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RTD to Voltage Reference Design Using Instrumentation Amplifier and Current Reference

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Circuit Description

This translates RTD resistance to a voltage level convenient for an ADC input. A precision current reference provides excitation and an instrumentation amplifier scales the signal. The design also uses a three wire RTD configuration to minimize errors due to wiring resistance.

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1 Design Summary

The design requirements are as follows:

- Supply Voltage: 5 V
- RTD temperature range: -50°C to 125°C
- RTD resistance range 80.3Ω to 147.9 Ω
- Output: 0.1V to 4.9V

The design goals and performance are summarized in Table 1. Figure 1 depicts the measured transfer function of the design.

Table 1. Comparison of Design Goals, Calculations, Simulation, and Measured Performance

<table>
<thead>
<tr>
<th></th>
<th>RTD</th>
<th>Goal</th>
<th>Calculated</th>
<th>Simulated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vout (Max scale)</td>
<td>80.3Ω</td>
<td>0.1V</td>
<td>0.112V</td>
<td>0.117V</td>
<td>0.113V</td>
</tr>
<tr>
<td>Vout (Min scale)</td>
<td>142.9Ω</td>
<td>4.9V</td>
<td>4.83V</td>
<td>4.82V</td>
<td>4.862V</td>
</tr>
</tbody>
</table>

Figure 1: Measured Transfer Function
Theory of Operation

Figure 2 and Figure 3 show the schematic of the RTD amplifier for minimum and maximum output conditions. Note that this circuit was designed for a -50°C to 150°C RTD temperature range. At -50°C the RTD resistance is 80.3Ω and the voltage across it is 8.03mV (VRTD = (100µA)(80.3Ω), see Figure 2). Notice that R3 develops a voltage drop that opposes the RTD drop. The drop across R3 is used to shift amplifiers input differential voltage to a minimum level. The output is the differential input multiplied by the gain (Vout = 698 ∙ 160µV = 0.111V). At 150°C the RTD resistance is 148Ω and the voltage across it is 14.8mV (VRTD = (100µA)(148Ω)). This produces a differential input of 6.93mV and an output voltage of 4.84V (Vout = 698 ∙ 6.93mV = 4.84V, see Figure 3).

Figure 2: RTD Amplifier with Minimum Output Condition

Figure 3: RTD Amplifier with Maximum Output Condition
2.1 Lead Resistance Cancelation (3 wire RTD)

Figure 4 below shows the three wire RTD configuration can be used to cancel lead resistance. Note that the resistance in each lead must be equal to cancel the error. Also, the two current sources in the REF200 need to be equal. Notice that the voltage developed on the two top leads of the RTD are equal and opposite polarity so that the amplifiers input is only from the RTD voltage. In this example, the RTD drop is 14.8mV and the leads each have 1mV. Notice that the 1mV drops cancel. Finally, notice that the voltage on the 3rd lead (2mV) creates a small shift in the common mode voltage. In some applications, a larger resistor is intentionally added to shift the common mode voltage. However, the INA326 has a rail to rail common mode range, so it can accept common mode voltages near ground.

2.2 Noise Calculation

The input noise is dominated by the INA326 noise (33nV/√Hz). The simplified calculation below ignores the noise from the REF200 and the thermal noise of the resistors. The noise simulation includes reference and thermal noise.

\[
f_c = \frac{1}{2 \cdot \pi \cdot R_s C_6} = \frac{1}{2 \cdot \pi \cdot (698k\Omega)(220pF)} = 1.0kHz \tag{1}
\]

\[
E_n = G \cdot e_n \sqrt{1.57 \cdot f_c} = 698 \cdot (33 \text{ nV/√Hz}) \sqrt{1.57 \cdot (1.0kHz)} = 0.91\text{mV rms} \tag{2}
\]

\[
E_{npp} = 6 \cdot E_n = 5.4\text{mVpp} \tag{3}
\]
2.3 **Input Filter**

Because the RTD leads are long, they may develop large common mode noise signals. The filter shown in Figure 5 is useful in attenuating the common mode noise pickup. Details on this configuration are covered in the Analog Engineers Pocket Reference (www.ti.com/analogrefguide).

