Precision Thermocouple Measurement with the ADS1118

Mike Beckman, Luis Chioye — *High-Performance Analog*

ABSTRACT

Thermocouples are a very common form of temperature measurement devices that are widely used in both industrial and general-purpose applications. Traditionally, achieving high system accuracy from thermocouple measurements can be difficult because there are many sources of error within a given system. The ADS1118 is an analog-to-digital converter (ADC) from TI that offers a precision analog front-end specifically designed for precise measurements of thermocouples. The ADS1118 makes thermocouple designs simple, and also provides on-chip cold junction compensation. This application note presents the basic principles of thermocouple operation as well as the real-world implications of these principles. It reviews both design and layout considerations for achieving a high-accuracy, robust design. Experimental results for ADS1118 thermocouple measurements and cold junction compensation are discussed, as well as a recommended software flow that demonstrates how to simplify a lookup table by using linear interpolation.

Contents

List of Figures

1 Introduction to Thermocouples

Thermocouples are a popular type of temperature measurement device. A relatively low price, wide temperature range, lack of required excitation, long-term stability, and proficiency with contact measurements make these devices very common in a wide range of applications. While achieving extremely high accuracy with a thermocouple can be more difficult than a resistance temperature detector (or RTD), the low cost and versatility of a thermocouple often make up for this difficulty in precision. Additionally, in contrast with thermistors and RTDs, the use of thermocouples often simplifies application circuitry because they require no excitation. That is, these devices generate voltage without any additional active circuitry. Thermocouples do, however, require a stable voltage reference and some form of ice point or cold junction compensation. The integration of an internal voltage reference, multiplexer, and temperature sensor make the ADS1118 an ideal option for thermocouple measurements.

A thermocouple is a length of two wires made from two dissimilar conductors (usually alloys) that are soldered or welded together at one end, as shown in Figure 1. The composition of the conductors used varies widely, and depends on the required temperature range, accuracy, lifespan, and environment that is being measured. However, all thermocouple types operate based on the same fundamental theory: the thermoelectric or Seebeck effect. Whenever a conductor experiences a temperature gradient from one end of the conductor to the other, a voltage potential develops. This voltage potential arises because free electrons within the conductor diffuse at different rates, depending on temperature. Electrons with higher energy on the hot side of the conductor diffuse more rapidly than the lower energy electrons on the cold side. The net effect is that a buildup of charge occurs at one end of the conductor and creates a voltage potential from the hot and cold ends. This effect is illustrated in Figure 2.

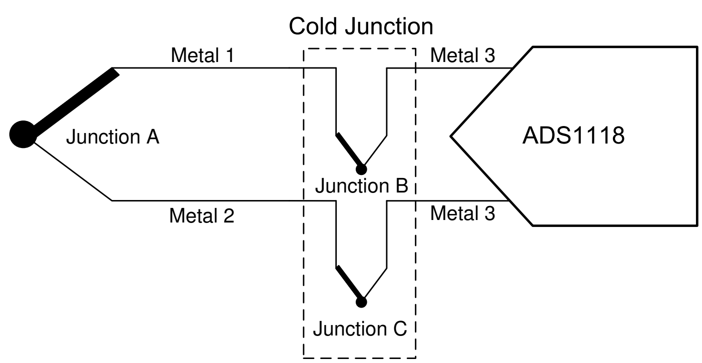

Figure 1. Thermocouple Junction Diagram

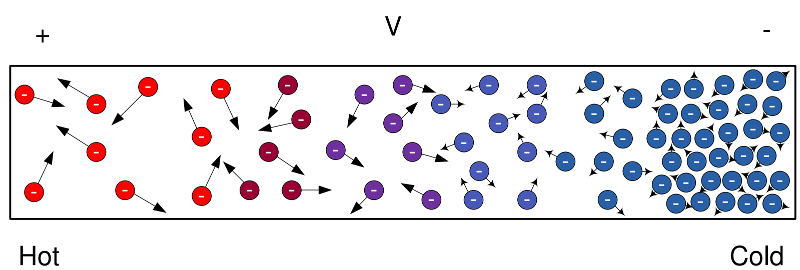

Figure 2. Illustration of the Seebeck Effect

Different types of metals exhibit this effect at varying levels of intensity. When two different types of metals are paired together and joined at a certain point (junction **A** in Figure 1), the differences in voltage on the end opposite of the short (junctions **B** and **C**) are proportional to the temperature gradient formed from either end of the pair of conductors. The implication of this effect is that thermocouples do not actually measure an absolute temperature; they only measure the temperature difference between two points, commonly known as the *hot*and *cold* junctions. Therefore, in order to determine the temperature at either end of a thermocouple, the exact temperature of the opposite end must be known.

