TI Designs – Precision
Single-Supply Thermocouple Amplifier With RTD Based Cold-Junction Compensation Reference Design

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Design Resources

TIPD209	Design Folder
TINA-TI™	SPICE Simulator
INA188	Product Folder
OPA2317	Product Folder
REF02	Product Folder

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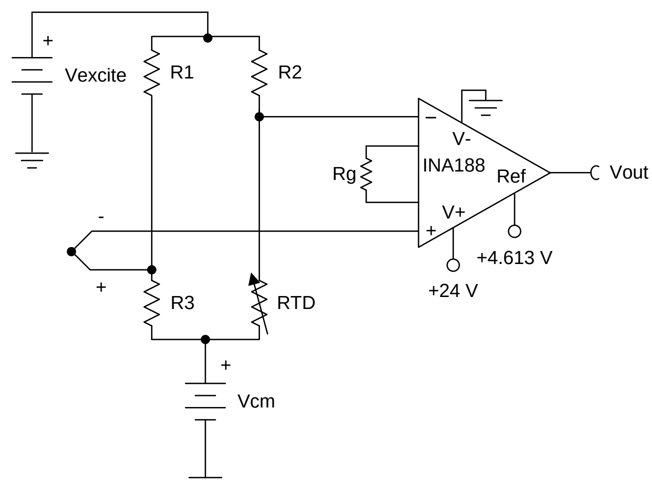
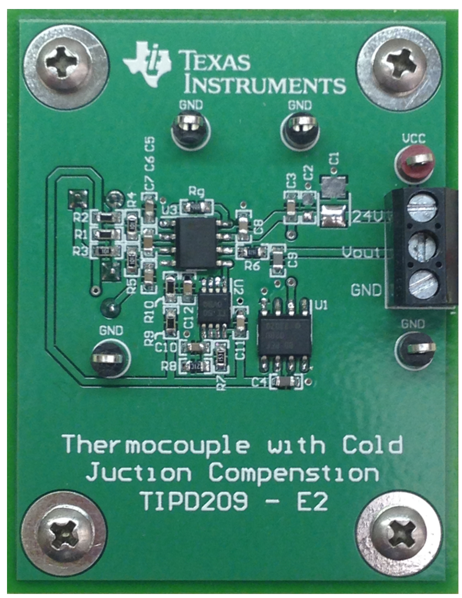
Circuit Description

This TI Design uses a thermocouple to measure temperatures from –50°C to +500°C. The design uses cold-junction compensation to reduce errors associated with changes in the cold-junction temperature of the thermocouple. The design operates on a single 24-V supply and has a linear-output range of 250 mV to 5 V.





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1 Design Summary

The following list details the design requirements:

- 6-V to 36-V supply voltage
- 24-V supply voltage
- 250-mV to 5-V output
- 2.6-V common-mode voltage
- 5-V excitation voltage
- –50°C to +500°C hot-junction temperature
- 0°C to 75°C cold-junction temperature

Table 1 lists the design goals and performance. Figure 1 shows the measured transfer function of the design.

Table 1. Comparison of Design Goals, Calculation and Measured Performance

	GOAL	CALCULATED (TYP)	MEASURED (% FSR)
Total error (% FSR)	±0.3% (1.65°C)	0.229% (1.26°C)	–0.037% (–0.2035°C)
Accuracy of cold-junction comparison	±3% (16.5°C)	–2.074% (11.41°C)	–2.12% (11.66°C)

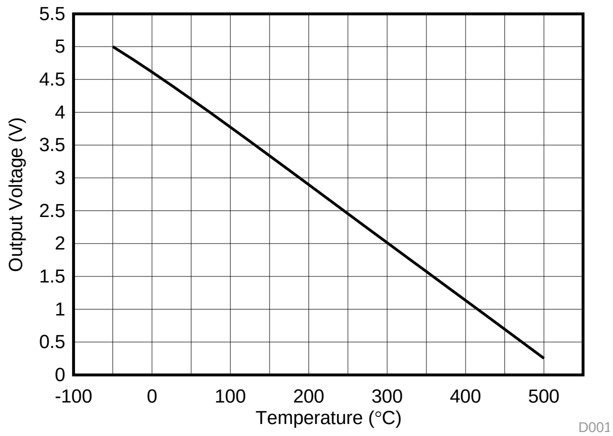

Figure 1. Output Voltage versus Hot-Junction Temperature

2 Theory of Operation

2.1 Thermocouple Measurement Topology

A thermocouple is a temperature sensor that produces a voltage that is dependent on the temperature difference between the hot junction and cold junction. The thermocouple is placed in the circuit configuration shown in Figure 2 to condition the voltage produced by the thermocouple (V_{tc}).

