Robot Sensing & Sensors

7/8/2025 Jing Jia

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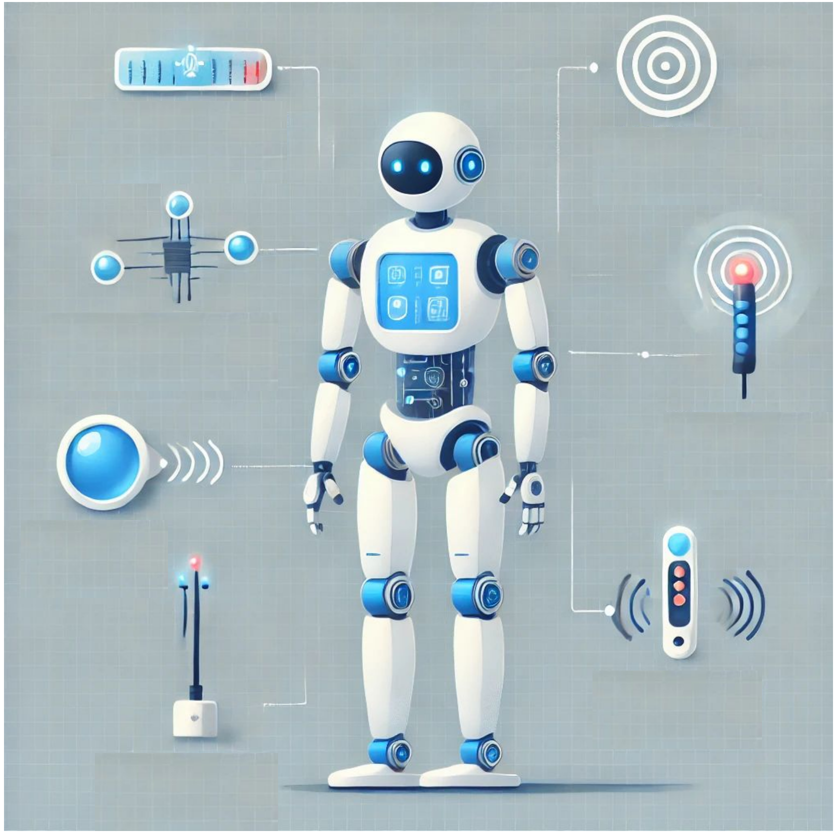


Meeting

Meeting ID: 934 7171 6808

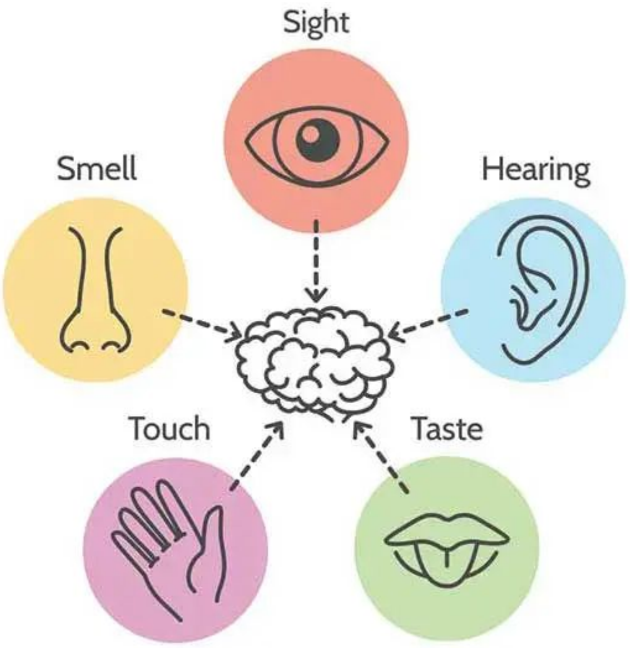
Passcode: 123456

What is Sensing ?

- Collect information about the world
- Sensor - an electrical/mechanical/chemical device that maps an environmental attribute to a quantitative measurement
- Each sensor is based on a transduction principle - conversion of energy from one form to another

Human sensing and organs

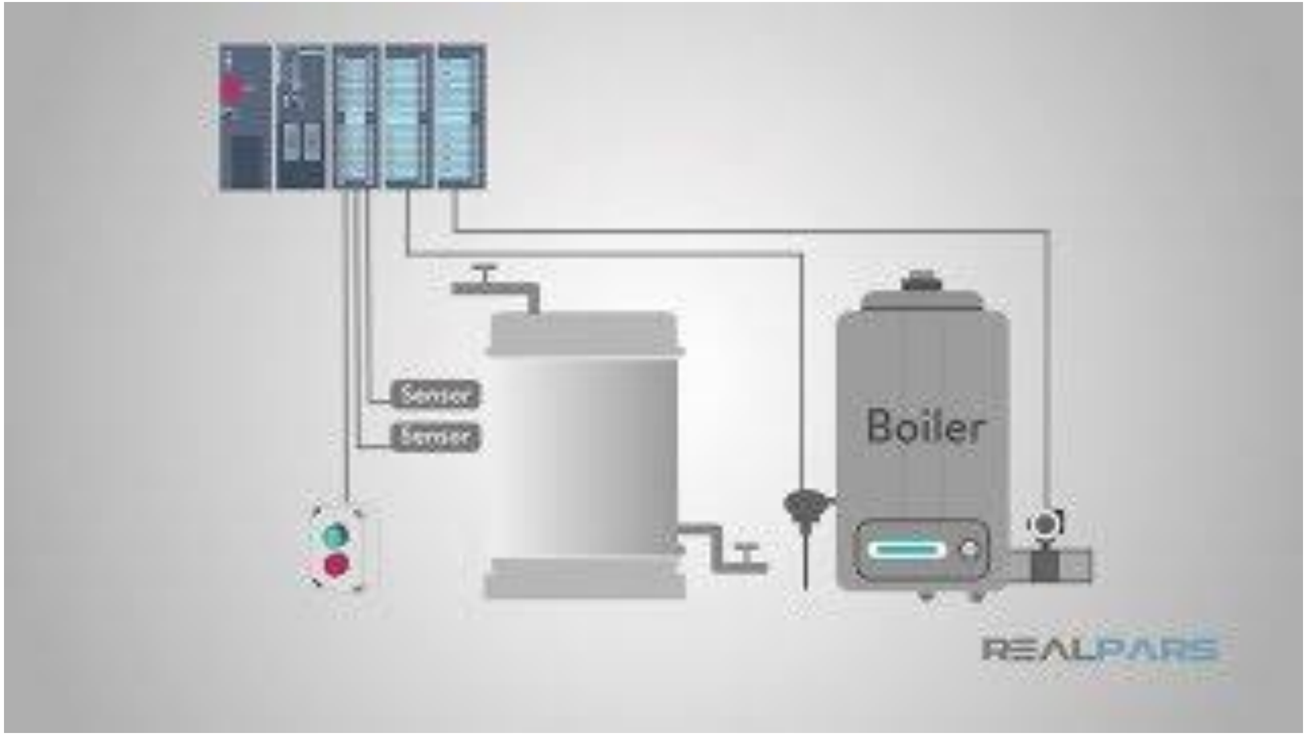
- Vision: eyes (optics, light)
- Hearing: ears (acoustics, sound)
- Touch: skin (mechanics, heat)
- Odor: nose (vapor-phase chemistry)
- Taste: tongue (liquid-phase chemistry)



https://marcus-jackson.com/2018/07/31/the-five-senses-and-the-first-day-of-school/

Types of Sensors in Control System

https://www.youtube.com/watch?v=J_KoRp8SnoE



Extended ranges and modalities

Vision Beyond RGB Spectrum

- Infrared Camera: Enables night vision by detecting infrared light.
- Active Vision: Uses radar and optical (laser) for precise range measurement.

Hearing Beyond 20 Hz – 20 kHz Range

- Ultrasonic Range Measurement: Utilizes high-frequency sound waves for distance measurement.

Chemical Analysis Beyond Taste and Smell

- Radiation Detection: Identifies α, β, γ-rays, neutrons, and other radiation type

Transduction to electronics

- **Thermistor**: temperature → resistance
- **Electrochemical**: chemistry → voltage
- **Photocurrent**: light intensity → current
- **Pyroelectric**: thermal radiation → voltage
- **Humidity**: humidity → capacitance
- **Microphone**: sound pressure → <anything>
- **Length** : position → inductance

(LVDT: Linear variable differential transformers)

Sensor Fusion and Integration

Human Sensory Integration

One Organ ⇎ One Sense?

Not Necessarily

- Balance: Ears
- Touch: Tongue
- Temperature: Skin

Robot Sensor Fusion

Combining readings from multiple sensors into a unified data structure.

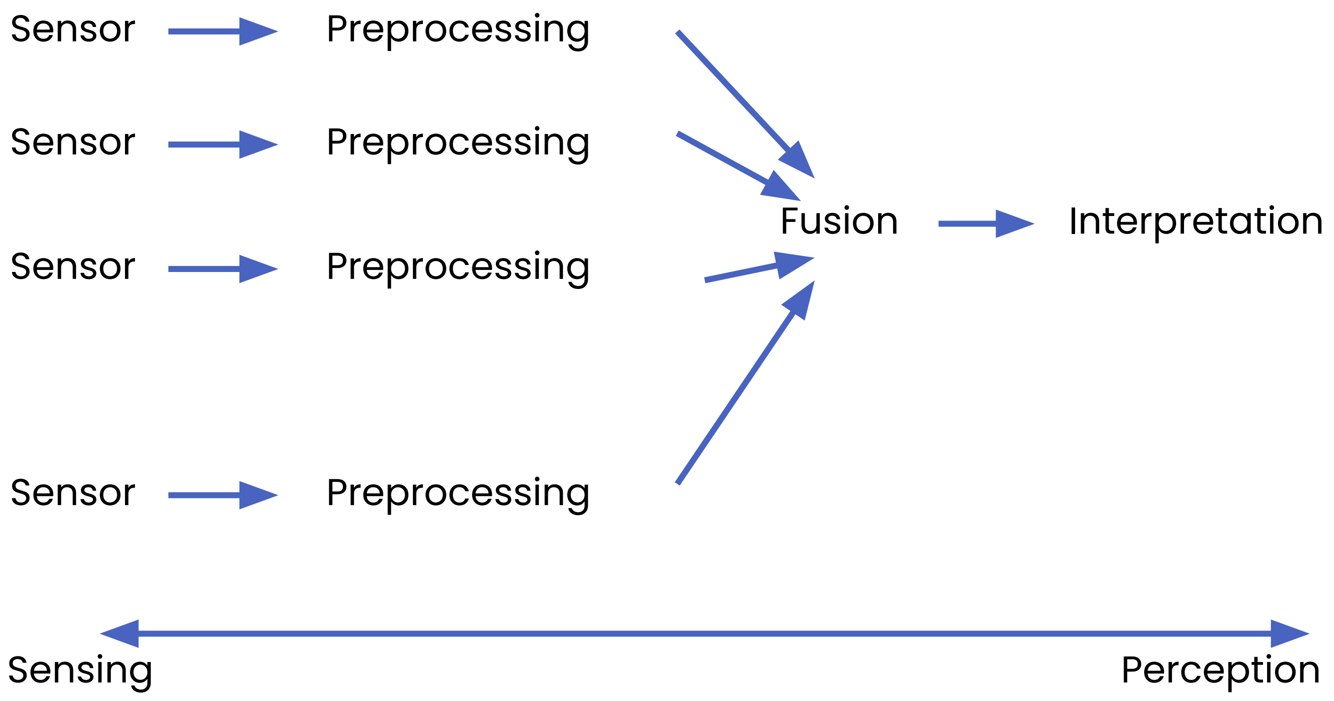
- Enhances the quality and reliability of information.
- Results in better overall data than using individual sensor sources.

