Temperature sensing fundamentals

Introduction to Temperature Sensing

In embedded systems, there is a constant need for higher performance and more features in a smaller form factor. This requires system designers to **monitor** the overall temperature to ensure safety and **protect** the systems. The trend of sensor data-logging further drives the need for temperature measurement to not only measure system or environmental conditions, but to **compensate** for temperature-sensitive components and maintain accuracy of the total system.

Thermal Design Considerations

Considerations for efficient thermal monitoring and protection include:

i. **Accuracy:** Sensor accuracy represents how close the temperature is to the true value. Applications should consider factors such as linearity and acquisition circuits across the operating temperature range.

ii. **Size:** While the size of the sensor makes an impact on the design, analyzing the overall circuit can yield a more optimized design.

iii. **Sensor Placement:** Package and placement can impact the response time and conduction path. Both are critical for effective thermal design.

Table 1. Temperature Sensing Technology Comparison

	IC Sensor	Thermistor	RTD	Thermo couple
Range	–55°C to +200°C	–100°C to +500°C	–240°C to 600°C	–260°C to +2300°C
Accuracy	Good / Best	Calibration dependant	Best	Better
Footprint / Size	Smallest	Small	Moderate	Large
Complexity	Easy	Moderate	Complex	Complex
Linearity	Best	Low	Best	Better
Topology	Point-to-point, Multi-drop, Daisy Chain	Point-to-point	Point-to-point	Point-to-point
Price	Low to Moderate	Low to Moderate	Expensive	Expensive

IC Sensors

IC temperature sensors rely on the predictive temperature dependence of a Silicon bandgap. The precision current sources the internal forward biased p-n junction with the resulting ΔV_{BE} that corresponds to the device temperature.

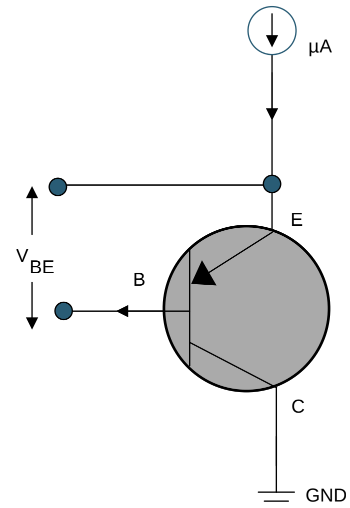

Figure 1. Temperature Dependence of Silicon Bandgap

$$\Delta V_{BE} = \frac{KT}{q} \times \ln\left(\frac{I_{C1}}{I_{C2}}\right) \tag{1}$$

Given the predictable behavior, ICs offer high linearity and accuracy across a wide temperature range (up to ±0.1°C). IC sensors can integrate system functionality that offers a small footprint and low power consumption. These sensors do operate in a limited temperature range and offer fewer packaging options that can measure off-board temperature when compared to thermistors.

These sensors are typically fully-integrated, and monolithic sensors and accuracy are designed for the entire system instead of for one element.

Thermistors

Thermistors are passive components that change resistance with temperature. Thermistors fall into two categories, negative temperature coefficient (NTC) and positive temperature coefficient (PTC).

While thermistors offer a variety of package options for onboard and off-board temperature sensing, typical implementation requires more system components. NTC thermistor are non-linear and often bear increased calibration cost and software overhead. An exception to this are Silicon-based PTC thermistors.

The true system accuracy for Thermistors are often difficult to determine. NTC system error contributors include NTC tolerance, bias resistor (Tolerance, Temperature Drift), ADC (quantization error), linearization error, reference voltage (Accuracy, Temperature Drift).

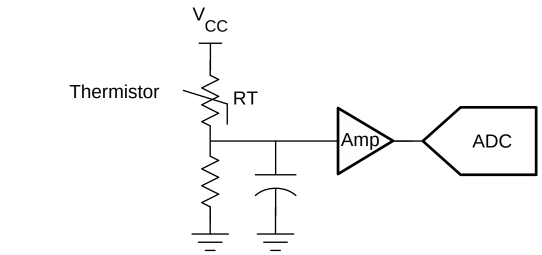

Figure 2. Typical Thermistor Implementation

Resistive Temperature Detectors (RTD)

RTDs are temperature sensors made of pure material, typically in platinum, nickel, or copper, with a highly predictable resistance-temperature relationship.

