

On/Off Temperature Control; Controlling Wall Current with an Op-Amp

1 Objectives

- Introduce the method of *closed loop control* with a sensor and an actuator
- Apply this method to building a rudimentary on/off heater controller that will maintain a sample at a desired temperature

Components used:

- thermistor
- Zener diode
- LED
- relay
- op-amp (as comparator only)
- bipolar transistor

2 Thermistor + Op-Amp + Relay = Sensor + Actuator

We are all familiar with using control circuits like a heating thermostat in the home. In general, a control circuit contains two essential elements:

- A *sensor* that responds electrically to a variable of interest (temperature, pressure, humidity, magnetic field, light level, etc.)

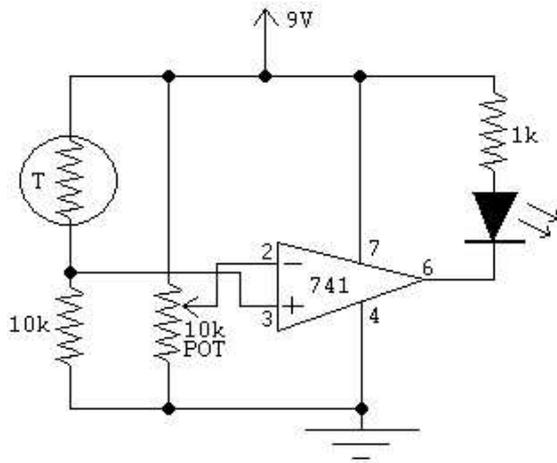


Figure 1: Basic Thermistor sensing circuit, using an op-amp without feedback as a comparator

- An *actuator* (heater, valve, humidifier, current source, light bulb, etc.) that the circuit causes to do something to influence the variable of interest.

In this lab we will control temperature. The sensor to be used is a “thermistor”, which is just a resistor that has a resistance which varies strongly and reproducibly with the temperature. We will use so-called “NTC thermistors”, which means the resistance decreases if the thermistor is heated up. Resistance changes are sensed by “biasing” the thermistor (running current through it) and comparing the voltage across the thermistor to another voltage (the “set point”) representing the temperature we want the sample to stay at.

The actuator to be used is an “AC-powered heater”, in other words something that plugs into the wall. These heaters are rather high-powered devices (50-1000 Watts). Part of the goal of the lab is to see how easily low-powered electronics on our breadboard can be made to control such high powered actuators, using an electromechanical switch called a “relay”.

3 Basic Sensor/Actuator Circuit

3.1 Circuit Explanation

Consider the circuit in Figure 1. This looks complicated but is really is not.

Start by looking at the op-amp inputs. The inverting input is connected to the wiper of a 10K potentiometer, and the ends of the potentiometer are connected to $V_{cc} = +9\text{ V}$ and $V_{ee} = \text{ground}$, respectively. (The op-amp we are using is specified to work with $V_{ee} = \text{ground}$, sometimes called “single-supply operation”) This input setup is of course a voltage divider with variable divider ratio. By adjusting the potentiometer setting we can vary the voltage V_- at the inverting input from 0 to 9 Volts. We will use

the potentiometer adjustment to set the temperature we want the thing to maintain, called the “set point”.

The non-inverting input is connected to another voltage divider, formed by the thermistor T and a fixed 10 K resistor to ground. In use, the thermistor would be in good thermal contact with 03 sample whose temperature we want to control. Remember that the thermistor resistance varies with temperature. So the divider ratio in this divider, and hence the voltage at the non-inverting input, will also vary with temperature.

Since we use an NTC thermistor, the voltage V_+ at the non-inverting input will increase as the temperature increases. (Better think this through.) When V_+ is bigger than the set point V_- , the op-amp output will go high. We will use this output to **turn off** the heater (the sample is already too hot). Whenever V_+ is smaller than the set point V_- , the op-amp output will go low. We will use this output to **turn on** the heater (the sample is still too cold).

To play with this circuit we start out with no sample, just the thermistor on the breadboard (we can change its temperature by touching it with a finger). Instead of a heater we use an LED (light emitting diode) to show whether the heater would be on or off.

Notice that there is no negative feedback applied to the op-amp. This is unusual and in a way is a 17-use of the op-amp. There is another special IC called a “comparator” which should really be used for this. If we wanted to do more sophisticated temperature control (for example reduce the heater current as the set point is approached) we could introduce feedback and get a signal out of the op-amp that was proportional to the difference between actual and set point temperatures.

