1 Introduction

In this lab, we will use a PID (Proportional, Integral, and Derivative) algorithm, implemented on an Arduino microprocessor, to maintain an aluminum block at a constant temperature. The temperature is measured using a thermistor, a device for which the resistance varies consistently with temperature. The active part of the temperature control is a thermoelectric (TE) device, which moves heat away or toward a heat reservoir depending on the magnitude and direction of the applied current. This lab is based on the exercise described in Chapter 12 and Appendix I of "Labview for Scientists and Engineers" by Essic (available for further reference in the lab).

2 Safety

- The thermoelectric device can get very hot or cold. DO NOT TOUCH unless your instructor tests it first.
- The transitors and heat sinks can get very hot. DO NOT TOUCH.
- Whenever the dual 3 A power supplies are powered, keep an eye on the current monitors. Only one supply should be powering the circuit at a time. If they both are drawing current, something has gone wrong, and you are driving current through both transistors... You also should not draw more than 2 A.

3 Thermistor

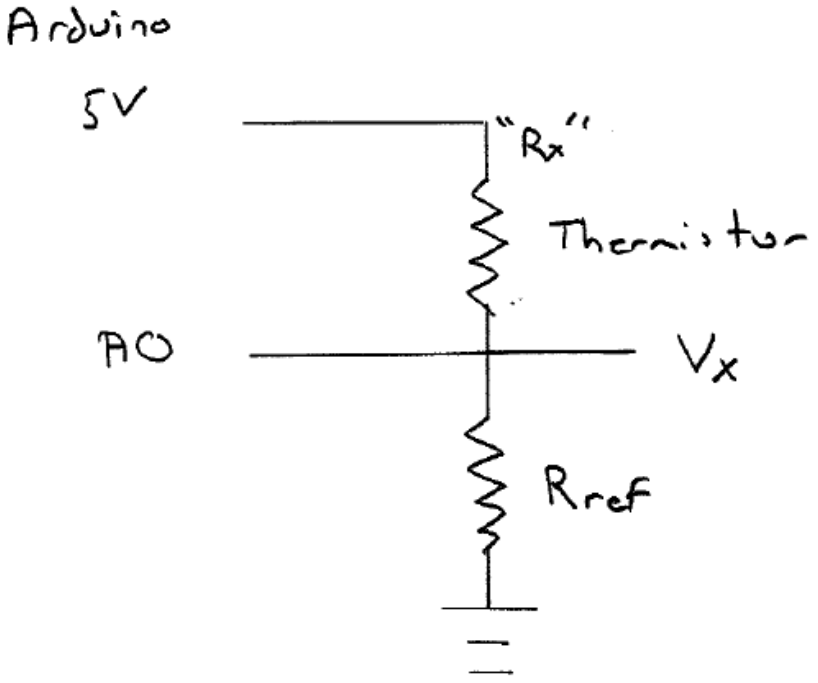


Figure 1: The voltage divider circuit.

You will probably be wondering wether or not your aluminum block is hot or cold, and will therefore be tempted to touch it. So let's quickly give you an alternative! First measure the resistance of the thermistor (which is connected across the two bus terminals labeled "Rx" on your Thermoelectric module) directly with your digital multimeter (DMM). You should measure something around 11 kΩ.

Next build the voltage divider (See Fig. 1) between the 5 volts and ground *on your Arduino protoboard* using a reference resistance of 10 kΩ. With the Arduino powered (no sketch needed yet) confirm with your DMM that you measure a voltage of about 2.4 V across the reference resistor. This is consistent with what you would expect for a voltage divider:

$$\frac{V_x}{V_0} = \frac{R_x}{R_x + R_{\text{ref}}}.$$

Next, with the voltage across the reference resistor supplied to Arduino analog input A0, run the "Simple Thermometer" Arduino sketch available from the course smart site. With a serial monitor open, you should see the Arduino reporting the voltage V_x (our proxy for the temperature) consistent with what you measured with the DMM across the references resistor.

In principle, we could calibrate this voltage to the actual temperature, but we do not have time! So instead we will just use the voltage directly in the PID and control algorithm. Keep in mind that a voltage of about $2.4V$ is room temperature, while more than $3V$ is noticably hot, and less than $2V$ is noticably cold. DO NOT TOUCH THE ALUMINUM BLOCK unless your instructor checks it for you first!

