

Two Ways to Measure Temperature Using Thermocouples Feature Simplicity, Accuracy, and Flexibility

By Matthew Duff and Joseph Towe

Introduction

The thermocouple is a simple, widely used component for measuring temperature. This article provides a basic overview of thermocouples, describes common challenges encountered when designing with them, and suggests two signal conditioning solutions. The first solution combines both reference-junction compensation and signal conditioning in a single analog IC for convenience and ease of use; the second solution separates the reference-junction compensation from the signal conditioning to provide digital-output temperature sensing with greater flexibility and accuracy.

Thermocouple Theory

A thermocouple, shown in Figure 1, consists of two wires of dissimilar metals joined together at one end, called the *measurement* (“hot”) junction. The other end, where the wires are not joined, is connected to the signal conditioning circuitry traces, typically made of copper. This junction between the thermocouple metals and the copper traces is called the *reference* (“cold”) junction.*

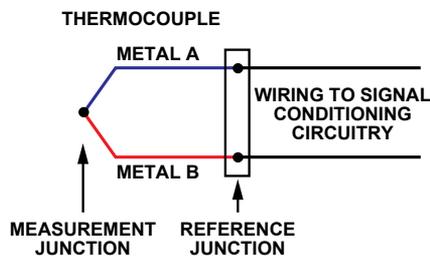


Figure 1. Thermocouple.

The voltage produced at the reference junction depends on the temperatures at both the measurement junction and the reference junction. Since the thermocouple is a differential device rather than an absolute temperature measurement device, the reference junction temperature must be known to get an accurate absolute temperature reading. This process is known as reference junction compensation (cold junction compensation.)

Thermocouples have become the industry-standard method for cost-effective measurement of a wide range of temperatures with reasonable accuracy. They are used in a variety of applications up to approximately +2500°C in boilers, water heaters, ovens, and aircraft engines—to name just a few. The most popular thermocouple is the type K, consisting of Chromel® and Alumel® (trademarked nickel alloys containing *chromium*, and *aluminum*, manganese, and silicon, respectively), with a measurement range of –200°C to +1250°C.

*We use the terms “measurement junction” and “reference junction” rather than the more traditional “hot junction” and “cold junction.” The traditional naming system can be confusing because in many applications the measurement junction can be colder than the reference junction.

Why Use a Thermocouple?

Advantages

- **Temperature range:** Most practical temperature ranges, from cryogenics to jet-engine exhaust, can be served using thermocouples. Depending on the metal wires used, a thermocouple is capable of measuring temperature in the range –200°C to +2500°C.
- **Robust:** Thermocouples are rugged devices that are immune to shock and vibration and are suitable for use in hazardous environments.
- **Rapid response:** Because they are small and have low thermal capacity, thermocouples respond rapidly to temperature changes, especially if the sensing junction is exposed. They can respond to rapidly changing temperatures within a few hundred milliseconds.
- **No self heating:** Because thermocouples require no excitation power, they are not prone to self heating and are intrinsically safe.

Disadvantages

- **Complex signal conditioning:** Substantial signal conditioning is necessary to convert the thermocouple voltage into a usable temperature reading. Traditionally, signal conditioning has required a large investment in design time to avoid introducing errors that degrade accuracy.
- **Accuracy:** In addition to the inherent inaccuracies in thermocouples due to their metallurgical properties, a thermocouple measurement is only as accurate as the reference junction temperature can be measured, traditionally within 1°C to 2°C.
- **Susceptibility to corrosion:** Because thermocouples consist of two dissimilar metals, in some environments corrosion over time may result in deteriorating accuracy. Hence, they may need protection; and care and maintenance are essential.
- **Susceptibility to noise:** When measuring microvolt-level signal changes, noise from stray electrical and magnetic fields can be a problem. Twisting the thermocouple wire pair can greatly reduce magnetic field pickup. Using a shielded cable or running wires in metal conduit and guarding can reduce electric field pickup. The measuring device should provide signal filtering, either in hardware or by software, with strong rejection of the line frequency (50 Hz/60 Hz) and its harmonics.

