Surpass Temperature Sensing Expectations with a Next-Generation Delta-Sigma Converter

Temperature is the most commonly detected characteristic in the sensor world. For instance, complex gas turbine engines need thorough instrumentation to operate safely and correctly, with temperature being one of the most critical final evaluation parameters.

In the gas turbine engine, hundreds of thermocouples provide inlet, interior, and exit temperatures to enable engine control under different operating conditions to monitor the health of high-temperature components, and to calculate the efficiency of compressors and turbines (Figure 1).

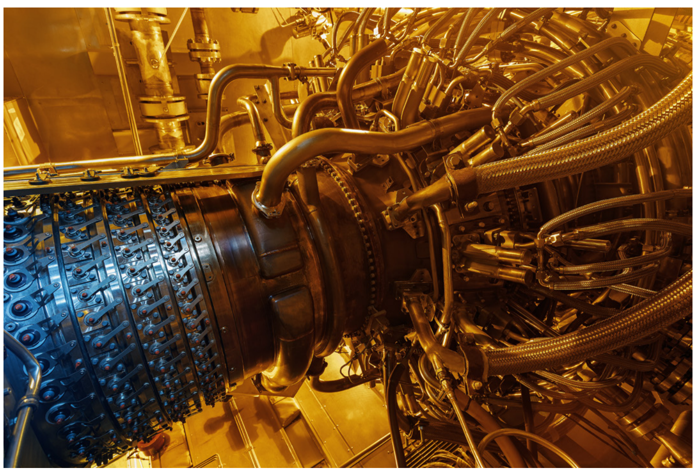


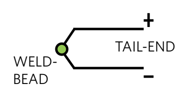
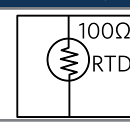
Figure 1. Offshore Oil Platforms Use a Gas Turbine Engine

This design solution evaluates the accuracy of thermocouples used for high-temperature measurements as well as resistance temperature detectors (RTDs) used for local cold-junction-compensation (CJC) points. In addition, we'll highlight how a multichannel, delta-sigma (ΔΣ) analog-to-digital converter (ADC) raises the bar of temperature accuracy by including an on-chip integrated programmable gain amplifier, current sources, and superior low-noise characteristics.

Thermocouple vs. RTD

The thermocouple and RTD may seem to be diametrically opposed but their individual characteristics fit perfectly in temperature sensing applications. The thermocouple measures the turbine engine's temperature extremes while the RTD provides an accurate PCB CJC measurement. Table 1 summarizes the main characteristics of an RTD and thermocouple temperature sensor.

Table 1. Comparison of Basic RTD and Thermocouple Temperature Sensor Characteristics

Characteristic	Thermocouple (TC)	Resistance Temperature Detector (RTD)
		
Temperature Range	-270°C to +1820°C	-200°C to +850°C
Linearity	Nonlinear	High (limited)
Power Consumption	Self Power	External Current or Voltage Source
Output Range	Low Voltage (mv)	100Ω or 1000Ω at 0°C
Sensitivity	-50µV/°C Very Low	High: -0.39%/°C
Operation	Requires CJC + Signal Amplifier	2, 3, or 4-Wire, Signal Conditioning

The thermocouple is front and center in the turbine engine's internal sensing activities because of its broad and high-temperature sensing ranges. The RTD accuracy appropriately addresses the CJC needs.

Thermocouple Characteristics

Thermocouples are the right sensors for high-temperature sensing due to their rugged operation and -270°C to +1820°C temperature range. The thermocouple's rugged capability allows this small-sized, inexpensive sensor to endure saturation in hostile environments such as liquid or gas, with varying degrees of atmospheric pressure.

A thermocouple has two wires (≥ 20 AWG and ≤ 100 feet) of dissimilar metals or alloys. For example, the two leads of a Type-K thermocouple are Chromel and Alumel. All thermocouples have a weld-bead at one end of the two wires that form a thermocouple junction. A difference in temperature between the weld-bead and the two open-wires or tail-end of the thermocouple creates a small electromotive-force (EMF) voltage that is responsive to temperature differences. The thermocouple does not require voltage or current excitation.