Sensor Fusion

One sensor is (usually) not enough

- **Noise**: Real sensors often produce noisy data.
- **Accuracy**: Single sensors have limited accuracy.
- **Reliability**: Sensors can fail; redundancy is necessary.
- **Perspective**: Single sensors provide a limited view of the environment.
- **Completeness**: One sensor may not capture the full picture.
- **Cost**: Combining inexpensive sensors can be more cost-effective than using a single expensive sensors

General Processing



Preprocessing

Colloquially: ‘Cleanup’ the sensor readings before using them.

Techniques:

- Noise Reduction: Filtering out unwanted noise.
- Re-calibration: Adjusting sensors for accurate readings.
- Basic Processing: Tasks like edge detection in vision sensors.

Typically unique to each sensor type.

Involves changing or transforming data representation.

Sensor/Data Fusion

Combining Data from Different Sources, Types of Measurements:

- From different sensors
- From different positions
- From different times

Techniques for Data Fusion: Mathematical Methods

- Discrete Bayesian methods
- Neural networks
- Kalman filtering

Produces a merged data set (as though there was one ‘virtual sensor’)

Interpretation

Task Specific

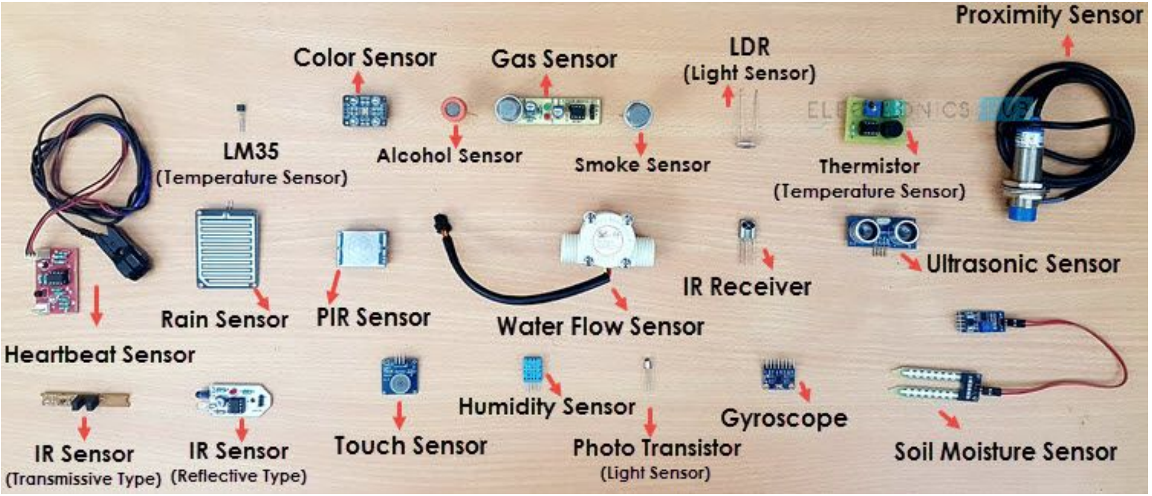
- Interpretation methods are tailored to specific tasks.
- Often modeled as a best fit problem given some a priori knowledge about the environment.
    - Uses existing knowledge to improve the accuracy of interpretations.
    - Involves fitting data to models to extract meaningful information.

Challenges

- Complexity of environments
- Variability in sensor data
- Inherent uncertainty

Classification of Sensors

- Proprioception (Internal state) v.s. Exteroceptive (external state)
- Active v.s. Passive
- Contact v.s. non-contact
- Visual v.s. non-visual



https://www.electronicshub.org/different-types-sensors/

Proprioception vs. Exteroception

Proprioception (Internal State):

- Measures internal values within the system (robot).
- Examples: battery level, wheel position, joint angle.

Exteroception (External State):

- Observes the environment and external objects.
- Examples: temperature sensors, proximity sensors.

Active vs. Passive

Active Sensors:

- Emit energy into the environment.
- Examples: radar, sonar.

Passive Sensors:

- Passively receive energy to make observations.
- Examples: cameras, thermometers.

Contact vs. Non-Contact

Contact Sensors:

- Require physical contact with the object being measured.
- Examples: touch sensors, pressure sensors.

Non-Contact Sensors:

- Do not require physical contact with the object.
- Examples: infrared sensors, ultrasonic sensors.

Visual vs. Non-Visual

Visual Sensors:

- Vision-based sensing, including image processing.
- Examples: video cameras, LIDAR.

Non-Visual Sensors:

- Sensing that does not rely on visual information.
- Examples: microphones, chemical sensors.

Proprioceptive Sensors

Encoders, Potentiometers

- measure angle of turn via change in resistance or by counting optical pulses

Gyroscopes

- measure rate of change of angles
- fiber-optic (newer, better), magnetic (older)

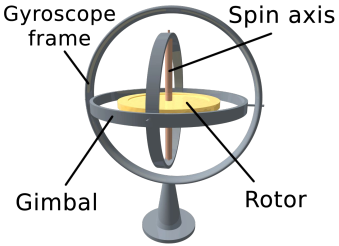
Compass

- measure which way is north

GPS

- measure location relative to globe

https://en.wikipedia.org/wiki/Potentiometer



https://en.wikipedia.org/wiki/Gyroscope

Touch Sensors

Whiskers, bumpers etc.

Mechanical Contact Leads To:

- **Closing/Opening of a Switch:** Detects physical contact by completing or breaking a circuit.
- **Change in Resistance:** Variation in resistance when contact is made.
- **Change in Capacitance:** Detects proximity or touch by measuring changes in capacitance.
- **Change in Spring Tension:** Measures the force or pressure applied through spring deformation.

https://en.wikipedia.org/wiki/Whiskers

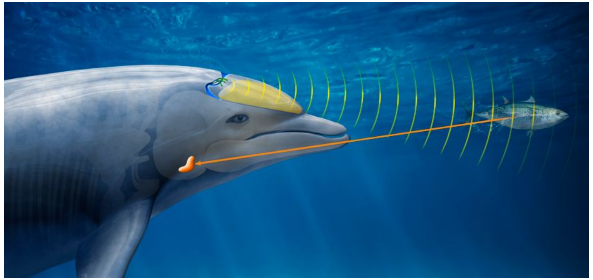
Sensors Based on Sound

SONAR: Sound Navigation and Ranging

- Uses sound waves to detect objects and measure distances.
- bounce sound off of objects
- measure time for reflection to be heard - gives a range measurement
- measure change in frequency - gives the relative speed of the object (Doppler effect)

Natural Examples: Bats and dolphins use sonar with amazing precision.

https://www.youtube.com/watch?v=Ur3F-JLdq_Q



https://creation.com/dolphin-double-sonar

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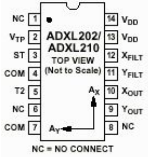
Sensors Used in Robot

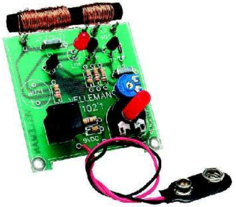


Accelero meter

Gyro

Pendulum Resistive Tilt Sensors

Piezo Bend Sensor

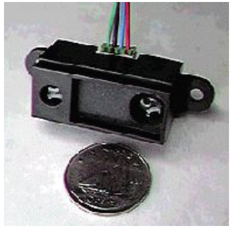


Metal Detector

Gas Sensor

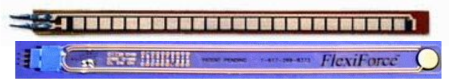
Gieger-Muller Radiation Sensor

Pyroelectric Detector



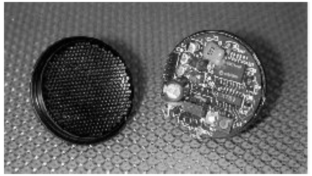
Digital Infrared Ranging

CDS Cell Resistive Light Sensor



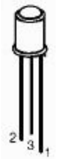
Resistive Bend Sensors

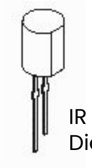
UV Detector



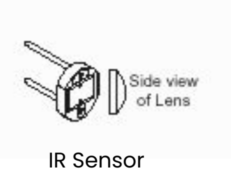
Miniature Polaroid Sensor

Pressure Switch





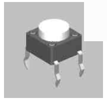
IR Pin Diode



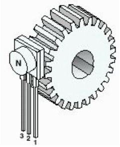
IR Sensor w/lens

Limit Switch

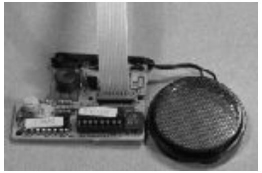
Mechanical Tilt Sensors



Touch Switch



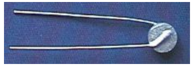
Hall Effect Magnetic Field Sensors



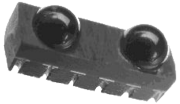
Polaroid Sensor Board

IR Reflection Sensor

IR Amplifier Sensor



Thyristor

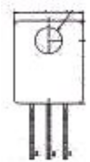


IRDA Transceiver

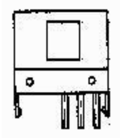
Magnetic Sensor

Magnetic Reed Switch

IR Modulator Receiver

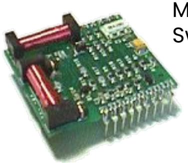


Lite-On IR Remote Receiver

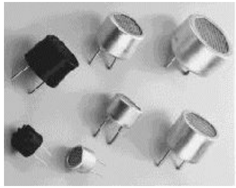


Radio Shack Remote Receiver

Solar Cell



Compass



Piezo Ultrasonic Transducers

Sensors Used in Robot

Resistive Sensors

- Bend sensors, potentiometers, resistive photocells.
- Measure changes in resistance due to various stimuli.

Tactile Sensors

- Contact switches, bumpers.
- Detect physical contact and touch.

Infrared Sensors

- Reflective sensors, proximity sensors, distance sensors.
- Use infrared light to detect objects and measure distances.

Ultrasonic Distance Sensor

- Use sound waves to measure distances by timing the echoes.

Sensors Used in Robot

Inertial Sensors

- Measure the second derivatives of position (acceleration and angular rate).
- Accelerometers, gyroscopes.

Orientation Sensors

- Compass, inclinometer.
- Measure direction and tilt.

Laser Range Sensors

- Use laser light to measure distances with high precision.

Vision and GPS

- Cameras, GPS receivers.
- Provide visual information and global positioning data.

Resistive Sensors

Bend Sensors

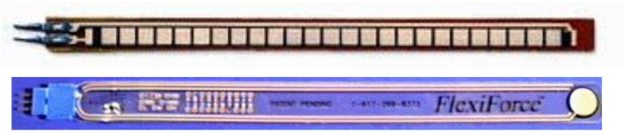
- Resistance: 10k to 35k
- Function: Resistance increases as the strip is bent.

