LAB 2
CMPE167
The Steady-State Shuffle

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1 Objective

2 Thermistors Fundamentals Review

There are many methods of sensing and calculating temperature with a thermistor. To help understand the design decisions behind the data acquisition equipment in this lab a brief review of the requisite material is as follows.

2.1 Thermistors

Most simply, the thermistor can be described as a non-linear active sensor which acts as a resistor whose impedance varies with temperature. More specifically, thermistors are either NTC (negative temperature coefficient – resistance goes up as temperature goes down) or PTC (positive temperature coefficient – resistance goes up as temperature goes up).

2.1.1 Non-linearity

While the thermistor is more linear device than an RTD or a thermocouple, its non-linearity is non-negligible and needs to be rectified in temperature sensing applications for it to be useful. Linearization can be achieved either through hardware or through software.

Post-processing of digitized non-linear data can be achieved either through the use of a look-up table, or through the use of some polynomial approximations. The method of polynomial approximation for linearization is usually achieved with the Steinhart-Hart equation:

$$T = \frac{1}{A_0 + A_1(ln(R_T)) + A_3(ln(R_T)^3)}$$

$$ln(R_T) = B_0 + \frac{B_1}{T} + \frac{B_3}{T_3}$$

Where T is the temperature of the thermistor in degrees Kelvin and $A_0, A_1, A_3, B_0, B_1, B_2$ are constants provided by the manufacturer of the thermistor, or calibration values obtained through individual testing of resistance at three temperatures with a large absolute difference between them. In practice, if implemented properly, this equation will yield a maximum accuracy of +/- .1 degree celsius across the entire temperature range on top of the error already inherent in a design.

Another equation useful in the linearization of a thermistor is Jacob Fraden's model:

$$\beta_m = \frac{log(R1/R0))}{\frac{1}{t1} - \frac{1}{t0}}$$

$$\beta_x = \frac{log(Rc/Rb)}{\frac{1}{Tc} - \frac{1}{Tb}}$$

$$\beta_y = \frac{log(Ra/Rb)}{\frac{1}{Ta} - \frac{1}{Tb}}$$

$$\gamma = (\frac{\beta_x}{\beta_y} - 1) * \frac{1}{(Tc - Ta)}$$

$$T = \frac{\frac{1}{t0} + log(\frac{R}{r0})}{\beta_m * (1 - \gamma .* (t1 - (1/t0 + log(R/r0)/Beta_m)^{-1})}^{-1}$$

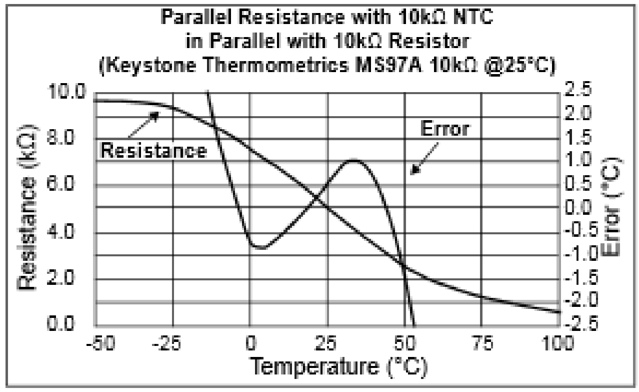

Figure 1: Error vs. resistance for a parallel linearization.

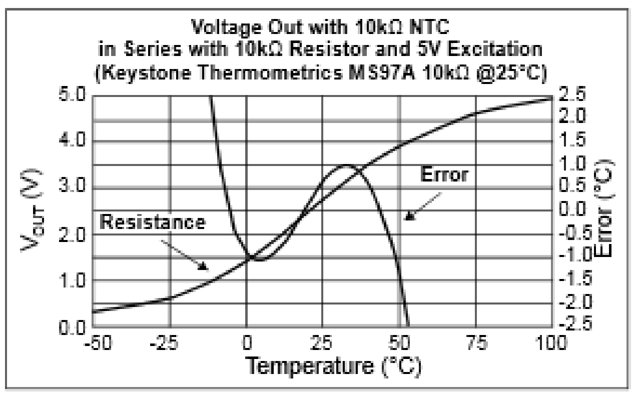

Figure 2: Error vs. resistance for a series linearization.

