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Application Report
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Semiconductor Temperature Sensors Challenge Precision RTDs and Thermistors in Building Automation

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ABSTRACT

Standalone semiconductor sensors have rarely been considered for implementation into sensor probes or assemblies due to their larger geometries. However, advances in process technology and design have led to new, tiny sensor structures with almost linear transfer functions.

In order to provide system designers with this new low-cost alternative to precision temperature measurement, this application report discusses the TMP117, ±0.1°C accurate digital temperature sensor and the LMT70 temperature sensor, whose footprint is less than 1 mm^2, while its parametric performance challenges the accuracy of RTDs at cost levels lower than those of thermistors.

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1 Introduction

Temperature measurement applications in building automation and here, in particular, commercial air-conditioning use a wide variety of temperature sensors, such as thermocouples, resistance temperature detectors (RTDs), and measurement resistors with negative temperature coefficient also known as NTC thermistors.

High temperature applications, such as flame detection in boiler systems, that approach temperatures up to 1000 degrees require the use of thermocouple or RTDs.

The majority of temperature-sensing applications measuring refrigerant, water, and air temperatures are limited to a range from 0°C to 100°C (32F to 212F).

This temperature range is commonly monitored by temperature probes using RTDs and thermistors, with the RTDs being perceived as the more accurate and stable, but also more costly, and the thermistor as the low-cost alternative with wider resistance tolerance over temperature and larger resistance drift over time.

2 Resistance Temperature Detectors (RTDs)

RTDs are considered to be amongst the most accurate temperature sensors available. In addition to high accuracy, they offer excellent stability, repeatability, and high immunity to electrical noise.

They are most commonly made using platinum (Pt) because it follows a very linear resistance-temperature relationship in a repeatable manner over a large temperature range.

RTDs can be flat film for low temperature applications or wire-wound for higher temperature applications.

Flat film detectors are manufactured by placing a fine layer of platinum wire onto a ceramic substrate. The element is then coated in epoxy or glass, which provides protection. They are a cheaper alternative to wire-wound detectors and have a fast response time, however, they offer less stability and have a lower temperature range than their wire-wound counterparts.

Wire-wound detectors consist of a length of fine coiled platinum wire wrapped around a ceramic or glass core. They are relatively fragile and are often supplied with a sheath for protection. They have greater accuracy over a wider temperature range than flat film detectors, however, they are more expensive.

DIN/IEC 60751 is considered the worldwide standard for platinum RTDs. For a PT100 RTD, the standard requires the sensing element to have an electrical resistance of 100.00 Ω at 0°C and a temperature coefficient of resistance (TCR) of 0.00385 Ω/Ω/°C between 0°C and 100°C.

The resistance-to-temperature relation is defined for temperature ranges above and below 0°C via:

$$\begin{aligned} &R_T = R_0[(1 + AT) + BT^2] \quad \textit{for } T \geq 0°C \\ &R_T = R_0[(1 + AT) + BT^2 + CT^3(100 - T)] \quad \textit{for } T < 0°C \\ &\textit{with}: A = 3.9083 \cdot 10^{-3}, B = -5.775 \cdot 10^{-7}, = C = -4.183 \cdot 10^{-12} \end{aligned} \tag{1}$$

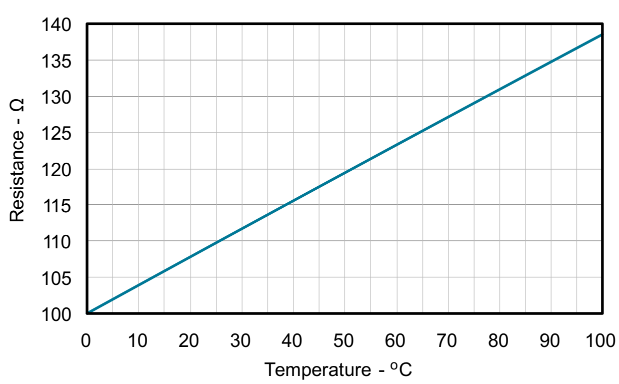


Figure 1. Resistance – Temperature Curve for PT100

For the small temperature range from 0°C to 100°C, the resistance temperature curve is almost linear.