In a classical design, one end of a thermocouple is kept in an ice bath (junctions **B** and **C** in Figure 1) in order to establish a known temperature. In reality, for most applications, it is not practical to provide a true ice point reference. Instead the temperature of junctions **B** and **C** of the thermocouple are continuously monitored and used as a point of reference to calculate the temperature at junction **A** at the other end of the thermocouple. These junctions are known as the *cold* junctions or *ice point* for historical reasons, although they do not need to be kept cold or near freezing. These endpoints are referred to as *junctions* because they connect to some form of terminal block that transitions from the thermocouple alloys into the traces used on the printed circuit board, or PCB (usually copper). This transition back to copper is what creates the cold junctions **B** and **C**. Because of the law of intermediate metals, junctions **B** and **C** can be treated as a single reference junction, provided that they are held at the same temperature or isothermal. Once the temperature of the reference junction is known, the absolute temperature at junction **A** can be calculated. Measuring the temperature at junctions **B** and **C** and then using that temperature to calculate a second temperature at junction **A** is known as *cold junction compensation*.

In many applications, the temperature of junctions **B** and **C** are measured using a diode, thermistor, or RTD. Because of the high-accuracy, onboard temperature sensor, small size, and minimal signal path requirements of the ADS1118, it is possible use the device to achieve cold junction compensation. As with any form of cold junction compensation, it is important that two conditions are met to achieve accurate thermocouple measurements:

- **Junctions B and C must be kept isothermal or be held at the same temperature.** This condition can be achieved by keeping junctions **B** and **C** in very close proximity to each other and away from any sources of heat that may exist on a PCB. Many times, isothermal blocks are used to keep the junctions at the same temperature. A large mass of metal offers a very good form of isothermal stabilization. For other applications, it may be sufficient to maximize the copper fill around the junctions. By creating an island of metal fill on both top and bottom layers, joined with periodically placed vias, a simple isothermal block can be created. It is important to ensure that this isothermal block cannot be impacted by parasitic heat sources from other areas in the circuit, such as power conditioning circuitry.
- **The isothermal temperature of junctions B and C must be accurately measured.** The closer that a temperature sensor (such as a diode, RTD, or thermistor) can be placed to the isothermal block, the better. This recommendation also applies to the ADS1118. With only 500 μW of power consumption, the effects of the ADS1118 self-heating are negligible for most applications. At 0.5ºC maximum error, the ADS1118 offers excellent uncalibrated precision, which can be further improved through a system calibration. Air currents can also act to reduce the accuracy of the cold junction compensation measurement. To achieve the best performance, it is recommended to ensure that the cold junction be kept within an enclosure and that air currents be kept to a minimum near the cold junction. In applications where air currents are unavoidable, it may be useful to find a mechanical method to cover the ADS1118 and connector block in the form of some type of shielding that protects the cold junction from air currents. It is also important to remember that the orientation of the PCB can impact the accuracy of the cold junction compensation. If there are heat-generating elements physically below the cold junction, for example, inaccuracies can become significant as heat from those elements rises.

2 Design and Layout Considerations

Figure 3 illustrates the basic connections for an independent, two-channel thermocouple system. This circuit contains a simple low-pass, anti-aliasing filter, mid-point bias, and open detection. While the digital filter of the ADS1118 strongly attenuates high-frequency components of noise, providing a first-order, passive RC filter to further improve this performance and avoid aliasing is a good practice. The differential RC filter formed by the 500-Ω resistors (R_{DIFFA} and R_{DIFFB}) and the 1-μF capacitor (C_{DIFF}) offers a cutoff frequency of approximately 320 Hz. Additional filtering can be achieved by increasing the differential capacitor or the resistance values. However, avoid increasing the filter resistance beyond 1 kΩ on each input, because the effects of interaction with ADC input impedance will begin to affect the linearity and gain error of the ADS1118. Also, as a result of the high sampling rates supported by the ADS1118, simple post digital filtering with a microcontroller can alleviate the requirements of the analog filter, and also offer the flexibility to implement filter notches at 50 Hz or 60 Hz. Two 0.1-μF capacitors (C_{CMA} and C_{CMB}) are also added to offer attenuation of high-frequency, common-mode noise components.

Because mismatches in the common-mode capacitors cause differential noise, it is recommended that the differential capacitor be at least an order of magnitude (10x) greater than the common-mode capacitors. To achieve good electromagnetic interference (EMI) immunity, it is important to remember that simply placing large capacitors in the signal path and supply are not effective at attenuating high noise frequency components. Using small (10 nF and lower) capacitors with low equivalent series resistance (ESR) and low dielectric absorption (DA) in parallel with another higher capacitance capacitor on sensitive supply and signal paths can offer significant improvements to EMI immunity. Additional EMI protection can further be realized by incorporating a ferrite bead or common-mode choke to the inputs. If there is significant concern that there may be frequent exposure to electrical overstress or electrostatic discharge (ESD), Schottky clamp diodes can be added to the exposed inputs before the input filter.