Fraden's model takes two measured resistances at certain temperatures as well as three characterizing resistances provided by the device manufacturer to create a model which is slightly more accurate than the steinhart model.

For applications where post-processing is not an option, hardware linearization can be implemented in most temperature sensing circuits with the addition of only one resistor. Two commom methods of hardware linearization include a reisitor in parallel with the thermistor or a resistor in series with the resistor. Figures 1 and 2[1] depict the relationship between error and resistance over temperature. In the series parallization the left Y-axis is shown as a voltage, this is due to the series resistor creating a voltage divider.

2.1.2 Voltage Versus Current Operation

When a thermistor is operated in a steady state self-heating condition, where a certain constant power is dissappated over the thermistor, it can be applied as a flow meter. As

[1]Microchip AN685 - Thermistors in Single Supply Temperature Sensing Circuits - Page 5

the thermistor reaches steady-state in an environment where the thermal resistance between the case of the thermistor and the ambient air remains constant, as the thermal resistance changes as a result of some change in the system, e.g. greater air flow, so too does the temperature of the thermistor, and thus its resistance.

2.1.3 Resistance Versus Temperature Operation

The most common application of thermistors uses the resistance versus temperature model. As this model requires a minimization of self-heating, the RVT setup is usually used in applications where the precision and accuraccy of the measurement is paramount.

Minimization of self-heating can be achieved by best approximating a mode of operation in which there is no power disappated across the thermistor as a result of excitation. As a thermistor is a resistive element, some current excitation is required to operate a thermistor, to emulate a zero-power operation mode the amount of power disappated across the device as a result of current excitation must not exceed the power dissipation capability of the thermistor's package.

2.1.4 Current Over Time Operation

The dissipation constant of a thermistor package and its thermal mass create a device whose resistance will start to decrease over time given a continuous current. This slow change in resistance adds a time delay to the amount of current passed through a circuit which can act as a very slow low-pass. Applications of such an implementation can be used in any circuit requiring a time-delayed current, e.g. relays to prevent false trigger events, rush current limiting, and surge protection.

3 Method

3.1 Schematic and Suggested Board Layout

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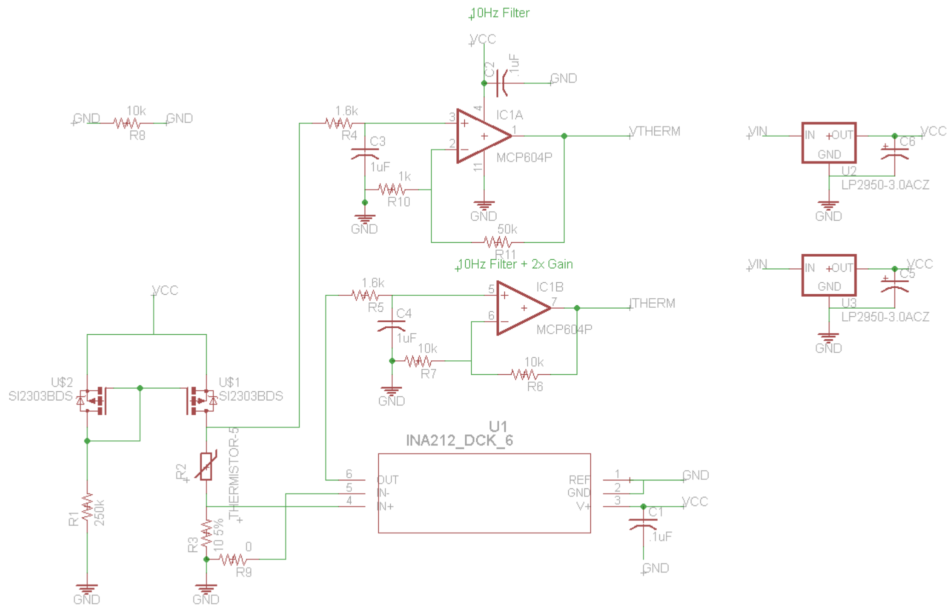