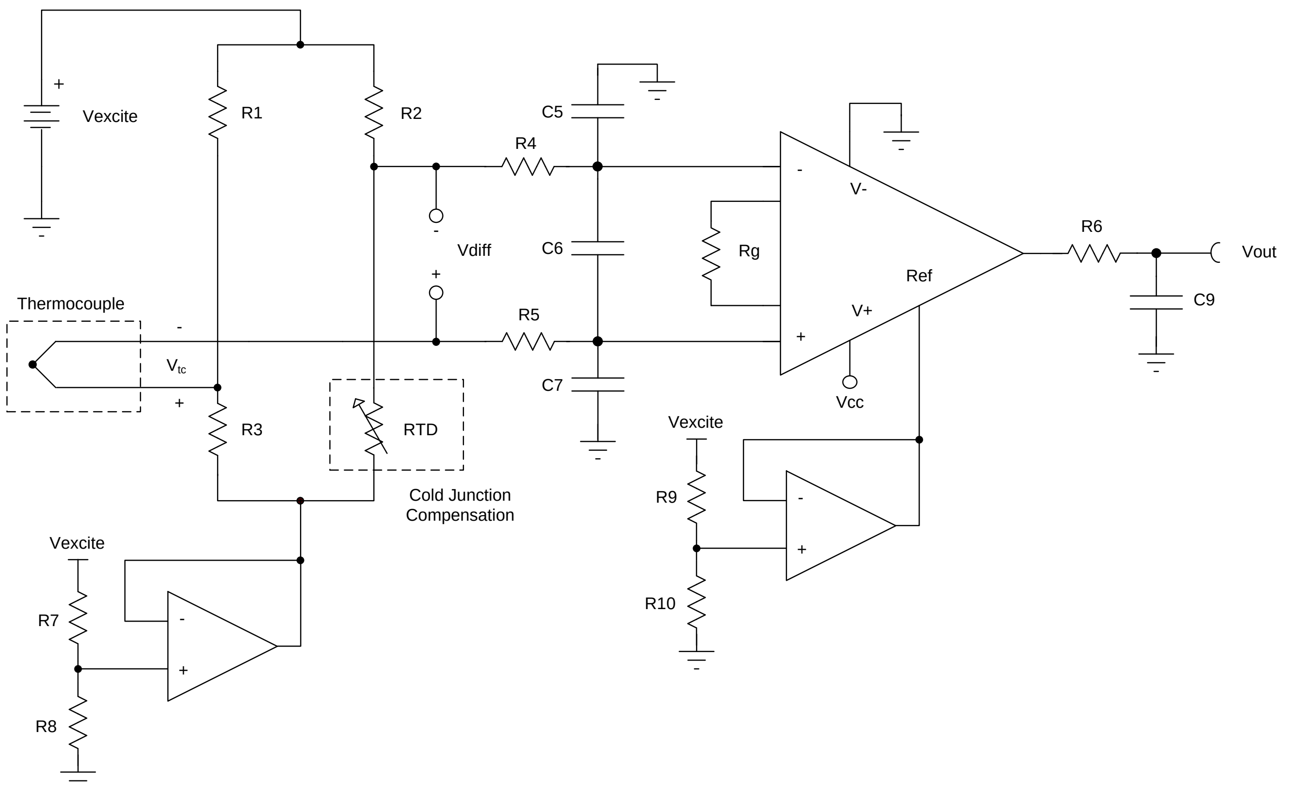

Figure 2. Thermocouple With Cold Junction Compensation Measurement Topology

Equation 1 shows the transfer function of the circuit shown in Figure 2.

$$V_{out} = V_{diff} \times G + V_{ref}$$

Where:

- V_{out} = the output voltage of the amplifier
- V_{diff} = the differential-input voltage of the amplifier
- G = the gain of the amplifier
- V_{ref} = the reference voltage of the amplifier (1)

Use Equation 2 to calculate the differential-input voltage.

$$V_{diff} = \frac{(R_{RTD}R_1 - R_2R_3)(V_{cm} - V_{excite})}{R_1R_2 + R_{RTD}R_1 + R_2R_3 + R_{RTD}R_3} - V_{tc} \quad (2)$$

2.2 Cold Junction Compensation

Cold-junction compensation is used to correct for a change in thermocouple voltage because of a change in the cold-junction temperature, but does not correct for linearity errors of the sensor. The resistance-temperature detector (RTD) shown in Figure 2 measures the cold-junction temperature and changes the resistance based on the cold-junction temperature. To compensate for the change in thermocouple voltage, the change in voltage across the RTD must be equal to the change in thermocouple voltage. Equation 3 shows the change in thermocouple voltage equal to the change in voltage across the RTD.

$$V_{SB} = \frac{(V_{excite} - V_{cm})}{R_2} \times \alpha$$

Where:

- V_{SB} = the Seebeck coefficient of the thermocouple in V/°C units
- α = the temperature coefficient of the RTD in Ω/°C units (3)

Use Equation 4 to calculate the value for the compensation resistor (R2).

$$R_2 = \frac{(V_{excite} - V_{cm})}{V_{SB}} \times \alpha \quad (4)$$

Resistors R_1, R_2, and R_3 must be selected so that the bridge is balanced at a cold-junction temperature of 0°C. R_1 must be set equal to R_2, and R_3 must be set equal to the resistance of the RTD at 0°C ($R_{RTD\ @\ 0°C}$). Use Equation 5 and Equation 6 to determine how to select the resistors in the bridge.

$$R_1 = R_2 \quad (5)$$

$$R_3 = R_{RTD@0°C} \quad (6)$$

2.3 Filtering

2.3.1 Common Mode and Differential Input Filter

Input filters are used in this design to reduce the noise that is fed into the instrumentation amplifier. Because the voltage produced by the thermocouple is a DC voltage, the cutoff frequencies of the filters must be set near DC to maximize filtered noise.

