Characterizing The Thermistor Using The Arduino UNO

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Abstract

A complete characterization of a thermistor was obtained. The values for the relationship between temperature as a function of resistance given by Steinhart equation, the thermal time constant, and the Heat capacity of the thermistor were successfully obtained and all agreed within error with the values provided by the manufacturer of the thermistor. Finally the heat capacity of an aluminium block as obtained using the characterized thermistor.

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1 Introduction

Accurate temperature measurements underpin many modern experiments and industrial applications. Serial sensors, thermal analog sensors, and thermistors are broadly used in industry and elsewhere, based on individual benefits and drawbacks. Thermistors, being rugged, reliable and most inexpensive, become of certain interest in a simple laboratory setting. A thermistor is a type of resistor whose resistance varies significantly with temperature. Technically, all resistors vary with temperature, but thermistors are constructed using a semiconductor with a resistivity that is particularly sensitive to temperature [1]. Accordingly, thermistors are widely used as temperature sensors, but also as current limiters, self-resetting overcurrent protectors, and self-regulating heating elements. Depending on which purpose one has in mind, there is a choice of two broad types of thermistors, Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC) thermistors. In an NTC thermistor, the environment temperature and resistance of the thermistor are negatively correlated, whereas in the PTC thermistor the correlation is positive. The former is mostly used in temperature sensing, and the latter for electric current control.

Since the input pins of the Arduino can only measure voltage, one cannot directly use it to measure the electrical resistance of a thermistor. Instead, we must find some voltage measurement that will give the resistance for free. One such method is to convert the varying resistance of the thermistor to a voltage via a voltage divider circuit. The voltage divider uses two resistors in a circuit of a known voltage to create a mathematically predictable voltage value. In the following experiment, we will use the Arduino and the above techniques to fully characterize a $10K\Omega$ NTC thermistor in order to test its role as a temperature sensor. In particular, we will use the thermistor to measure the heat capacity of a system.

2 Theory

2.1 NTC Thermistor

NTC thermistors are made from different kinds of metal oxides. Common metals are magnesium, nickel, copper, and iron. The oxides are semiconductors with a resistivity that decreases with temperature. As the temperature of the contained semiconductor rises, the number of active charge carriers increases, resulting in an increase in resistance.

This flexibility allows thermistors to be used in a variety of applications, including voltage regulation, temperature sensing, and circuit protection. As temperature sensors, they have many advantages over digital sensor chips or thermocouples. NTC thermistors are an order of magnitude more sensitive than other temperature resistors[2]. This is in fact one of the main advantages of NTC thermistors. They are also exceptionally cheap, will work at any voltage, rather than having to be in the 3/5V logical range, and they do not require an amplifie as a thermocouple otherwise would. The main disadvantage of thermistors manifests in their smaller operating range, having high precision only within a temperature range of 200° K.

Thermistors are characterized by many different parameters. The most important of which which include the dissipation constant, the thermal time constant and the heat capacity.

2.2 Temperature Dependence Of The Thermisor

In the most simple linear approximation, the resistance change with respect to temperature is given by:

$$\Delta R = k\Delta T \tag{1}$$

where ΔR is the change in thermistor resistance, ΔT is the corresponding change in temperature, and k is a proportionality constant of first order [?]. This is, however, a relatively poor approximation outside of a very specific temperature range. The Steinhart-Hart equation gives a third-order approximation that is predictive over a much wider temperature range:

$$\frac{1}{T} = a + b\ln(R) + c(\ln(R))^3 \tag{2}$$

where a, b, c are the Steinhart-Hart coefficients [?]. There is a second-order term in the approximation, though it is generally neglected as its effect is largely diminished by the other more dominating terms in the equation. By using a voltage divider, it is easy to measure the thermistor resistance R and hence, using 2, obtain the temperature of the resistor.

2.3 Heat-Transfer

From conservation of energy:

External energy added = Energy absorbed+ Energy dissipated

Some of the external energy supplied is absorbed by the NTC thermistor which raises its temperature. The rest of the energy is dissipated to the surroundings via radiation, or conduction. By the heat transfer equation, then:[2]

$$P = C_{th}\frac{dT}{dt} + \delta_{th}(T - T_a) \tag{3}$$

Where, P, is the power supplied externally to the thermistor, (normally given by $P = I^2R = VI$). C_{th} is the heat capacity of the thermistor, Σ_{th} is the dissipation factor, T is the thermistor temperature, and T_a is the ambient temperature. Formally, the two factors are defined as follows.

