Signal Conditioning and Linearization of RTD Sensors

Collin Wells
Texas Instruments
HPA Precision Linear Applications
9/24/11
Introduction

• Primary Support
  – 4-20mA Loop Drivers (XTRXXX)
  – Gamma Buffers (BUFXXXXX)

• Other Support
  – Temperature Sensors (TMP)
  – IR Temperature Sensors (TMP006)
  – OPA Stability
  – Instrument Amplifiers

• Applications (Other)
  – Industrial – Programmable Logic Controllers (PLC)
  – RTD
  – Reference Designs
Contents

• RTD Overview
• RTD Nonlinearity
• Analog Linearization
• Digital Acquisition and Linearization
What is an RTD?

- **Resistive Temperature Detector**
- Sensor with a predictable resistance vs. temperature
- Measure the resistance and calculate temperature based on the Resistance vs. Temperature characteristics of the RTD material

![RTD Diagram]

**RTD Resistance vs. Temperature**

- **PT100**
- \( \alpha = 0.00385 \)
How does an RTD work?

Resistance = \( R = \frac{\rho \cdot L}{A} \)

Resistivity = \( p = \frac{1}{e \cdot n \cdot \mu} \)

• The product \( n \cdot u \) decreases over temperature, therefore resistance increases over temperature (PTC)

• Linear Model of Conductor Resistivity Change vs. Temperature

\[ \rho(t) = \rho_0 \left(1 + \alpha(t - t_0)\right) \]
What is an RTD made of?

- Platinum (pt)
- Nickel (Ni)
- Copper (Cu)

- Have relatively linear change in resistance over temp
- Have high resistivity allowing for smaller dimensions
- Either Thin-Film or Wire-Wound

<table>
<thead>
<tr>
<th>Metal</th>
<th>Resistivity (Ohm/CMF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold (Au)</td>
<td>13</td>
</tr>
<tr>
<td>Silver (Ag)</td>
<td>8.8</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>9.26</td>
</tr>
<tr>
<td>Platinum (Pt)</td>
<td>59</td>
</tr>
<tr>
<td>Tungsten (W)</td>
<td>30</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>36</td>
</tr>
</tbody>
</table>

*Images from RDF Corp*
How Accurate is an RTD?

• Absolute accuracy is “Class” dependant - defined by DIN-IEC 60751. Allows for easy interchangeability of field sensors

<table>
<thead>
<tr>
<th>Tolerance Class (DIN-IEC 60751)</th>
<th><strong>Temperature Range of Validity</strong></th>
<th>Tolerance Values (C)</th>
<th>Resistance at 0C (Ohms)</th>
<th>Error at 100C (C)</th>
<th>Error over Wire-Wound Range (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wire-Wound</td>
<td>Thin-Film</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*AAA (1/10 DIN)</td>
<td>0 - +100</td>
<td>0 - +100</td>
<td>+/(0.03 + 0.0005*t)</td>
<td>100 +/- 0.012</td>
<td>0.08</td>
</tr>
<tr>
<td>AA (1/3DIN)</td>
<td>-50 - +250</td>
<td>0 - +150</td>
<td>+/(0.1 + 0.0017*t)</td>
<td>100 +/- 0.04</td>
<td>0.27</td>
</tr>
<tr>
<td>A</td>
<td>-100 - +450</td>
<td>-30 - +300</td>
<td>+/(0.15 + 0.002*t)</td>
<td>100 +/- 0.06</td>
<td>0.35</td>
</tr>
<tr>
<td>B</td>
<td>-196 - +600</td>
<td>-50 - +500</td>
<td>+/(0.3 + 0.005*t)</td>
<td>100 +/- 0.12</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>-196 - +600</td>
<td>-50 - +600</td>
<td>+/(0.6 + 0.01*t)</td>
<td>100 +/- 0.24</td>
<td>1.6</td>
</tr>
</tbody>
</table>

*AAA (1/10DIN) is not included in the DIN-IEC-60751 spec but is an industry accepted tolerance class for high-performance measurements

**Manufacturers may choose to guarantee operation over a wider temperature range than the DIN-IEC60751 provides

- Repeatability usually very good, allows for individual sensor calibration
- Long-Term Drift usually <0.1C/year, can get as low as 0.0025C/year
### Why use an RTD?