There are four tolerance classes specified in DIN/IEC751 and two more tolerance classes used in the industry that have not been standardized yet:

CLASS	TOLERANCE °C
Class AA =	± (0.1 + 0.0017·|T|)
Class A =	± (0.15 + 0.002·|T|)
Class B =	± (0.3 + 0.005·|T|)
Class C =	± (1.2 + 0.005·|T|)
1/3 Class B	± 1/3 (0.3 + 0.005·|T|)
1/10 Class B	± 1/10 (0.3 + 0.005·|T|)

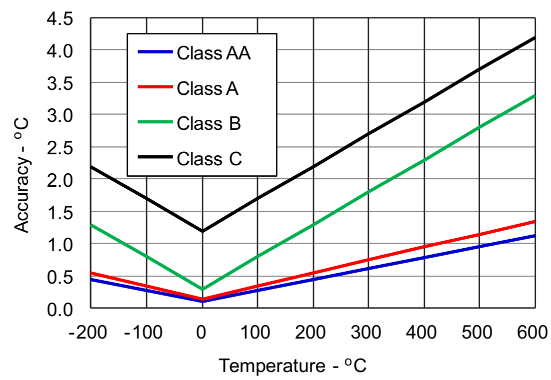


Figure 2. Accuracy Classes for RTDs

These tolerance classes also represent the interchangeability of a detector. Should a detector become damaged, good interchangeability assures that the replacement sensor delivers the same readings under the same conditions as the predecessor.

Another important criterion for selecting a temperature sensor is the long term stability. Great stability produces little output signal drift over time, thus reducing the frequency of costly calibrations. Depending on the application requirement, today's RTDs can provide long-term drifts from as little as 0.003°C/year up to 0.01 and 0.05°C/year.

Often times RTDs are considered the most precise elements amongst temperature sensors. In order to convert the change in resistance of an RTD into a sensible output signal, a current source that drives a constant current through the sensing element is commonly used, thus creating a temperature dependent voltage across the RTD.

This method bares two sources for measurement errors.

First, the current through the RTD causes a certain amount of self heat that adds to the sensing elements temperature, thus falsifying the actual measurement reading. Therefore, in order to minimize the impact of self heating, currents in the range of 500 µA to 1 mA maximum are recommended.

The second error source is the voltage drop across long measurement leads particularly in PT100 applications. Here, voltage divider action between lead resistance and RTD can significantly reduce the measured output voltage at the signal amplifier input, yielding a false temperature reading. To minimize the impact of lead resistance, the leads must either be short when using a 2-wire RTD, or the RTD itself must accommodate lead-compensation wires, as provided in 3-wire and 4-wire RTD designs.

3 Thermistors (NTCs)

Thermistors are made from mixtures of powdered metal oxides. Recipes are closely guarded secrets of the various thermistor manufacturers. The powdered metal oxides are thoroughly mixed and formed into the shape needed for the thermistor's manufacturing process. The formed metal oxides are heated until the metal oxides melt and turn into a ceramic. Most thermistors are made from thin sheets of ceramic cut into individual sensors. The thermistors are finished by putting leads on them and dipping them into epoxy or encapsulated in glass. The most prevalent types of thermistors are glass bead, disc, and chip configurations.

NTC thermistors exhibit a decrease in electrical resistance with increasing temperature. Depending on the materials and methods of fabrication, they are generally used in the temperature range of -50°C to 150°C, and up to 300°C for some glass-encapsulated units. The resistance value of a thermistor is typically referenced at 25°C (abbreviated as R25). For most applications, the R25 values are between 100 Ω and 100 kΩ.

The resistance versus temperature (R/T) characteristic of the NTC thermistor is a nonlinear, negative, exponential function. Several interpolation equations are available that accurately describe the R/T curve. The best known is the Steinhart-Hart equation:

$$1/T = A + B \cdot \ln R + C \cdot (\ln R)^3 \tag{2}$$

Coefficients A, B, and C are derived by calibrating at three temperature points and then solving the three simultaneous equations. The uncertainty associated with the use of the Steinhart-Hart equation is less than ± 0.005°C for 50°C temperature spans within the 0°C-260°C range, so using the appropriate interpolation equation or lookup table in conjunction with a microprocessor can eliminate the potential non-linearity problem.

The relatively large change in resistance from the NTC thermistor versus temperature, typically on the order of -3%/°C to -6%/°C, provides an order of magnitude greater signal response than RTDs.

