

5.4.5: Temperature Measurement System Design

Overview:

In this lab, we will design a simple temperature measurement system which outputs a DC voltage which indicates temperature. Our system will use a *thermistor* to indicate the temperature; the electrical resistance of the thermistor changes as the temperature changes. We will use a *Wheatstone bridge* circuit to convert this resistance change to a voltage change. The voltage output of the Wheatstone bridge circuit will be small relative to the amount of temperature change (the measurement is said to have low *sensitivity*), so we will use a *difference amplifier* to increase the overall sensitivity of the temperature measurement system.

Before beginning this lab, you should be able to:

- State rules governing ideal op-amps
- Analyze electrical circuits which include ideal op-amps
- Describe the operation of a thermistor (Background information for Lab assignments 1.4.4, 2.1.1)





After completing this lab, you should be able to:

- Design and balance a Wheatstone bridge circuit
- Design and implement an operational amplifier-based difference amplifier
- Integrate the above subsystems to create an overall temperature measurement system

This lab exercise requires:

- Analog Discovery module
- Digilent Analog Parts Kit
- Digital multimeter (optional)

Symbol Key:

	Demonstrate circuit operation to teaching assistant; teaching assistant should initial lab notebook and grade sheet, indicating that circuit operation is acceptable.
	Analysis; include principle results of analysis in laboratory report.
	Numerical simulation (using PSPICE or MATLAB as indicated); include results of MATLAB numerical analysis and/or simulation in laboratory report.
	Record data in your lab notebook.

General Discussion:

In this lab assignment, we will design and implement a measurement system which outputs a voltage which is indicative of temperature. A thermistor will be used to measure temperature. The resistance of the thermistor changes with temperature.

The design requirements for the system are as follows:

1. The output voltage from the system is $0V \pm 20mV$ at room temperature (approximately $25^{\circ}C$).
2. Output voltage is positive for temperatures above room temperature, negative for temperatures below room temperature.
3. Output voltage increases by a minimum of 2V over a temperature range of $25^{\circ}C$ to $37^{\circ}C$. (These temperatures correspond approximately to room temperature and body temperature, respectively.)

A common approach to this problem (and the one we will implement) is to use a Wheatstone bridge circuit in conjunction with a difference amplifier circuit to achieve the necessary sensitivity between temperature and output voltage. A block diagram of the overall system is shown in Figure 1. The input to the overall system is the temperature of the thermistor. The thermistor converts this temperature into an output resistance. This resistance change is used in a Wheatstone bridge circuit, which converts this resistance change to a voltage change. The voltage difference output by the Wheatstone bridge is generally smaller than desired, so an amplifier is used to increase the amplitude of the overall output voltage from the system.

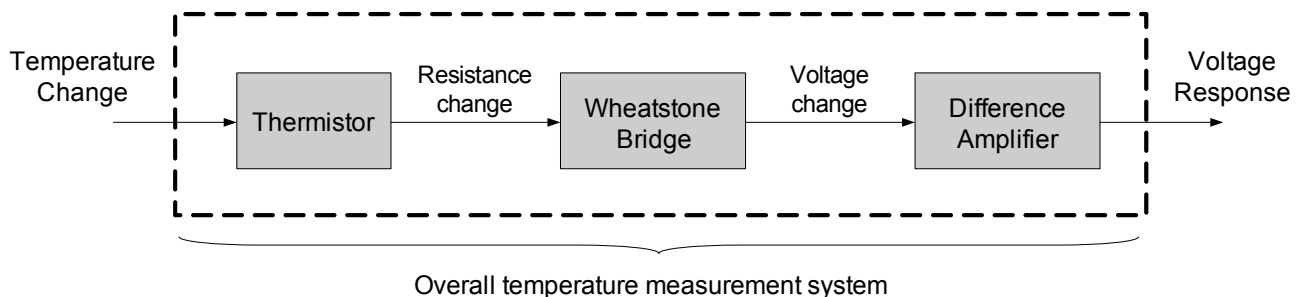


Figure 1. Overall temperature measurement system block diagram.

Pre-lab:

ANALYSIS

Read the information relative to Wheatstone bridge circuits provided in Appendix A of this lab assignment. It is not necessary to exhaustively follow all derivations provided in Appendix A, but you should be able to summarize, in a few sentences, the overall approach toward setting up and balancing a Wheatstone bridge circuit prior to coming to lab. Pay particular attention to equation (A9), which can be used to choose nominal resistances for the bridge circuit, and the practical note on adjusting the nominal values to balance the circuit. Please be sure to note that Appendix A recommends using a potentiometer to balance your Wheatstone bridge circuit.

