# Sensors

“**Sensor** is a device, module, or subsystem whose purpose is to detect events or changes in its environment, (convert them to electrical form – V.K.) and send the information to other electronics, frequently a computer processor.”

**Sensors classification.**

By the form of physical phenomenon the sensors can be converting acoustic, biological, chemical, electrical, magnetic, mechanical, optical, radiational, or thermal stimuli into an electrical signal for the purpose of transmitting information.

# Sensors, Actuators, Transducers

In an embedded system, **sensors** are on the input side and they sense specific phenomena in the environment. **Actuators** are on the output side and they manipulate or adjust phenomena in the environment. **Both sensors and actuators are transducers** because they convert one form of energy into another form. **Sensors** typically convert physical energy into electrical energy. **Actuators** convert electrical energy into physical energy. A microphone is a sensor that converts sound waves into electrical signals. A speaker is an actuator that converts the electrical signals into sound waves. Both are transducers.

# Overview of Sensors, Transducers and Other Devices

**Sensors** (give me your examples)

**Transducers** (2-way: piezoelectric mike or speaker, el/mechanical mike or speaker…; 1-way: photovoltiac, el/chemical…)

**Gauges** (pressure, vacuum, RPM…)

**Detectors** (photo, ion, alpha, beta, gamma, X-Ray…)

**Indicators**: Test the pH of a substance by means of the dye litmus.

We will use the word sensors, although, in some cases (digital output), they may be  data loggers or data acquisition systems.

# Sensors from Sensorsportal.com

| | | |
|---|---|---|
| Optical sensors | Biosensors | Torque sensors |
| Chemical sensors | Position sensors | Level sensors |
| Rotation speed sensors | Proximity sensors | Ultrasonic sensors |
| Temperature sensors | Displacement sensors | Load Cells |
| Pressure sensors | Resonant sensors | Vacuum sensors |
| Gas sensors | Flow sensors | Magnetic sensors |
| Nano-sensors | Humidity sensors | Viscosity sensors |
| Accelerometers | Tilt sensors | Mechanical sensors |
| Oxygen sensors | Inclination sensors | Wireless sensors |
| Acoustic sensors | pH sensors | Moisture sensors |

# Selection of Sensors

We will operate with the term “sensor”, even if that sensor is an embedded subsystem. The sensors selection is dictated by the requirements to the ES (MRD -> Functional Specs -> Hardware Requirements Specification):

What physical phenomena to be measured

What is the range of the parameter change

What is the required accuracy of measurement

Any requirements to (non)linearity (calibration)

Speed of measurements (samples per second)

What type of interface does the sensor have to provide

What is the price limit

# Static Sensors Deviations (from Wikipedia)

- The sensitivity may in practice differ from the value specified. This is called a sensitivity error, but the sensor can be still linear.
- Since the range of the output signal is always limited, the output signal will eventually reach a minimum or maximum when the measured property exceeds the limits. The full scale range defines the maximum and minimum values of the measured property.
- If the output signal is not zero when the measured property is zero, the sensor has an offset or bias. This is defined as the output of the sensor at zero input.
- If the sensitivity is not constant over the range of the sensor, this is called nonlinearity. Usually this is defined by the amount the output differs from ideal behavior over the full range of the sensor, often noted as a percentage of the full range.

# Dynamic Sensors Deviations

- If the deviation is caused by a rapid change of the measured property over time, there is a dynamic error. Often, this behavior is described with a Bode plot showing sensitivity error and phase shift as function of the frequency of a periodic input signal.
- If the output signal slowly changes independent of the measured property, this is defined as drift.
- Noise is a random deviation of the signal that varies in time.
- Hysteresis is an error caused by changing direction in approaching the measured value creating a different offset error in one direction than in the other. Think about ferromagnetic hysteresis.

# Temperature Sensors

- Semiconductor Diode (−2 mV/˚C at low constant current through the diode, needed additional circuitry)
- Integrated Circuit (analog or digital output)
- Thermistor: THERM-ally sensitive res-ISTOR. Can be NTC or PTC – both need additional circuitry
- RTD – Resistive Temperature Detector (carbon, platinum layer on substrate): Rt = Ro (1 + K*T), K tempco, Ro– resistance at T = 0 or 25C
- Thermocouple - Junction of different metals or alloys. Need some methods of cold-junction compensation to adjust for varying temperature at the cold ends. Need linearization (can be done by HW or SW – more often).