Potentiometers

- Used as position sensors for sliding mechanisms or rotating shafts.
- Easy to find and mount.

Light Sensor (Photocell)

- Good for detecting direction/presence of light.
- Non-linear resistance.
- Slow response to light changes.



Resistive Bend Sensor

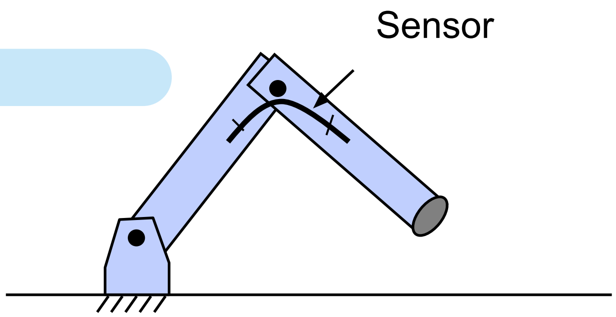
Potentiometer

Photocell

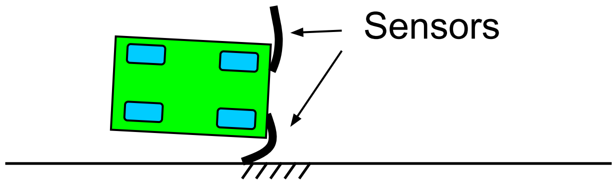
R is small when brightly illuminated

Applications

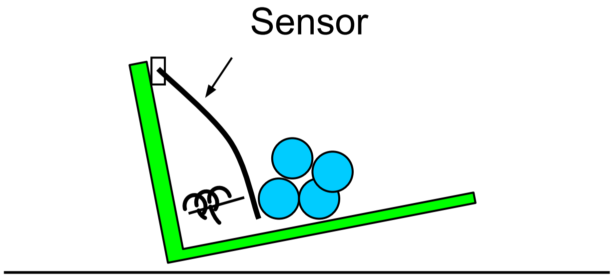
Measure bend of a joint



Wall Following/Collision Detection



Weight Sensor



Infrared Sensors

Intensity Based Infrared, Reflective Sensors:

- Easy to implement.
- Susceptible to ambient light.

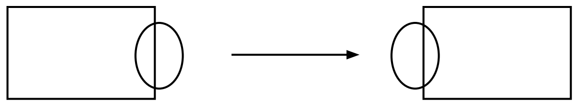
Modulated Infrared, Proximity Sensors:

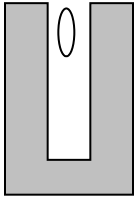
- Requires modulated IR signal.
- Insensitive to ambient light.

Infrared Ranging, Distance Sensors:

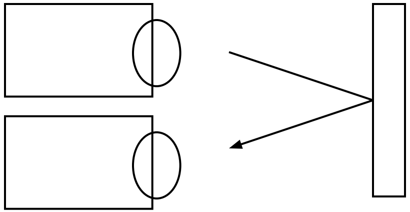
- Short range distance measurement.
- Impervious to ambient light, color, and reflectivity of objects

Intensity Based Infrared





Break-Beam sensor



Reflective Sensor

- Easy to implement (few components)
- Works very well in controlled environments
- Sensitive to ambient light

IR Reflective Sensors

Reflective Sensor:

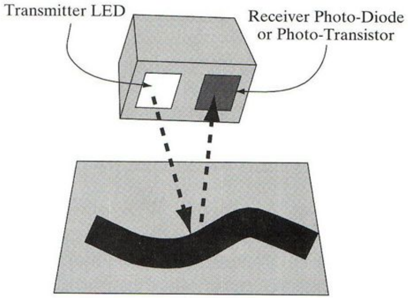
- Emitter IR LED + detector photodiode/phototransistor
- Phototransistor: the more light reaching the phototransistor, the more current passes through it
- A beam of light is reflected off a surface and into a detector
- Light usually in infrared spectrum, IR light is invisible

Applications:

- Object detection,
- Line following, Wall tracking
- Optical encoder (Break-Beam sensor)

Drawbacks:

- Susceptible to ambient lighting
  - Provide sheath to insulate the device from outside lighting
- Susceptible to reflectivity of objects
- Susceptible to the distance between sensor and the objet



Modulated Infrared

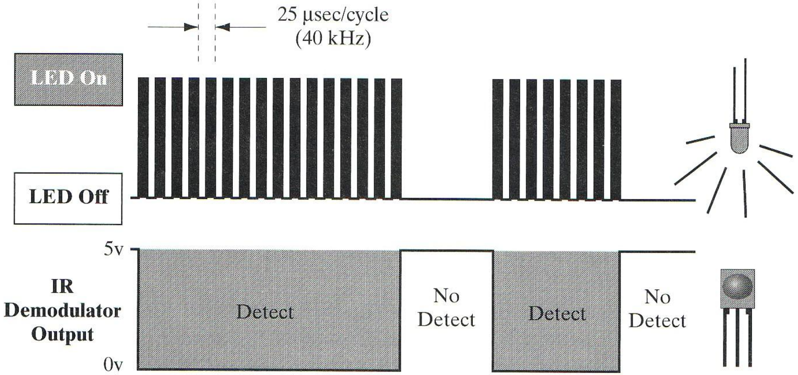
Modulation and Demodulation

- Flashing a light source at a particular frequency
- Demodulator is tuned to the specific frequency of light flashes. (32kHz~45kHz)

Flashes of light can be detected even if they are very weak

Less susceptible to ambient lighting and reflectivity of objects

Used in most IR remote control units, proximity sensors



Negative true logic:

Detect = 0v

No detect = 5v

3

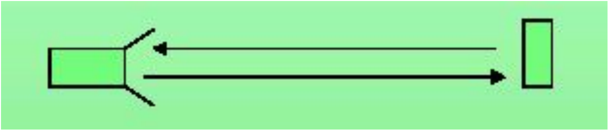
Range FInder

Time of Flight

The measured pulses typically come from ultrasonic, RF and optical energy sources.

$$D = v \times t$$

D = round-trip distance



v = speed of wave propagation

t = elapsed time

Sound = 0.3 meters/msec

RF/light = 0.3 meters / ns (Very difficult to measure short distances 1-100 meters)

Ultrasonic Sensors

Basic principle of operation:

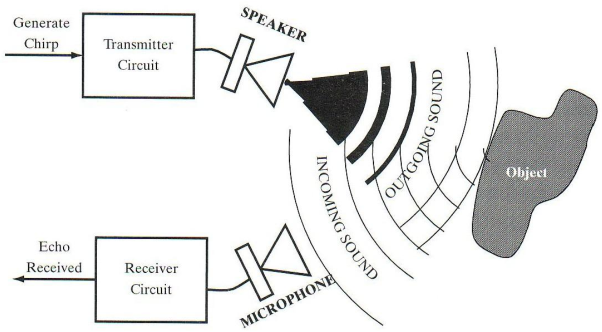
- Emit a quick burst of ultrasound (around 50kHz, above human hearing range of 20Hz to 20kHz).
- Measure the elapsed time until the receiver indicates that an echo is detected.
- Determine how far away the nearest object is from the sensor

$$D = v \times t$$

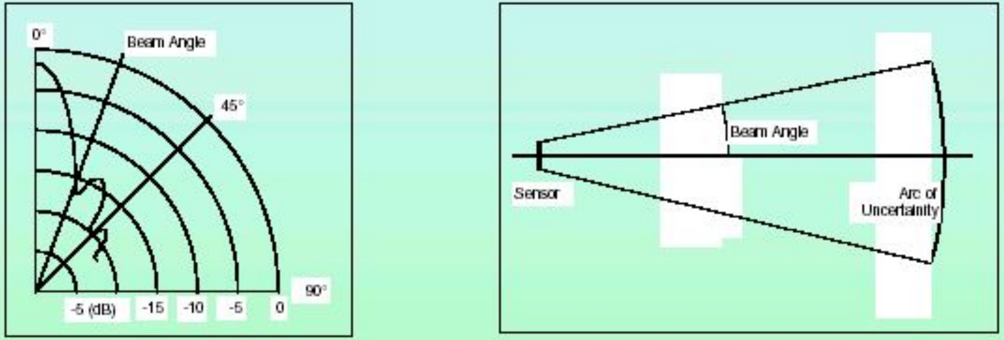
D = round-trip distance

v = speed of propagation (340 m/s)

t = elapsed time



Ultrasonic Sensors



Sensor Specification

Sensor Model, angle = 15 degrees

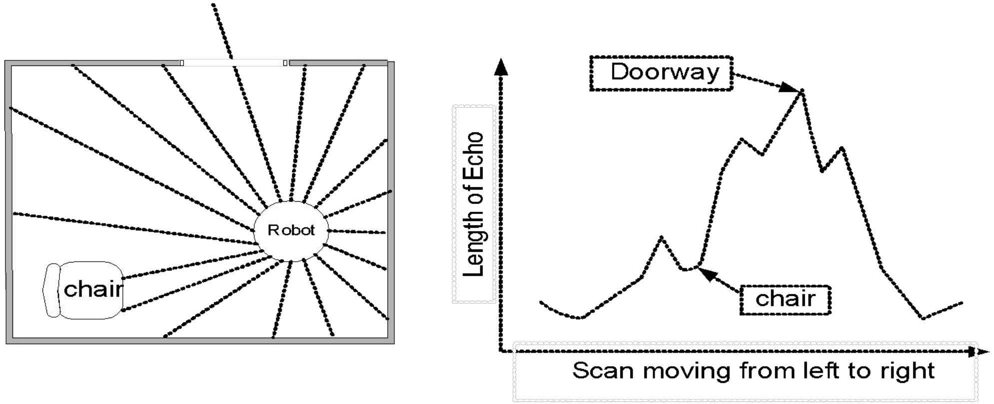
- Ranging is accurate but bearing has a 30 degree uncertainty. The object can be located anywhere in the arc.
- Typical ranges are of the order of several centimeters to 30 meters.
- Another problem is the propagation time. The ultrasonic signal will take 200 msec to travel 60 meters. (30 meters roundtrip @ 340 m/s)