Difficulties Measuring with Thermocouples

It is not easy to transform the voltage generated by a thermocouple into an accurate temperature reading for many reasons: the voltage signal is small, the temperature-voltage relationship is nonlinear, reference junction compensation is required, and thermocouples may pose grounding problems. Let’s consider these issues one by one.

Voltage signal is small: The most common thermocouple types are J, K, and T. At room temperature, their voltage varies at 52 $\mu\text{V}/^\circ\text{C}$, 41 $\mu\text{V}/^\circ\text{C}$, and 41 $\mu\text{V}/^\circ\text{C}$, respectively. Other less-common types have an even smaller voltage change with temperature. This small signal requires a high gain stage before analog-to-digital conversion. Table 1 compares sensitivities of various thermocouple types.

Table 1. Voltage Change vs. Temperature Rise (Seebeck Coefficient) for Various Thermocouple Types at 25°C.

Thermocouple Type	Seebeck Coefficient ($\mu\text{V}/^\circ\text{C}$)
E	61
J	52
K	41
N	27
R	9
S	6
T	41

Because the voltage signal is small, the signal-conditioning circuitry typically requires gains of about 100 or so—fairly straightforward signal conditioning. What can be more difficult is distinguishing the actual signal from the noise picked up on the thermocouple leads. Thermocouple leads are long and often run through electrically noisy environments. The noise picked up on the leads can easily overwhelm the tiny thermocouple signal.

Two approaches are commonly combined to extract the signal from the noise. The first is to use a differential-input amplifier, such as an instrumentation amplifier, to amplify the signal. Because much of the noise appears on both wires (*common-mode*), measuring differentially eliminates it. The second is low-pass filtering, which removes out-of-band noise. The low-pass filter should remove both radio-frequency interference (above 1 MHz) that may cause rectification in the amplifier and 50 Hz/60 Hz (power-supply) *hum*. It is important to place the filter for radio frequency interference ahead of the amplifier (or use an amplifier with filtered inputs). The location of the 50-Hz/60-Hz filter is often not critical—it can be combined with the RFI filter, placed between the amplifier and ADC, incorporated as part of a sigma-delta ADC, or it can be programmed in software as an averaging filter.

Reference junction compensation: The temperature of the thermocouple's reference junction must be known to get an accurate absolute-temperature reading. When thermocouples were first used, this was done by keeping the reference junction in an ice bath. Figure 2 depicts a thermocouple circuit with one end at an unknown temperature and the other end in an ice bath (0°C). This method was used to exhaustively characterize the various thermocouple types, thus almost all thermocouple tables use 0°C as the reference temperature.

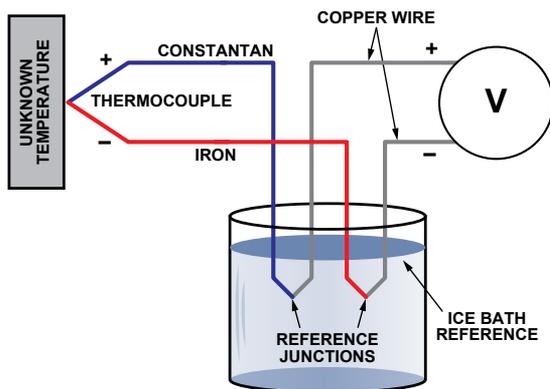


Figure 2. Basic iron-constantan thermocouple circuit.

But keeping the reference junction of the thermocouple in an ice bath is not practical for most measurement systems. Instead most systems use a technique called *reference-junction compensation*, (also known as *cold-junction compensation*). The reference junction temperature is measured with another temperature-sensitive device—typically an IC, thermistor, diode, or RTD

(resistance temperature-detector). The thermocouple voltage reading is then compensated to reflect the reference junction temperature. It is important that the reference junction be read as accurately as possible—with an accurate temperature sensor kept at the same temperature as the reference junction. Any error in reading the reference junction temperature will show up directly in the final thermocouple reading.

