Temperature-to-Bits converter helps solve challenges in sensor measurement

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Although temperature is a fundamental aspect of our lives, it is difficult to measure accurately. Before the era of modern electronics, Galileo invented a rudimentary thermometer capable of detecting temperature changes. Two hundred years later, Seebeck discovered the thermocouple, a device capable of generating a voltage as a function of temperature gradients in dissimilar metals. Today, thermocouples as well as temperature dependent resistance elements (RTDs and thermistors) and semiconductor elements (diodes) are commonly used to electrically measure temperature. While methods for extracting temperature from these elements are well known, accurately measuring temperatures to better than 0.5ºC or 0.1ºC accuracy is challenging (see Figure 1).

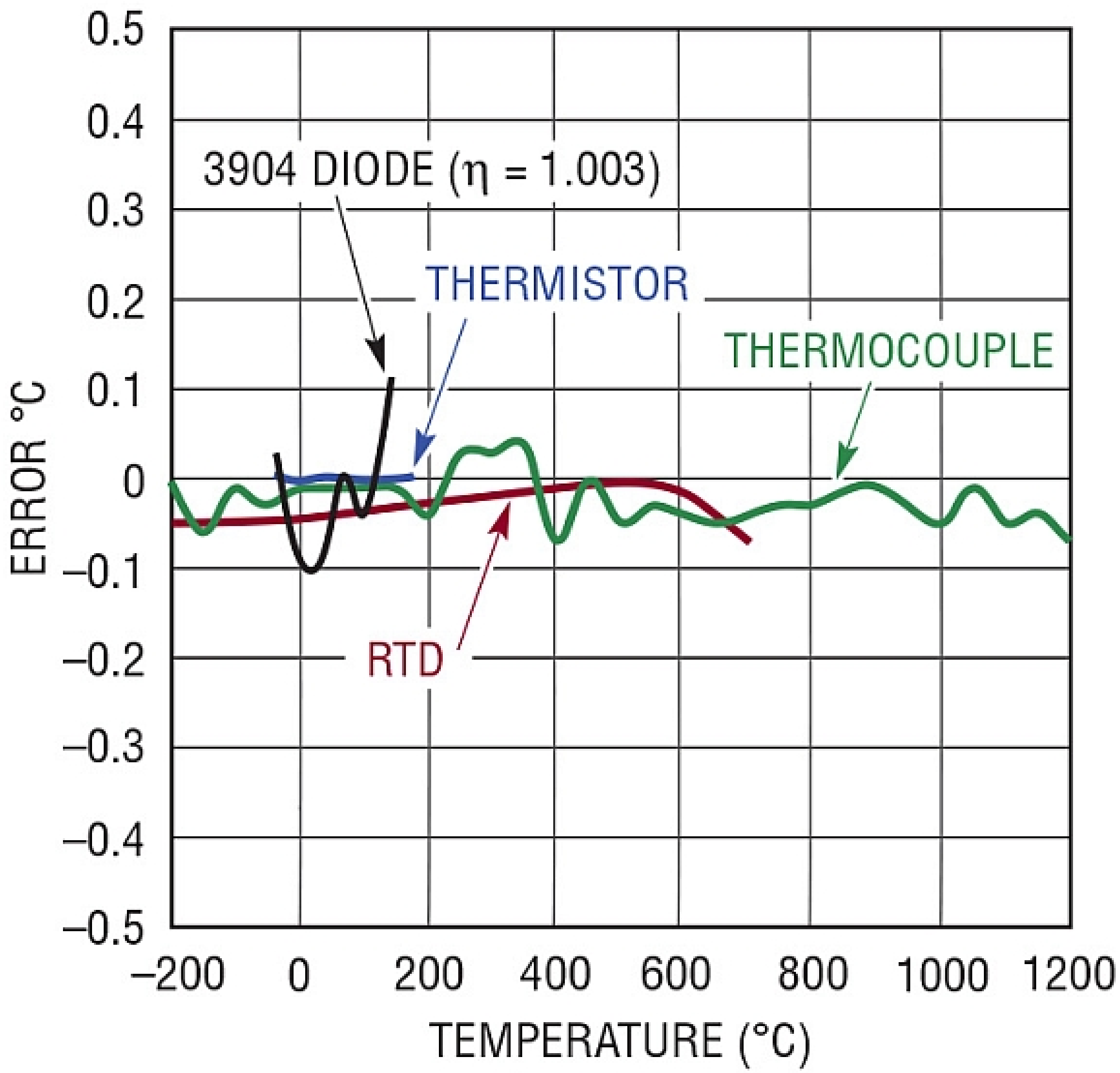

Figure 1 Temperature Accuracy of the LTC2983

Digitizing these basic sensor elements requires expertise in analog circuit design, digital circuit design, and firmware development. The LTC2983 packs this expertise in to a single IC and solves each of the unique challenges associated with thermocouples, RTDs, thermistors, and diodes. It combines all analog circuitry necessary for each sensor type with temperature measurement algorithms and linearization data to directly measure each sensor and output the result in degrees C.

Thermocouples Overview

Thermocouples generate voltage as a function of the temperature difference between the tip (thermocouple temperature) and the electrical connection on the circuit board (cold junction temperature). In order to determine the thermocouple temperature, an accurate measurement of the cold junction temperature is required; this is known as cold junction compensation. The cold junction temperature is usually determined by placing a separate (non-thermocouple) temperature sensor at the cold junction.

