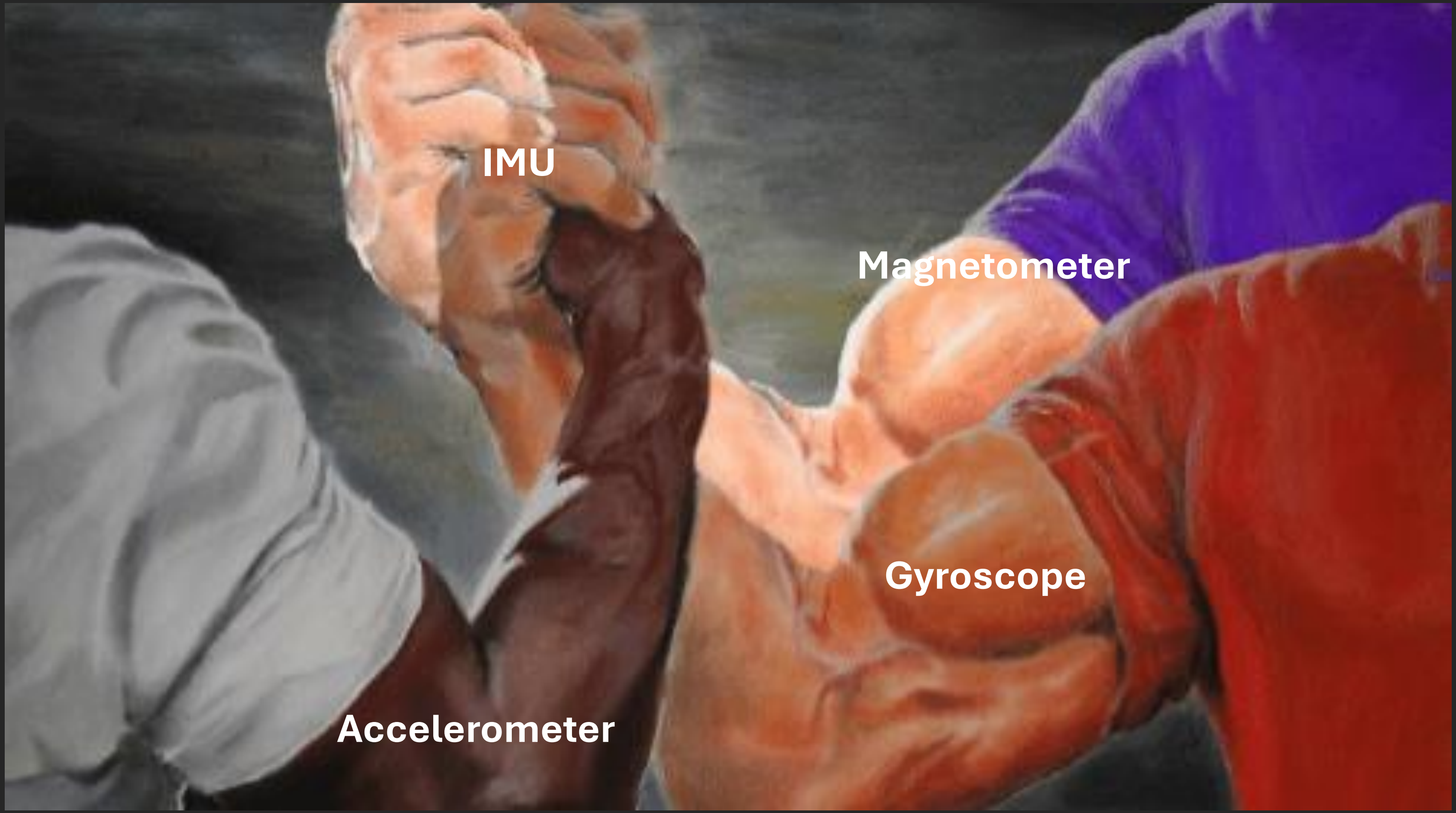
- Accelerometers
  - Absolute pitch and roll
  - Very noisy
- Gyroscopes
  - Very low noise
  - Drifts over time
- Magnetometers
  - Very noisy
  - Constant magnetic field



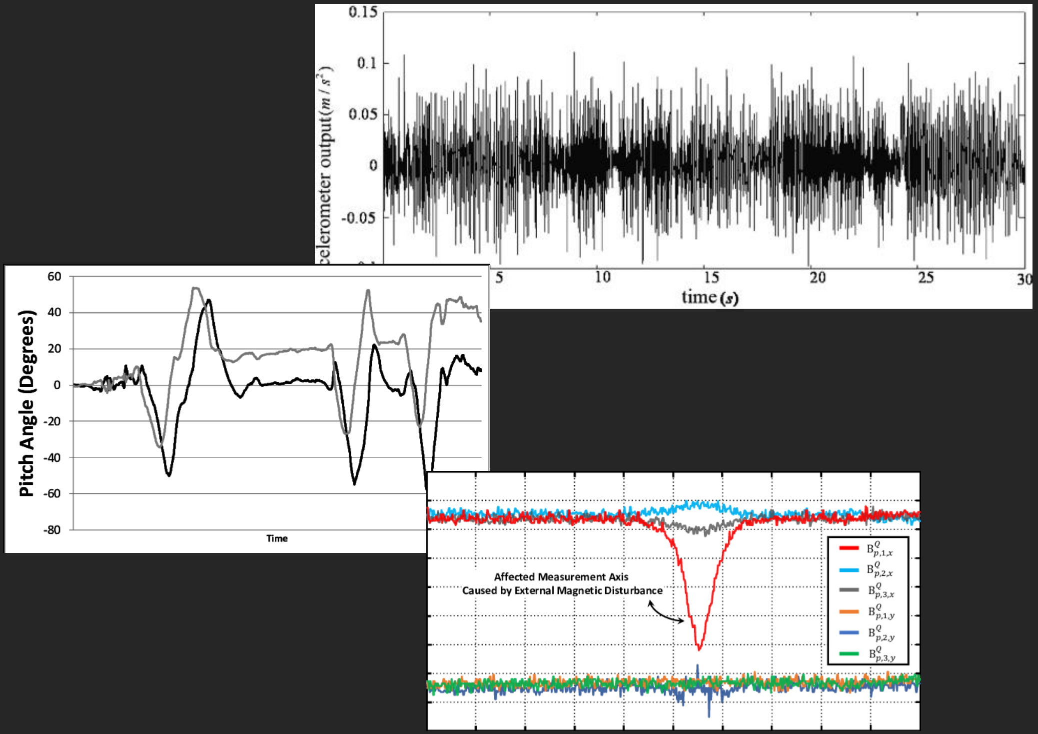


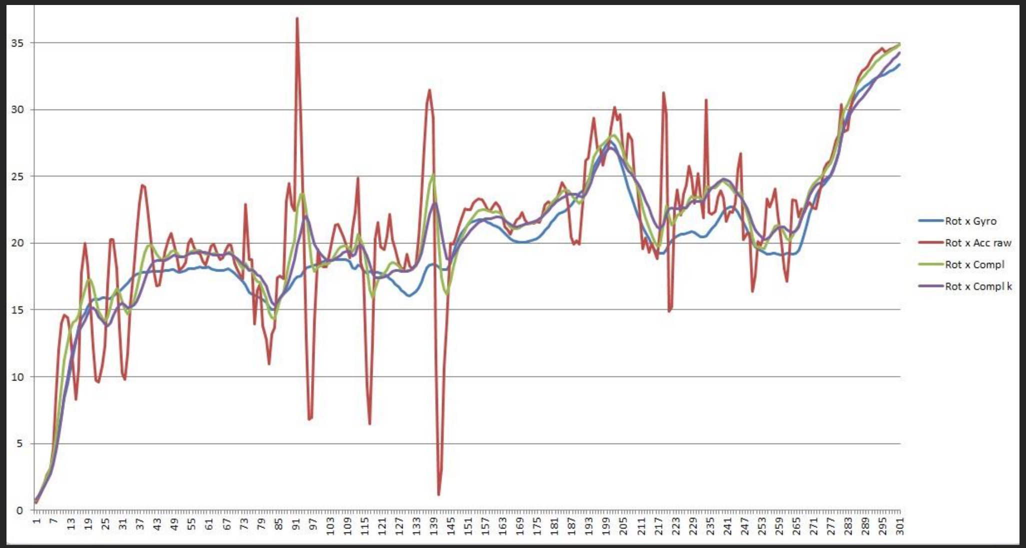


IMUs



IMUs


0.15
0.1
0.05
0
-0.05
celerometer output(m/s^2)
5
10
15
20
25
30
time (s)
Pitch Angle (Degrees)
60
40
20
0
-20
-40
-60
-80
Time
Affected Measurement Axis
Caused by External Magnetic Disturbance


Rot x Gyro
Rot x Acc raw
Rot x Compl
Rot x Compl k

Applications

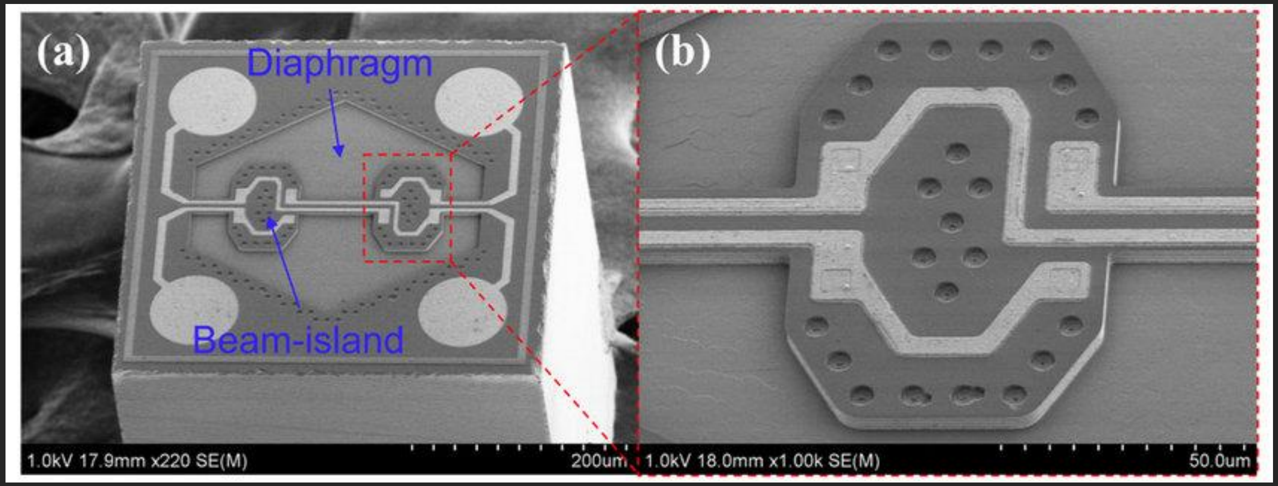
- Consumer Electronics
  - Smartphones, wearables, gamming controllers
- Automotive Safety
  - Airbag deployment, electronic stability control, GPS
- Industrial & Structural Monitoring
  - Vibration Sensing, tilt sensors
- Aerospace & Defense
  - Drones, aircraft, spacecraft, navigation
- Medical & Healthcare
  - Fall detection, prosthetics