The cutoff frequency of the differential-input filter must be set to greater than 20 times the cutoff frequency of the common-mode filter to prevent common-mode noise from being translated to a differential signal. These cutoff frequencies are achieved by sizing the differential capacitor to be 10 times the size of the common-mode capacitors. Use Equation 7 to calculate the common-mode filter cutoff frequency (f_{cm}), and use Equation 8 to calculate the differential-filter cutoff frequency (f_{diff}).

$$f_{cm} = \frac{1}{2 \times \pi \times R_4 \times C_5} \quad (7)$$

$$f_{diff} = \frac{1}{2 \times \pi \times (R_4 + R_5) \times \left(C_6 + \frac{C_5}{2}\right)} \quad (8)$$

2.3.2 Output Filter

An output filter is used in this design to reduce noise on the output of the instrumentation amplifier. Use Equation 9 to calculate the cutoff frequency of the output filter.

$$f_{out} = \frac{1}{2 \times \pi \times R_6 \times C_9} \quad (9)$$

2.4 Gain

The instrumentation amplifier amplifies the input-differential voltage to create an output-voltage swing of 250 mV to 5 V. Use Equation 10 to calculate the required gain of the instrumentation amplifier.

$$G = \frac{V_{out\_max} - V_{out\_min}}{V_{diff\_max} - V_{diff\_min}} = \frac{5\text{ V} - 250\text{ mV}}{2.431\text{ mV} - (-27.393\text{ mV})} = 159.3\text{ V / V} \tag{10}$$

2.5 Reference Voltage

A reference voltage is supplied to the instrumentation amplifier to offset negative-input differential voltages produced by the thermocouple and cold-junction compensation. Use Equation 11 to calculate the reference voltage.

$$V_{ref} = V_{out\_min} - V_{diff\_min} \times G = 250\text{ mV} - (-27.393\text{ mV}) \times 159.3\text{ V / V} = 4.614\text{ V}$$

Where:

- V_{out_min} = minimum-output voltage
- V_{diff_min} = minimum-differential input (11)

3 Component Selection

3.1 Instrumentation Amplifier

The INA188 instrumentation amplifier was selected for this design because of the low drift, low offset, and high supply-voltage specifications.

3.2 Reference Voltage Supply

The REF02B was chosen to supply the OPA2317, the common-mode voltage divider, and the INA188 reference-voltage divider because it has low drift, high-accuracy specifications.

3.3 Common Mode Voltage

The common-mode voltage is 2.6 V to allow the output of the instrumentation amplifier to swing from 250 mV to 5 V. The common-mode voltage is set by using a voltage divider that uses the 5-V supply from the REF02, resistor R_7 , and resistor R_8. Resistors R_7 and R_8 are 15.0 kΩ and 16.2 kΩ, respectively. A tolerance of 0.1% was used for resistors R_7 and R_8 to reduce errors associated with the common-mode voltage. Figure 3 shows the common mode versus the output-voltage plot for the INA188 with a common-mode voltage of 2.6 V. With a common-mode voltage of 2.6 V, the INA188 is able to have an output swing of 220 mV to 9.37 V.