Ultrasonic Sensor Applications

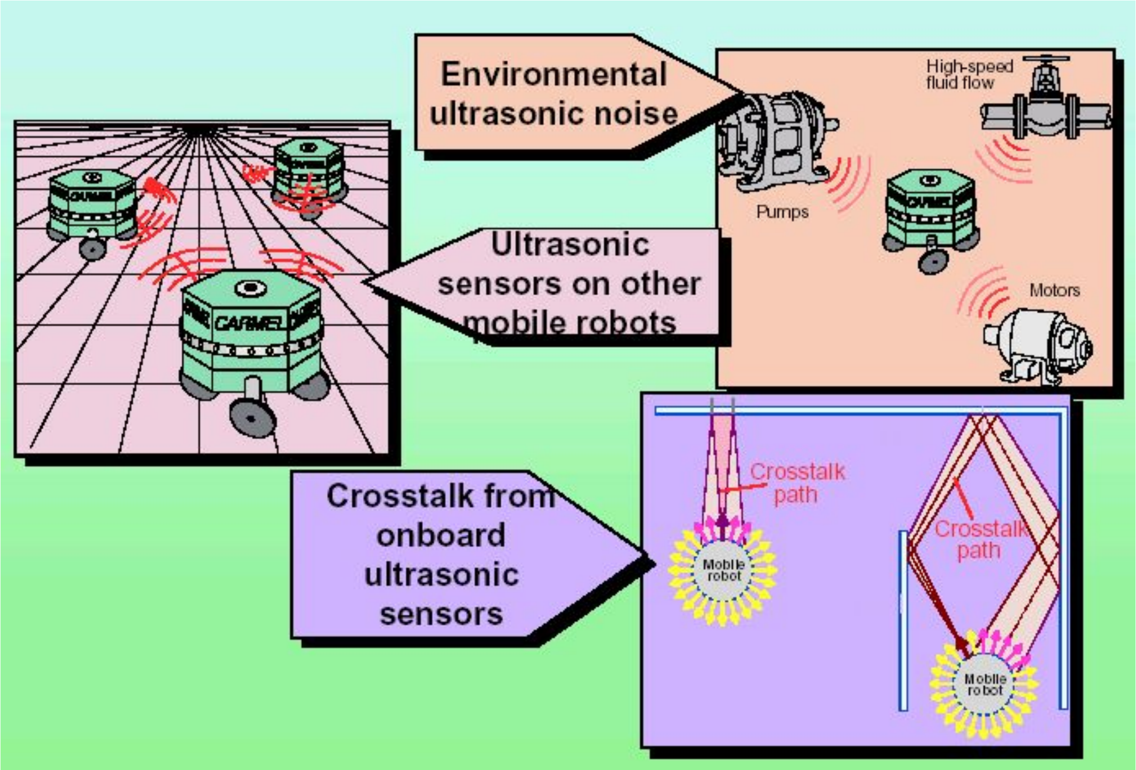
Distance Measurement: Accurately measure distances to nearby objects.

Mapping: Rotating proximity scans to map the proximity of objects surrounding the robot.

Scanning Angle: Scanning at an angle of 15° apart can achieve the best results.

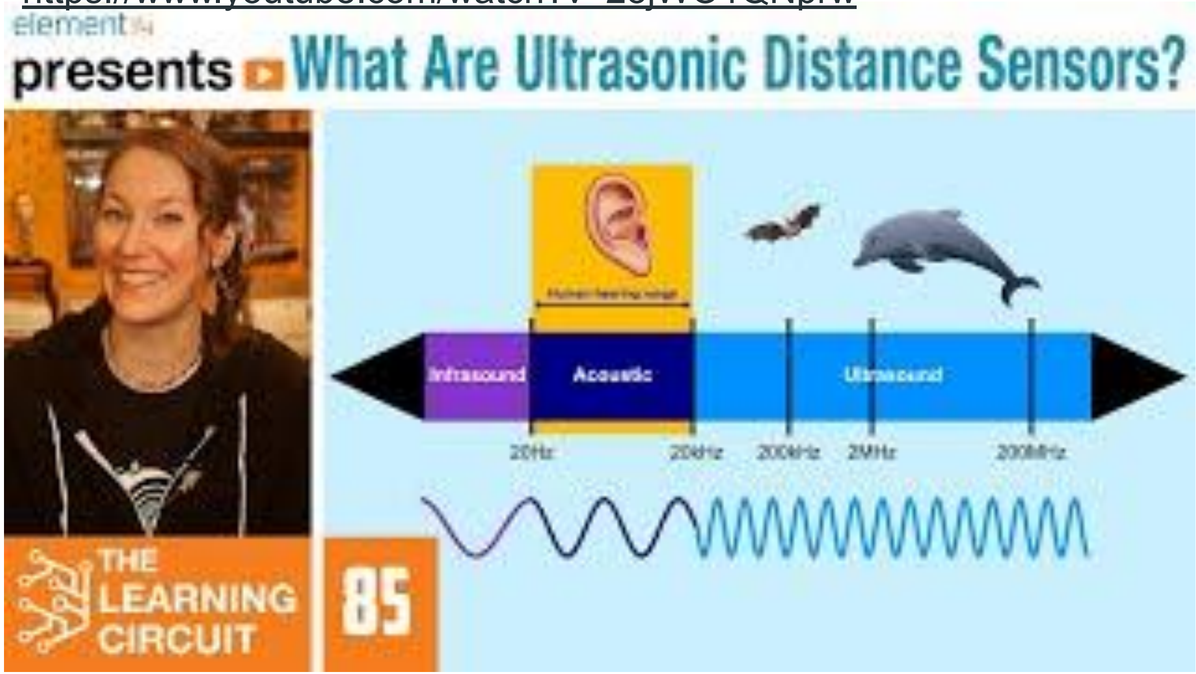


Noise Issues



Ultrasonic Sensors

https://www.youtube.com/watch?v=2ojWO1QNprw



Laser Range Finder

Specifications

- Range: 2-500 meters
- Resolution: 10 mm
- Field of View: 100 - 180 degrees
- Angular Resolution: 0.25 degrees
- Scan Time: 13 - 40 msec

Advantages

- More immune to dust and fog compared to other sensing technologies.

Inertial Sensors

Gyroscopes

- Measure the rate of rotation independent of the coordinate frame.
- Heading sensors
- Full Inertial Navigation Systems (INS)

Accelerometers

- Measure accelerations with respect to an inertial frame.
- Tilt sensor in static applications
- Vibration analysis
- Full Inertial Navigation Systems (INS)

Accelerometers

Measure the inertial force generated when a mass is affected by a change in velocity.

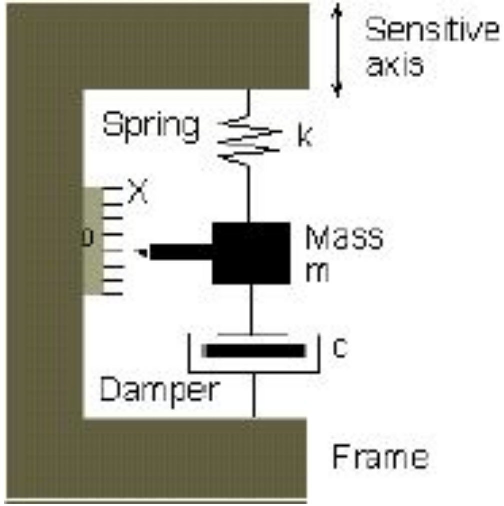
This force may change

- The tension of a string
- The deflection of a beam
- The vibrating frequency of a mass

https://www.youtube.com/watch?v=To7JagpPDwY

Main elements of an accelerometer

- **Mass:** The part of the accelerometer that responds to acceleration forces.
- **Suspension Mechanism**: Supports the mass and allows it to move in response to acceleration.
- **Sensing Element:** Detects the movement of the mass and converts it into an electrical signal.



$$F = m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx$$

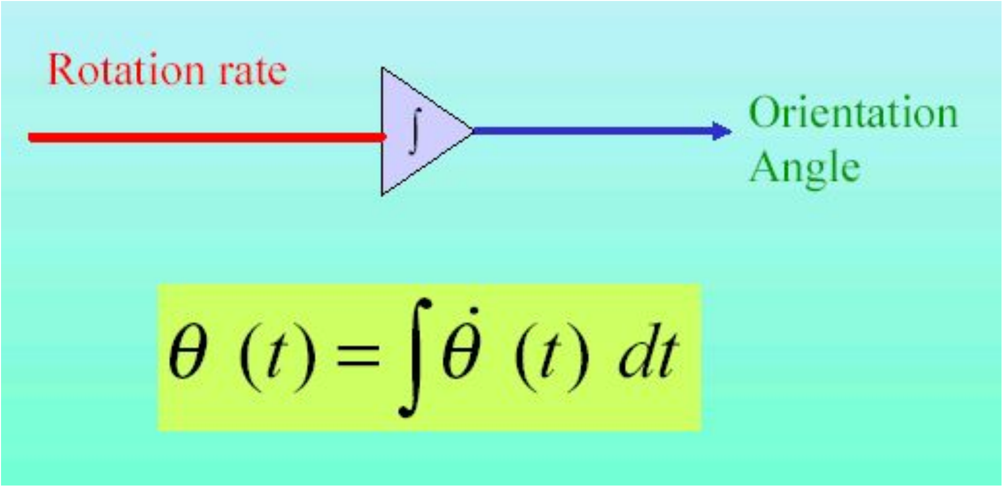
High quality accelerometers include a servo loop to improve the linearity of the sensor.

Gyroscopes

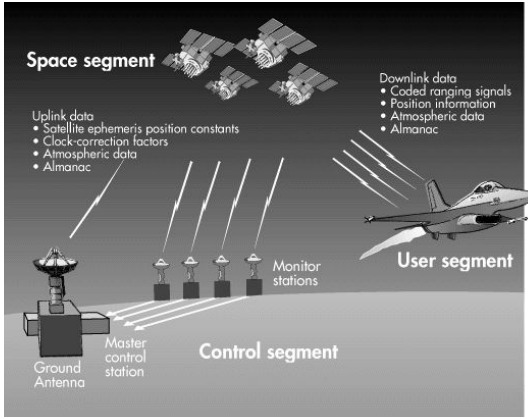
These devices return a signal proportional to the rotational velocity.

There is a large variety of gyroscopes that are based on different principles

https://learn.sparkfun.com/tutorials/gyroscope/all



Global Positioning System (GPS)

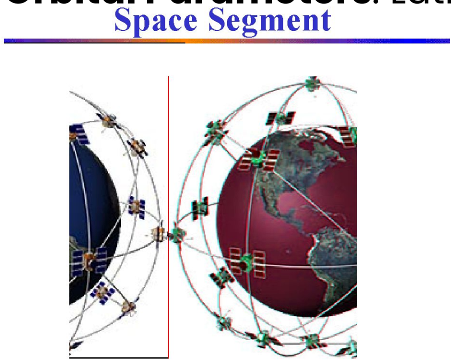


Satellite Network

- 24 satellites (+ several spares)

Broadcast Information

- **Time**: Precise timing signals.
- **Identity**: Unique identifiers for each satellite.
- **Orbital Parameters**: Latitude, longitude, altitude.



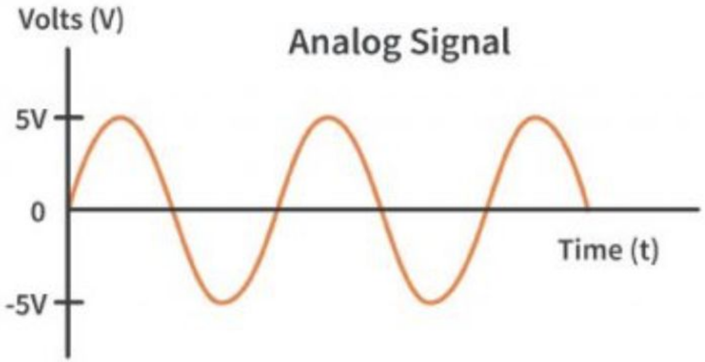
https://www.youtube.com/watch?v=wCcARVbL_Dk

IMU (Inertial Measurement Unit)

https://www.youtube.com/watch?v=fG-JQlzQxWQ

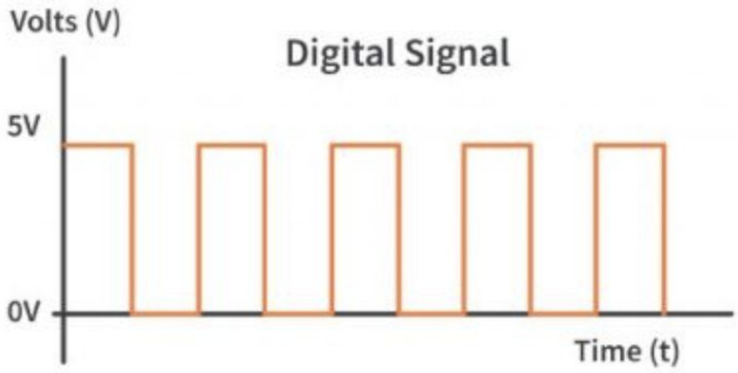
What is Analog Signal?