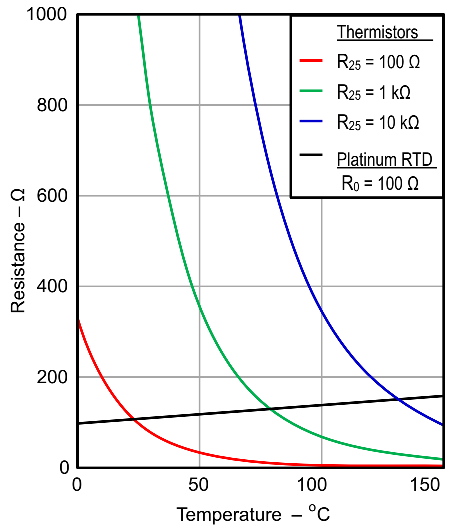


Figure 3. R-T Curve Comparison Between Thermistors and RTD

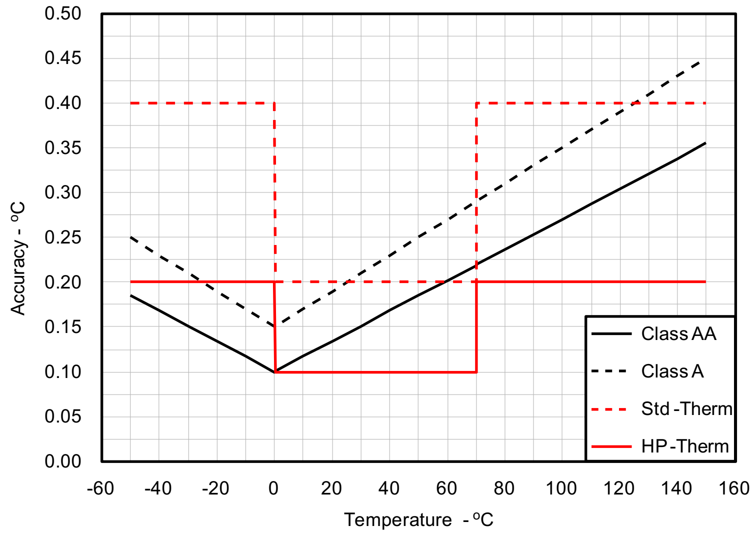


Figure 4. Accuracy Comparison Between Precision RTDs and Standard and Precision Thermistors

Another important feature of the NTC thermistor is the high degree of interchangeability that can be offered at a relatively low cost. Interchangeability describes the degree of accuracy or tolerance to which a thermistor is specified and produced, and is normally expressed as a temperature tolerance over a temperature range. For example, disc and chip thermistors are commonly specified to tolerances of ±0.1°C and ±0.2°C over the temperature ranges of 0°C to 70°C and 0°C to 100°C. Interchangeability helps the systems manufacturer to reduce labor costs by not having to calibrate each instrument/system with each thermistor during fabrication or use in the field.

The small dimensions of thermistors make for a very rapid response to temperature changes. This feature is particularly useful for temperature monitoring and control systems requiring quick feedback.

As a result of improvements in technology, NTC thermistors are better able to handle mechanical and thermal shock and vibration than other temperature sensors.

The R/T characteristic and R25 value of a thermistor are determined by the particular formulation of oxides. Over the past 10 years, better raw materials and advances in ceramics processing technology have contributed to overall improvements in the reliability, interchangeability, and cost-effectiveness of thermistors.

4 Semiconductor Temperature Sensors

Semiconductor temperature sensors, such as the LMT70, are manufactured using semiconductor technology which allows these devices to be produced efficiently and inexpensively. It also allows these devices to have properties designed to easily interface with many other types of semiconductor devices, such as amplifiers, power regulators, buffer output amplifiers, and microcontrollers for signal conditioning, monitoring, and display purposes.

These sensors offer high accuracy and high linearity over an operating range of about –55°C to +150°C.

Semiconductor temperature sensors make use of the temperature dependent relationship between a bipolar junction transistor (BJT) base-emitter voltage and its collector current:

$$V_{BE} = \frac{kT}{q} \cdot \ln\left(\frac{I_C}{I_S}\right) \quad (3)$$

where

- k is Boltzmann's constant
- T is the absolute temperature
- q is the charge of an electron
- I_S is a current related to the geometry and the temperature of the transistor

Because of the non-linear temperature dependency of I_S, many sensor designs use proportional-to-absolute-temperature (PTAT) circuits to eliminate the temperature impact of I_C and I_S all together. Figure 5 shows the simplified principle. Here, the difference between the base-emitter voltage of a single transistor and the base-emitter voltage of n in parallel connected transistors is used as a linear, temperature-dependent output. This principle is applied in the so-called Brokaw cell that can be either used to create a temperature independent bandgap voltage, or a PTAT sensor circuit (see Figure 6).