2.3.1 Heat Capacity Factor

This is the amount of heat required to raise the NTC thermistor's body by 1 Kelvin. Values are normally in the range 20-250 mJ/K [3]

2.3.2 Dissipation Factor

This is the power the thermistor must dissipate in order to raise its body temperature by 1K, normally measured in units of W/k. Thermal equilibrium is assumed so that $\frac{dT}{dt}$ in equation (1) is 0, and thus $P = \delta_{th}(T - T_a)$.[4]

While the heat capacity of a thermistor is a property of the thermistor material, the dissipation factor is not constant. In a aqeuous environment the thermistor has a higher dissipation factor than the thermistor in air, since water conducts heat more effectively.

2.4 Thermal Time Constant

The time constant is the time, in seconds, required for the thermistor to change through 63.2% of the difference between its initial and final body temperatures, when subjected to a step change in temperature under Zero-Power conditions. [3]. Zero-Power conditions is a term that is often encountered in NTC thermistor literature. When current flows through the NTC thermistor, it self-heats, which in turn changes the resistance. When this change is of negligble extent, the thermistor is said to be in Zero-Power condition. Using the Zero-Power condition and equation (1):

$$\frac{dT}{dt} = \frac{(T - T_a)}{\tau} \tag{4}$$

where,

$$\tau = \frac{C_{th}}{\delta_{th}} \tag{5}$$

τ is called the thermal time constant of the thermistor. The term is derived from assuming the zero-power condition and an initial temperature for the thermistor, T_i. Using these assumptions one could solve the ODE presented by Equation 4 and obtain[1]:

$$T = T_A + (T_i - T_A)e^{-\frac{t}{\tau}} \tag{6}$$

Accordingly, the larger the ratio $\frac{t}{\tau}$ is the longer it takes for the thermistor to reach thermal equilibrium when it is subject to a sudden change in temperature. Since $e^{-1} = 0.3679$, the thermal time constant is also the time required for the thermistor's temperature to reach $1 - 0.3679 = 0.6321 = 63.2\%$ of its final value.

[1]This equation is a special case of Newton's Law of Cooling

2.5 Heat Capacity

Heat capacity is the measurable physical quantity of heat energy required to change the temperature of an object by 1 Kelvin. The heat capacity can be obtained by combining Equation 4 and Equation 7, and the definition of the time constant in terms of the heat capacity and the dissipation factor.

If the body is allowed to come to equilibrium with the environment given the power provided [2], the term, $\frac{dT}{dt}$ is 0, since the temperature remains constant at equilibrium. Equation 4 then becomes:

$$P = \delta_{Body} \cdot (T_{Equi} - T_A)$$
$$\delta_{Body} = \frac{P}{(T_{Equi} - T_A)} \tag{7}$$

Where, T_{Equi} the temperature at which the body reaches equilibirum given that external power, and T_A is the ambient temperature of the room.

Lastly, from a cooling curve, one can use Newton's Cooling Law given by Equation 4, and obtain a value for the time constant, τ.

The heat capacity is then easily computed by combining Equations 6 and Equation 8:

$$C_{Body} = \tau \cdot \frac{P}{(T_{Equi} - T_A)} \tag{8}$$

3 Experimental Methods

The apparatus 1. The experiment contained three sections: The calibration of the thermistor in order to obtain temperature values, using the thermistor as a temperature sensor to determine the value for the heat capacity of an aluminium block, and lastly, determining the thermal time constant of the thermistor.

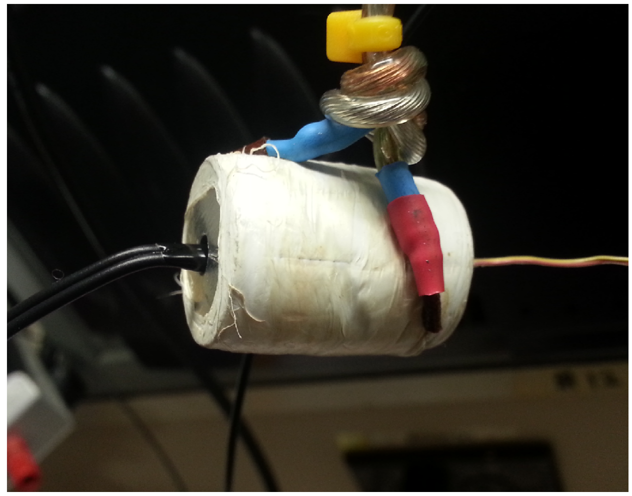

Figure 1: Experimental apparatus. The thermistor is the black PVC tube on the left, the thermocouple is on the right, and the power supply is connected to the cables wrapped around the aluminum block in white.