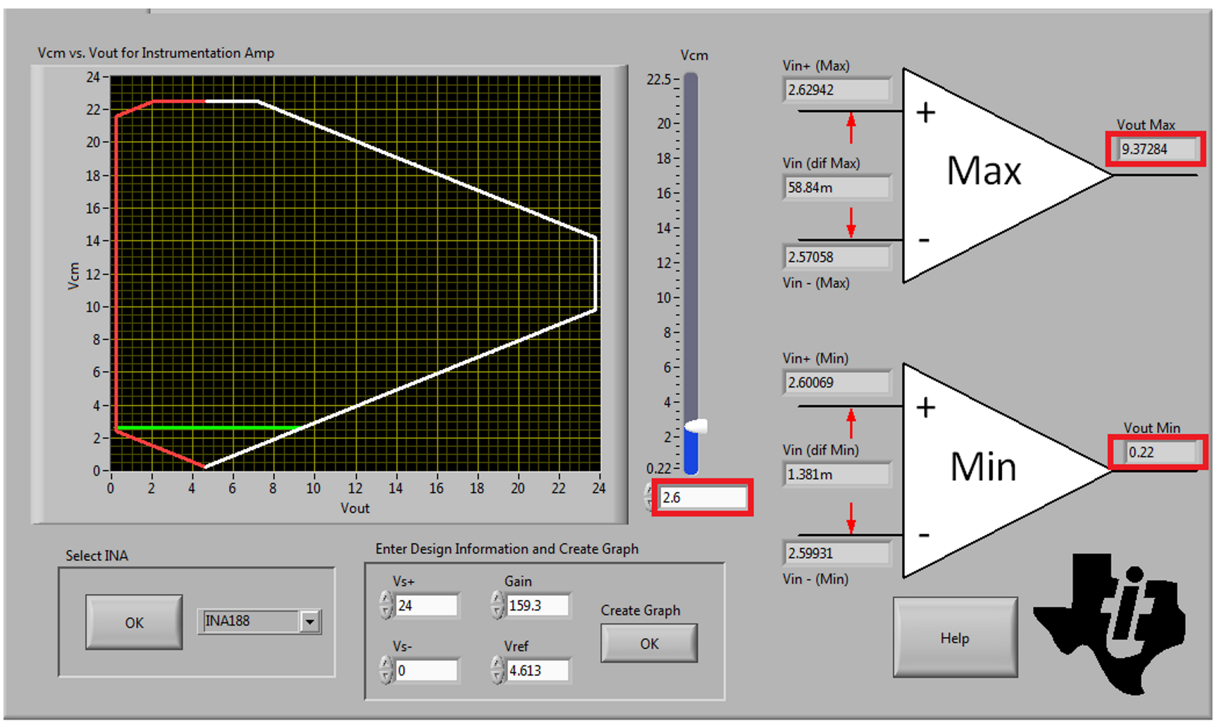

Figure 3. INA188 Common Mode versus Output Voltage

3.4 Common Mode and Reference-Pin Buffer

The OPA2317 was chosen as the buffering amplifier for the common-mode voltage and reference pin of the instrumentation amplifier because it has low drift, low offset, dual package, and low cost.

3.5 Reference Voltage

The INA188 reference voltage is 4.614 V. This was set with a voltage divider using the 5-V supply from the REF02 and resistors R_9 and R_{10}, set to 1.15 kΩ and 13.7 kΩ, respectively. A tolerance of 0.1% was chosen for the resistors to reduce an offset error because of the reference voltage.

3.6 Passive Components

3.6.1 Gain Setting Resistor

The gain-setting resistor is calculated to be 315.9 Ω. Using the closest standard value, R_g is valued at 316 Ω. A tolerance of 0.1% was used for R_g to reduce the gain error because of the resistor. Use Equation 12 to calculate the gain-setting resistor for the INA188. This equation is in the product datasheet.

$$R_g = \frac{50,000}{G - 1} = 315.9\ \Omega \tag{12}$$

3.6.2 Resistors R_1, R_2 , and R_3

Resistor R_3 is 100 Ω to match the resistance of the RTD at 0°C. Resistor R_2 is 18.7 kΩ as shown in Equation 4. Resistor R_1 is 18.7 kΩ to equal the resistance of R_2.

3.6.3 Common Mode and Differential Filter

The cutoff frequencies of the input common-mode and differential filter are 3.38 kHz and 161 Hz, respectively. To achieve these cutoff frequencies, resistors R_4 and R_5 are 100 Ω, and capacitors C_5, C_6, and C_7 are valued at 0.47 µF, 4.7 µF, and 0.47 µF, respectively.

3.6.4 Output Filter

The output filter has a cutoff frequency of 100 Hz to filter out noise. R_6 and C_9 are 162 Ω and 10 µF, respectively.

4 Simulation and Error Calculations

4.1 Simulation

Figure 4 shows the TINA-TI™ circuit used for the simulation.