The sensor's output voltage from the weld-bead to the tail-end is in the millivolt range with a Seebeck or temperature coefficient (typically 50µV/°C). The Seebeck coefficient is the first derivative of the thermocouple's EMF voltage as a function of temperature.

The thermocouple's temperature range and the Seebeck coefficient depends on the specific thermocouple type or metal-lead materials (Table 2). Table 2 shows the variety in thermocouple conductors, their specified temperature ranges and the Seebeck coefficients that depend on two-metal conductors.

Thermocouples produce voltages that range from 0V to tens of millivolts over wide temperature ranges. Thermocouple output voltages are repeatable but nonlinear over temperature. Since all thermocouples are nonlinear, the value of the Seebeck coefficient also varies with temperature.

The American Society of Testing and Materials (ASTM) fully characterizes IST-90 units per NIST Monograph 175, is specified in the thermocouples featured in Table 2. Additionally, a table of the EMF voltage versus temperature is usually available from the thermocouple manufacturer.

The small, absolute and delta thermocouple voltages align perfectly with a 24-bit ΔΣ delta-sigma analog-to-digital converter (ΔΣ ADC), with a typical least-significant-bit (LSB) that equals the supply voltage divided by the number of converter codes.

$$LSB = \frac{V_{IN\_MAX}}{G \times 2^N} \qquad \text{Eq. 1}$$

Where N = ADC resolution

G = (PGA) gain

If the ADC's maximum input range is 5V and it has , with a PGA gain of 8, the LSB of a 24-bit converter is 37.25nV.

Table 2. Types of Thermocouples

Thermocouple Type	Conductors	Typical Specified Temperature Range (°C)	Seebeck Coefficient (at 20°C)	Application Environments
E	Chromel (+) Constantan (-)	-200 to +900	62µV/°C	Oxidizing, inert, vacuum
J	Iron (+) Constantan (-)	0 to +760	51µV/°C	Oxidizing, reducing, inert
T	Copper (+) Constantan (-)	-200 to +371	40µV/°C	Corrosive, moist, subzero
K	Chromel (+) Alumel (-)	-200 to +1260	40µV/°C	Completely inert
N	Nicrosil (+) Nisil (-)	0 to +1260	27µV/°C	Oxidizing
B	Platinum (30% Rhodium)(+) Platinum (6% Rhodium) (-)	0 to +1820	1µV/°C	Oxidizing, inert
S	Platinum (10% Rhodium) (+) Platinum (-)	0 to +1480	7µV/°C	Oxidizing , inert
R	Platinum (13% Rhodium) (+) Platinum (-)	0 to +1480	7µV/°C	Oxidizing, inert

RTD Characteristics

Thermocouple systems require a second accurate temperature system that operates as a CJC point of reference. RTD temperature sensors are standard in industrial and medical applications, because of their high accuracy and repeatability over a -200°C to +850°C temperature range. The RTD sensor's accuracy and repeatability characteristics meet the needs of the thermocouple system's CJC.

Typically, the RTD consists of a fine temperature sensitive wire, such as pure platinum, nickel, or copper wrapped around a ceramic or glass nonconductive core. The RTD's resistance increases linearly with increasing temperatures.

The RTD's resistance vs. temperature curve is reasonably linear, but has some curvature, as the Callendar-Van Dusen equation describes:

$$R(T) = R0(1 + aT + bT^2 + c\,(T - 100)\,T^3)$$

Where:

T = Temperature (°C)

R(T) = Resistance at T

R0 = Resistance at T = 0°C

The 0°C specification for the platinum PT100 is 100Ω. The PCB position of the RTD sensor must be close to the thermocouple-to-PCB wire connections. The RTD resistor requires a current or voltage excitation to change the resistance of the element to volts. The actual thermocouple weld-bead temperature is the measured thermocouple's weld-bead temperature plus the measured RTD's temperature.

Get It Right the First Time

The challenge with all thermocouple and RTD systems is to acquire the most accurate temperature reading the first time. This high level of temperature monitoring ensures that the environment under test provides accurate and repeatable results over time.

