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REFERENCE DESIGN 5032 INCLUDES: √Tested Circuit √Schematic √Description √Test Data

Modern Thermocouples and a High-Resolution Delta-Sigma ADC Enable High-Precision Temperature Measurement

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Abstract: Many industrial and medical applications require temperature measurements with accuracies of ±1°C or better, performed with reasonable cost over a wide range of temperatures (-270°C to +1750°C), and often with low power consumption. Properly selected, standardized, modern thermocouples paired with high-resolution ADC data acquisition systems (DASs) can cover this wide temperature range and ensure reproducible measurements, even in the harshest industrial environments.

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Introduction

Thermocouples are used in a wide range of temperature-sensing applications. Recent developments in thermocouple designs, as well new standards and algorisms, have greatly extended their temperature ranges and precision. Accuracies up to ±0.1°C are now possible over a very wide -270°C to +1750°C range. To utilize all the new thermocouple capabilities, high-resolution thermocouple temperature-measurement systems are required. A low-noise, 24-bit, delta-sigma analog-to-digital converter (ADC) with the ability to resolve very small voltages perfectly fits this task. When a data acquisition system (DAS) uses the evaluation (EV) kit for a 24-bit ADC, thermocouple temperature measurements can be made across that wide temperature range. When the thermocouple, platinum resistance temperature detector (PRTD), and ADC are integrated in a circuit, they enable a high-performance temperature-measurement system. The ADC-based DAS can also be designed to operate at very reasonable cost and with low power consumption, making it ideal for portable sensing applications.

A Primer on Thermocouples

Thomas Seebeck discovered the principle of a thermocouple in 1822. A thermocouple is a simple temperature-measurement device consisting of a junction of two dissimilar metals, Metal 1 and Metal 2 (**Figure 1**). Seebeck discovered that different metals will produce different electric potentials based on the temperature gradient applied to them. If these metals are welded together on the temperature-sensing junction (T_{JUNC}, also known as the hot junction), the other differential unconnected junction (T_{COLD}, which is kept at a constant reference temperature) will show a voltage, V_{OUT}, that is directly proportional to the applied temperature at the welded junction. This makes thermocouples a voltage/charge generating device that does not require any voltage or current excitation.

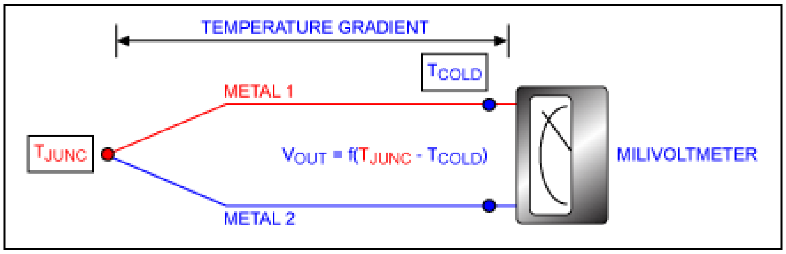


Figure 1. Simplified thermocouple circuit.

V_{OUT} is the function of the temperature differential (T_{JUNC} - T_{COLD}) and the types of metal in Metal 1 and Metal 2. This function is precisely defined in the National Institute of Standards and Technology (NIST) ITS-90 Thermocouple Database [1] for most practical Metal 1 and Metal 2 combinations. The database allows calculation of relative temperature, T_{JUNC}, based on the V_{OUT} measurements values. However, since the thermocouple measures T_{JUNC} differentially, the absolute cold-junction temperature (in °C, °F, or K) must be known to determine the actual temperature measured at the hot junction. All modern thermocouple-based systems use additional absolute temperature sensors (PRTD, silicon sensors, and so forth) to accurately measure the temperature of cold junction end and mathematically compensate for the difference.

Temperature equation for the simplified thermocouple circuits shown at Figure 1 is:

$$Tabs = T_{JUNC} + T_{COLD} \quad \text{(Eq. 1)}$$

Where:
Tabs is the absolute temperature of the hot junction;
T_{JUNC} is the relative temperature of the hot junction versus cold reference junction;
T_{COLD} is the absolute temperature of the reference cold junction.