The LTC2983 allows diodes, RTDs, and thermistors to be used as cold junction sensors. In order to convert the voltage output from the thermocouple into a temperature result, a high order polynomial equation (up to 14^{th} order) must be solved (using tables or mathematical functions) for both the measured voltage and the cold junction temperature. The LTC2983 has these polynomials built in for all 8 standard thermocouples (J, K, N, T, R, S, T, and B) as well as user programmed table data for custom thermocouples. The LTC2983 simultaneously measures the thermocouple output and the cold junction temperature, and performs all required calculations to report the thermocouple temperature in degrees C.

Thermocouples: What's Important

A thermocouple's generated output voltage is small (<100mV full-scale) (see Figure 2). As a result the offset and noise of the ADC making the voltage measurement must be low. Furthermore, it is an absolute voltage reading requiring an accurate/low drift reference voltage. The LTC2983 contains a low noise, continuously offset calibrated 24-bit delta sigma ADC (offset and noise <1μV) with a 10ppm/ºC MAX reference (see Figure 3).

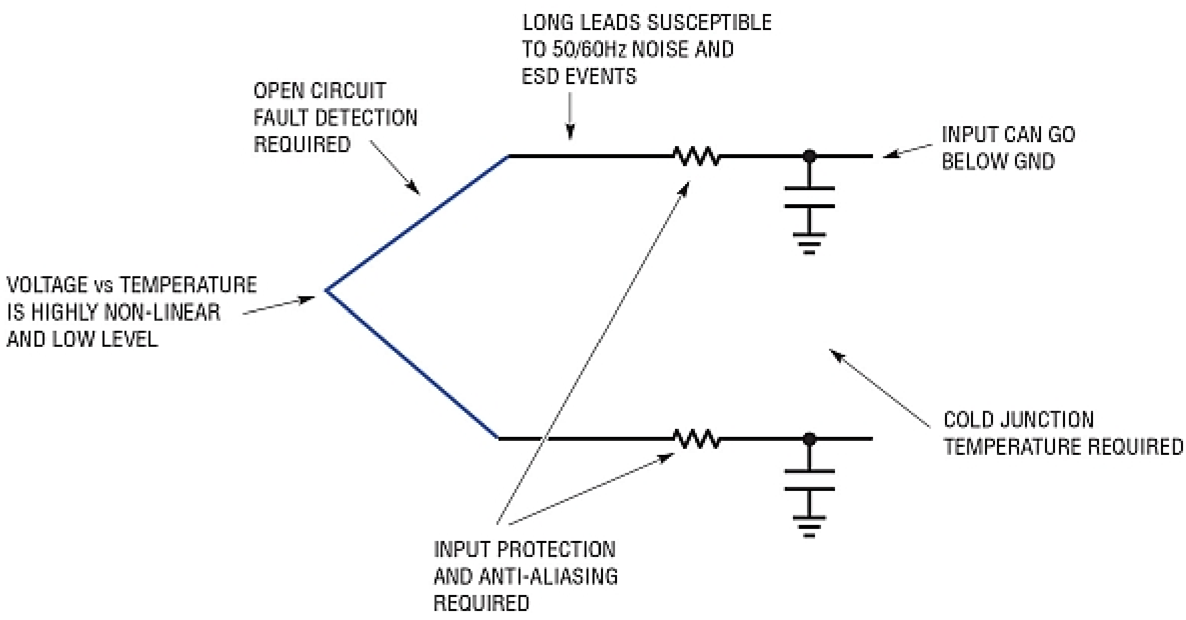

Figure 2 Thermocouple Design Challenges

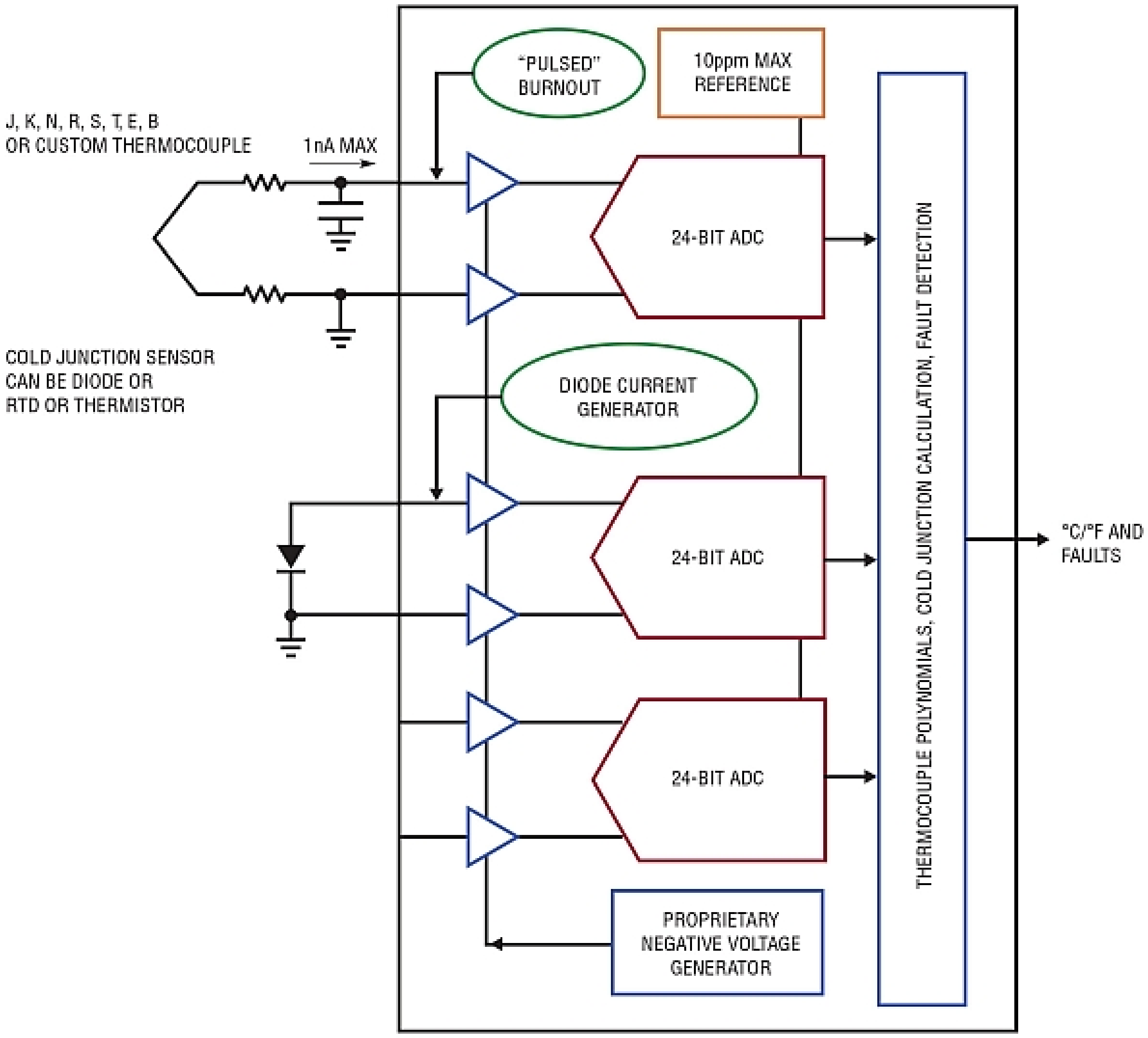

Figure 3 Thermocouple Measurement Using Diode Cold Junction Compensation

A Thermocouple's output voltage can also go below ground when the tip is exposed to temperatures below the cold junction temperature. This complicates systems by either forcing the addition of a second negative supply or an input level shifting circuit. The LTC2983 incorporates a proprietary front end capable of digitizing signals below ground on a single ground-referenced supply.

In addition to high accuracy measurements, thermocouple circuits need to incorporate noise rejection, input protection, and anti-alias filtering. The LTC2983 input impedance is high, with a maximum input current of less than 1nA. It can accommodate external protection resistors and filtering capacitors without introducing extra errors. It includes an on chip digital filter with 75dB rejection of both 50Hz and 60Hz.