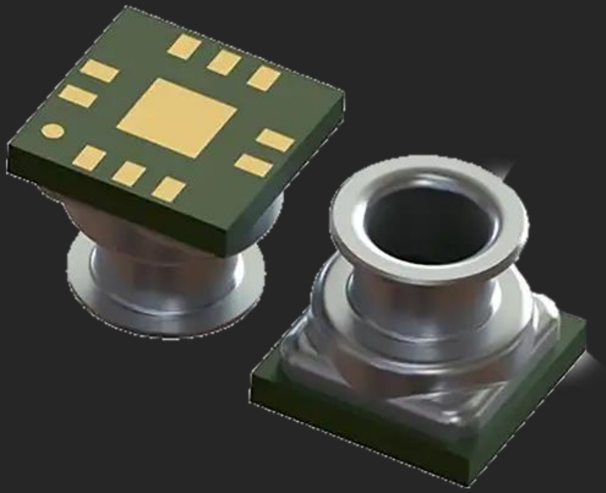
IMU Challenges

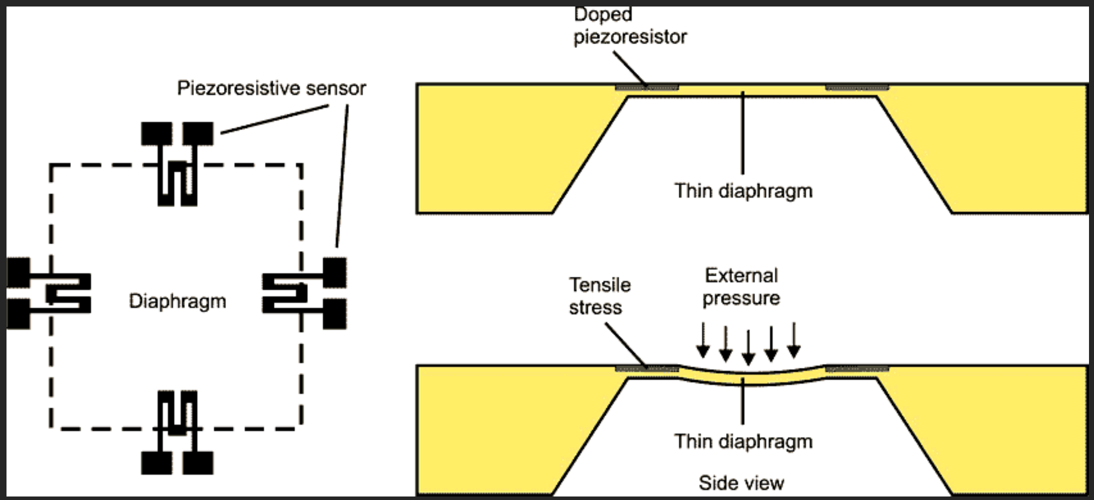
- Accelerometer ambiguity
  - Distinguishing between movement and tilt
- Magnetometer reliability
  - Very susceptible to noise
- Sensor fusion algorithms
  - Lag vs noise

MEMS Pressure Sensor

- Sense changes in
  - Absolute pressure
  - Differential pressure
  - Gauge pressure
- Mechanisms
  - Piezoresistive
  - Capacitive
  - Resonant

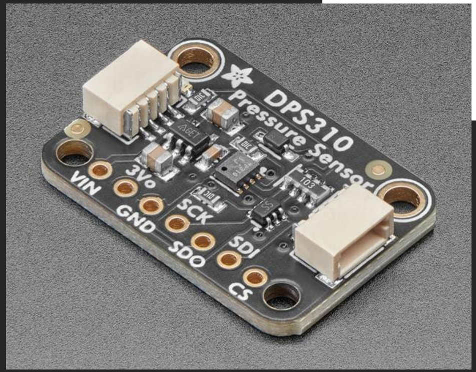






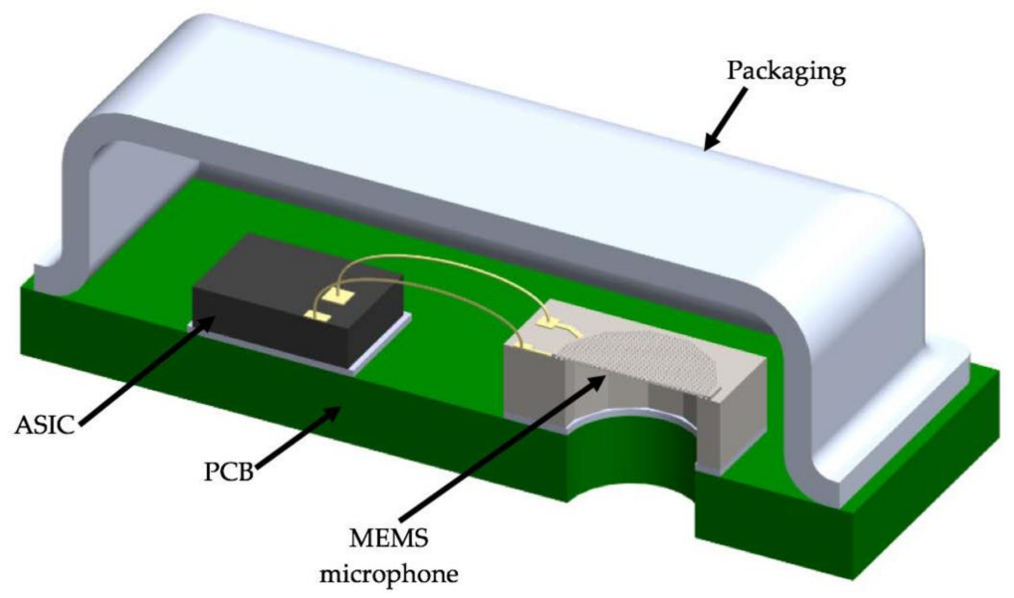
MEMS Pressure Sensors

- Automotive & Transportation
  - Intake air manifold sensor for engine control, tire pressure, altitude
- Medical
  - Blood pressure, raspatory ventilators, prosthetics and exoskeletons
- Industrial
  - HVAC, process control for fluid flow
- Consumer Electronics
  - Wearables and smart home devices



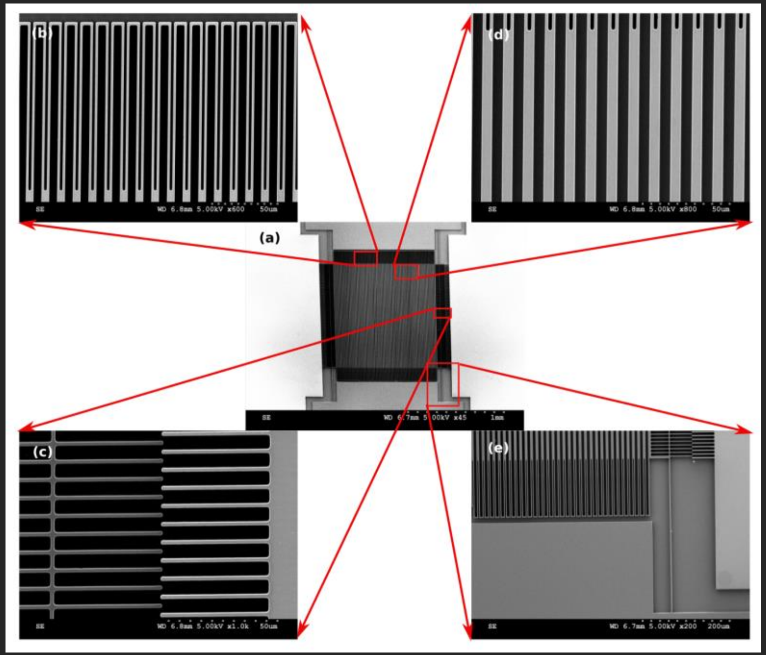
MEMS Microphone

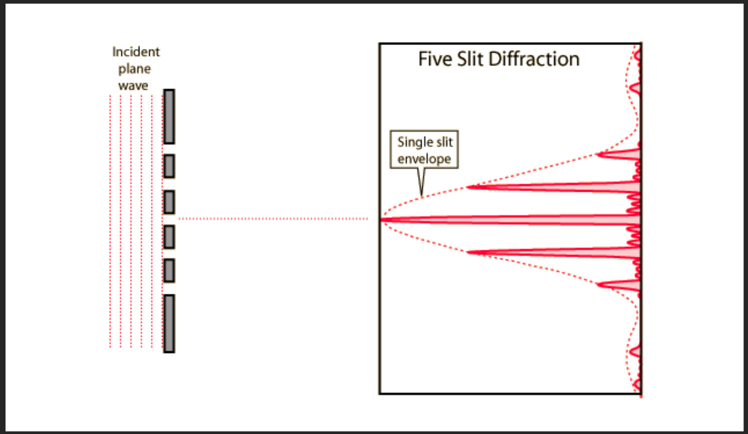
- Specially designed pressure sensor
- Uses capacitive sensing