3.1 Resistance Measurement

In order to obtain a value of the resistance the voltage divider is necessary since the Arduino only deals with voltage values through the ADC pins. The equation relating the ADC values and the Arduino resistance values is:

$$R_t = \frac{R}{(\frac{1023}{ADC} - 1)} \tag{9}$$

Where R_t is the thermistor value, R is the fixed resistor, and 1023 is the maximum ADC pin value. Every value recorded as a resistance was the mean of 80 measurements given by the arduino, this way the discretization and the error of measurement was decreased.

3.2 Thermistor Temperature Calibration

In order to use the thermistor to measure temperature, the coefficients in Equation 2 are to be determined. The aluminium block was used to provide a change of temperature for the thermistor (inside which the thermistor was placed), along with a thermocouple used as a thermometer. Different values for the temperature and the resistance were obtained through the thermocouple and the voltage divider circuit respectively.

[2] Normally the power is given by $P = I^2R = VI$, where V and I are specific to the power source

3.3 Estimating Heat Capacity

The estimation of heat capacity depends on the system and its environment, and is characterized from allowing the system to cool in constant room temperature from various starting temperatures. Given a constant influx of power, the system will eventually stabilize at some temperature at which the heat radiated by the aluminium block is equal to the heat entering the system through the heating coil. It should be noted that this is a rough estimation of the heat capacity; the system is not well isolated.

Constant voltage and corresponding current were supplied to the system using a variable laboratory power supply. Once the aluminium block reached equilibrium, the power supply was turned off, and the block was allowed to cool. Thermistor resistance was measured at a fairly fine resolution, and temperature readings were taken with a thermocouple for comparison.

3.4 Thermal Time Constant

As mentioned previously, the thermal time constant represents the time scale on which the thermistor will reach its appropriate resistance when it changes temperature. To measure this, the thermistor was allowed to reach a stable room temperature. Then, the aluminium block was heated to a stable temperature significantly above room temperature. The resistance response of the thermistor was then measured with respect to time as it was inserted into the heated aluminium block. Data was recorded until the resistance reached a plateau. The thermal time constant is then be computed according to Equation 6.

4 Results

Data acquisition proceeded as outlined above. There were four main data sets obtained: one for the calibration of the Arduino ADC for a constant output of 3.3 V, one simple series data of resistance and temperature for comparison to the relationship expected by the Steinhart-Hart equation, one set of cooling curves for the aluminium block from various starting temperatures, and another measurement of the thermistor response to sudden environment change to determine the thermal time constant. In all cases, reference temperature from the thermocouple was recorded. The arduino ADC calibration was performed to find the ADC pin value. This data may be seen in Figure 2. The temperature/resistance relationship was taken over a reasonably wide temperature range within the limits imposed by the PVC coating and room temperature. This relationship can be seen in Fig. 4. Three stable temperatures $(117.1 \pm 0.1, 96.0 \pm 0.2, 80.3 \pm 0.1)$ were reached from constant applied voltage to the aluminium block, and the block was allowed to cool towards room temperature. These three cooling trials may be seen in Figure 9. Finally, data was taken for the thermistor's response to a change in environment; the thermistor, at room temperature, was inserted into the pre-heated aluminium block, and resistance response was measured over time to determine the time scale of its change in resistance. This data may be seen in Figure 5.

