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TI Designs – Precision: Verified Design

RTD to Voltage Reference Design Using Instrumentation Amplifier and Current Reference

TEXAS INSTRUMENTS

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Design Resources

Design Archive	All Design files
TINA-TI™	SPICE Simulator
REF200	Product Folder
INA326	Product Folder

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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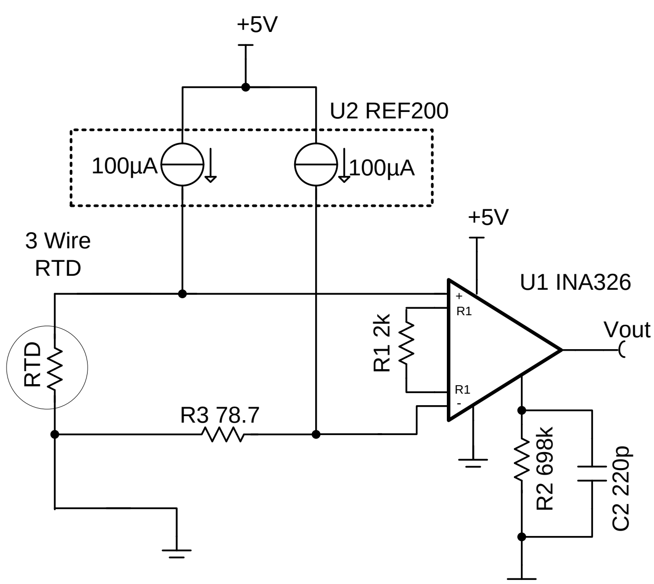

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1 Design Summary

The design requirements are as follows:

- Supply Voltage: 5 V
- RTD temperature range: -50℃ to 125℃
- 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

	RTD	Goal	Calculated	Simulated	Measured
Vout (Max scale)	80.3Ω	0.1V	0.112V	0.117V	0.113V
Vout (Min scale)	142.9Ω	4.9V	4.83V	4.82V	4.862V

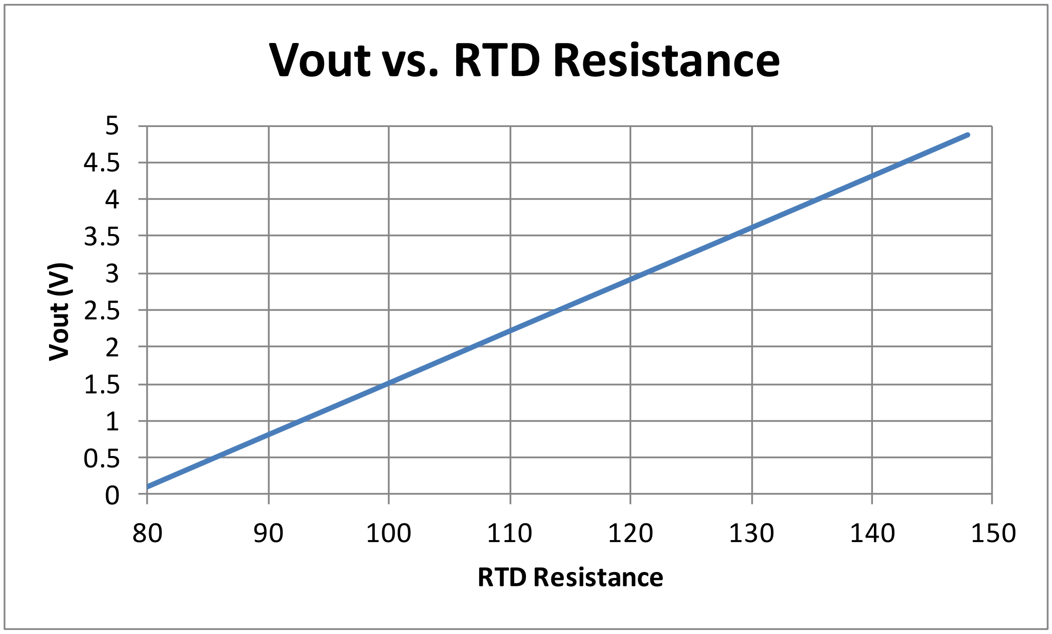

Figure 1: Measured Transfer Function

2 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℃ to 150℃ RTD temperature range. At -50℃ 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℃ 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).