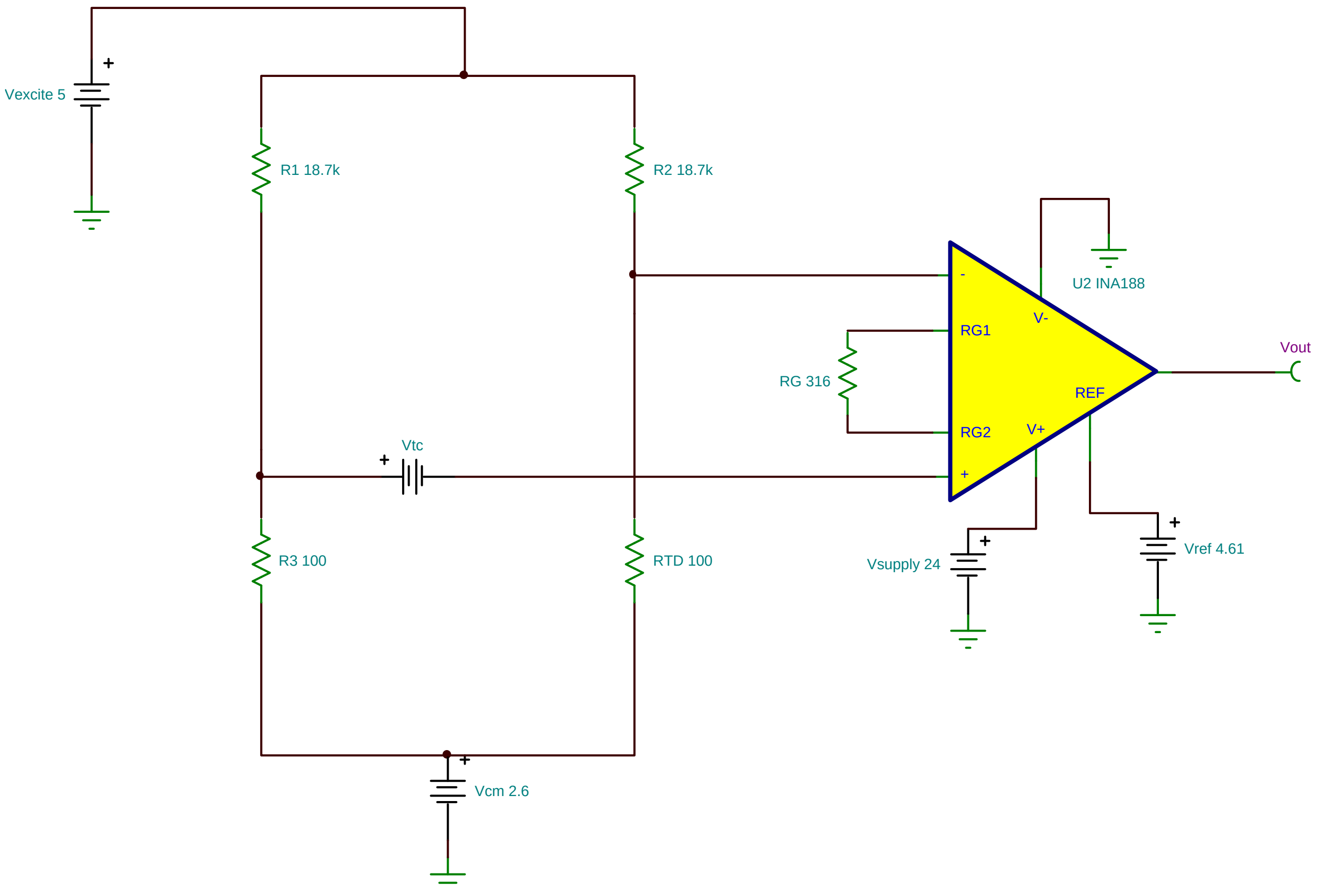

Figure 4. TINA-TI Simulation Circuit

Figure 5 displays the simulated-output voltage for a hot-junction temperature from –50°C to +500°C, and a cold-junction temperature of 0°C. To produce these simulated results, V_{tc} was swept from –2.431 mV to +27.393 mV, which corresponds to the voltage produced by the thermocouple with a hot-junction temperature ranging from –50 °C to +500°C, and a cold-junction temperature of 0°C. The RTD resistance equals 100 Ω, which corresponds to a cold-junction temperature of 0°C.

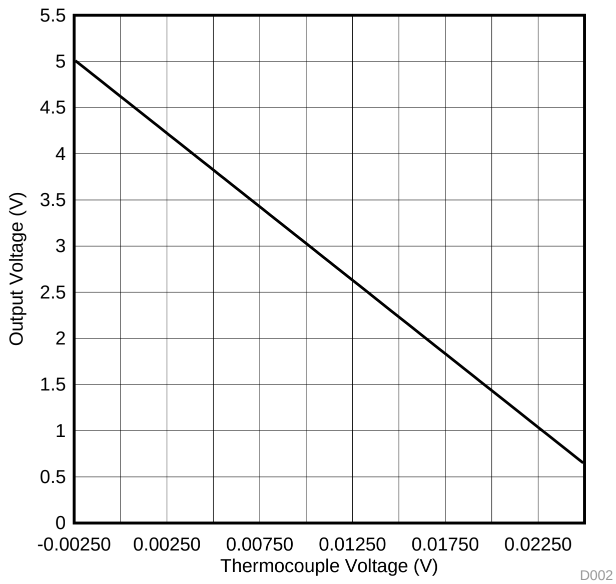

Figure 5. Simulation Results

4.2 *Error Calculations*

All error calculations can be found in Appendix A.

4.2.1 Passive Component Errors

Table 2 shows how each passive component contributes to the error of the system given a cold-junction temperature of 0 °C. For all of the calculations listed in Table 2, the passive components were adjusted to give the worst-possible outcome using the typical tolerance of the component.

Table 2. Passive Component Errors

	COMPONENT TOLERANCE	INPUT-REFERRED ERROR	INPUT-REFERRED ERROR (% FSR)
Bridge resistors R_1, R_2 and R_3	0.1%	12.6542 µV	0.0424%
INA188 reference-voltage resistors R_9 and R_{10}	0.1%	1.341 µV	0.0045%
Common-mode resistors R_7 and R_8	0.1%	4.921 µV	0.0165%

4.2.2 INA188 Errors

Table 3 shows how the errors of the INA188 contribute to the error of the system. Typical specifications were used for all the calculations in the following table.

Table 3. INA188 Errors

	DATA-SHEET SPECIFICATION	INPUT-REFERRED ERROR (V)	INPUT-REFERRED ERROR (%FSR)
Input-offset voltage	(25 + 60/G) µV	25.377 µV	0.0851%
Gain error	0.06%	17.8944 µV	0.06%
Common-mode rejection ratio (CMRR)	130 dB	99.67 µV	0.01%

4.2.3 REF02 Errors

Table 4 shows how the REF02 affects the excitation voltage, common-mode voltage divider, and INA188 reference-voltage divider. Because there is no effect on the differential-input voltage due to the REF02 at a cold-junction temperature of 0°C, the error calculations for the excitation voltage and common-mode voltage were calculated at a cold-junction temperature of 75°C. No typical specification is provided in the REF02 datasheet. Because of this, all calculations use a maximum specification.

