Metrology Experiment for Engineering Students: Platinum Resistance Temperature Detector

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Abstract

This paper describes the use of a platinum resistance temperature detector to develop a calibration experiment and to introduce metrology principles. The Callender-Van Dusen equation is used to analyze the temperature-resistance characteristic of a detector. Linearity of this characteristic is explored using a MATLAB simulation. Resistance is measured at four different temperatures to estimate all of the parameters in Callender-Van Dusen equation. Since the uncertainty of temperature and resistance measurements during calibration determines the accuracy of the temperature measurements using platinum detector, it is necessary to assess the calibration errors. A simulation package is developed that applies different levels of errors into measurements used for parameter estimation. The goal is to study the influence of calibration uncertainty on the temperature detector's readings. The next challenge is a practical realization of the calibration process. A simple experiment is proposed and the least square fit is used to estimate the parameters.

1. Introduction

Electrical resistivity of metals and semiconductors increases when they are heated. This mechanism is used in temperature measurements. Platinum resistance temperature detectors yield a reproducible resistance temperature relationship as resistance varies with temperature. The relationship between resistance and temperature for platinum wire resistance temperature detectors is given by Callender-Van Dusen equation [1]:

$$R_t = R_0 \ \{1 + a[t + b(1-t/100)(t/100) + d(1-t/100)(t/100)^3]\} \qquad (1)$$

Where R_t = resistance at temperature t,
R_0 = ice point resistance at 0.01°C,
a = temperature coefficient of resistance near 0°C,
b = temperature coefficient of resistance near 100°C,
d = Van Dusen constant,
t = temperature in degrees Celsius.

Typical values are a= 0.003926, b= 1.491 and d = 0 when t > 0°C, and d = 0.1103 when t < 0°C. Based on this information a typical temperature-resistance characteristic for a platinum resistance temperature detector is as shown in figure 1.

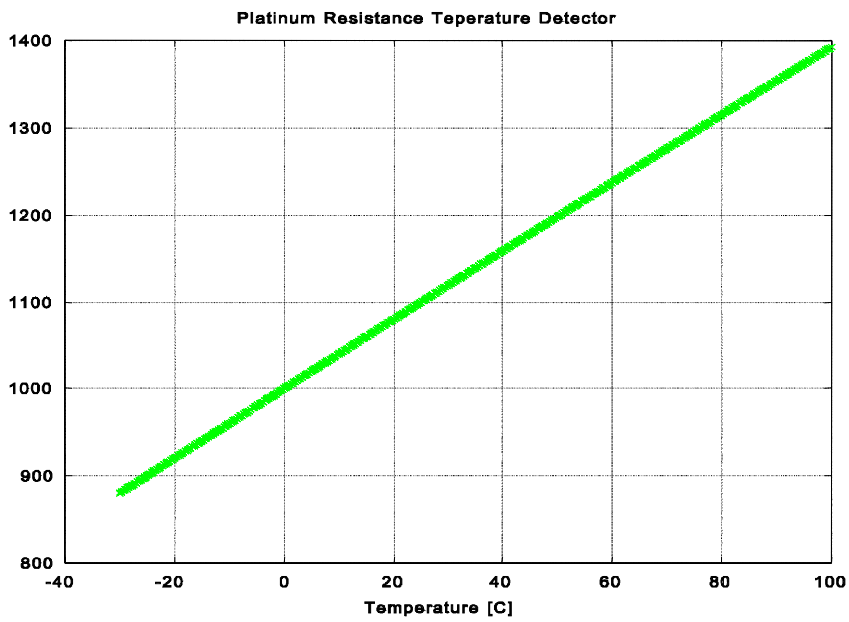

Figure (1) Resistance vs. Temperature for a Platinum Resistance Temperature Detector

2. Calibration Experiment Analysis

The first step in the analysis is to establish a working range. In order to calibrate a platinum resistance temperature detector, we must measure its resistance at four different temperatures and use equation (1) to calculate parameters a, b, d and R_0. It is obvious that measurements need to be performed at 0 °C and 100 °C in order to calculate R_0 and a. From the practical point of view it is relatively easy to provide boiling water in a student laboratory to reach 100 °C. Ice can be used to produce 0 °C. To estimate the parameter b, measurements must be made at room temperature. To estimate d it is necessary to establish a temperature well below 0 °C. This could prove relatively difficult in a student lab. Based on the above discussion a good working range could be temperatures from -30°C to 100°C.