Read the information relative to difference amplifiers provided in Appendix B of this lab assignment.

Lab Procedures:

Design approaches tend to vary from individual to individual, however, the recommended lab procedures for this assignment consist of the three discrete steps provided below. Feel free to modify these steps if you wish, but be prepared to explain your design approach to a teaching assistant.

1. Thermistor Characterization

DATA

Measure the nominal resistance of the thermistor (when the thermistor is at room temperature) and the resistance variation from this value when the thermistor is approximately at body temperature (37°C). Apply the 37°C temperature to the thermistor by firmly grasping the thermistor between two fingers. Record these values in your lab notebook.

2. Wheatstone bridge design and balancing

ANALYSIS

Design and build a Wheatstone bridge circuit which converts the resistance variation of the thermistor to a voltage variation. The output of this circuit should be (approximately) zero volts when the thermistor is at room temperature. Provide a schematic of your Wheatstone bridge circuit in your lab notebook, along with the desired and actual resistance values used in the circuit. Also in your lab notebook, record the voltage variation provided by the Wheatstone bridge circuit, resulting from the full range of temperature change.

DATA

Design Hint:

You may not wish to spend a lot of time balancing the bridge at this stage. It is probably more productive to roughly balance the bridge at this point, and then do a final balance after the amplification stage described in step (c) has been implemented.

DEMO

Demonstrate your Wheatstone bridge operation to a teaching assistant and have them initial your lab notebook and the lab checklist.

3. Difference amplifier design and implementation

ANALYSIS

Design a difference amplifier which amplifies the output voltage difference from the Wheatstone bridge to the levels specified in the design requirements. The circuit schematic and governing equations for a difference amplifier are provided in Appendix B. Implement the circuit. Provide a schematic of your circuit, along with desired and actual resistance values used in your circuit in your lab notebook.

DATA

DATA

Connect your circuit to the thermistor/Wheatstone bridge assembly and measure the output voltage resulting from the temperature range provided in the specifications (approximately 25°C to 37°C). Verify that voltage increases for as temperature increases and decreases as temperature decreases. Record the range of voltages in your lab notebook, corresponding to the full range of temperature change provided in the design requirements. Compare your measured voltage response to the original design requirements. You do not need to re-design your system if the design requirements are not met, but you should provide comments in your lab notebook as to why you think the circuit behaves differently than expected.

DEMO

Demonstrate your Wheatstone bridge operation to a teaching assistant and have them initial your lab notebook and the lab checklist.

Design Hint:

1. Your amplifier circuit in step (c) may “load” your Wheatstone bridge circuit in a different manner than was done in step (b) above. (In step (b), you measured the output voltage from the Wheatstone bridge with a DMM; your difference amplifier may require the Wheatstone bridge to provide different power levels than the DMM does. These effects can be mitigated by using relatively high resistance values in your difference amplifier. (Recall the discussion of input resistance provided in Lab 2. The DMM has a very high input resistance; an alternate circuit may have lower input resistance, and thus make different power demands on the Wheatstone bridge. The change in power requirements may affect the operation of the Wheatstone bridge.
2. After implementing your amplifier circuit in step (c), you may wish to re-balance the Wheatstone bridge circuit. The added sensitivity of the overall system will make the balancing process simpler.
3. The amplifier circuit of Lab 4 (the inverting voltage amplifier) is not appropriate for the implementation of step (c) of this lab assignment. The inverting voltage amplifier of Lab 4 amplifies a voltage which is relative to the ground of the amplifier. In our current application, we have two voltages which are both measured relative to ground; we need to amplify the difference between these voltages.

Appendix A – Wheatstone Bridge Circuits

Overview:

Wheatstone bridge circuits are most often used to convert variations in resistance to variations in voltage. Wheatstone bridges are commonly used in measurement systems, as a number of common sensors provide a resistance variation in response to some external influence. For example, *thermistors* change resistance in response to temperature changes, *strain gages* change resistance in response to deformations, and *photoconductive transducers* change resistance in response to changes in light intensity. Wheatstone bridges are generally used in conjunction with these sensors in order to convert these resistance changes to voltage changes since voltages are generally easier to record and transmit than resistances.