With no feedback, the high gain of the op amp makes its output just go to one or the other of the power supply voltages in response to any tiny difference ($V_+ - V_-$). This is called “railing” or “hitting the rails”. The power supply voltages V_{cc} and V_{ee} are called the “rails”.

The LED shown in the circuit is there to indicate the state of the op-amp output without having to measure it on a meter all the time. An LED lights when it is “forward biased”, which means conventional positive current flows in the direction of the arrow in the diode symbol. Therefore it will light when the op-amp output goes **low**. When the op-amp output goes high, the LED is reverse biased. That doesn’t hurt anything, but it doesn’t light the thing up either.

So, putting this altogether, when the temperature sensed by the thermistor is less than the set point (controlled by the potentiometer), V_{out} at pin 6 of the op-amp is near $V_{ee} = \text{ground}$, and the LED lights up. When the temperature is higher than the set point, the output is close to

$V_{cc} = +9\text{V}$ the LED has no forward bias voltage across it and does not light. To reverse this behavior, we could switch the inputs to pins 2 and 3 of the op-amp.

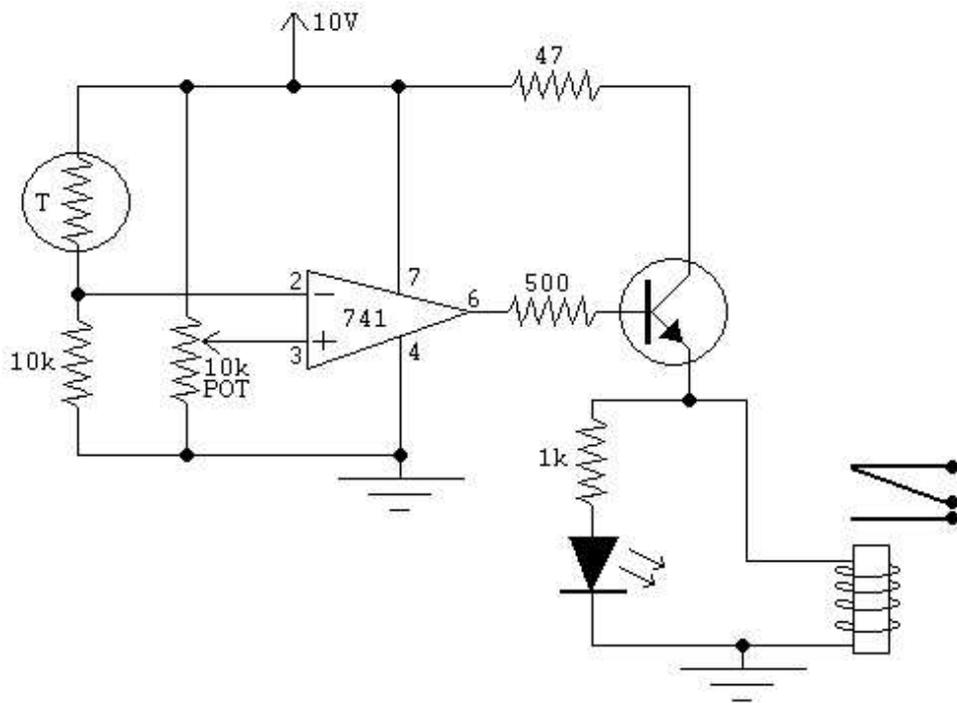


Figure 2: Thermistor sensing circuit with 4 and output driver stage added

3.2 Build It!

1. Build the circuit of Figure 1 on your breadboard. To get the LED oriented properly, the longer lead must go to the positive voltage.
2. Rotate the potentiometer until LED just goes on.
3. Warm the thermistor with a finger – the LED will go off.
4. Wait till thermistor cools – the LED will go on again.
5. Try reversing inputs to op-amp and verify that the operating cycle is also reversed. This could be used to control temperature by cooling rather than heating– or for other purposes (see below).