# Diode-Based Temperature Measurement

Moderate-precision temperature measurement from -40 to +150C

Linear temperature coefficient –2mV/C° in operating temperatures

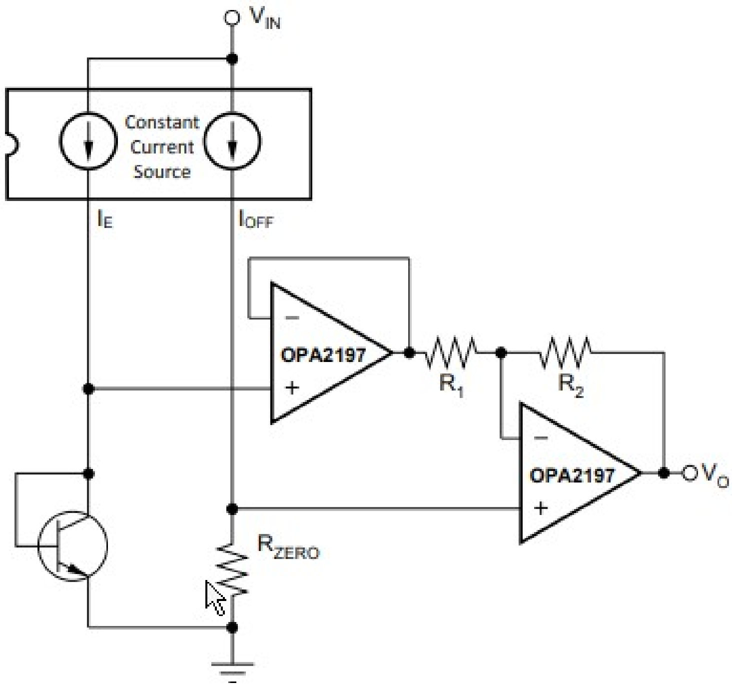
Requires excitation, offsetting, and amplification – it is not too complex

Mouser sells analog output temp sensors with prices from $0.32 to $24/ea

Digital output temperature sensors cost from $0.38 to $22

For the Positive Transfer Function Temperature Measurement Circuit with Positive Supply, shown on the next slide, the Basic transfer function: $Vo = Ioff \times Rz \times (1 + R2 / R1) - Vbe \times R2 / R1$

# Positive Transfer Function Circuit



# HTS221 Relative Humidity and Temp

The HTS221 is an ultra-compact sensor for relative humidity and temperature. It includes a sensing element and a mixed signal ASIC to provide the measurement information through digital serial interfaces.

The sensing element consists of a polymer dielectric planar capacitor structure capable of detecting relative humidity variations and is manufactured using a dedicated ST process.

The HTS221 is available in a small top-holed cap land grid array (HLGA) package guaranteed to operate over a temperature range from -40 °C to +120 °C.

# Features of HTS221

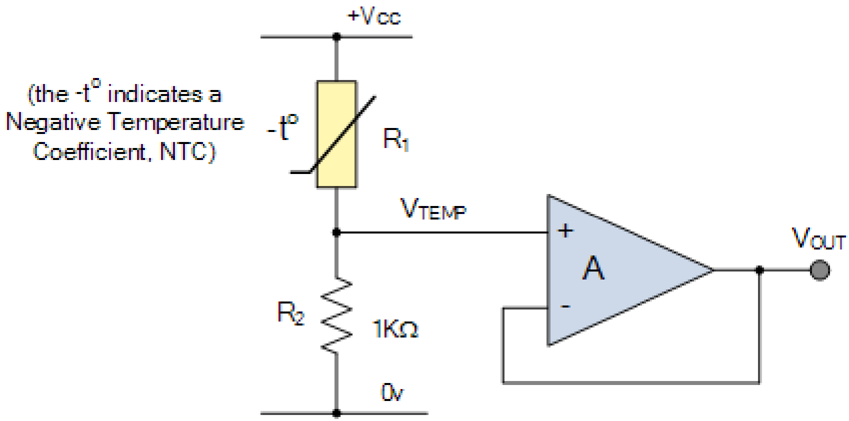
| | |
|---|---|
| 0 to 100% relative humidity range | SPI and $I^2C$ interfaces |
| Supply voltage: 1.7 to 3.6 V | Factory calibrated |
| Low power consumption: 2 µA @ 1 Hz ODR | Humidity accuracy: ± 3.5% rH, 20 to +80% rH |
| 16-bit humidity and temperature output data | Temperature accuracy: ± 0.5 °C for 15 to +40 °C |
| High rH sensitivity: 0.004% rH/LSB | Selectable ODR from 1 Hz to 12.5 Hz |
| Embedded 16-bit ADC | Tiny 2 x 2 x 0.9 mm package |