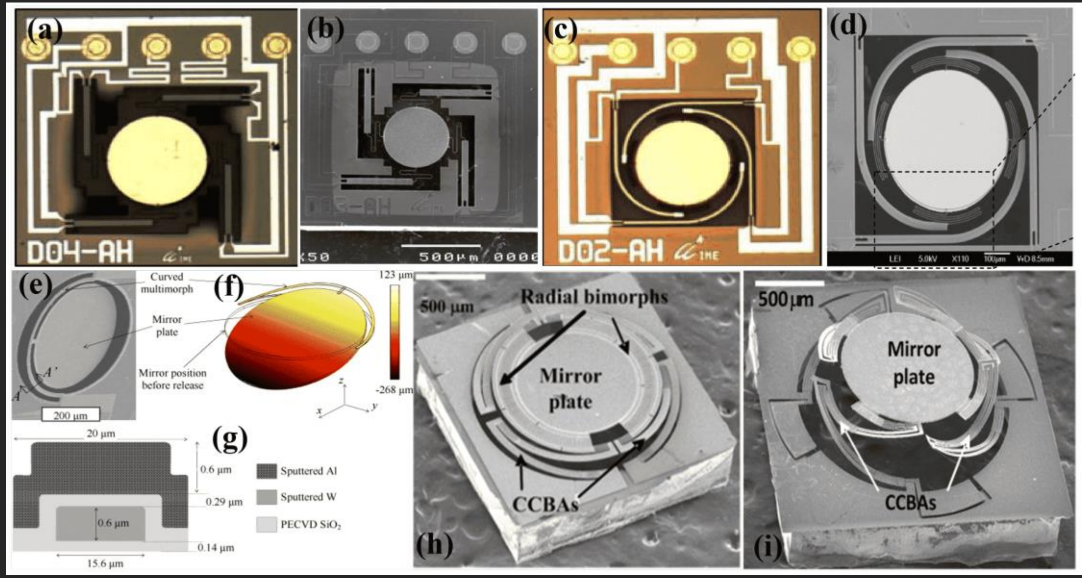


MEMS Optical Sensor

- Photodetectors
- Micromirrors
- Diffraction Gratings
- Optical Filters

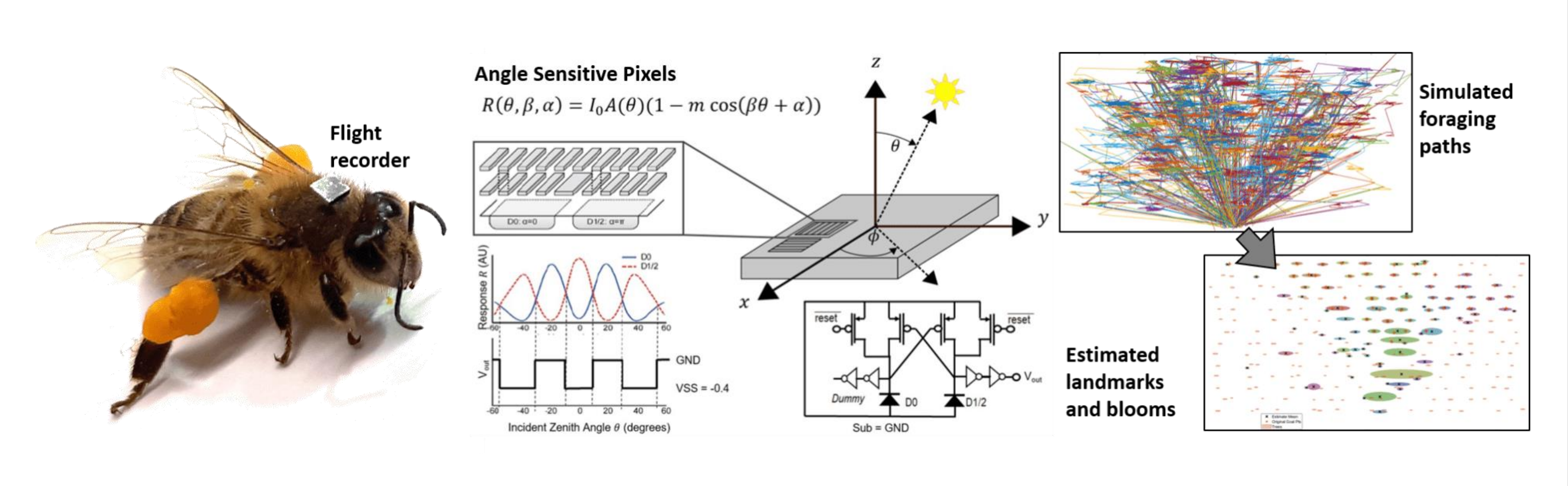






MEMS Optical Sensor - Applications

- LiDAR
- Medical imaging
- Fiber optic
- 3D scanning



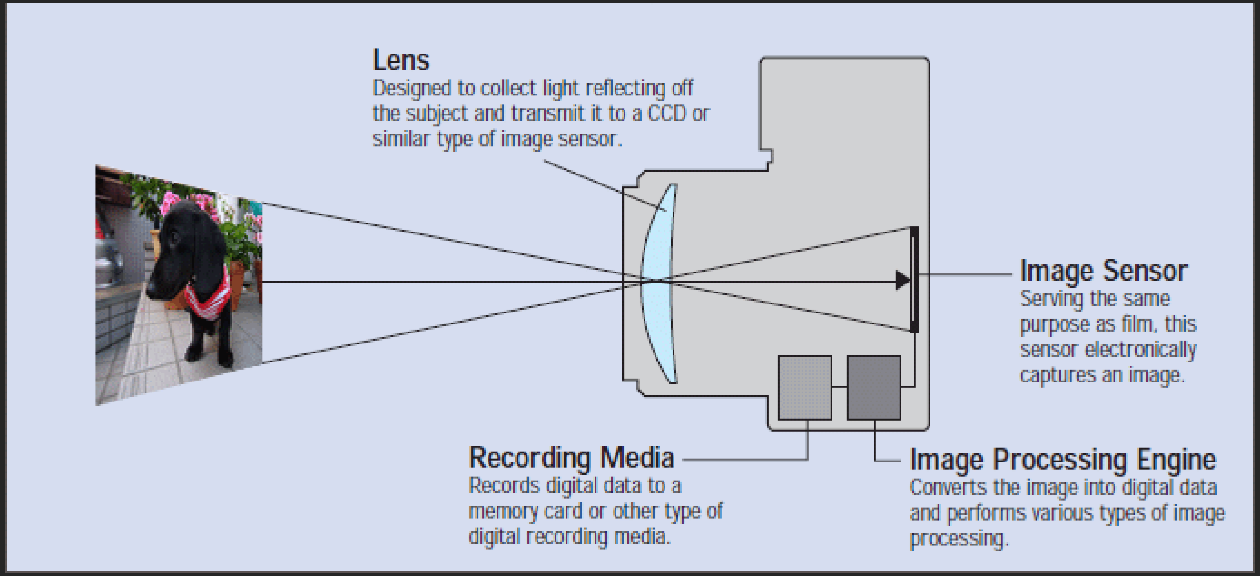
MEMS Humidity & Electrochemical Sensor

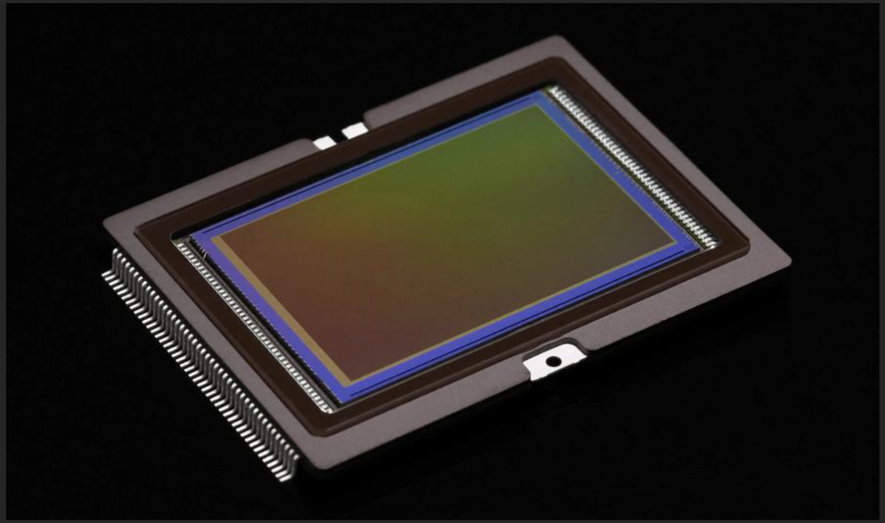
- A humidity-sensitive material (polymer, ceramic, or oxide film) absorbs water molecules from the air.
  - This changes the material's capacitance, resistance, or thermal properties
- Electrochemical sensor works based off redox reaction
- Metal-oxide semiconductor
  - A metal oxide (SnO_2, ZnO, TiO_2) changes resistance when exposed to gas
  - High sensitivity to toxic and combustible gases

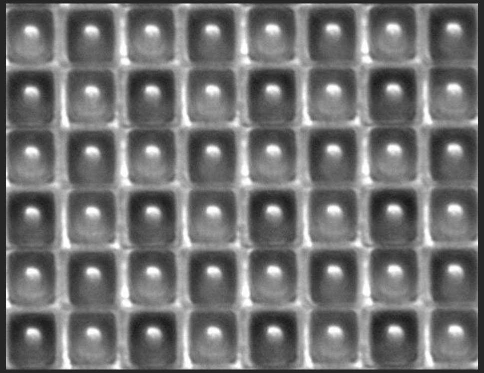
Cameras

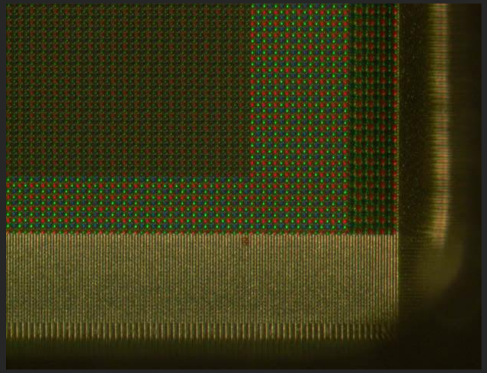
- A device that captures light and converts it into a digital image.
  - Lens – focuses light onto sensor
  - Aperture – controls the amount of light entering the camera
  - Shutter – regulates exposure time
  - Image Sensor – converts light into electrical signal
  - Processor & Storage – converts raw sensor data into usable image