Figure 3: Resistance and Current Signal Conditioning/Anti-Aliasing

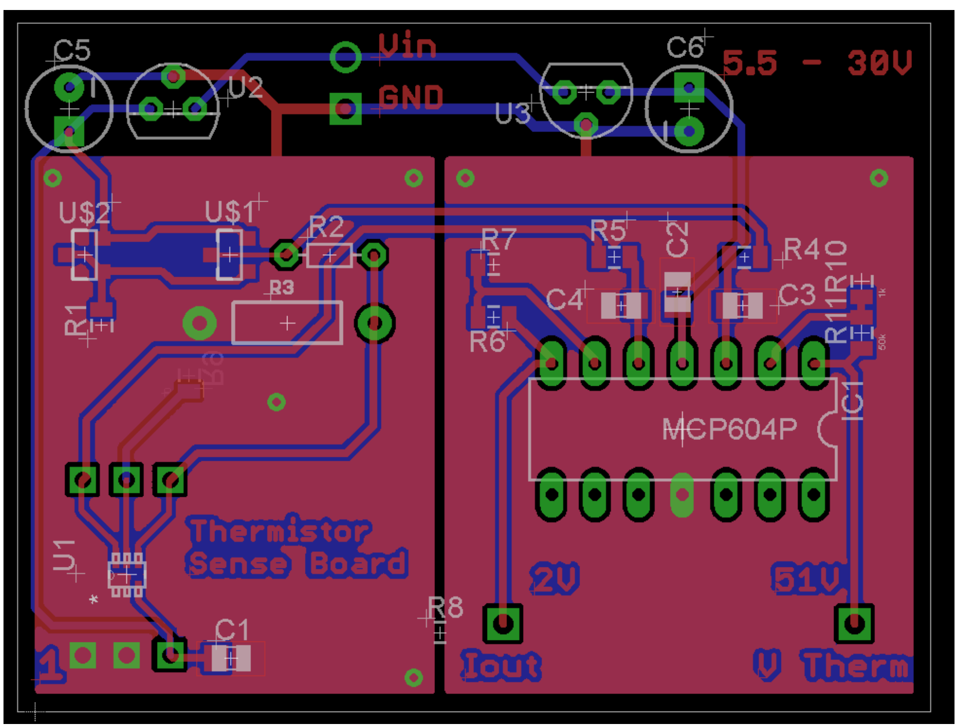

Figure 4: Board layout used.

3.2 Design Considerations

Originally the design of this board was going to incorporate both analog and digital components, thus stuandard mixed signal design was used as the basis of the design with the thought that a modifications to the design including a digital component would be made easier; the two LDOs and split ground planes were included for that reason.

As the application of this circuit would include the calculation of the thermal resistance of a heat-sink, use of the RVT setup described in section 2.1.3 of this report made the most sense to implement. Using an RVT setup meant that a zero-power state would have to be best approximated, to do so, the total power through the thermistor would have to be limited to well under 1mW. This was achieved through the use of a constant current source set to 25μA.

In using a constant current source with a current shunt for post-processing temperature stability correction, and reading the voltage of the node above the thermistor, the resistance of the thermistor could be found for every time step without the addition of high degrees of error across the entire range of the thermistor inherent in the voltage divider design described in Figure 2.

As the constant current source will vary the voltage potential at the node just above the thermistor to maintain constant current, and that the thermistor changes in resistance as the system, the amount of power disappated through the resistor is not constant over the entire temperature range of the system. Analytically, using ohm's law to calculate the voltage drop across a resistance, this voltage should range from .17v at room temperature to .31v at the 50 degrees celsius, meaning that the power disappated through the resistor, given a constant current, should vary between $\tilde{8}1\mu$W to $\tilde{4}4\mu$W, well within the zero-power approximation requirement.