# Thermistors

Most types of thermistors have a Negative Temperature Coefficient of resistance or (NTC) and their resistance/temperature curve has a negative slop and is highly nonlinear. Small excitation current reduces loss in wires and selfheating.
Thermistors have an exponential change with temperature and therefore have a Beta temperature constant ( β ) which can be used to calculate its resistance for any given temperature point: $R2=R1\exp(\beta/T2 - \beta/t1)$, where R2= resistance at T2, R1=resistance at t1.
Thermistors are generally connected in series with a suitable biasing resistor to form a potential divider network and the choice of resistor gives a voltage output at some pre-determined temperature point or value, for example:

# NTC Thermistor Sensor

Thermistor has a resistance value of 10kΩ at 25C and a resistance value of 100Ω at 100C. Let's calculate the output voltages for 25C and 100C, assuming the Vcc=12V.

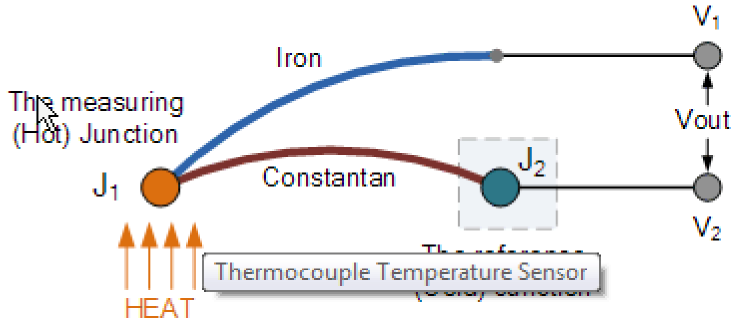



Vout for 25C: Vout = Vcc *R2/(R1+R2)=12V*1k/(10k+1k)=1.09V

Vout at 100C = Vcc * 1k / (0.1k+1k) = 10.9V

# Thermocouple

Thermocouples are popular due to its simplicity, ease of use and their speed of response to changes in temperature, due mainly to their small size. Thermocouples also have the widest temperature range of all the temperature sensors from below -200ºC to well over 2000ºC.




Vout = V1 – V2 = Cab(Th – Tc), where Cab is the Seebeck coefficient (nonlinear), Th – temp at hot end, Tc – temp at cold end.

# Pressure Sensors

Pressure sensor is a device consisting of a pressure sensitive element to determine the actual pressure (of gas or liquid) applied to the sensor (using different working principles) and some components to convert this information into an output signal (electrical).

Common units of pressure are: Pascal (Pa), Bar (bar), N/mm2 or psi

Working Principles of Pressure Sensors:

- Strain gauge based pressure sensors
- Capacitive pressure sensors
- Piezo-resistive pressure sensors
- Resonant pressure sensors.

Applications: Medical, Industrial; HVAC = Heating, Ventilating and Air Conditioning.

# MEMS Nano Pressure Sensor LPS22HB

Ultra-compact piezoresistive absolute pressure sensor which functions as a digital output barometer.
The device comprises a sensing element and an IC interface which communicates through I2C or SPI to a microcontroller.
The LPS22HB is available in a full-mold, holed LGA package (HLGA-10L). It is guaranteed to operate over a temperature range extending from -40 °C to +85 °C and covers 260 to 1260 hPa pressure range.
24-bit pressure data output
Output Data Rate: from 1 Hz to 75 Hz
The sensor is available from many distributors, including Mouser, where it is priced at $4.21per unit.

# Magnetic Field Sensors

There are many magnetic sensors which can work as limit (end) switches: based on Hall effect, reed switches, inductors, and so on.
We are looking for a magnetic sensor to measure strength of the magnetic field in three dimensions, so we should exclude all types of switching (not measuring strength and direction of the magnetic field) sensors from consideration.
The preferred type of sensors is Hall effect, due to their small size and well developed technology.
After that, again, we have to make a choice: analog output or digital.
We should select digital because they are either calibrated or/and calibratable and will provide, in our ES, better accuracy than analog.

# Digital Output Magnetic Sensor LIS3MDL

Ultra-low-power high performance three-axis magnetic sensor

User-selectable full scales of ±4/±8/±12/±16 Gauss

The Integrated Circuit is factory calibrated for sensitivity and offset levels.