A variety of sensors are available for measuring the reference temperature:

1. Thermistors: They have fast response and a small package; but they require linearization and have limited accuracy, especially over a wide temperature range. They also require current for excitation, which can produce self-heating, leading to drift. Overall system accuracy, when combined with signal conditioning, can be poor.
2. Resistance temperature-detectors (RTDs): RTDs are accurate, stable, and reasonably linear, however, package size and cost restrict their use to process-control applications.
3. Remote thermal diodes: A diode is used to sense the temperature near the thermocouple connector. A conditioning chip converts the diode voltage, which is proportional to temperature, to an analog or digital output. Its accuracy is limited to about $\pm 1^\circ\text{C}$.
4. Integrated temperature sensor: An integrated temperature sensor, a standalone IC that senses the temperature locally, should be carefully mounted close to the reference junction, and can combine reference junction compensation and signal conditioning. Accuracies to within small fractions of 1°C can be achieved.

Voltage signal is nonlinear: The slope of a thermocouple response curve changes over temperature. For example, at 0°C a T-type thermocouple output changes at $39 \mu\text{V}/^\circ\text{C}$, but at 100°C, the slope increases to $47 \mu\text{V}/^\circ\text{C}$.

There are three common ways to compensate for the nonlinearity of the thermocouple.

Choose a portion of the curve that is relatively flat and approximate the slope as linear in this region—an approach that works especially well for measurements over a limited temperature range. No complicated computations are needed. One of the reasons the K- and J-type thermocouples are popular is that they both have large stretches of temperature for which the incremental slope of the sensitivity (Seebeck coefficient) remains fairly constant (see Figure 3).

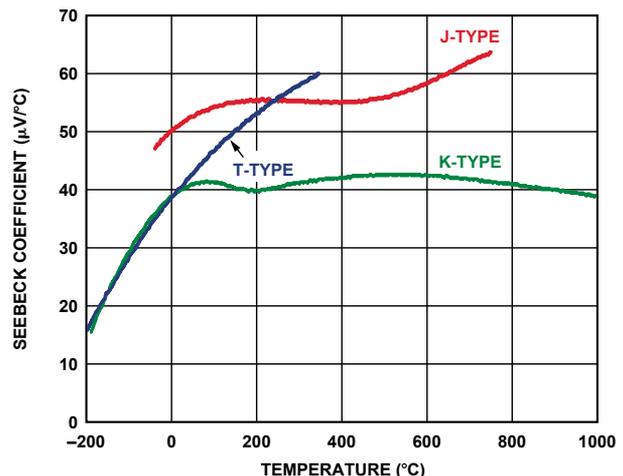


Figure 3. Variation of thermocouple sensitivity with temperature. Note that K-type's Seebeck coefficient is roughly constant at about $41 \mu\text{V}/^\circ\text{C}$ from 0°C to 1000°C.

Another approach is to store in memory a lookup table that matches each of a set of thermocouple voltages to its respective temperature. Then use linear interpolation between the two closest points in the table to get other temperature values.

A third approach is to use higher order equations that model the behavior of the thermocouple. While this method is the most accurate, it is also the most computationally intensive. There are two sets of equations for each thermocouple. One set converts temperature to thermocouple voltage (useful for reference junction compensation). The other set converts thermocouple voltage to temperature. Thermocouple tables and the higher order thermocouple equations can be found at <http://srdata.nist.gov/its90/main/>. The tables and equations are all based on a reference junction temperature of 0°C. Reference-junction compensation must be used if the reference-junction is at any other temperature.

Grounding requirements: Thermocouple manufacturers make thermocouples with both insulated and grounded tips for the measurement junction (Figure 4).

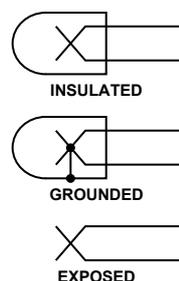


Figure 4. Thermocouple measurement junction types.