A conventional thermocouple-plus-RTD sensor signal chain includes two discrete front-end amplifiers, followed by analog filters, and then a SAR ADC. This cumbersome, multi-package, PCB-hungry solution can be accurate. However, the compact ΔΣ ADC includes all these functions on-chip in a single compact package.

Delta-Sigma ADC and the Thermocouple

A low-noise ΔΣ ADC, with a built-in PGA, 50Hz/60Hz digital filter, and external lowpass filter, is an appropriate alternative for digitizing the Type-K thermocouple's output (Figure 2).

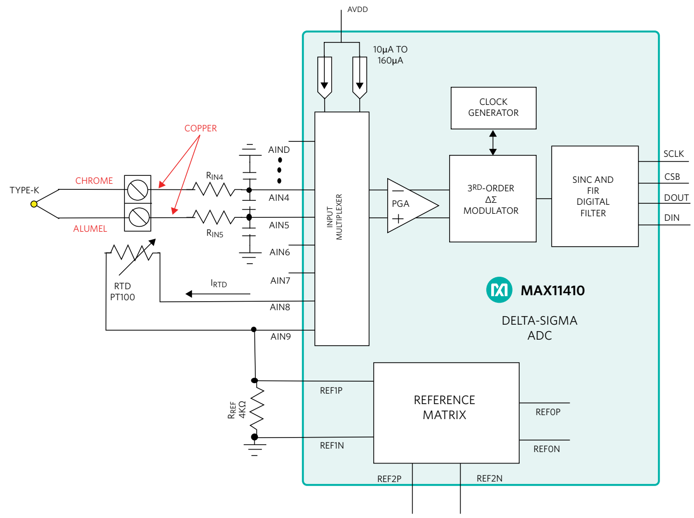


Figure 2. ΔΣ ADC with Internal PGA Stage Followed by a Powerful Third Order Modulator and Sinc/FIR Digital Filter

In Figure 2, a Type-K thermocouple connects to the ΔΣ ADC's analog AIN4 and AIN5 pins. An RTD, which spans across AIN8 and AIN9, senses the temperature of the thermocouple's tail-end connections to the PCB copper traces. All four connections travel through the input multiplexer and an internal PGA, followed by a third order ΔΣ modulator/SINC/FIR digital filter combination.

The MAX11410 24-bit ΔΣ ADC is a low-power multi-channel converter. The configuration of the ten analog inputs can be single-ended or fully differential connections in any combination. These ten inputs allow the connection of up to four thermocouples and one CJC RTD. Two integrated and matched current sources, with sixteen programmable current levels, provides excitation for the RTD sensors. The current sources can connect to any of the analog input pins while an additional current sink and current source aids in detecting broken thermocouple sensor wires. The integrated bias voltage source can connect to one or more analog input. This bias voltage source is used to provide bias voltage for thermocouple measurement.

The configuration between the analog input and the delta-sigma modulator input can include a PGA mode with gain steps from 1 to 128. The 24-bit ΔΣ ADC achieves 90dB simultaneous 60Hz and 50Hz power line rejection and 3ppm INL, with no missing codes. The selection of reference sources is between multiple reference input pins and the analog power supply.

The thermocouple creates millivolt output signals, and the turbine engine requires temperature measurements from +400°C to +1000°C. Over this temperature range, the Type-K thermocouple has an output range of approximately 16.397mV to 33.275mV, with a Seebeck Coefficient of 41±2µV/°C. The correct setting for the Type-K thermocouple connected to a

3.3V-powered ΔΣ ADC is a PGA gain of 8 and a sampling rate of 8.4sps (samples per second). This configuration renders 19.8 bits RMS of resolution, with the RMS noise level equal to $0.684\mu V_{RMS}$.

Delta-Sigma ADC and the RTD

The RTD measures the thermocouple's tail-end at the copper connection to provide a CJC reference. It is critical that the RTD is as close to the junction connector as possible. The RTD, with platinum PT100's excitation current (I_{RTD} using the internal MAX11410 current source), is 300µA with a PGA setting of 8. The RTD element has a temperature coefficient of 0.00385Ω/Ω/°C, with a resistance of 84.27Ω at -40°C and 140.39Ω at +105°C.