Fault detection is an important feature of many thermocouple measurement systems. The most common fault reported is an open circuit (broken or unplugged thermocouple). Historically, current sources or pull-up resistors were applied to the thermocouple input in order to detect this type of fault. The problem with this approach is that these induced signals lead to errors and noise, and interact with input protection circuitry. The LTC2983 includes a unique open circuit detection circuit that checks for a broken thermocouple just prior to the measurement cycle. In this case, the open circuit excitation currents/resistors do not interfere with measurement accuracy.

The LTC2983 also reports faults related to the cold junction sensor. It can also detect, report, and recover from electrostatic discharge (ESD) events that may occur when long sensor connections are used in industrial environments. The LTC2983 also indicates through its fault reporting if the measured temperature is above/below the expected range for that specific thermocouple.

Diodes Overview

Diodes Overview

Diodes are inexpensive semiconductor based devices that can be used as temperature sensors. These devices are typically used as the cold junction sensor for a thermocouple. When an excitation current is applied to a diode, they generate a voltage as a function of temperature and the current that is applied. If two perfectly matched excitation current sources of known ratio are applied to the diode a voltage of know proportionality to temperature (PTAT) is output.

Diodes: What’s Important

In order to generate a PTAT voltage with known proportionality, two highly matched ratioed current sources are required (see Figure 4). The LTC2983 accurately generates this ratio by relying on delta sigma oversampling architecture. Diodes and the leads connecting to the ADC contain unknown parasitic diode effects. The LTC2983 contains a 3-current measurement mode that removes parasitic lead resistances. Various diode manufacturers specify different diode non-ideality factors. The LTC2983 allows individual programming of each diode’s non-ideality factor. Since absolute voltages are measured, the value and drift of the ADC reference voltage are critical. The LTC2983 includes a factory trimmed 10ppm/ºC Max reference.