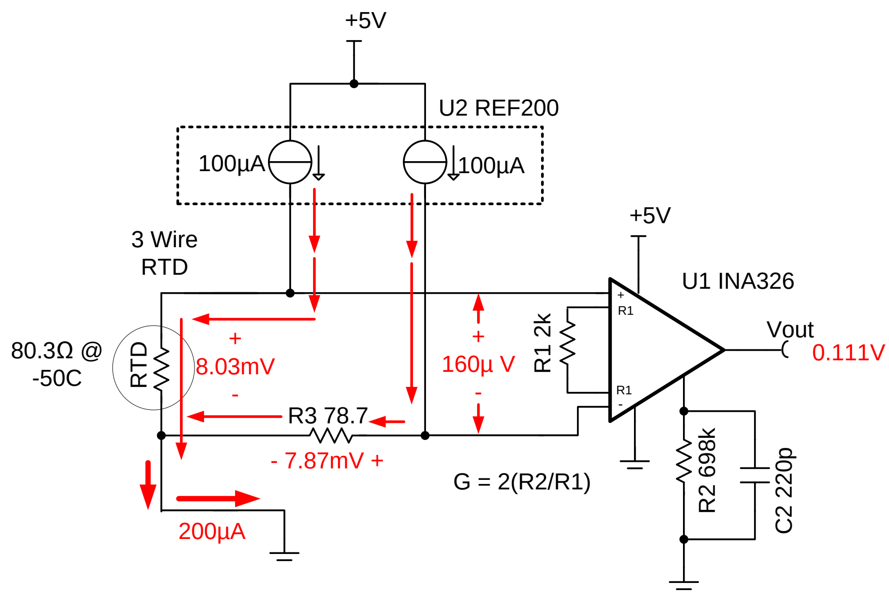

Figure 2: RTD Amplifier with Minimum Output Condition

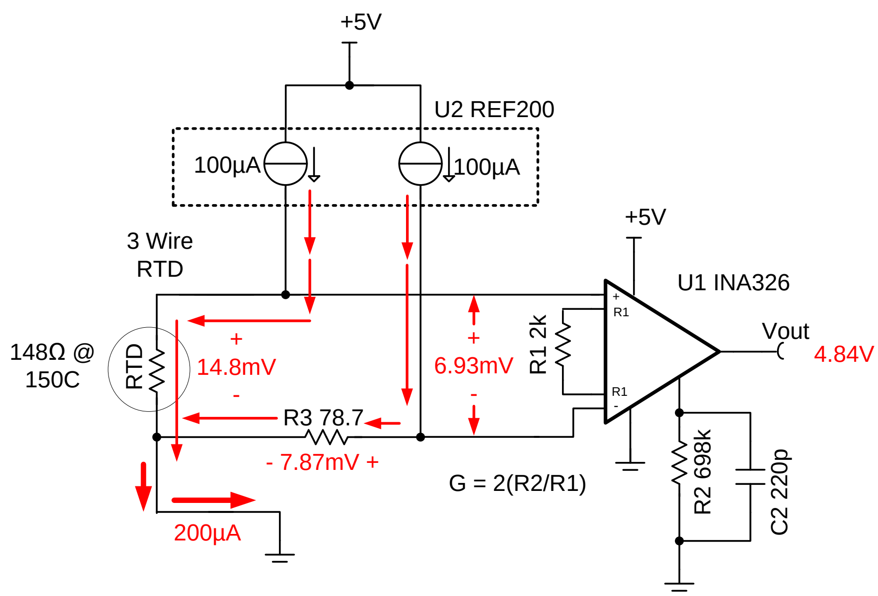

Figure 3: RTD Amplifier with Maximum Output Condition

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.

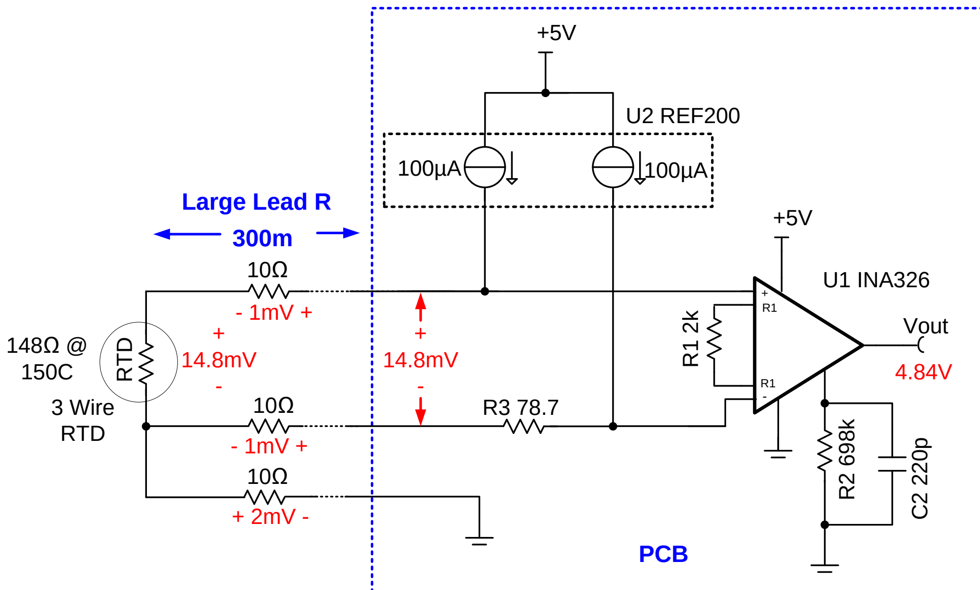

Figure 4: Three wire RTD configuration cancels lead resistance

2.2 Noise Calculation

The input noise is dominated by the INA326 noise (33nV/rtHz). 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.

$$f_c = \frac{1}{2 \cdot \pi \cdot R_4 C_6} = \frac{1}{2 \cdot \pi \cdot (698k\Omega)(220pF)} = 1.0kHz \quad (1)$$

$$E_n = G \cdot e_n \sqrt{1.57 \cdot f_c} = 698 \cdot \left(33\,nV/\sqrt{Hz}\right)\sqrt{1.57 \cdot (1.0kHz)} = 0.91mV\ rms \quad (2)$$

$$E_{npp} = 6 \cdot E_n = 5.4mVpp \quad (3)$$

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).