3.2.1 Constant Current Source

While there are many different forms of constant current sources, a current mirror was used due to its simplicity. While in most practical applications a current mirror can be approximated as having no frequency limitations, and has no sensitivity to heat or power-supply fluctuations, this is of-course not true. As a current sensor was going to be used on the low side of the sensor to evaluate how much current was flowing at every time-step, its temperature instability could be ignored. Additionally, as the bandwidth requirement of the sensor is practically DC, frequency limitations due to parasitic capacitances of the transistors can be ignored.

3.2.2 Current Sensor

A 10 Ohm current shunt on the low side of the thermistor feeds into a bi-directional current sensor with a practical gain of 1000V/V, +/- 1%. The current shunt itself is a high-quality differential op-amp with internal precision laser-trimmed resistors which has been tested to adhere to its specifications, a requirement if it is to be used as a reference for reading corrections in this lab.

The INA212 Datasheet provides the following equation as a way of determining the relative accuracy of the amplified value as a function of the gain-error, internal op-amp noise, and shunt resistance:

$$ErrorFactor = \frac{5000}{(17 * R_s) + 5000}$$

When R_s is set to 10 Ohms +/- 5% the error factor becomes 1.6% in the worst case. This means that given a current of 25μA, the expected value can be 216nA +/- the actual read value, which leads to a change in resistance, given a voltage of .250 above the thermistor of +/- 80 Ohms around 10k. At 10k, $\tilde{5}00$ ohms constitues 1 degree celsius, which means that the error factor introduced adds a +/- temperature accuraccy error of +/- .16 degrees celsius.

3.3 Data Acquisistion

As the system will be sampled at 10Hz, an anti-aliasing filter with an fc of 10Hz was implemented on both the current and voltage output. The current and thermistor-high side voltage readings were given a gain of 2 and 5.1 to make better use of the full range of the DAQ's ADC module.

To help reduce the amount of error in the final thermal resistance calculations, the thermal mass was supported by aerogel blocks such that no thermal conduction would occur to nearby objects as a result of direct contact.

3.4 Thermistor Calibration

As all thermistors need to be calibrated before use with linearization equations, three temperature baths were prepared with measured temperatures of .3 degrees C, 23.6 degrees C, and 79.2 degrees C. At these temperatures the thermistor read 32.7kΩ, 10.91kΩ, and 1.31kΩ.

3.5 Thermal Resistance Calculation

Part of the lab requirements are to use a thermistor to determine the thermal resistance of a heatsink. In using a power resistor in the thermal circuit, the thermal resistivity of the junction to the case of the resistor can be ignored as I know that at the case, 7.5 watts is being dissipated. To attempt to reduce the amount of heat being dissipated by the entire resistor into the ambient air, all sides of the resistor not in contact with the heat-sink through thermal paste were covered by a thin layer of fiberglass insulation.

Using the thermal resistivity of the thermal grease given on the bottle of the Thermalcote II bottle, .00167 $\frac{\frac{cal}{s}}{\frac{cm}{C}}$ and converting it to watts per cm per degree celsius gives a thermal resistance of .007 between the case of the power resistor and the heatsink.

Finally, once steady state is reached, the thermal resistivity of the heatsink can be found using:

$$\frac{\Delta T_{C-A}}{Power_{in}} = \Theta_g + \Theta_{hs} \text{ and, } \frac{T_c - T_{hs}}{Power_{in}} = \Theta_g$$

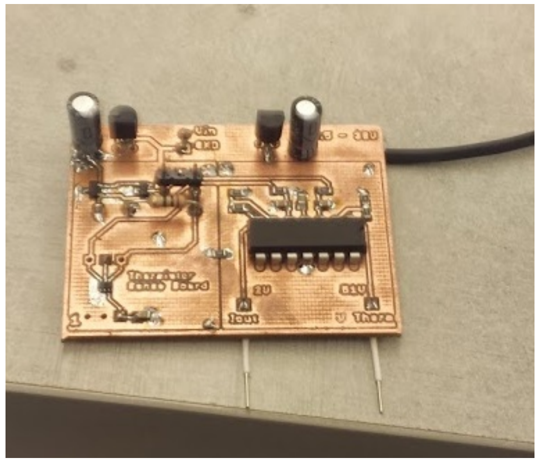

Figure 5: Completed thermistor driver board.