The thermocouple signal conditioning should be designed so as to avoid ground loops when measuring a grounded thermocouple, yet also have a path for the amplifier input bias currents when measuring an insulated thermocouple. In addition, if the thermocouple tip is grounded, the amplifier input range should be designed to handle any differences in ground potential between the thermocouple tip and the measurement system ground (Figure 5).

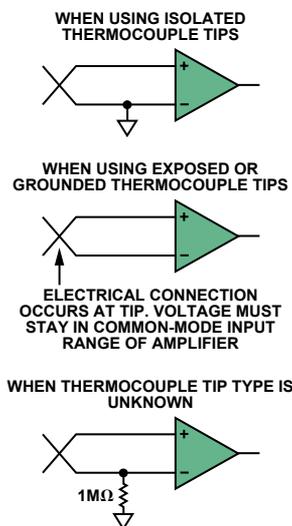


Figure 5. Grounding options when using different tip types.

For nonisolated systems, a dual-supply signal-conditioning system will typically be more robust for grounded tip and exposed tip types. Because of its wide common-mode input range, a dual-supply amplifier can handle a large voltage differential between the PCB (printed-circuit board) ground and the ground at the thermocouple tip. Single-supply systems can work satisfactorily in

all three tip cases if the amplifier's common-mode range has some ability to measure below ground in the single-supply configuration. To deal with the common-mode limitation in some single-supply systems, biasing the thermocouple to a midscale voltage is useful. This works well for insulated thermocouple tips, or if the overall measurement system is isolated. However, it is not recommended for nonisolated systems that are designed to measure grounded or exposed thermocouples.

Practical thermocouple solutions: Thermocouple signal conditioning is more complex than that of other temperature measurement systems. The time required for the design and debugging of the signal conditioning can increase a product's time to market. Errors in the signal conditioning, especially in the reference junction compensation section, can lead to lower accuracy. The following two solutions address these concerns.

The first details a simple analog integrated hardware solution combining direct thermocouple measurement with reference junction compensation using a single IC. The second solution details a software-based reference-junction compensation scheme providing improved accuracy for the thermocouple measurement and the flexibility to use many types of thermocouples.

Measurement Solution 1: Optimized for Simplicity

Figure 6 shows a schematic for measuring a K-type thermocouple. It is based on using the AD8495 thermocouple amplifier, which is designed specifically to measure K-type thermocouples. This analog solution is optimized for minimum design time: It has a straightforward signal chain and requires no software coding.

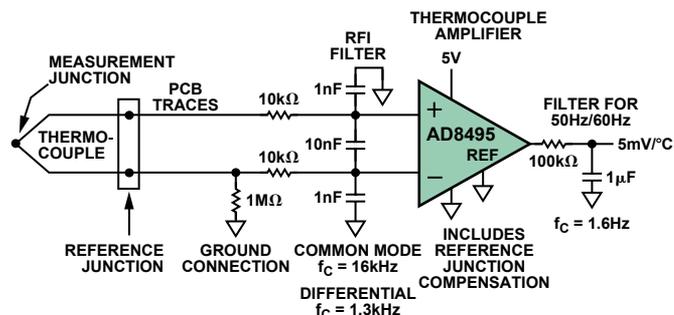


Figure 6. Measurement solution 1: optimized for simplicity.

How does this simple signal chain address the signal conditioning requirements for K-type thermocouples?

Gain and output scale factor: The small thermocouple signal is amplified by the AD8495's gain of 122, resulting in a 5-mV/°C output signal sensitivity (200°C/V).

Noise reduction: High-frequency common-mode and differential noise are removed by the external RFI filter. Low frequency common-mode noise is rejected by the AD8495's instrumentation amplifier. Any remaining noise is addressed by the external post filter.

Reference junction compensation: The AD8495, which includes a temperature sensor to compensate for changes in ambient temperature, must be placed near the reference junction to maintain both at the same temperature for accurate reference-junction compensation.