Measurement uncertainty is obtained by taking into account all of the errors associated with a measurement process. In our case measurement uncertainty will depend upon how well temperature and resistance are measured. The instruments used in the experiment determine the errors related to these measurements.

A simulation routine has been developed that uses the model given in equation (1) and introduces random errors in measuring resistance and temperature. Errors have standard deviation equal to instrument accuracy and have a zero mean. In the first case it was assumed that resistance and temperature could be measured with uncertainty of 1mili Ohm and 0. 1 °C respectively. To more realistically portray the experiment, ten measurements were taken at each temperature point [-30 °, 0 °C, 50 °C, 100°C]. This is the level of accuracy easily achieved in a student laboratory. The results are plotted in figure 2. The obtained parameters, a, b, d and $R_{0,}$ as well as deviation from the model suggest that the equipment used is not adequate for such an experiment.

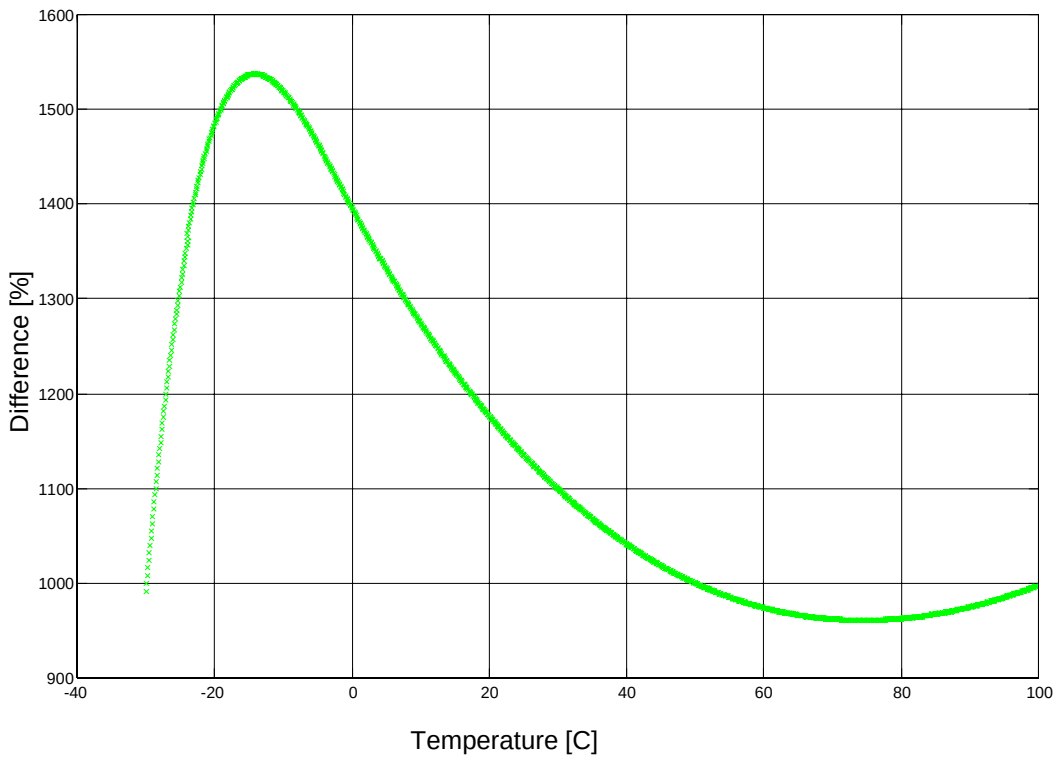

Figure (2) Case 1: Comparison Between the Model and the Simulation Using Realistic Instruments. a = 0.0039204, b = 6.1676, d = 1.2922 and R_0 = 1001.399

In the second case it was assumed that measuring instruments are accurate at the level of national standards so that resistance and temperature can be measured with uncertainty of 1 micro Ohm and 0. 45 mili °C. respectively. The results are demonstrated in figure 3.