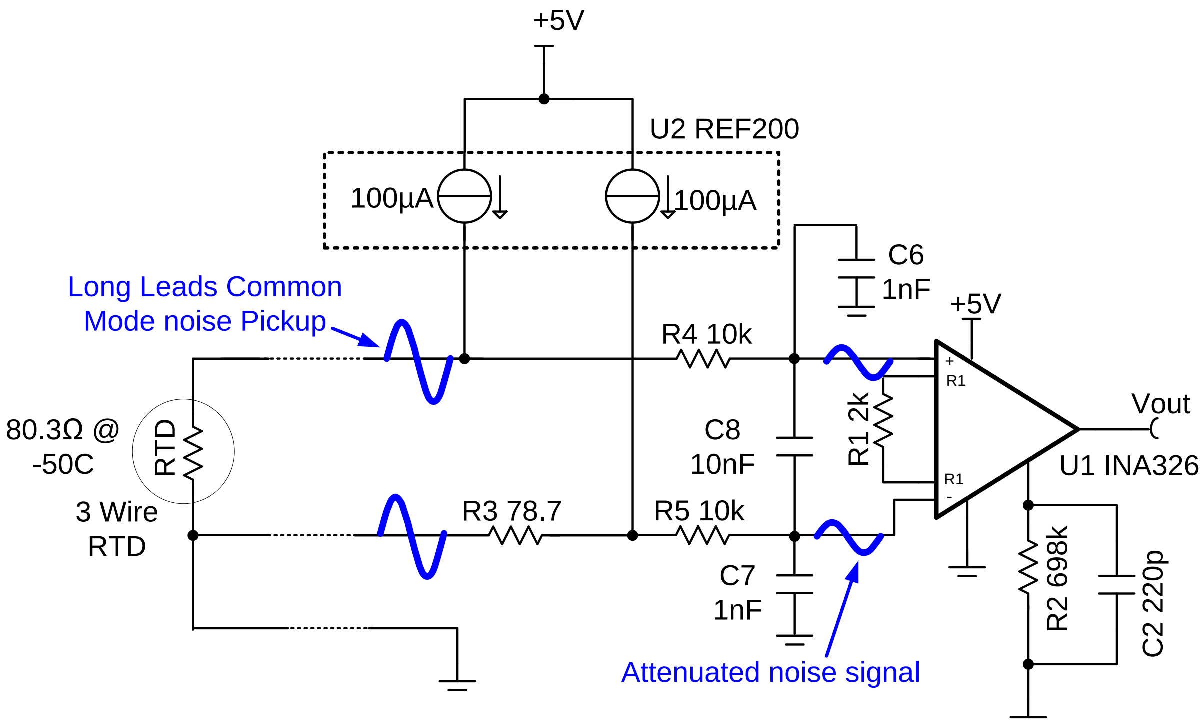

Figure 5: Common Mode and Differential Noise filter

$$R4 = R5, \quad C6 = C7 = C_{cm}, \quad C8 = C_{dif}$$

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

$$f_{dif} = \frac{1}{2 \cdot \pi \cdot R_4 (C_8 + 0.5 \cdot C_6)} = \frac{1}{2 \cdot \pi \cdot (10k\Omega)(10nF + 0.5nF)} = 1.52kHz \quad (5)$$

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℃ to 150℃. 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.

$$A_0 = 3.9083 \cdot 10^{-3}, \quad B_0 = -5.775 \cdot 10^{-7}, \quad C_0 = -4.183 \cdot 10^{-12} \qquad (6)$$

$$RTD(-50°C) = 100 \cdot (1 + A_0 \cdot T + B_0 \cdot T^2 + C_0 \cdot (T - 100) \cdot T^3 = 80.31\Omega \qquad (7)$$

$$RTD(150°C) = 100 \cdot (1 + A_0 \cdot T + B_0 \cdot T^2) = 157.33\Omega \qquad (8)$$

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 (ΔVout/ΔVin)

$$G = \frac{V_{outmax} - V_{outmin}}{(R_{RTDmax} - R_{RTDmax})I_{ref}} = \frac{4.9V - 0.1V}{(148\Omega - 80.3\Omega)(100\mu A)} = 709V/V \qquad (9)$$

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 a 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**).