Nonlinearity correction: The AD8495 is calibrated to give a 5 mV/°C output on the linear portion of the K-type thermocouple curve, with less than 2°C of linearity error in the -25°C to +400°C temperature range. If temperatures beyond this range are needed, Analog Devices Application Note AN-1087 describes how a lookup table or equation could be used in a microprocessor to extend the temperature range.

Table 2. Solution 1 (Figure 6) Performance Summary

Thermocouple Type	Measurement Junction Temperature Range	Reference Junction Temperature Range	Accuracy at 25°C	Power Consumption
K	-25°C to +400°C	0°C to 50°C	±3°C (A grade) ±1°C (C grade)	1.25 mW

Handling insulated, grounded, and exposed thermocouples:

Figure 5 shows a 1-MΩ resistor connected to ground, which allows for all thermocouple tip types. The AD8495 was specifically designed to be able to measure a few hundred millivolts below ground when used with a single supply as shown. If a larger ground differential is expected, the AD8495 can also be operated with dual supplies.

More about the AD8495: Figure 7 shows a block diagram of the AD8495 thermocouple amplifier. Amplifiers A1, A2, and A3—and the resistors shown—form an instrumentation amplifier that amplifies the K-type thermocouple’s output with a gain appropriate to produce an output voltage of 5 mV/°C. Inside the box labeled “Ref junction compensation” is an ambient temperature sensor. With the measurement junction temperature held constant, the differential voltage from the thermocouple will decrease if the reference junction temperature rises for any reason. If the tiny (3.2 mm × 3.2 mm × 1.2 mm) AD8495 is in close thermal proximity to the reference junction, the reference-junction compensation circuitry injects additional voltage into the amplifier, so that the output voltage stays constant, thus compensating for the reference temperature change.

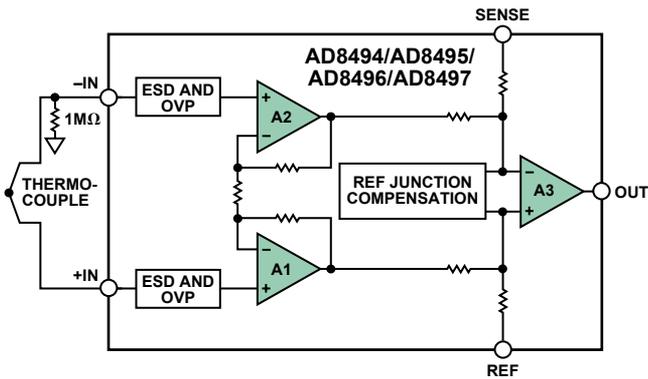


Figure 7. AD8495 functional block diagram.

Table 2 summarizes the performance of the integrated hardware solution using the AD8495:

Measurement Solution 2: Optimized for Accuracy and Flexibility

Figure 8 shows a schematic for measuring a J-, K-, or T-type thermocouple with a high degree of accuracy. This circuit includes a high-precision ADC to measure the small-signal thermocouple voltage and a high-accuracy temperature sensor to measure the reference junction temperature. Both devices are controlled using an SPI interface from an external microcontroller.

How does this configuration address the signal conditioning requirements mentioned earlier?

Remove noise and amplify voltage: The AD7793, shown in detail in Figure 9—a high-precision, low-power analog front end—is used to measure the thermocouple voltage. The thermocouple output is filtered externally and connects to a set of differential inputs, AIN1(+) and AIN1(-). The signal is then routed through a multiplexer, a buffer, and an instrumentation amplifier—which amplifies the small thermocouple signal—and to an ADC, which converts the signal to digital.

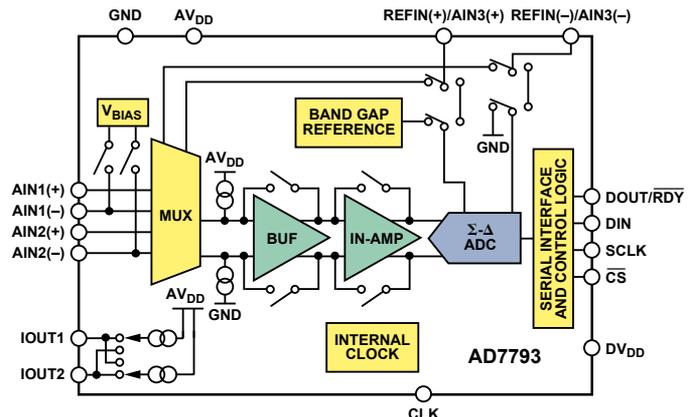


Figure 9. AD7793 functional block diagram.