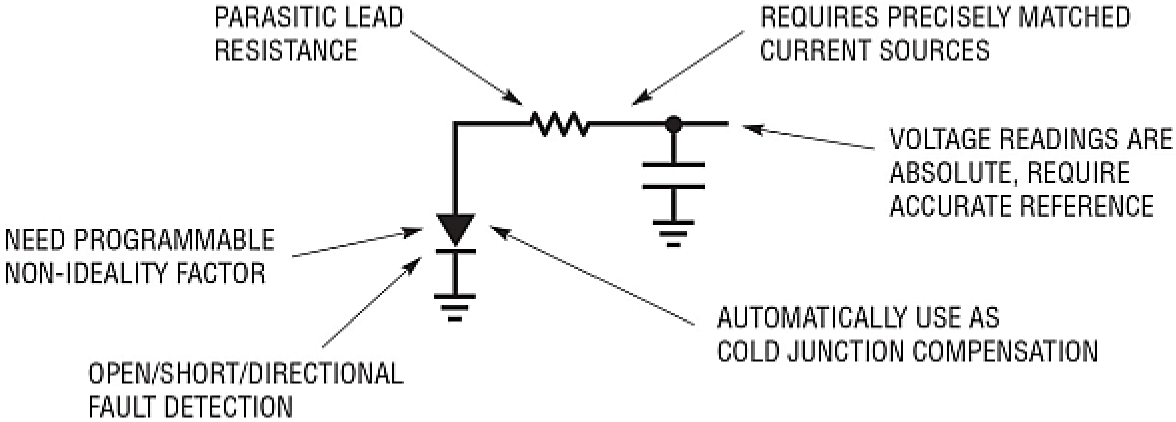

Figure 4 Diode Design Challenges

The LTC2983 automatically generates the ratioed currents, measures the resultant diode voltage, calculates the temperature using the programmed non-ideality, and outputs the results in degrees C. It can also be used as the cold junction sensor for thermocouples. If the diode is broken, shorted, or inserted incorrectly, the LTC2983 detects this fault and reports it in the conversion result output word and the corresponding thermocouple result, if it was used to measure the cold junction temperature.

RTDs: Overview

RTDs are resistors that change value as a function of temperature. In order to measure one of these devices a low drift precisely known sense resistor is tied in series with the RTD. An excitation current is applied to the network and a ratiometric measurement is made. The value, in ohms, of the RTD can be determined from this ratio. This resistance is used to determine the temperature of the sensor element using a table lookup.

The LTC2983 automatically generates the excitation current, simultaneously measures the sense resistor and RTD voltage, calculates the sensor resistance and reports the result in degrees C. RTDs can measure temperatures over a wide temperature range, from as low as -200ºC to 850ºC. The LTC2983 can digitize most RTD types (PT-10, PT-50, PT-100, PT-200, PT-500, PT-1000, and NI-120) and has built in coefficients for many standards (American, European, Japanese, and ITS-90), as well as user-programmed table data for custom RTDs.

RTDs: What’s Important

A typical PT100 RTD (see Figure 5) resistance varies less than 0.04Ω per tenth of a degree C corresponding to a signal level of 4µV at 100µA current excitation. Low ADC offset and noise are critical for accurate measurements. The measurement is ratiometric relative to the sense resistor; however the absolute values of the excitation current and reference voltage are not as important when calculating the temperature.

