SENSORS AND TRANSUDCERS

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(Notes adapted from Prof. Qimin Yang’s lecture, Spring 2011)
YOU GET TO CHOOSE SENSORS FOR YOUR ROCKET!

- http://www.eng.hmc.edu/NewE80/FlightVideos.html

- http://www.eng.hmc.edu/NewE80/MuddI11_10_06-800Kbps.mov

- Lego Man in Space (just for fun):
  http://www.youtube.com/watch?v=MQwLmGR6bPA
AGENDA

- Rocket sensors

- Common sensors/transducers
  - Gas sensor
  - Humidity sensor
  - Pressure sensor
  - Vibration sensor

- Rocket hardware (next week)
BRAINSTORM

- What sort of data might you want to collect from your rocket?
BRAINSTORM

- Environment (inside and outside of rocket)
  - Temperature
  - Humidity
  - Pressure

- Motion of the rocket
  - Altitude / time to apogee
  - Velocity
  - Acceleration

- Vibration (of the rocket, of the stand)
COMMON SENSORS

- Temperature Sensor (Done)
- Rate Gyros / Accelerometers (Done)
- Gas / Chemical Sensor
- Humidity Sensor
- Pressure Sensor
- Vibration Sensor
GAS/CHEMICAL SENSORS

- Solid electrolyte sensors [NO$_2$, CO$_2$, O$_2$]
- Metal oxide sensors [combustible & toxic gases]
- Catalytic bead sensors [combustible gases]
- Electrochemical sensors [toxic gases & oxygen]
GAS/CHEMICAL SENSORS

What sort of characteristics are important to consider when choosing gas or chemical sensors?

- Sensitivity (ppm, ppb)
- Operation temperature range
- Power consumption
- Size

http://www.futurlec.com/Gas_Sensors.shtml (output voltage)


EXAMPLE: CO₂ GAS SENSORS

Cathodic reaction: \[ 2\text{Li}^+ + \text{CO}_2 + \frac{1}{2}\text{O}_2 + 2e^- = \text{Li}_2\text{CO}_3 \]
Anodic reaction: \[ 2\text{Na}^+ + \frac{1}{2}\text{O}_2 + 2e^- = \text{Na}_2\text{O} \]
Overall chemical reaction: \[ \text{Li}_2\text{CO}_3 + 2\text{Na}^+ = \text{Na}_2\text{O} + 2\text{Li}^+ + \text{CO}_2 \]

Nernst Equation:

\[ \text{EMF} = E_c - \frac{RT}{2F \ln(P_{\text{CO}_2})} \]

- \( P_{\text{CO}_2} \) = partial pressure of CO₂ gas
- \( E_c \) = constant cell potential under standard conditions [V]
- \( R \) = ideal gas constant = 8.31 J/(mol-K)
- \( T \) = absolute temperature [K]
- \( F \) = Faraday constant = 9.65 \times 10^4 C/mol

http://chemistry.about.com/od/electrochemistry/a/nernstequation.htm
PARTIAL PRESSURE

- Ideal gas law: \( PV = nRT \)  
  n: number of moles

- Dalton's Law of Partial Pressure:
  
  \[
  \text{Partial pressure ratio} = \text{mole ratio}
  \]

  - Partial pressure = total absolute pressure * volume fraction of gas component
  - 1 ppm = 1 part per 1,000,000 parts

Alternate form of ideal gas law: \( PV = nRT = \left( \frac{m}{M} \right)RT \)

- Mass per volume: \( \frac{m}{V} = \frac{PM}{RT} \)  
  m: mass  
  M: molar mass
Example: What is the partial pressure of 1% CO₂ at atmospheric pressure (101.325 kPa) and room temperature (25 °C or 298.15 K)?

Hint: Molar mass of CO₂ = 44 g/mol

- ppm = ?
- Partial pressure of CO₂ = ?
- Mass per volume \( \frac{PM}{RT} \) = ?
PARTIAL PRESSURE

Example: What is the partial pressure of 1% CO₂ at atmospheric pressure (101.325 kPa) and room temperature (25 °C or 298.15 K)?

