Temperature sensing with thermistors

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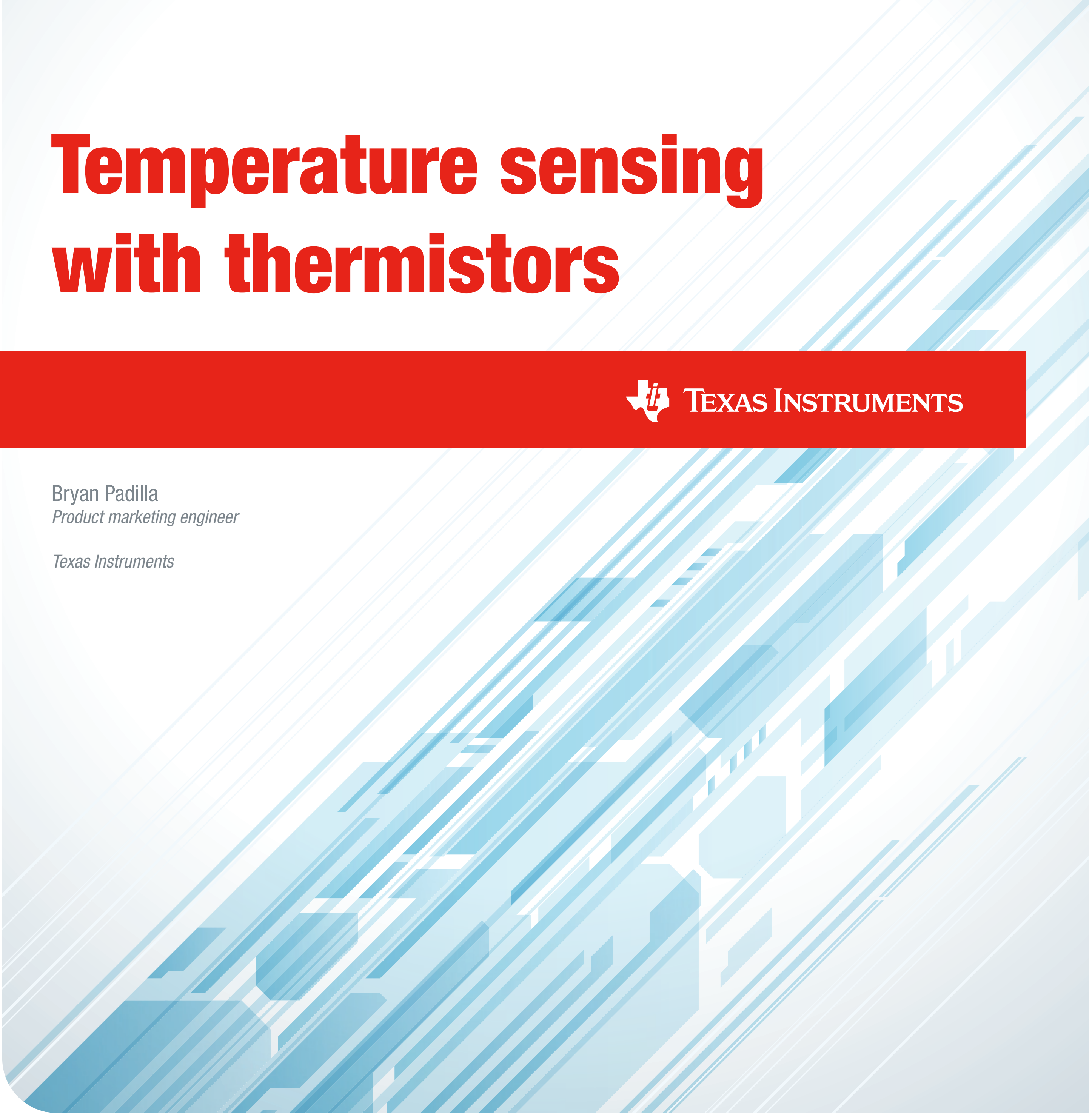

Introduction

Billions of people every day use technology that has drastically increased in complexity over the years. This means that the operational safety of those devices is now (and always should have been) very important. Thankfully, designers can prevent thermal disasters, like batteries catching on fire or damaged components, by triggering a function to cool down, heat up or alter the performance of their system in some other way based on the surrounding temperature.