- A continuous signal in which one time-varying quantity (such as voltage, pressure, etc.) represents another time-based variable
- For example, a dimmer switch tied to a light bulb: the dimmer will have an infinite number of positions between “off” and “full” – and a correspondingly infinite number of levels of output by the light bulb.



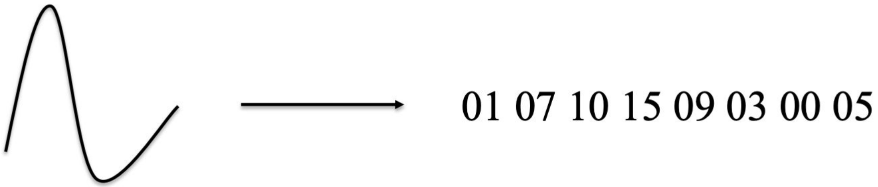
What is Digital Signal?

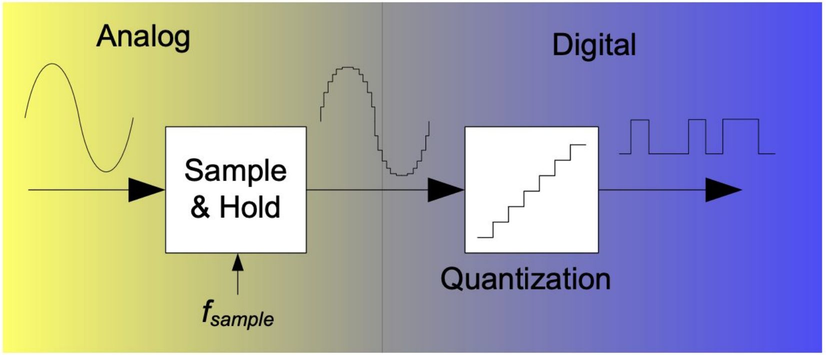
- A type of signal that represents data as a sequence of discrete values. Unlike an analog signal, which is continuous and can take any value in a range, a digital signal is binary, meaning it can only take on specific values, typically two: 0 and 1.
- For example, a simple on-off light switch tied to a light bulb which has only two positions: “off” and “on”. There are no intermediate positions.



Analog to Digital Converter

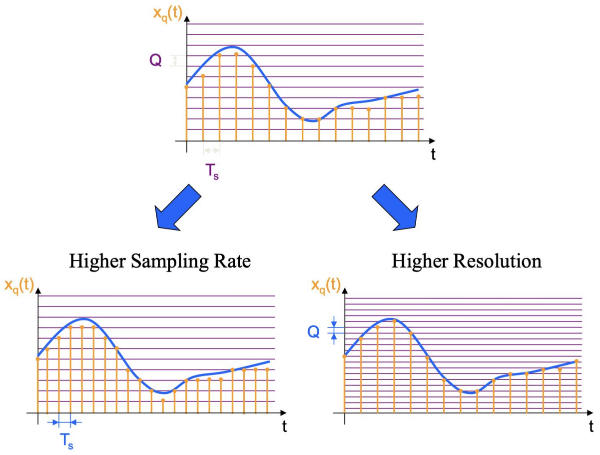
Objective: Representing an analog varying physical quantity by a sequence of discrete numerical values.

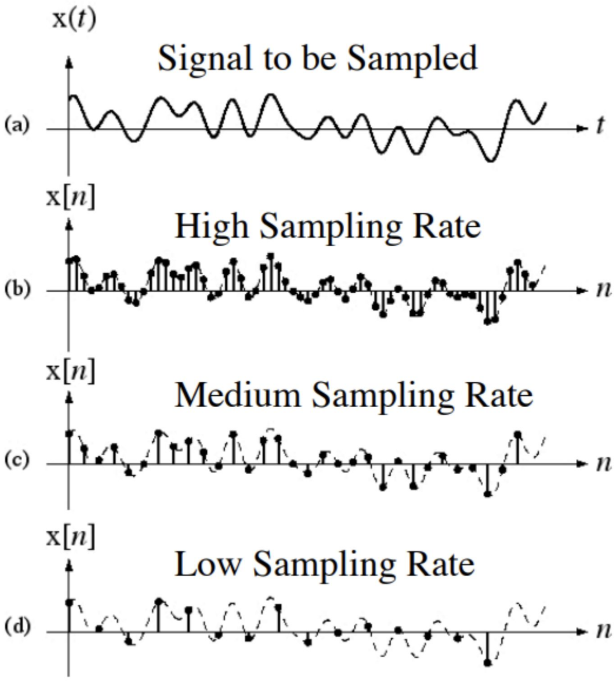




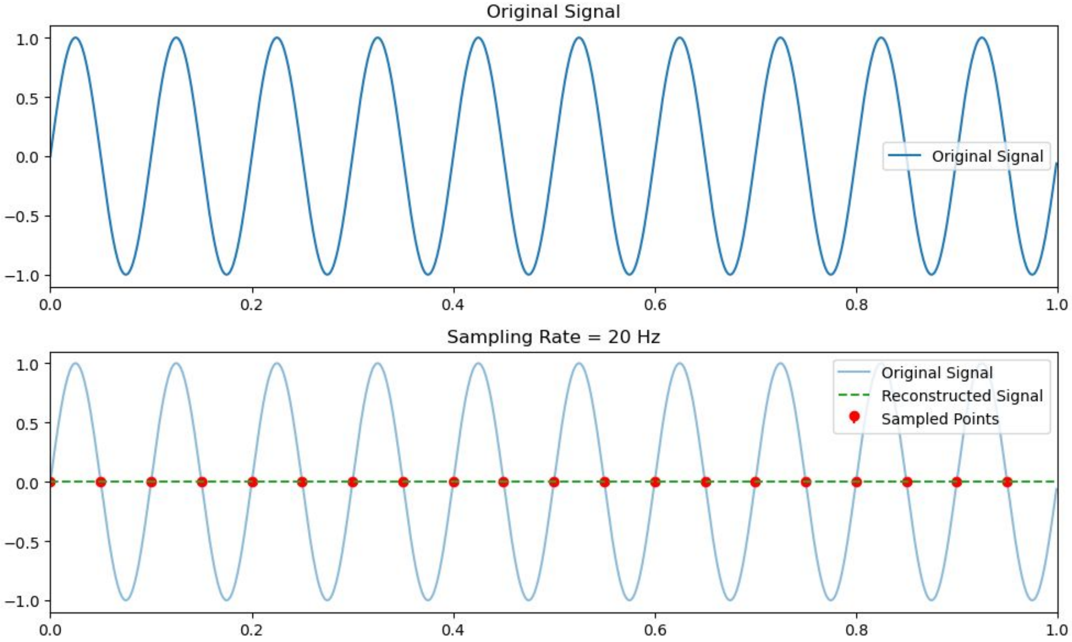
Accuracy

If you can exactly reconstruct the signal from the samples, then you have done a proper sampling and captured the key signal information

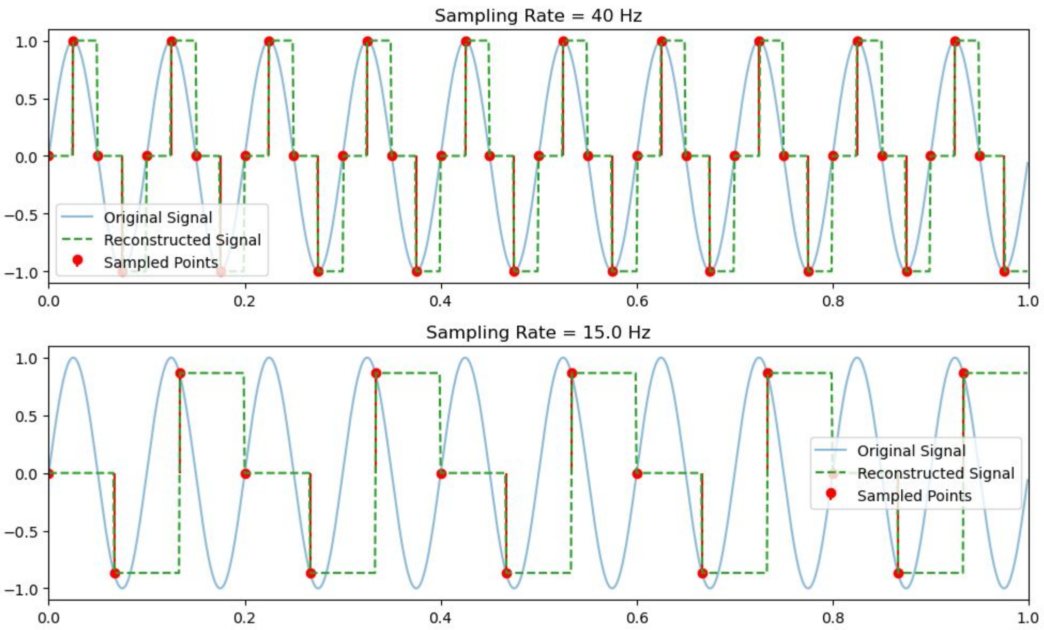




Example of Different Sample Rate



Example of Different Sample Rate



Resolution

To accurately represent an analog value using a binary number with N bits, the resolution and the number of possible values need to be considered. The resolution defines the smallest change that can be distinguished by the binary representation.

Binary Representation: With N bits, there are 2^N possible values.

Resolution: Resolution = $A/2^N$

where A is the range of the analog value.

Selection of ADC

Error/Accuracy:

Quantizing error represents the difference between an actual analog value and its digital representation.

Ideally, the quantizing error should not be greater than ± ½ LSB (Least Significant Bit).

Resolution:

The change in input voltage (ΔV) required to cause a 1-bit change in output.

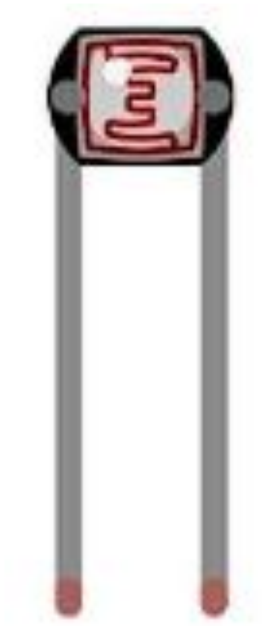
The Nyquist Rate:

A signal must be sampled at a rate at least twice that of the highest frequency component that must be reproduced.