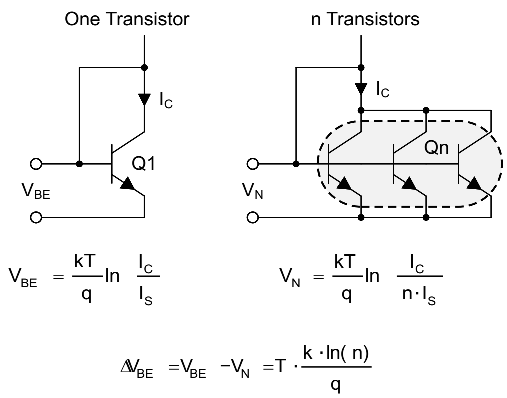


Figure 5. Principle of Eliminating I_C and I_S

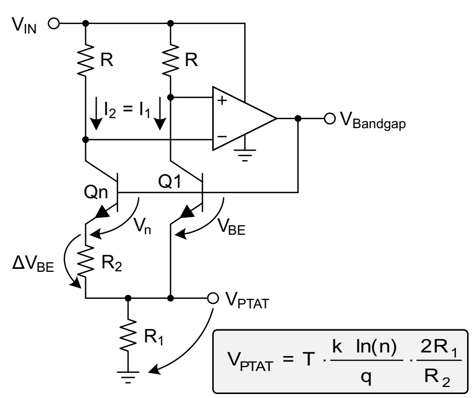


Figure 6. V_{PTAT} Temperature Sensor

The voltage, $\Delta V_{BE} = V_{BE} - V_N$, appears across resistor R_2. Therefore, the emitter current in Q2 is $\Delta V_{BE} / R_2$. The servo loop of the op amp and the resistors, R, force the same current to flow through Q1. The Q1 and Q2 currents are equal and are summed and flow into resistor R_1. The corresponding voltage developed across R_1 is proportional to absolute temperature (PTAT).

The bandgap cell reference voltage, $V_{Bandgap}$, appears at the base of Q1 and is the sum of $V_{BE(Q1)}$ and V_{PTAT}. $V_{BE(Q1)}$ is complementary to absolute temperature (CTAT), and summing it with V_{PTAT} causes $V_{Bandgap}$ to be constant over temperature. This circuit is the basic band-gap temperature sensor, which has been widely used in semiconductor temperature sensors.

5 The TMP117

The TMP117 is a high-precision digital temperature sensor which provides a 16-bit result with a resolution of 0.0078 °C and an accuracy of up to ±0.1°C across the –20°C to +50°C temperature range with no calibration. The TMP117 is I^2C™ and SMBus™ interface compatible, has a programmable alert function, and can allow up to four devices on a single bus. The overall accuracy of the TMP117 across its operating range is given in Table 1.

Table 1. TMP117 Accuracy Specification

TEMPERATURE RANGE	ACCURACY
–20°C to +50°C	±0.1°C
–40°C to +100°C	±0.2°C
–55°C to +150°C	±0.3°C

The accuracy of the TMP117 versus an RTD is plotted in Figure 7 across the operating temperature range of –55°C to +150 °C. It is evident looking in the Figure 7 that the TMP117 with no calibration has the same or better accuracy as an RTD Class-AA sensor. Note that this is the raw accuracy of the two devices and that the final system layout has a minor effect on the TMP117 and a major effect on the accuracy of an RTD sensor due to a number of parameters like the choice of ADC, layout of signal traces, and component tolerances, and so forth.