$$G = \frac{2 \cdot R2}{R1} \qquad (10)$$

Figure 1 INA326 data sheet

$$R2 = \frac{G \cdot R1}{2} = \frac{709 \cdot (2k\Omega)}{2} = 709k\Omega \qquad (11)$$

$$R2 = 698k\Omega \qquad (12)$$

Closes standard value $G_a \leq G$

$$G_a = \frac{2 \cdot R2}{R1} = \frac{2 \cdot (698k\Omega)}{(2k\Omega)} = 698 \qquad (13)$$

$$C2 = \frac{1}{2 \cdot \pi \cdot R2 \cdot f_c} = \frac{1}{2 \cdot \pi \cdot 698k\Omega \cdot 1kHz} = 228pF \qquad (14)$$

$$C2 = 220pF \qquad (15)$$

Closes standard value

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
10,000	2k	10M || 0.5

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

$$\mathbf{V_{outmin} = G_{actual} \cdot (R_{RTDmin} - R3) \cdot I_{ref}}$$ Solve for R3 (16)

$$\mathbf{R3 = \frac{G_a \cdot I_{ref} \cdot R_{RTDmin} - V_{outmin}}{G_a \cdot I_{ref}} = \frac{698 \cdot 100\mu A \cdot 80.3\Omega - 0.1V}{698 \cdot 100\mu A} = 78.8\Omega}$$ (17)

$$\mathrm{R3} = 78.7\Omega$$ Standard Value (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.

4 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 -50C 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.

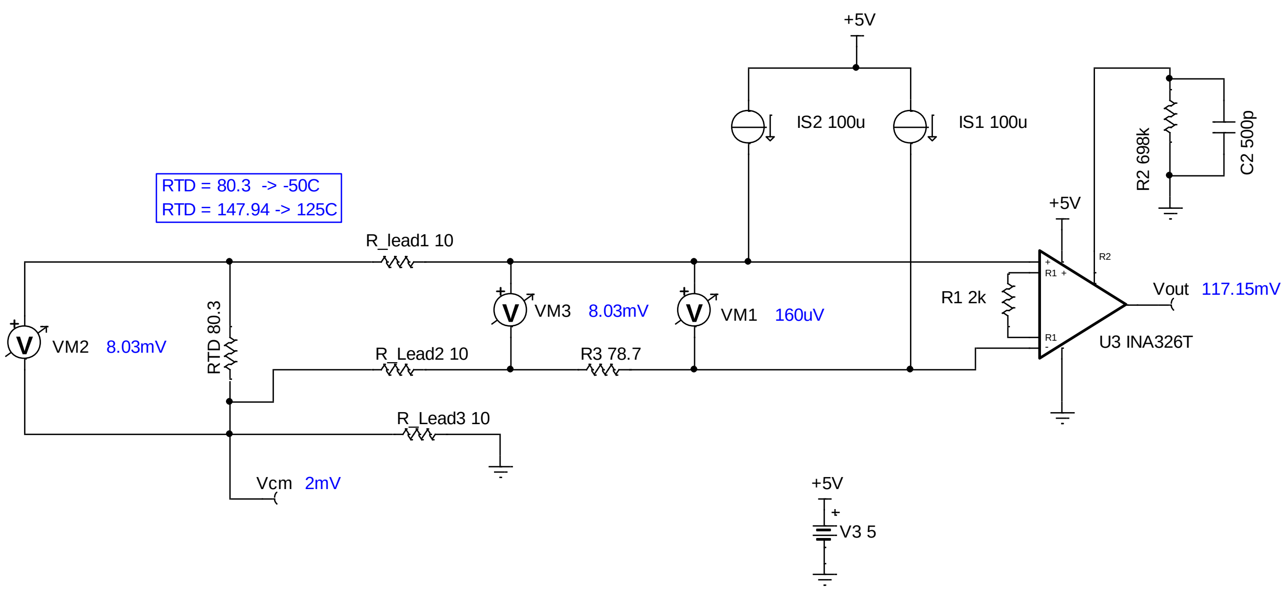

Figure 6: Frequency response for OPA376 ac coupled amplifier

Table 3: DC Output for RTD Resistance

Temperature	**RTD Value**	**Output (0Ω line R)**	**Output (10Ω line R)**
-50℃	80.3Ω	0.117V	0.117V
150℃	149.94Ω	4.82V	4.82V

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)**).