Cameras – Operating Principle

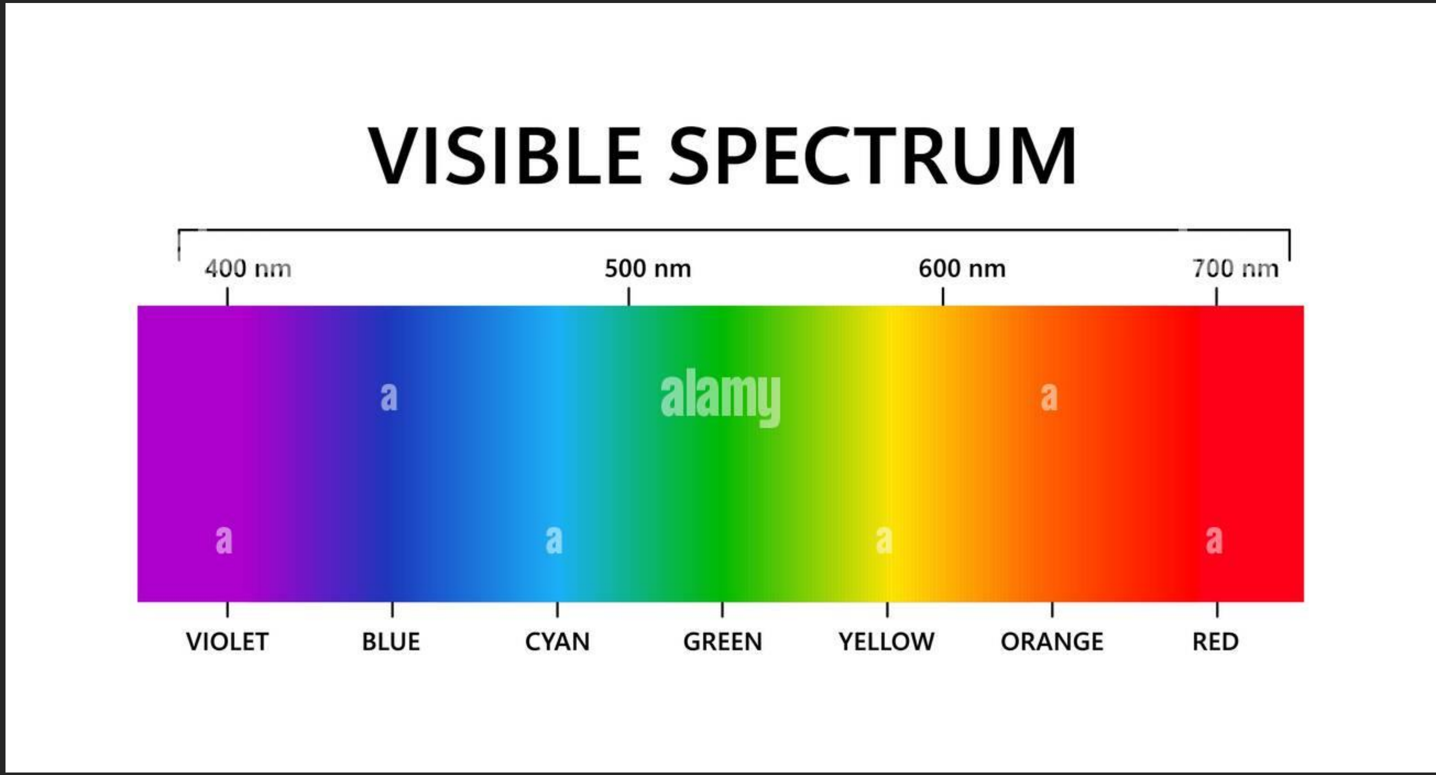






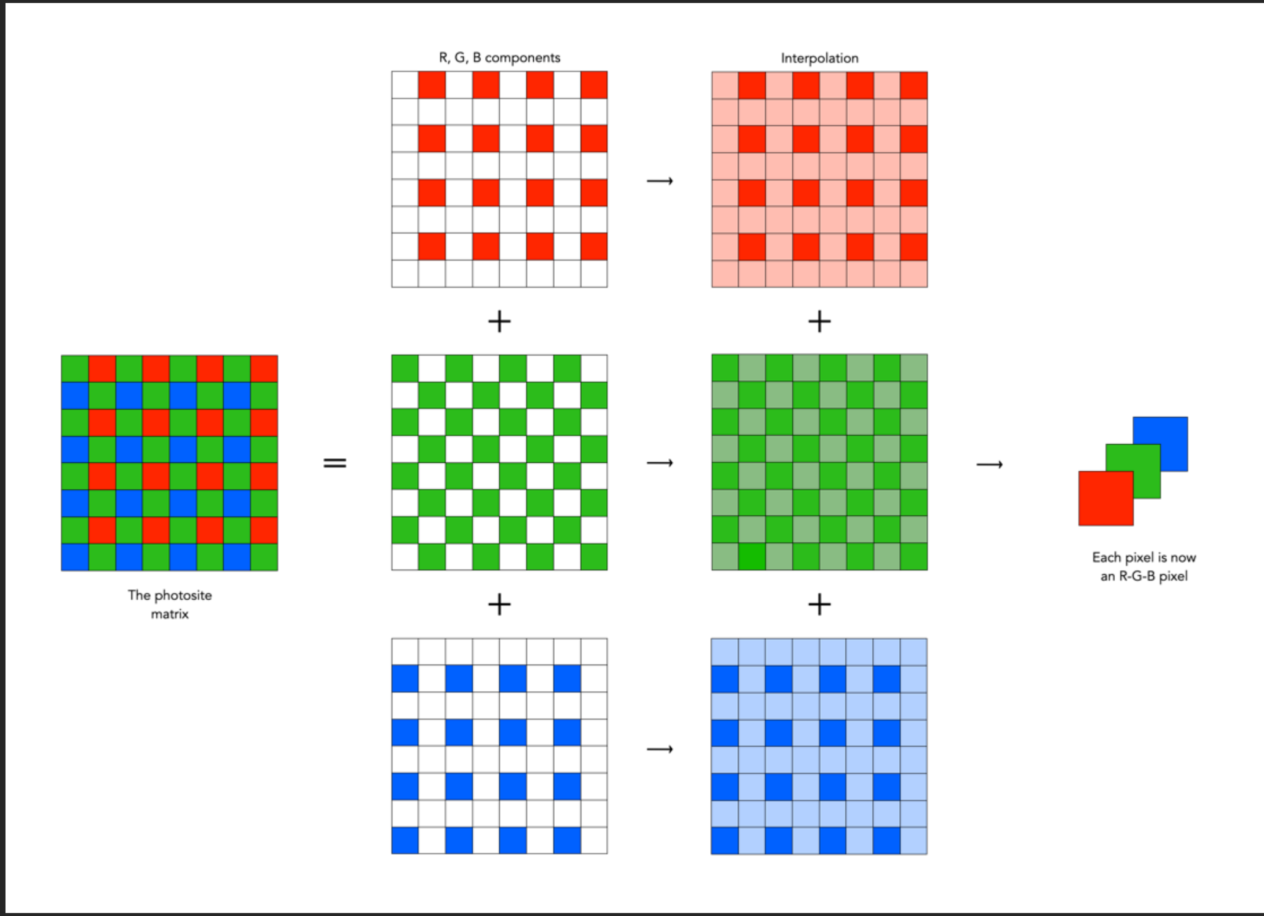


Bayer Interpolation (Demosaicing)



Bayer Interpolation (Demosaicing)

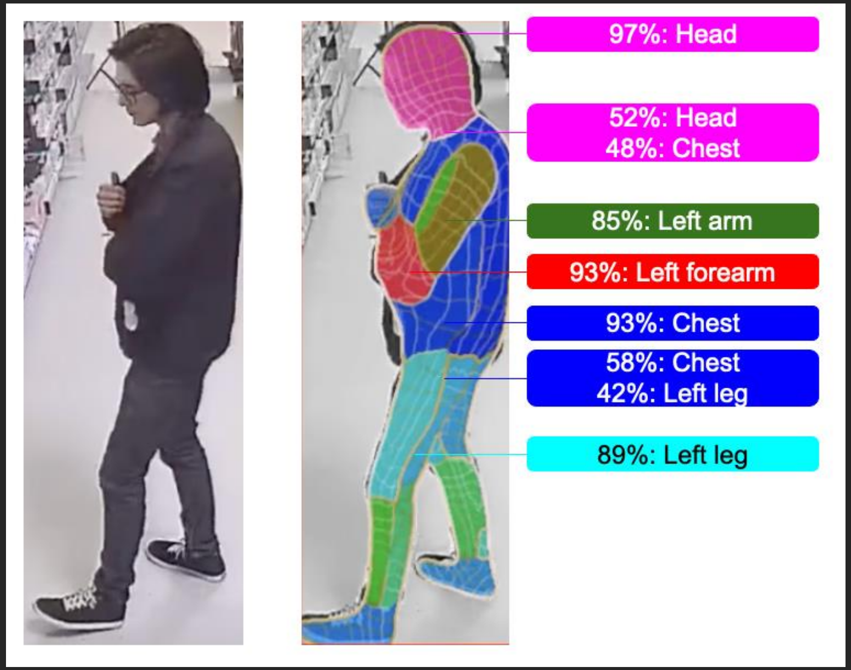
- Human Eyes
  - S-cones
    - ~420 nm
    - Blue
  - M-cones
    - ~530 nm
    - Green
  - L-cones
    - ~560 nm
    - Red



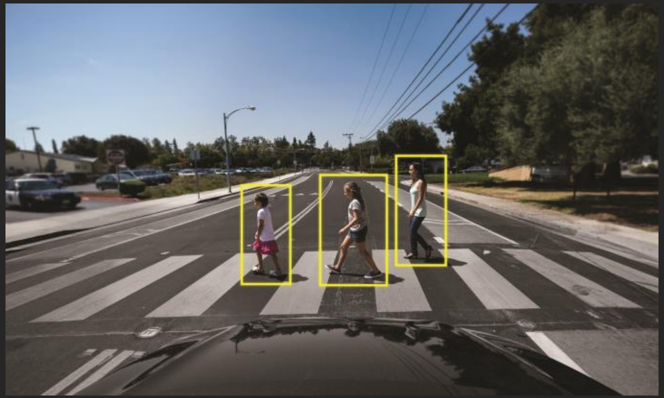
Yellow

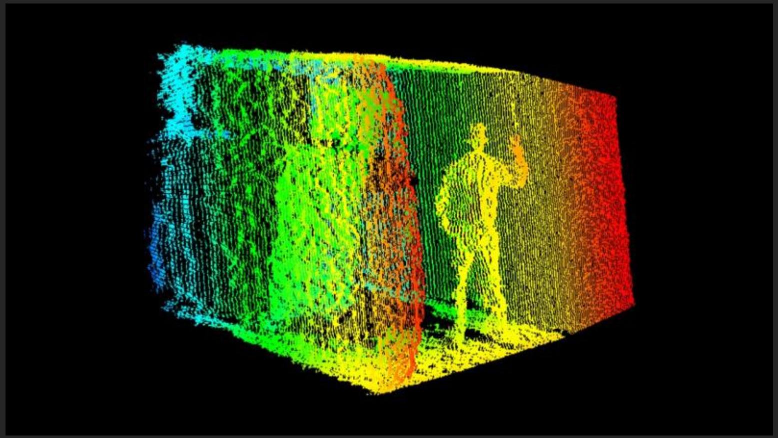
- How do we see yellow?
  - True Yellow Light (~580 nm)
  - A Combination of Red (~650 nm) and Green (~530 nm) Light
- Yellow light stimulates L-cones and M-cones