The two 1-MΩ resistors (R_{PU} and R_{PD}) serve two purposes. First, these components offer a common-mode bias near midsupply. Connecting only one of the inputs to a common point decreases performance by converting common-mode noise into differential signal noise that is not strongly attenuated. The second purpose of these 1-MΩ resistors is to offer a weak pull-up and pull-down for sensor open detection. If a sensor is disconnected, the inputs to the ADC will extend to supply and ground and yield a full-scale readout that indicates a sensor disconnection. For extremely long thermocouples, these 1-MΩ resistors may impact measurement accuracy. Increasing the resistance can alleviate these effects. Alternatively, two 1-MΩ resistors connected as a resistor divider to one of the inputs can maintain the midpoint bias without affecting measurement results. This method, however, sacrifices open detection and a small amount of common-mode noise rejection.

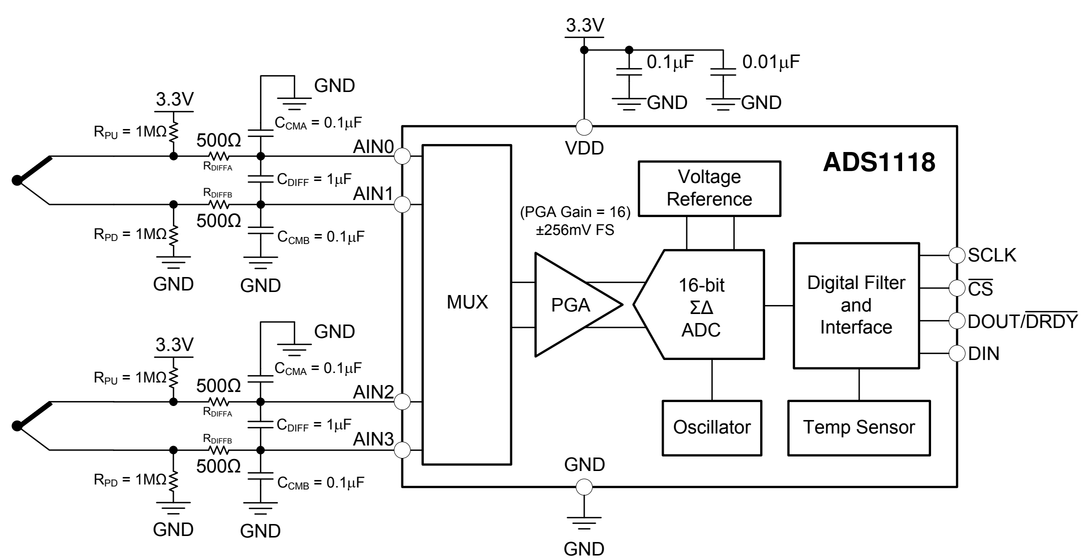

Figure 3. Two-Channel Thermocouple System

Because the accuracy of the overall temperature sensor depends on how accurately the ADS1118 can measure the cold junction, careful PCB layout considerations must be employed when designing an accurate thermocouple system. The ADS1118EVM provides a good starting point and offers an example of one way to achieve good cold junction compensation performance. The ADS1118EVM uses the same schematic shown in Figure 3, except with only one thermocouple channel connected. The layout for the evaluation module (EVM) is shown in Figure 4 and Figure 5. In the layout diagram in Figure 4, C10 corresponds to C_{DIFF}, C2 corresponds to C_{CMA}, C3 corresponds to C_{CMB}, R3 corresponds to R_{DIFFA}, R4 corresponds to R_{DIFFB}, R1 corresponds to R_{PU} and R2 corresponds to R_{PD}.