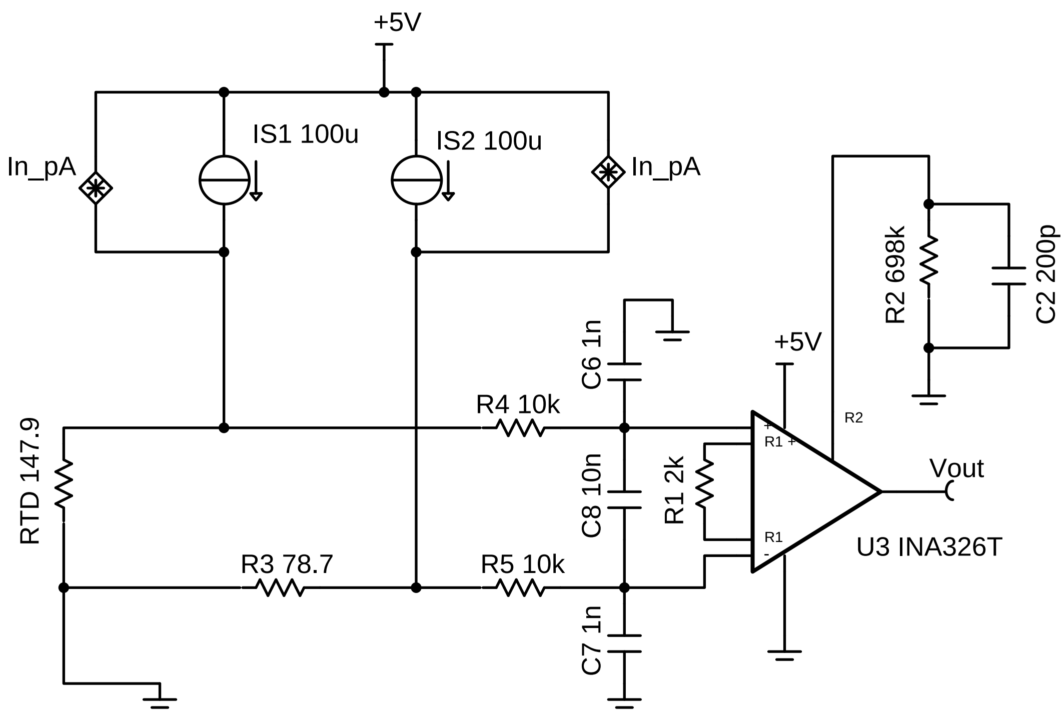

Figure 7: Noise Simulation Circuit

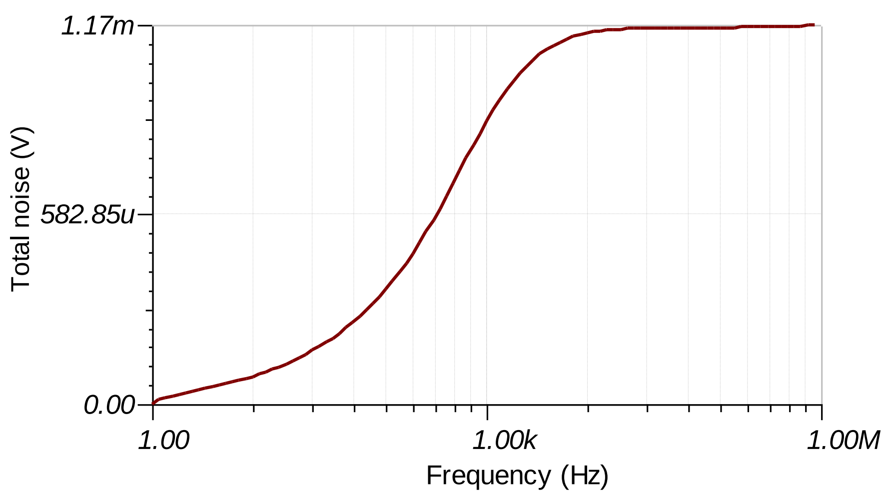

Figure 8: Output Total rms Noise Simulation

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).

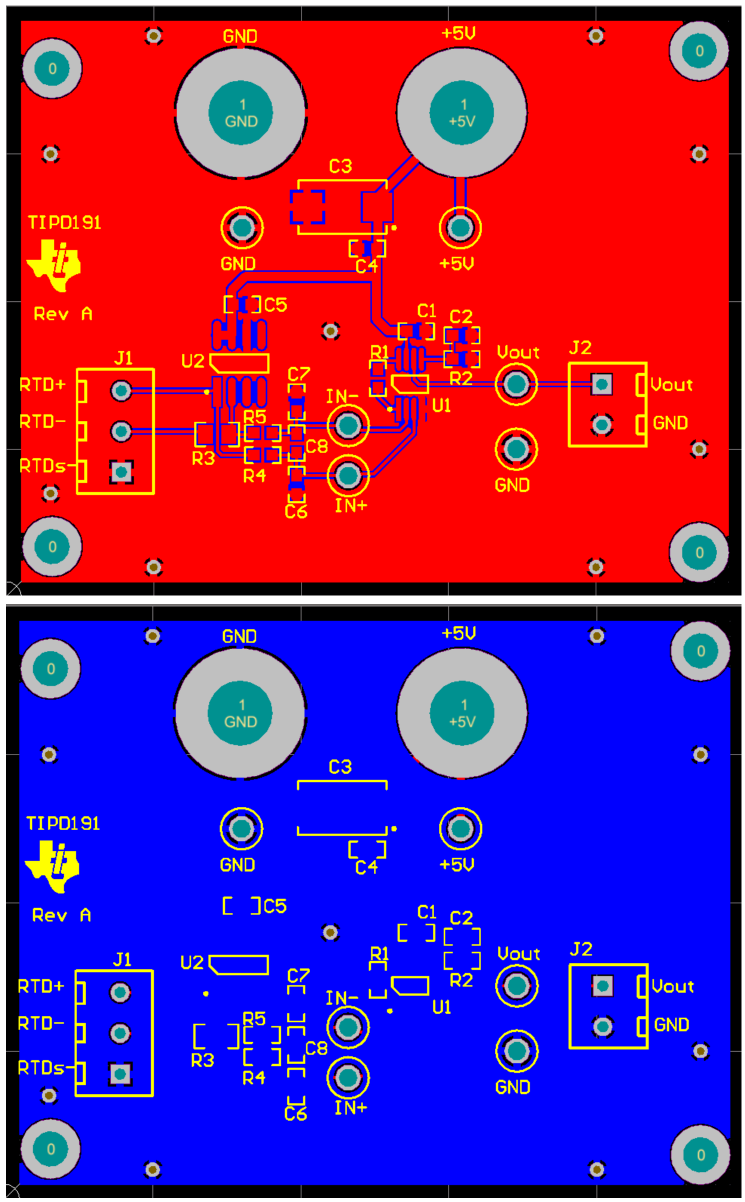

Figure 9: PCB Layout (Top - Red, Bottom - Blue)

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.