Table 4. REF02 Errors

	DATA-SHEET SPECIFICATION	INPUT-REFERRED ERROR (V)	INPUT-REFERRED ERROR (%FSR)
Excitation voltage and common-mode voltage at CJ = 75°C	0.2%	13.711 µV	0.0459%
INA188 reference voltage	0.2%	1.9418 mV	0.194%

4.2.4 Total Error

Equation 13 shows how to calculate the total error of the system by taking the root-sum square (RSS) of each error term. The total error referred to the input is calculated as 0.229%. However, the calculated error has a maximum specification for the REF02 and a worst-case scenario for passive components. Because of this, the measured performance is expected to be better than the calculated error.

$$E_{total} = \sqrt{0.04243^2 + 0.0045^2 + 0.0165^2 + 0.0851^2 + 0.06^2 + 0.01^2 + 0.0459^2 + 0.194^2} = 0.229\% \quad (13)$$

4.2.5 Cold Junction Compensation Accuracy

The cold-junction compensation accuracy equals –2.074%. The non-linearity of the thermocouple and the RTD increase as temperature decreases. As the cold-junction temperature deviates from 0°C, the cold-junction compensation accuracy decreases. Because of this, the calculation uses a hot-junction temperature of –50°C and a cold-junction temperatures of 0°C and 75°C.

5 PCB Design

5.1 PCB Layout

Figure 6 shows the PCB layout for this design. The traces to the input of the instrumentation amplifier were kept as short and balanced as possible to prevent a differential voltage from developing because of trace-impedance mismatch. The terminal blocks connecting the RTD and the thermocouple are placed on the bottom layer to minimize trace length that connects R_2 and R_3 to the terminal blocks. General layout guidelines (such as placing decoupling capacitors close to the devices and pouring a solid-ground plane) are used.