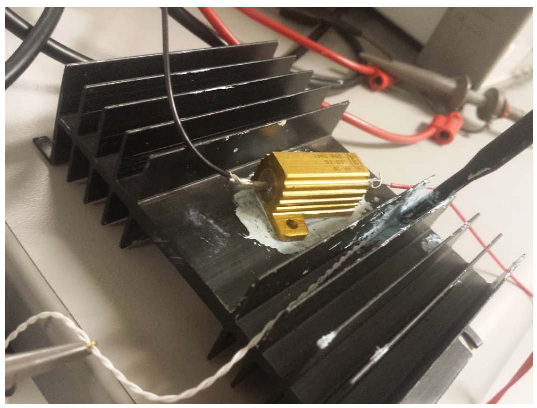

Figure 6: Heatsink with 7.5W power source without aerogel or power-resistor insulation

4 Experimental Results

4.1 Experimental Setup

During the construction of the board I had used the wrong component values creating a voltage gain of 51 instead of 5.1 on one of the op-amps, saturating the output continuously. This was a simple mistake rectified by a simple fix consisting of replacing a single resistor.

Figure 5 depicts the completed thermistor driver and signal conditioning board. Figure 6 shows the heatsink heating setup without the aerogel and power resistor insulation jacket used to get more accurate thermal resistivity results.

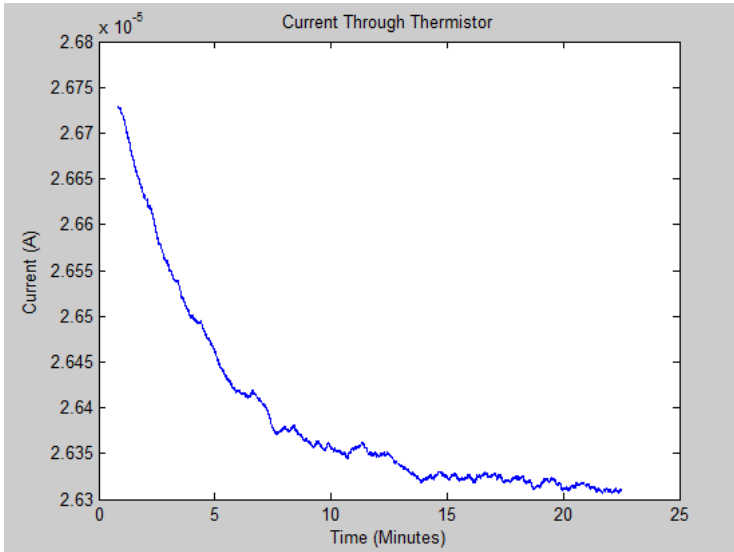

Figure 7: Completed thermistor driver board.

4.2 Stability of Constant Current Source

It's interesting to note that over the course of the experiment, the current mirror's output current through the thermistor did actually change by 4μV, a non-trivial change which would have lead to an innaccuracy of +/- 2.7 degrees celsius if it hadn't been wrapped into the final temperature calculations.

4.3 Temperature of Thermistor

After waiting two hours to ensure that the heatsink had reached steady-state, the power resistor was removed from the heatsink and voltage/current data began to be acquired. After scaling the voltage and current values to determine the resistance of the thermistor, the normalized resistance was converted into a plot of the temperature using the Steinhart-Hart equation, a simple model, and Fraden's equation. The plot of these temperatures can be found in figure 8.

It's interesting to note that the steinhart-hart, and Fraden models don't differ that much, suggesting that the actual computed resistance curve is close to what the manufacturer described, and that the calibration points were accurately measured.