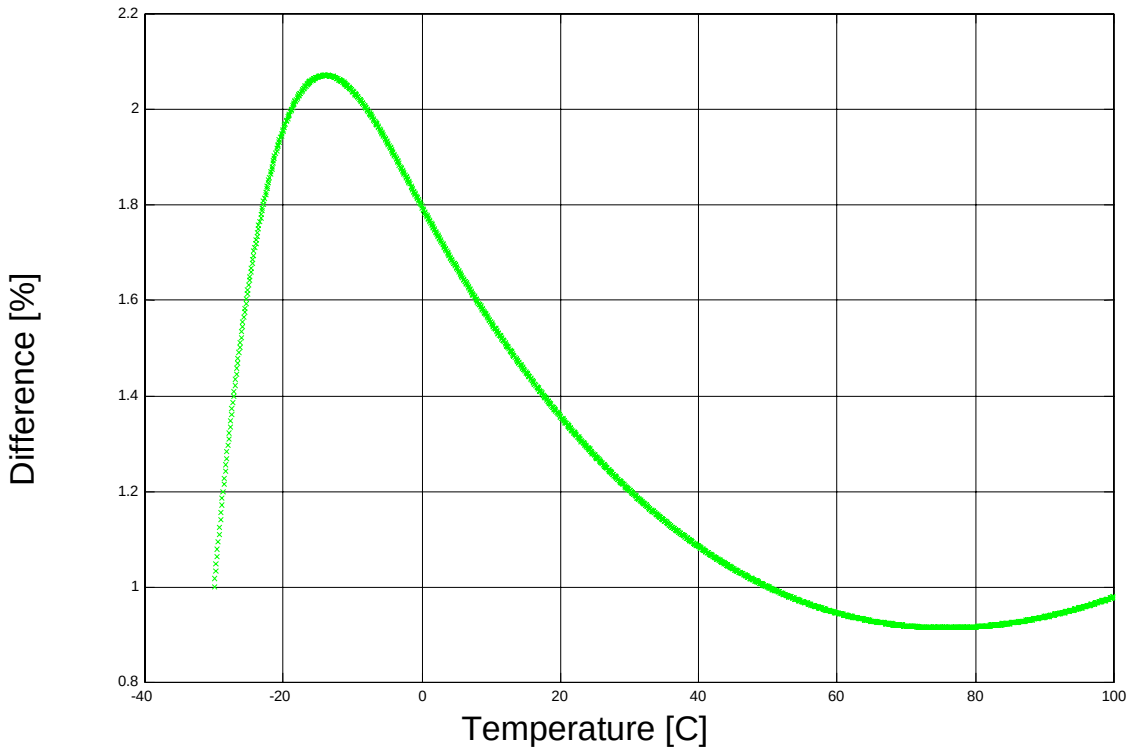

Figure (3) Case 2: Comparison Between the Model and the Simulation Using National Standards. a = 0.003926, b = 0.12223, d = 1.4906 and R_0 = 1000.0018

This simple analysis shows students the importance of accuracy of the instrument that they use. Students too often assume that the instruments are accurate to the number of digits displayed. Based upon this exercise students are expected to reasonably estimate uncertainty level with which they will calibrate a platinum temperature detector.

A calibration procedure is practically determined by a required measurement uncertainty. In order to optimize the calibration process it is essential to determine the minimal effort required to achieve desired performance. If it proves that the influence of a certain parameter on the necessary uncertainty level is negligible, then a set of measurements related to its estimation can be dropped.

Let us explore how much error will be introduced if only "linear" parameters, α and R_0, are estimated. The basis for this analysis is the fact that for some applications the platinum resistance temperature detector may be approximately linear and all the other errors may be negligible. Let us consider linear approximation given by equation (2).

$$R_{linear} = R_0 (1 + a\, t) \qquad (2)$$

The measure of non-linearity of a platinum resistance temperature detector is the difference between the equation (1) and (2). Temperature deviation from linear approximation for a platinum resistance temperature detector is plotted in Fig. 4.