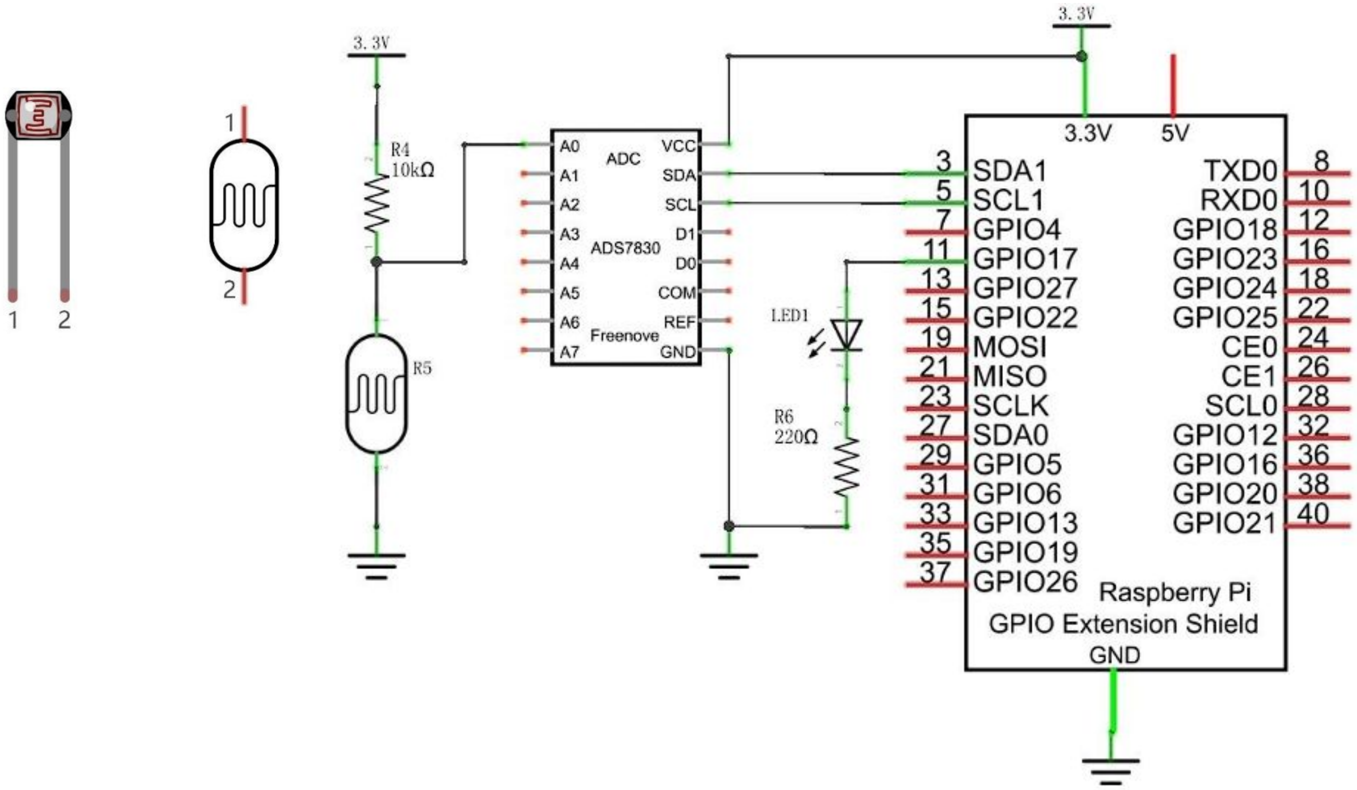
Lab

Photoresistor – Components

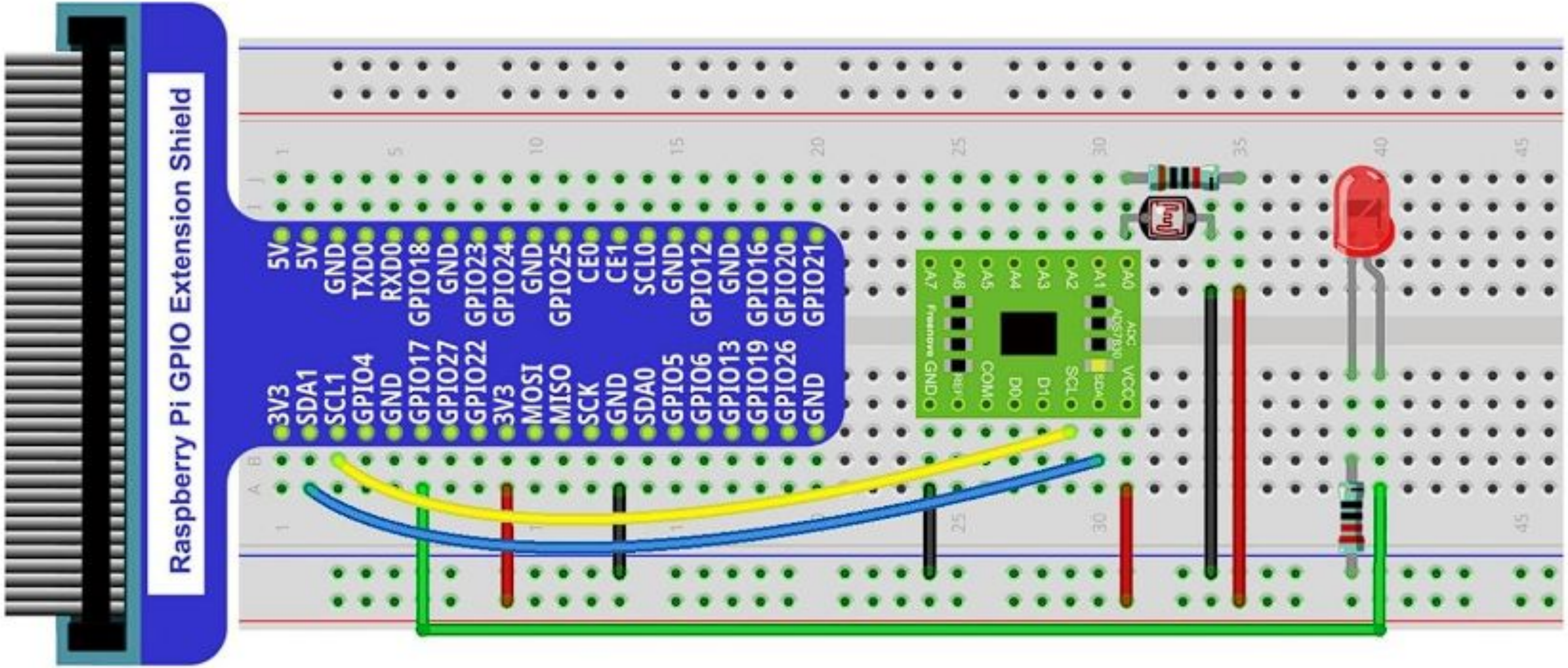
- Photoresistor * 1
- ADC Module * 1
- Resistor 10kΩ * 1
- LED * 1
- Resistor 220Ω * 1
- Jumper Wires



Photoresistor – Schematic diagram



Photoresistor- Circuit



Thermometer

- Thermistor * 1
- ADC Module * 1
- Resistor 10kΩ * 1
- Jumper Wires

Thermometer – Schematic diagram

Rt=R*EXP [B*(1/T2-1/T1)]