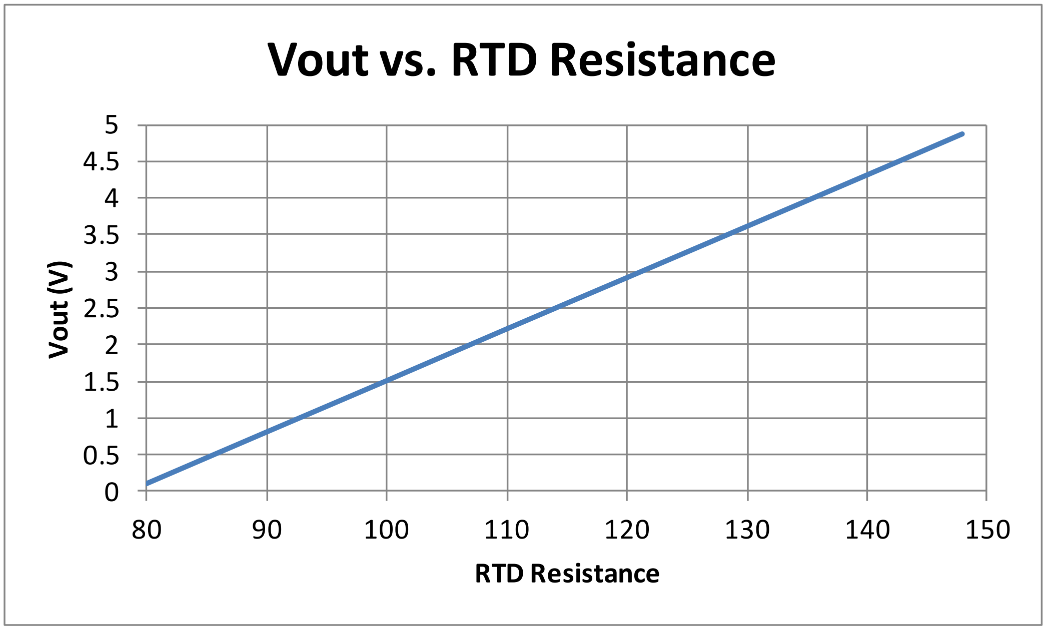

Figure 10: RTD to Vout Transfer function

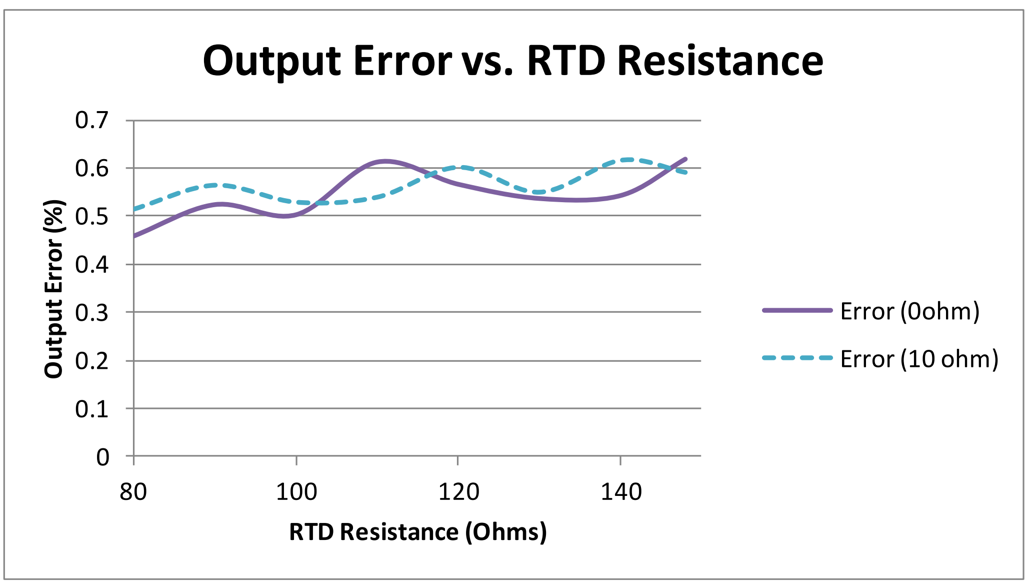

Figure 11: Measured Error vs. RTD Resistance

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 calculate 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.