Wheatstone bridge sensitivity to resistance variations:

A Wheatstone bridge circuit is shown in Figure A1. The bridge is generally presented as shown in the figure to the left; we will use the equivalent circuit shown to the right in our analysis. A Wheatstone bridge is commonly used to convert a variation in resistance to a variation in voltage. A constant supply voltage V_s is applied to the circuit. The resistors in the circuit all have a nominal resistance of R ; the variable resistor has a variation ΔR from this nominal value. The output voltage v_{ab} indicates the variation ΔR in the variable resistor. The variable resistor in the network is often a transducer whose resistance varies dependent upon some external variable such as temperature.

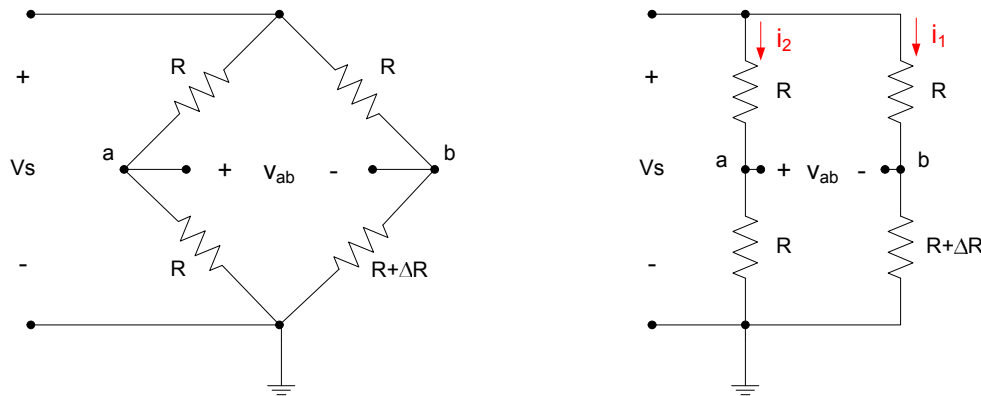


Figure A1. Wheatstone bridge circuit.

By voltage division, the voltages v_b and v_a (relative to ground) are

$$v_b = \frac{(R + \Delta R)}{2R + \Delta R} V_s \text{ and } v_a = Ri_2 = \frac{V_s \cdot R}{2R} = \frac{V_s}{2} \quad (\text{A1})$$

The voltage v_{ab} is then

$$v_{ab} = v_a - v_b = \left(\frac{1}{2} - \frac{R + \Delta R}{2R + \Delta R} \right) V_s = \left(\frac{(2R + \Delta R) - 2(R + \Delta R)}{2(2R + \Delta R)} \right) V_s = -\frac{\Delta R}{2(2R + \Delta R)} \cdot V_s \quad (\text{A2})$$

For the case in which $\Delta R \ll 2R$, this simplifies to:

$$v_{ab} \approx -\frac{V_s}{4R} \Delta R \quad (\text{A3})$$

and the output voltage is proportional to the change in resistance of the variable resistor.

Balancing the Wheatstone Bridge Circuit:

In Figure A1, it is assumed that all four resistances in the Wheatstone bridge have identical nominal values. In the case when the Wheatstone bridge output voltage is to result from a varying resistance sensor, this requires one to obtain three resistors with resistance exactly equal to the sensor's nominal resistance. In general, this is not possible. In this chapter, we present an approach for balancing a Wheatstone bridge so that the output voltage is zero when the variable resistance is at its nominal value (i.e. ΔR in Figure A1 is zero), even if the other three resistances in the bridge are not identical.

A schematic of a Wheatstone bridge with non-equivalent resistances is shown in Figure A2. R_{Nom} is the nominal value of a variable resistance; it is desired that the output voltage from the bridge circuit is zero for this resistance value. R_2 and R_3 are fixed resistors; R_1 is a variable resistor which will be used to *balance* the bridge circuit.

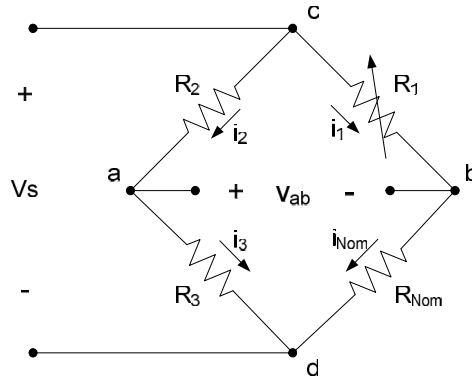


Figure A2. Wheatstone bridge.