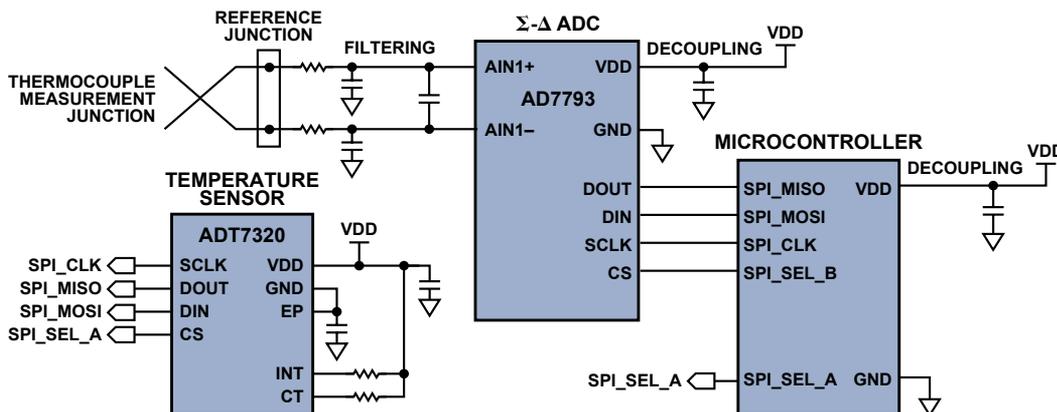


Figure 8. Measurement solution 2: Optimized for accuracy and flexibility.

Table 3. Solution 2 (Figure 8) Performance Summary

Thermocouple Type	Measurement Junction Temperature Range	Reference Junction Temperature Range	Accuracy	Power Consumption
J, K, T	Full Range	-10°C to +85°C -20°C to +105°C	±0.2°C ±0.25°C	3 mW 3 mW

Compensate for reference junction temperature:

The ADT7320 (detailed in Figure 10), if placed close enough to the reference junction, can measure the reference-junction temperature accurately, to ±0.2°C, from -10°C to +85°C. An on-chip temperature sensor generates a voltage proportional to absolute temperature, which is compared to an internal voltage reference and applied to a precision digital modulator. The digitized result from the modulator updates a 16-bit temperature value register. The temperature value register can then be read back from a microcontroller, using an SPI interface, and combined with the temperature reading from the ADC to effect the compensation.

Correct nonlinearity: The ADT7320 provides excellent linearity over its entire rated temperature range (-40°C to +125°C), requiring no correction or calibration by the user. Its digital output can thus be considered an accurate representation of the reference-junction state.

To determine the actual thermocouple temperature, this reference temperature measurement must be converted into an equivalent thermoelectric voltage using equations provided by the National Institute of Standards and Technology (NIST). This voltage then gets added to the thermocouple voltage measured by the AD7793; and the summation is then translated back into a thermocouple temperature, again using NIST equations.

Handle insulated and grounded thermocouples: Figure 8 shows a thermocouple with an exposed tip. This provides the best response time, but the same configuration could also be used with an insulated-tip thermocouple.

Table 3 summarizes the performance of the software-based reference-junction measurement solution, using NIST data:

Conclusion

Thermocouples offer robust temperature measurement over a quite wide temperature range, but they are often not a first choice for temperature measurement because of the required trade-offs between design time and accuracy. This article proposes cost-effective ways of resolving these concerns.