There are a dozen varieties of thermocouples, but some specific material pairs of dissimilar metals work better in certain industrial or medical conditions. These combinations of the metals and/or alloys were standardized by the NIST and the International Electrotechnical Commission (IEC), and are abbreviated with E, J, T, K, N, B, S, R, etc. The NIST and IEC provide thermocouple reference tables for the each of the popular thermocouple types. [1]

The NIST and IEC also developed standard mathematical models for each type of thermocouple. These power series models use unique sets of coefficients which differ for different temperature segments within a given thermocouple type. [1]

Examples of some common popular thermocouple types (J, K, E, and S) are shown in **Table 1**.

Table 1. Typical Examples of Selected Popular Thermocouples

Thermocouple Type	Positive Conductor	Negative Conductor	Temperature Range (°C)	Seebeck Coefficient at +20°C
J	Chromel	Constantan	0 to 760	51µV/°C
K	Chromel	Alumel	-200 to +1370	41µV/°C
E	Chromel	Constantan	-100 to +1000	62µV/°C
S	Platinum (10% Rhodium)	Rhodium	0 to 1750	7µV/°C

Type-J thermocouples are widely used because of their relatively high Seebeck coefficient, high precision, and low cost. These thermocouples allow measurements with precision up to ±0.1°C, using a relatively simple linearization calculation algorithm.

Type-K thermocouples are very popular for industrial measurements covering a wide temperature range. These thermocouples offer a modestly high Seebeck coefficient, low cost, and good resistance to oxidation. Type K allows measurements with precision up to ±0.1°C.

Type-E thermocouples are less widespread than other thermocouples. However, the Seebeck coefficient is highest in this group. Measurements made by a Type-E thermocouple require less measurement resolution than other types. Type E allows measurements with precision up to ±0.5°C and requires a relatively complex linearization calculation algorithm.

Type-S thermocouples are comprised of platinum and rhodium, a combination that allows more stable and reproducible measurements at very high temperatures in oxidizing atmospheres. Type-S thermocouples have a low Seebeck coefficient and are relatively high cost. Type S allows measurements with precision up to ±1°C and requires a relatively complex linearization calculation algorithm.

Application Examples

The electronics interface to a thermocouple consists of a high-resolution ADC with differential inputs and the ability to resolve small voltages; a stable and low-drift reference; and some method of measuring the cold junction temperature accurately.

Figure 2 details a simplified schematic example. The MX7705, a 16-bit delta-sigma ADC integrates an internal programmable-gain amplifier (PGA), eliminates the need for an external precision amplifier, and resolves microvolt-level voltages from thermocouples. Cold-junction temperature is measured using a MAX6627 remote diode sensor and an external diode-connected transistor located at the thermocouple connector. A limited range of the negative temperatures can be accommodated by the MX7705, whose input common-mode range extends 30mV below ground. [2]