Temperature sensors are a basic building block of every electronic system, helping keep devices safe for users while operating at maximum performance. There are multiple types of temperature sensors, including integrated circuit temperature sensors, thermistors, thermocouples and resistance temperature detectors; all have their pros and cons.

In this white paper, I'll focus on one of the most common temperature sensors, the thermistor; highlight some important considerations when using thermistors for temperature-sensing applications; and compare two different types of thermistors: negative temperature coefficient (NTC) thermistors and silicon-based linear positive temperature coefficient (PTC) thermistors.

Thermistors (short for **therm**al res**istors**) are very simple, discrete two-terminal solid-state devices whose resistance values change with temperature—enough to measure the change with the correct circuitry. They follow Ohm's law, just like a resistor, except that a thermistor's resistance value will vary depending on the temperature to which the device is exposed.

The thermistor family tree

Thermistors alter their resistance with temperature. Using different semiconductor materials and fabrication processes, thermistors can carry either a NTC or a PTC. As the temperature increases, NTC thermistors decrease their resistance value, while PTC thermistors increase their resistance value. As shown in **Figure 1**, it's possible to further generalize

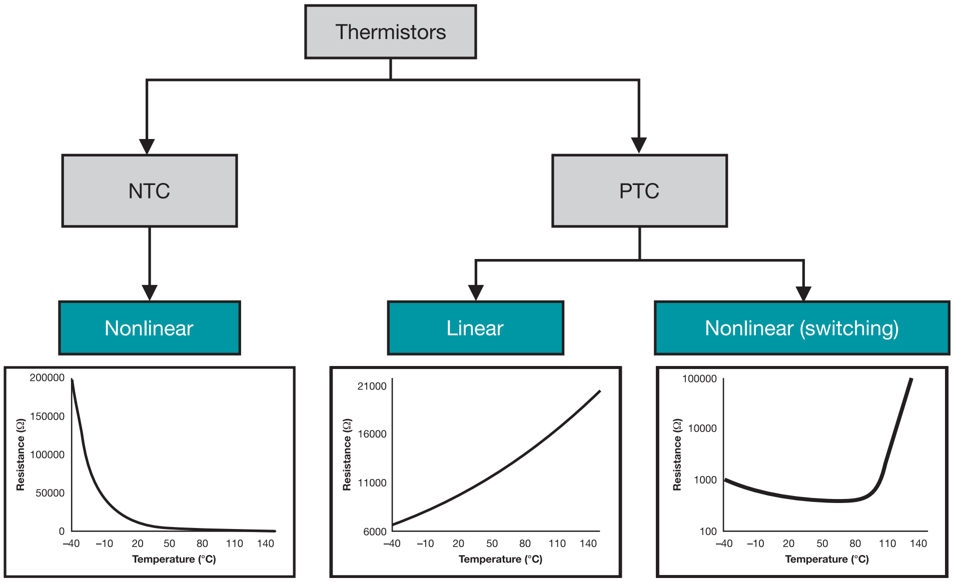

***Figure 1**. Thermistor family overview.*

the resistance vs. temperature (R-T) characteristic into linear and nonlinear characteristics across the thermistor's operating temperature range.

NTC thermistors have been around for many decades and have become the default component for thermistor-based temperature sensing because of their low price point. However, linear thermistors are becoming increasingly popular given their advantages over NTC thermistors. Linear thermistors made out of silicon are typically referred to as "silistors" (**sili**con therm**istors**) or KTY devices. These devices fall under the PTC thermistor umbrella because their resistance typically increases as the temperature rises. Nonlinear PTC thermistors are typically used for current-limiting applications due to their rapid increase of resistance beginning at a specific temperature, known as the Curie point. Because of this characteristic, nonlinear PTC thermistors are commonly referred to as "switching PTC thermistors."