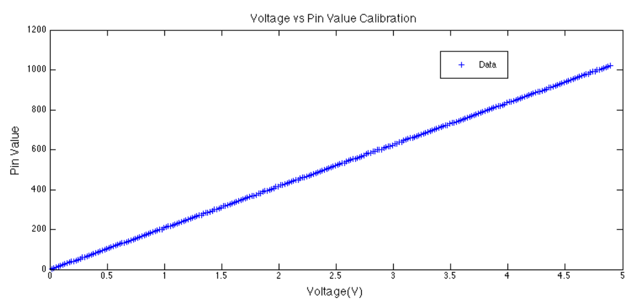

Figure 2: Calibration of ADC1 Pin Values and the Corresponding Voltage

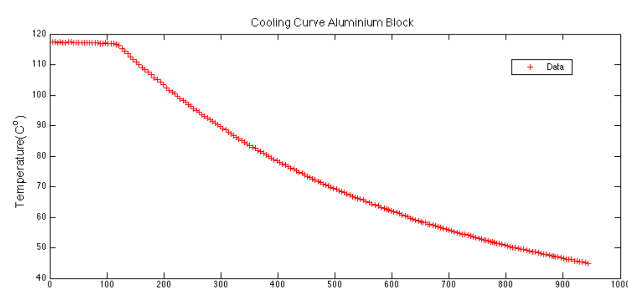

Figure 3: One of the Cooling Curves for the Aluminium Block

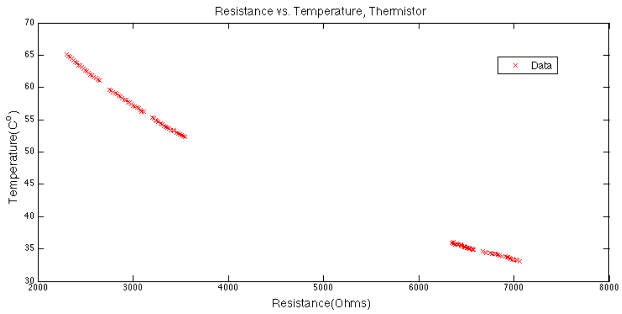

Figure 4: The resistance vs temperature data used for the Steinhart-Hart Equation

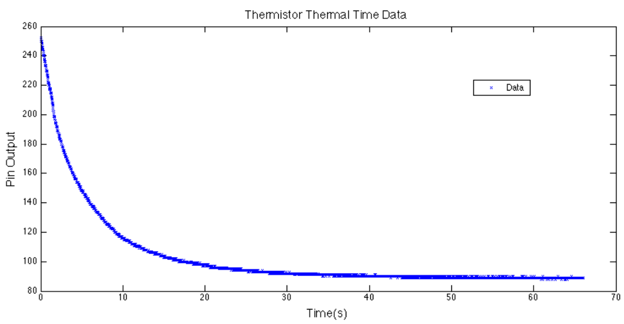

Figure 5: Data used to obtained the thermal time constant of the thermistor

5 Analysis

5.1 Temperature vs Resistance and the Steinhart-Hart Equation

The temperature vs. resistance relation of the thermistor was characterize through Steinhart-Hart equation, Figure 6, shows this relationship along with the model for the data.

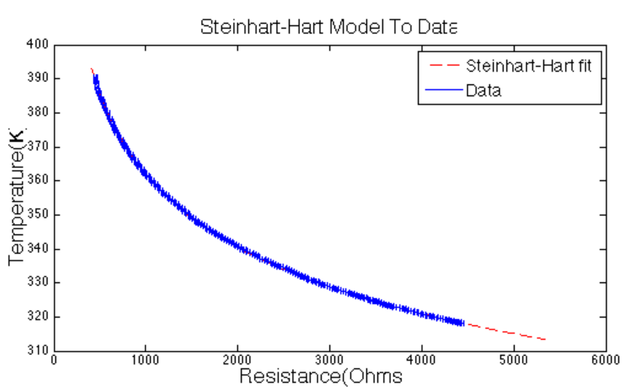

Figure 6: The data obtained was plotted against the Steinhart-Hart fit with error bars

There were different sources of error for the measurement of the resistance. There were three recorded sources of error. The discretization error, the error from the pin values, and the error of temperature from the thermocouple. To reduce the discretization of error eighty measurements for each resistance were recorded, to each of the resistance values the standard deviation of those 80 measurements was found. The other source of error came from Equation 9, the voltage provided by the arduino to the circuit was of 3.3V, the error was characterized from the calibration of pin value vs. voltage which was obtained from the calibration curve of that ADC pin. The χ^2 value obtained for the model was of 0.2372, the error for the data seems to be little overestimated, a reason could be not taking enough values to account for the discretization error.

Parameter	Measured	Tabulated
a	$1.10(3)\times10^{-3}$	$1.2(3)\times10^{-3}$
b	$2.64(5)\times10^{-4}$	$2.679(9)\times10^{-4}$
c	$1.6(3)\times10^{-7}$	$1.16(5)\times10^{-7}$

Table 1: The values of the parameters, for the Steinhart-Hart fit to the data are shown along with their respective errors.

The model obtained from the measured values was then compared to a model made from the values tabulated from the website where the thermistor was bought [6].

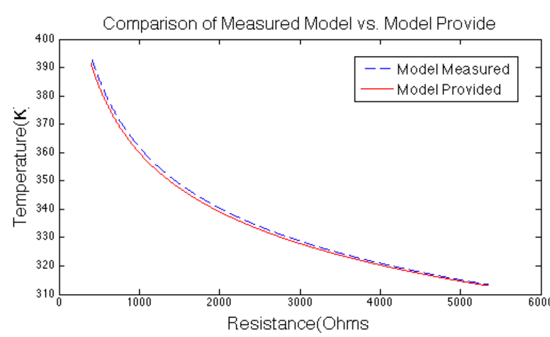

Figure 7: A comparison between the two fits is shown, the parameters in the two models agreed within two sigma

Figure 7. shows the two models plotted together. In Table 1, the values obtained for the

parameters in the Steinhart-Hart equation are shown along with their respective errors. All the parameters are within a 2σ error, which means they were in agreement. [3] There were some possible sources of error, the most prominent seems to be that the thermistor was larger in radius compared to the thermocouple. Which implies the temperature change would reach the thermocouple after it reaches the thermistor. This would explain the discrepancy of the data, as the measured fit seems to be slight shifted upwards (towards a higher temperature). Other sources, such as the air between the block and the thermistor could have affected the readings.

5.2 Thermal Time Constant of the Thermistor

The thermal time constant was obtained as mentioned in the experimental methods. 5000 measurements were obtained, if the pin gave the same values they were then binned together into a single value. Since the values could not be averaged because the heat capacity of the thermistor is low, so the change of temperature was too sudden at certain points, as can be observed in the curve, the error was found by taking the standard deviation of 1000 measurements of the resistance at room temperature. This error was

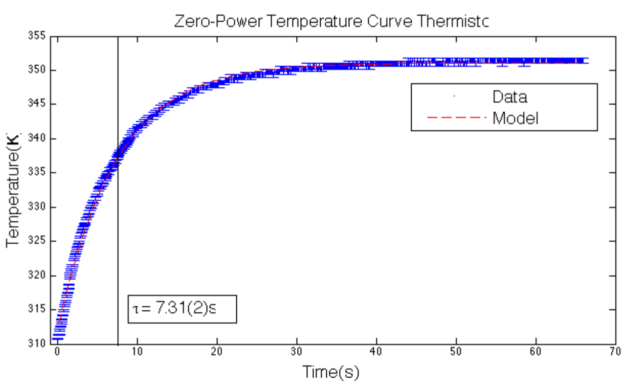

Figure 8: The zero-power temperature curve as a function of time is shown for the thermistor is shown, τ is the value of the thermal time constant, the data is plotted along with the model that best represents the data.

[3]It is assumed that the data provided is accurate and reliable

then propagated using Equation 2. Figure 8 despicts the temperature vs. time relation, this data was modelled by a modification of Equation 6: [4]

$$T(t) = b \cdot e^{-\frac{t}{a}} + c$$

The value of the three parameters was $a = 7.31(2)s$, $b = 38.78(3)K$, and $c = 351.09(2)K$, the parameter c represents the environment temperature, which was the temperature inside the block, as we placed the thermistor inside and waited for it to stabilize, this temperature was 351.8(4)K, which is well within the error, the b values represents the difference in temperature between the initial temperature and the environment temperature, 41.0(4)K, this value is not within the errors present. Lastly the a values, represents the thermal time constant, the given by the manufactorer was <=15 seconds. The result therefore is in agreement with the manufacturer, which means, the thermistor will not lose too much heat to the environment, and can be accurately used by the manufacturer's specifications[5][6].

5.3 Heat Capacity Of The Aluminium Block

The procedure followed to obtain a value of the heat capacity was outline in Section 2.5 and 3.3. As mention the thermal time constant was obtain from the cooling curves, while the dissipation constant was obtain from the measured of the power applied.