The first solution concentrates on reducing the complexity of the measurement by means of a hardware-based analog reference junction compensation technique. It results in a straightforward signal chain with no software programming required, relying on the integration provided by the AD8495 thermocouple amplifier, which produces a 5-mV/°C output signal that can be fed into the analog input of a wide variety of microcontrollers.

The second solution provides the highest accuracy measurement and also enables the use of various thermocouple types. A software-based reference junction compensation technique, it relies on the high-accuracy ADT7320 digital temperature sensor to provide a much more accurate reference junction compensation measurement than had been achievable until now. The ADT7320 comes fully calibrated and specified over the -40°C to +125°C temperature range. Completely transparent, unlike a traditional thermistor or RTD sensor measurement, it neither requires a costly calibration step after board assembly, nor does it consume processor or memory resources with calibration coefficients or linearization routines. Consuming only microwatts of power, it avoids self-heating issues that undermine the accuracy of traditional resistive sensor solutions.

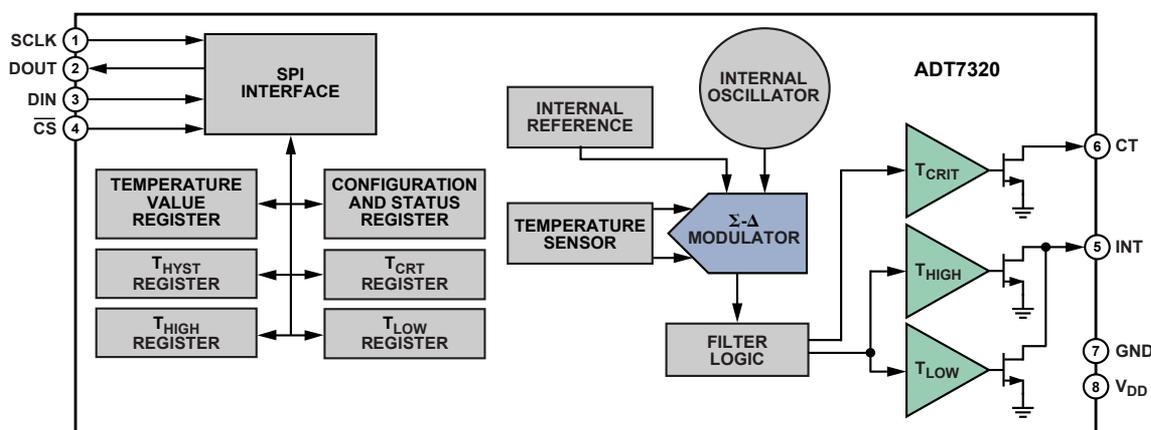


Figure 10. ADT7320 functional block diagram.

Appendix

Use of NIST Equation to Convert ADT7320 Temperature to Voltage

The thermocouple reference junction compensation is based on the relationship:

$$\Delta V = V @ J_1 - V @ J_2 \quad (1)$$

where:

ΔV = thermocouple output voltage

$V @ J_1$ = voltage generated at the thermocouple junction

$V @ J_2$ = voltage generated at the reference junction

For this compensation relationship to be valid, both terminals of the reference junction must be maintained at the same temperature. Temperature equalization is accomplished with an isothermal terminal block that permits the temperature of both terminals to equalize while maintaining electrical isolation.

After the reference junction temperature is measured, it must be converted into the equivalent thermoelectric voltage that would be generated with the junction at the measured temperature. One technique uses a power series polynomial. The thermoelectric voltage is calculated:

$$E = a_0 + a_1T + a_2T^2 + a_3T^3 + \dots + a_nT^n \quad (2)$$

where:

E = thermoelectric voltage (microvolts)

a_n = thermocouple-type-dependent polynomial coefficients

T = temperature ($^{\circ}\text{C}$)

n = order of polynomial

NIST publishes tables of polynomial coefficients for each type of thermocouple. In these tables are lists of coefficients, order (the number of terms in the polynomial), valid temperature ranges for each list of coefficients, and error range. Some types of thermocouples require more than one table of coefficients to cover the entire temperature operating range. Tables for the power series polynomial are listed in the main text.

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