Common thermistor circuits

Let's first look at how these discrete devices are typically used. Because current passing through a resistive component will produce a voltage drop across that component, thermistors require an external excitation in order to operate.

An easy and cost-effective way to bias thermistors is to use a constant voltage source and a voltage divider circuit, as shown in **Figure 2**. As the temperature changes, you will see a change in the voltage drop (V_{TEMP}) across the thermistor. When designing with a voltage source, it's always a good idea to use the ratiometric approach, which could help negate the effect of power-supply variation. For more information on ratiometric and absolute methods, see this article.

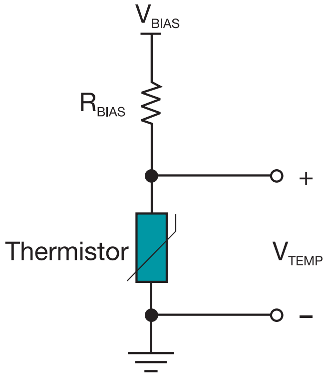

Figure 2*. Thermistor placed in a voltage divider configuration.*

Another biasing circuit typically used is that of a constant current source, as shown in **Figure 3**, which will better control the V_{TEMP} sensitivity in order to achieve high accuracy and make full use of the analog-to-digital converter's (ADC's) full-scale range.

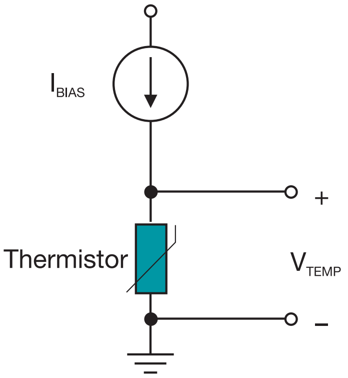

Figure 3*. Thermistor biased with a constant current source.*

The V_{TEMP} voltage is most commonly fed either directly into an ADC or routed through a comparator for discrete threshold detection, as shown in **Figure 4**. The output of the comparator will remain low until V_{TEMP} rises above the threshold voltage set by R_1 and R_2. When the output goes high, the

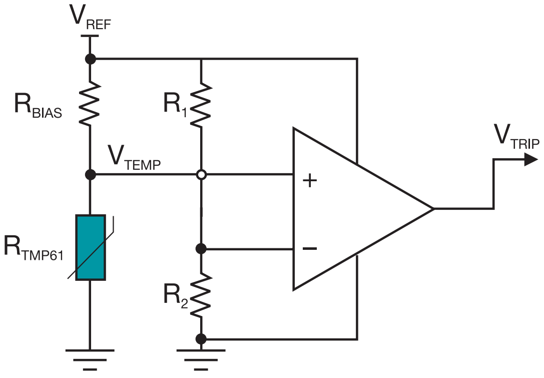

Figure 4*. Using a thermistor plus comparator for threshold detection.*

comparator signals an overtemperature warning signal. To hold this alert signal until the temperature settles back down to a specified value (to add hysteresis), you could either use a comparator with built-in hysteresis or add feedback resistors to your design.

You might prefer to have a linear V_{TEMP} response across a thermistor, because it makes the software implementation easier and leads to less error from device variances. Traditionally, you would have had to combine several NTC thermistors with fixed resistors in order to achieve a linear voltage response across temperature. At minimum, using an NTC thermistor requires the addition of a parallel resistor (**Figure 5**) to linearize V_{TEMP}.

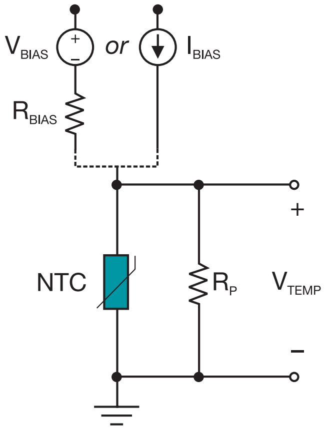

Figure 5. *An NTC with a parallel resistor to linearize* V_{TEMP}.