#### Table Comparing Advantages and Disadvantages of Temp Sensors

<table>
<thead>
<tr>
<th></th>
<th>Thermocouple</th>
<th>RTD</th>
<th>Thermistor</th>
<th>I. C. Sensor</th>
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</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td></td>
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<tr>
<td>Self-powered</td>
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<td></td>
<td>Most linear</td>
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<tr>
<td>Simple</td>
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<td>Highest output</td>
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<td>Rugged</td>
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<td>Inexpensive</td>
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<td>Inexpensive</td>
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<td>Wide variety</td>
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<td>Wide temperature</td>
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<td>range</td>
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<td>Most stable</td>
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<td>Most stable</td>
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<td>Most accurate</td>
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<td>High output</td>
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<tr>
<td>More linear</td>
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<td>Fast</td>
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<td>than thermocouple</td>
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<td></td>
<td>Two-wire</td>
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<td>ohms</td>
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<td></td>
<td>measurement</td>
<td></td>
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<tr>
<td><strong>Disadvantages</strong></td>
<td>Non-linear</td>
<td>Expensive</td>
<td>Non-linear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low voltage</td>
<td>Current source required</td>
<td>Limited temperature range</td>
<td>T&lt;200°C</td>
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<tr>
<td></td>
<td>Reference required</td>
<td>Small ΔR</td>
<td></td>
<td>Power supply required</td>
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<tr>
<td></td>
<td>Least stable</td>
<td>Low absolute resistance</td>
<td>Fragile</td>
<td>Slow</td>
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<td></td>
<td>Least sensitive</td>
<td>Self-heating</td>
<td>Current source required</td>
<td>Self-heating</td>
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<td></td>
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<td>Self-heating</td>
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<td></td>
<td></td>
<td>Limited configurations</td>
</tr>
</tbody>
</table>
How to Measure an RTD Resistance?

- Use a…….

**Current Source** or **Wheatstone Bridge**

\[
V_{\text{meas}} = I_{\text{source}} \cdot R_{\text{RTD}}
\]

\[
R_{\text{RTD}} = \frac{V_{\text{meas}}}{I_{\text{source}}}
\]

\[
V_{\text{meas}} = V_{\text{source}} \cdot \left[ \left( \frac{R_{\text{RTD}}}{R_A + R_{\text{RTD}}} \right) - \frac{1}{2} \right]
\]

\[
R_{\text{RTD}} = \frac{2 \cdot R_A \cdot V_{\text{meas}} + R_A \cdot V_{\text{source}}}{V_{\text{source}} - 2 \cdot V_{\text{meas}}}
\]
Note on Non-Linear Output of Bridge

\[ V_{\text{meas}} = V_{\text{source}} \left( \frac{R_{\text{RTD}}}{R_{A} + R_{\text{RTD}}} \right) - \frac{1}{2} \]

Denominator causes a non-linear output even for a linear sensor

\[ \Delta RTD = 50 \text{Ohms} \]
Simple Current Source / Sink Circuits

**Circuit 1:**
- +5V
- R3 40k
- R4 10k
- U1 OPA333
- Q1
- I_Out 100uA
- Rset 10k

**Circuit 2:**
- +5V
- R8 40k
- R9 10k
- U2 OPA333
- Q2
- I_Out 100uA
- RTD 100

**Circuit 3:**
- +5V
- R1 10k
- R2 200k
- U8 REF5025
- Vin
- Vout
- Temp
- GND
- Trim
- Rset 25k
- RTD 100

**Circuit 4:**
- +5V
- R4 100
- U9 OPA340
- Vin
- Vout
- Temp
- GND
- Trim
- Rset 25k
- RTD 100

**REF200:**
- I_High
- I_Low
- Substrate
- Mirror Common
- Mirror Out

**Additional Circuits:**
- INA326T1 INA326T
- V2 2.5
- V3 2.5
- C1 100n
- V_diff -49.85m
- V_cm 2.5
- V2 2.5
- R1 10k
- R2 200k
- R3 49.9
RTD Types and Their Parasitic Lead Resistances

