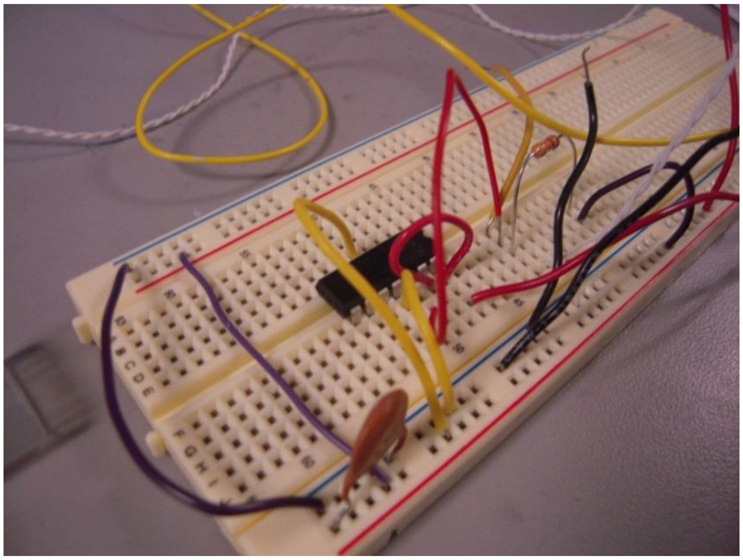
<u>CMPE167 Lab 2: Thermistors</u>



By Troy Pandhumsoporn

Instructor: Stephen Petersen

Date: 2/13/2013

Winter 2013

Introduction:

The topic of sensors often serves as an attractive lure to design engineers and the general public alike. When considering buying a product or inspecting a datasheet of a complex module, the basic marketing strategy of the salesperson/applications engineer almost always provide a wide array of colorful sensing capabilities of the device. Associated as the “bells and whistles” of a system, sensor applications cover the measurement of physical properties such as light, motion, temperature, magnetic fields, pressure, electric fields, sound, moisture, gravity, vibrations, humidity, and other physical aspects of the environment. As fledgling design engineers, students should understand the scientific processes, physical properties, practical mathematical theory and techniques to correctly implement sensors from a systems perspective.

ATTRIBUTES OF THERMOCOUPLES, RTDS, THERMISTORS AND SILICON IC SENSORS

Attribute	Thermocouple (type K)	RTD	Thermistor	Silicon IC
Range	-184°C to 1260°C	-200°C to 850°C	-55°C to 150°C	-55°C to 125°C
Temperature (t) Accuracy	Greater of ±2.2°C or ±0.75%	Class B = ± [0.012 + (0.0019 |t|) – 6 X $10^{-7}t^2$]	Various, ±0.5°C to 5°C	Various, ±0.5°C to 4°C
Output Signal	40 µV/°C	≈ 0.00385 Ω /Ω/°C	≈ 4% ΔR/°C for 0°C ≤ t ≤ 70°C	Analog, Serial, Logic, Duty Cycle
Linearity	Fair	Excellent	Poor	Good
Precision	Fair	Excellent	Poor	Fair
Durability	Good at lower temp., Poor at high temp, Open-circuit vibration failures	Good, Wire wound prone to open-circuit vibration failures	Good, Power derated with temperature	Excellent
Thermal Response Time	Fast (function of probe material)	Fast (function of probe material)	Moderate	Slow
Cost	Low	Wire wound – High, Thin-film – Moderate	Low	Moderate
Interface Issues	Cold junction compensation, Small ΔV	Small ΔR/°C	Non-linear resistance	Sensor located on PCB

Figure 1: Types of temperature sensors with its advantages & disadvantages (Additional documentation Microchip App. note when looking at MCP6004 datasheet)

Some applications of temperature sensors provide are thermal protection for electrical devices, thermostat control for home applications, and insertion tools in biomedical applications. Although there are many ways to measure temperature, in this lab, students will particularly investigate the use of negative temperature (NTC) thermistors to simulate an accurate thermometer used to measure the thermal resistance and thermal time constant of one of the professor’s commercial heat-sinks. Good systems engineering design requires students to recognize the trade-offs necessary in designing a temperature measurement system and evaluating the sensor, test equipment, and circuit elements’ voltage/current noise and transients effects on one another. In addition, the lab serves to provide an interactive understanding of thermal characteristics and problems associated with their function and calibration.

NTC Thermistor:

Thermistors are semiconductor devices that exhibit a negative coefficient of resistance with temperature. Available in all sorts of packages, ranging from tiny glass beads to armored probes, they are intended for accurate temperature measurement compensation elements in circuits and typically have a resistance of a 1-10kΩ at room temperature. Adhering to tight conformity with standard curves, the thermistor possesses a large coefficient of resistance change, which makes them easy to use, inexpensive and stable. While the thermistor provides a near-optimum solution for temperature-dependent regulation, thermistor circuits are prone to self-heating effects. A typical small thermistor probe might have a dissipation constant of 1 mW/C meaning that I^2R heating should be kept well below 1 mW if you would like your reading accurate to better than 1 degree. Another tradeoff of using thermistors is that in exchange for simplicity and accuracy, they suffer from fragility and a narrow temperature range. Nevertheless, thermistors serve as a good choice for temperature measurement and control.

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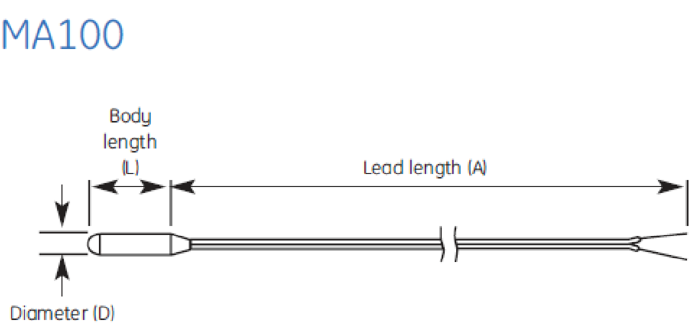


Figure 2: GE Sensing Thermistor provided in the lab kit.

Contrary to the lab description, the NTC thermistor provided in the lab kit is a GE Sensing Type MA100 thermistor used for biomedical applications. It is a 10k room temperature (25°C) low-cost temperature-sensitive resistor constructed of molded plastic or kapton sleeve for catheters assemblies. However, the most stable and hermetic thermistors are enclosed with glass. Most thermistors are also not affected by shock or vibration. The device is guaranteed best overall stability at less than 70°C or within the 0°C - 50°C range.