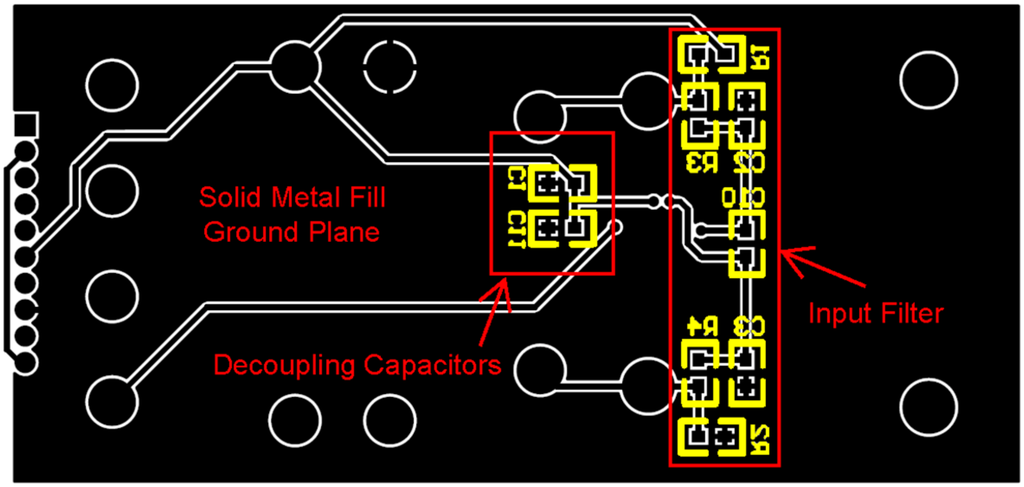

Figure 4. ADS1118EVM Bottom Side Layout

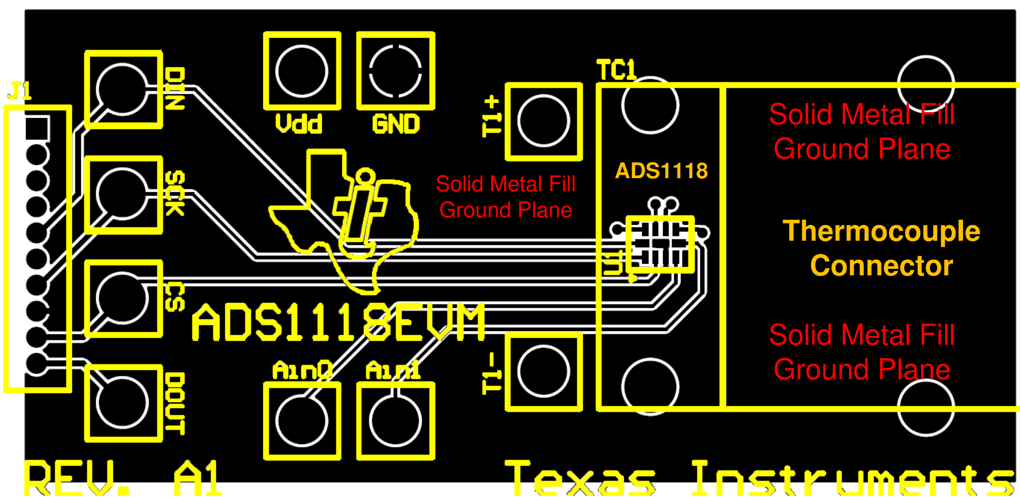

Figure 5. ADS1118EVM Top Side Layout

The ADS1118EVM layout is designed in a modular way that allows an interfacing board with a microcontroller. In an actual system, a microcontroller, power conditioning, and some form of interface transceiver is likely to be present. In order to achieve optimal noise and thermal performance, it is important to isolate the ADS1118 away from digital components as well as any heat-generating components. Because there are no digital or heat-generating ICs on the ADS1118EVM, there is very little error because of noise and parasitic thermal gradients on the board. However for many systems, careful consideration regarding the parasitic heat generated by other components should be carefully considered when performing system layout.Figure 6 shows a good component placement diagram for thermocouple systems using the ADS1118 in addition to commonly-used components within a typical thermocouple system. Notice that the ADS1118 is kept as close to the thermocouple connection as possible. Also note that there is a ground fill around the device and connector.

In the example of Figure 6, several vias are shown that connect to another ground fill on the other side of the board. Having an additional layer helps to improve the temperature consistency of the board. The metal fill not only conducts the temperature of the cold junction to the ADS1118 very well, it also helps ensure that both junctions are kept isothermal. Furthermore, there is a ground fill cut that isolates all other active components from the ADS1118 and the thermocouple cold junction. This layout helps avoid parasitic heat transfer from other active components in the system and can greatly improve noise performance.

