CIRCUIT CELLAR ONLINE

FEATURE ARTICLE

Jonathan Valvano

Measuring Temperure Using Thermistors

Taking into consideration the parameters of range, resolution, accuracy, and speed, Jonathan provides an overview of thermistor-based temperature measurement. Beyond basic information, in this article he shows us valuable ways to calibrate and explores three designs demonstrating different methods of interfacing temperature probes to a microcomputer.

When faced with the need to measure temperature for a design, you must first consider some parameters—temperature range, resolution, and accuracy, and time constant. The temperature range might be just a few degrees Celsius if you are building an oral thermometer, or it might be hundreds of degrees Celsius in some industrial applications. The temperature resolution is the smallest temperature change that can be reliably detected by the system. Resolution can usually be improved by using a more sensitive transducer and by reducing noise. The temperature accuracy is the difference between the measured and true temperatures. Accuracy can usually be improved by using a more stable transducer and by careful calibration. The time constant is the time it takes the temperature measuring system to reach 0.632 of its final value after a step change in temperature. The speed can usually be improved by using a faster transducer.

In this article, I'll begin with some basic information about thermistors, discuss effective ways to calibrate, and conclude with three specific designs, illustrating various approaches to interfacing these temperature probes to a microcomputer.

THERMISTOR CONSTRUCTION

The thermistor is a temperature transducer made from a ceramic-like semiconductor. The thermistor resistance is sensitive to temperature. This sensitivity is the slope of the resistance temperature response. Thermistors come with both positive (PTC) and negative (NTC) temperature coefficients. Although PTC thermistors are more sensitive, NTC thermistors are typically used because they are more stable.

Thermistors are made from combinations of metal oxides of manganese, nickel, cobalt, copper, iron, and titanium. A mixture of milled semicon-

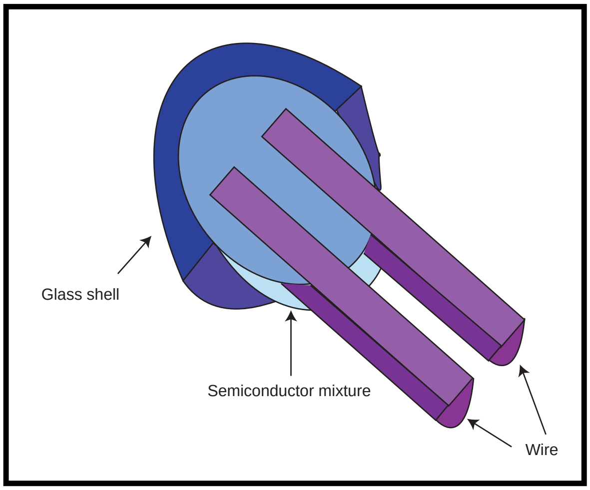

Figure 1—*Here you can see a mechanical cut-out drawing of a Thermometrics P60 glass-coated thermistor. This spherical bead has a diameter of 0.06^{2}, or 1.4 mm.*

ductor oxide powders and a binder are first shaped into the desired geometry. Next, the mixture is dried and sintered (under pressure) at an elevated temperature. Lastly, the wire leads are attached, and the combination is coated with glass or epoxy. This coating provides mechanical strength and electrical resistance. Because the electrical resistance of the epoxy/glass shell is high, the only noise pickup occurs through capacitive coupling.

By varying the mixture of oxides, a range of resistance values from 30 ohms to 20 megaohms (at 25°C) is possible. Spherical thermistor beads come in diameters ranging from 0.3 to 2 mm (see Figure 1). The speed of a temperature transducer is related to its surface area, so you can design a system with a fast response time by using a small thermistor.

ALTERNATIVE TRANSDUCERS

Although this article focuses on thermistors, it is advisable to compare them to other probe-type transducers. Platinum probes are simple resistance temperature devices (RTD) made from thin, long, platinum wires. Because of the purity of the platinum, these transducers are stable. You could use RTDs in systems that demand high accuracy. On the other hand, because of the length of the platinum wire, these probes are usually large and slow.

You can build a thermocouple by welding together wires made with two different metals. Typically two weld junctions are created, and a voltage output occurs, depending on the temperature difference between the two weld points. If one of the junctions is at a known temperature (reference), then you can measure the output voltage and calculate the temperature of the other junction. (A temperature reference, like an ice bath, is needed in order to use thermocouples.)

Thermistors	Resistance temperature devices	Thermoouples
most sensitive	least sensitive	medium sensitivity
best resolution	best accuracy	most sturdy
requires frequent calibration	inert, stable	inert, stable
each calibrated separately	interchangeable calibration	interchangeable calibration
fast	slow	fastest
wide range of sizes	large	wide range of sizes
nonlinear	linear	linear
does not require a reference	does not require a reference	requires a reference
lowest cost	highest cost	medium cost

Table 1—*Here you can see the tradeoffs between thermistors and thermocouples.*

You can use thermocouples in applications demanding large temperature ranges, fast responses, or simple calibration. Alternatively, you can use thermistors in low-cost and high-resolution applications. Thermistors are particularly attractive in designs involving a microcomputer because the nonlinear response can be easily compensated for in the software. Table 1 lists the tradeoffs between the three major kinds of probe-type temperature transducers.

THERMISTOR TYPES

Thermistors are classified according to the method by which the electrodes are attached. There are two major types of thermistors—beads and flakes. The platinum alloy lead wires are sintered into the ceramic body of bead-type thermistors. This thermistor group includes bare beads, glass-coated beads, ruggedized beads, glass probes, and glass rods. Flake thermistors (and chips) have metallized surface contacts. Figure 2 shows typical thermistor shapes.

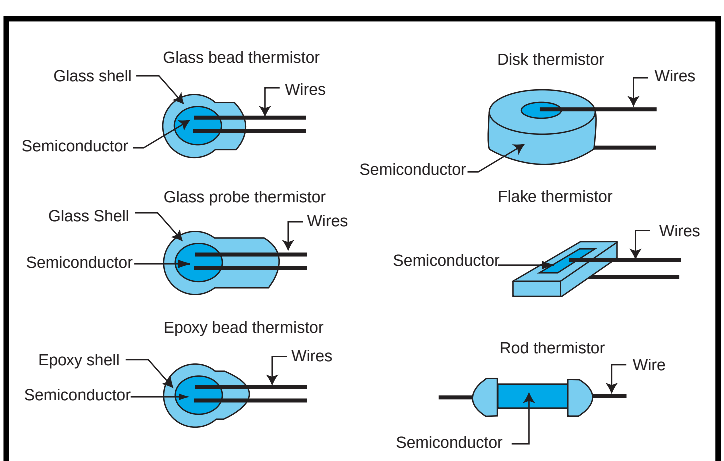

Figure 2—*Thermistors come in many shapes and sizes. Bare beads have diameters ranging from 0.1 to 1.3 mm, glass-coated beads have diameters ranging from 0.3 to 1.4 mm, and glass-coated probes have diameters ranging from 1.5 to 2.5 mm.*

RESISTANCE VS. TEMPERATURE CALIBRATION

The basic temperature-dependent mechanism is the population of charge carriers into a conduction band. If the temperature is expressed in degrees Celsius, the NTC thermistor resistance is:

$$R = R_0 e^{+\frac{\beta}{T + 273.15}} \qquad (1)$$

The basic idea of a thermistor-based thermometer is to measure the thermistor resistance and then calculate temperature using an equation that relates temperature as a function of resistance. You can rewrite equation 1, solving for T (in degrees Celsius) in terms of R (in ohms). I replaced the two thermistor parameters (R_0 and b) in equation 1 with two other calibration parameters, H_0 and H_1.

$$T = \frac{1}{\left(H_0 + H_1\left(\ln(R)\right)\right)} + 273.15 \qquad (2)$$

You need to perform a resistance temperature calibration to determine the coefficients H_0 and H_1. Because each thermistor is different, the calibration experiment is an important step when temperature accuracy is desired. On the other hand, if relative temperature is more important than accuracy, you could skip the calibration and simply

Resistance (ohm)	True Temp. (°C)	Equation 2 Error (°C)	Equation 3 Error (°C)
1101.0	25.113	–0.023	0.002
911.3	30.131	0.004	–0.002
754.8	35.285	0.016	–0.004
636.0	40.120	0.024	0.005
533.7	45.202	0.005	0.001
451.1	50.218	–0.030	–0.002

Table 2—*The first two columns are the temperature calibration data. The last two columns are the regression errors when fitting the data to equations 2 and 3, respectively.*

use the coefficients given by the manufacturer.

I placed a Thermometrics P60DA102N NTC thermistor next to a reference temperature probe and placed the two in a water bath. I measured the thermistor resistance with my instrument and measured the true temperature with the reference thermometer. Table 2 shows a temperature calibration for this thermistor. I performed a linear regression of:

$$\frac{1}{(T + 273.15)} \qquad (3)$$

versus ln(R) to obtain the calibration coefficients, H_0 = 1.3091E–03 and H_1 = 2.9175E–04. The average error was 0.017°C.

For small temperature ranges or in systems where accuracy is secondary, this approach is sufficient. In systems that demand better accuracy, I use this three-term equation:

$$T = \frac{1}{\left(H_o + H_1(\ln(R)) + H_3(\ln(R))^3\right)} + 273.15 \qquad (4)$$

Although there is no fundamental theory to support it, I have found that equation 4 produces excellent results for a wide range of thermistor types.

The least squared fit of this same data in equation 4 gives an average error of only 0.002°C. For this thermistor, H_0 = 1.38077E–3, H_1 = 2.75309E–4, and H_3 = 1.27290E–7.

LINEARIZATION

Because the microcomputer (even without a floating-point processor) is capable of calculating these nonlinear equations, thermistors can easily be used for accurate temperature measurements. Sometimes, however, it is convenient to use a linear transducer.

For small temperature ranges, a simple resistor network can be used to create a more linear resistance versus temperature response. In particular, a fixed resistor placed in parallel with the thermistor will reduce the sensitivity but increase the linearity of the combination. The parallel combination of a fixed resistor and a thermistor will flatten and straighten resistance versus temperature response. Let R_T be the thermistor resistance, R_p be the fixed parallel shunt resistor, and R_n be the network resistance:

$$R_n = \frac{R_T R_P}{R_T + R_P} \qquad (5)$$

T_m is the midpoint temperature in Kelvin, and R_m is the thermistor resistance at that temperature. To maximize the linearity of equation 5, R_p will be chosen such that:

$$R_p = \frac{R_m(\beta - 2T_m)}{\beta + 2T_m} \qquad (6)$$

where *b* (from equation 1) is expressed in Kelvin. For the temperature range 25°C to 50°C, T_m is 311°K, b is 3428°K, and R_m is 697 ohms. Using these values in equation 5 yields an R_p of 483 ohms.

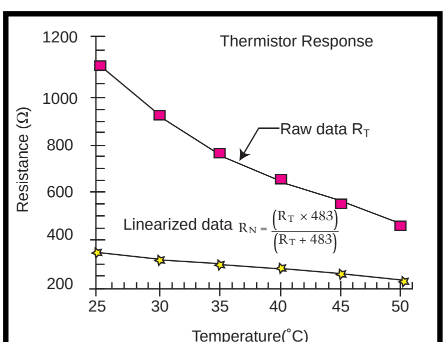

Figure 3—*Here you can see the resistance temperature response of the P60DA thermistor (raw data) and the resistance temperature response of this thermistor in parallel with a fixed 483-ohm resistor.*

In Figure 3, you can see that the 483-ohm parallel shunt resistor decreases the sensitivity but improves the linearity. The decrease in sensitivity means a larger gain in the analog amplifier is required, which will make the system more susceptible to noise. On the other hand, you can also see that without linearization, the system is more sensitive (higher R versus T slope) to temperature at low temperatures. This means the instrument will work better for low temperatures than for high temperatures. For small temperature ranges, this disparity is not a problem, but for large temperature ranges, consider using a linearized system.

DISSIPATION CONSTANT

When electrical power is delivered to a thermistor, its temperature will rise. When using the thermistor to measure temperature, the temperature rise caused by self-heating represents a measurement error. The dissipation constant (*D*) is defined as:

$$D = \frac{q}{\delta T} \qquad (7)$$

where *q* is the applied electrical power to the thermistor and *dT* is the resulting temperature rise in the thermistor as a result of self-heating.

Typically, you use equation 7 to determine the maximum allowable power that can be applied to the thermistor. For example, if the desired temperature resolution is DT, then design the interface so that the power is less than DT × D. It is important to take into account the thermal environment around the thermistor when considering errors caused by self-heating. The dissipation constant for the typical thermistor is:

$$\frac{2.5\,\text{mW}}{°\text{C}} \qquad (8)$$

in still air and

$$\frac{0.5\,\text{mW}}{°\text{C}} \qquad (9)$$

in still water.

ACCURATE TEMPERATURE MEASUREMENT

In this article, I present three thermistor-based temperature-measuring systems. In the first system, accuracy is of prime importance, and the system is built around an IBM-compatible PC. The objective of this system is to measure temperature in the range of 25°C to 50°C with a resolution (DT) of 0.01°C. The frequencies of interest range from 0 to 0.1 Hz. You begin designing by choosing a thermistor. I chose a Thermometrics P60DA102N thermistor because of its small size and rugged construction. In this interface, I employ a constant current source to convert thermistor resistance to voltage (see Figure 4). Given the dissipation constant of:

$$\frac{2.5\,\text{mW}}{°\text{C}} \qquad (10)$$

and a temperature resolution of 0.01°C, the electrical power ($q = I^2 \times R$) must be kept below 0.025 mW. For a constant current source, the power increases with resistance. So, the maximum power occurs when the resistance is largest. Therefore, the current must be less than:

$$\sqrt{\frac{0.025\,\text{mW}}{1101\,\Omega}} \qquad (11)$$

which is 0.15 mA. Adding a little bit of safety, I designed a 0.1-mA precision constant-current source.

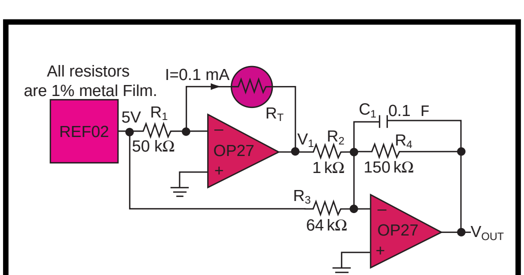

Figure 4—*Here is an analog circuit that interfaces a thermistor to an ADC. As the thermistor resistance varies from 464 to 1101 ohms, the output voltage varies from –5 to 5 V. The output voltage is connected to the PCL711 ADC input.*

I use OP27 precision op-amps because of their low noise and low offset voltage. Because of negative feedback, the negative terminal of the first op-amp is at virtual ground. Therefore, the current through the resistor (R_1) is 0.1 mA. This makes the intermediate voltage (V_1) equal to $-0.1\text{ mA} \times R_T$.

The second stage op-amp circuit provides the gain and offset so the output voltage matches the full-scale –5- to 5-V range of the ADC. The ratio $\frac{R_4}{R_2}$ determines the gain, and the offset is determined by $\frac{R_4}{R_3}$. This second stage could easily be adjusted for other temperature ranges, thermistor parameters, and ADC ranges.

The capacitor on the feedback creates a single-pole 10-Hz low-pass filter. I chose this capacitor value so 60-Hz noise would be removed. To select the correct number of ADC bits, multiply the sensitivity of the instrument by the desired temperature resolution. For an NTC thermistor, the worst cases are at higher temperatures. Using Table 3, I calculated the sensitivity $\frac{\partial V_{out}}{\partial T}$ at 50°C to be:

$$\frac{(-4.952)-(-3.713)}{50.22-45.20} = \frac{-0.25\,\text{V}}{°\text{C}} \qquad (12)$$

Because a temperature resolution of 0.01°C is desired, the ADC voltage resolution must be £0.0025 V. I chose the PCL711 12-bit ±5-V ADC because it has a resolution of:

$$\frac{10}{4096} = 0.0024\,\text{V} \qquad (13)$$

The last column in Table 3 shows N, which is the resulting ADC digital sample from the 12-bit ±5-V ADC.

Because the analog circuit and ADC perform a linear translation from resistance to ADC digital output, the software uses a linear function to calculate thermistor resistance from the ADC sample. Let m and b be two calibration coefficients:

T (°C)	R_T (ohm)	V_1 (V)	V_{OUT} (V)	N
25.11	1101.0	–0.1101	4.796	1965
30.13	911.3	–0.0911	1.951	799
35.29	754.8	–0.0755	–0.397	–163
40.12	636.0	–0.0636	–2.179	–892
45.20	533.7	–0.0534	–3.713	–1521
50.22	451.1	–0.0451	–4.952	–2028

Table 3—*On the left is the parameter to be measured. Columns are added to show the signal as it passes through the various stages of the data acquisition system.*

$$R_T = m(N) + b \qquad (14)$$

For this particular circuit, *m* is 0.16276 ohms and *b* is 781.25 ohms. Equation 4 is then used to calculate temperature.

The key to accurate temperature measurements is careful calibration. The advantage of this approach (the linear translation from resistance to ADC sample) is that the entire instrument (transducer, cables, analog circuits, and ADC) can be calibrated together.

First, I calibrated the resistance measuring circuit. The m and b coefficients can be empirically determined by inserting precision resistors in place of the thermistor and measuring ADC sample (N). Next, I calibrated the T versus R_T response. Rather than use a precision ohmmeter, I used the instrument itself to calculate the thermistor resistance. In other words, I measured the ADC sample (N), then calculated the thermistor resistance using equation 14.

The C++ program, part of which is shown in Listing 1, was compiled with Borland C 5 and runs on an IBM-compatible PC in DOS mode. I added a timeout feature to the ADC software interface so the program would not crash if the ADC board is missing or broken. The sample function calculates thermistor resistance and temperature.

LOW-COST EMBEDDED TEMPERATURE MEASUREMENT

In the second system, keeping the cost low is of prime importance. The system is built around a Motorola 6812, which provides eight 8-bit ADC channels (see Figure 5). The objective of this system is to measure tempera-

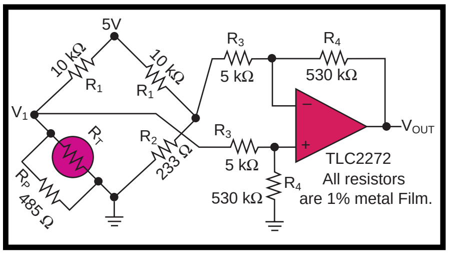

Figure 5—*The analog circuit interfaces a thermistor to an ADC. As the thermistor resistance varies from 464 to 1101 ohms, the output voltage varies from 0 to 5 V. The output voltage is connected to the 6812-ADC input.*

ture in the range of 25°C to 50°C with a resolution (DT) of 0.1°C. Again, the frequencies of interest range from 0 to 0.1 Hz.