4 Diffential Amplifier

The Arduino PWM outputs are between 0 and 5 V. To control the TE, we need to send a voltage level between -9 V and $+9$ V. To make this conversion, we'll construct a differential amplifier, which outputs a voltage proptional to its *two* input voltage levels: $V_{\text{out}} = G * (V_+ - V_i)$. To set a positive output voltage, the Arduino sets V_+ to a positive value and V_- to zero. To set a negative output voltage, the Arduino sets V_- to a positive value and V_+ to zero. No negative input voltages are needed!

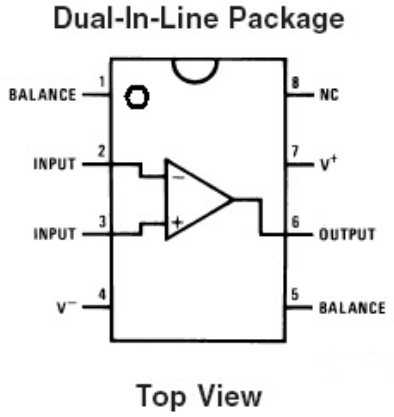


Figure 2: The LF411 Op Amp.

We will build our differential amplifier around the LF411 Op Amp shown in the Fig. 2. Built the circuit detailed in Fig. 3 based using the component values in Table 1. *Do not connect the*

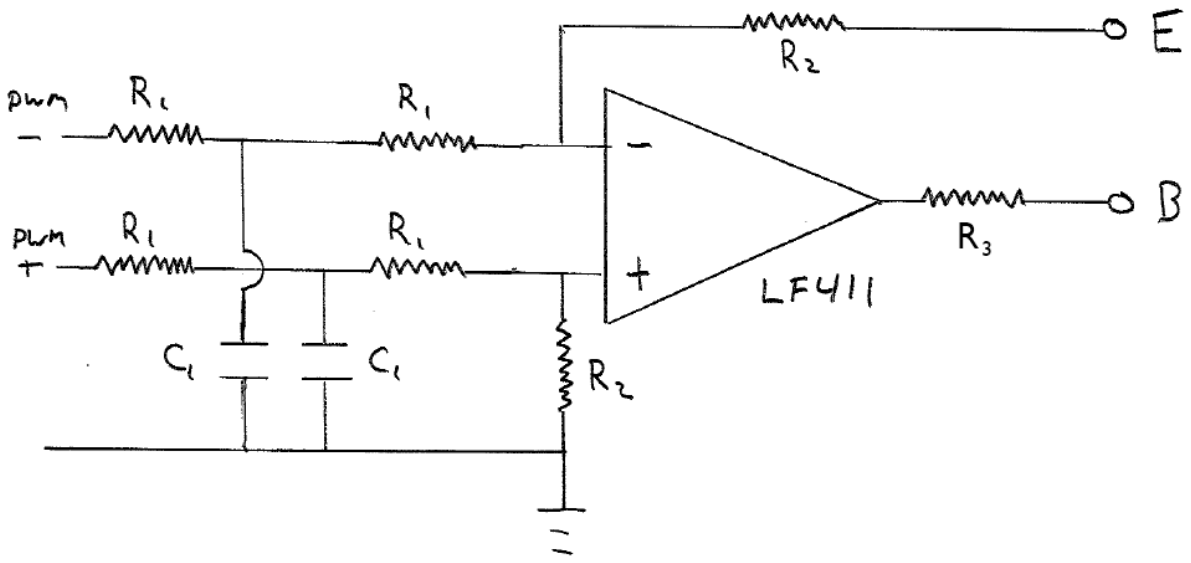


Figure 3: The differential amplifier circuit.

TE module yet! Note that for this differential amplifier to have symmetric gain for positive and negative signals, the feedback resistor has the same value as the grounding resistor: R_2. Also note that, though not shown in the diagram to avoid clutter, you will have to hookup the LF411 to power supplied by your lab proto-board. PRO TIP: for initial debugging, adjust your supply voltages on your protoboard to a low value still adequate to operate the device: 6 volts. (After things are working reliably, you will adjust these to 9 volts for full power later.)