2-Wire

3-Wire

4-Wire

2-Wire with Compensating Loop
2-Wire Measurements

\[ V_{\text{meas}} = I_{\text{source}} \cdot R_{\text{RTD}} + I_{\text{source}} \cdot 2 \cdot R_L \]

Error = \( I_{\text{source}} \cdot 2R_L \)

\[ V_{\text{meas}} = V_{\text{source}} \cdot \left[ \frac{R_{\text{RTD}} + 2R_L}{R_A + R_{\text{RTD}} + 2R_L} \right] - \frac{1}{2} \]

Error = \( V_{\text{source}} \left[ \frac{2 \cdot R_A \cdot R_L}{(R_A + R_{\text{RTD}})(R_A + 2 \cdot R_L + R_{\text{RTD}})} \right] \)
3-Wire Measurements

\[ I_{source1} = I_{source2} = I \]

\[ V_{meas_+} = I \cdot R_L + I \cdot R_{RTD} + (2 \cdot I) \cdot R_L = I \cdot R_{RTD} + 3 \cdot I \cdot R_L \]

\[ V_{meas_-} = I \cdot R_L + (2 \cdot I) \cdot R_L = 3 \cdot I \cdot R_L \]

\[ V_{meas_+} - V_{meas_-} = (I \cdot R_{RTD} + 3 \cdot I \cdot R_L) - (3 \cdot I \cdot R_L) = I \cdot R_{RTD} \]

Error = 0 as long as \( I_{source1} = I_{source2} \) and \( R_L \) are equal
4-Wire Measurements

\[ V_{\text{meas}} = I_{\text{source}} \cdot R_{\text{RTD}} \]

System Errors reduced to measurement circuit accuracy

\[ V_{\text{meas}} = -\frac{R_A \cdot V_{\text{source}} \cdot (R_A - R_{\text{RTD}})}{2 \cdot R_A^2 + 6 \cdot R_A \cdot R_L + 2 \cdot R_{\text{RTD}} R_A + 4 \cdot R_L^2 + 2 \cdot R_{\text{RTD}} R_L} \]

Error = \[ V_{\text{source}} \left( \frac{R_L \cdot (2.0R_A - 2.0R_{\text{RTD}})}{(R_A + R_{\text{RTD}})(R_A + 4.0R_L + R_{\text{RTD}})} \right) \]
Self-Heating Errors of RTD

- Typically 2.5mW/C – 60mW/C
- Set excitation level so self-heating error is <10% of the total error budget
Callendar-Van Dusen Equations

For (T > 0): \( \text{RTD}(T) := R_0 \left[ 1 + A \cdot T + B \cdot (T^2) \right] \)

For (T < 0): \( \text{RTD}(T) := R_0 \left[ 1 + A \cdot T + B \cdot (T^2) + C \cdot (T^3) \cdot (T - 100) \right] \)

Equation Constants for IEC 60751 PT-100 RTD (\( \alpha = 0.00385 \))

\[
\begin{align*}
R_0 & := 100 \\
A & := 3.9083 \times 10^{-3} \\
B & := -5.7751 \times 10^{-7} \\
C & := -4.1831 \times 10^{-12}
\end{align*}
\]
RTD Nonlinearity

Linear fit between the two end-points shows the Full-Scale nonlinearity

Nonlinearity = 4.5%
Temperature Error > 45°C
For \((T > 0)\): \(\text{RTD}(T) := R_0 \left[1 + A \cdot T + B \cdot (T^2)\right]\)

For \((T < 0)\): \(\text{RTD}(T) := R_0 \left[1 + A \cdot T + B \cdot (T^2) + C \cdot (T^3) \cdot (T - 100)\right]\)

\(R_0 := 100\)

A := \(3.9083 \times 10^{-3}\)

B := \(-5.7751 \times 10^{-7}\)

C := \(-4.1831 \times 10^{-12}\)

\(\text{RTDlinear}(T) := R_0 \cdot (1 + A \cdot T)\)

B and C terms are negative so 2\text{nd} and 3\text{rd} order effects decrease the sensor output over the sensor span.
Measurement Nonlinearity

\[ V_{\text{meas}} = I_{\text{source}} \cdot R_{\text{RTD}} \]