In this system, I added a 483-ohm parallel shunt resistor, so the response is more linear. A simple resistor divider circuit converts thermistor resistance to voltage (V_1), as shown in Figure 5. This time, I used the dissipation constant in air:

$$\frac{0.5\,\text{mW}}{^\circ\text{C}} \qquad (15)$$

Because the desired resolution is 0.1°C, I had to keep the electrical power below 0.05 mW. Therefore, the current had to be below:

$$\sqrt{\frac{0.05\,\text{mW}}{1101\,\Omega}} \qquad (16)$$

which is about 0.2 mA. I selected R_1 to be 10 kilohms, which made the thermistor current about 0.2 mA and the maximum power about 0.04 mW.

Because of the low-cost and embedded constraints, I wanted all electronics to operate on a single 5-V supply. Therefore, I used a rail-to-rail op-amp similar to the TLC2272. The resistance bridge and differential amplifier maps the 25°C to 50°C temperature range into the entire 0- to 5-V ADC range. I chose the value of R_2 to be 233 ohms because it is the minimum value of R_n. Next, I chose the $\frac{R_4}{R_3}$ ratio to be:

$$\frac{530\,\text{k}\Omega}{5\,\text{k}\Omega} \qquad (17)$$

in order to map the temperature range into the 0- to 5-V range of my ADC.

When you build this circuit, you can empirically adjust the R_2 resistor to compensate for the offset voltage of the op-amp. First, adjust R_2 so V_{OUT} is just above zero at the maximum temperature. Next, adjust the two R_4 resistors so V_{OUT} is just below 5 V at the minimum temperature. To select the correct number of ADC bits, multiply the sensitivity of the instrument by the desired temperature resolution.

Using Table 4, I calculated the sensitivity $\frac{\partial V_{out}}{\partial T}$ at 50°C to be:

$$\frac{(0.012 - 0.992)}{(50.22 - 42.20)} \qquad (18)$$

which is about

$$R_p = \frac{R_m(\beta - 2T_m)}{\beta + 2T_m} \qquad (6)$$

$$\frac{-0.2\text{V}}{^\circ\text{C}}$$

Because a temperature resolution of 0.1°C is desired, the ADC voltage resolution must be £0.02 V. Conveniently, the 6812's built-in 8-bit 5-V ADC has a resolution of:

$$\frac{5}{256} = 0.02\text{V} \qquad (19)$$

The last column in Table 4 shows N, which is the resulting ADC digital sample from the 8-bit 5-V ADC. (If the thermistor is not linearized, you would need a 9-bit ADC to build this 0.1°C resolution system.)

One approach to implementing a data acquisition system is use table lookup with linear interpolation. Notice in Listing 2 that the first and last columns of Table 4 are stored in constant arrays. Also notice that the temperature values are stored in decimal fixed point format, with a 0.1°C resolution. For example, 25.11°C is stored as the integer 251. The software samples the ADC to get N, then finds two adjacent entries in the table, such that N1 £ N < N2. With T1 and T2 as the corresponding temperature values for N1 and N2, you use linear interpolation to calculate the temperature.

T (°C)	R_T (ohm)	R_n (ohm)	V_1 (V)	V_{OUT} (V)	N
25.11	1101.0	335.7	0.1623	4.920	252
30.13	911.3	315.7	0.1529	3.968	203
35.29	754.8	294.5	0.1430	2.959	152
40.12	636.0	274.5	0.1335	2.001	102
45.20	533.7	253.5	0.1236	0.992	51
50.22	451.1	233.3	0.1139	0.012	1

Table 4—*These are the signals as they pass through the various stages of the data acquisition system.*

When implementing integer mathematics, it is important to consider overflow. Because *T2 – T1* and *N1 – N* are always less than 100, their products will fit in a 16-bit number. Linear interpolation is such an important operation that the 6812 has two machine instructions (TBL and ETBL), which perform:

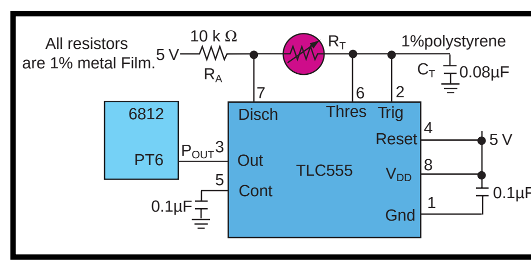

Figure 6—*This circuit converts thermistor resistance to period. As the thermistor resistance varies from 198.3 to 551.2 kilohms, the period of the square wave varies from 22,542 to 61,671 µs. The square wave is connected to a 6812 input capture pin.*

$$T = T1 + \frac{(T2 - T1)(N1 - N)}{N1 - N2} \qquad (20)$$

To calibrate this system, I used the reference thermometer to measure true temperature and my thermistor, analog amp, 6812 ADC, and digital filter to determine *N*. Calibration simply involves collecting the six T and N sample pairs for the software table. The sample function performs an ADC conversion and calculates temperature.

HIGH-PRECISION TEMPERATURE MEASUREMENT

Another approach to interface this transducer to

T (°C)	R_T (kilohm)	P_{OUT} (ms)
25.011	551.2	61,671
30.596	432.0	48,455
35.473	351.8	39,562
39.989	292.5	32,987
45.261	237.4	26,877
49.947	198.3	22,542

Table 5—*Here are the signals as they pass through the various stages of the data acquisition system.*

the microcomputer is to use an astable multivibrator (see Figure 6). In this system, I used a thermistor with a higher resistance (see Table 5). The period of a 555 timer is about $0.693 \times C_T \times (R_A + 2R_T)$. Given a fixed R_A and C_T, the period of the output signal (P_{OUT}) is a linear function of R_T.

Microcontrollers have a rich set of mechanisms to measure frequency, pulse width, or period. To change the slope and offset of the conversion between R_T and P_{OUT}, the fixed resistor and capacitor can be adjusted. Even though the period does not include zero, the precision of this measurement is over 32,000 alternatives, or more than 15 bits. Because of the uncertainties in the 555 timer and the capacitor, the accuracy of this system will not be as good as the first example, but it can resolve temperature changes of 0.001°C. The software shown in Listing 3 measures period with a resolution of 1 µs and calculates temperature using a table lookup scheme similar to the previous example.

WHAT'S LEFT?

I've provided you with a brief overview of thermistor-based temperature measurement. Measuring high-speed temperature transients will require special transducer design and instrumentation circuits. I have not discussed the choice of sampling rate, nor shown you the software to implement periodic real-time sampling. Because 60 Hz is a typical problem that most data acquisition systems must deal with, you can include either a digital low-pass or a digital notch filter to remove this unwanted noise. For a more detailed treatment of these issues, I refer you to the references provided. ■

Jonathan W. Valvano is a full professor of electrical and computer engineering at the University of Texas at Austin, teaching and performing research since 1981 in the fields of medical instrumentation and embedded systems. He received his BS and MS degrees in Electrical Engineering and Computer Science at MIT in 1977. He received his doctorate in 1981 in Medical Engineering from the Harvard University/MIT Health Sciences and Technology Program. He has authored over 60 journal articles, four book chapters, and one textbook. He can be reached at valvano@uts.cc.utexas.edu*, or visit his web site at* http://www.ece.utexas.edu/~valvano.

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J. Valvano, *Embedded Microcomputer Systems: Real Time Interfacing*, Chapters 6, 11, 12, and 15, Brooks-Cole Publishing, 2000.

SOURCES

PCL711 ADC board
PCLabs
(423) 547-0651
www.pclabs.com

Thermistors
Thermometrics
(732) 287-2870
www.thermometrics.com

6812 Adapt12 microcomputer
Technological Arts
(416) 963-8996
www.interlog.com/~techart

ICC12 Compiler
ImageCraft
(408) 749-0702
www.imagecraft.com