Experiment:

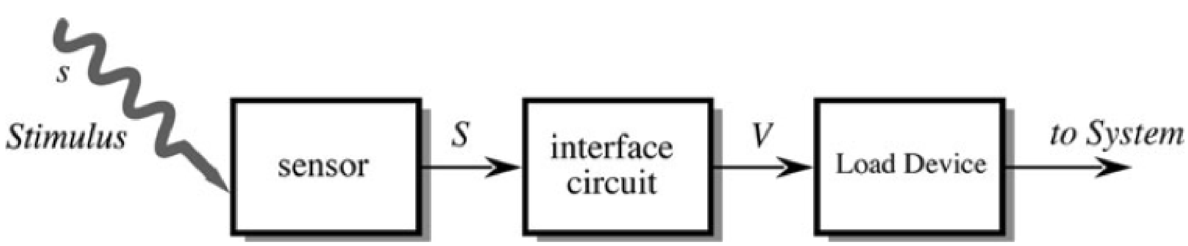


Figure 3: Fraden's elementary block diagram for an interface circuit that matches the signal formats of a sensor and a load device. Similarly for control engineering applications, the above block diagram would be divided into a sensing stage (sensor), a signal conditioning stage [amplification of the signal (done with operational amplifiers)], and a processing stage (usually carried by an ADC and microcontroller).

Signal conditioning is the operation of manipulating an analog signal in the manner of meeting requirements of next stage, either through amplification, filtering, converting, isolation, or range matching for further processing (ADCs). This intermediary operation is primarily used for data acquisition, in which the sensor signals must be "conditioned" appropriate to analog-to-digital conversion to be read by computerized devices.

The preliminary block diagram from Fraden allows us to classify the circuit into three sections: the thermistor voltage divider as the sensor, the interface circuit as the buffer amplifier, and the load as the NI-6008 DAQ. The resistor/power diode, heat-sink, and power supply part of the circuit are an extension of the sensor stage.

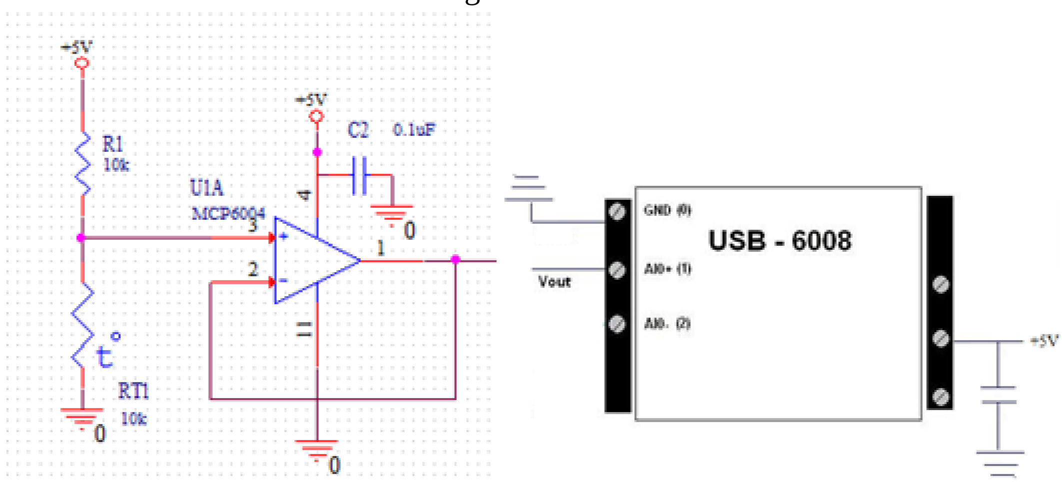


Figure 4: Full circuit schematic (the Nyquist filter that I later found out about mentioned at the end would be a series resistor with shunt capacitor to ground)

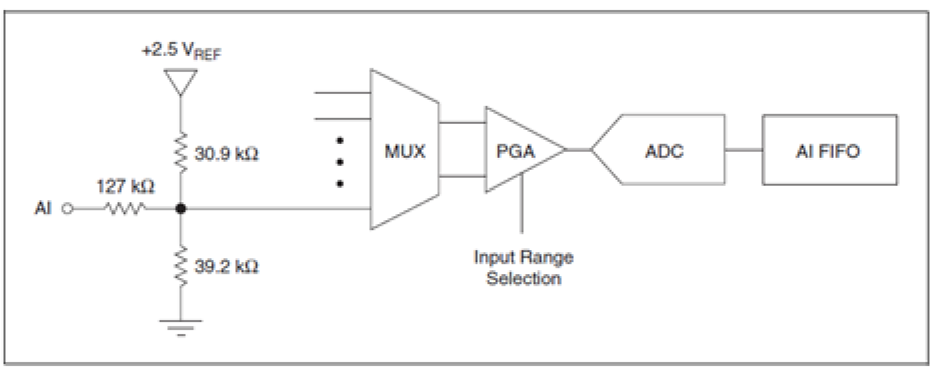


Figure 5: The NI USB-6008/6009 Analog Input Circuitry

The impedance looking in through the analog input of the NI DAQ 6008 is 144 kΩ, or 127 kΩ added with the parallel resistance of 30.9kΩ and 39.2 kΩ. Since the designer would want the circuit to have zero impedance from both sides (voltage divider and the DAQ device), a simple unity gain buffer achieves that condition to prevent loading (drawing the low current provided by the DAQ or other devices in Figure 6) and losses by imposing an ideal voltage source fed into the DAQ device.

External Reference and Power Source

The NI USB-6008/6009 creates an external reference and supplies a power source. All voltages are relative to ground (GND).

+2.5 V External Reference

The NI USB-6008/6009 creates a high-purity reference voltage supply for the ADC using a multi-state regulator, amplifier, and filter circuit. You can use the resulting +2.5 V reference voltage as a signal for self-test.

+5 V Power Source

The NI USB-6008/6009 supplies a 5 V, 200 mA output. You can use this source to power external components.

Figure 6:

The voltage divider setup of the sensor block evidently uses voltage mode linearization. Since the divider circuit is biased with a constant linear regulated supply, the effect of the output voltage is linear over temperature. The resistor's value is chosen to be equal to the thermistor's resistance at room temperature so that the region of linear voltage is symmetrical around room temperature.