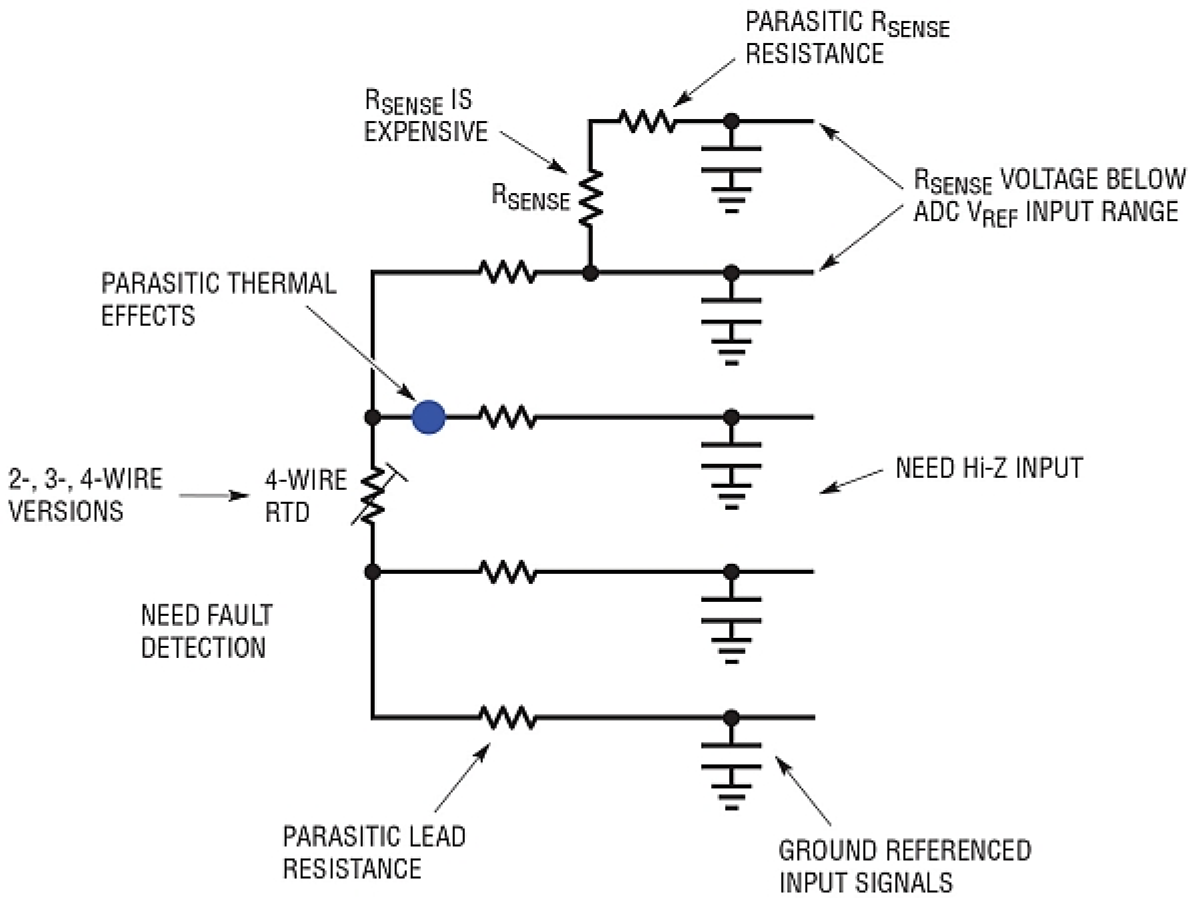

Figure 5 RTD Design Challenges

Historically, the ratiometric measurement between the RTD and sense resistor was performed with a single ADC. The sense resistor's voltage drop was used as the reference input of the ADC measuring the RTD voltage drop. This architecture requires 10KΩ or larger sense resistors, which need to be buffered to prevent droop due to the ADC reference input dynamic currents. Since the sense resistor value is critical, these buffers need to have low offset, drift, and noise.

This architecture makes it difficult to rotate current sources in order to remove parasitic thermocouple effects. Delta sigma ADC reference inputs are much more susceptible to noise than the inputs, and small values of reference voltage can lead to instability. All these problems are solved by the LTC2983's multiple ADC architecture (see Figure 6). The LTC2983 uses two highly matched, buffered, auto-calibrated ADCs, one for the RTD and one for the sense resistor. They simultaneously measure both RTD and Rsense, calculate the RTD resistance, and apply this to a ROM-based lookup table to ultimately output the RTD temperature in ºC.

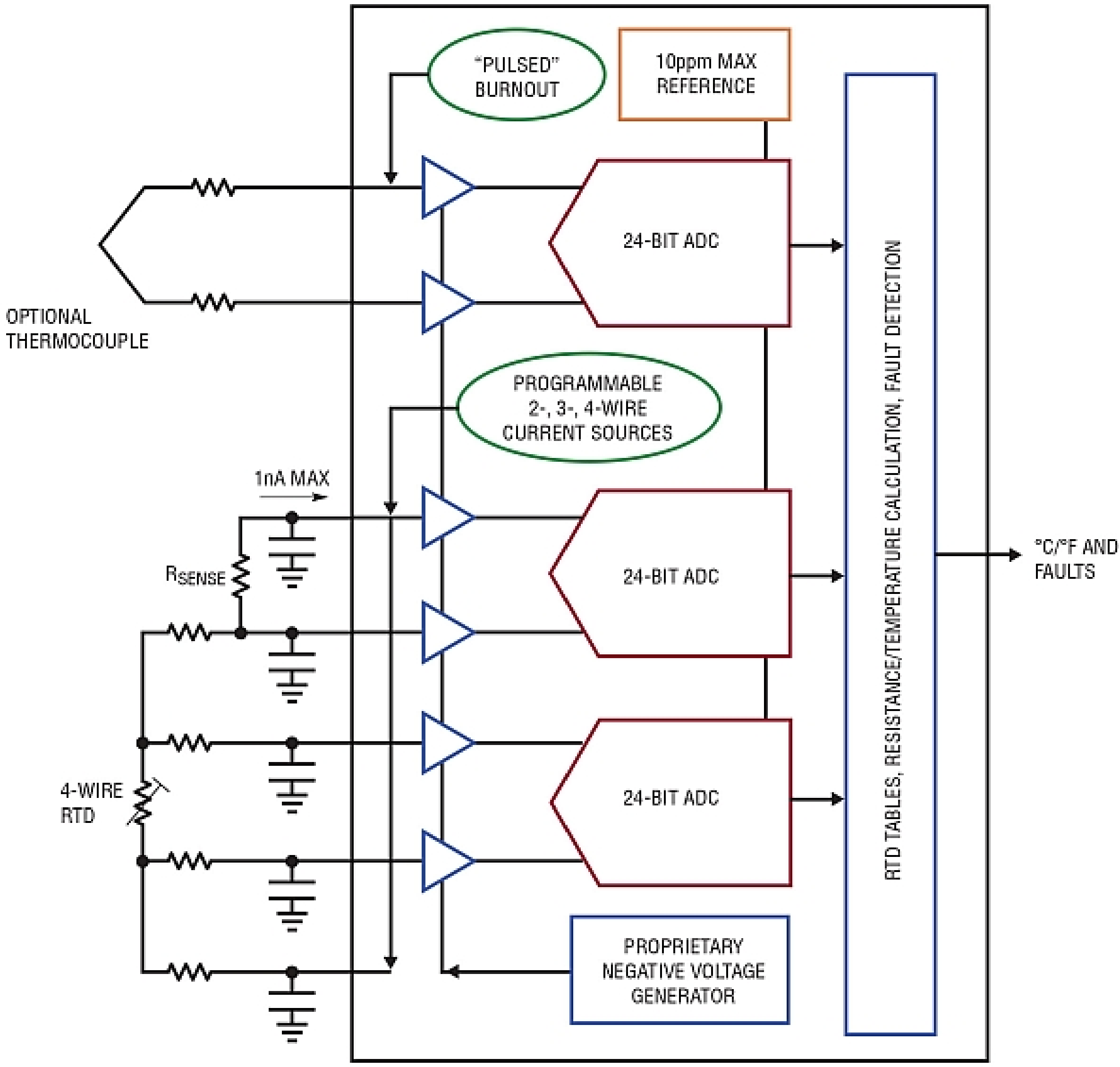

Figure 6 RTD Temperature Measurement Using the LTC2983

RTDs come in many configurations: 2-wire, 3-wire, and 4-wire. The LTC2983 can accommodate all three configurations with a configurable single hardware implementation. It can share a single sense resistor among multiple RTDs. Its high impedance input allows external protection circuits between the RTD and ADC inputs without introducing errors. It can also autorotate the current excitation to eliminate external thermal errors (parasitic thermocouples). In cases where parasitic lead resistance of the sense resistor degrades performance, the LTC2983 allows Kelvin sensing of Rsense.