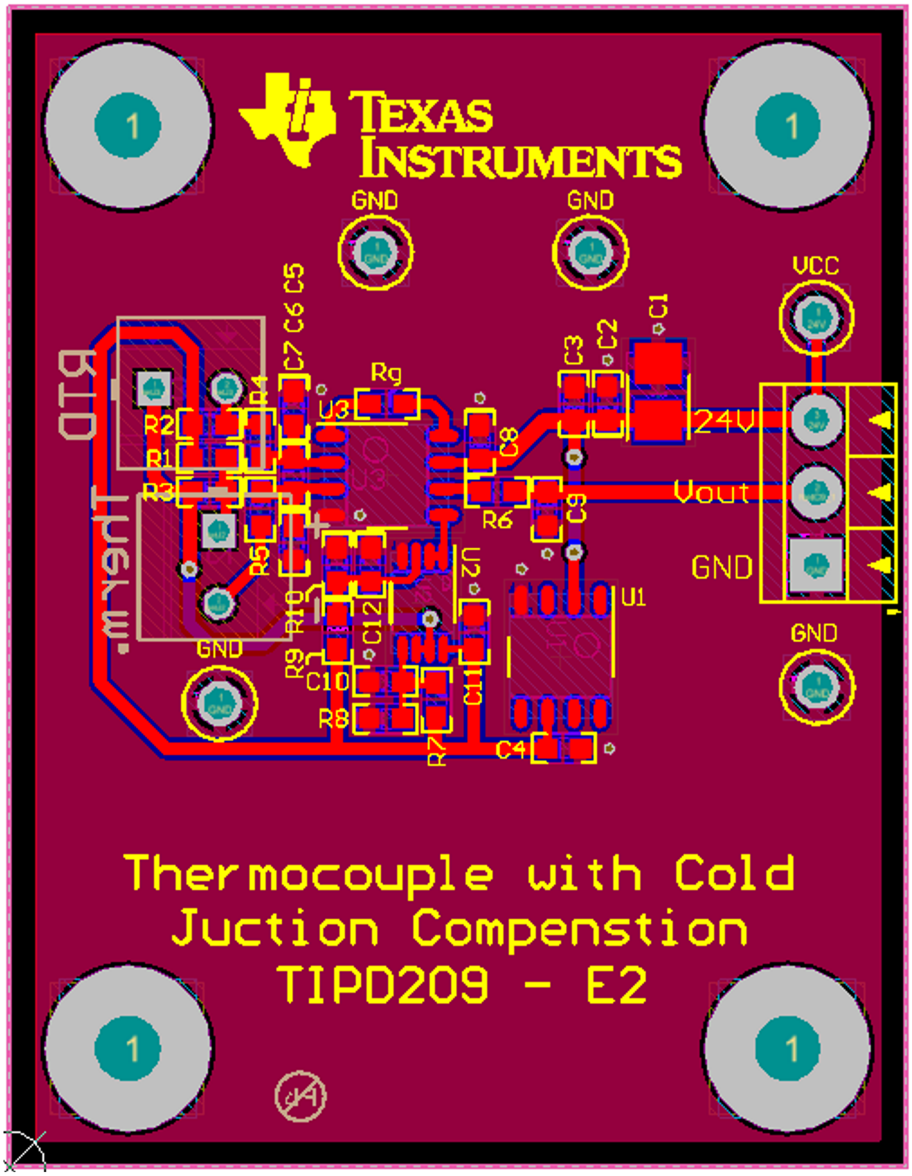

Figure 6. PCB Layout

6 Verification and Measured Performance

6.1 Output Voltage versus Hot-Junction Temperatures

Figure 7 shows the output voltage versus hot-junction temperatures from –50°C to +500°C with cold-junction temperatures of 0°C, 25°C, 50°C, and 75°C. To simulate the cold-junction temperature, ultra low-drift, high-precision resistors replaced the RTD based on the cold-junction temperature of each test. For the cold-junction temperatures of 0°C, 25°C, 50°C, and 75°C, resistance values of 100 Ω, 110 Ω, 120 Ω, and 130 Ω represented the RTD resistance.

To simulate the voltage produced by the thermocouple, a voltage source replaced the thermocouple. Because the voltage the thermocouple produces is dependent on the cold-junction temperature, the voltage applied in place of the thermocouple was adjusted for each cold-junction temperature. To simulate the non-linear effects of the thermocouple, a look-up table was used to determine the required voltage.

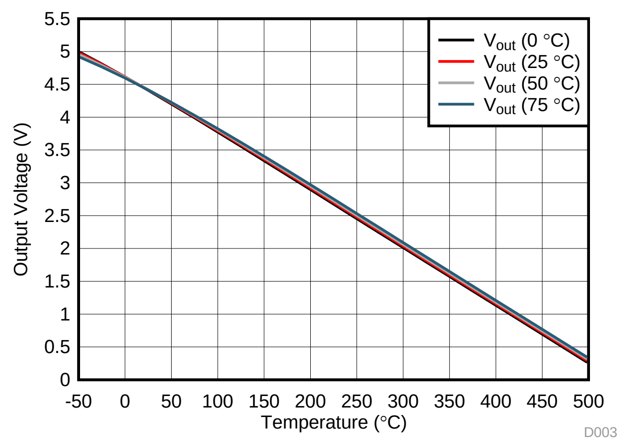

Figure 7. Output Voltage versus Hot-Junction Temperature

Figure 8 shows the total full-scale error at the cold-junction temperatures of 0°C, 25°C, 50°C, and 75°C. The errors from the inaccuracy of the cold-junction compensation have been removed from these results so the accuracy of the bridge, reference voltages, component tolerances, and the instrumentation amplifier can be verified independently of the cold-junction compensation circuitry.

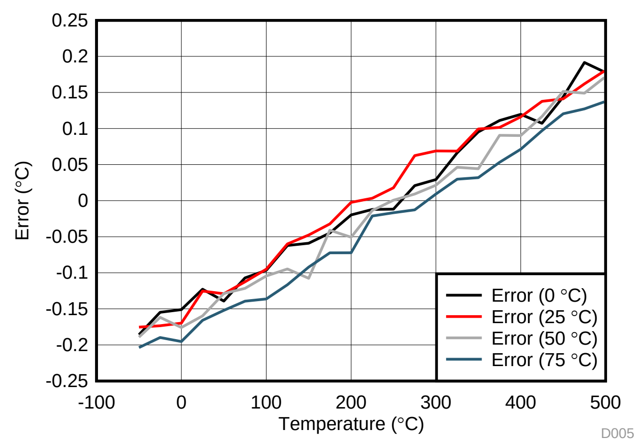

Figure 8. Total Full-Scale Error

Figure 9 shows the accuracy of the cold-junction compensation. This was calculated by subtracting the output voltage at a cold-junction temperature of 0°C from the output voltage at a cold-junction temperature of 25°C, 50°C, and 75°C, and then dividing by the full-scale output-voltage range. The non-linearity seen in the error is a result of non-linearity in the thermocouple- and RTD-transfer functions. Because the error of the cold-junction compensation is greater than the total full-scale error, the accuracy of the cold-junction compensation is more prominent than the accuracy of the system in cold-junction temperatures above 0°C.

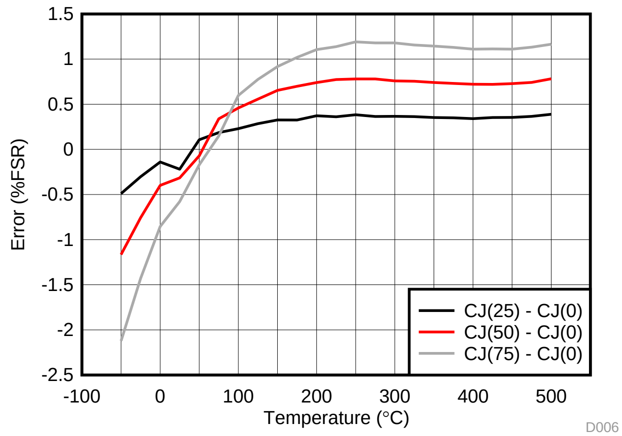

Figure 9. Cold-Junction Compensation Accuracy

7 Modifications

7.1 Instrumentation Amplifier

The INA333 may be used for a low-drift, high-accuracy solution that requires a single 5-V supply. If the INA333 is used, the 5-V output from the REF02 may be used to supply the INA333. The INA826 may be used for a low-cost, high-voltage solution. However, the common mode of the instrumentation may need to be adjusted based on desired output swing and supply voltages.