Cameras and CPS



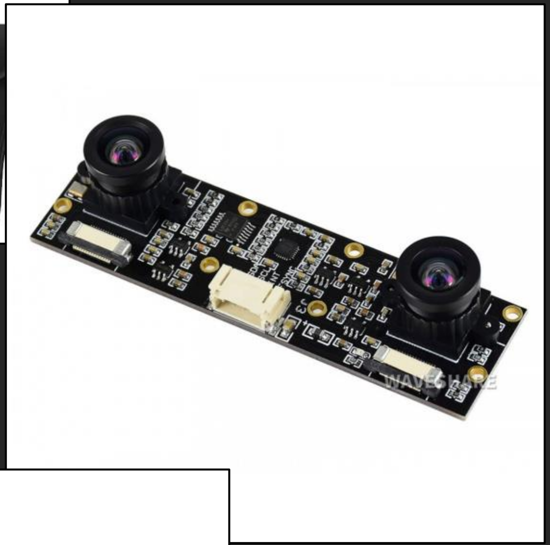
- Real-time Monitoring
- Object Detection and Recognition
- 3D Mapping and Depth Sensing
- Thermal & Infrared Imaging
- Quality Inspection and Defect Detection





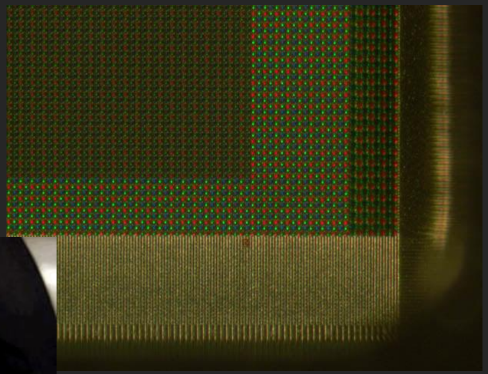
Types of Cameras

- RGB (visible light)
- Infrared & Thermal
- LiDAR
- High-speed
- Hyperspectral & Multispectral



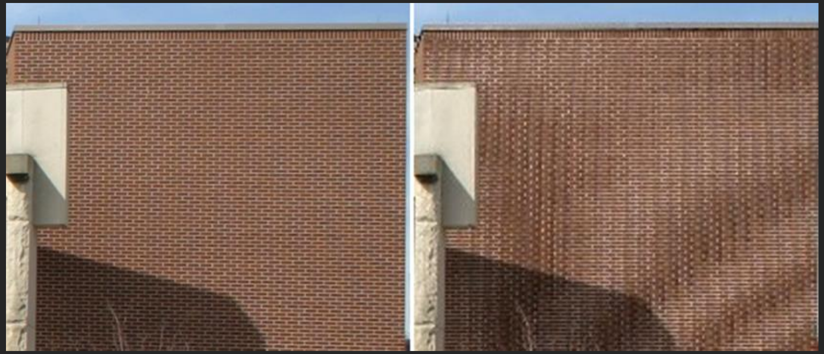
Camera Parameters

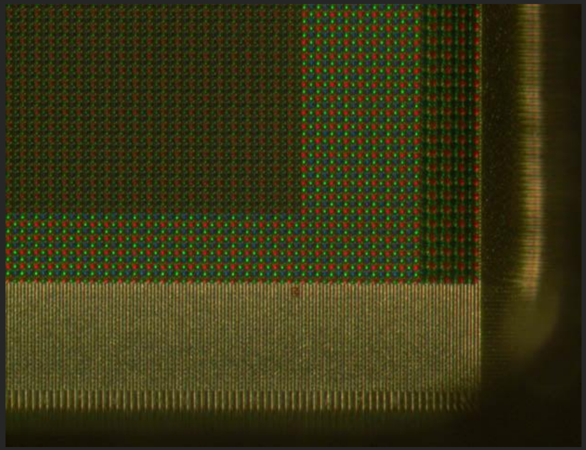
- Resolution & Pixel Size
- Frame Rate
- Shutter Type (Global Vs Rolling)
- Low-light Performance
- Spectral Range
- Connectivity & Latency



Resolution & Sensor Size

- More Pixels -> Higher resolution
  - -> Higher spatial frequency
  - -> Less aliasing
- Bigger Sensor -> More light
  - -> Better low light performance
  - -> Less noisy images



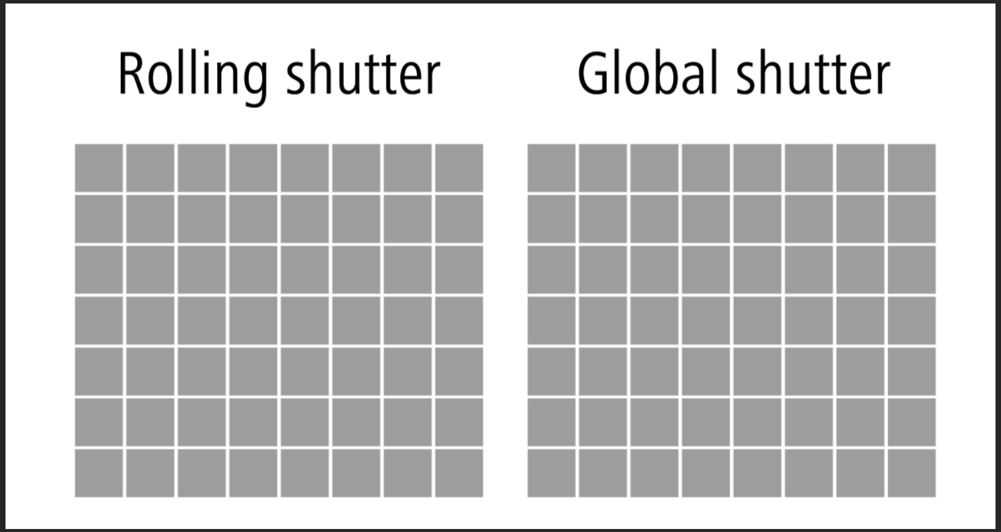


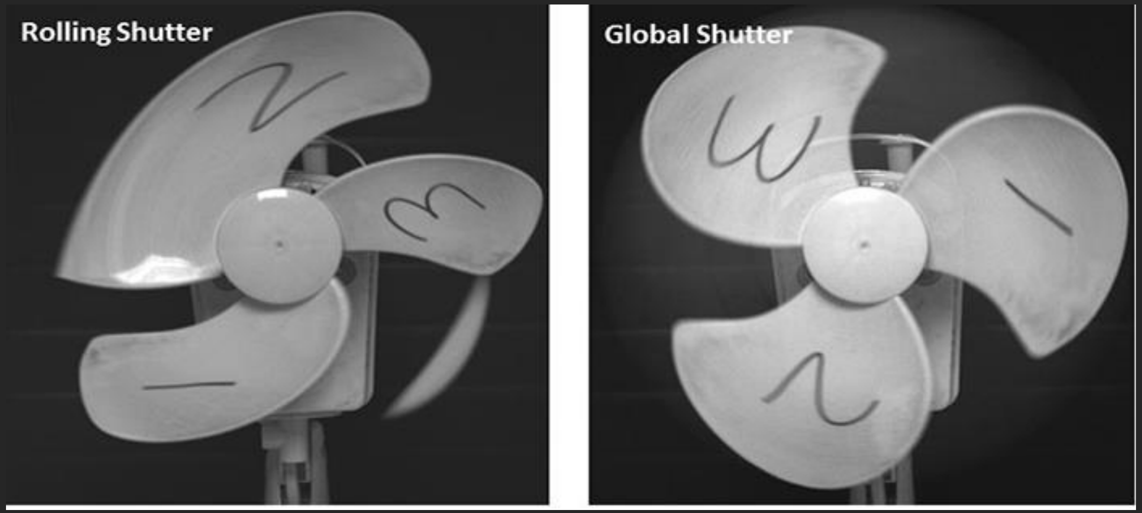
Frame Rate

- Higher Frame Rate
  - Higher temporal frequency
  - Less light per image
- Exposure time
  - How long the camera sensor is exposed to incoming light
- Trade-offs
  - Blurriness
  - Brightness
  - Noisiness

Shutter Type

- Rolling Shutter
  - Captures image one row at a time
- Global Shutter
  - Captures entire image at once