$$f_{cm} = \frac{1}{2 \cdot \pi \cdot R_4 C_6} = \frac{1}{2 \cdot \pi \cdot (10k\Omega)(1nF)} = 15.9kHz$$  \hspace{2cm} (4)

$$f_{dif} = \frac{1}{2 \cdot \pi \cdot R_4 (C_8 + 0.5 \cdot C_6)} = \frac{1}{2 \cdot \pi \cdot (10k\Omega)(10nF + 0.5nF)} = 1.52kHz$$  \hspace{2cm} (5)
2.4 Selecting Gain and Offset Shift Resistors

1. Select the temperature measurement range and the corresponding RTD resistance at the temperature extremes. In this example we selected -50°C to 150°C. The RTD value can be calculated using the equations given in the Analog Engineers Pocket Reference (www.ti.com/analogrefguide). Note this is a PT-100 RTD that adheres to IEC-751 standards.

\[ A_0 = 3.9083 \times 10^{-3}, \quad B_0 = -5.775 \times 10^{-7}, \quad C_0 = -4.183 \times 10^{-12} \]  
(6)

\[ \text{RTD}(-50^\circ\text{C}) = 100 \cdot (1 + A_0 \cdot T + B_0 \cdot T^2 + C_0 \cdot (T - 100) \cdot T^3) = 80.31\Omega \]  
(7)

\[ \text{RTD}(150^\circ\text{C}) = 100 \cdot (1 + A_0 \cdot T + B_0 \cdot T^2) = 157.33\Omega \]  
(8)

2. Select the desired output voltage at the temperature extremes. Look at the output swing limitations of the amplifier. In this example, the INA326 output swing limitation is 75mV from each power supply rails. For a more robust design, use 100mV (0.1V < Vout range < 4.9V).

3. Calculate the required gain (\(\Delta V_{\text{out}}/\Delta V_{\text{in}}\))

\[ G = \frac{V_{\text{out max}} - V_{\text{out min}}}{(R_{\text{RTD max}} - R_{\text{RTD min}}) I_{\text{ref}}} = \frac{4.9V - 0.1V}{(148\Omega - 80.3\Omega)(100\mu\text{A})} = 709V/V \]  
(9)

4. Choose standard resistors to assure that the actual gain is equal to or less than the calculated gain. Do not choose a gain that is larger than the calculated gain as this may drive the output outside the linear range. Table 2 is an excerpt from the INA326 data sheet. Use Table 2 to determine the value of R1 and C2. The value of R2 is determined using the gain equation. Note that C2 can also be determined using Equation (14).

\[ G = \frac{2 \cdot R_2}{R_1} \]  
(10)

\[ R_2 = \frac{G \cdot R_1}{2} = \frac{709 \cdot (2\text{k}\Omega)}{2} = 709\text{k}\Omega \]  
(11)

\[ R_2 = 698\text{k}\Omega \]  
Closes standard value \(G_a \leq G\)  
(12)

\[ G_a = \frac{2 \cdot R_2}{R_1} = \frac{2 \cdot (698\text{k}\Omega)}{(2\text{k}\Omega)} = 698 \]  
(13)

\[ C_2 = \frac{1}{2 \cdot \pi \cdot R_2 \cdot f_c} = \frac{1}{2 \cdot \pi \cdot 698\text{k}\Omega \cdot 1\text{kHz}} = 228\text{pF} \]  
(14)

\[ C_2 = 220\text{pF} \]  
Closes standard value  
(15)
Table 2: Table excerpt from INA326 Data sheet.

| Desired Gain | R1 (Ω) | R2 || C2 (Ω || nF) |
|--------------|--------|------------------|
| 0.1          | 400k   | 20k || 5         |
| 0.2          | 400k   | 40k || 2.5       |
| 0.5          | 400k   | 100k || 1        |
| 1            | 400k   | 200k || 0.5      |
| 2            | 200k   | 200k || 0.5      |
| 5            | 80k    | 200k || 0.5      |
| 10           | 40k    | 200k || 0.5      |
| 20           | 20k    | 200k || 0.5      |
| 50           | 8k     | 200k || 0.5      |
| 100          | 4k     | 200k || 0.5      |
| 200          | 2k     | 200k || 0.5      |
| 500          | 2k     | 500k || 0.5      |
| 1000         | 2k     | 1M || 0.5      |
| 2000         | 2k     | 2M || 0.5      |
| 5000         | 2k     | 5M || 0.5      |
| 10000        | 2k     | 10M || 0.5     |