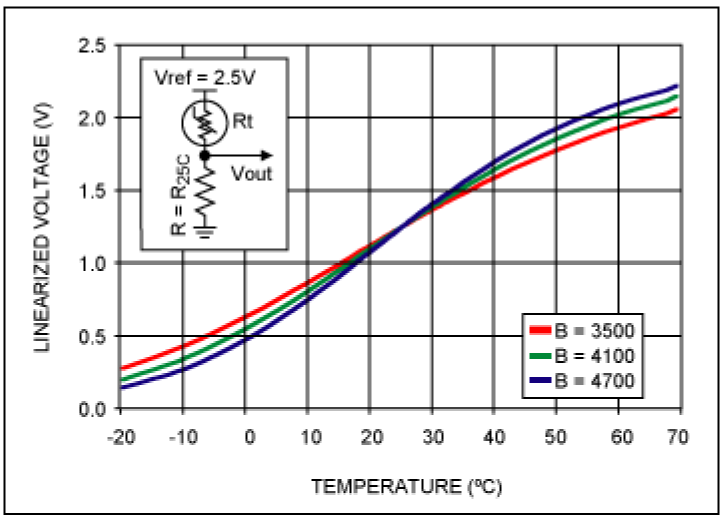


Figure 7: Maxim Integrated's App Note Graph on Voltage temperature linearization mode

<u>Calibration</u>:

February 12, 2013

The General Electric NTC MA100 thermistor was calibrated using the Steinhart-Hart equation using three measured data-points using an accurate analog bulb thermometer with a 0°C – 100°C scale employing cold and semi-boiling water. A cursory glance at the sensor's datasheet gives A, B, and C coefficients for a specific temperature range using the Steinhart-Hart equation. This is a common occurrence for thermistor datasheets from vendors such U.S. Sensors, Vishay, and Murata using DigiKey's part search engine. An accurate thermistor calibration will use these temperature extremes and an intermediate, convenient data point chosen as ambient room temperature; these contact measurements obtained eliminates self-heating effects. Later on as the experiment is carried out, the experimental contact measurements can be compared with a non-contact ambient measurement to verify the presence of self-heating and sensor-to-air thermal resistance.

Temperature (C)	Temperature (K)	Resistance (kΩ)
0°	273	32.06 (32)
23°	296	10.5
56°	329	2.882 (2.9)

Figure 8: Experimental measurements from water bath calibration.

Since the thermistor calibration is limited by the range of the analog lab bulb thermometer, only two significant figures at most are displayed and thus should be appropriate for the corresponding resistance measurement (in parentheses). Boiling water temperature (100°C) is not tested because of the datasheet's recommendation of the thermistor's best overall stability is maintained when exposure temperatures remain below 70°C. The thermistor's non-contact ambient measurement was given as 23.313080°C. Since the calibration of the thermistor was done with a water bath, the thermistor suffers much less self-heating effects; this explains the non-contact room temperature measurement difference of 0.31°C from the sensor-to air temperature. In ambient room temperature settings, current passing through the thermistor causes self-heating and the thermistor temperature rises with thermal time constant. A difficult design trade-off of the thermistor systems is eliminating self-heating over increasing Johnson noise. In order to eliminate self-heating effects, the designer should choose low-supply voltage and high resistances to make the current "i" low and temperature rise ΔT relatively small. Johnson noise is however related to the relation "$v_n = \sqrt{4kTBR}$", which creates problems if R is made large from the former statement.

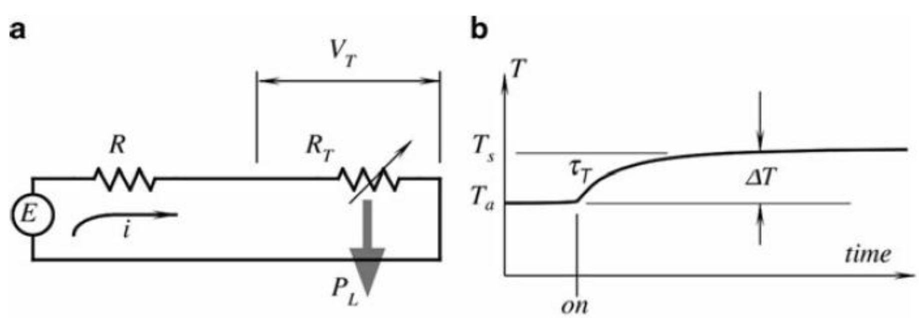


Figure 9: Current passing through thermistor causes self-heating (a) and thermistor temperature rises with thermal time constant τ_L. P_L is the thermal power lost to surroundings.

$$\delta(T_S - T_a) = \delta\Delta T = P\left[1 - e^{-\frac{\delta}{C}t}\right] = V_t i \;\; [self - heating\ relationship]$$

P = constant electric power supplied to the sensor
$V_t = thermistor\ voltage\ drop$
ΔT = temperature rise
C = thermistor thermal capacity
I = current flowing in the system
$\delta = dissipation\ factor$

Mathematical Model:

The Steinhart-Hart mathematical model is appropriate to our system since three resistances respectively three temperatures are known and is considered industry-standard when the highest possible accuracy is required for the precision thermistor circuit. For thermistor sensors, most datasheets from Digi-Key give the Steinhart-Hart coefficients for the designer to linearize the thermistor with. While the Fraden model also boasts high accuracy as well, the slope parameter γ depends on material characteristics β_x and β_y that do not have much explanation on what they represent in dimensional units. Using the tabulated values, I used the coefficient relationships from the Steinhart-Hart paper that Wikipedia referenced (alternatively, pg 538 in Fraden has these relationships).

Steinhart–Hart coefficients

To find the coefficients of Steinhart–Hart, we need to know at-least three operating points. For this, we use three values of resistance data for three known temperatures.

$$\begin{cases} A + (\ln R_1)\, B + (\ln R_1)^3\, C = \frac{1}{T_1} \\ A + (\ln R_2)\, B + (\ln R_2)^3\, C = \frac{1}{T_2} \\ A + (\ln R_3)\, B + (\ln R_3)^3\, C = \frac{1}{T_3} \end{cases}$$

With R_1, R_2 and R_3 values of resistance at the temperatures T_1, T_2 and T_3, one can express A, B and C (all calculations):

$$L_1 = \ln(R_1),\quad L_2 = \ln(R_2) \quad \text{and} \quad L_3 = \ln(R_3),$$

$$Y_1 = \frac{1}{T_1},\quad Y_2 = \frac{1}{T_2} \quad \text{and} \quad Y_3 = \frac{1}{T_3},$$

$$\gamma_2 = \frac{Y_2 - Y_1}{L_2 - L_1},\quad \gamma_3 = \frac{Y_3 - Y_1}{L_3 - L_1}$$

$$\Rightarrow C = \left(\frac{\gamma_3 - \gamma_2}{L_3 - L_2}\right)(L_1 + L_2 + L_3)^{-1}$$

$$\Rightarrow B = \gamma_2 - C\left(L_1^2 + L_1 L_2 + L_2^2\right)$$

$$\Rightarrow A = Y_1 - \left(B + L_1^2 C\right) L_1$$

Figure 10: Steinhart-Hart coefficients formulas, further description of the parameters are derived from the original research papers

The relationships are inputted into an m-file and calculated using the MATLAB command interface by copying and pasting the MATLAB code, which is provided for reference in the appendix.