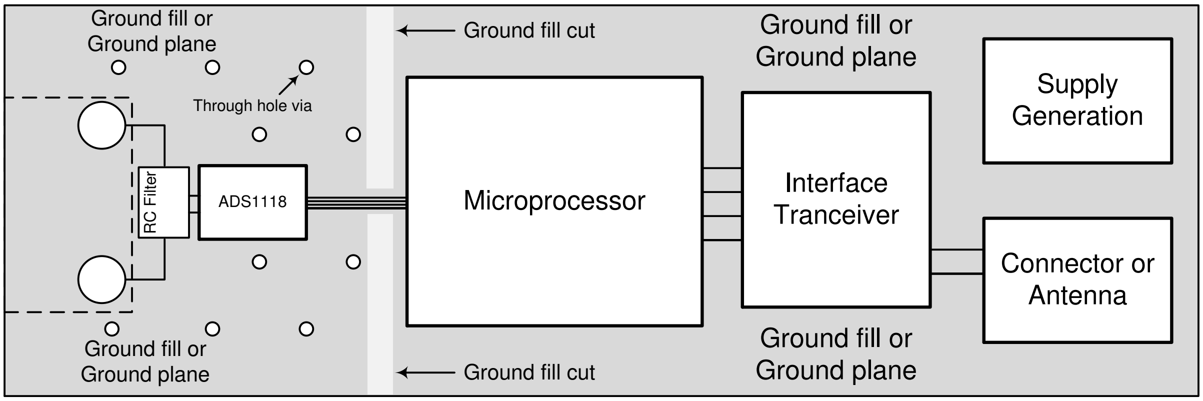

Figure 6. Typical ADS1118 Thermocouple Application Component Placement

3 Software Flow

The calculation procedure to achieve cold junction compensation is simple and can be done in several ways. One typical way is to interleave readings between the thermocouple inputs and the temperature sensor. That is, acquire one on-chip temperature result for every thermocouple ADC voltage measured. If the cold junction is in a very stable environment, more periodic cold junction measurements may be sufficient. These operations, in turn, will yield two results for every thermocouple measurement and cold junction measurement cycle: the thermocouple voltage or V_{TC}, and the on-chip temperature or T_{CJC}. In order to account for the cold junction, the temperature sensor within the ADS1118 must first be converted to a voltage that is proportional to the thermocouple currently being used, to yield V_{CJC}. This process is generally accomplished by performing a reverse lookup on the table used for the thermocouple voltage-to-temperature conversion. Adding the two voltages then yields the thermocouple-compensated voltage V_{Actual}, where $V_{CJC} + V_{TC} = V_{Actual}$. V_{Actual} is then converted to temperature using the same lookup table from before, and yields T_{Actual}. A block diagram showing this process is given in Figure 7

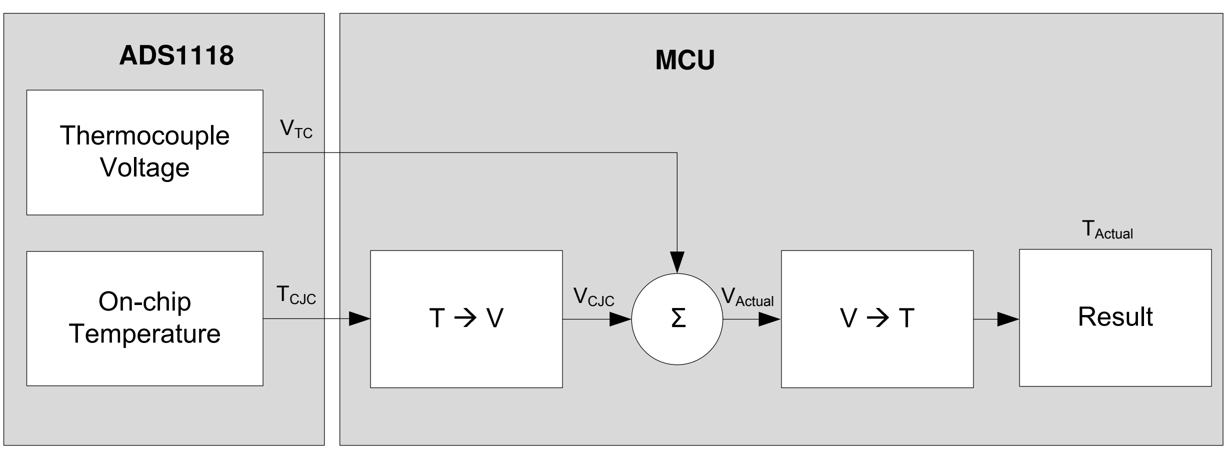

Figure 7. Software Flow Block Diagram

The conversion from thermocouple temperature to voltage and voltage to temperature can be performed in two ways. First, the coefficients can be programmed into the microcontroller from the high-order polynomial, and then the calculation can be performed on each reading. While this method offers the smallest introduced error during the conversion, it is extremely processor-intensive and is not practical for most applications. The second and most common way to perform the conversion is through the use of a lookup table. Thermocouple manufacturers usually provide a lookup table with their respective thermocouple devices that offer excellent accuracy for linearization of a specific type of thermocouple. The granularity on these lookup tables is also very precise—approximately 1°C for each lookup value. To save microcontroller memory and development time, an interpolation technique applied to these values can be used. An example of this method when converting from voltage to temperature with eight look-up table entries is shown in Figure 8.

