Electronic Instrumentation

Resistive sensors

Romano Giannetti

Univ. Pontificia Comillas — ICAI
1. Introducción
2. Resistive sensors: big variations.
3. $\Delta R$ conditioning
4. Linearization methods

Logo image from https://openclipart.org/detail/172330/oscilloscope
Resistive sensors

Electric sensor

- Analog
  - Active
    - Voltage
  - Passive
    - Current
    - Reactive
    - Resistive
      - Big variations
      - Small variations

Digital

Done!
The sensor is called a *small variations* sensor if:

\[
\frac{\Delta R}{R_{\text{avg}}} \ll 1
\]

and a *big variation* otherwise.

<table>
<thead>
<tr>
<th>(\Delta R / R_{\text{avg}}) type</th>
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</thead>
<tbody>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.12</td>
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In the last case, it’s a grey area...
The sensor is *linear* when the sensitivity is constant. So:
- S1 is *not* linear;
- S2 is *not* linear;
- S3 is *linear*;
- S4 is ...?

Typically, $\Delta R$ sensors are not linear; the exception are potentiometric (electro-mechanic) sensors.
In a descriptive way, the conditioning of a resistive sensor, big variations, is simple:

\[ V_1(x) = I_0 R(x) \]

\[ V_o(x) = I_0 R(x) + E_0 \]

Sensitivity adjustment

Zero adjustment
Often the current through the sensor is limited, so it is impossible to do the sensitivity adjustment in one step:

\[ I_0 R(x) E_0 \]

Clearly, the adder and the amplifier can be swapped.
If the sensor is floating:

\[ v_o = \frac{R_2}{R_1} \left( -\frac{E_0}{R_0} R(x) + E_Z \right) \]
Important details!

When designing the circuits, keep in mind the following details:

- If the sensor is **not** floating, you have to change the supply stage (there are several possible configurations, look around).
- **Always** check that the operational amplifiers do not saturate at each stage!
- Yes, you can compact this into a two op-amp’s circuit (even with just one, sometime) but be careful: early optimization is evil!

You can use the (several) degrees of freedom to optimize your design toward various target (low error, low consumption, and so on).
Unfortunately, $\Delta R$ sensors are often non-linear. Non-linear output in an instrument is better avoided, for several reasons, but basically:

- Reading the value on a non-linear scale is difficult and error-prone;
- when in a control loop, the local gain depend on the value, which can be a nightmare for stability.
linearization: the objective

Sensor’s calibration curve

Output’s calibration curve

\[ R(x) \]

\[ v_o(x) \]
Linearization methods

Basically, we will study three methods for linearizing a sensor (or an instrument):

**Method #0**: pass. The lazy engineer’s one.

**Method #1**: invent something special. The smart engineer’s one.

**Method #2**: do that *exactly*. The rich (and with a lot of time available) engineer’s one.
How-to linearize: method #0

Let’s look at it…

1. …well, it’s not so non-linear, no?

2. So we will *ignore* the non-linearity and design everything as if the sensor were linear.

3. Then, we will compute the difference between our (invented) sensor and the real one as a *linearity error*.
How-to linearize: method #2

(Yes, I know. Method #1 later...)

Sensor’s calibration curve

Let’s look at it...

1. We measure a value for \( R(x) = R_M \) through a linear conditioning system.

2. With a μC, we will compute \( x_M = f_{f^{-1}}(R_N) \).

3. Finally, you can recreate the output with a DAC or directly use it.

This is almost exact (with sufficient bits) but expensive.
How-to linearize: method #1

Method #1 for linearizing is based on the specific characteristics of the sensor; the basic concept is to design a conditioning circuit *ad-hoc* for it.

- we can find a *physical* circuit that cancels out the non linearity (for example: a logarithmic amplifier can linearize a sensor with an exponential calibration curve);
- we can modify the sensor by adding components that (totally or partially) compensate the non-linearity;
- and so on; the key is the inventiveness of the designer.
Linear conductance sensors

Some resistive sensor has a calibration curve where its *conductance* is linear with the measured quantity.

If the sensor has a calibration curve like:

\[ R(x) = \frac{k}{x} \]

I can supply it with constant \( V \) and convert the resulting \( I \) in voltage:

\[ v_x = -E_0 \frac{R_0}{R(x)} = -E_0 \frac{R_0}{k} x \]

...and then continue with the normal zero and sensitivity adjustment.
Almost linear conductance sensors

Sometimes is worth mixing two methods. For example, in this case the sensor is (green)

\[ R(x) = \frac{k}{x^\alpha}, \quad \alpha = 0.7 \]

You can apply method \#1 as if it were of the \(1/x\) kind and obtain a much less non-linear curve (red).

Then you can apply method \#0 or \#2 with better results overall.
If you have a sensor that
- has high sensitivity, and
- is wildly nonlinear
you can trade part of your sensitivity with linearity by using a parallel fixed resistor.

This is commonly used with NTC thermistors.
NTC sensors

NTC (Negative Temperature Coefficient) are probably the most common used resistive temperature sensors.

\[ R(T) = R_0 e^{\frac{\beta}{T} - \frac{\beta}{T_0}} \], \ T \text{ in K}

where \( \beta \) is the “sensitivity” (sic) of the NTC — in the range of 1000 K–5000 K.
Parallel resistor, intervals

How do we find a value for $R_p$?

![Graph showing the parallel connection of $R(x)$ and $R_p$. The graph illustrates the resistance $R(x)$ and $R_p$ at different intervals $x_1$, $x_2$, and $x_3$, with the differences $\Delta_1$ and $\Delta_3$ highlighted.]
The idea is choosing $R_p$ so that the two intervals $\Delta_1$ and $\Delta_2$ are equals, as if the calibration curve were lineal.

$$\Delta_1 = \Delta_2 \Rightarrow R(x_1) \parallel R_p - R(x_2) \parallel R_p = R(x_2) \parallel R_p - R(x_3) \parallel R_p$$

Solving for $R_p$ leads to:

$$R_p = \frac{R(x_2)(R(x_1) + R(x_3)) - 2R(x_1)R(x_3)}{R(x_1) - R(x_3) - 2R(x_2)}$$

Obviously, you have to check that the value for $R_p$ is reasonable: positive (!) and not too small — otherwise the sensitivity will drop too much.
Parallel resistor, tangent

If the range of interest is a small portion around $x_2$, we can find the value of $R_p$ giving the maximum linearity with:

$$\left. \frac{\partial^2 R(x) \parallel R_p}{\partial x^2} \right|_{x=x_2} = 0$$

which is still an equation with just $R_p$ as unknown.

For NTC (where $x$ is $T$), we can find

$$R_p = \frac{\beta - 2T_2}{\beta + 2T_2} R(T_2).$$

\[1\] Not easily...