5. Calculate a value of R3 based on the minimum output voltage and the gain.

\[
V_{out\min} = G_{\text{actual}} \cdot (R_{RTDmin} - R3) \cdot I_{\text{ref}}
\]

Solve for R3 \hspace{1cm} (16)

\[
R3 = \frac{G_a \cdot I_{\text{ref}} \cdot R_{RTDmin} - V_{out\min}}{G_a \cdot I_{\text{ref}}} = \frac{698 \cdot 100 \mu A \cdot 80.3 \Omega - 0.1V}{698 \cdot 100 \mu A} = 78.8 \Omega
\]

\[
R3 = 78.7 \Omega
\]

Standard Value \hspace{1cm} (18)
3 Component Selection

3.1 Current Reference

The REF200 was because it is a convenient and simple way to generate a matched current source. The current setting of 100µA will work well for PT-100 and PT-1000 RTDs.

3.2 Passive Components

This design uses 1% thin film resistors and X7R ceramic capacitors. Special low distortion capacitors are not required in this application as the desired signal is dc.
Simulation

4.1 Transfer Function

The upper end points (temperature extremes) dc operating values were verified in simulation. The circuit below shows the simulation for the -50°C point (80.3Ω). Note that the value of the RTD was manually adjusted to the appropriate value to test the condition. Table 3 shows the results for this simulation. Note that the ability of the three wire RTD configuration to reject lead resistance was also tested in simulation.

![Circuit Diagram]

**Figure 6: Frequency response for OPA376 ac coupled amplifier**

**Table 3: DC Output for RTD Resistance**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>RTD Value</th>
<th>Output (0Ω line R)</th>
<th>Output (10Ω line R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50°C</td>
<td>80.3Ω</td>
<td>0.117V</td>
<td>0.117V</td>
</tr>
<tr>
<td>150°C</td>
<td>149.94Ω</td>
<td>4.82V</td>
<td>4.82V</td>
</tr>
</tbody>
</table>

Note: All lead resistances are equal (R_lead1 = R_lead2 = R_lead3)
4.2 Noise

The circuit used to simulate noise is shown in Figure 7 and the total integrated noise is shown in Figure 8. The simulated results compare well to the hand calculations (see Equations (1), (2), (3)).

![Figure 7: Noise Simulation Circuit](image1)

![Figure 8: Output Total rms Noise Simulation](image2)
5 PCB Design

The PCB schematic and bill of materials can be found in the Appendix.

5.1 PCB Layout

Normal PCB layout precautions were in this layout (i.e. short traces, solid ground connections, minimized vias, close decoupling capacitors).

Figure 9: PCB Layout (Top - Red, Bottom - Blue)
6 Verification & Measured Performance

6.1 Transfer Function

The measured and simulated ac transfer function are compared to each other in section 4.1. The measured results compare well with the simulations.

![Vout vs. RTD Resistance](image1)

**Figure 10: RTD to Vout Transfer function**

![Output Error vs. RTD Resistance](image2)

**Figure 11: Measured Error vs. RTD Resistance**
6.2 Noise Measurement

The measured noise results are shown in Figure 12. Note that the unfiltered noise is significantly higher than the calculated noise calculated and simulated earlier and the filtered is slightly higher. The previous calculations assumed a 1kHz low pass filter which was not included on the PCB design. Note that the noise contains auto-zero switching noise.

![Figure 12: Measured Noise](image)

![Figure 13: External 1.6kHz Low Pass Filter](image)
# Modifications

Depending on your design goal you may choose different values.

<table>
<thead>
<tr>
<th>Design Goal</th>
<th>Modification</th>
<th>Trade off</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTD Range</td>
<td>Select R1, R2, R3, and C1 based on the procedure in Section 2.4. This will change the gain and offset to accommodate the new range.</td>
<td>More narrow temperature ranges will be more sensitive to noise as the gain needed will be high.</td>
</tr>
<tr>
<td>RTD Type</td>
<td>Select R1, R2, R3, and C1 based on the procedure in Section 2.4</td>
<td>PT-1000 will produce larger signals, so it will require less gain and be less sensitive to error sources (noise, and dc amplifier errors).</td>
</tr>
<tr>
<td>Reduce Noise</td>
<td>Add simple low pass filter. See Figure 13</td>
<td>Extra cost and complexity. This change will also increases the output impedance. See Figure 13</td>
</tr>
<tr>
<td>Improved Gain and Offset Accuracy</td>
<td>Use 0.1% resistors to set gain and offset (R1, R2, and R3)</td>
<td>Cost</td>
</tr>
</tbody>
</table>
8 About the Author