The approximated coefficients of the Steinhart-Hart model are given here:

A = 9.0968e-004
B= 2.7137e-004
C = -5.7532e-008

$$\frac{1}{T} = (9.1\ x\ 10^{-4}) + (2.7\ x\ 10^{-4})(\ln R) + (-5.75\ x\ 10^{-8})(\ln R)^3$$

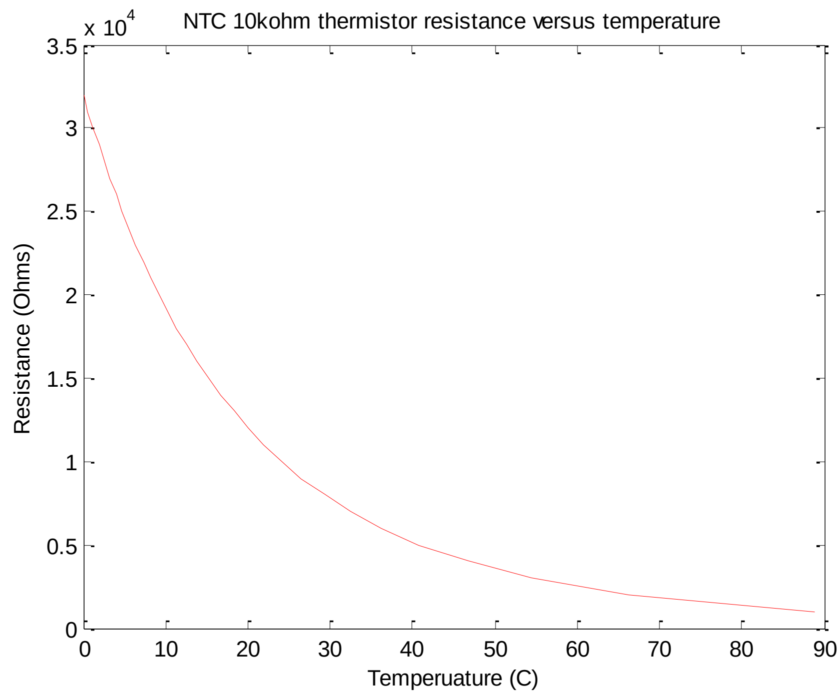


Figure 11: Resistance versus Temperature Mode. In precision temperature measurement environments, the "zero-power" condition appears to falls around 20-23℃.

LabVIEW Setup:

After hooking up the NI-DAQ 6008 hooked to the computer USB port, I fed a wire through the analog input A10 (or A01) to obtain the voltage buffered signal from the voltage divider circuit during the heat-sink measurement. The website pdf below (or just "Google thermistor LabVIEW) gives all the basic details to setup LabVIEW for data acquisition and outputting to a notepad file and importing it to Excel. The two columns of data can be easily separated with Excel's spreadsheet format and can be copied to another notepad file as two columns of data (.dat). Using the MATLAB code provided in the Appendix, the user can import the notepad (.dat file) and graph the relationship provided by the graphs following below. If the user wishes, the signal could be resistance and the new graph would show resistance vs. temperature instead.

http://zeus.phys.uconn.edu/wiki/images/LabViewThermistor.pdf

Results:

At steady-state temperature, the NI DAQ 6008 measurement of the voltage and the manual DMM reading of the voltage were slightly off by 1-3%.

1.838939	1.88
1.838939	1.88
1.838939	1.88

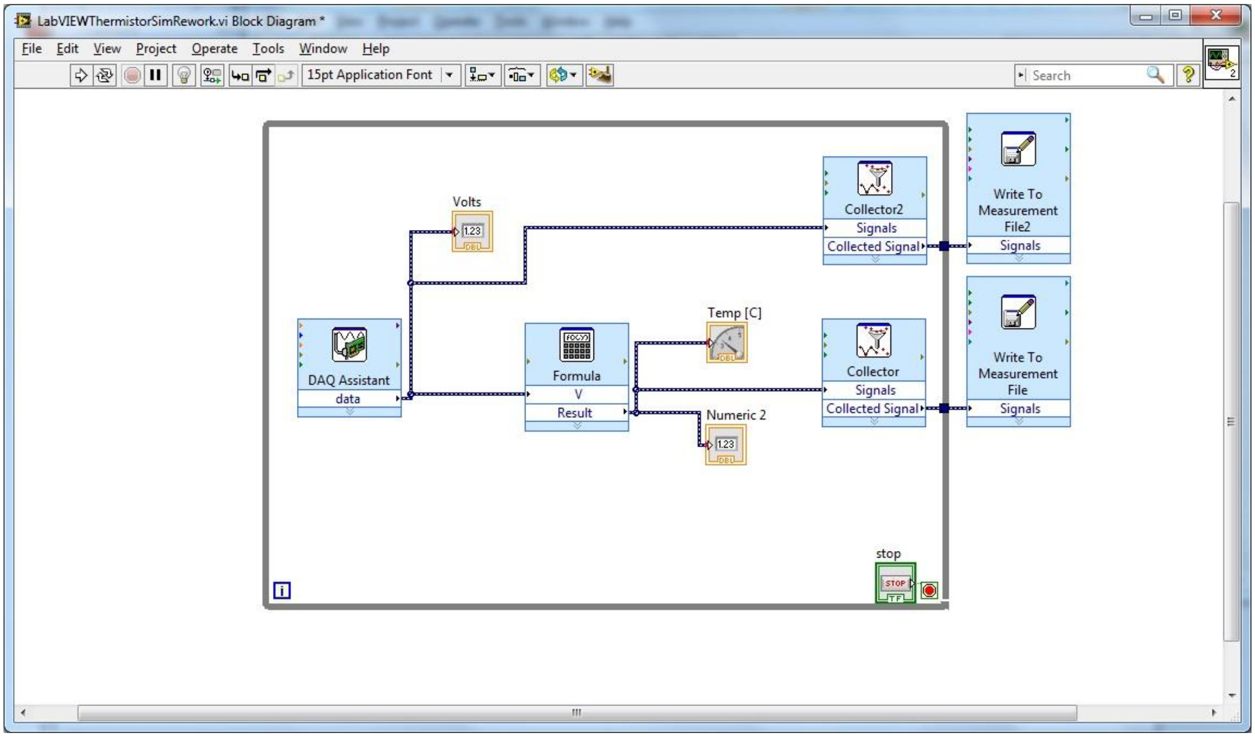


Figure 12: Block Diagram of LabVIEW Data Acquisition Thermistor Experiment.

