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## Experiment C2 Analog Thermostat Procedure

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Deliverables: Checked lab notebook, Technical Memo

### Overview

A thermostat is a device that turns an actuator ON or OFF depending on the input from some sensor. Because of their abrupt switching, thermostats are often referred to as “bang-bang” controllers. The most common example is in an HVAC system, where the furnace or air conditioning is turned ON or OFF depending on the measured temperature in the room.

In this lab, you will use a famous analog Op-Amp circuit known as a “Schmitt trigger” to switch a heater or a fan, depending on the temperature measured by a thermistor. The same circuit will also be used to switch a pressure relief valve depending on the measured pressure in a cylinder. The Schmitt trigger has a special feature known as *hysteresis*, where the threshold voltage changes depending on whether the output is ON or OFF. This hysteresis prevents the thermostat from slipping into rapid oscillation.

### Part I: System Identification and Characterization

#### Background

The resistive heater and thermistor used in this lab will be modeled as a lumped thermal mass. When the heater is off and the system is cooling, the thermal energy balance takes the form

$$mc_p \frac{dT}{dt} = Ah(T_{Air} - T), \quad (1)$$

where  $T$  is the temperature of the system,  $T_{Air}$  is the temperature of the ambient air,  $m$  is the system mass,  $c_p$  is specific heat,  $A$  is the surface area, and  $h$  is the heat transfer coefficient. When the heater is on, the energy balance becomes

$$mc_p \frac{dT}{dt} = Ah(T_{Air} - T) + q, \quad (2)$$

where  $q = iV$  is the heater power. Equations (1) and (2) can be rewritten as

$$\tau \frac{dT}{dt} = T_{Air} - T, \quad (3)$$

and

$$\tau \frac{dT}{dt} = T_{Air} - T + S, \quad (4)$$

where  $\tau = mc_p/Ah$  is the time constant and  $S = q/Ah$  is the source term. The values of  $T_{Air}$ ,  $\tau$ , and  $S$  are unknown and must be experimentally measured.

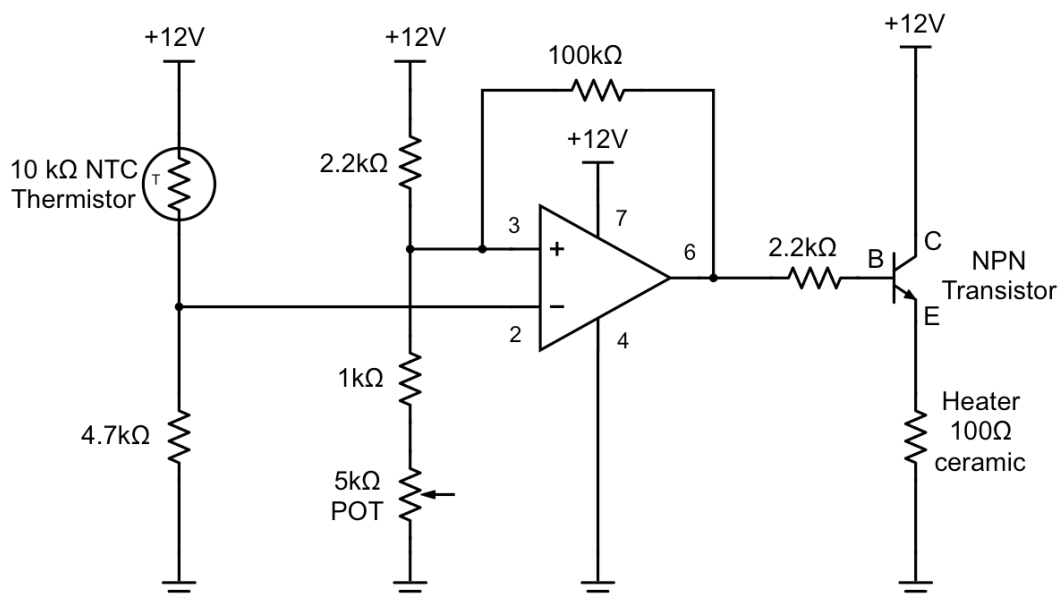
## Experimental Procedure

In this portion of the lab, you will measure  $T_{Air}$ ,  $\tau$ , and  $S$ .

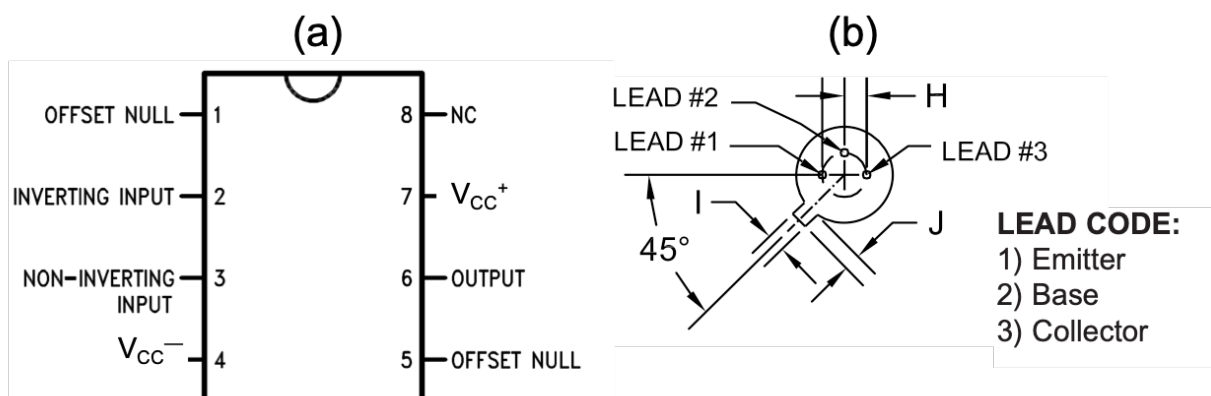
1. Use the alcohol thermometer to measure the temperature of the air in the lab  $T_{Air}$ . Record the value in your lab notebook.
2. Construct the thermistor voltage divider circuit from last week's lab near the bottom of the breadboard. Place a ceramic  $100\Omega$  power resistor in the bread board next to the thermistor. Bend the thermistor so it touches the resistor, and inject a small dab of thermal paste between the two.
3. Connect the output of the voltage divider  $V_s$  to the analog input on the analog input of the USB-6341 and use the LabView program from last week to measure the temperature vs. time at a rate of 4 samples/second. Save a new copy of the program to the C2 folder.
4. Run the LabView program, and apply 12V across the  $100\Omega$  resistor. Watch the temperature rise, and wait for it to get to a steady state maximum  $T_{max}$ . This will take time—be patient!
5. Record the state maximum temperature  $T_{max}$  in your lab notebook. Use the formula you derived in the pre-lab assignment to compute  $S$ . Then calculate the power  $q = V^2/R$  and use it to calculate  $Ah$ .
6. With the LabView program still running, turn off the 12V to the heater. Watch the temperature drop.
7. When the thermistor temperature gets close to the ambient air temperature, stop the program and save the data to your C2 folder.
8. Use the data to determine the time constant  $\tau$ . Use it and your value of  $Ah$  to calculate  $mc_p$ .

## Part II: Implementing and Testing the Thermostat

A Schmitt trigger Op-Amp circuit is used to create a thermostat. The output of the Op-Amp is 0V if the input  $V_- > V_+$ . Conversely, the output is +12V if the input  $V_- < V_+$ . Note that the input  $V_-$  is connected to the output of the thermistor voltage divider circuit, such that  $V_- = V_S$ . The threshold voltage (or set point) connected to  $V_+$  can be adjusted by turning the 5k $\Omega$  potentiometer. Applying +12V to the base of the NPN transistor (relative to the emitter) turns ON the transistor and allows current to flow from the collector to the emitter and down through the heater.