Arthur Kay is an applications engineering manager at TI where he specializes in the support of amplifiers, references, and mixed signal devices. Arthur focuses a good deal on industrial applications such as bridge sensor signal conditioning. Arthur has published a book and an article series on amplifier noise. Arthur received his M.S.E.E. from Georgia Institute of Technology, and B.S.E.E. from Cleveland State University.

9 Acknowledgements & References


Appendix A.

A.1 Electrical Schematic

Figure A-1: Electrical Schematic
## A.2 Bill of Materials

<table>
<thead>
<tr>
<th>QTY</th>
<th>Designator</th>
<th>Description</th>
<th>LibRef</th>
<th>Supplier Part Number</th>
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<td>3</td>
<td>C1, C4, C5</td>
<td>CAP, CERM, 0.1 µF, 25 V, +/-10%, X5R, 0603</td>
<td>06033D104KAT2A</td>
<td>478-1244-1-ND</td>
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<td>1</td>
<td>C2</td>
<td>CAP, CERM, 220 pF, 50 V, +/-5%, C0G/NP0, 0603</td>
<td>GRM1885C1H221JA01D</td>
<td>490-1435-1-ND</td>
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<td>C3</td>
<td>CAP, TA, 10 µF, 50 V, +/-10%, 0.8 ohm, SMD</td>
<td>293D106X9050E2TE3</td>
<td>718-1022-1-ND</td>
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<tr>
<td>2</td>
<td>C6, C7</td>
<td>CAP, CERM, 1000 pF, 100 V, +/-5%, X7R, 0603</td>
<td>06031C102JAT2A</td>
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<td>C8</td>
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<td>06031C103JAT2A</td>
<td>478-3700-1-ND</td>
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<td>1</td>
<td>J1</td>
<td>Screw Terminal, 3 Pos, 3.5mm Spacing, Through Hole</td>
<td>ED555/3DS</td>
<td>ED1515-ND</td>
</tr>
<tr>
<td>1</td>
<td>J2</td>
<td>Screw Terminal, 2 pos, 3.5mm Spacing, Through Hole</td>
<td>ED555/2DS</td>
<td>ED1514-ND</td>
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<tr>
<td>2</td>
<td>J4, J5</td>
<td>JACK NON-INSULATED .218&quot;, Banana Jack</td>
<td>575-4</td>
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<td>RES, 2.00 k, 0.1%, 0.063 W, 0603</td>
<td>MCT06030C2001FP500</td>
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<tr>
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<td>R2</td>
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<td>CRCW0603698KFKEA</td>
<td>541-698KHCT-ND</td>
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<td>R3</td>
<td>RES, 78.7, 1%, 0.125 W, 0805</td>
<td>CRCW080578R7FKEA</td>
<td>541-78.7CCT-ND</td>
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<tr>
<td>2</td>
<td>R4, R5</td>
<td>RES, 10 k, 0.1%, 0.063 W, 0603</td>
<td>MCT06030C1002FP500</td>
<td>MCT0603-10.0K-CFCT-ND</td>
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<tr>
<td>4</td>
<td>TP1, TP3, TP4, TP5</td>
<td>Test Point, TH, Compact, Red</td>
<td>5005</td>
<td>5005K-ND</td>
</tr>
<tr>
<td>2</td>
<td>TP2, TP6</td>
<td>Test Point, TH, Compact, Black</td>
<td>5006</td>
<td>5006K-ND</td>
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<tr>
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<td>U1</td>
<td>Precision, Rail-to-Rail I/O INSTRUMENTATION AMPLIFIER, VSSOP-8</td>
<td>INA326EA</td>
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<td>1</td>
<td>U2</td>
<td>REF200</td>
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<td>Keystone Electronics</td>
<td>2205K-ND</td>
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<td></td>
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<td>MACHINE SCREW PAN PHILLIPS 4-40</td>
<td>B&amp;F Fastener Supply</td>
<td>H703-ND</td>
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