Param.	Data Set 1	Data Set 2	Data Set 3
a(K)	111.92(1)	80.1(2)	62.36(1)
τ(s)	497.4(6)	501.8(2)	524.8(3)
c(K)	301.4(2)	301.6(4)	300.0(5)

Table 1: The values of the parameters for the cooling curve fit to the three sets of data

[4]In Equation 6, the thermistor cools down as time progresses, in the data obtained however the thermistor was warming up as time progressed

[5]The manufactorers specified an error of 1% in the resistance

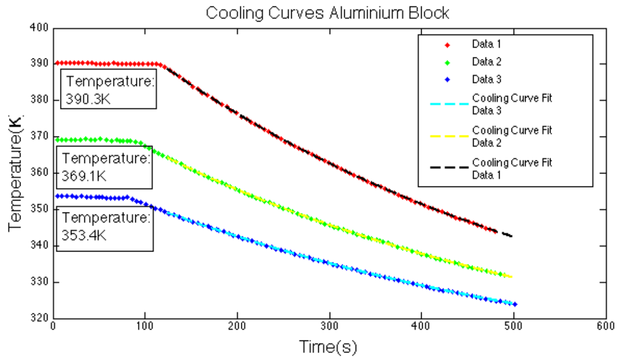

Figure 9: The graph displays three cooling curves of the aluminium block at different temperatures along with the appropiate fits modelled by Newton's Cooling Law, all the measurements were taken at an average ambient temperature of 297.5K

The equation fitted to the three sets of data:

$$T = a \cdot e^{\frac{-t}{\tau}} + c$$

The values for τ are the thermal time constant values for the block.They are not in agreement within the uncertainties. A possible and most likely source of error was the heat lost to the environment by the wires and the system containing the aluminium block. Based on the thermal time values obtained, the value for the time constant is lower when the temperature is higher. This means the object takes a shorter time to reach 63.2% of its final temperature at higher temperature. This in turn implies that the system loses more heat to the environment when as its temperature is higher.

Power(W)	τ(s)	δ(W/K)	C_{Block}(J/K)
4.2(1)	497.4(6)	0.0359(8)	17.6(4)
3.1(1)	501.8(2)	0.035(1)	17.5(5)
2.2(1)	524.8(3)	0.027(1)	14.3(3)

Table 1: The values obtained for the heat capacity of the block

The error in the measurement of the dissipation factor comes from the error in temperature, and the error in power. The dissipation factors for the values obtained go up as the temperature goes up, this implies that the block loses more heat as the equilibrium temperature reached by the block goes up.Tha values for the dissipation factor are then in complete agreement with the values obtained for the thermal time constant. At a higher temperature the time constant is lower, which means the dissipation factor must be higher[6], which is what we observed with the results obtained.
The mean value for the heat capacity of the aluminium block is 16.5(4)J/K. The first two heat capacity values seem to agree within the error, the third measurement is not however, the source of error for the discrepancy of the last measurement is unknown. [7]
The mass of the block is estimated to be within one order of magnitude. The specific heat capacity of aluminium is 0.91J/kg K [5], therefore the heat capacity of the block should be within one order of magnitude, which agrees with the values obtained for the heat capacity.

6 Conclusions

A characterization of the thermistor in terms of the thermistor's describing factors was obtained. The thermistors application as a temperature sensor then was used to measure the heat capacity of an aluminium block. The Steinhart-Hart equation describes best the relationship between resistance and temperature of the thermistor, the values for the parameters obtained were: a=$1.10(3)\times10^{-3}$, b=$2.64(5)\times10^{-4}$ and c=$1.6(3)\times10^{-7}$, this parameters were all in agreement with the provided values from the manufacturer within 2σ, The thermisor and the charerization obtained can thus be use as a temperature sensor with a error of one decimal place. The thermal time constant for the thermistor was obtained through a fit of Newton's Cooling Law. The value obtained was of 7.31(2)s, this value is less than 15s, the specification provided by the manufacturer, the result is thus in agreement with the provided value.
Lastly, the heat capacity of an aluminium block was measured, two values of three values mea-

[6]Refer to Equation 5
[7]Any plausible explanation would just be a guess, all the measurements for this part were thought to be done under the same conditions.

sured were in agreement within one sigma. The mean value obtained was 16.5$\pm$2J/K, this value agrees with the expected value estimate.
Further research includes a measurement of the dissipation constant for the thermistor to completely characterize and obtain all the factors that describe the behaviour of a thermistor. Measuring the dissipation constant of the thermisor in different medium and the use of the thermistor in a variety of different applications.

Acknowledgments

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