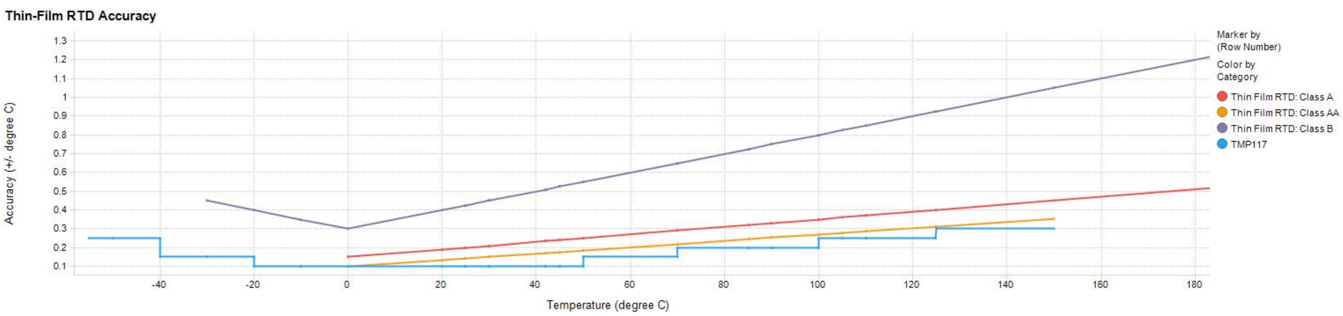


Figure 7. Accuracy Chart for TMP117 and RTD

6 The LMT70

However, recent advances in process technology and test methodology made it possible to produce modern semiconductor temperature sensors, such as the LMT70. This device uses a much smaller design structure while providing superior accuracy of less than ± 0.15°C at 25°C. Also the tiny 0.9-mm x 0.9-mm package allows for the use in small sensor probes. All of these advantages come at a fraction of the cost of competing devices.

The sensing element of the LMT70 consists of stacked BJT base emitter junctions that are biased by a current source. The output of the sensing element is buffered by a precision amplifier whose class AB push-pull output stage can easily source and sink currents of up to 3 mA.

The amplifier output connects to an output switch that is turned on and off by the digital control input T_ON (see Figure 8). This switch allows for the multiplexing of multiple sensors on one signal line.

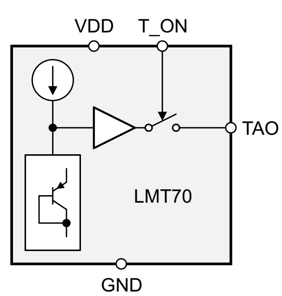


Figure 8. Simplified Block Diagram

The left diagram of Figure 9 shows the most simple sensor interface. For a regulated, low-noise supply in combination with a light load, such as an analog-to-digital converter (ADC) with internal input buffer, it is possible to use the LMT70 without additional external components.

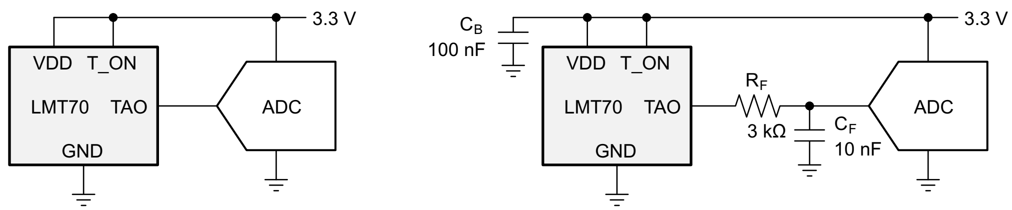


Figure 9. Circuit Examples for Noise-Free and Noisy Environments

For a noisy supply and ADCs without internal buffer, a supply bypass capacitor of C_B = 100 nF is recommended. This capacitor filters supply noise and also provides sufficient supply current during ADC switching cycles.

In very noisy environments, an additional R-C low-pass filter can be implemented. While the LMT70 is capable of driving heavy capacitive loads of up to 1 nF without a series resistor, larger capacitance requires a decoupling series resistor to maintain internal loop stability of the device.

Typically the R-C time constant of the external filter is significantly larger than the ADC internal time constant made up by the multiplexer input resistance (~ 5 kΩ) and sampling capacitance (~ 10 pF). This affects ADC sampling frequency. The time required to charge the sampling capacitor to n-bit accuracy is half the period of the sampling frequency (assuming a 50% duty cycle) and is given by using Equation 4:

$$t = \tau \cdot \ln\left(\frac{1}{2^n}\right)$$

where

- where, τ is the external filter's time constant
- n is the ADC resolution in bits (4)

Some data converters are limited in their range of sampling frequency and specifying the maximum external resistance to maintain accuracy. Check the device-specific ADC data sheet for this information since it impacts the external filter component values.

7 Accuracy and Calibration

The LMT70 is trimmed and calibrated during production. Its accuracy over the temperature range from -50°C to 140°C is better than 0.3°C, thus challenging even class AA RTDs. These are, however, the minimum and maximum accuracy limits that narrow down further to less than 0.15°C at 25°C. Actual characterized components lie within an even narrower band of ± 0.15°C across the entire temperature range.

For easy implementation of a controller look-up table, the *LMT70, LMT70A ±0.1°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC Data Sheet* lists the minimum, typical, and maximum sensor output voltages in single degree steps for the entire temperature range. This data sheet also provides suggestions on how and when to apply linear, quadratic, or cubic polynomials to achieve the rated accuracies.

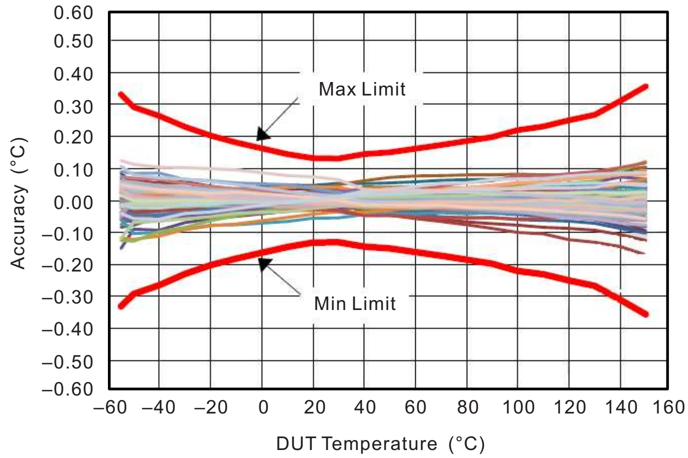
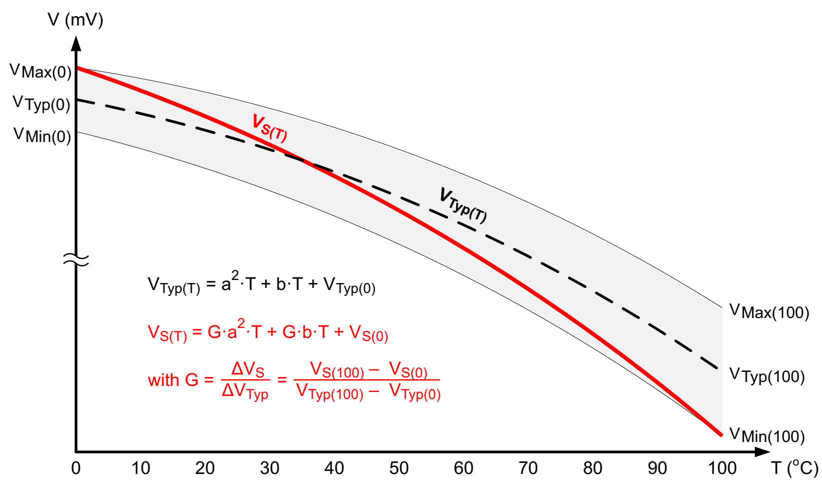


Figure 10. LMT70 Accuracy Over Temperature

For higher accuracies, it is possible to apply further calibration. The following example assumes a sensor whose output voltage-over-temperature characteristic crosses the typical characteristic taken from the look-up table in the *LMT70, LMT70A ±0.1°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC Data Sheet* (see Figure 11).

The most commonly applied and inexpensive calibration techniques are single-point and dual-point calibrations. In the case of a single-point calibration, the user usually has only one reference temperature available, such as an ice-bath that allows you to compare your sensor against it. This type of calibration however, only allows for an adjustment of the offset between sensor and reference at 0°C.



T (°C)	V_{Typ} (mV)	V_S (mV)
0	1097.774	1098.611
10	1046.647	1047.245
20	995.051	995.461
30	943.227	943.499
40	891.179	891.330
50	838.883	838.883
60	786.360	786.189
70	733.608	733.243
80	680.654	680.065
90	627.490	626.646
100	574.117	572.940

Figure 11. Sensor Output Characteristic Versus Typical Characteristic

However, depending on the sensor characteristic, adjusting the offset at cold temperatures can lead to increased deviation at higher temperatures, which makes single-point calibration questionable (see the left diagram of Figure 12).

In order to achieve high accuracy, it is necessary to also adapt the slope of the typical characteristics to the slope of the sensor, which is known as gain adjustment. Because a slope is defined by two coordinates in the voltage-temperature diagram, a second reference temperature, such as the boiling point of water at 100°C, is required to determine the second sensor output voltage.

