A. Introduction

The American Cancer Society estimates that about one million Americans each year are diagnosed to have cancer. Each person in the United States has approximately a 30% percent chance of having cancer in his or her lifetime. Among the many methods of treating cancer is hyperthermia, that is, heating of cancerous tissue. The use of heat to treat cancerous tumors dates back almost 100 years. More recently, interest in hyperthermia for cancer therapy has increased since the late 1960s, when a research group in Rome published the first report of a systematic study on the biological and clinical aspects of heating, thus providing the rationale for a new scientific and clinical field.

In a hyperthermia treatment, the tumor is heated to at least 42°C by any of a variety of methods such as electromagnetic fields, ultrasound, and implanted radiofrequency electrodes. An essential element of the treatment is measurement of the temperature in the tumor. Without some satisfactory method of measuring temperature, the tissue temperature cannot be maintained at the required level. In one commonly used temperature-measuring technique, a tiny thermistor (component that changes resistance significantly with temperature) is inserted into the tissue, and the temperature is monitored by measuring the resistance of the thermistor. Such a system has the advantage that the temperature information is contained in an electrical signal that can be connected to a recorder or computer to produce a continuous record of the temperature. Changes in temperature can also be used with a feedback loop to adjust the applied heat to maintain a relatively constant temperature.

A local company manufactures a thermistor temperature-probe system for use in hyperthermia systems. The system includes a number of thermistors that are inserted into tumors, and instrumentation to record the temperatures and use the temperature information in treatment management. It is capable of measuring temperatures within (about ) 0.1°C. Other commercial temperature-probe systems use optical methods to sense the temperature. One advantage of the thermistor system is that it requires calibration less often than the optical systems.

B. Your Design Project

Your project is to design a thermistor temperature-probe system consisting of a thermistor, an operational amplifier, three resistors, two batteries, and an ammeter or voltmeter. A thermistor costs about $5, the operational amplifier about 75 cents. A suitable ammeter costs $8 or $9, but you may use one you already have, or if you don't
have one and don't wish to purchase one, you may use one on a lab bench in the EE lab. For your convenience the needed parts are available from the EE stockroom, but you may get them elsewhere if you like.

The basic circuit for the temperature probe is shown in Fig. 1. It is similar to a commonly used circuit known as a Wheatstone bridge, named after the man who invented it, but unlike the original Wheatstone bridge circuit, this one includes an operational amplifier, which improves the circuit.

First you will construct a mathematical model of your thermistor by measuring its resistance as a function of temperature and using MATLAB (a software package) to arrive at a mathematical equation that best fits the data. Using Kirchhoff's laws and the linear model of the operational amplifier, you will derive the equation for the output voltage as a function of the resistors, including the thermistor. Then you will use MATLAB to choose values of the resistances that will optimize the response, that is, give the most linear relationship between the output voltage and temperature. This sophisticated design procedure will result in a simple and practical, but at the same time elegant, temperature probe.

C. Model the Thermistor

During the first laboratory period, you must measure the properties of the thermistor that you will use. An adequate model of a thermistor is that its resistance as a function of temperature is given by
\[ R_T = R_0 e^{\beta \left( \frac{1}{T} - \frac{1}{T_0} \right)} \]  

(1)

where

- \( T \) is the temperature in degrees Kelvin
- \( T_0 \) is a reference temperature (typically 300°K)
- \( \beta \) is a constant
- \( R_0 \) is the value of \( R_T \) when \( T = T_0 \)

\( R_0 \) and \( \beta \) are given by the manufacturer, but you should measure them for your thermistor because tolerances are typically only 10 percent.

1. Put heat-shrink tubing on your thermistor to waterproof it.
2. Use a water bath to produce a variable temperature and use a thermometer as a temperature standard.
3. Measure \( R_T \) as a function of \( T \) over as wide a range of \( T \) as you can.
4. Plot \( \ln (R_T) \) versus \( (1/T) \), which should be close to the straight line predicted by Eq. 1. Plot the data by hand before you dismantle your equipment to be sure that your results are correct.
5. Use MATLAB to do a linear regression to fit the best straight line to your data to obtain \( \beta \) and \( R_0 \) for your thermistor.

D. Derive \( V_0 \) (T)

1. Using Kirchhoff’s laws and the linear model of the operational amplifier, derive an expression for \( V_0 \), which will be a function of the resistances.
2. Make at least two consistency checks on your expression.