4 Controlling A Real Actuator with a Relay

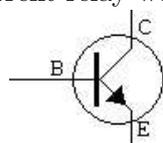
4.1 Circuit Explanation

We wish to use the thermistor to control a "real" heater, not just an LED. A suitable heater requires 1 - 10 Amps, while the maximum output power the op-amp can directly supply is less than 250 mA. To control such a high-current element using the puny op-amp output, we need two additional components. The "relay" is shown at the extreme lower right of Figure 2. A relay is an electrically operated switch. A spring-loaded contact is mechanically "pulled in" (opened or closed) by the magnetic force of a coil. The

coil requires only a low current, low voltage input to operate the switch, but the switch has enough power-handling capability to open or close the 120V circuit. The relay used here actually has two switches in it, one “normally” (with no current in the coil) open (normally open is abbreviated NO) and one normally closed (NC). Of course there are also solid-state relays which have no mechanical moving parts.

For safety reasons, the 120VAC connections don’t go on your breadboard. They are built into an aluminum “chassis” box with connectors for standard “IEC line cords” to supply the 120 VAC input from the wall and output to the heater.

The circuit in Figure 2 also has another complication. A “bipolar transistor” has been added to increase the current available to drive the relay. The bare op-amp output would be marginal for this unless a special low current relay were used. The transistor is denoted by:



. This writeup is not the place for an introduction to bipolar transistors. Suffice it to say that in this circuit the transistor is used basically as a voltage-controlled resistor. When the voltage at B is higher than that at E, terminals C and E are basically shorted together. Current then flows 1 from the 9 V supply through the transistor and into the relay coil and the LED. When the voltage at B is lower than that at E, the transistor acts like a very high resistance (more than a megohm). No current flows through the transistor. The advantage of using a transistor in this way is that very little current (microamps) is required from the op-amp input to drive the B input, while the EC side of the transistor easily handles several hundred milliamps of drive current needed for the relay coil.

Note also that the input connections to the op-amp have been reversed in Figure 2. This allows the “normally open” contacts of the relay to be used to run the relay.

4.2 Build It!

1. Build the circuit of Figure 2, using a 2N222 transistor. The data-sheet shows the pin-out. Use the relay boxes provided but do not connect any 120 VAC for now.
 - 2) Test in the same manner as for the previous version, warming and cooling around the set point. You can hear the relay clicking as it is turned on and off. The LED should also light when the relay is energized.
 - 3) Check the state of the relay outputs (NO and NC) when the measured temperature is above set point. Which set is doing the right thing to power a *heater*?

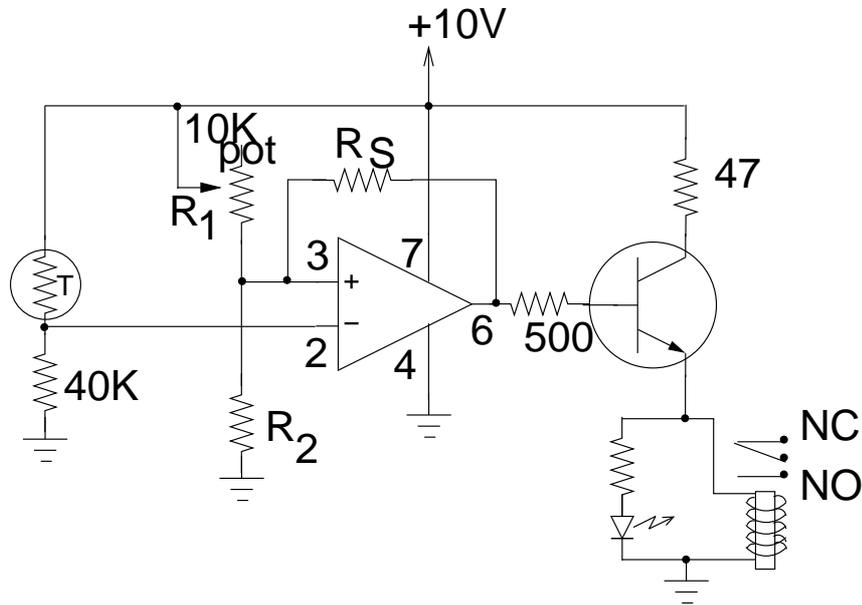


Figure 3: Thermistor sensing circuit with relay and output driver stage added

5 Final Circuit

5.1 Improving the Stability with Schmitt Trigger

Figure 3 shows the final circuit. Notice that the setpoint circuit has been changed. There is now a fixed resistor R_2 to ground. The 10K pot is now being used as a single variable resistor. Only two of its three terminals are connected to anything—the “lower” end and the wiper. The upper end is not connected to anything.