The device may be configured to generate interrupt signals for magnetic field detection.

I2C serial bus (100 kHz and 400 kHz) or SPI serial standard interface.

LIS3MDL is available in a small thin plastic land grid array package (LGA) and operates over temperature range of -40 °C to +85 °C.

Wide supply voltage, 1.9 V to 3.6 V

Current consumed at ultra-high-resolution, ODR = 20 Hz:  270uA

# Accelerometer

An accelerometer is a device that measures the vibration, or acceleration of a mass. The force caused by vibration or a change in motion (acceleration) causes the mass to "squeeze" the piezoelectric material which produces an electrical charge that is proportional to the force applied to the mass. Since the charge is proportional to the force, and the mass is a constant, then the charge is also proportional to the acceleration.

Newton's second law: The acceleration (a) of an object as produced by a net force (F) is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass (m) of the object: $a = F/m$.

# 3-D Accelerometer and Gyro, LSM6DSL

The LSM6DSL is a system-in-package featuring a 3D digital accelerometer and a 3D digital gyroscope in one package.

Gyro used for measuring or maintaining orientation and angular velocity.

The LSM6DSL supports up to 4 kByte data batching FIFO.

Low current intake is only 0.65mA by both sensors at 1.6 kHz ODR.

It has an embedded temperature sensor.

The chip has two interfaces: SPI (10MHz max) and I2C (400kHz max).

The LSM6DSL is available in a plastic Land Grid Array (LGA) package. It has a reference designator U3 is located on the IoT board next to PMOD and CN2 connectors.

# Signal Conditioning

In most practical cases a proper interface between a sensor and an ADC is required.

The purpose of the interface is to provide the ADC with:

Full-scale signal (voltage) on the output of conditioning circuitry must be the same as full-scale input of ADC,

Low-pass frequency filtering of the input signal equal or lower than half sampling frequency of ADC,

If necessary: differential and/or isolated from the sensor signal (CT),

Phase correction – in case of simultaneous sampling or S&H from different kinds of sensors (Wattmeter),

Linearization of sensor's characteristic, if possible.

# Components of Signal Conditioners

Operational Amplifiers (OpAmps)

Passive components:

- Resistors
- Capacitors
- Inductors (warning),
- Transformers,
- Optoisolators.

Example of R-C low-pass filter (LPF) is on the next slide.

Time Constant; error vs. time in response to step function – important characteristics of this signal conditioner.

Graphical illustration of a transient process with an input step function can be observed from the other window in LTSpice (last slide).

# Analysis of RC Filter in LTSpice

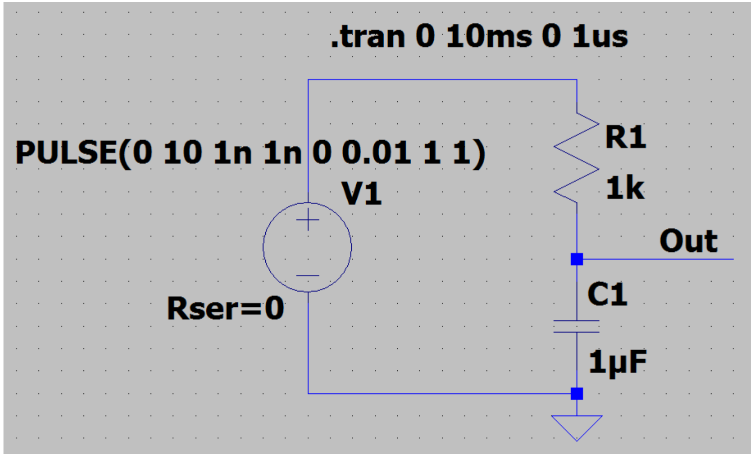
This is a transient analysis, as a reaction to a step function of 10V.

Time Constant: R1*C1,
Output voltage, as a response to step-function:

Vo=Vin(1-exp(-t/RC));

Err = Vo – Vin =

-Vin*exp(-t/RC).



# Transient Process in LPF

IIn order to simulate transient response, the power supply V1 must be set (right click on it) to PULSE, Vinitial = 0, Von = 10, Tdelay = 1n;  Trise = 1n;  Tfall = 0,  Ton = 0.01,  Tperiod =1s, N of Cycles =1.

Mode of simulation can be set via Simulate → Edit Simulation Cmd, - to: Transient, Stop time = 10ms, Time to start saving data = 0, Maximum timestep = 1us. Then click on Run icon and you should see the following diagram: