Some Basic Math Creates A Low-Cost Nonlinear Thermocouple Interface

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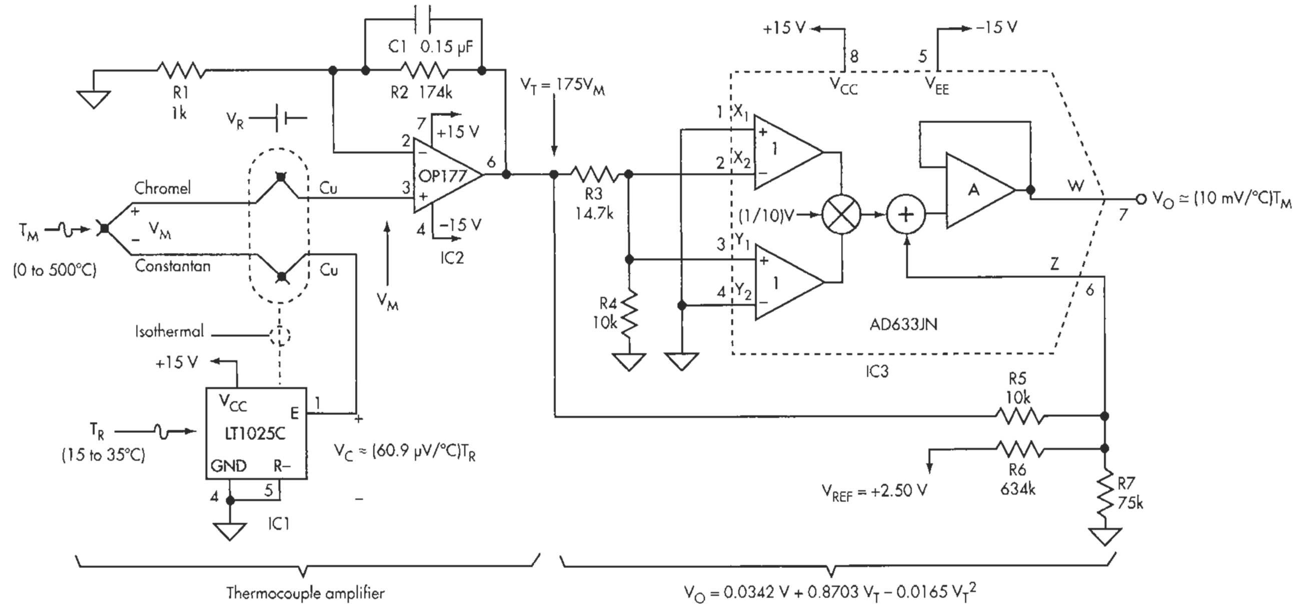

Instead of a software linearization algorithm, this circuit uses a hardware solution to perform the required curve fitting for a nonlinear sensor.

Measurement and process control loops often use 8-bit microcontrollers. The devices are inexpensive and widely available, and they can be programmed in many popular high-level languages—like C and Basic. However, if the loop requires a nonlinear sensor, the designer faces the added challenge of having to develop a software linearization algorithm.

One solution is to design hardware to perform the required curve fitting before the sensor's output signal is applied to the microcontroller's analog-to-digital converter (ADC) input. This is an especially attractive solution if processor memory is limited and cost and component count can be kept low. An added benefit is a small printed-circuit board (PCB) footprint.

An example is the circuit shown in the figure, which uses a type-E thermocouple to measure temperatures that are expected to vary from 0°C to 500°C. The circuit's output ranges from 0 to 5 V—the full span of the ADC—and can be expressed as a linear system equation:

$$V_O \approx \left(\frac{10\ \text{mV}}{°\text{C}}\right)T_M \qquad (1)$$

The thermocouple amplifier section consists of a thermocouple cold-junction compensator (IC1), an op amp (IC2), and accompanying circuitry. IC1 tracks ambient temperature (T_R) and adds a correction voltage (V_C) to cancel the cold-junction voltage (V_R) created when chromel-constantan thermocouple leads are attached to the copper pads of a PCB. IC2 then amplifies the thermocouple's temperature-dependent signal (V_M) by 175 to produce V_T prior to linearization. A gain of 175 eliminates the need for additional amplification during curve fitting.

Low-pass filter C1-R2 has a pole at approximately 6 Hz to remove power-supply noise.

You can use an Excel spreadsheet to create the nonlinear mathematical relationship between the output of the thermocouple amplifier (V_T) and the input to the ADC (V_O). The table shows 11 temperature entries for T_M (0°C to 500°C in 50°C steps) with their corresponding thermoelectric voltages, V_M. The values of V_M were derived from a standard type-E thermocouple reference table. Also shown are V_T and V_O, which are charted using the (XY) Scatter feature of the software. The equation for V_O is created using the software's trendline feature:

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$$V_O = 0.0342\ V + 0.8703\ V_T - 0.0165\ V_T^2 \quad (2)$$

An analog multiplier (IC3) and five 1% resistors implement this equation, a second-order polynomial of the form:

$$V_O = a + bV_T + cV_T^2 \quad (3)$$

The four (X and Y) inputs of IC3 are wired to create a negative square term that's scaled at the chip's output by an internal scale factor of 0.1 V. Comparing terms, we note that c must equal 0.0165. Since R3 and R4 form a voltage divider to attenuate V_T, we can express c as follows:

$$c = \frac{1}{10}\left(\frac{R4}{R3 + R4}\right)^2 \quad (4)$$

You can then solve for R3 by substituting c = 0.0165 and selecting a value for R4, which for this design was chosen to be 10 kΩ.

Resistors R5, R6, and R7 form a passive adder to create the offset term, a, and the linear coefficient, b, in Equation 3. The output of the passive adder is applied directly to the Z-input of IC3, which adds the offset and linear terms to the square term. Again comparing terms, a *(Equation 3)* equals 0.0342 V *(Equation 2)*. We can express this as:

$$a = \frac{bV_{REF}R5}{R6} \quad (5)$$

To design this part of the passive adder, we chose a stable 2.500-V reference for V_{REF}, selected R5 to be 10 kΩ, and solved for R6.

Finally, compare b *(Equation 3)* with the corresponding value of 0.8703 *(Equation 2)* and express the linear coefficient b as:

$$b = \frac{1}{\left(1 + \frac{R5}{R7} + \frac{R5}{R6}\right)} \quad (6)$$

This equation is solved to determine the final component, R7:

$$R7 = \left(\frac{R5R6}{\left(\frac{1 - b}{b}\right)R6 - R5}\right) \quad (7)$$

We evaluated the circuit by replacing the thermocouple with a low-impedance voltage source to simulate V_M. IC3's output voltage (V_O) exhibited a worst-case error of about 3.4°C at 0°C (V_O = 0.034 V) and an error of −1.8°C at 500°C (V_O = 4.982 V) at full scale. At 250°C, a mid-range error of 0.2°C (V_O = 2.502 V) was recorded.

Reference:

"IC Generates Second-Order Polynomial," *Electronic Design*, Aug. 5, 1993, p . 83.

T_M (°C)	V_M (V)	V_T = 175 V_M (V)	V_O (V)
0	0	0	0
50	0.003047	0.533225	0.5
100	0.006317	1.105475	1
150	0.009787	1.712725	1.5
200	0.013419	2.348325	2
250	0.017178	3.00615	2.5
300	0.021033	3.680775	3
350	0.024961	4.368175	3.5
400	0.028943	5.065025	4
450	0.03296	5.768	4.5
500	0.036999	6.474825	5