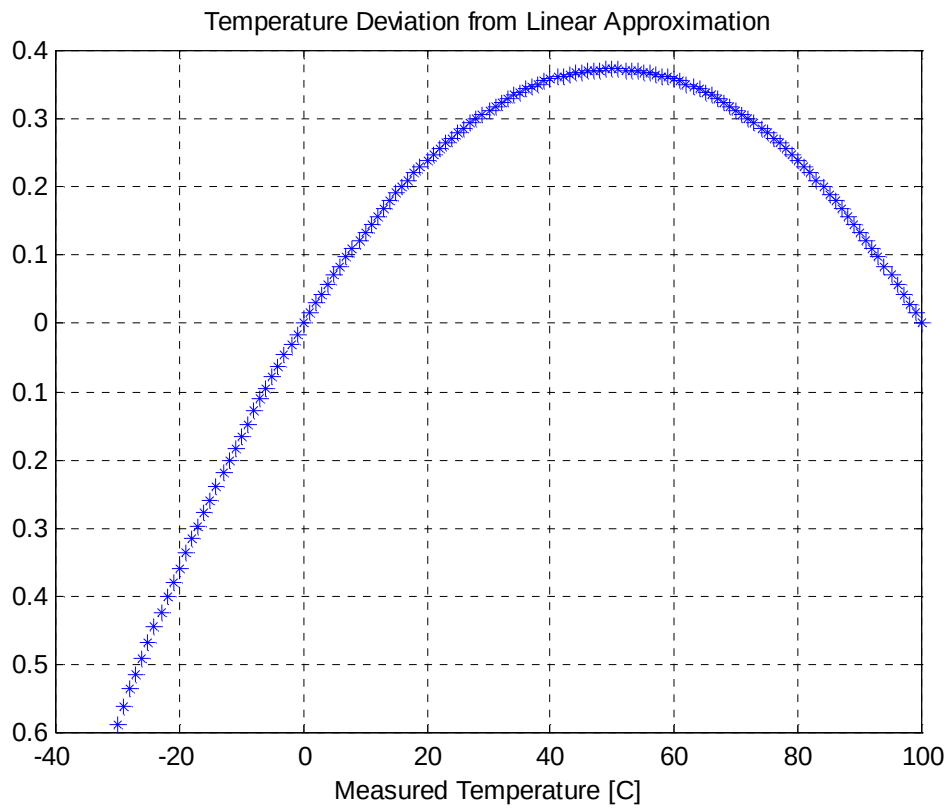

Figure (4) Temperature Deviation From Linear Approximation

From the calibration point of view it is much easier to establish only two parameters, R_o and a, as compared to four needed for the full representation shown in figure (1). Figure (4) demonstrates the level of errors at the order of +- 0.5 °C over the range –30°C to 100°C in the case of linear approximation. This is a systematic error that has to be taken into account when estimating total calibration uncertainty.

Figure (5) shows the simulated residual error between actual temperature and that computed by equation (1). This suggests that the simulation error is not significant in our determining the uncertainty of the calibration process.

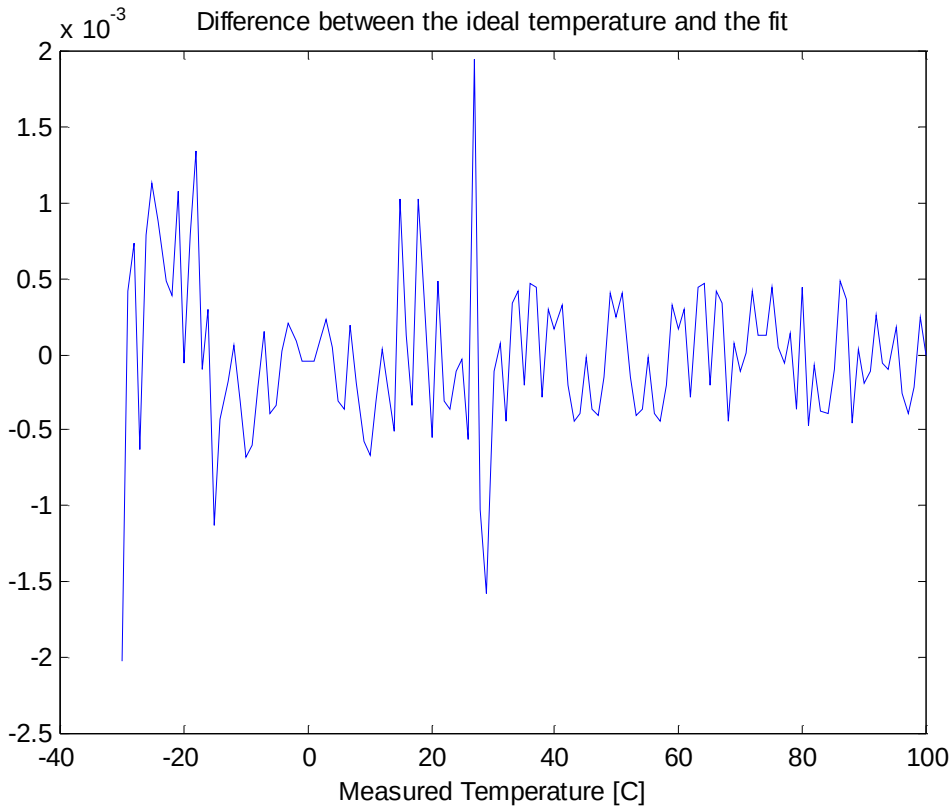

Figure (5) Difference Between the Ideal Temperature and the Fit.