7.2 Reference Voltage Supply

The REF5050 may be used to supply the reference voltage if a more accurate reference voltage is required. However, another supply voltage must be generated to reduce the 24-V supply down to 18 V.

7.3 Common Mode and Reference Voltage Buffer

The OPA2180 may be used to buffer the reference pin of the instrumentation amplifier and the common-mode voltage if a high voltage device is required in the application. The OPA2180 provides a high voltage, low drift, and low offset solution.

8 Design Files

8.1 Schematics

To download the schematics, see the design files at TIPD209.

8.2 Bill of Materials

to download the bill of materials (BOM) for each board, see the design files at TIPD209.

9 Acknowledgments

The author would like to thank Collin Wells for his technical contributions during this design.

10 References

1. *Omega Temperature Measurement Handbook 7th Edition. 2010*
2. Texas Instruments, *V_{cm} vs V_{out} Calculator for Instrumentation Amplifiers*, (INA-CMV-CALC)

11 About the Author

TIMOTHY CLAYCOMB is an Analog Applications Engineer in the Precision Linear group at Texas Instruments. He earned his B.S. in Electrical Engineering from Michigan State University in 2013.

Appendix A

A.1 Passive Component Error Calculations

$$FSR = 2.431\ \text{mV} - (-27.393\ \text{mV}) = 29.824\ \text{mV} \tag{14}$$

$$V_{diff\_ideal@0°C} = 0\ \text{V} \tag{15}$$

$$V_{diff\_bridge\_passives} = 12.6542\ \mu\text{V} \tag{16}$$

$$V_{ref\_passives} = 4.61301\ \text{V} \tag{17}$$

$$V_{ref\_ideal} = 4.6128\ \text{V} \tag{18}$$

$$V_{diff\_ideal@75°C} = -3.80335\ \text{mV} \tag{19}$$

$$V_{cm\_passives} = 2.5969\ \text{V} \tag{20}$$

$$V_{diff\_cm\_passives@75°C} = -3.80826\ \text{mV} \tag{21}$$

$$E_{diff\_offset\_passives} = \left| \frac{\left(V_{diff\_bridge\_passives} - V_{diff\_ideal@0°C}\right)}{FSR} \times 100 \right| = 0.04243\% \tag{22}$$

$$E_{ref\_passives} = \left| \frac{\left(V_{ref\_passives} - V_{ref\_ideal}\right)}{G \times FSR} \times 100 \right| = 0.0045\% \tag{23}$$

$$E_{diff\_offset\_cm\_passives@75°C} = \left| \frac{\left(V_{diff\_cm\_passives@75°C} - V_{diff\_ideal@75°C}\right)}{FSR} \times 100 \right| = 0.0165\% \tag{24}$$

A.2 INA188 Error Calculations

$$V_{cm\_sys} = 2.6\ \text{V} \tag{25}$$

$$V_{cm\_spec} = 12\ \text{V} \tag{26}$$

$$INA_{GE} = 0.06\% \tag{27}$$

$$INA_{CMRR\_spec} = 130\ \text{dB} = 316.23\ \text{nV / Va} \tag{28}$$

$$E_{offset} = \frac{\left(25 \pm \frac{60}{G}\right) \times 10^{-6}}{FSR} \times 100 = 0.0851\% \tag{29}$$

$$E_{GE} = \left(\frac{INA_{GE} \times FSR}{100}\right) = 17.8944\ \mu\text{V} \tag{30}$$

$$E_{CMRR} = \left| \frac{\left(V_{cm\_spec} - V_{cm\_sys}\right)\left(INA_{CMRR\_spec}\right)}{FSR} \times 100 \right| = 0.01\% \tag{31}$$

A.3 REF02 Error Calculations

$$INA_{ref\_ideal} = 4.6128\ V \quad (32)$$

$$INA_{ref\_REF02} = 4.62202\ V \quad (33)$$

$$V_{diff\_REF02} = -3.81706\ mV \quad (34)$$

$$E_{INA\_ref\_REF02} = \left| \frac{INA_{ref\_REF02} - INA_{ref\_ideal}}{G \times FSR} \times 100 \right| = 0.194\% \quad (35)$$

$$E_{diff\_REF02} = \left| \frac{V_{diff\_REF02} - V_{diff\_ideal@75°C}}{FSR} \times 100 \right| = 0.0459\% \quad (36)$$

A.4 Accuracy of Cold-Junction Compensation

$$V_{diff@0°C} = 2.431\ mV \quad (37)$$

$$V_{diff@75°C} = 1.8125\ mV \quad (38)$$

$$E_{Cold\_Junction\_Comp} = \frac{V_{diff@0°C} - V_{diff@75°C}}{FSR} \times 100 = -2.074\% \quad (39)$$

A.5 Conversions From %FSR to °C

$$E_{Volts} = \frac{E_{\%FSR}}{100} \times FSR \quad (40)$$

$$E_{°C} = \frac{T_{range}}{FSR} \times E_{Volts} \quad (41)$$

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