Governing equations for balanced circuit:

If the Wheatstone bridge of Figure A2 is balanced, $v_{ab} = 0$, and

$$i_2 R_2 = i_1 R_1 \quad (\text{A4})$$

KCL at nodes a and b tells us that $i_2 = i_3$ and $i_1 = i_{\text{Nom}}$. Using this along with Ohm's law gives:

$$V_s = i_2 (R_2 + R_3) \quad (\text{A5})$$

and

$$V_s = i_1 (R_1 + R_{\text{Nom}}) \quad (\text{A6})$$

Equating (A4) and (A5) and taking advantage of equation (A3) provides

$$i_2 R_3 = i_1 R_{Nom} \quad (A7)$$

or

$$\frac{i_1}{i_2} = \frac{R_3}{R_{Nom}} \quad (A8)$$

From equation (A3), $\frac{i_1}{i_2} = \frac{R_2}{R_1}$, so equation (A7) becomes

$$\frac{R_2}{R_1} = \frac{R_3}{R_{Nom}} \quad (A9)$$

and the variable resistance can be set according to:

$$R_1 = \frac{R_2 R_{Nom}}{R_3} \quad (A10)$$

Where R_{Nom} is the variable resistance for which the circuit is balanced.

Practical Note:

The value of the resistance R_1 must be set very accurately, so it is common to use a variable-resistance potentiometer to set the resistance R_1 . Specifically, a relatively large-resistance potentiometer can be placed in parallel with a fixed resistor with a resistance slightly higher than the value specified by equation (9) in order to provide the ability to provide very fine adjustments to the value of the resistor R_1 .

Balancing the bridge circuit is commonly performed by setting the variable resistance to its nominal value R_{Nom} , and monitoring the voltage v_{ab} while adjusting the resistance R_1 . The resistance R_1 is at its desired value when the voltage v_{ab} is zero. (The actual value of R_1 required to balance the circuit is generally not important – setting the output voltage to zero at the nominal variable resistance is the ultimate goal.)

Appendix B – Difference Amplifier

The circuit shown in Figure B1 is called a difference amplifier. The output of the circuit (v_{out} in Figure B1) is proportional to the difference between the two inputs, v_a and v_b . With the four independent resistances (R_1 , R_2 , R_3 , and R_4) shown in Figure B1, the input voltages can be scaled independently. In order to apply the same scaling factor to both inputs, we can apply a requirement to the choice of the resistances. If we choose

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

then the expression for the output voltage becomes:

$$v_{out} = \frac{R_2}{R_1} (v_b - v_a)$$

The output voltage is, then, a scaled version of the difference between the two input voltages. Note that if v_a is zero, the circuit is a *non-inverting* amplifier. (The output is a scaled version of the single input v_b , with no sign change.) Also note that if $R_1 = R_2 = R_3 = R_4$, the circuit simply subtracts the voltage v_a from the voltage v_b .

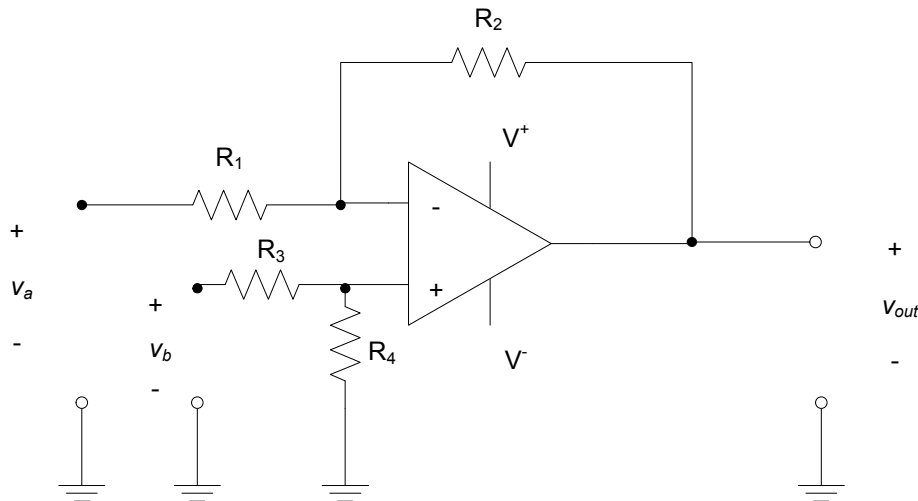


Figure B1. Difference amplifier circuit.