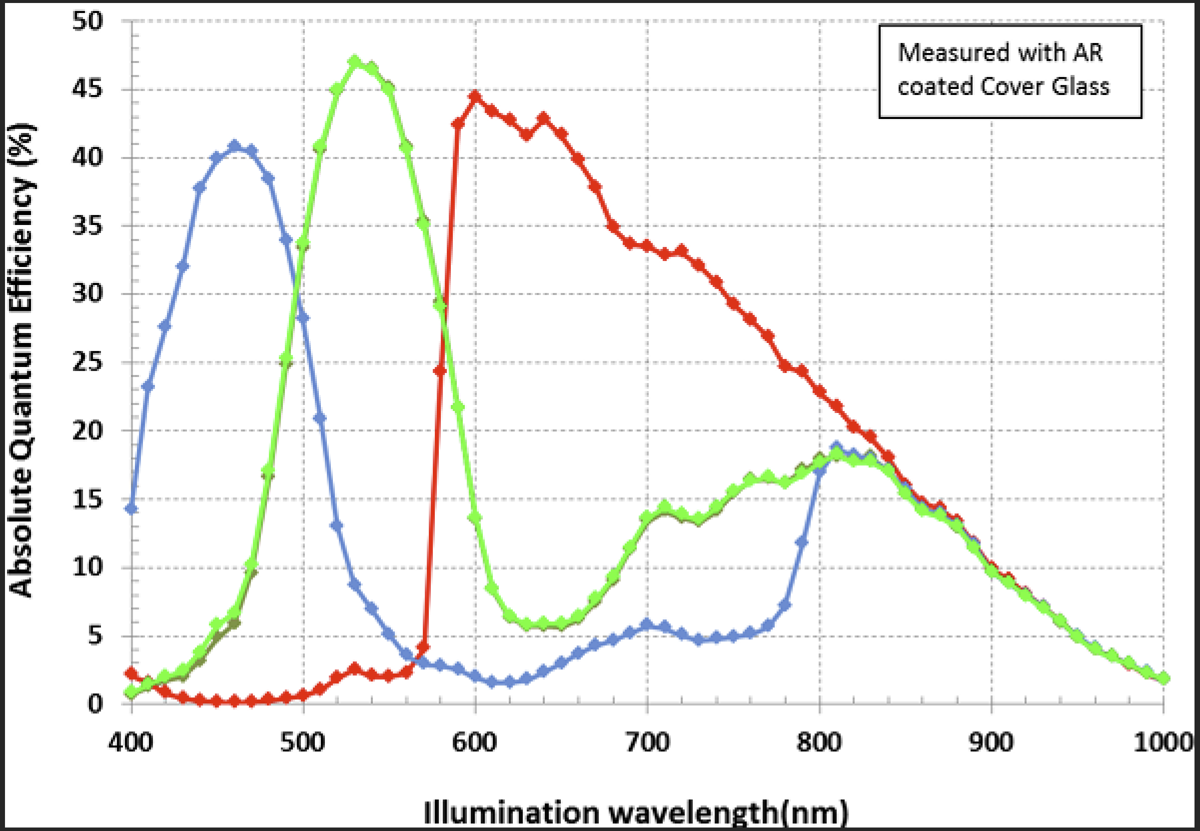


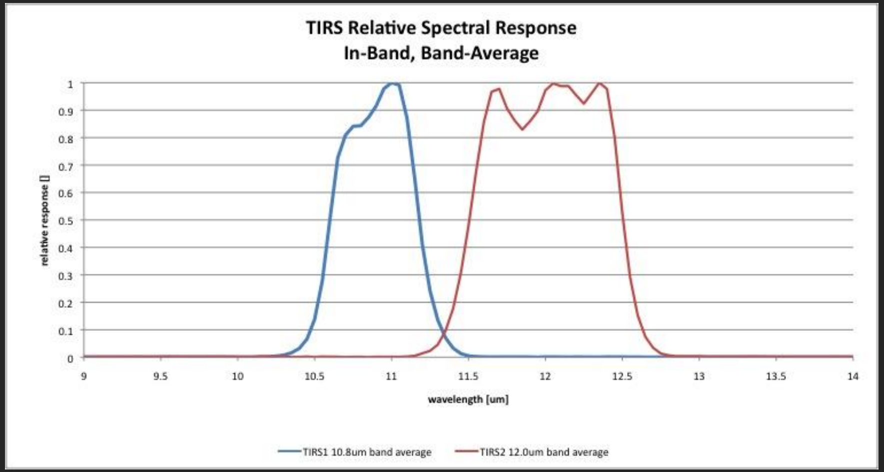
Low-Light Performance

- ISO (International Organization for Standardization)
  - Controls how sensitive the pixels are two incoming light

Spectral Sensitivity

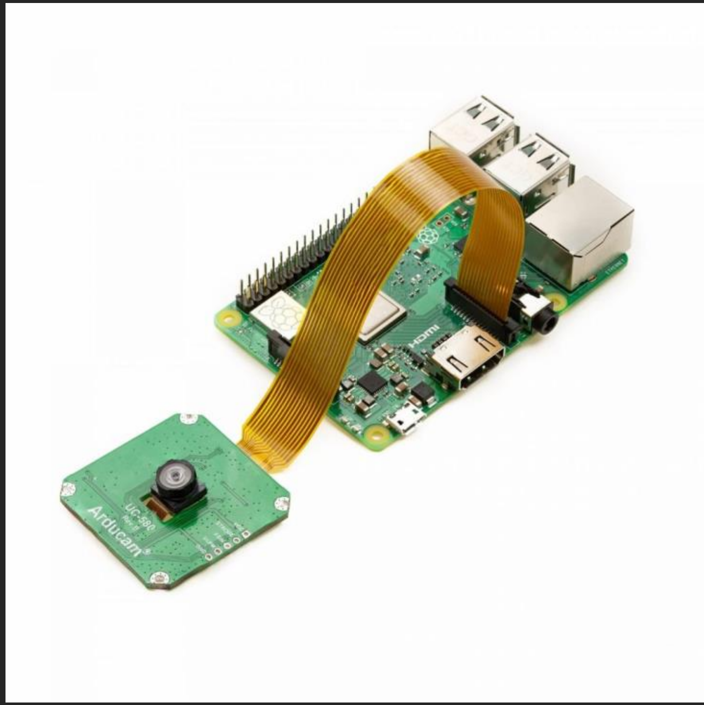
- How sensitive to a particular frequency of light the camera sensor is
  - Semiconductor properties
  - Filters





Connectivity & Latency

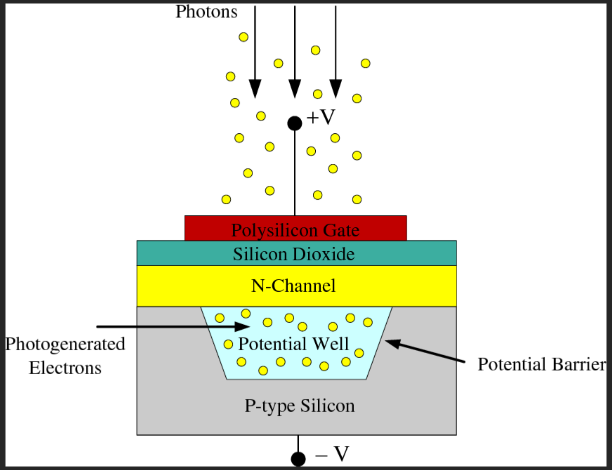
- Uncompressed data rate
  - Bit-depth x # Channels x # Pixels # Framerate
- Video Compression
  - Format (H.264)
  - Codec (OpenH264)



Camera Sensing Technologies

- Charge-Coupled Device (CCD)
- Complementary Metal-Oxide-Semiconductor (CMOS)
  - Front-side Illumination
  - Back-side Illumination
  - Stacked
- Single-Photon Avalanche Diode (SPAD)
- Foveon X3 Sensor (Stacked RGB)

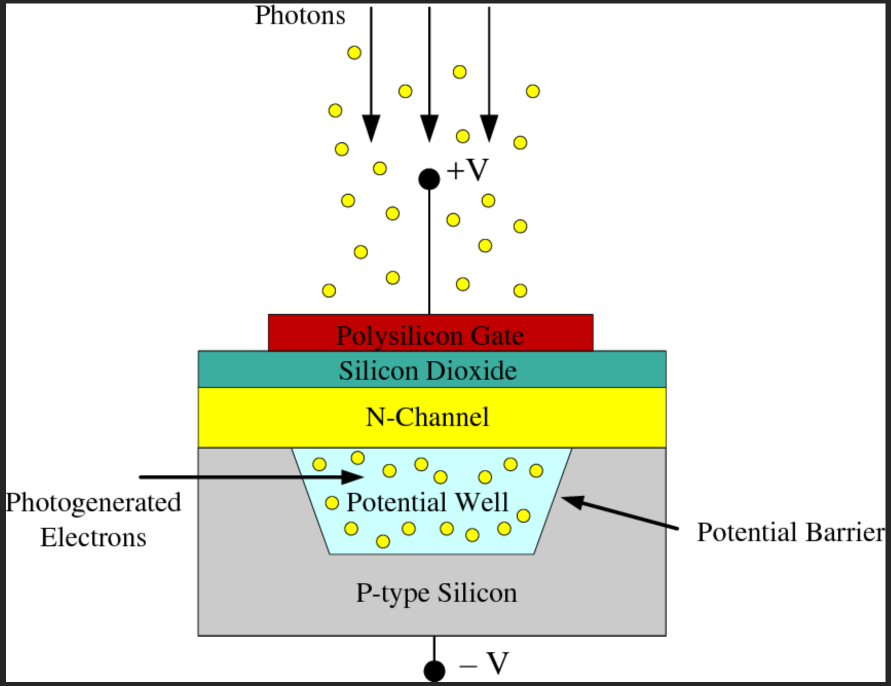
Charge-Coupled Device



- Light absorption – photon hits a photodiode
  - Number of electrons is proportional to the light intensity
- Collection – pixel stores electrons in a capacitor
  - Charge remains accumulated to “readout”
- Charge transfer – stored values are shift to edge of sensor
  - Readout amplifier at the edge of the camera sensor
- Digital conversation – Charge is converted to voltage
  - Voltages is converted to digital value using ADC

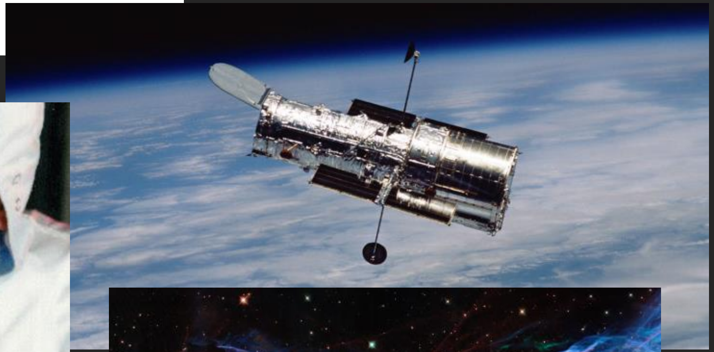
Charge-Coupled Device

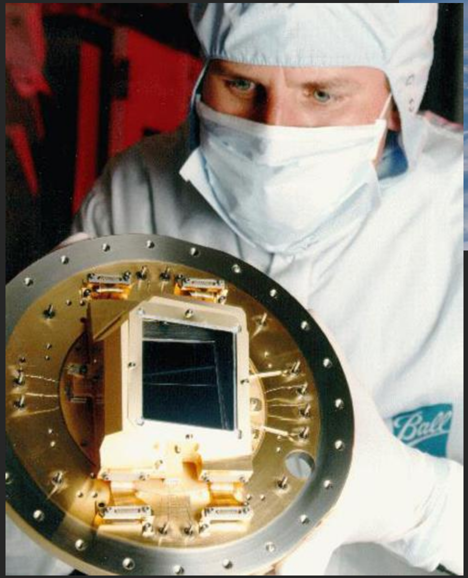
- Advantages
  - Low noise
  - Good low-light performance
  - High dynamic range
  - Uniform pixel response
- Disadvantages
  - Slower readout speeds
  - High power consumption
  - Expensive