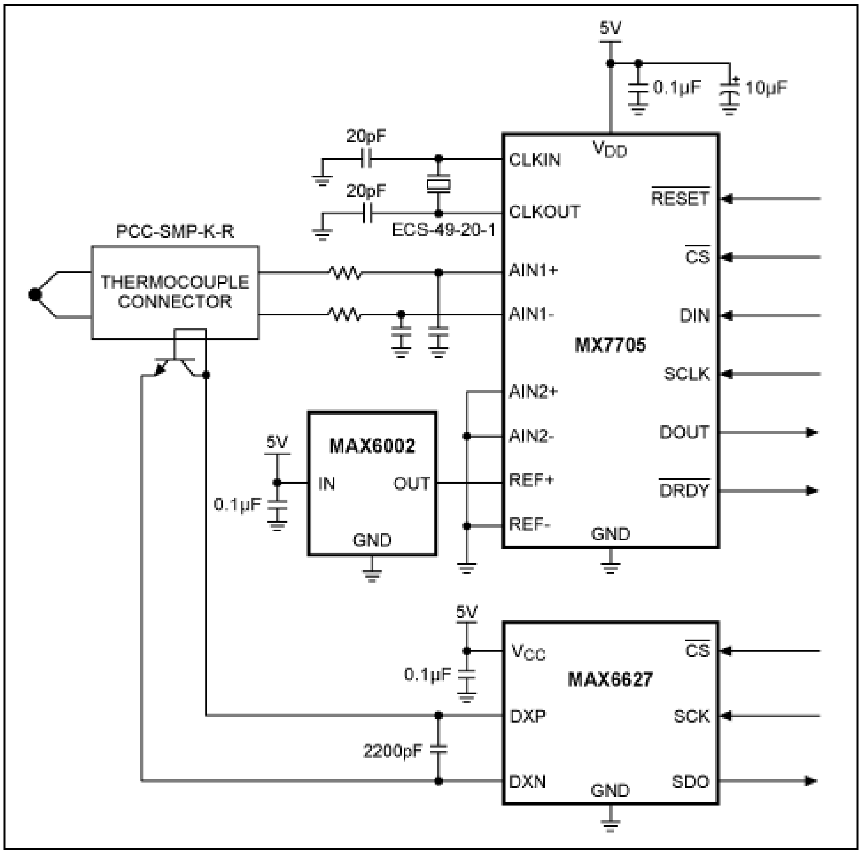


Figure 2. Thermocouple measurement circuit. The MX7705 measures the thermocouple output; the MAX6627 and external transistor measure the cold-junction temperature. The MAX6002 provides a 2.5V precision voltage reference to the MX7705.

Application-specific ICs are also available for thermocouple signal conditioning. These ICs integrate a local temperature sensor, precision amplifier, ADC, and voltage reference. For example, the MAX31855 is cold-junction-compensated thermocouple-to-digital converter that digitizes the signal from a K, J, N, T, or E Type thermocouple. The MAX31855 measures thermocouple temperatures with 14-bit (0.25°C) resolution (**Figure 3**).

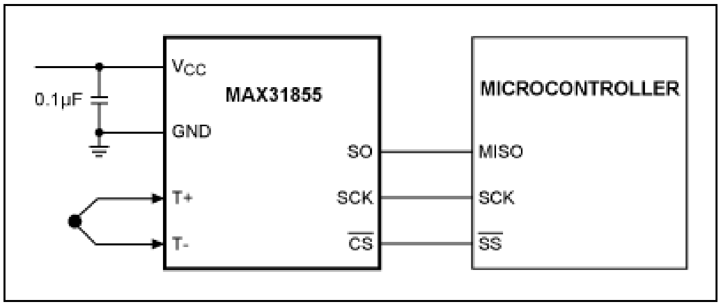


Figure 3. An ADC with integrated cold-junction compensation converts the thermocouple voltage without the need for external compensation.

Error Analysis

Cold-Junction Compensation

Thermocouples are differential sensors in which the output voltage is generated by a temperature difference between hot and cold junctions. According to Equation 1 above, the absolute temperature of the hot junction (Tabs) can be found only if the absolute temperature of the reference cold junction (T_{REF}) can be precisely measured.

A modern platinum RTD (PRTD) can be used for absolute temperature measurement of the reference cold junction. It offers the good performance across the wide temperature range with a small form factor, low power consumption, and very reasonable cost.

Figure 4 is a simplified schematic showing a precision DAS that uses the evaluation (EV) kit for the MAX11200 24-bit delta-sigma ADC and allows thermocouple temperature measurements. Here, R1 - PT1000 (PTS 1206, 1000Ω) is used for absolute temperature measurement of the cold junction. This solution allows the cold junction temperature to be measured with ±0.30°C accuracy, or better. [3]