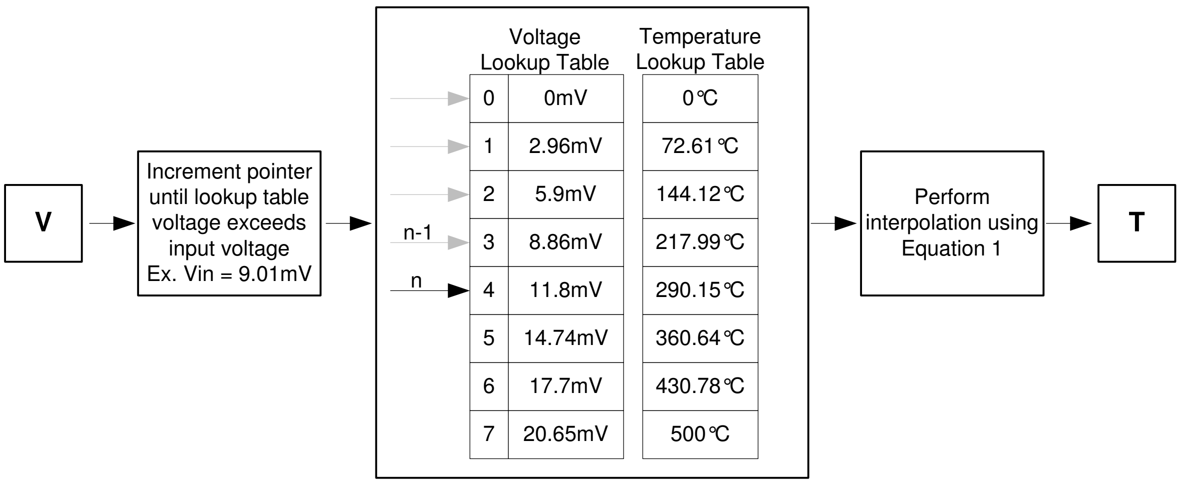

Figure 8. V-to-I Conversion Block Diagram

To perform a linear interpolation using a lookup table, first compare the value that must be converted to values in the lookup table, until the lookup table value exceeds the value that is being converted. Then, use Equation 1 to convert to temperature, where V_{LT} is the voltage lookup table array and T_{LT} is the temperature lookup table array. This operation involves four additions, one multiplication, and one division step, respectively. This operation can be done easily on most 16- and 32-bit microcontrollers. Converting from temperature to voltage is the same, except that the lookup tables and the temperature variables are reversed, as shown in Equation 2.

$$T = T_{LT}[n-1] + (T_{LT}[n] - T_{LT}[n-1])\left(\frac{V_{IN} - V_{LT}[n-1]}{V_{LT}[n] - V_{LT}[n-1]}\right) \tag{1}$$

$$V = V_{LT}[n-1] + (V_{LT}[n] - V_{LT}[n-1])\left(\frac{T_{IN} - T_{LT}[n-1]}{T_{LT}[n] - T_{LT}[n-1]}\right) \tag{2}$$

The number of entries used for a lookup table will affect the accuracy of the conversion. For the majority of applications, 16 to 32 lookup table entries should be sufficient. Also, the lookup table entries do not need to equally spaced. By carefully placing them in highly nonlinear portions of the thermocouple transfer functions, the number of required lookup table entries can be minimized. Furthermore, they also do not need to be incorporated in powers of 2, as shown in the examples within this document.

Figure 9 shows the conversion error that can be expected from linear interpolation using a lookup table for a K-type thermocouple from 0ºC to +500ºC. Because the number of lookup table entries exceeds 16, the improvement in accuracy become smaller and smaller.