Hint: Molar mass of CO₂ = 44 g/mol

- ppm = (0.01) * 10⁶ = 10⁴

- Partial pressure of CO₂ = 0.01 * 101.325 kPa = 1013.25 Pa

- Mass per volume = \( \frac{PM}{RT} = \frac{(1013.25 \text{ Pa})(44 \text{ g/mol})}{8.31447 \frac{\text{m}^3 \cdot \text{Pa}}{\text{K} \cdot \text{mol}}(298.15 \text{ K})} = 18 \text{ g/m}^3 \)
Example Sensor MG811

\[ EMF = E_c - \frac{RT}{2F \ln(P_{CO2})} \]

Temp : 28°C
RH: 65%
Oxygen : 21%

http://www.futurlec.com/CO2_Sensor.shtml
HUMIDITY SENSOR

What is humidity (relative humidity)?

\[ \varphi = \frac{e_w^*}{e_w} \times 100\% \]

- \( e_w \): partial pressure of water vapor
- \( e_w^* \): saturated vapor pressure of water at a prescribed temperature
  maximum water vapor that the air can hold without condensing

\[ e_w^* = f(T, P) \] empirically correlated

http://en.wikipedia.org/wiki/Relative_humidity
http://en.wikipedia.org/wiki/Hygrometer
HUMIDITY SENSOR

Relative humidity measurement (%RH)

- Capacitive
- Resistive

Examples:


HUMIDITY SENSOR

Capacitive RH sensor:
- Dielectric constant of a polymer or inorganic material changes as it absorbs water vapor
- Dielectric constants: 80 (water) vs. 3.4 (polyimide)
- More water $\rightarrow$ more capacitance?
- How to measure capacitance?
Resistive RH sensor:

- Electrical resistance of a material changes as it absorbs water vapor
- Typical materials: salts, conductive polymers
- Less sensitive than capacitive RH sensors
- Material properties also tend to depend both on humidity and temperature (in practice, must be combined with temperature sensor)
PRESSURE SENSOR

- What is pressure?
  - e.g. atmospheric pressure at sea level is 101.325 kPa
  - e.g. tire pressure gauge reads 0 PSI
  - e.g. pressure drop for flow measurement

- What kind of pressure do you want to measure?
  - Absolute pressure sensor
  - Gauge pressure sensor
  - Differential pressure sensor
TYPES OF PRESSURE SENSORS

- Force-based
  - Piezoresistive strain gauge
  - Potentiometric
  - Piezoelectric
  - Capacitive

- Other kinds
  - Resonance (MEMS)
  - Thermal (Pirani gauge)

http://en.wikipedia.org/wiki/Piezoresistive
SENSOR EXAMPLE: MPXA6115A

Figure 1. Fully Integrated Pressure Sensor Schematic

Features:

- 1.5% Maximum Error over 0° to 85°C
- Ideally suited for Microprocessor or Microcontroller-Based Systems
- Temperature Compensated from −40° to +125°C
- Durable Epoxy Unibody Element or Thermoplastic (PPS) Surface Mount Package

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CHARACTERISTICS OF PRESSURE SENSOR:

- **Pressure range:** 15-115 kPa
- **Sensitivity:** 45.9 mV/kPa
- **Supply voltage:** 5V
- **Output analog voltage:**
  - Offset voltage \( V_{\text{off}} \): output voltage at minimum rated pressure (Typical @ 0.204V)
  - Full scale output \( V_{\text{fso}} \): output voltage at maximum rated pressure (Typical @ 4.794 V)