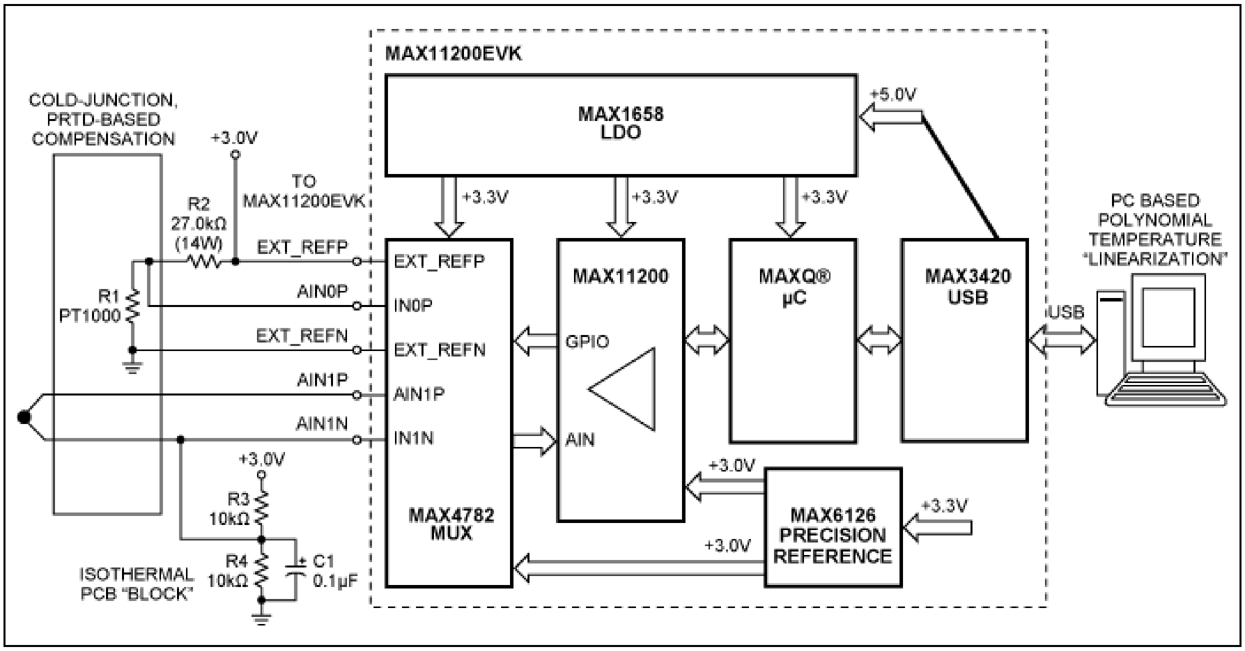


Figure 4. Simplified thermocouple DAS.

As shown in Figure 4, the MAX11200's GPIO is set to control the precision multiplexor, the MAX4782, which selects either the thermocouple or the PRTD R1 - PT1000. This approach allows dynamic thermocouple or PRTD measurements using a single ADC. The design improves the system precision and reduces the requirements for calibration.

Nonlinearity Errors

Thermocouples are voltage-generating devices. But output voltages as a function of temperature from the most common thermocouples [2, 4] are highly nonlinear.

Figure 4 and **Figure 5** demonstrate that without proper compensation, nonlinear errors for the popular industrial type-K thermocouples could exceed tens of °C.

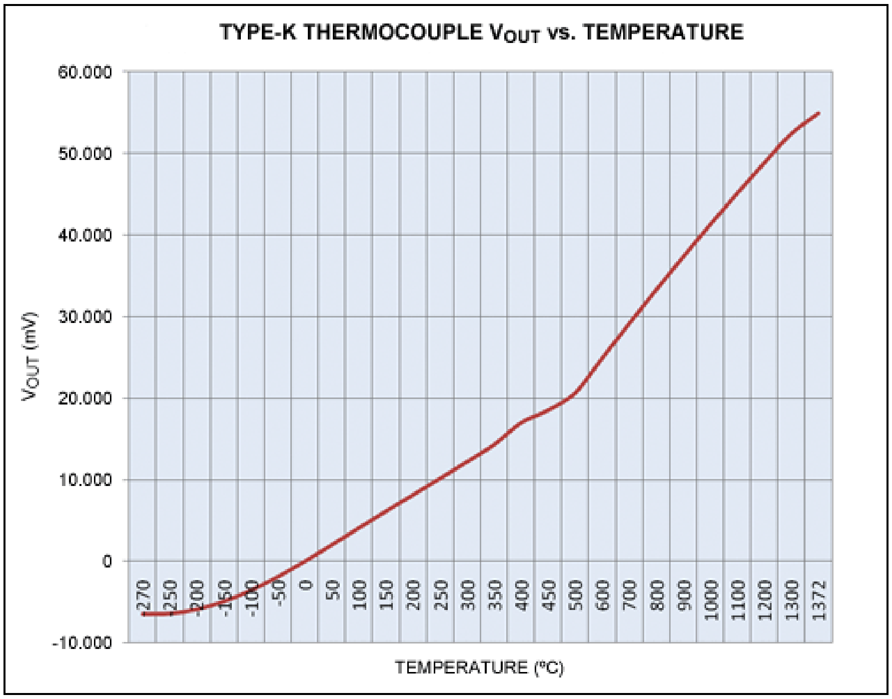


Figure 5. The output voltage vs. temperature for a type-K thermocouple. The curve is reasonably linear in the range of -50°C to +350°C; it clearly has significant deviations from absolute linearity—below -50°C and above +350°C. [1]