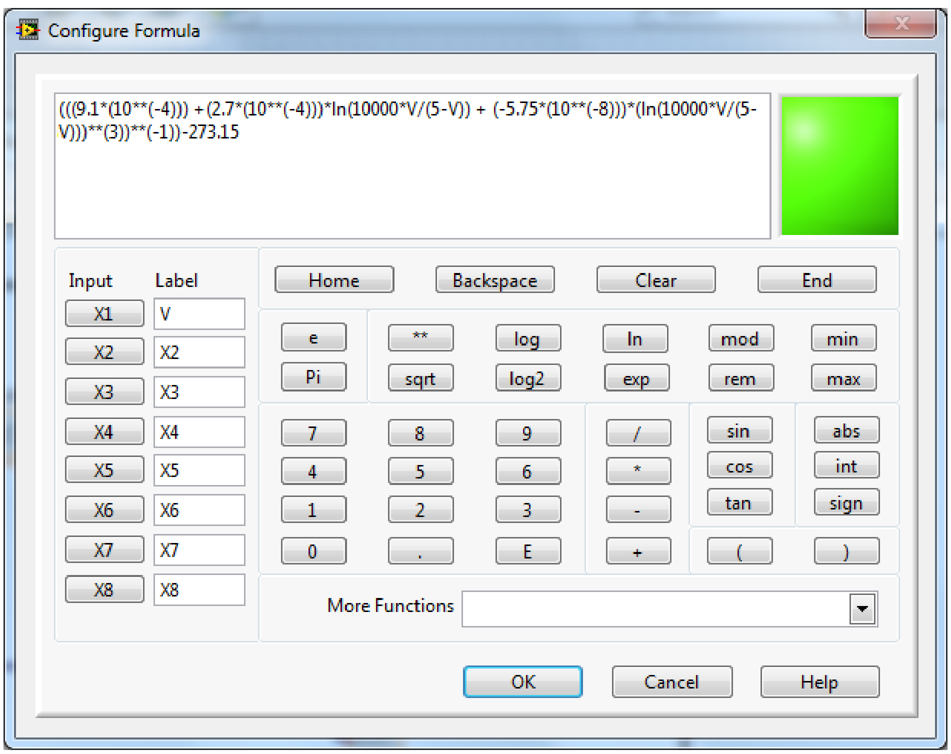


Figure 13: Formula Input Block (referenced to make it easier to modify the format)

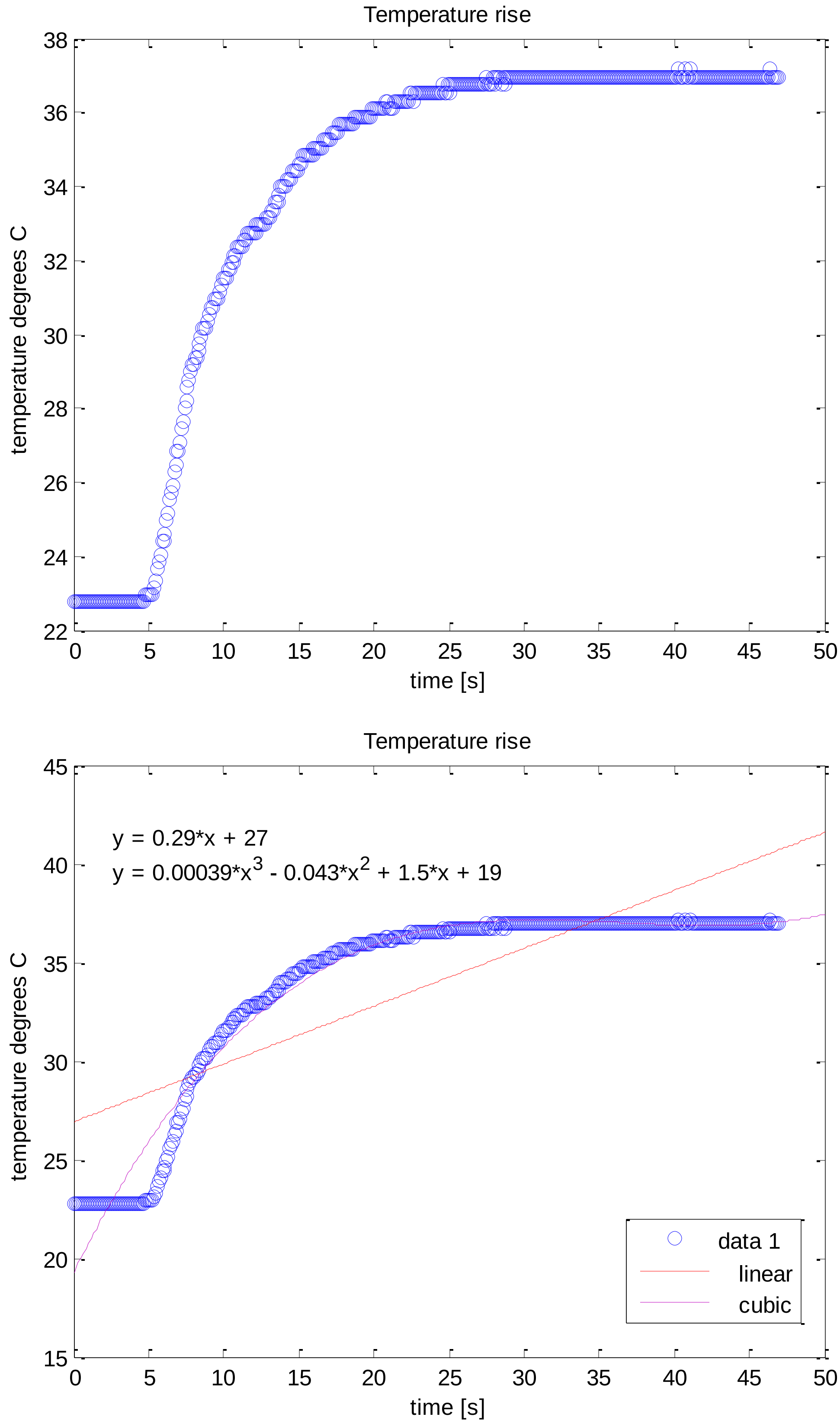


Figure 14 and 15: Temperature changes of a sensor when the object has limited thermal conductivity

Power Supply Stability:

Stability, ±(% of output + offset)

Following a 30-minute warm-up, with the output in the ON state according to the operating mode (CC with load or CV), and with a change in the output over 8 hours under constant load, line, and ambient temperature

	+6V Output	+25V Output	-25V Output
Voltage	0.03% + 1 mV	0.02% + 2 mV	0.02% + 2 mV
Current	0.1% + 3 mA	0.05% + 1 mA	0.05% + 1 mA

Figure 16: The Agilent E3631A linear power supply stability specification.
http://cp.literature.agilent.com/litweb/pdf/E3631-90011.pdf (pdf 17)

From a voltage source of 5 V, the voltage using the +6 V output and the +25 V output for a single supply rail gives respectively 0.15 V + 1 mV = 151 mV and 0.1 V + 2 mV = 102 mV for the voltage fluctuations. This voltage fluctuation from the power supply affects the circuit significantly considering if the output signal from the sensing stage is within the mV (or very low volt) range, and consequently dependent on the value of the source voltage powering the circuit (5V as opposed to 2.5V). Proper capacitor bypassing and filtering practices on the experimental circuit will minimize these effects.