Also new is the *positive* feedback resistor R_S . The reason for putting this in is explained below.

During testing you may have noticed the relay “buzzing” - chattering open and closed very rapidly as the temperature fluctuates very slightly around the set point. Even if your setup did not exhibit this behavior, it is generally a problem with simple on/off controllers like this. You can imagine what would happen if this behavior occurred in a circuit controlling a 100 KW gas furnace in a house.

To eliminate the chattering behavior we use an electronic fix called a Schmitt Trigger. Basically what this does is *change the setpoint* a bit depending on whether the output state is on or off. Say the temperature is low and the heater is on. After awhile the sample warms up, the setpoint is exceeded, and the heater turns off. With the previous circuit (Figure 2, as soon as the heater goes off and the sample barely cools off, we will again be below the set point temperature and the heater will be turned on again. Hence the chattering. What we would like is to slightly *lower* the setpoint

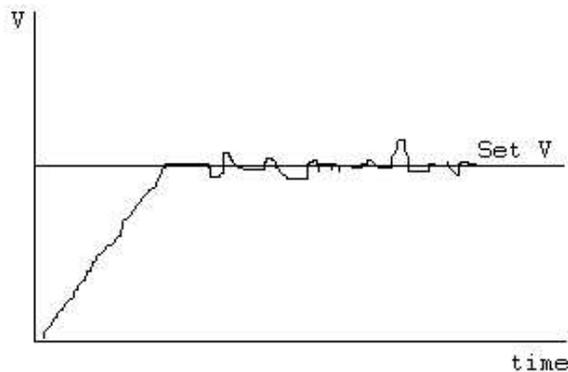


Figure 4: Temperature vs. time plot for circuit of Figure 2, no Schmitt Trigger. Temperature is tightly controlled but heater is cycled on and off very rapidly.

every time the heater turns off because the old setpoint was exceeded. That way it will be awhile before the sample cools below the new setpoint and calls for heat again. This is amazingly easy to do with a Schmitt Trigger. We trade a little looser control of the actual temperature for not wearing out our expensive gas furnace ignitors.

The Schmitt trigger consists simply of resistor R_S connected as *positive* feedback. Say we initially start adjusting the set point with the op-amp output low (output at ground; set point temperature below sample temperature). Then R_S is connected to ground in parallel with R_3 . The set point voltage we get will be slightly smaller than $10V * R_3/(R_3+R_4)$. This does not really matter, we just adjust it to the desired temperature.

But the magic occurs when the sample heats up and the op-amp output goes high (10 Volts), R_S is then connected to 10 V in parallel with R_4 . *This changes the setpoint.* The setpoint voltage divider ratio is now *higher* than it was before, due to the extra resistor R_S now in parallel with R_4 . A higher setpoint voltage corresponds to a *lower* set point temperature because we are using an NTC thermistor.

The effect on sample temperature control can be seen from Figures 4 and 5.

To determine the proper value for R_S some design decisions and calculations are required.

5.2 Design of Schmitt Trigger

First off, notice a mathematical fact about the equation for resistors in parallel. Say we want to figure out what resistor R_p to put in parallel with some existing resistor R , to get a parallel combination with 1% lower resistance than R alone. Some algebra or just trial and error should convince you that $R_p = 100 R$ will accomplish this. In general to get a parallel resistance $(1-\delta)R$, (for small δ) we need to put in parallel $R_p = R/\delta$. Conversely, we can see that $\delta = R/R_p$. The per cent effect of adding a given resistor in parallel is less, the larger the resistor to which it is added in parallel.

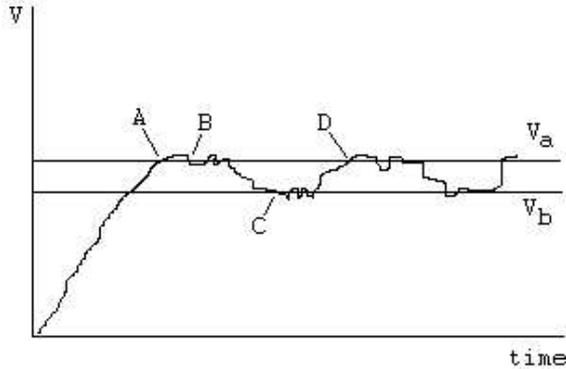


Figure 5: Temperature vs. time plot for circuit of Figure 3, including Schmitt Trigger. Note the “dead zone between upper and lower set points, which reduces heater cycling.