Delta-Sigma ADC, Thermocouple, and RTD Errors

The thermocouple (site measurement) and RTD (CJC measurement) temperature accuracy errors equally contribute to the final temperature measurement. Table 3 summarizes these contributions as well as provides worst-case summation and the square-root-of-the-sum-of-the-squares (RSS) calculations.

Table 3. MAX11410 Digitizer Errors

Parameter	MAX11410	TC Temp	RTD (CJ) Value
Gain Error	0.02%	0.2°C	0.05°C
Input Current (I_{IN})	1nA	—	—
Input Resistance (R_{IN4}, R_{IN5})	2kΩ	—	—
I_{IN} R Error	2.0µV	0.04°C	—
ADC/PGA Offset	0.5µV	0.01°C	—
R_{REF}	4kΩ	—	—
Ref. Input Current	61nA	—	0.2°C
Sum of TUE Errors	0.50°C		
RSS of TUE Errors	0.29°C		

***Note:** TC errors at +1000°C, TC = thermocouple assuming Seebeck Coefficient or SC of 50µV/°C, CJ = Cold Junction, IR = ADC input bias current times 1kΩ + 1kΩ external resistors.*

The TC Temp values in Table 3 are equal to:

Gain Error → Gain Error x 1000°C

IR Error → Input Current x (R_{IN4} + R_{IN5})/SC

ADC/PGA Offset → ADC/PGA Offset/SC

The RTD (CJ) values in Table 3 are equal to:

Gain Error → Gain Error/(RTD Tempco)

Ref Input Current → SC/(Ref Input Current x R_{REF})

From Table 3, the summation or worst-case thermocouple and RTD accuracy error is equal to 0.50°C, calculated over the thermocouple's +400°C to +1000°C temp range and the RTD's -40°C to +105°C temperature range.

The RSS accuracy error is valid, as there is no correlation between the four errors and two sensors in Table 3. In this system, the RSS accuracy error equals 0.29°C, over the same temperature ranges.

Figure 3 shows the MAXREFDES1154 dual-channel RTD/TC measurement system based on the MAX11410. This reference design provides a complete proof of concept for the thermocouple/RTD/MAX11410 combination.

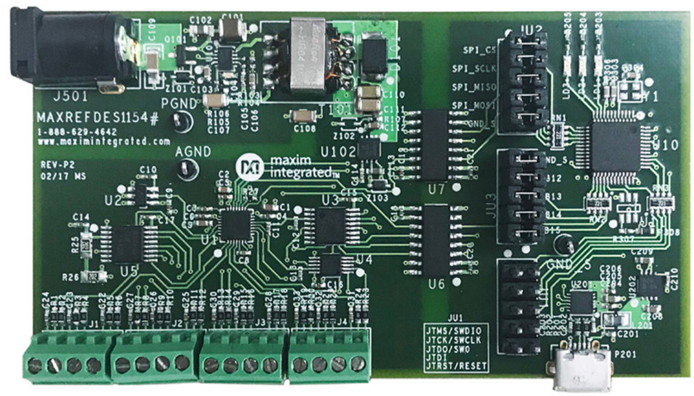


Figure 3. MAXREFDES1154 Hardware

Conclusion

Engine, industrial, and process control applications demand an electrical environment that has highly precise temperature sensing activities over wide temperature ranges. This design solution evaluates the accuracy of the thermocouple and RTD temperature sensors and finds that a 24-bit ΔΣ ADC, with auxiliary current sources and voltage reference matrix successfully acquires high-precision thermocouple results.

Learn more:

MAX11410 24-Bit Multi-Channel Low-Power 1.9ksps Delta-Sigma ADC with PGA

MAX11410EVKIT MAX11410 Evaluation Kit

MAXREFDES1154: Configurable 4-Channel RTD/TC Measurement System Using The MAX11410

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