Charge-Coupled Device

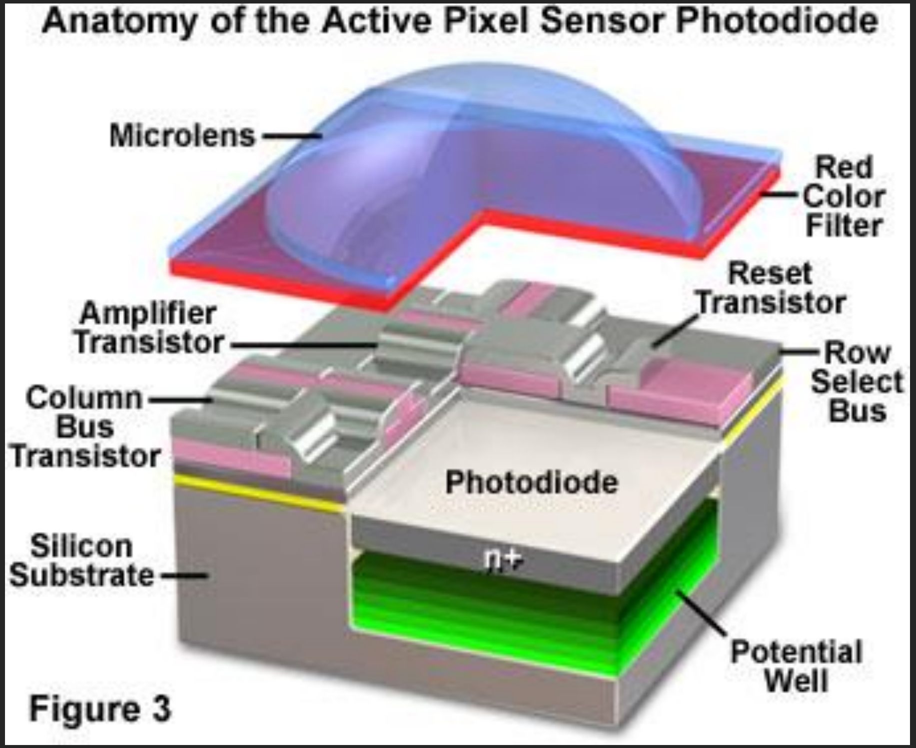
- Medical
  - Florescence Microscopy
  - X-ray & CT Scanners
- Industrial Control & Security
  - Defect detection
  - Low-light cameras
- Scientific Research
  - Astronomy & space exploration
  - Spectroscopy





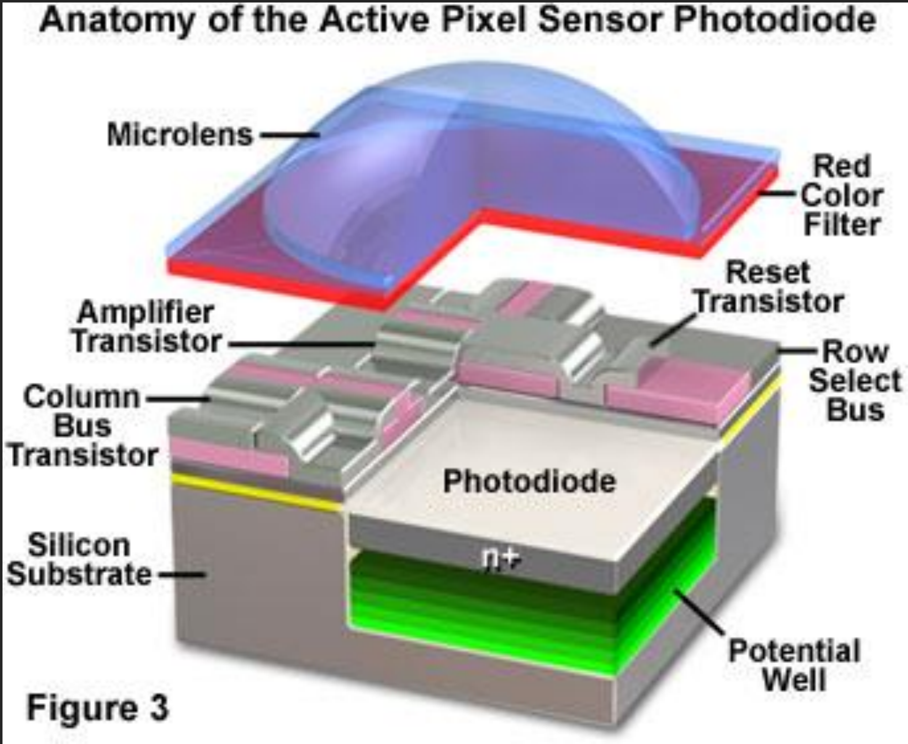
Complementary Metal-Oxide-Semiconductor

- Same as CCD, but each pixel has its own amplifier & readout circuit
  - Column-wide ADC (rolling shutter)
- Front-side illuminated
  - Older tech, lower efficiency
- Back-side illuminated
  - +80% efficiency
- Stacked
  - Separated photodiode



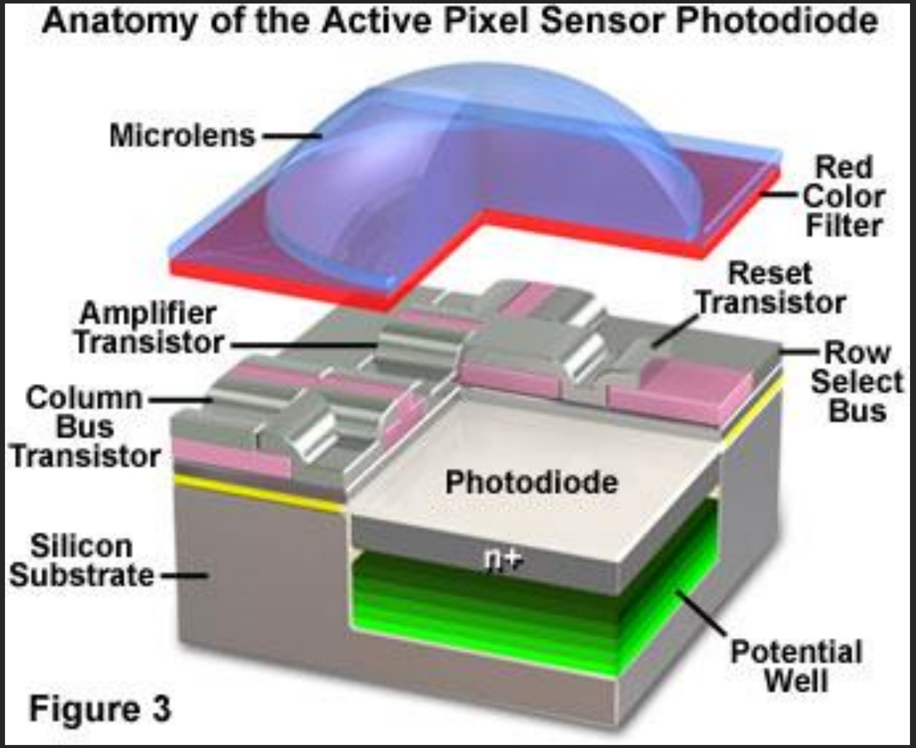
Complementary Metal-Oxide-Semiconductor

- Same as CCD, but each pixel has its own amplifier & readout circuit
  - Column-wide ADC (rolling shutter)
- Front-side illuminated
  - Low-cost sensors
- Back-side illuminated
  - Smartphones
- Stacked
  - Sony Alpha cameras, AI vision



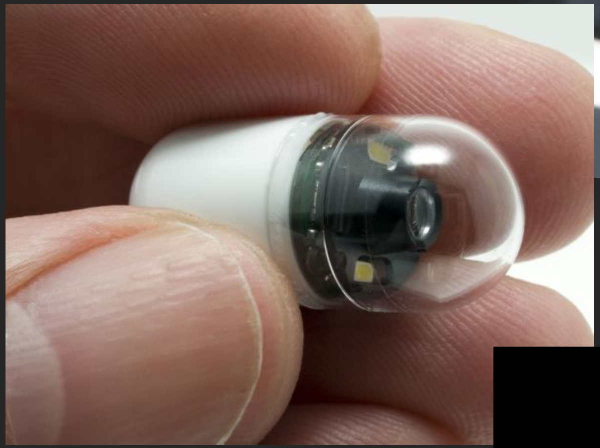
Complementary Metal-Oxide-Semiconductor

- Advantages
  - High speed readout
  - Low power consumption
  - Cost effective
  - Embedded processing capabilities
- Disadvantages
  - Higher noise
  - Lower dynamic range
  - Rolling shutter