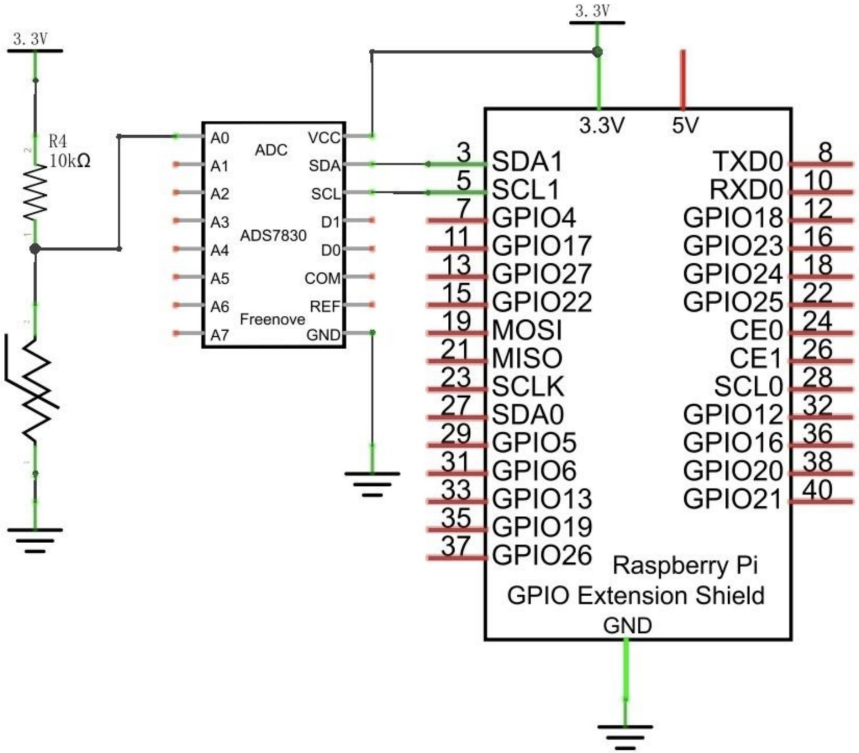
B=3950

R=10k

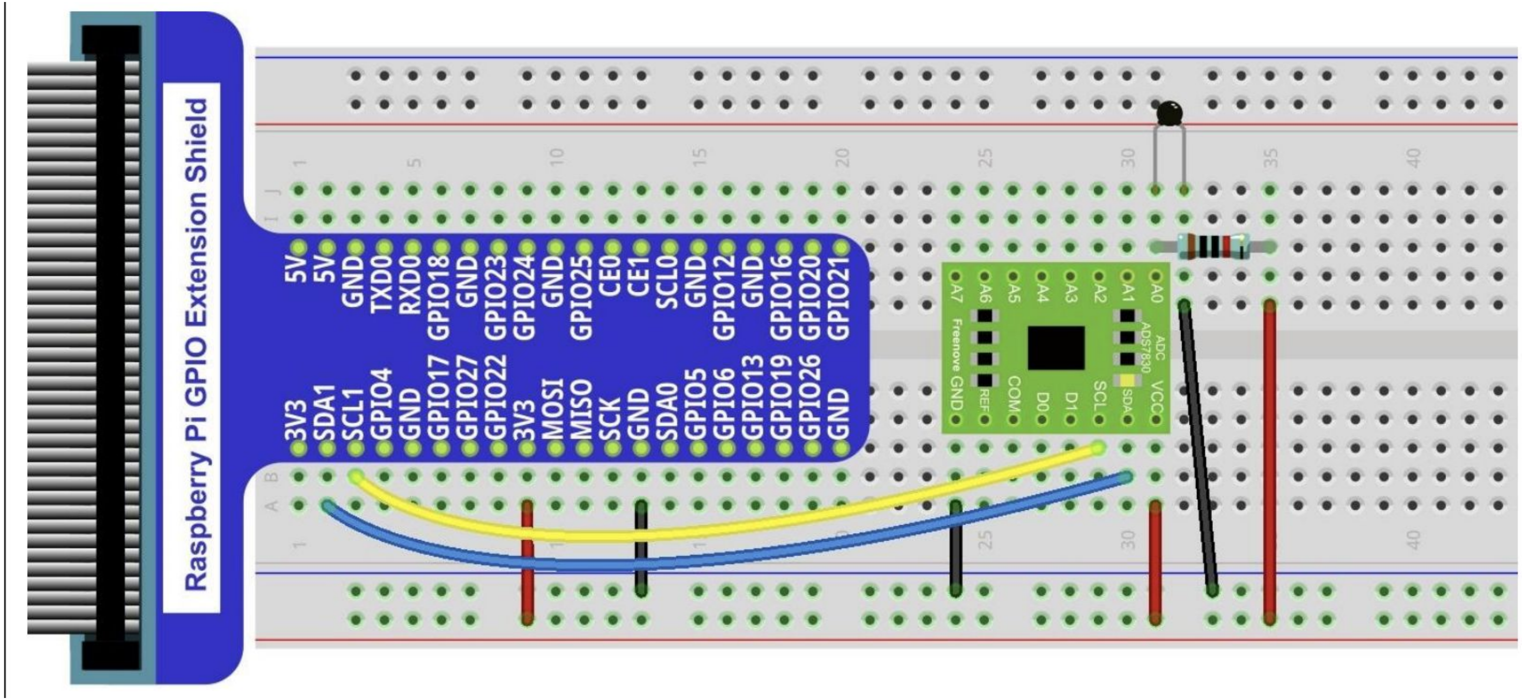
T1=25

reading from A0 -> voltage

T2 = 1/(1/T1 + ln(Rt/R)/B)

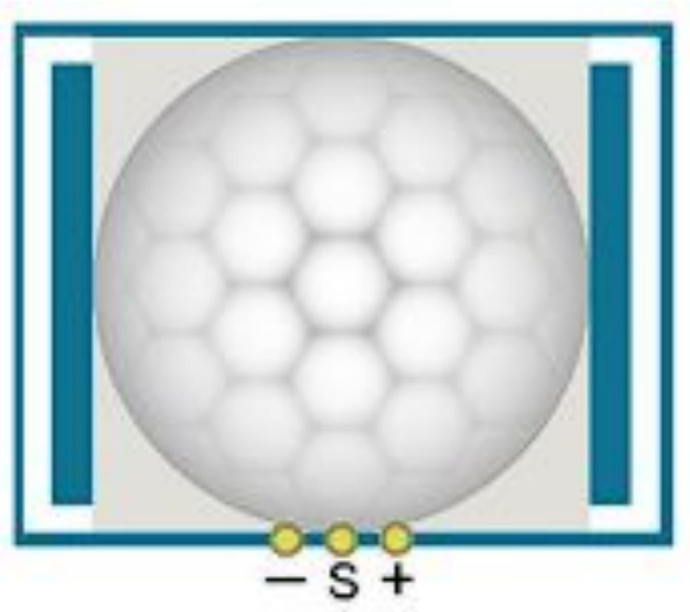


Thermometer – Circuit

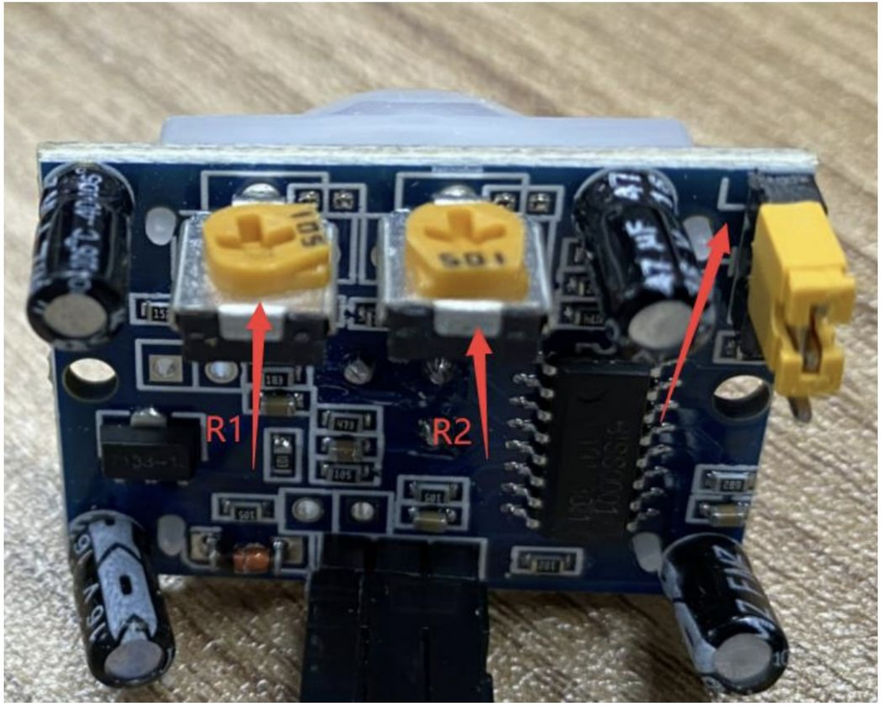


Motion Detector – Components

- HC SR501 Motion Detector * 1
- LED * 1
- Resistor 220Ω * 1
- Jumper Wires



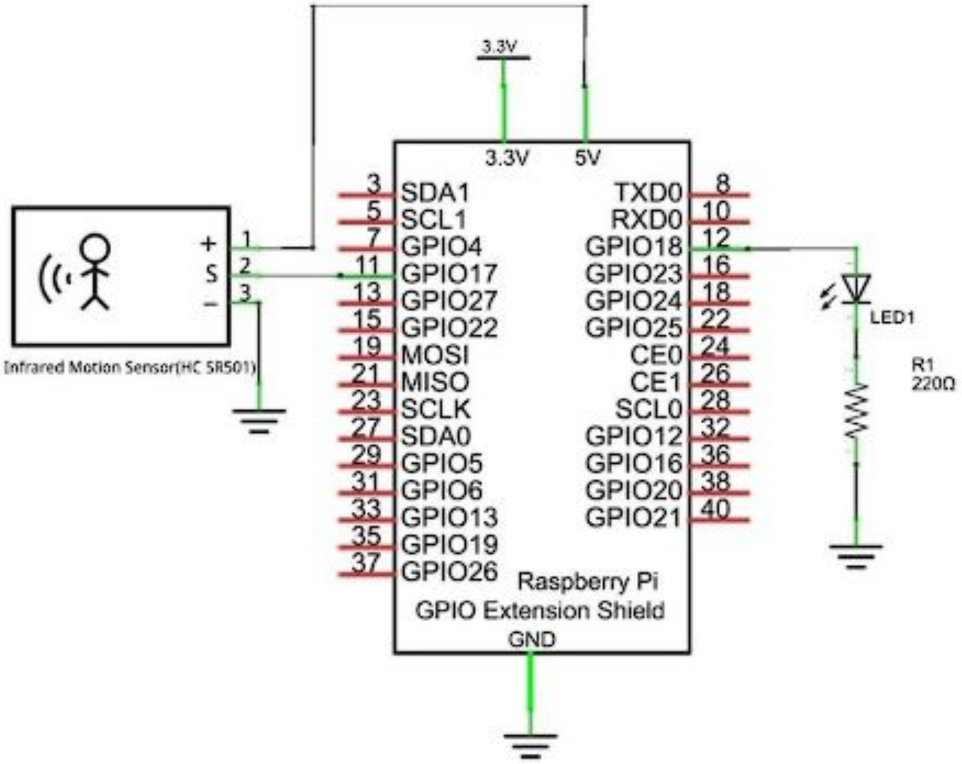
HC SR501 Motion Detector

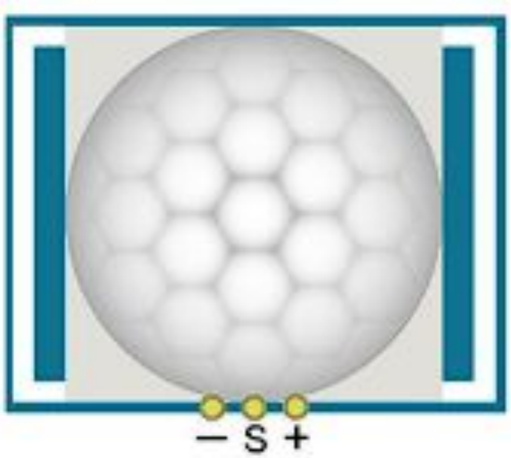


HC SR501 Motion Detector

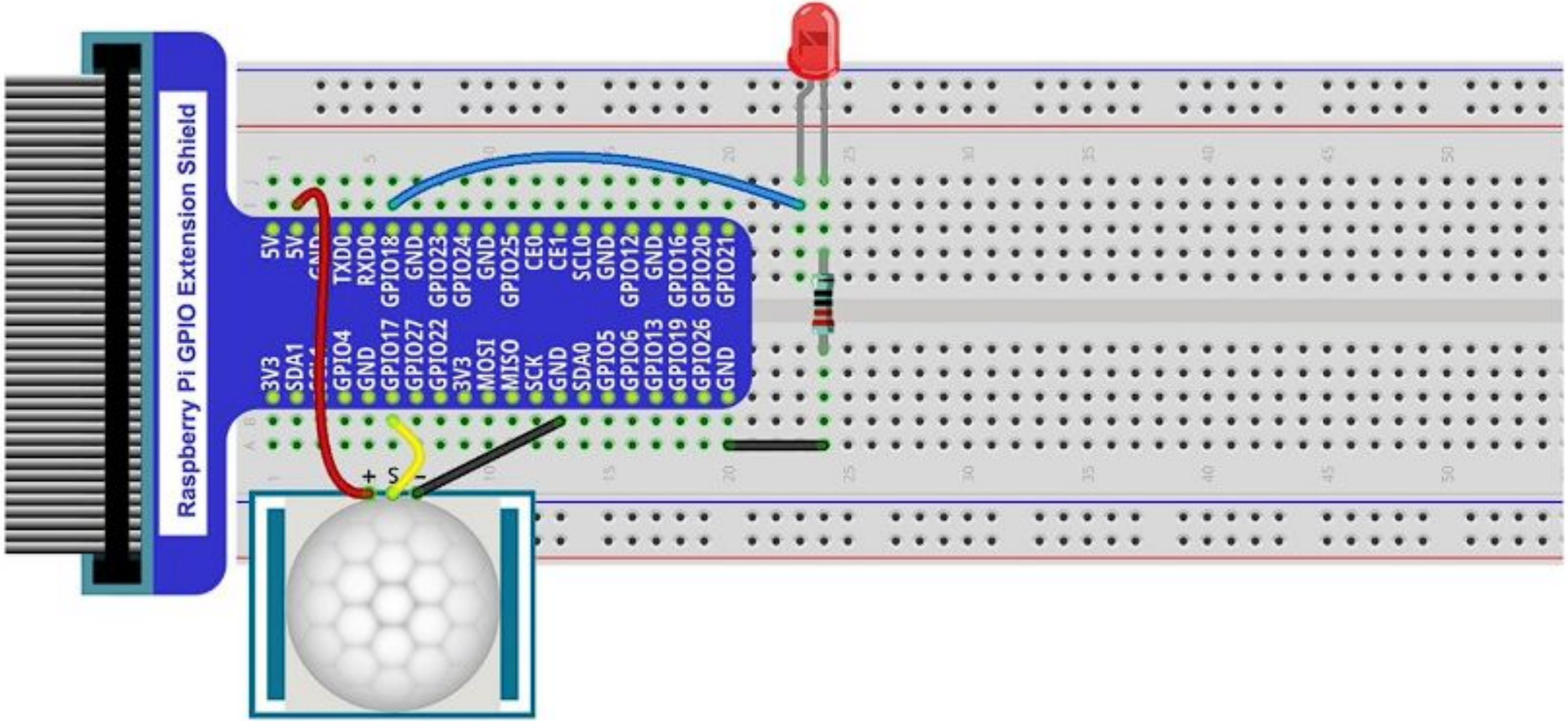
1. You can choose non-repeatable trigger modes or repeatable modes.
   - L: non-repeatable trigger mode. The module output high level after sensing a body, then when the delay time is over, the module will output low level. During high level time, the sensor no longer actively senses bodies.
   - H: repeatable trigger mode. The distinction from the L mode is that it can sense a body until that body leaves. After this, it starts to time and output low level after delaying T time.
2. R1 is used to adjust HIGH level lasting time when sensor detects human motion, 1.2s-320s.
3. R2 is used to adjust the maximum distance the sensor can detect, 3~5m.