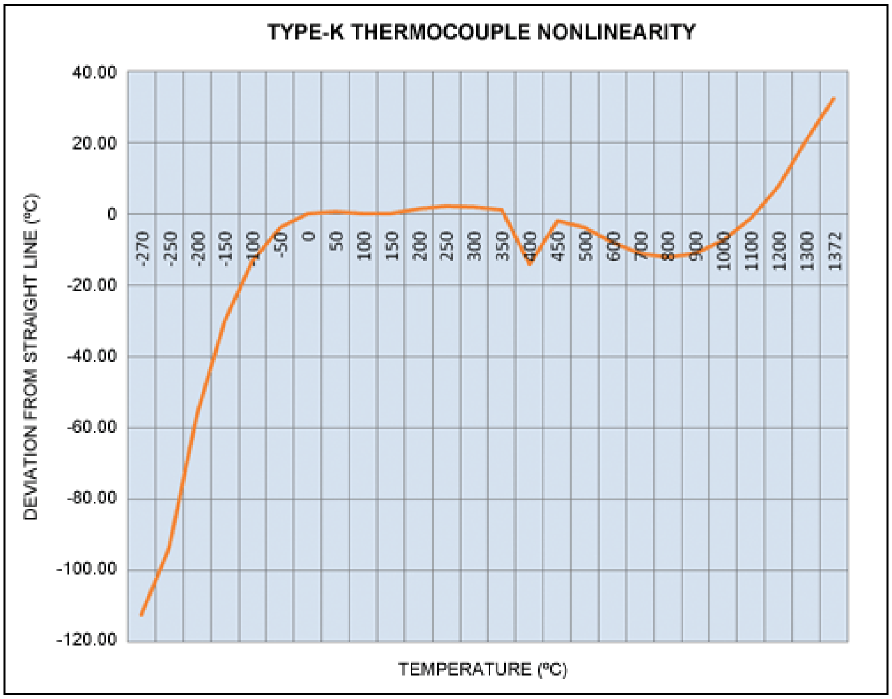


Figure 6. The deviation from a straight-line approximation, assuming a linear output from -50°C to +350°C, for an average sensitivity of k = 41µV/°C. [1]

Modern thermocouple standards, tables, and formulas such as the NIST ITS-90 Thermocouple Database [1] were adopted by the IEC and currently represent the foundation for substantial interchange of thermocouple types among systems. These standards make it easy to replace thermocouples with one from the same or a different manufacturer, while ensuring rated performance with minimal redesign or recalibration of the system.

The NIST ITS-90 Thermocouple Database provides detailed look-up tables. By using standardized polynomial coefficients [1], it also allows the polynomial equation to be used to convert thermocouple voltage to temperature (°C) over a wide range of temperatures.

Polynomial coefficients, according to the NIST ITS-90 Thermocouple Database, are:

$$T = d_0 + d_1E + d_2E^2 + \dots d_NE^N \qquad \text{(Eq. 2)}$$

Where:
T – is the temperature in °C;
E is the V_{OUT} - thermocouple output in mV;
d_N is the polynomial coefficients unique to each thermocouple;
N = maximum order of the polynomial.

NIST (NBS) polynomial coefficients for a type-K thermocouple are shown **Table 2**.

Table 2. Type-K Thermocouple Coefficients

Type-K Thermocouple Coefficients			
Temperature Range (°C)	**-200 to 0**	**0 to 500**	**500 to 1372**
Voltage Range (mV)	**-5.891 to 0**	**0 to 20.644**	**20.644 to 54.886**
Coefficients			
d0	0.0000000E+00	0.0000000E+00	-1.3180580E+02
d1	2.5173462E+01	2.5083550E+01	4.8302220E+01
d2	-1.1662878E+00	7.8601060E-02	-1.6460310E+00
d3	-1.0833638E+00	-2.5031310E-01	5.4647310E-02
d4	-8.9773540E-01	8.3152700E-02	-9.6507150E-04
d5	-3.7342377E-01	-1.2280340E-02	8.8021930E-06
d6	-8.6632643E-02	9.8040360E-04	-3.1108100E-08
d7	-1.0450598E-02	-4.4130300E-05	—
d8	-5.1920577E-04	1.0577340E-06	—
d9	—	-1.0527550E-08	—
Error Range (°C)	-0.02 to 0.04	-0.05 to 0.04	-0.05 to 0.06