Ripple and Noise (with outputs ungrounded, or with either output terminal grounded, 20 Hz to 20 MHz)

	+6V Output	+25V Output	-25V Output
Voltage	<0.35 mV rms	<0.35 mV rms	<0.35 mV rms
	<2 mV p-p	<2 mV p-p	<2 mV p-p
Current	<2 mA rms	<500 µA rms	<500 µA rms
Common mode current	<1.5 µA rms		

Figure 17: The Agilent E3631A internal noise specification.
http://cp.literature.agilent.com/litweb/pdf/E3631-90011.pdf (pdf 15)

One of the most common tests performed on a power supply is measuring the AC noise on the DC output. Linear power supplies use an AC to DC transformer to convert the line voltage to a stable DC output, usually having a 50/60 Hz noise ripple. The 16 gauge wires connecting the power supply to the heat sink and power diode are 31 inches long for one wire for total of 62 inches (154.94 cm) for both wires (1 inch = 2.54 cm). Using the wire resistance and inductance calculator on this website http://www.ampbooks.com/home/amplifier-calculators/wire-inductance/ , the results are computed into the small table.

	Frequency	resistance (milliohms)	reactance (micro-ohms)	inductance (microhenries)
16 AWG	50 Hz	20.4147	752.3877	2.3949
	60 Hz	20.4147	902.8653	2.3949
	20 MHz	20.4147	300955090.1184	2.3949

Figure 18: Wire Resistance, Reactance, Inductance values for different frequencies.

The only change to the table is the reactance from the different frequency from the $\omega = 2\pi f$ factor. Since the wire length is a function of the resistance and inductance, the tabulated values make sense.

Thermal Response Time
(63% Response)

Series	Still Air	Still Water*
MA100 Catheter Assembly	15 seconds	2.0 seconds
MA200 Oral-Rectal Assembly	35 seconds	0.6 seconds
MA300 Skin Surface Assembly	45 seconds	2.0 seconds

*Response time provided is for assembly plunged fromm 77°F (25°C) air to 41°F (5°C) still water.

Figure 19: One time constant is defined to be 15 sec. for room temperature (25°C). Since ambient temperature varies, we have to use the time constant relationship to derive the theoretical time constant for our system.

The thermal time constant is a measurement of the time required for the thermistor to change 63.2% of the net difference between an initial (ambient temperature) and final body temperature when subjected to an incremental change in temperature.

<u>Theoretical Calculation</u>:

$$\Delta T(t) = \Delta T_o(1 - e^{-t/\tau})$$

We can rearrange this equation to represent the temperature change at time t as a percentage of the initial temperature difference.

$$5 = 25(1 - e^{-t/\tau})$$
$$t = 0.22\ s$$

$$23 = 37(1 - e^{-t/\tau})$$
$$t = 0.97\ s$$

The results are inaccurate since the small fraction of time they occupy seems instantaneous, but I could not find the right relationship to yield a good estimate.

<u>Experimental Calculation</u>:

Figure 20: On the left, the heat-sink has been dissipating heat from the power supply from over one to two hours. On the right is the result of the voltage and current sourced into the heat-sink/power diode.

Using the measurements on the power supply, the experimental values obtained from the LabVIEW temperature data, and heat-sink/semiconductor setup with the leads connected to ±6V rails, the following formulas and relationships on this website will give a true representation of the thermal time constant. The ±6 V supplies used to connect and dissipate heat into the heat sink resulted in a faster heat-up time.

The thermal resistance measurement is based on knowing the voltage and current applied to the heat sink heating system and using the LabVIEW data acquisition to accurately measure the ambient and heat sink temperature. Before using the thermistor, the heat-sink temperature is allowed to stabilize, which took at least 45 minutes to an hour to reach steady state values.

http://sound.westhost.com/heatsinks.htm#s4

$$T_r = Temperature\ Rise = T_h - T_a = 36.965285 - 22.761046 = 14.204239 \cong 14.2°C$$

$$T_a = Ambient\ temperature = 22.761046°C\ \ (Obtained\ from\ LabVIEW\ data)$$

$$T_h = Heatsink\ temperature = 36.965285°C\ \ (Obtained\ from\ LabVIEW\ data)$$

$$V_h = Voltage\ to\ heater = 0.921\ V$$

$$C_h = Current\ to\ heater = 5.1252\ A$$

$$P_h = Power\ applied\ to\ heat\ sink = V_h\ x\ C_h = 0.921\ V\ x\ 5.1252\ A \cong 4.72\ W$$

$$\boldsymbol{R_{th} = Thermal\ resistance\ \left(\frac{°C}{W}\right) = \frac{T_r}{P_h} = \frac{14.2°C.}{4.72\ W} \cong 3.01\frac{°C}{W}}$$

The power supply measurement is accurate to three significant figures, so for a reasonable accuracy value, the measurement is the least accuracy is computed for the final result, which is the thermal resistance. In practical individual lab experiments, this value is accurate as one can obtain. If the student performs this experiment a few more times with different heat sinks and power resistor values, he or she can intuitively guess the power handling capacity of a heat sink by observing the shape/package and the manufacture's datasheets. Few manufacturers actually provide all the important temperature rise information in their datasheets.

THERMAL AND MECHANICAL SPECIFICATIONS							
PARAMETER	SYMBOL	TEST CONDITIONS	1N1183	1N3765	1N1183A	1N2128A	UNITS
Maximum operating case temperature range	T_C		- 65 to 190 (1)		- 65 to 200		°C
Maximum storage temperature range	T_{Stg}		- 65 to 175 (1)		- 65 to 200		
Maximum internal thermal resistance, junction to case	R_{thJC}	DC operation	1.00 (1)		1.1 (1)	0.65 (1)	°C/W
Thermal resistance, case to sink	R_{thCS}	Mounting surface, smooth, flat and greased	0.25				

Figure 21: The 1N1183 power diode datasheet heat-sink specs.