The LTC2983 includes fault detection circuitry. It can determine if the sense resistor or RTD is broken or shorted. It warns if the measured temperature is above or below the maximum specified for the RTD. When an RTD is used as the cold junction sensor for a thermocouple, three ADCs simultaneously measure the thermocouple, the sense resistor, and the RTD. RTD faults are passed to the thermocouple result and the RTD temperature is automatically used to compensate for the cold junction temperature.

Thermistors Overview

Thermistors Overview

Thermistors are resistors that change value as a function of temperature. Unlike RTDs, thermistors' resistance varies many orders of magnitude over their temperature range. In order to measure one of these devices, a sense resistor is tied in series with the sensor. An excitation current is applied to the network and a ratiometric measurement is made. The value, in ohms, of the thermistor can be determined from this ratio. This resistance is used to determine the temperature of the sensor solving Steinhart-Hart equations or table data.

The LTC2983 automatically generates the excitation current, simultaneously measures the sense resistor and thermistor voltage, calculates the thermistor's resistance and reports the result in degrees C. Thermistors typically operate from -40ºC to 150ºC. The LTC2983 includes coefficients for calculating the temperature of standard 2.252kΩ, 3kΩ, 5kΩ, 10k Ω, and 30k Ω thermistors. Since there is a large variety of thermistor types and values, the LTC2983 can be programmed with custom thermistor table data (R vs. T) or Steinhart-Hart coefficients.

Thermistors: What's Important

A thermistor's resistance (see Figure 7) varies many orders of magnitude over its temperature range. For example, a thermistor measuring 10k Ω at room temperature can go as low as 100 Ω at its highest temperature and >300k Ω at its lowest, while other thermistor standards can go above 1MΩ.

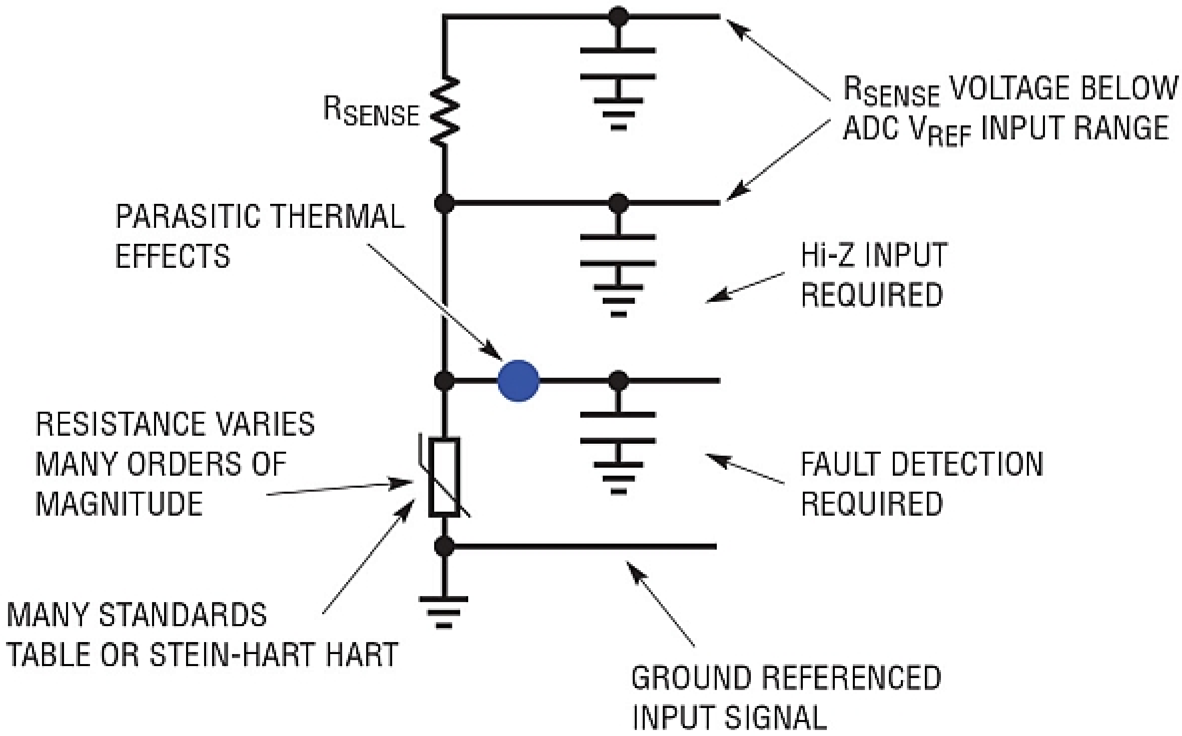

Figure 7 Thermistor Design Challenges

Typically, in order to accommodate large valued resistance, very small excitation current sources are used in conjunction with large sense resistors. This results in very small signal levels at the low end of the thermistor's range. Input and reference buffers are required to isolate the ADC's dynamic input current from these large resistors. But buffers don't work well near ground without separate supplies and offset/noise errors need to be minimized. All these problems are solved by the LTC2983 (see Figure 8). It combines a proprietary, continuously calibrated buffer capable of digitizing signals at or even below ground with a multiple ADC architecture.