A calibration that applies offset and gain adjustment to a sensor characteristic is known as two-point or dual-point calibration.

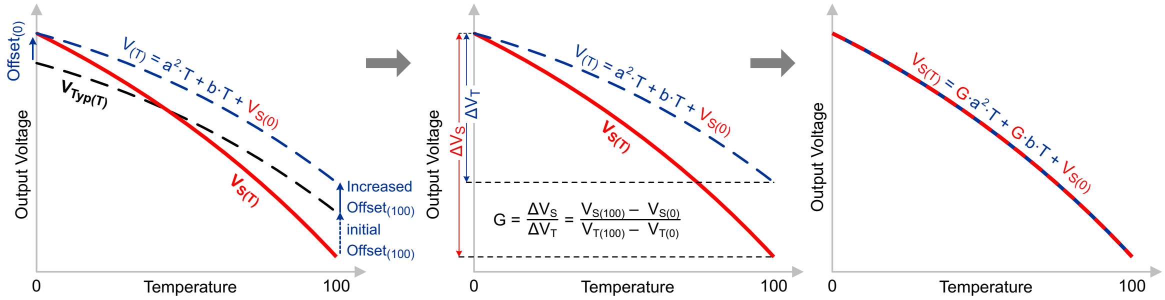


Figure 12. Two-Point Calibration Requires Offset Adjustment (left), Gain Adjustment (middle) to Yield the Final Transfer Function (right)

In this example, the typical output characteristic of the LMT70 in the *LMT70, LMT70A ±0.1°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC Data Sheet*) (see Figure 11) is approximated by the least-square fitting method. In this case, use a second order polynomial of the form:

$$V_{Typ(T)} = a \cdot T^2 + b \cdot T + c \quad (5)$$

Then, the output voltages of the actual sensor are measured at 0°C and 100°C.

For a first offset adjustment, $V_{S(0)}$ is used to replace c in Equation 5.

$$V_{(T)} = a \cdot T^2 + b \cdot T + V_{S(0)} \quad (6)$$

Then, the ratio of the actual sensor slope to the typical sensor slope, also known as Gain, is computed using Equation 7.

$$G = \frac{\Delta V_S}{\Delta V_T} = \frac{V_{S(100)} - V_{S(0)}}{V_{T(100)} - V_{T(0)}} \quad (7)$$

The *a* and *b* coefficients are then multiplied with *G* to yield Equation 8.

$$V_{S(T)} = G \cdot a \cdot T^2 + G \cdot b \cdot T + V_{S(0)} \quad (8)$$

To determine the sensor accuracy, Equation 8 is solved for temperature and calculated for each of the sensor output voltages, V_S, listed in Figure 11.

$$T_{(V_S)} = \frac{-b - \sqrt{b^2 - 4a\left(V_{S(0)} - V_{S(T)}\right)}}{2a} \quad (9)$$

Figure 13 shows the differences between the calculated and actual temperatures of the sensor accuracies.

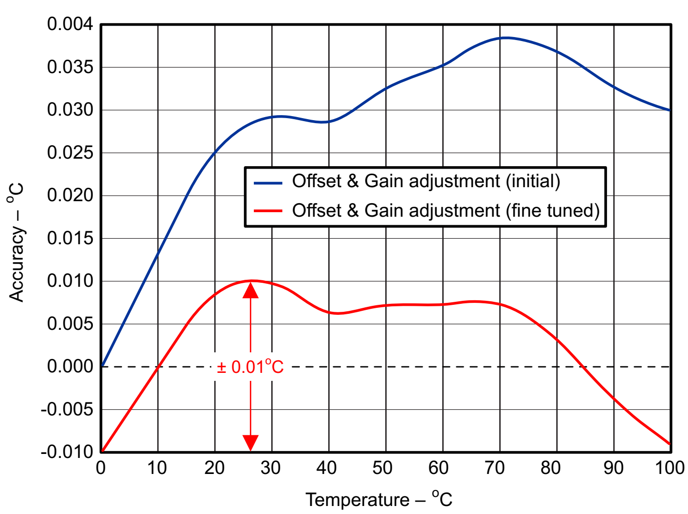


Figure 13. Sensor Accuracy After Initial 2-Point Calibration and Further Fine-Tuning

Figure 13 shows best accuracy at 0°C. This is due to the offset compensation at this temperature. By lowering the initial offset, the curve can be adjusted symmetrically around zero. Because of the lower resolution of a second order polynomial across a wide temperature range, the application of additional finer gain adjustment has an impact on accuracy by yielding levels of up to ± 0.01°C across the entire temperature range.