The 1N1183 power diode has an internal thermal resistance given by the datasheet, so the true thermal resistance of the heat-sink is $2.76\frac{°C}{W}$ from subtracting $0.25\ \frac{°C}{W}$ from the calculated answer above. If the designer includes the internal thermal resistance from junction to case added with the thermal resistance from case to sink, the resulting heat-sink thermal resistance is given as $3.01 - 1.25 = 1.76\ \frac{°C}{W}$.

Thermal Time Constant Calculation:

The NI-DAQ 8008 can be set up to generate the time versus temperature data. A good measurement of thermal time-constant is choose two temperatures that correspond when $\tau = 1$ and $\tau = 2$ using the LabVIEW measurement file. Using the steady state temperature value, we can approximate the time constant at $\tau = 1$ and $\tau = 2$.

The temperature that corresponds to 63.2% value is

$$36.965285\ x\ 0.632\ = 23.362°C$$

Time, Temperature

5.500000, 23.313080

The temperature that corresponds to 86.4% value is

$$36.965285\ x\ 0.864 = 31.938°C$$

Time,Temperature

10.600000, 31.939000

These two temperatures can be compared with other temperatures with the time versus temperature data to find a match with a reasonable time value that gives the thermal time constant.

$\Delta\tau = \tau_2 - \tau_1 =$ 10.60 – 5.50 = 5.10 seconds

Having $\tau_2 = 5$ would not be suitable value to use for thermal time constant since five time constants is considered steady state time (99.3%). The slope at this point is flat. To model the exponential curve, the two temperatures have to be picked at two time constants at steep enough slopes to temperatures versus time data. The thermal time constant mentioned in the datasheet may be inaccurate since the thermistor assembly is tested from ambient room temperature 25°C to 5°C in still water, which is different from ambient temperature to a higher temperature of a heat sink. Water has one of the highest specific heat constants, and also covers the entire contact area of the thermistor unlike the temperature measurement of a heat sink.

Conclusion:

In designing the thermistor measurement system, the designer had multiple methods of conducting the experiment. The system could have been powered using 5V from the NI 6008 DAQ or the ±6 V and ±25 V binding posts of the linear power supply; moreover, the semiconductor/heat-sink pair could be measured with the ±6 V and ±25 V supplies, respectively pumping high current or high voltage (e3631a ±6 V with 5 A max, ±25 V with 1 A max). As an extension of the experiment, the designer could have tested different values of power resistors Despite the misleading prestige of using high quality of measuring instruments such as the Agilent DC linear power supply, DMV, and the NI DAQ 6008, these instruments are not perfect. The design engineer has to account for internal input impedances, power supply fluctuations, loading, and noise considerations and calculations would have affected the collected LabVIEW temperature and voltage measurements.

In computing the time constant at τ =1 and τ = 2, the value of 5 seconds seem small for since the datasheet specified a longer time constant when the thermistor is exposed to air than water. One might assume the difference between two time constants $\tau_{n=1,2,3,..}$ will not yield consistently the same approximate time constant because of the exponential rate at different intervals of the curve. Another factor would be the actual heat-up time in which the steady-state measurements were acquired. For example, I left my heat sink powered by the power supply for an hour and a half, with only a couple degrees increase in temperature to oscillate from 35-37 degrees. From the results, the “ripples” in the exponential decay curve is due to noise contributions from the circuit, lab test equipment, and ADC quantization noise that at the time the designer did not account for, which serves as real-life non-idealities when building a system. Leakages of thermal conductance are emitted by the heat-sink under test, the power supply’s heat sink, and the thermistor circuit itself from exposure of the experimented heat-sink.

Improvements:

Analog Input Modes and Signal Sources (ADC Errors)

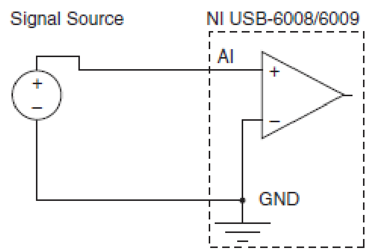
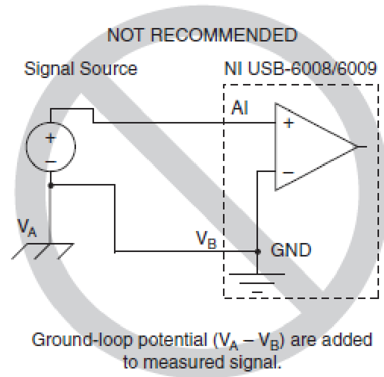
Referenced Single-Ended (RSE)		

Figure 22: Analog Input Configurations: On the left is a floating signaling source (unconnected ground) and on the right is the ground referenced signal source. A differential mode exists as well, though we are just using a voltage buffer in which the signal feeds into one input.

In the NI DAQ 6008/6009 User Guide, different analog input configurations affect its measurement performance of the signal source entering the ADC channel. Since the experiment used a single-ended signal input voltage buffer, more electrostatic and magnetic noise couples into the signal connections than differential input modes. Magnetic coupling is proportional to the area between two conductors. Electrical coupling is related to how much the electric field differs between two conductors. Concerning the caution sign from the figure above, the designer should be aware of not using the referenced single-ended connections with ground referenced signal source. The fundamental problem lies in the difference in ground potential between two instruments connected to the same assembly power system (typically 1mV-100mV), which can be much higher if power distribution circuits are improperly connected. The potential difference (voltage) of the two grounds can appear/contribute as a measurement error.

<u>Noise Filtering Technique</u>

Since regular bypass filtering capacitors cannot fully minimize the effect of noise in the circuit, an anti-aliasing filter (Nyquist filter) composed of a series resistor and parallel capacitor can be coupled into the input of the buffer op-amp to attenuate any frequency content > $f_s/_2$.

We are given from the LabVIEW DAQ Assistant of one sample per second (10 samples/10 Hz), so that accounts to time constant $\tau = 2$ sec, and choosing R_s and C_p to satisfy that relationship. (Analog to Digital Conversions Lecture Notes 02/22/13) To keep the resistor choice within reasonable, choose $R_s = 2\ k\Omega$ and $C_p = 1000\ \mu F$.

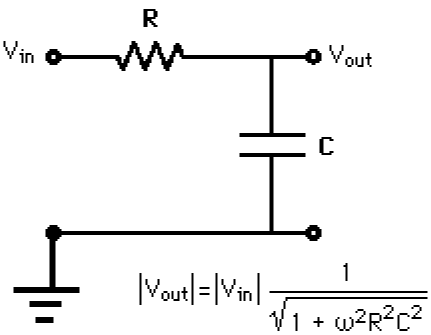


Figure 23: Simple low pass filter placed in between the output of the voltage divider and the voltage buffer. The frequency f is dependent on what frequencies the designer wishes to filter out.