Table 2 shows that polynomial coefficients allow temperature, T, calculations with precision better than ±0.1°C for a -200°C to +1372°C temperature range. Similar tables with different unique coefficients are available for most popular thermocouples. [1]

Contemporary NIST ITS-90 coefficients that are provided for the temperature intervals -200°C to 0, 0 to +500°C, and +500°C to +1372°C allow temperatures to be calculated with much better accuracy (below ±0.1°C vs. ±0.7°C). This can be seen in the comparison with older "single" interval tables. [2]

ADC Characteristics/Analysis

Table 3 shows the basic performance specifications of the MAX11200, featured in the circuit of Figure 4.

Table 3. MAX11200 Key Specifications

	MAX11200	Comments
Sample Rate (sps)	10 to 120	The MAX11200's variable oversampling rate can be optimized for low noise and for -150dB line-noise rejection at 50Hz or 60Hz.
Channels	1	GPIOs allow external multiplexer control for multichannel measurements.
INL (ppm, max)	±10	Provides very good measurement linearity.
Offset Error (µV)	±1	Provides almost zero offset measurements.
Noise-Free Resolution (Bits)	19.0 at 120sps; 19.5 at 60sps; 21.0 at 10sps	Very high dynamic range with low power.
V_{DD} (V)	AVDD (2.7 to 3.6) DVDD (1.7 to 3.6)	AVDD and DVDD ranges cover the industry's popular power-supply ranges.
I_{CC} (µA, max)	300	Highest resolution per unit power in the industry; ideal for portable applications.
GPIOs	Yes	Allows external device control, including local multiplexer control.
Input Range	0 to V_{REF}, $\pm V_{REF}$	Wide input ranges
Package	16-QSOP, 10-µMAX® (15mm²)	Some models like the MAX11202 are offered in a 10-µMAX package—a very small size for space-constrained designs.

The MAX11200 used in this article is a low-power, 24-bit delta-sigma ADC suitable for low-power applications that require a wide dynamic range and a high number of noise-free bits. Using this ADC, you can calculate the resolution in temperature for the Figure 3 circuit using Equations 3 and 4:

$$\text{Rtlsb} = \frac{V_{REF} \times (\text{Tcmax} - \text{Tcmin})}{\text{FS} \times (\text{Vtmax} - \text{Vtmin})} \qquad \text{(Eq. 3)}$$

$$\text{Rtnfr} = \frac{V_{REF} \times (\text{Tcmax} - \text{Tcmin})}{\text{NFR} \times (\text{Vtmax} - \text{Vtmin})} \qquad \text{(Eq. 4)}$$

Where:
Rtlsb is the thermocouple resolution at 1 LSB;
Rtnfr is the thermocouple noise-free resolution (NFR);
V_{REF} is the reference voltage;
Tcmax is the maximum thermocouple temperature in the measurement range;
Tcmin is the minimum thermocouple temperature in measurement range;
Vtmax is the maximum thermocouple voltage in the measurement range;
Vtmin is the minimum thermocouple voltage in the measurement range;
FS is the ADC full-scale code for a MAX11200 in a bipolar configuration (2^{23}-1);
NFR is the ADC noise-free resolution for a MAX11200 in the bipolar configuration (2^{20}-1) at 10 samples per second.

Table 4 lists the calculations of the measurement resolution using Equations 3 and 4 for the type-K thermocouples identified in Table 1.

Table 4. Measurement Resolution for Type-K Thermocouples Across Different Temperature Ranges

Temperature Range (°C)	-200 to 0	0 to 500	500 to 1372
Voltage Range (mV)	-5.891	20.644	34.242
Rtlsb Resolution (°C/LSB)	0.0121	0.0087	0.0091
Rtnfr Resolution (°C/NFR)	0.0971	0.0693	0.0729

Table 4 provides the calculated values of °C/LSB error and °C/NFR error for each temperature range. Noise-free resolution (NFR) represents the minimum temperature values that can be reliably differentiated by the ADC. For all temperature ranges, NFR values are below 0.1°C, which is more than sufficient for most thermocouples in industrial and medical applications.