RTD Sensor Output vs. Temperature (\(I_{\text{source}} = 100\mu\text{A}\))

- \(V_{\text{RTD}} (\text{Temp})\)
- \(V_{\text{RTD linear}} (\text{Temp})\)
Correcting for Non-Linearity

Sensor output decreases over span? Compensate by increasing excitation over span!

\[ V_{\text{meas}} = I_{\text{source}} \cdot R_{\text{RTD}} \]

Increasing excitation source over measurement span produces linear sensor output
Correcting for Non-linearity

\[ I_{source} := 0.0005 \]

\[ V_{RTD}(T) := RTD(T) \cdot I_{source} \]

\[ V_{RTD\_linear}(T) := RTD_{linear}(T) \cdot I_{source} \]

\[ I_{source\_correction}(T) := I_{source} + \frac{V_{RTD\_linear}(T) - V_{RTD}(T)}{RTD(T)} \]

\[ V_{RTD\_correction}(T) := RTD_{linear}(T) \cdot I_{source\_correction}(T) \]

\[ V_{RTD\_linearized}(T) := I_{source\_correction}(T) \cdot RTD(T) \]
Analog Linearization Circuits
Analog Linearization Circuits

Two-Wire Single Op-Amp

This circuit is designed for a 0-5V output for a 0-200°C temperature span. Components R2, R3, R4, and R5 are adjusted to change the desired measurement temperature span and output.

Example Amplifiers:

Low-Voltage:
OPA333
OPA376

High Voltage:
OPA188
OPA277

A voltage-controlled current source is formed from the op-amp output through R4 into the RTD.
Analog Linearization Circuits
Two-Wire Single Op-Amp

Non-linear increase in excitation current over temperature span will help correct non-linearity of RTD measurement.
Analog Linearization Circuits
Two-Wire Single Op-Amp

This type of linearization typically provides a 20X - 40X improvement in linearity.
Analog Linearization Circuits

Three-Wire Single INA

A voltage-controlled current source is formed from the INA output through Rlin into the RTD.

This circuit is designed for a 0-5V output for a 0-200°C temperature span. Components Rz, Rg, and Rlin are adjusted to change the desired measurement temperature span and output.

Example Amplifiers:

Low-Voltage:
INA333
INA114

High Voltage
INA826
INA114

Components Rz, Rg, and Rlin are adjusted to change the desired measurement temperature span and output.
Analog Linearization Circuits

Three-Wire Single INA

This type of linearization typically provides a 20X - 40X improvement in linearity and some lead resistance cancellation.
Analog Linearization Circuits
XTR105 4-20mA Current Loop Output

R1 975
R2 25
- + OA3
RL 250
i_Q1
Q1_INT
R4 1k
R5 1k
R_CL 0
Iref1 800μA
Iref2 800μA
Rz 100
Rlin1 16.099k
V_PS 24
Rcm 1.5k
Rg 162.644
Rlin 1k
- + OA1
- + OA2
i_jfet
VIN-
VCM
Q1
i_afe
I_Out
i_lin
VIN+
Q1_EXT
i_rtd
V_420
RTD 100
VCM

Texas Instruments
Analog Linearization Circuits

XTR105 4-20mA Current Loop Output

Temperature (°C)

I_{Out} (A)
Analog + Digital Linearization Circuits
XTR108 4-20mA Current Loop Output
Digital Acquisition Circuits and Linearization Methods
Digital Acquisition Circuits
ADS1118 16-bit Delta-Sigma 2-Wire Measurement with Half-Bridge
Digital Acquisition Circuits

ADS1220 24-bit Delta-Sigma Two 3-wire RTDs

3-wire + Rcomp shown for AIN2/AIN3
Digital Acquisition Circuits
ADS1247 24-bit Delta-Sigma Three-Wire + Rcomp

Note: $R_{\text{BIAS}}$ and $R_{\text{COMP}}$ should be as close to the ADC as possible.
Digital Acquisition Circuits
ADS1247 24-bit Delta-Sigma Four-Wire

Note: $R_{\text{BIAS}}$ should be as close to the ADC as possible.
Digital Linearization Methods