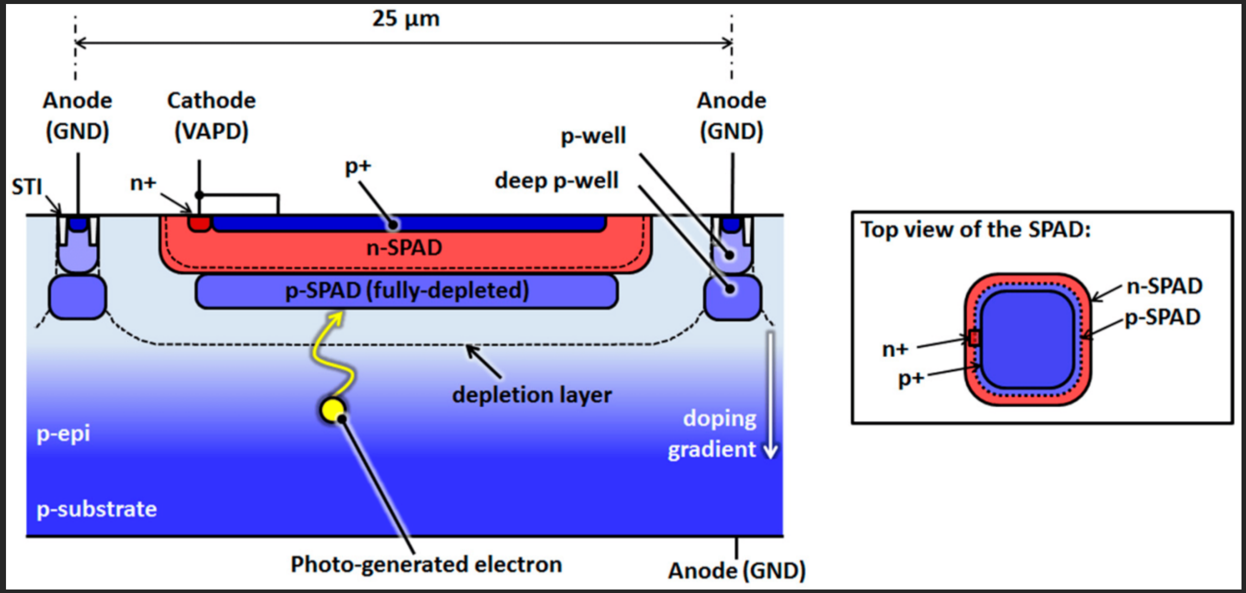
Complementary Metal-Oxide-Semiconductor

- Automotive
  - Advanced Driver Assist
  - LiDAR
- Healthcare
  - Endoscopy & Microscopy
  - Wearables
- Smartphones
  - Apple’s lidar sensor
  - Facial recognition



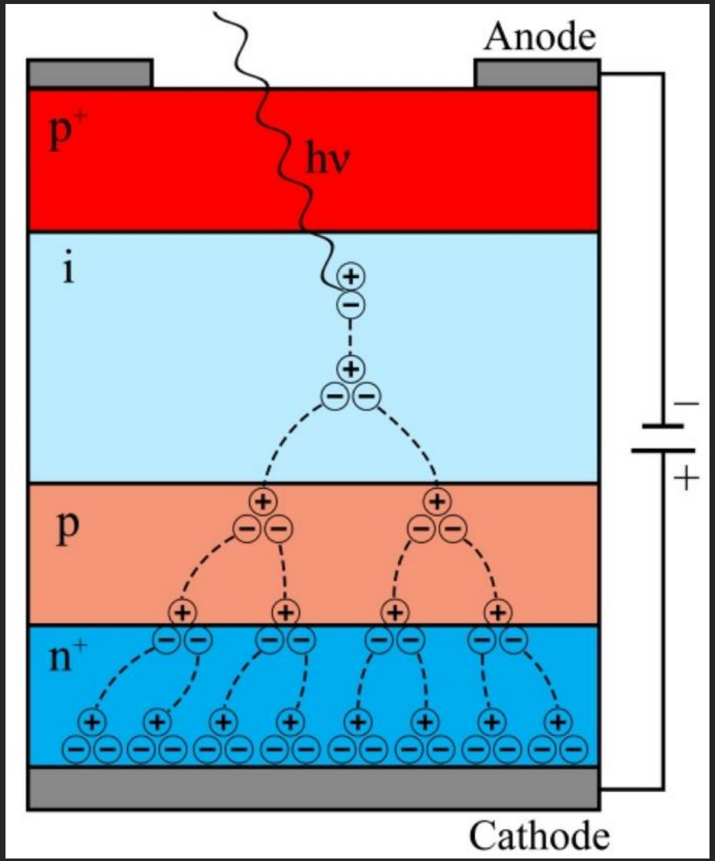
Single-Photon Avalanche Diode (SPAD)

- Measures single-photon events
- Uses avalanche multiplication (like a photo-multiplier tube)



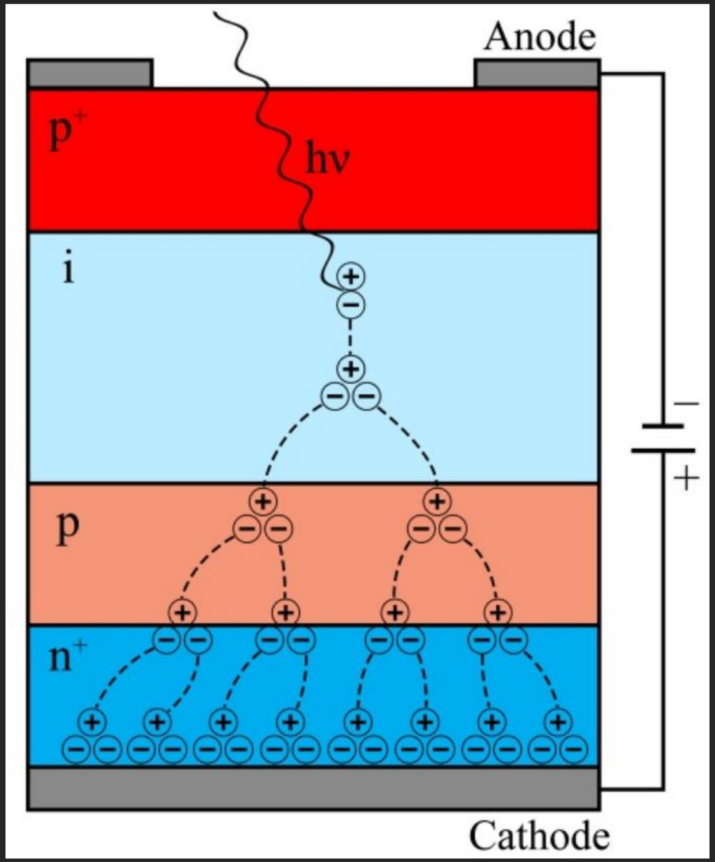
Single-Photon Avalanche Diode (SPAD)

- Advantages
  - Can detect a single photon
  - Picosecond timing precision
  - Integrated into CMOS
- Disadvantages
  - Sensitive to noise
  - Can require cooling
  - High power consumption



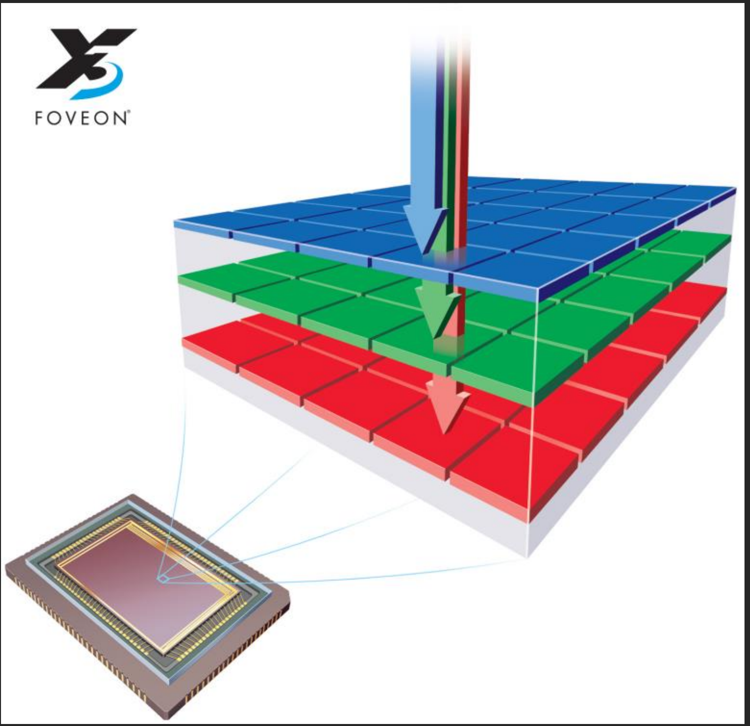
Single-Photon Avalanche Diode (SPAD)

- Depth Sensing
  - LiDAR
- Optical Communication
  - Deep space communication systems
- Medical & Scientific
  - Positron Emission Tomography (PET)
- Security
  - Object detection in darkness



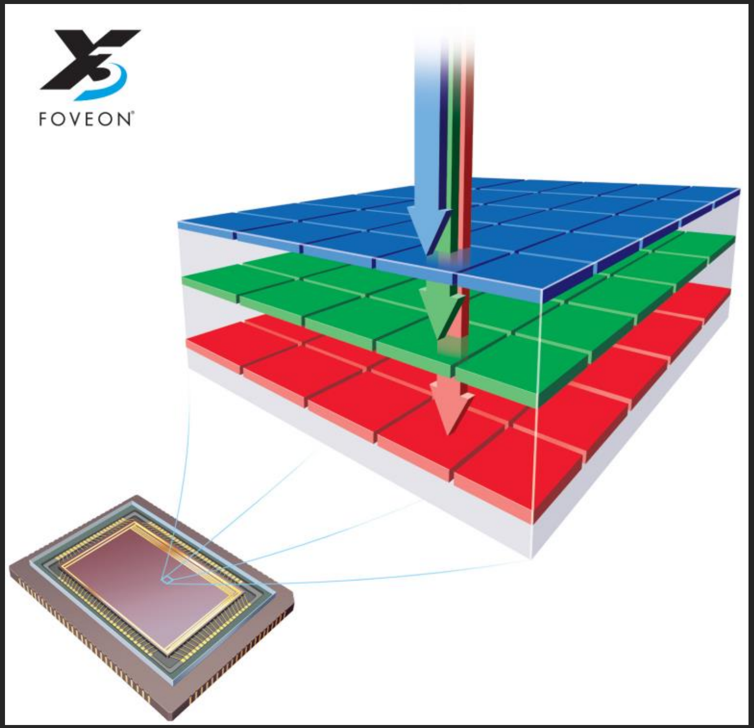
Foveon X3 Sensor (Stacked RGB)

- Silicon naturally absorbs wavelengths of light ad different depths
- Three vertically stacked photodiodes
- Advantages
  - Higher color fidelity and tonal depth
  - Higher resolution
- Disadvantages
  - Higher noise
  - Lower sensitivity
  - Expensive



Foveon X3 Sensor (Stacked RGB)

- Industrial and medical
  - Color variations in chemical analysis
  - Dermatology for high fidelity imaging
- Fine Art Reproduction and Money
  - True-to-life colors
  - Banknote & documentation verification



What are Cyber-Physical Systems?