Two matched, buffered ADCs simultaneously measure the thermistor and sense resistor and calculate (based on the standard) the thermistor temperature in ºC. Large value sense resistors are not required, allowing multiple RTDs and thermistors of different types to share a single sense resistor. The LTC2983 can also auto-range the excitation current depending on the thermistor's output resistance.

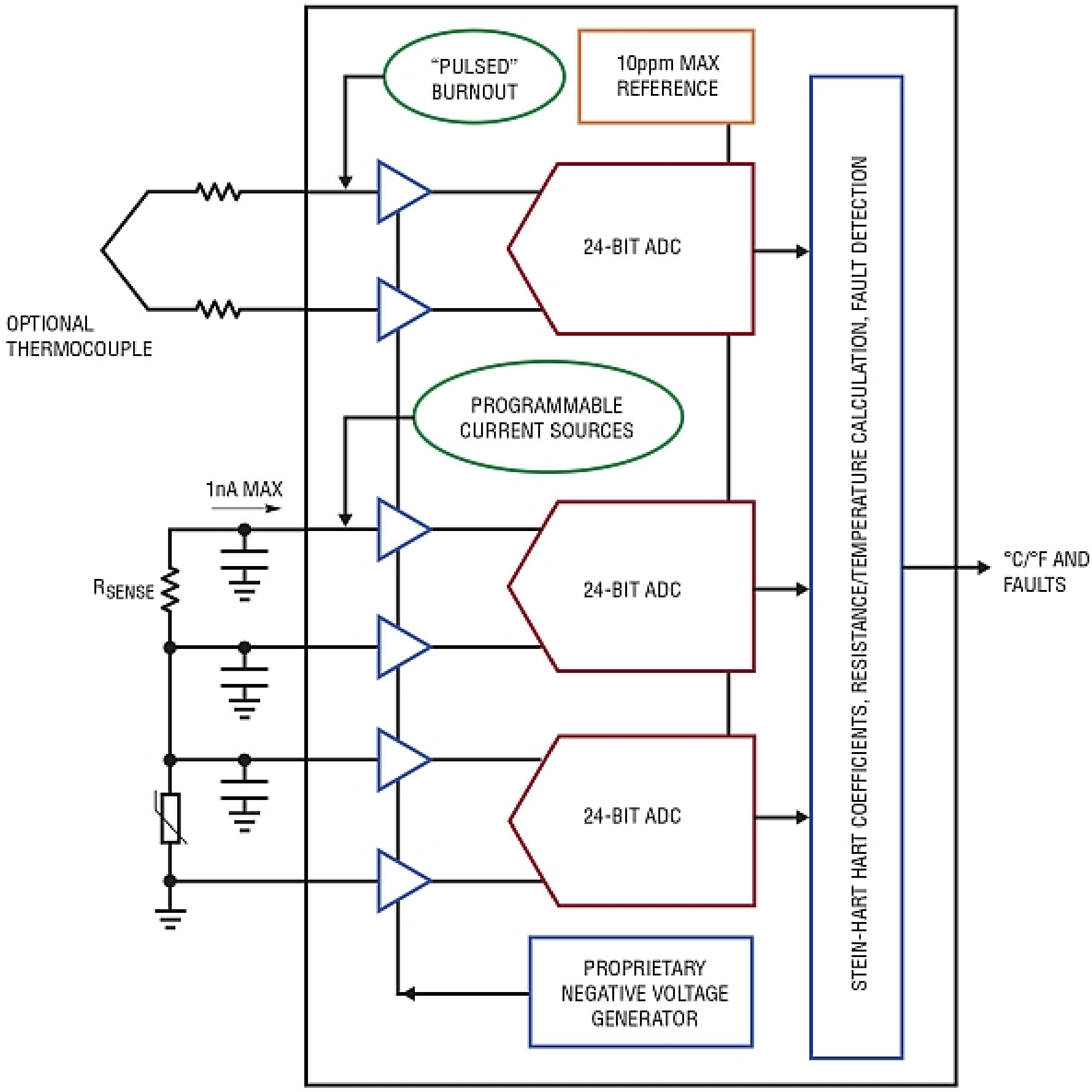

Figure 8 Thermistor Temperature Measurement Using the LTC2983

The LTC2983 includes fault detection circuitry. It can determine if the sense resistor or thermistor is broken/shorted. It warns if the measured temperature is above or below the maximum specified for the thermistor. The thermistor can be used as the cold junction sensor for a thermocouple. In this case three ADCs simultaneously measure the thermocouple, the sense resistor, and the thermistor. Thermistor faults are passed to the thermocouple result and the thermistor temperature is automatically used to compensate the cold junction temperature.

Universal Measurement System

The LTC2983 can be configured as a universal temperature measurement device (see Figure 9). Up to 4 sets of universal inputs can be applied to a single LTC2983. Each of these sets can directly digitize a 3-wire RTD, 4-Wire RTD, thermistor, or thermocouple without changing any onboard hardware. Each sensor can share the same 4 ADC inputs and protection/filtering circuitry and is configured using software. One sense resistor is shared among all 4 banks of sensors and cold junction compensation is measured by a diode. The LTC2983 input structure allows any sensor on any channel. Any combination of RTDs, sense resistors, thermistors, thermocouples, diodes, and cold junction compensation can be applied to any and all the 21 analog inputs on the LTC2983.