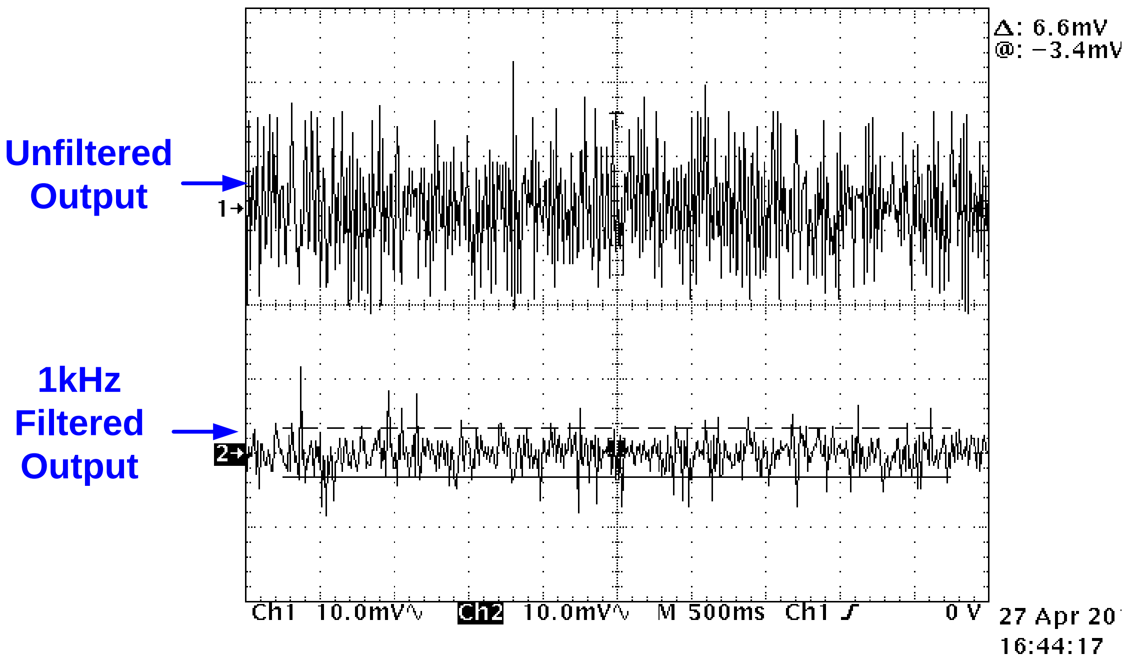

Figure 12: Measured Noise

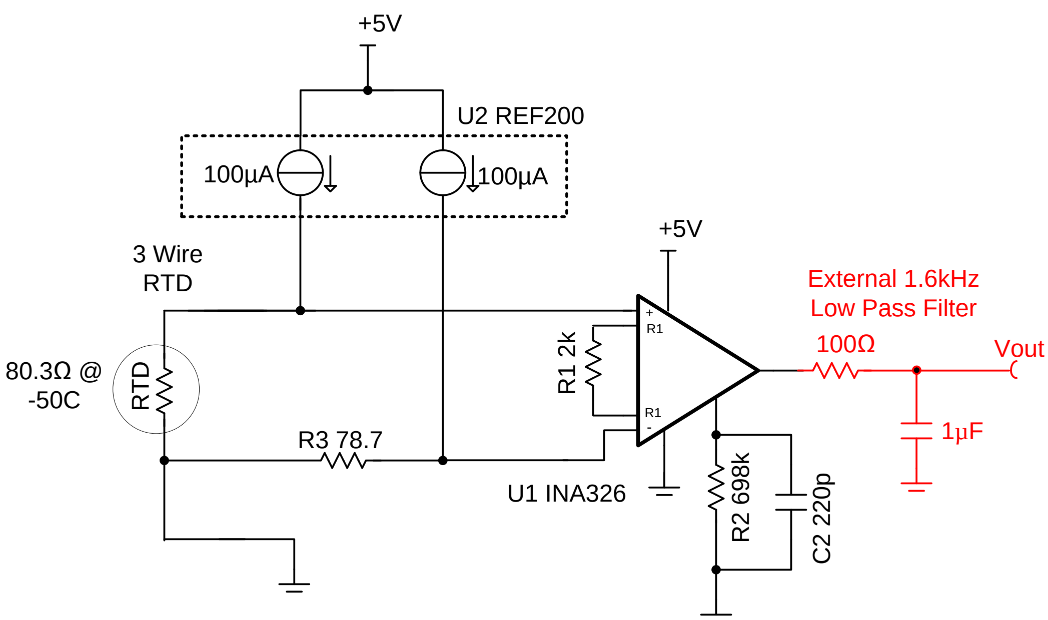

Figure 13: External 1.6kHz Low Pass Filter

7 Modifications

Depending on your design goal you may choose different values.

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

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

1. *A. Kay, Operational Amplifier Noise: Techniques and Tips for Analyzing and Reducing Noise. Elsevier, 2012.*

2. *A. Kay and T. Green. (2012, February 8). Analog Engineer's Pocket Reference. Available: www.ti.com/analogrefguide*

Appendix A.