8 4-to-20 mA Temperature Transmitters

In building automation, the distance between a sensor and its control processor unit can reach up to several hundreds of yards. The most reliable method of transmitting sensor data across noisy environment is the 4-to-20 mA current loop due to its high noise immunity. In order to maintain high accuracy during transmission, high resolution data converters are used. Figure 14 shows the simplified schematic of a high precision data acquisition system with current-loop output.

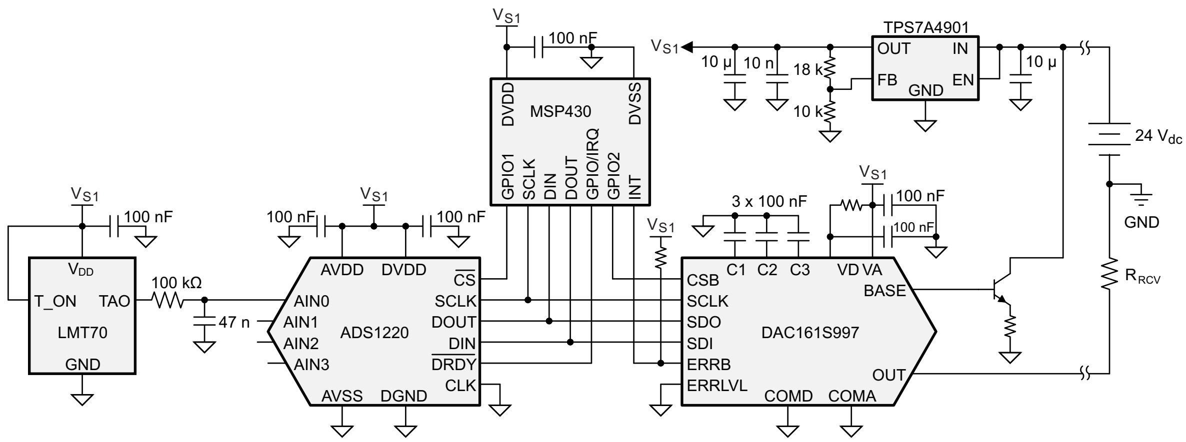


Figure 14. High Precision Temperature Transmitter With 4-to-20 mA Output

For inexpensive sensor transmitters with lower accuracy requirements, the circuit in Figure 15 can be applied. The operational amplifier (OPA317) converts the negative slope of the sensor output into a positive slope and also provides gain and offset adjustment. The 4-20 mA transmitter (XTR117) converts the sensor output current into the appropriate loop current.

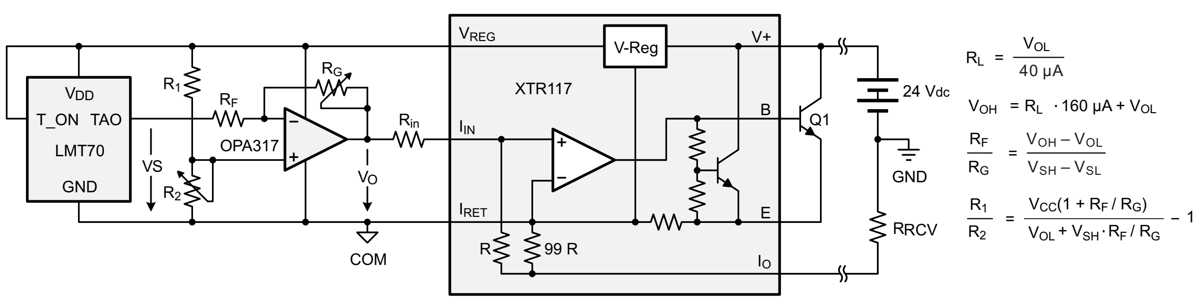


Figure 15. Low-Cost Temperature Transmitter With 4-to-20 mA Output

9 References

- Texas Instruments, *LMT70, LMT70A ±0.1°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC Data Sheet*
- Texas Instruments, *RTD Class-AA Replacement With High-Accuracy Digital Temperature Sensors in Field Transmitters Application Report*

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (April 2015) to A Revision	Page
• Added the TMP117 to the abstract.	1
• Revised app report for clarity.	1
• Added section about the TMP117 device.	6