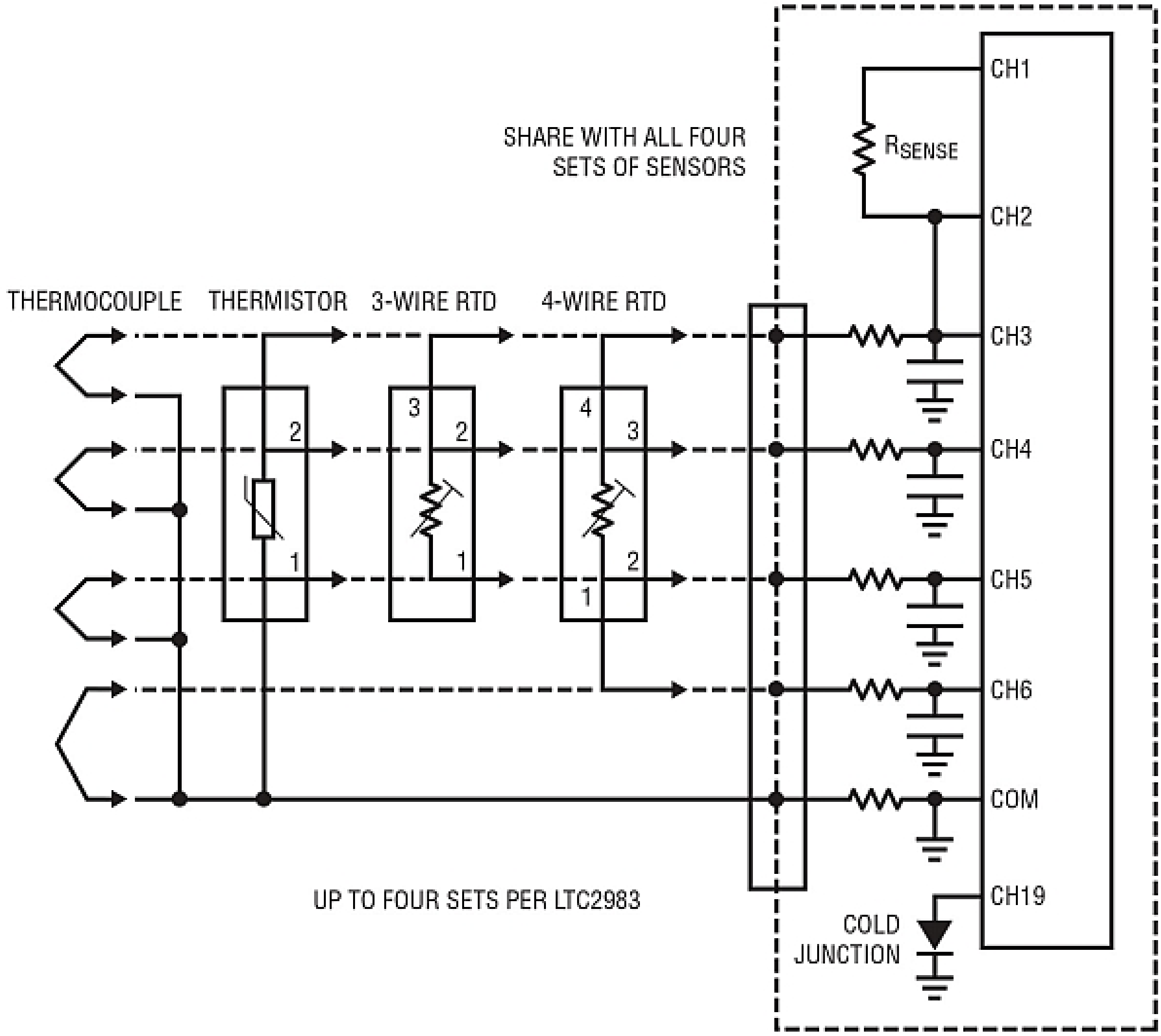

Figure 9 Universal Temperature Measurement System

Conclusion

The LTC2983 is a groundbreaking, high performance temperature measurement system. It can directly digitize thermocouples, RTDs, thermistors, and diodes with laboratory grade precision. It combines three 24-bit delta sigma ADCs with a proprietary front end to solve many problems typically associated with temperature measurements. High input impedance with live at zero input range enables direct digitization of all temperature sensors and easy input projection. Twenty flexible analog inputs enable one hardware design to measure any sensor by reprogramming the device through a simple SPI interface.

The LTC2983 automatically performs cold junction compensation, can use any sensor to measure the cold junction, and includes fault reporting. It can directly measure 2-, 3-, or 4-wire RTDs, and can easily share sense resistors to save on cost and rotate current sources to remove parasitic thermal effects. It includes auto-ranging current sources for increased accuracy and reduced noise associated with thermistor measurements. The LTC2983 allows custom, user-programmable sensors. Custom table-driven RTDs, thermocouples, and thermistors can be programmed into the device. The LTC2983 combines high accuracy, easy sensor interface, and high flexibility into a complete, single-chip temperature measurement system.

See the LTC2983 in action in this video from electronica 2014.