• Three main options
  – Linear-Fit
  – Piece-wise Linear Approximations
  – Direct Computations

\[ V_{\text{RTD}(\text{Temp})} \]

Temperature (°C) vs. RTD Sensor Output (V) (\( I_{\text{source}} = 100\mu\text{A} \))
Digital Linearization Methods

**Linear Fit**

**Pro's:**
- Easiest to implement
- Very Fast Processing Time
- Fairly accurate over small temp span

**Con's:**
- Least Accurate

\[ T_{\text{Linear}}(t) = A \cdot \text{RTD}(t) + B \]

**End-point Fit**

RTD Sensor Output vs. Temperature (Isource = 100uA)

**Best-Fit**

RTD Sensor Output vs. Temperature (Isource = 100uA)
Digital Linearization Methods

Piece-wise Linear Fit

Pro’s:

• Easy to implement
• Fast Processing Time
• Programmable accuracy

Con’s:

• Code size required for coefficients

\[
T_{\text{Peicewise}} = T(n - 1) + (T(n) - T(n - 1)) \left( \frac{\text{RTD} - \text{RTD}(n - 1)}{\text{RTD}(n) - \text{RTD}(n - 1)} \right)
\]

RTD Sensor Output vs. Temperature (Isource = 100uA)
Digital Linearization Methods

Direct Computation

Pro’s:
• Almost Exact Answer, Least Error
• With 32-Bit Math Accuracy to +/-0.0001C

Con’s:
• Processor intensive
• Requires Math Libraries
• Negative Calculation Requires simplification or bi-sectional solving

Positive Temperature Direct Calculation

\[ T_{Direct}(t) = -A + \sqrt{A^2 - 4B \cdot \left(1 - \frac{RTD(t)}{R_0}\right)} \]

Negative Temperature Simplified Approximation

\[ T_{Direct}(t) = -241.96 + 2.2163 \times RTD(t) + 2.8541 \times 10^{-3} \times RTD(t)^2 \]
\[ -9.912 \times 10^{-6} \times RTD(t)^3 - 1.7052 \times 10^{-8} \times RTD(t)^4 \]

RTD Sensor Output vs. Temperature (Isource = 100uA)
Digital Linearization Methods

Direct Computation

Bi-Section Method for Negative Temperatures

\[ T_{\text{Bisection}} := -99.999 \]

\[ \text{RTDError} := 100 \quad \text{Res} := 60.256 \quad \text{Tlow} := -250 \quad \text{Thigh} := 50 \]

\[ T_{\text{Bisection}} := \text{RTDTemp} \leftarrow 0 \]

\[ \text{while} \ (|\text{RTDError}| > 0.0001) \]

\[ T_{\text{mid}} \leftarrow \frac{(\text{Tlow} + \text{Thigh})}{2} \]

\[ \text{Real} \leftarrow 100 \left[ 1 + A \cdot T_{\text{mid}} + B \cdot T_{\text{mid}}^2 + (T_{\text{mid}} - 100) \cdot C \cdot T_{\text{mid}}^3 \right] \text{ if } T_{\text{mid}} < 0 \]

\[ \text{Real} \leftarrow 100 \left( 1 + A \cdot T_{\text{mid}} + B \cdot T_{\text{mid}}^2 \right) \text{ if } T_{\text{mid}} > 0 \]

\[ \text{Real} \leftarrow 0 \text{ if } \text{Real} < 0 \]

\[ \text{RTDError} \leftarrow \text{Res} - \text{Real} \]

\[ \text{Tlow} \leftarrow T_{\text{mid}} \text{ if } \text{RTDError} > 0 \]

\[ \text{Thigh} \leftarrow T_{\text{mid}} \text{ if } \text{RTDError} < 0 \]

\[ \text{RTDTemp} \leftarrow T_{\text{mid}} \]

\[ \text{return } \text{RTDTemp} \]

\[ T_{\text{Bisection}} = -99.999 \]
Questions/Comments?

Thank you!!

Special Thanks to:
Art Kay
Bruce Trump
PA Apps Team
Mike Beckman
Omega Sensors
RDF Corp
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Only those TI components that TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components that have not been so designated is solely at Buyer’s risk, and Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
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