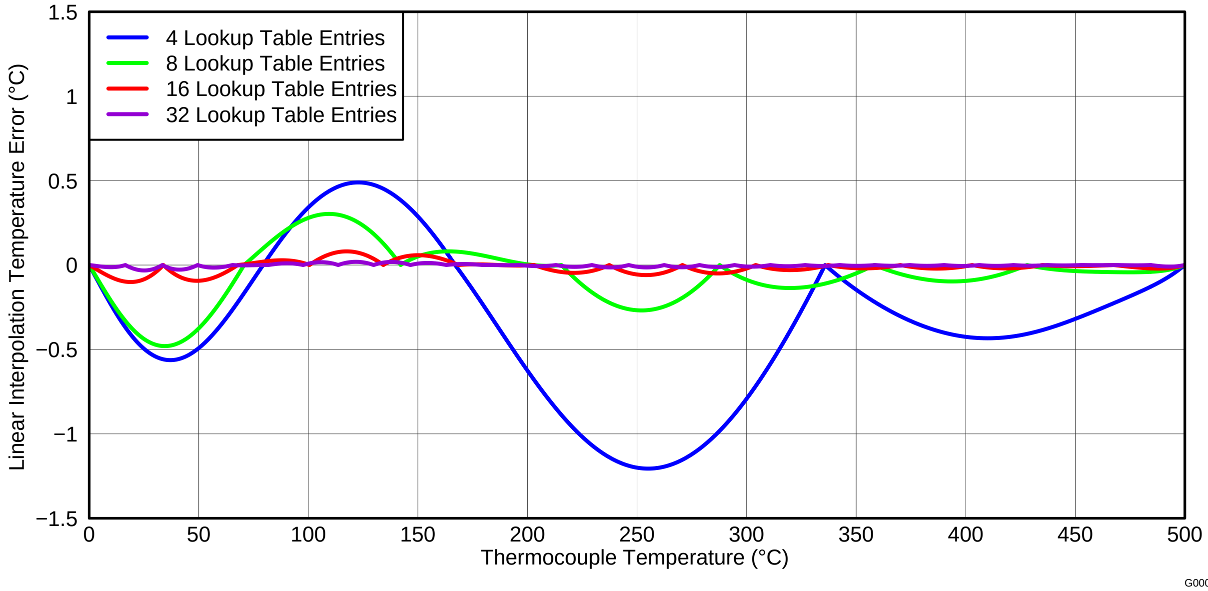

Figure 9. Comparison of Interpolation Errors Using Various Lookup Tables

4 Experimental Results

An excellent way to test the accuracy of the on-chip cold junction compensation with the ADS1118 is to place the ADS1118 and cold junction into a temperature-controlled environment, and place the other end of the thermocouple into a known constant temperature source such as a thermal bath. This experimental setup is shown in Figure 10. When performing this experiment, it is best to try and mimic the actual environment in which the system board is to be used. If the ADS1118 and cold junction are within an enclosure that does not have significant air currents present, a simple oven should be sufficient. However, in applications that must endure high air currents, a temperature-forcing system with aggressive air currents may be useful to benchmark the system performance. The accuracy of the oven or temperature-forcing system used on the ADS1118 system board and cold junction does not need to be highly accurate. The other end of the thermocouple, however, must be held at a very constant and accurate temperature. One of the best ways to achieve this constant temperature is by using a thermal bath or a well-insulated bath of ice water.

In order to perform this experiment, the temperature of the ADS1118 PCB and thermocouple cold junction is swept, while the temperature of the end of the thermocouple is held constant in the thermal bath. The temperature measurements of the thermocouple are recorded and plotted against the cold junction temperature (oven temperature).

Figure 10 shows the set-up using the ADS1118EVM board and a K-type thermocouple. The SM-USB-DIG Platform and USB cable remain outside the oven.

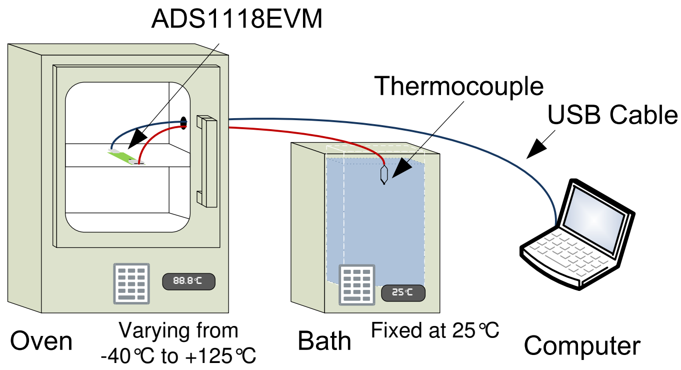

Figure 10. Experimental Setup With Varying Cold Junction Temperature

Figure 11 shows the plot of the thermocouple measurements against the cold junction temperature obtained in this experiment. This setup is intended to reveal inaccuracies that arise because of changes to the system board temperature, cold junction temperature, and ADS1118 temperature. The results indicate an approximately 0.4ºC drift when the system is drifted from 0ºC to +70ºC and around 0.9ºC variation over the complete specified temperature range of –40ºC to +125ºC for the ADS1118. These results were obtained with a factory-trimmed ADS1118 with no additional calibrations, and include all errors as a result of ADS1118 internal reference drift, internal temperature sensor error, and isothermal errors.

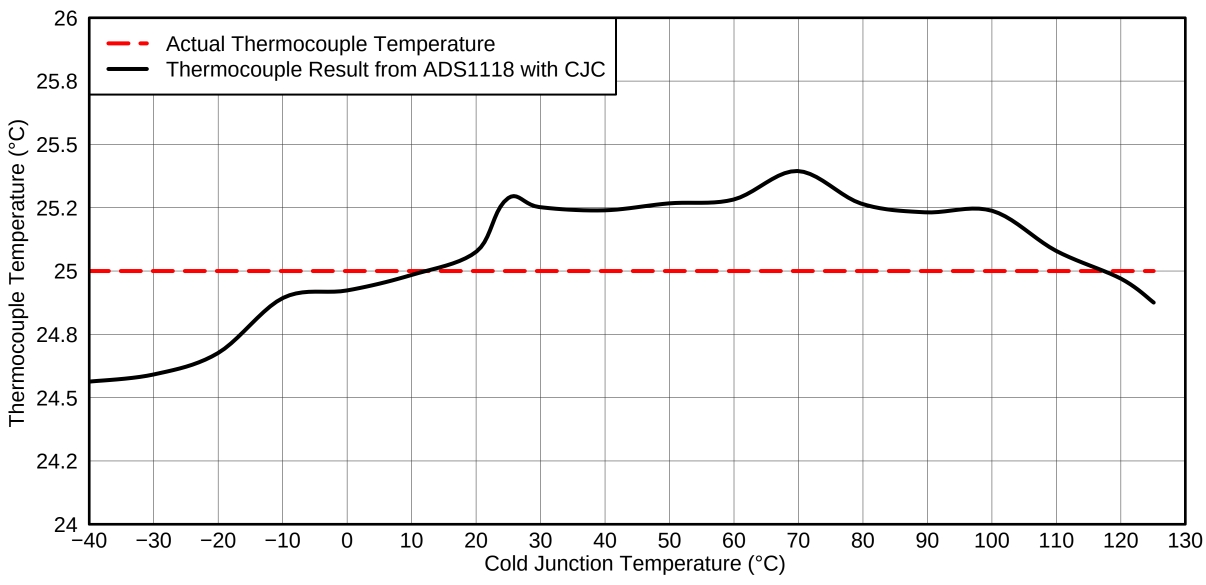

Figure 11. Thermocouple Accuracy with Varying Cold Junction Temperature on ADS1118 EVM