But linear PTC thermistors have **inherent** linearity. These devices offer a linear V_{TEMP} characteristic because of their linear R-T curve, and therefore don't need any extra circuitry, as shown in **Figure 6**. So if you need to save space and cost while maintaining a linear V_{TEMP} response, a linear PTC thermistor may be the better option.

Resistance tolerance and sensitivity

Thermistors are categorized by their resistance tolerance: the ± variance of resistance at any given temperature. This parameter ranges anywhere from 0.5% to +10%, and is usually listed as the resistance tolerance at 25°C in data sheets. When choosing a thermistor, make sure to calculate the resistance tolerances at the temperatures to which your thermistor will be exposed by using the minimum, typical and maximum resistance values provided in the manufacturer's R-T table. This calculation is important because traditional NTC thermistors typically have a much larger resistance tolerance as they move away from 25°C than what data sheets specify. In some cases, the resistance tolerance can increase from ±1% at 25°C to as much as ±4% or more at –40°C and 150°C.

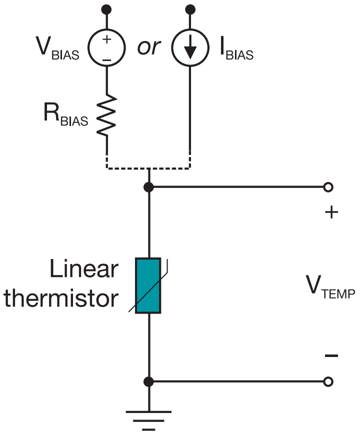

Figure 6. *A linear PTC thermistor eliminates the need for a parallel resistor.*

Silicon-based linear thermistors have a much more stable resistance tolerance due to their material composition and consistent resistance sensitivity. In comparison to the ±1% NTC thermistor, some ±1% silicon-based linear thermistors have a maximum resistance tolerance of up to ±1.5% at –40°C and 150°C. That's a big difference when compared to an NTC thermistor's ±4% tolerance at temperature extremes.

Another parameter for thermistors is the change in resistance per degree Celsius, also known as sensitivity. Having a sensitivity too small for your ADC to measure can affect the precision of your temperature measurements. In general, NTC thermistors have very large sensitivity at low temperatures because of their exponentially nonlinear decrease in resistance. At high temperatures, however, their sensitivity drastically decreases, which can introduce incorrect temperature readings when combined with a high resistance tolerance.

Compared to NTC thermistors, silicon-based linear thermistors have much more consistent sensitivity values, which enable stable measurements across the whole temperature range. These thermistors also have greater sensitivity than NTC thermistors because of the drastic decrease in an NTC thermistor's sensitivity above 67°C. So if you need to accurately measure hot temperatures, silicon-based linear thermistors offer a great alternative to traditional NTC thermistors.

Calibration

It's always a good idea to calibrate thermistors during the assembly process in order to obtain more accurate temperature readings, typically by measuring the output of the thermistor at a known temperature and implementing an offset. Depending on the type of thermistor and the application's specific temperature range, the number of calibration points recommended can vary. For example, if you need to measure a wide temperature range (>50°C), NTC thermistors typically require multiple calibration points in order to reduce the error given by the resistance tolerance and sensitivity variance across temperature. Conversely, silicon-based linear thermistors only need one-point calibration due to the consistency of silicon, the linearity of the R-T characteristic and the low resistance tolerance.

Self-heating and sensor drift

Self-heating occurs as a thermistor dissipates power in the form of heat whenever there is current flowing through it. This heat is generated in the thermistor's core and can affect measurement precision.

The amount of self-heating a thermistor can exhibit depends on factors such as:

- Material composition.
- Thermistor size.
- The amount of current flowing through the thermistor.
- Environmental conditions, such as the thermal conduction of the sensor's surroundings.
- Electrical board layout.

Looking at the R-T characteristics of an NTC thermistor, its resistance decreases as temperature rises, therefore increasing power consumption. As the power increases, so does the NTC thermistor's dissipated heat, which leads to self-heating. On the other hand, a silicon-based linear PTC thermistor's resistance increases as the temperature rises, which decreases power consumption. And because they are made out of silicon, these devices have minimal self-heating compared to the materials of NTC thermistors.