A.1 Electrical Schematic

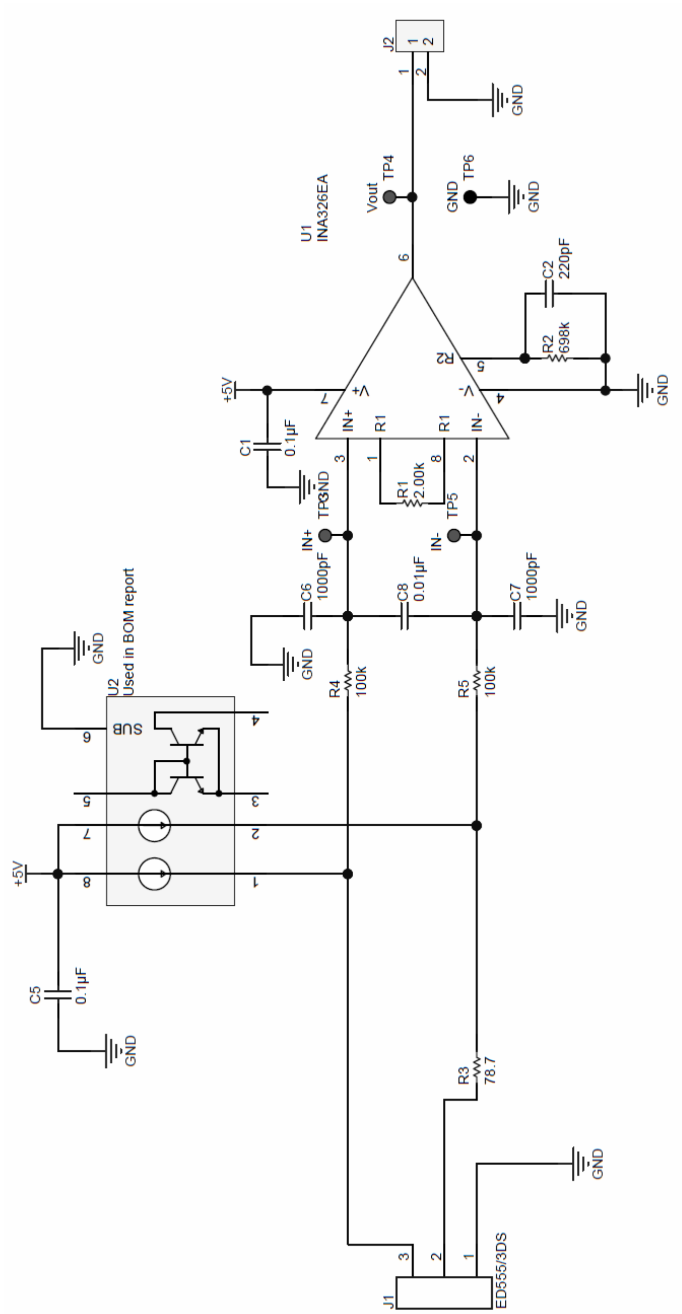

Figure A-1: Electrical Schematic

A.2 Bill of Materials

QTY	Designator	Description	LibRef	Supplier Part Number
3	C1, C4, C5	CAP, CERM, 0.1 µF, 25 V, +/- 10%, X5R, 0603	06033D104KAT2A	478-1244-1-ND
1	C2	CAP, CERM, 220 pF, 50 V, +/- 5%, C0G/NP0, 0603	GRM1885C1H221JA01D	490-1435-1-ND
1	C3	CAP, TA, 10 µF, 50 V, +/- 10%, 0.8 ohm, SMD	293D106X9050E2TE3	718-1022-1-ND
2	C6, C7	CAP, CERM, 1000 pF, 100 V, +/- 5%, X7R, 0603	06031C102JAT2A	478-3698-1-ND
1	C8	CAP, CERM, 0.01 µF, 100 V, +/- 5%, X7R, 0603	06031C103JAT2A	478-3700-1-ND
1	J1	Screw Terminal, 3 Pos, 3.5mm Spacing, Through Hole	ED555/3DS	ED1515-ND
1	J2	Screw Terminal, 2 pos, 3.5mm Spacing, Through Hole	ED555/2DS	ED1514-ND
2	J4, J5	JACK NON-INSULATED .218",Banana Jack	575-4	575-4K-ND
1	R1	RES, 2.00 k, 0.1%, 0.063 W, 0603	MCT06030C2001FP500	MCT0603-2.00K-CFCT-ND
1	R2	RES, 698 k, 1%, 0.1 W, 0603	CRCW0603698KFKEA	541-698KHCT-ND
1	R3	RES, 78.7, 1%, 0.125 W, 0805	CRCW080578R7FKEA	541-78.7CCT-ND
2	R4, R5	RES, 10 k, 0.1%, 0.063 W, 0603	MCT06030C1002FP500	MCT0603-10.0K-CFCT-ND
4	TP1, TP3, TP4, TP5	Test Point, TH, Compact, Red	5005	5005K-ND
2	TP2, TP6	Test Point, TH, Compact, Black	5006	5006K-ND
1	U1	Precision, Rail-to-Rail I/O INSTRUMENTATION AMPLIFIER, VSSOP-8	INA326EA	INA326EA/2K5CT-ND
1	U2		REF200	296-27726-1-ND
		STANDOFF HEX 4-40THR ALUM 1L"	Keystone Electronics	2205K-ND
		MACHINE SCREW PAN PHILLIPS 4-40	B&F Fastener Supply	H703-ND