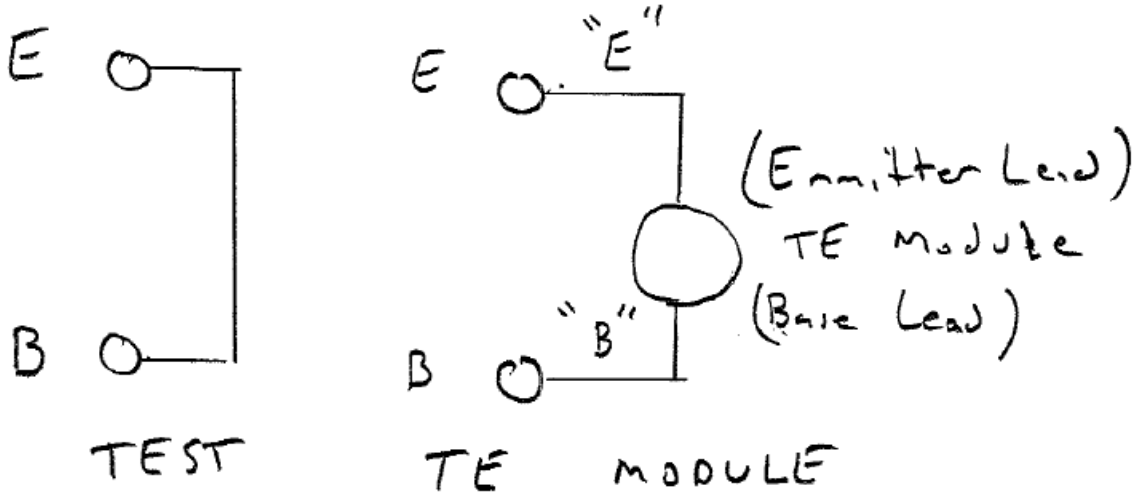
Table 1: Components

R_1	10 kΩ
R_2	22 kΩ
R_3	470 Ω
C_1	10 μF (or 4.7 μF)

First we will debug the differential amplifier without using the TE module. Instead of using the TE module to close the feedback loop in our circuit, we use a small section of wire shorting connections "E" and "B" (see Fig. 4). Note that while E and B are shorted together for this test, it will not be the case that E and B are shorted together when we connect the TE module. So when we say measure the voltage V_E at E, make sure you have the correct position (end of feedback resistor opposite the LF411)!

Thoroughly debug your differential amplifier with the following checks:

- Play with the settings of the Arduino software. Make sure you can set the manual (constant) Arduino output voltage (`vman` in the sketch) to any value you like between −2 V and +2 V. (At this point, there is software protection limiting your range.)
- Change the `vman` setting to several different values between −2 V and +2 V. Confirm that the voltage V_E is this value scaled by a small gain factor between about 1.0 and 1.2.



(a) (c)

Figure 4: Two alternatives for closing the feedback loop. For initial testing, we do not use the TE module and close the feedback loop with the short circuit (a). After testing, we'll connect the TE module as shown in (b) and described below.

- Confirm that you have approximately the same gain factor for both positive and negative voltages. (If not, you probably forgot that the feedback resistor at $V-$ and grounding resistor at $V+$ must have the same value (22 kΩ). Check the circuit diagram!)
- With both filter capacitors removed from the circuit, measure the AC ripple voltage at V_E for an output voltage of +2 V and −2 V. With the filter capacitors in place, confirm that the ripple voltage drops to something below 10 mA at both +2 V and −2 V. (You can also check this with a scope if you would like.)
- Return your multimeter to measure the DC output voltage at V_E. Set `vman` to zero and confirm that you measure 0 V at V_E.

5 Connecting the Thermoelectric Device

You are now ready to connect your thermoelectric (TE) device! The TE device requires more current than your protoboard or Arduino can supply, so each lab setup includes two 3 A power supplies. These supplies are ganged together (see Fig. 5) with the positive output of LOWER supply connectd to the negative output of the UPPER,and to the ground of your proto-board. With this arrangement, the postive (red) output of UPPER supply provides a POSIVE voltage relative to ground, while the negative (black) output of the LOWER supply provides a NEGATIVE volrage relative to ground.