Interfacing a Thermocouple with the MAX11200 EV Kit

The MAX11200EVKIT offers a fully functional, high-resolution DAS. The EV kit can help a design engineer expedite real-life developments, such as verification of the schematic solution suggested in Figure 4.

On the Figure 4 schematic, the popular type-K OMEGA thermocouple (KTSS-116 [5]) was connected to differential EV kit input A1. The absolute measurement of the cold junction temperature was done using the cost-effective ratiometric method described in Maxim's application note 4875. [3] Output of the R1 (PT1000) was connected to EV kit input A0. The MAX11200's GPIO was set to control the precision multiplexor, MAX4782, which dynamically selects either the thermocouple or the PRTD R1 outputs connected to the MAX11200's input.

The type-K thermocouple (Figures 3, 4) is reasonably linear across the -50°C to +350°C range. For some noncritical applications, linear approximation formulas (Equation 5) allow substantially reduced calculation volume and complexity.

Approximate absolute temperature could be calculated as:

$$\text{Tabs} = \frac{\text{E} + \text{Ecj}}{\text{k}} \qquad \text{(Eq. 5)}$$

Where:
E is the measured thermocouple output in mV;
Tabs is the absolute temperature of the type-K thermocouples in °C;
Tcj is the temperature of the cold junction of the thermocouples (°C) measured by PT1000; [3]
Ecj is the cold-junction thermocouple equivalent output in mV calculated by using Tcj.

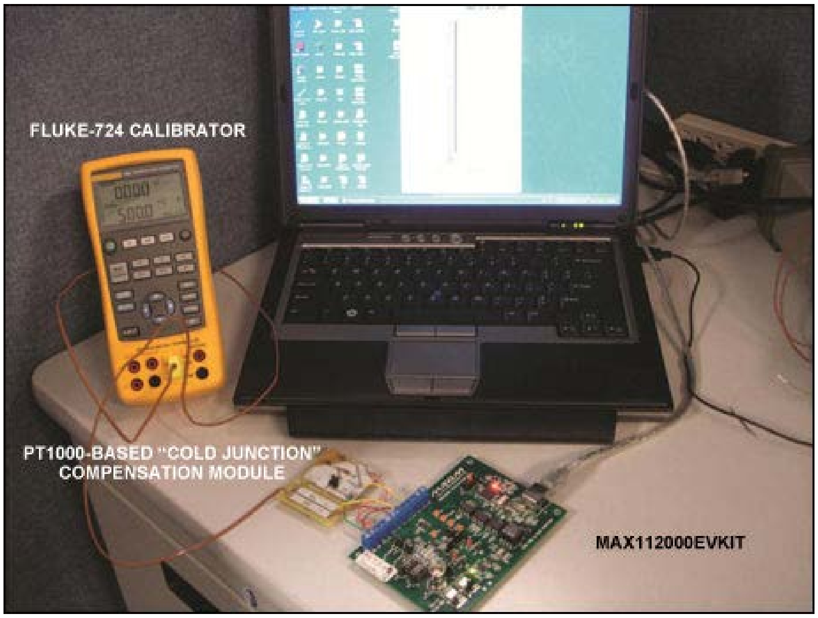
Therefore:
k = 0.041mV/°C - average sensitivity from -50°C to +350°C

To make precision measurements in the wider temperature range (-270°C to +1372°C), however, implementation of the polynomial formulas (Equation 2) and coefficients (according NIST ITS-90) is strongly recommended:

$$\text{Tabs} = f(\text{E} + \text{Ecj}) \qquad \text{(Eq. 6)}$$

Where:
Tabs is the absolute temperature of the type-K thermocouples in °C;
E is the measured thermocouple output in mV;
Ecj is the cold-junction thermocouple equivalent output in mV calculated by using Tcj;
f is the polynomial function according equation 2;
T_{COLD} is the temperature of the cold junction of the thermocouples (°C) measured by PT1000.

Figure 7 shows the development system for Figure 4. This system features a certified precision calibrator, Fluke®-724, used like temperature simulator to replace the type-K OMEGA thermocouple.



More detailed image (PDF, 3.1MB)

Figure 7. The development system for Figure 4.