In addition to self-heating, the tolerances I mentioned in the "Resistance tolerance and sensitivity" section can lead to sensor drift over a thermistor's lifetime. Sensor drift specifications—which should be included in a thermistor's data sheet—are very important for applications where the devices will be used for multiple years or in harsh conditions. Typically, the thermistor manufacturer provides these specifications after conducting accelerated environmental stress-testing methods, such as temperature and humidity cycling. Silicon-based linear PTC thermistors also have a much smaller sensor drift than NTC thermistors, because silicon is more stable. For more information, see this paper on Measurement error caused by self-heating in NTC and PTC thermistors.

Common software conversion methods

There are multiple ways of converting the V_{Temp} into a temperature value in software. Initially, they all start the same; your code will read in a value from an ADC and assign that value to a variable. From there, you can calculate the resistance value and use one of many conversion methods.

One common method is the use of a look-up table (LUT), which consists of pre-populating an array of temperatures with their expected resistance values. The code searches for the closest resistance value in the LUT by rounding up or down and finds the corresponding temperature value. If you need more accuracy, you could use a LUT with interpolation, which will calculate the temperature in between two values of the LUT instead of rounding up or down, leading to a more accurate reading.

Another method of temperature conversion preferable for memory-conscious applications is a curve-fit equation that accurately represents the R-T curve of the device. A common method for NTC thermistors entails the use of the Steinhart-Hart equation (**Equation 1**):

$$\frac{1}{T} = A + B\ln R + C(\ln R)^3 \qquad (1)$$

where T is the temperature in Kelvin, R is the calculated resistance value, A, B and C are calculated coefficients, and ln is the natural log function.

But silicon-based thermistors can use a simple fourth-order polynomial regression formula, **Equation 2**, that leads to a quicker processing time than the Steinhart-Hart equation:

$$T = A_4R^4 + A_3R^3 + A_2R^2 + A_1R + A_0 \qquad (2)$$

where T is the temperature in Celsius, R is the calculated resistance value and $A_{(0–4)}$ are the polynomial coefficients.

Conclusion

Silicon-based linear thermistors have many advantages over traditional NTC thermistors. Multiple silicon-based linear thermistor options are available, but a big barrier to adoption has been their price when compared to NTC thermistors.

Texas Instruments has eliminated this barrier with a family of silicon-based linear thermistors in the same small-package footprints and comparable price points to NTC thermistors. **Table 1** compares traditional NTC thermistors and TI's silicon-based linear thermistors.

Silicon-based linear thermistors offer many performance benefits that can be helpful across a wide variety of industrial and automotive

Parameter	Traditional NTC thermistors	TI silicon-based linear thermistors
Bill-of-materials cost	• Low-cost device • May require extra linearization circuitry	• Low-cost device • No need for extra linearization circuitry
Resistance tolerance	• Increases up to ±5% at temperature extremes from ±1% at 25°C	• Increases up to ±1.5% at temperature extremes from ±1% at 25°C
Sensitivity	• Significant decrease in sensitivity with rising temperatures	• Stable sensitivity across the whole temperature range
Calibration points	• Multiple points needed for wide-temperature-range applications	• Single-point calibration suitable across the whole temperature range
Self-heating and sensor drift	• Increase in power consumption as temperature rises • < 5% typical sensor drift	• Decrease in power consumption as temperature rises • < 0.5% typical sensor drift

***Table 1**. NTC thermistors vs. silicon-based linear PTC thermistors.*

applications. For more information about TI's portfolio of silicon-based linear thermistors, see the TI thermistor page.

Additional resources

- TMP61 data sheet
- *Analog Design Journal* article, Measurement error caused by self-heating in NTC and PTC thermistors
- *EE World* Online article, Error analysis in temperature sensing with NTC and silicon-based PTC thermistors: Comparng the ratiometric and absolute methods

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