These plots are not difficult to generate using MATALAB and they certainly need to be included in students' analysis experience.

3. The Experiment

The actual experiment was very simple. It was performed using a 100-Ohm platinum resistance sensor, a bucket of ice, and a pot full of boiling water. A digital ohmmeter and a digital thermometer were used to make 10 measurements in the range from 0°C to 100°C. Since it was not possible to get the temperature to fall all the way to 0°C and to rise up to 100°C (see Table 1.) due to the very simple apparatus, search algorithm was developed to best estimate the parameters R_o, a and b. A reasonable range of values with very fine resolution was given for each parameter and the minimal residue was found. A MATLAB routine is given in Appendix A. Estimated values for the parameters are listed in Table 2.

Temperature	Resistance
25.0000	110.0740
24.9000	110.0650
5.9000	102.5200
6.3000	102.5510
4.1000	101.9670
72.2000	129.6400
68.3000	127.2400
64.6000	125.7800
88.6000	135.7300
84.5000	133.8000

Table (1) Measured temperature and resistance

Temperature	R_0	a	b
25.0000	100.4216	0.0038	2.7809
24.9000	100.3212	0.0039	0.4878
5.9000	99.8996	0.0044	0.9290
6.3000	99.8193	0.0043	1.4139
4.1000	100.2409	0.0041	1.8460
72.2000	101.7667	0.0038	2.6120
68.3000	98.7954	0.0042	0.6374
64.6000	99.8996	0.0040	3.1154
88.6000	99.7792	0.0040	4.3297
84.5000	100.8231	0.0038	4.0920

Table (2) Measured Temperatures and Estimated Values for Parameters

Manufacturer's calibrated values for the sensor are R_o=100.040 and α=0.0038.

The most dominant influence on the parameter estimations accuracy is the uncertainty of the thermometer used. It had resolution of 0. 1°C and uncertainty of 0.3 °C. The results obtained are significant due to the fact that the least square fit algorithm is used to estimate parameters for each measured temperature.

4. Summary

A simple experiment is developed to measure temperature-resistance characteristic of a platinum resistance temperature detector. The characteristic is analyzed using MATLAB. Preliminary experimental results are shown. This calibration exercise introduces students to several aspects of metrology: Learning about models for physical devices and how to use them in order to simulate sensor's performance over extended operating range;

Dealing with non-linear characteristics and estimating the error of non-linearity; Realizing what is the influence on the parameter estimation of instrumentation used in the experiment; Setting up very simple experiment and making set of measurements; Analyzing data using least square fit algorithm to obtain optimal estimates for the parameters.

Reference

1. C. F. Coombs Jr., editor in chief, "Electrical Instrument Handbook", 2nd edition, McGraw-Hill, Inc., 1994.

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Appendix A MATLAB Script File Meas.m

```
clear
format long e
measresv=[110.074 110.065 102.520 102.551 101.967 129.640 127.240 125.780 135.730
133.800]';
meastempv=[25 24.9 5.9 6.3 4.1 72.2 68.3 64.6 88.6 84.5]';
alfa=0.003856;
beta=1.5;
r0nom=100;

A1=ones(size(meastempv));B1=meastempv;C1=(B1/100-(B1.^2)/(100)^2);
ABC=[A1 B1 C1];
result=inv(ABC'*ABC)*(ABC)'*measresv;
r0out=result(1)
alfaout=result(2)/r0out
betaout=result(3)/alfaout/r0out
r=(measresv-ABC*result)/r0nom;
r1=(measresv-r0out*(ones(size(measresv))+alfaout*B1))/r0nom;
r2=r1-r

deltar=abs(r0out-r0nom)*10;
resid=0.1*ones(size(measresv));
for k=1:10;
  measres=measresv(k);
  meastemp=meastempv(k);
  for r0=r0out-deltar:deltar/100:r0out+deltar;r0
    for alfa=alfaout-alfaout/10:alfaout/100:alfaout+alfaout/10;
      for beta=0:0.0001:5;
      residue=r0*(1+alfa*(meastemp+beta*(1-meastemp/100)*(meastemp/100)))-
measres;
      if abs(residue)<resid(k)
        resid(k)=abs(residue);
        alfaf(k)=alfa;betaf(k)=beta;r0f(k)=r0;
      end
    end
  end
end
end
```