Secondly, consider the effect on the voltage divider ratio if we change one of the resistors. If we change R_1 by a fraction δ the ratio becomes:

$$V_{out} = V_{in} \frac{R_1(1 + \delta)}{R_1(1 + \delta) + R_2} \quad (1)$$

Applying the binomial theorem to expand the denominator and keeping only terms up to first order in the small parameter δ we obtain:

$$V_{out} = V_{in} \frac{R_1}{R_1 + R_2} \left(1 + \delta - \delta \frac{R_1}{R_1 + R_2}\right) \quad (2)$$

What this says is the following. If R_1 (the one we changed) is by far the smaller of the two resistors, the first δ term dominates and so the divider ratio also changes by a fraction δ . If R_1 is by far the larger, then the two δ terms nearly cancel. The fractional change in the divider ratio is smaller than δ by a factor of the (small) divider ratio itself. Finally, if R_1 is about equal to R_2 , the divider ratio changes by a fraction $\sim \delta/2$.

In Figure 3 let's choose $R_2 = 40K$, the same as the resistor forming a divider with the thermistor. Since the thermistor resistance ranges from about $0.5K\Omega$ to $2.5K\Omega$ depending on temperature, the variable resistor formed out of the $10K$ pot will cover that same resistance range depending on the desired temperature. So we have $R_1 \ll R_2$. Now consider the case $R_S \gg R_2$. According to the above discussion of parallel resistors and voltage dividers, the biggest change in the divider ratio for the setpoint divider will take place when R_S is switched into parallel with R_2 , changing by a fraction $\delta \sim R_2/R_S$. So to pick the value of R_S to use, we should decide how much we want the set point to change when the op-amp switches.

Referring to Figures 4 and 5 we see that the set point change leads to a range of temperature fluctuations. For a household thermostat, fluctuations of say $2^\circ C$ would be acceptable. For scientific applications, more precise control might be necessary. The choice here also depends on how much heater cycling we can tolerate. For this example we will choose a setpoint change equivalent to $1^\circ C$. Using the thermistor calibration data provided,

calculate the change of setpoint divider ratio that is equivalent to this temperature fluctuation, and from there get the value of R_S . (hint: Show that the thermistor resistance changes by about 3.5% per °C near 60 °C. Since the ratios for the thermistor divider and the setpoint divider are similar, we want R_2 to change by about this much when R_S is switched in.)

5.3 Run It!

1. Build the circuit of Figure 3. For initial testing without the heater, the relay leads can be left un-connected and the thermistor can be left on the breadboard.
2. Verify that the Schmitt trigger provides separate heater-on and heater-off setpoints. Explain exactly what you measured to verify this.
3. Choose a set point temperature in the range 30 - 60 °C and calculate the corresponding value of R_1 using the thermistor calibration data provided. Show your calculation to the instructor.

Next, prepare for testing with the relay and heating appliance.

4. Use half-a-meter of hook up wire to connect the relay leads to the relay box. Verify operation of the relay box *before applying AC power* and have the instructor check it.
5. When the instructor gives the OK, connect the IEC line cords to the wall plug and the heater appliance.
6. Move the thermistor off the breadboard (use hook up wire to extend its leads), and put it in good thermal contact with the sample. Results will be more interesting if the sample has a significant but not too large heat capacity, for example one of the drilled graphite blocks provided. Have the instructor verify your setup.
7. Operate your controller, monitoring the temperature of the sample using a passive, visually read thermometer provided. Watch and record the temperature and the amplitude of its fluctuations. Compare with expected values.

5.4 Extra Credit—Chart It!

It is interesting to chart the temperature vs. time to compare with Figures 4 and 5. An old-fashioned ink-on-paper X-Y recorder is available in the lab for this. Why not hook the recorder inputs directly to pin 2 and ground?

To run the recorder, put the thermistor voltage through an op-amp buffer and then to the chart recorder input. (The chart recorder input requires a signal range of 0 - 5 V and draws several mA of current). See if you can get curves like Figures 4 and 5 by keeping and removing R_S .