E. Design the Circuit

1. Write a MATLAB program that will:
   a. Calculate \( V_0 \) as a function of \( T \) for any given set of parameters \( R_1, R_2, R_3, R_4, V_A \) and including \( R_T \) (which is a function of \( T \)).
   b. Include saturation of the operational amplifier. That is, set \( V_0 = V_R \) if the calculated \( V_0 > V_R \), and \( V_0 = -V_R \) if \( V_0 < -V_R \), where \( V_R \) is the rail voltage = 10 V.
   c. Calculate the mean squared error between \( V_0 \) and the desired linear response. Note: The desired linear response is one for which \( V_0 = 0 \) at \( T = 0^\circ C \), and which has a slope which is adjusted by the MATLAB function \( fmins \) to minimize the error.
   d. Plot \( V_0 \) vs. \( T \) and plot the desired linear response vs. \( T \) on the same set of axes.
2. Use the \( fmins \) function in MATLAB and the function you wrote for Part E.1 above to optimize the response, that is, to choose values of \( R_1, R_2, R_3, \) and
R₄, to get the most linear response, V₀(T), over a temperature range from 0° to 100°C. Figure 2(a) shows a typical response that has not been optimized. Figure 2(b) shows a response optimized by MATLAB. The response in Fig. 2(b) is obviously much the better of the two.

Fig. 2. (a) Typical response of V₀(T) versus T for the circuit of Fig. 1 when no linearization procedure is used.
(b) Typical response optimized by MATLAB.
F. Test the Circuit
1. Construct the circuit that you designed and measure $V_0$ as a function of $T$. It would be wise first to connect the operational amplifier as a simple inverting and/or noninverting amplifier to be sure that everything is working properly.
2. Measure the values of the actual resistors that you use in the circuit and calculate $V_0(T)$ for these values to get the most accurate calculated data to compare with measured data. Plot measured values and calculated values of $V_0$ versus $T$ on the same set of axes. Make your plot before you dismantle the setup.

G. Design a Temperature Meter
Design a meter circuit using a voltmeter to register the temperature:
1. Design a potentiometer circuit (that you can add to your existing circuit) that yields an output of 0 V for $T = 0^\circ C$ and 100 mV for $T = 100^\circ C$. Draw a diagram showing the potentiometer and voltmeter connected to the output of the operational amplifier.
2. Make a full-scale drawing of a thermometer. On the drawing, show tick marks evenly spaced from 0 to 100°C in 5°C increments. On the other side of the thermometer, show where the calculated tick marks would be for your optimized temperature probe. For example, if your voltmeter would read 29 mV when $T = 30^\circ C$, on the drawing put a tick mark at the point corresponding to 29 mV on the scale, and label the mark 30. If the response were linear, of course, the voltmeter would read 30 mV when $T = 30^\circ C$.
3. Calculate $V_0(T)$ for the following parameters: $R_2 = 50\, k\Omega$, $R_3 = 10\, k\Omega$, $R_4 = 10\, k\Omega$, and $R_1 =$ the value that makes $V_0 = 0$ when $T = 0$. Repeat Part 2 for this unoptimized response.
4. Compare the calibration of the optimized and unoptimized temperature probes and discuss the advantages of the optimized probe.

H. Write a Formal Report
Write a formal report describing your work on this project. See instructions in "Course Procedures" about how to write the report. Include at least the following in your report:
1. A short introduction. You may attach this handout to the report in the appendix and refer to it so that you don't have to copy the information in it.
2. A careful description of the work that you did in parts C through G above.
   a. Give clear derivations of the mathematical expressions. Include consistency checks.
   b. Explain how you chose the value of the components and include a table listing the component values.
c. Explain all measurements carefully and include data appropriately in clearly labeled tables and graphs in the body of the report.
d. Include a listing of your computer program in an appendix, and explain how the program works.
e. Give a clear comparison of measured and calculated values. Include a plot of calculated and measured $V_0(T)$ on the same set of axes. Explain why calculated and measured values are not the same.

3. Conclusions, including:
   a. A discussion of the validity of the models used for the thermistor and the operational amplifier.
   b. A discussion of the success of your design procedure and the usefulness of your device for measuring temperature. State its limitations and advantages.

I. Your Grade
Your report will be graded according to the following:

<table>
<thead>
<tr>
<th>Category</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communications</td>
<td>30</td>
</tr>
<tr>
<td>C. Thermistor modeling</td>
<td>11</td>
</tr>
<tr>
<td>D. Derivation of $V_0(T)$</td>
<td>12</td>
</tr>
<tr>
<td>E1. Computer program</td>
<td>12</td>
</tr>
<tr>
<td>E2. Circuit Parameters</td>
<td>13</td>
</tr>
<tr>
<td>F. Circuit measurements</td>
<td>12</td>
</tr>
<tr>
<td>G. Temperature meter</td>
<td>5</td>
</tr>
<tr>
<td>H. Conclusions</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
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