A second experiment that tests the overall system performance by verifying the accuracy of the thermocouple temperature measurement system is to sweep the temperature of the thermocouple using a very stable, uniform, and accurate temperature source. A calibrated thermal bath is a good temperature source for this test. The setup for this test is shown in Figure 12. This experiment is specifically intended to reveal inaccuracies in the thermocouple itself and any errors that occur because of the analog-to-digital conversion process. The cold junction is held at a relatively constant ambient temperature (room temperature) with no temperature forcing. The results in Figure 13 indicate approximately 1.5ºC of error from –40ºC to +150ºC. This result is well within the accuracy limitations of the K-type thermocouple used (also included with the ADS1118EVM), which is specified to be accurate to within 2.2°C. More precise tests can be performed using a calibrated thermocouple.

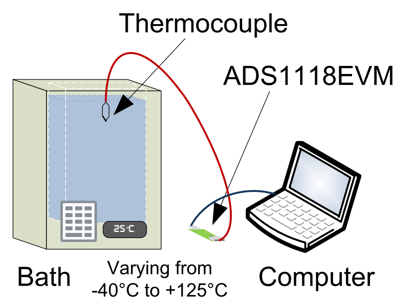

Figure 12. Experimental Setup with Varying Thermocouple

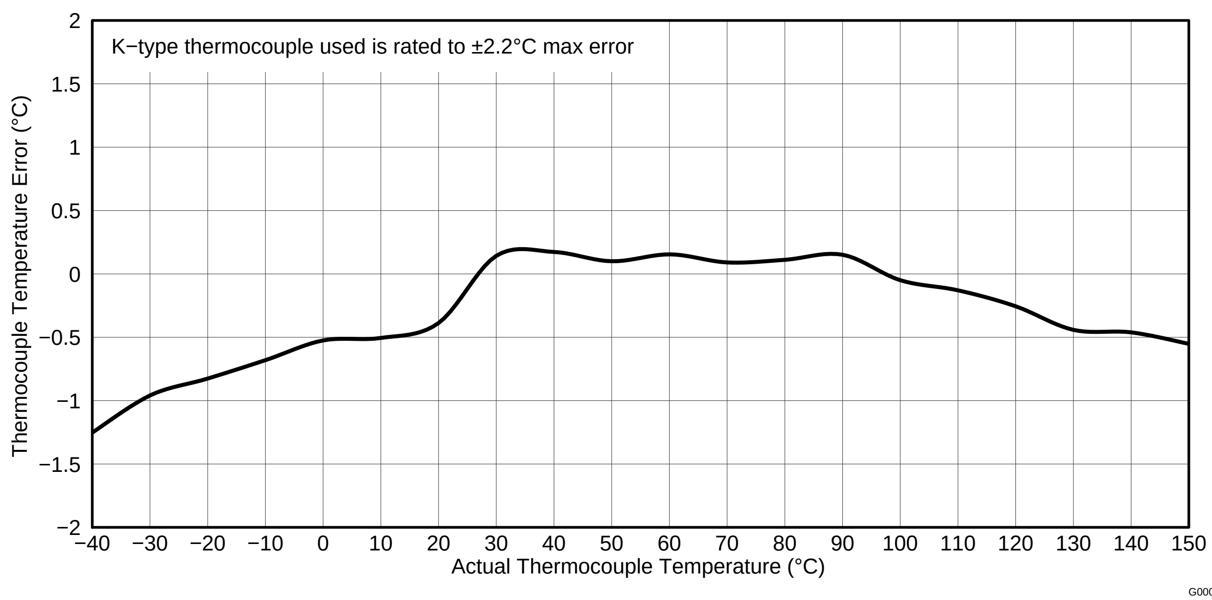

Figure 13. Experimental Temperature Error for Cold Junction Compensation on ADS1118EVM

The results shown in Figure 11 and Figure 13 are typical results using the ADS1118EVM and the thermocouple provided with the EVM. The actual performance in a given system may be different and depends on many variables, including (but not limited to) the application schematics, PCB layout, temperature-forcing system accuracies, and environmental noise contributions, among other factors. TI offers no assurance of system performance other than the performance parametrics detailed in the *Electrical Characteristics* section of the ADS1118 product data sheet.