The Fluke-724 calibrator is supplying precision voltage that corresponds to the Type-K thermocouple output in the -200°C to +1300°C range to the PT1000-based cold-junction compensation module. The MAX11200-based DAS dynamically selects either the thermocouple or the PRTD measurement and transmits data though a USB port to the laptop computer. Specially developed DAS software collects and processes data generated by the thermocouple and PT1000 outputs.

Table 5 lists measurement and calculations using Equations 5 and 6 for the -200°C to +1300°C temperature range.

Table 5. Measurement Calculations Across -200°C to +1300°C

Temperature (Fluke-724) (°C)	PT1000 Code Measured at "Cold Junction" (LSB)	Thermocouple Code Adjusted to 0°C by PT1000 Measurements (LSB)	Temperature Calculated by Equation 6 and Table 2 (°C)	Temperature Error vs. Calibrator (°C)	Temperature Calculated by "Linear" Equation 5 (°C)
-200	326576	-16463	-199.72	0.28	-143.60
-100	326604	-9930	-99.92	0.08	-86.62
-50	326570	-5274	-50.28	-0.28	-46.01
0	326553	6	0.00	0.00	0.05
20	326590	2257	20.19	0.19	19.68
100	326583	11460	100.02	0.02	99.96
200	326486	22779	200.18	0.18	198.69
500	326414	57747	500.16	0.16	503.70
1000	326520	115438	1000.18	0.18	1006.92
1300	326544	146562	1300.09	0.09	1278.40

As Table 5 shows, by using Equation 6 the MAX11200-based DAS achieves in the order ±0.3°C precision over a very wide temperature range. Linear approximation by Equation 5 allows only a 1°C to 4°C degree of precision in the narrower -50°C to +350°C temperature range.

Note that using Equation 6 required relatively complex linearization calculation algorithms.

Around a decade ago implementation of such algorithms could present both technical and cost constrains in DAS system design. Today's modern processors resolve these challenges quickly and cost effectively.

Conclusion

In recent years cost-efficient, thermocouple-based temperature-sensing measurement has developed for a very wide temperature range in the order -270°C to +1750°C. Improvements in the temperature measurements and range have been accompanied by reasonable costs and often very low power consumption.

These thermocouple-based temperature measurement systems require a low-noise ADC (like the MAX11200), if the ADC and thermocouple are to be connected directly. When integrated in a circuit, the thermocouple, PRTD, and ADC provide a high-performance temperature-measurement system that is ideal for portable sensing applications.

High noise-free resolution, integrated buffers, and GPIO drivers allow the MAX11200 to interface directly with any traditional thermocouples and high-resolution PRTDs like the PT1000 without the need for an additional instrumentation amplifier or dedicated current sources. Less wiring and lower thermal errors further reduce the system complexity and cost, thus allowing the designer to implement a simple DAS interface with a thermocouple and cold-junction compensation module.

References

[1] See the NIST online databases.

[2] See application note 4679, "Thermal Management Handbook."

[3] For more details about high-accuracy temperature measurements using a PRTD, see Maxim's application note 4875, "High-Accuracy Temperature Measurements Call for Platinum Resistance Temperature Detectors (PRTDs) and Precision Delta-Sigma ADCs."

[4] Using Thermocouples - Thermocouple Introduction and Theory (PDF).

[5] Type-K OMEGA thermocouple KTSS-116 (PDF).

Related Parts		
MAX11200	24-Bit, Single-Channel, Ultra-Low Power, Delta-Sigma ADCs with GPIO	Free Samples
MAX11200EVKIT	Evaluation Kits for the MAX11200, MAX11206, MAX11209, MAX11210, and MAX11213	
MAX31855	Cold-Junction Compensated Thermocouple-to-Digital Converter	Free Samples
MAX6002	Low-Cost, Low-Power, Low-Dropout, SOT23-3 Voltage References	Free Samples
MAX6627	Remote ±1°C Accurate Digital Temperature Sensors with SPI-Compatible Serial Interface	Free Samples
MX7705	16-Bit, Low-Power, 2-Channel, Sigma-Delta ADC	Free Samples

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More Information

Application Note 5032: http://www.maximintegrated.com/an5032
REFERENCE DESIGN 5032, AN5032, AN 5032, APP5032, Appnote5032, Appnote 5032