Check the following:

- Verify that the ground connections are connections are correct. With nothing else connected, turn on each suply and use a multimedia to adjust the voltage setting to +8 V and −8 V. Make sure that your multimedia is grounded to the protoboard ground and confirm that the polarity is correct!

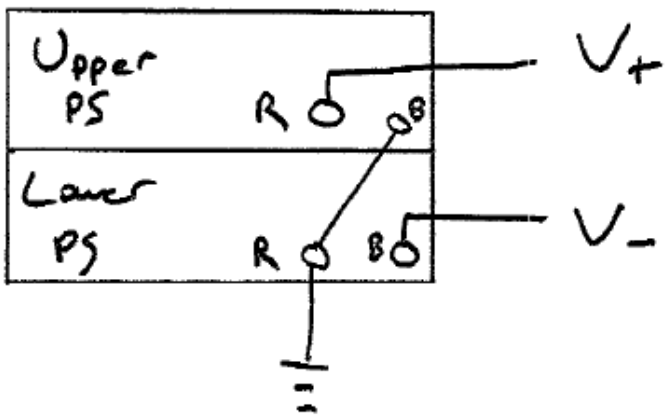


Figure 5: Two powersupplies ganged together to provide a postive and negative supply voltage.

- Turn both supplies off. Now connect the supplies to the TE board as follows: Negative supply voltage to GREEN, ground to BLACK, and postive to RED. (These should also be labeled -, ground, +).
- Turn on the negative (LOWER) supply, and confirm that the fan located underneath the TE turns on. Turn on the UPPER supply. Confirm that the current draw is nearly zero. Turn off both supplies.
- Check that the 8 volt supplies are both OFF and that the measured output of your differential amplifier measured at point "E" is zero.

Next, *remove the short cicuit between points "E" and "B"*. This was only for testing, do not leave the short circuit when connecting the TE module! Connect the emitter (labled "E") of the TE module to point "E" in your cicuit. Connect the base (labeled "B") of the TE module to point "B" in your circuit. Check that the voltage measured at point "E" is still zero. Do not attempt to change this voltage while the 8 V supplies are off.

If you did everything correctly so far, you are probably NOT about to burn out a power transistor on the Thermoelectric (TE) module. We'll see! Turn on the lower supply, check that the current is nearly zero. Turn on the upper supply, check the current is nearly zero. Check that V_E is still nearly zero.

Ready? Change the manual (constant) voltage setting in the Arduino (`vman`) to 1 V and upload the sketch. Check that the V_E changes to a value of around 1.1 V. You should see a small current draw in the UPPER supply (less than 0.5 A) and no current in the LOWER supply. Change the `vman` to -1 V and repeat. You should see V_E change to value of around -1.1 V and a small current draw in the LOWER supply.

Adjust the supply voltages on your protoboard to plus and minus 9 volts.

Now change the value of `vman` between positive and negative 2 V. Using the the serial monitor, you should see the effect of the temperature changing: the thermistor resistance should change, which should change the output of your voltage divider circuit, which should change the reported voltage V_x in the serial monitor. Some of the TE modules are wired such that the a positive value of `vman` tends to decrease V_x (positive control cools the aluminum block) while negative values of

`vman` tends to decrease V_x (negative control voltage warms the aluminum block). But some modules have opposite polarity! Take note of the polarity of your module (does postive `vman` cool or warm your block?)

Remove the software limits on the output voltage by changing the values of `safe_vout_max` and `safe_vout_min` to +5 V and -5 V. Now, stepping up in units of 1 V, check the current draw at each voltage setting and make sure that you (1) only draw from one supply at a time, and (2) only draw up to around 1 A of current all the way to 5 V.

6 Automatic Control

The Arduino sketch includes a simple themometer mode which simply turns on heating or cooling to specified values once it falls outside the comfort range. It keeps heating or cooling until it crosses the set point within the comfort range, then turns off and waits.

Turn off the manual control and turn on the simple thermostat by setting `manual=0` and `thermostat=1`. Set the cooling and heating amounts to something appropriate for your polarity.

You should be able to control the temperature of the aluminum block to within 10% of a target temperature beween 2 and 3 volts.

Once you can achieve this, you are done with the scripted part of this lab. You are free to leave.

Or, if you prefer, you can improve the feedback algorithm to implement a PID algorithm, and see if you can do better.