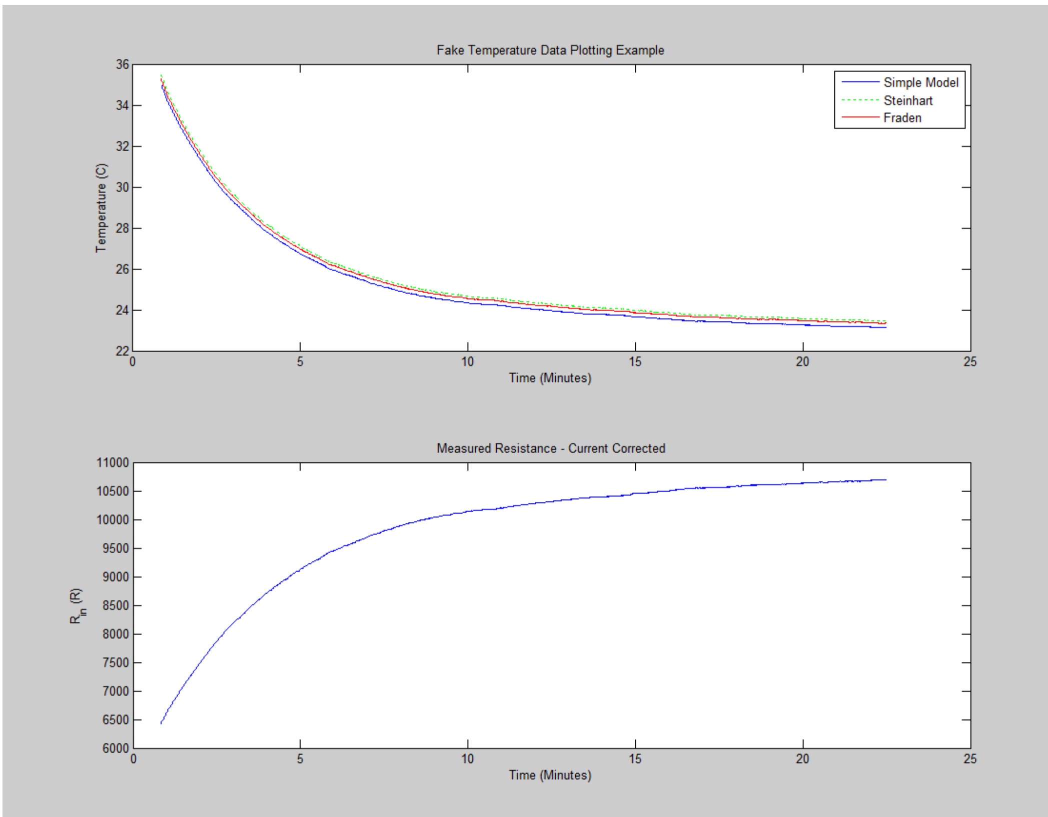

Figure 8: Resistance, and temperature according to the simple, Fraden, and Steinhart-Hart models.

4.4 Thermal Resistance of Heatsink and Time Constant

In using the steady state, and ambient temperature derived from the temperature models used in section 4.3 of this report (35.7 degrees C and 23.3 degrees C), it is now possible to determine the thermal resistance of the heatsink used in this experiment. Applying these two values into the equations described in section 3.5 of this report, we find that the temperature of the case of the power resistor is equal to 35.7525 degrees celsius, and thus Θ_{hs} is equal to 1.6533 watts per cm per degree celsius.

Finding the thermal time constant of the heatsink requires the analysis of data between two points where the change in temperature is large enough to get an accurate result. This is best done by calculating how long it takes to reach $\tilde{6}3.2\%$ of its maximum value. Using matlab to analytically to determine the index of the 63.2% point yielded a time constant of 4.436 minutes.

5 Conclusion

While analyitically this system should produce an accuracy of +/- .26 degrees Celsius when using the Steinhart-Hart model, other sources of error, e.g. heat loss due to conduction through aerogel and power-resistor going directly to ambient air, improper calibration., the system may actually be less accuarate. Most important to note is the fact that all of the data seen depicted in this lab report and most of my peer's lab reports are invalid as one of the calibration points used for our thermistor is above 70 degrees celsius, and to quote the MA100GG103C datasheet, "Best overall stability is maintained when the exposure and storage temperatures do not exceed 70 degrees celsius." That being said, this lab has been a great excercise in developing a system using non-linear sensing elements and has been good practice in analytically determining unknowns in thermal circuits.