Motion Detector – Schematic diagram





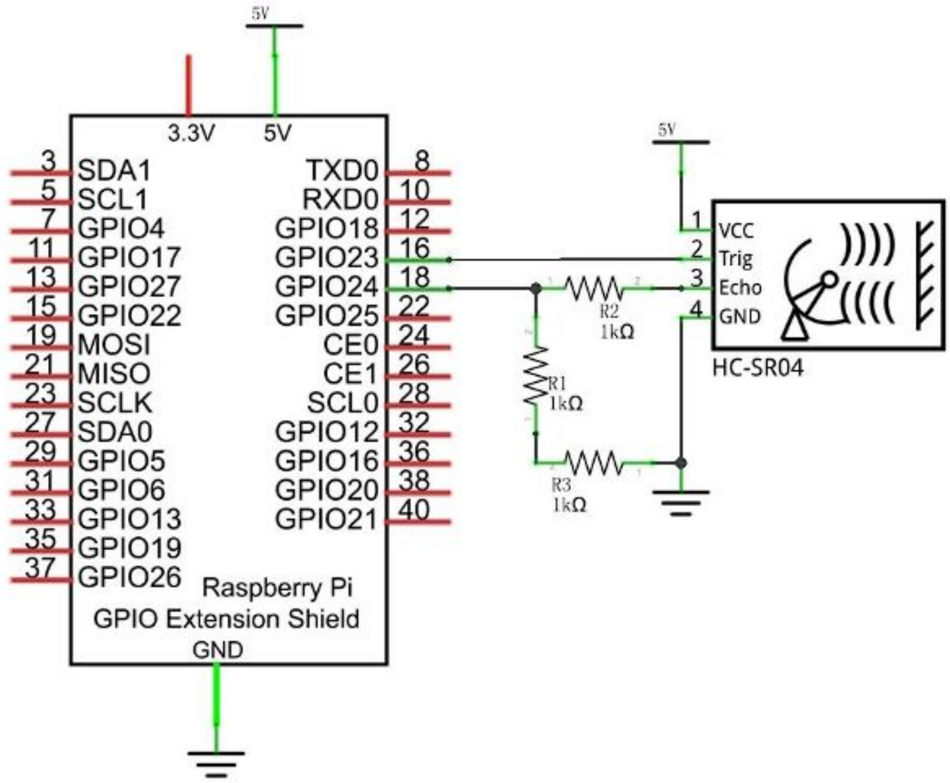
Motion Detector – Circuit



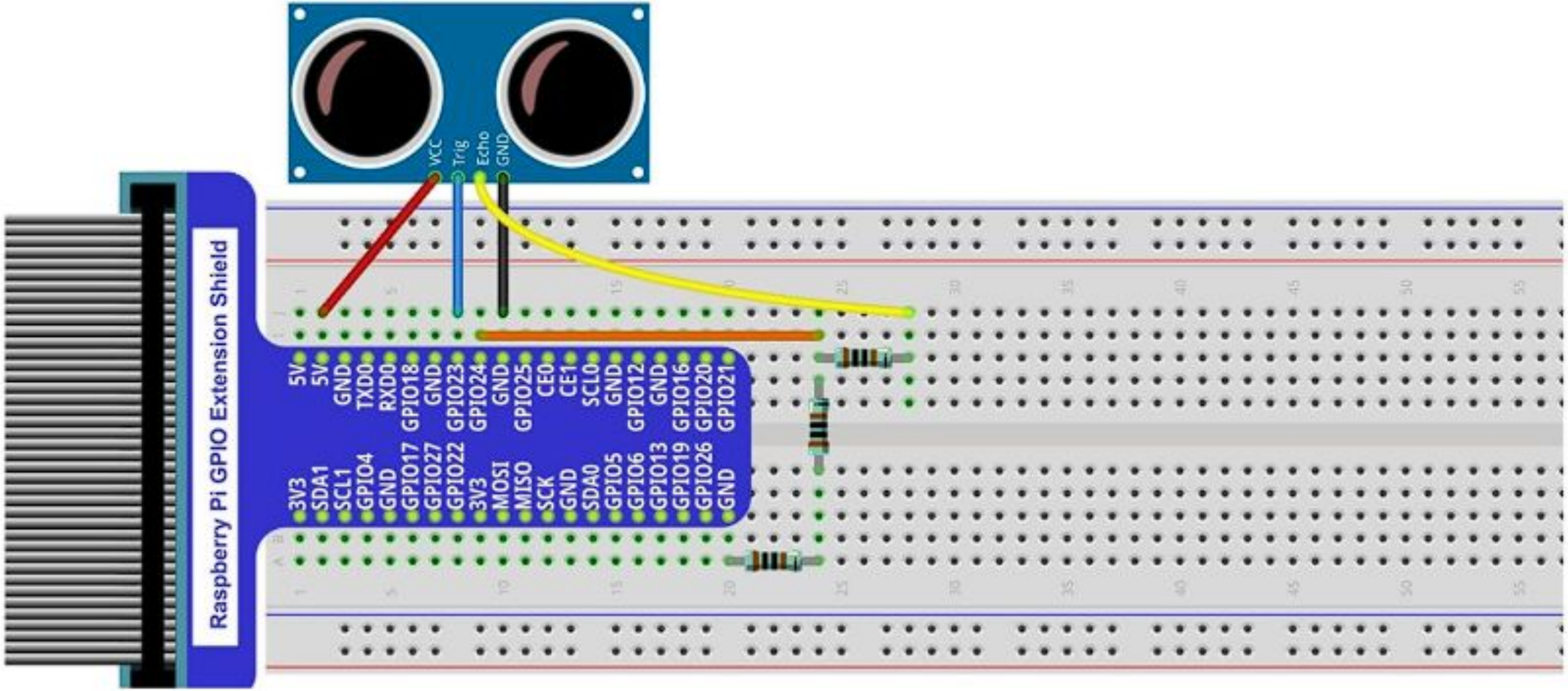
Ultrasonic Ranging – Components

- Ultrasonic Module * 1
- Resistor 1kΩ * 3
- Jumper Wires

Ultrasonic Ranging – Schematic diagram

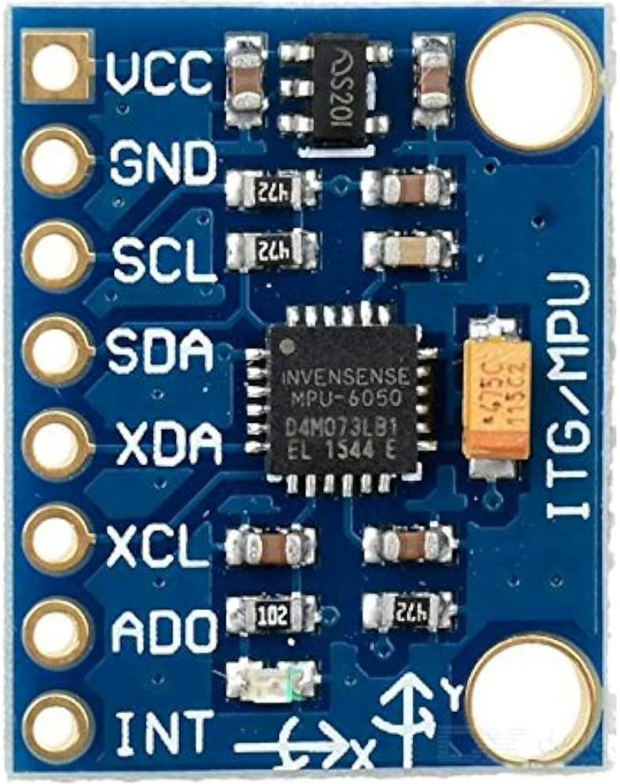


Ultrasonic Ranging – Circuit

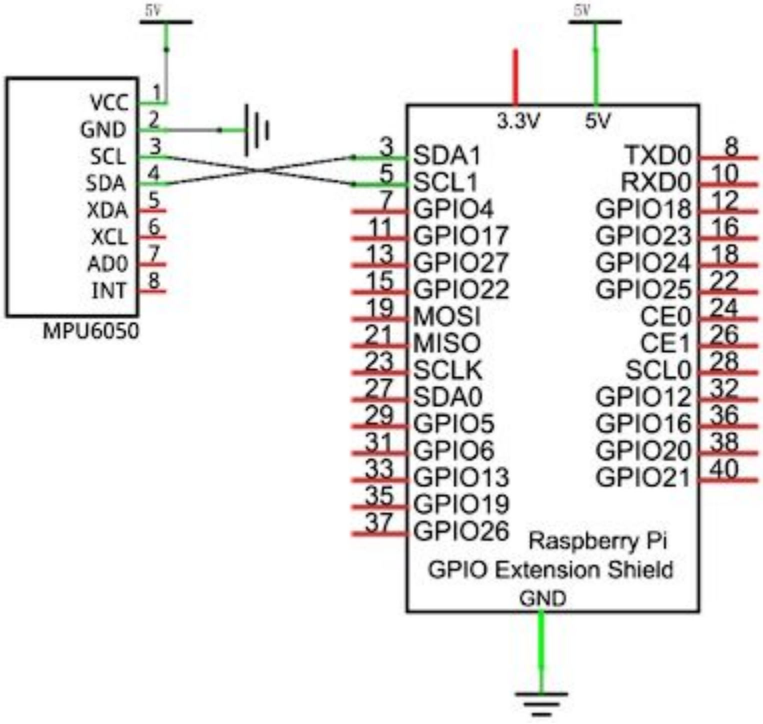


Six DoF Sensor - Components

- MPU6050 6 DoF Sensor * 1
- Jumper Wires



Six DoF Sensor – Schematic diagram



Six DoF Sensor – Circuit