- **Pressure units**
  - Pascal (Pa) = N/m\(^2\): standard atmosphere
    \[ P_0 = 101325 = 101.325 \text{ kPa} \]
  - Psi = (Force) pound per square inch: 1 Psi = 6.89465 KPa
PRESSURE SENSORS FOR ALTITUDE SENSING

\[ P \cdot V = nRT \]  "ideal gas law"

\[ \rho = \frac{\text{mass}}{\text{volume}} = \frac{nM}{nRT} = \frac{M \cdot P}{R \cdot T} \]

\[ \Delta P = -\rho g \cdot \Delta h = -\frac{MP}{RT} g \cdot \Delta h \]

\[ P(h) = P_0 \exp \left( -\frac{Mg}{RT} h \right) \]

Method #1:

Method #2:

M: Molar Mass
n: Number of moles
T: Temperature
P: Pressure
h: Altitude

http://en.wikipedia.org/wiki/Gas_constant
PRESSURE SENSORS FOR ALTITUDE SENSING
PRESSURE SENSORS FOR ALTITUDE SENSING

Method #3:

\[ h = \frac{T_0}{-(dT/dh)} - \left[ 1 - \left( \frac{P_0}{P} \right) \frac{(dT/dh)_R}{gM} \right] \]

where

- \( h \) = altitude (above sea level) (in meters)
- \( P_0 \) = standard atmosphere pressure = 101.325 kPa
- \( T_0 \) = 288.15 K (+15°C)
- \( dT/dh = -0.0065 \) K/m: thermal gradient or standard temperature lapse rate
- \( R \) = gas constant (8.31432 N*m/mol*K)
- \( g \) = (9.80665 m/s²)
- \( M \) = molar mass of earth’s air (0.0289644 kg/mol)
PRESSURE SENSORS FOR ALTITUDE SENSING

Plug in all the constants

Method #3:

\[
h = 4.43 \times 10^4 \times \left(1 - \left(\frac{101.325\text{kPa}}{P}\right)^{-0.1902}\right)
\]

- \(h\) is measured in meters.
- Equation calibrated up to 36,090 feet (11,000m).
- Different values of \(dT/dh\) for different layers of the atmosphere
EXAMPLES

Suppose, $P = 85 \text{kPa}$ (from Pressure sensor)

**Method 1:**

$$\Delta h = -\frac{\Delta P}{\rho g} = -\frac{(85 - 101) \text{kPa}}{(1.2 \frac{\text{kg}}{\text{m}^3} \times 9.8 \frac{\text{m}}{\text{s}^2})} = 1.36 \text{ km}$$

**Method 2:**

$$h = -\frac{RT}{Mg} \ln\left(\frac{P}{P_0}\right) = -8440 \ln\left(\frac{85 \text{kPa}}{101 \text{kPa}}\right) = 1.46 \text{ km}$$

**Method 3:**

$$h = 4.43 \times 10^4 \times \left(1 - \left(\frac{101.325 \text{kPa}}{85 \text{kPa}}\right)^{-0.1902}\right) = 1.43 \text{ km}$$
VIBRATION/IMPACT SENSOR

Mechanical force/ deformation → resistance/ voltage output

Examples:
• Strain gauges
• Piezoelectric films


http://en.wikipedia.org/wiki/Strain_%28physics%29

http://www.vishaypq.com/micro-measurements/transducer-class-strain-gages/

VIBRATION SENSOR

LDT0: Voltage Output vs Tip deflection
(Figure 2)

ACCELEROMETERS AS VIBRATION SENSORS

- [http://www.sparkfun.com/tutorials/167](http://www.sparkfun.com/tutorials/167)

- Full-scale range
- Number of axes
- Interface (analog, digital, pulse output)
- Bandwidth (50-100 Hz)
- Power consumption (supply voltage)
NOW WHAT?

(1) Electronics should fit within rocket
(2) Easy to transmit/store/retrieve data
(3) Telemetry
(4) Video system

http://www.sparkfun.com/products/9228
http://www.sparkfun.com/products/10216

http://www.youtube.com/watch?v=f0Qr1g70aOg&feature=related
http://www.youtube.com/watch?v=2Ax64jfeVCc