<u>LabVIEW Options</u>

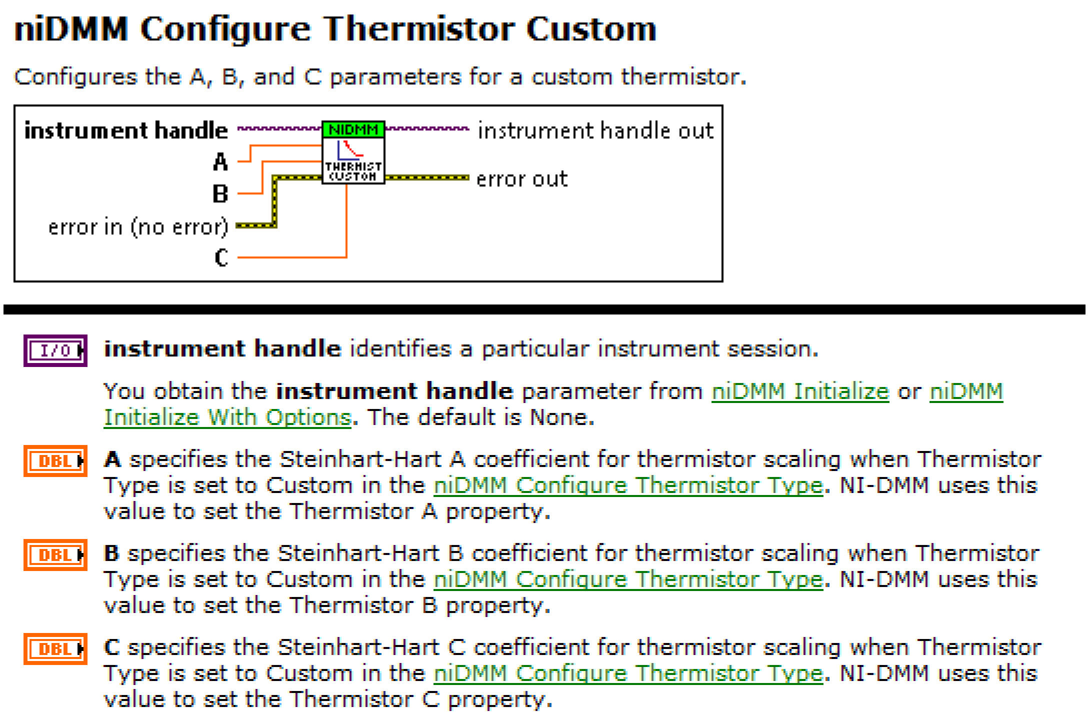


Figure 24: Help screen for thermistor module from the Controls/Function toolbars.

In the search of looking for simpler LabVIEW tutorials perform data acquisition, this VI block was found specifically for temperature measurements through the Express subcategory. Since the block abstracts much of details of the experiment and ineptness with LabVIEW, it is left as another possibility for a more experienced LabVIEW user to play with. While I was able to procure real time data values for time versus temperature, the waveform chart kept re-plotting each individual value rather than tracing a continuous graph with increasing time x-axis values. Despite taking out the waveform chart out of the while loop box (the cause), I was not able to obtain the results from LabVIEW in traced out graphical format.

APPENDIX:

Works Cited

General Information:

http://en.wikipedia.org/wiki/Signal_conditioning

Handbook of Modern Sensors, Jacob Fraden; Chapter 16, Chapter 3

http://www.allaboutcircuits.com/vol_3/chpt_8/9.html

Manufacturer's App Notes:
http://www.youtube.com/watch?v=rFp44PgtX8Q

LabVIEW thermistor examples (white papers, tutorials)

http://www.youtube.com/watch?v=7znlYLkk-mw

http://www.onsemi.com/pub_link/Collateral/TND392.PDF

http://books.google.com/books?id=I9XRU9mtBeoC&pg=PA190&lpg=PA190&dq=measuring+thermal+resistance+LabVIEW&source=bl&ots=knZwPM7yIY&sig=EvfSs3-HoTH9a8-XzWKRNQy7cmI&hl=en&sa=X&ei=rPcsUaujIarIiwLInIHACQ&ved=0CEEQ6AEwAjgU#v=onepage&q=measuring%20thermal%20resistance%20LabVIEW&f=false

http://multimechatronics.com/images/uploads/mech_n/Thermal_Systems_&_Thermal_System_Investigation.pdf

http://www.maximintegrated.com/app-notes/index.mvp/id/817

http://www.ni.com/white-paper/4513/en

MATLAB Code: Steinhart-Hart Equation

```
%% Declared Variables

%% Operating Point #1
R1 = 32060;
T1 = 273.15;

%% Operating Point #2
R2 = 10500;
T2 = 296.15;

%% Operating Point #3
R3 = 2882;
T3 = 329.15;

%% Coefficient Relationships
```

```
L1 = log(R1);
L2 = log(R2);
L3 = log(R3);

Y1 = (1/T1);
Y2 = (1/T2);
Y3 = (1/T3);

g2 = ((Y2 - Y1)/(L2 - L1));
g3 = ((Y3 - Y1)/(L3 - L1));

%% Experimentally-Derived Coefficients

C = ((g3-g2)/(L3-L1))*((L1 + L2 + L3)^(-1))
B = g2 - C*((L1^2) + (L1*L2) + (L2^2))
A = Y1 - (B + (L1^2)*C)*L1

%% Completed Steinhart Hart Equation

R = 1000:1000:32000;
T = (A + B*log(R) + C*(log(R).^3)).^(-1);
C = T - 273.15;
plot (R, C, 'r');
xlabel('Temperuature (C)');
ylabel('Resistance (Ohms)');
title('NTC 10kohm thermistor resistance versus temperature');
```

MATLAB Code: Steinhart-Hart Equation

```
load CMPE167_Lab2.dat;
time = CMPE167_Lab2(:,1);
temperature = CMPE167_Lab2(:,2);
plot(time,temperature, 'o');
xlabel('time [s]');
ylabel('temperature degrees C ');
title('Temperature rise');
fit1 = polyfit(CMPE167_Lab2(:,1),CMPE167_Lab2(:,2), 1)

fit1 =

  1.0e+005 *

   -0.0194    1.7286

 %%Fitting Exponential Curves
 fit = polyfit(time, log(temperature), 1)

 %%%Output%%%
%%fit =
%%
%%   -0.0406   10.6203

semilogy(time, temperature, '-', time, exp(fit(2)).*exp(fit(1)*time))
```