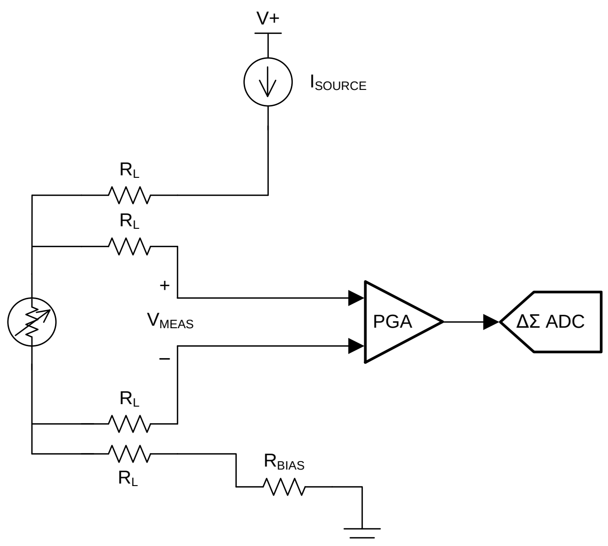

Figure 3. Complex 4-Wire RTD Circuit

Platinum RTDs can be highly accurate and very linear across a very wide temperature range up to 600°C. Implementation with these analog sensors involve complex circuitry and design challenges. Ultimately, the accurate systems involve complex error analysis due to a higher number of contributing components that also impact the overall system size. RTDs also require calibration during manufacturing followed by an annual calibration process in the field.

Contributors to the RTD system error include RTD Tolerance, self-heating, ADC (quantization error) and references used in the system.

Thermocouples

Thermocouples are made of two dissimilar electrical conductors that form electrical junctions at different temperatures. A thermocouple produces a temperature-dependent voltage as a result of the thermoelectric seebeck effect. This voltage translates to the difference of temperature between the hot junction (T_h) and the cold junction (T_c).

The temperature of the cold junction must be known to derive the hot junction temperature. Here, accuracy is limited by the fact that there are two systems that have separate tolerances and capabilities interacting with each other.

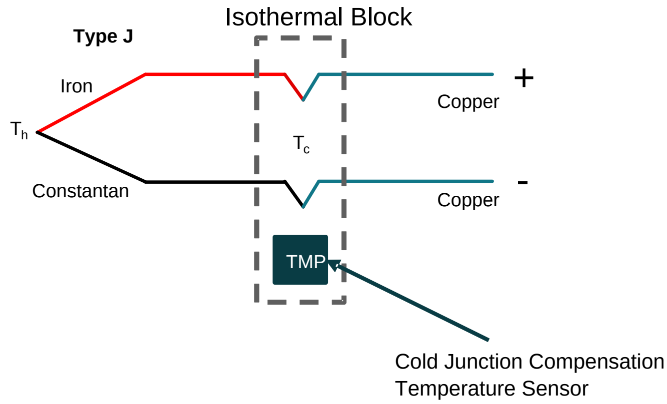

Figure 4. Thermocouple With CJC Temperature Sensor

Thermocouples do not require external excitation, and hence are not impacted by self-heating issues. They can also support extreme temperatures (>2000°C). While they are rugged and inexpensive, thermocouples do require an additional temperature sensor for cold-junction-compensation (CJC). They tend to be non-linear and are highly sensitive to parasitic junctions where the thermocouple is attached to the board.

Finally, digitizing a thermocouple would be susceptible to previously discussed ADC errors.

Device Recommendations

For 40 years, Texas Instruments has manufactured several IC-based temperature sensors, including:

- Digital temperature sensors:
  - Highest accuracy temperature sensors
  - Lowest power with the smallest footprint
  - LM75 / TMP75 temperature sensors
  - Multi-channel remote diode temperature sensors
- High-accuracy analog temperature sensors
- Linear thermistors
- Temperature switches or thermostats that offer integrated hysteresis for enhanced noise immunity

Table 2. Related Documentation

COLLATERAL	DESCRIPTION
Application Report - Accuracy	*Layout Considerations for Accurately Measuring Ambient Temperature*
Application Report - Temperature Calibration	*Methods to Calibrate Temperature Monitoring Systems*