**Figure 1** – An analog thermostat circuit uses a Schmitt trigger Op-Amp circuit. The Op-Amp is “triggered” by the thermistor voltage divider circuit. The output of the Op-Amp drives the base of an NPN transistor and switches the 100 $\Omega$  heater ON and OFF.



**Figure 2** – The pin-out for (a) the LM741 Op-Amp and (b) the NPN transistor.

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## Experimental Procedure

1. Sketch the circuit shown in Fig. 1 in your lab notebook.
2. Sketch the pin-outs shown in Fig. 2.
3. Construct the potentiometer portion of the circuit that is used to adjust the set-point voltage. Test to make sure it work. Use the multimeter to measure the set-point voltage, which will eventually be connected to Pin 3 of the Op-Amp. Turning the knob, you should see this voltage change from approximately 3.5V to 10V.
4. Construct rest of the circuit. Refer to the pin-outs in Fig. 2. The thermistor should still be in thermal contact with the heater.

**Pro-tip:** Be thoughtful when you choose colored breadboard wires. It is extremely difficult to debug a circuit when every wire is the same color.

5. Test the circuit. Use the handheld DMMs to measure the sensor output  $V_S$  and heater voltage.
6. Create a copy of the LabView program from Part I. Rename it with an intelligent file name (i.e. C2\_thermostat\_yourName.vi).
7. Use the USB-6341 to measure the analog voltages across the heater and the set-point voltage going into the Schmitt trigger (pin 3).
  - a. Double-click the “DAQ Assistant” icon in your while loop and press the “Add Channels” button to add two more voltage measurements to ai1 and ai2.
  - b. Make sure both channels are set to “1 Sample (On Demand)” and “RSE” terminal configuration.
  - c. Right click the “data” wire coming out of the DAQ Assistant icon and select “Signal Manipulation Palette” > “Split Signals”.
8. Cut off two more strips of wire (new colors) and make the appropriate connections from the USB-6341 to the breadboard. Press “Run” in the DAQ Assistant window to make sure it works.
9. Configure the data wires coming out of the DAQ Assistant.
  - a. Right click the “data” wire coming out of the DAQ Assistant icon and select “Signal Manipulation Palette” > “Split Signals”.
  - b. You may also need to convert each dynamic data wire to a double. Right click the “data” wire, select “Insert” > “Signal Manipulation Palette” > “From DDT”. Then in the pop-up window, select “Single scalar” for the resulting data type, and click OK.
10. Use expression nodes to convert the set-point voltage to temperature. Use the same formulas from the C1 pre-lab to map the analog voltage to temperature.
11. Use more expression nodes to convert the heater voltage to power in Watts.
12. Add a numeric *indicator* to display the set-point temperature on the front panel.
13. Add another shift register to the loop and save the heater power values into a new array.

14. Add an express XY graph to the front panel that displays the heater *power* as a function of time, similar to the temperature graph.
  - a. Right click a blank spot in the Front Panel, go to “Express” > “Graph Indicators” > “XY Graph”, and. place it somewhere in the front panel.
  - b. Ctrl + e back to the block diagram and wire up the relevant arrays to the x and y data inputs.
15. The heater power should also be saved, along with the temperature and time when the program is stopped.
16. Test the thermostat with the LabView program. You should see the temperature rise to the upper set point  $T_{HS}$  then fall to the lower set-point  $T_{LS}$ , as the heater cycles ON and OFF. You should also see the set-point displayed on the front panel switch between  $T_{HS}$  and  $T_{LS}$ . Record the values of  $T_{HS}$  and  $T_{LS}$  in your lab notebook.
17. Measure traces of temperature and heater power vs. time for two different temperature set-point, one near 305 K and another near 325 K. Save the data. Record data for long enough that you see at least 3 full cycles of the thermostat.
18. Increase the set point by turning the 5k $\Omega$  potentiometer knob and record more traces.
19. Take a screen shot of the front panel and block diagram code.
20. Disassemble your circuit. Use paper towel to clean off the thermal paste. Return all components to their appropriate bins. Carefully store everything in the large tote and place it the cabinet above your lab bench.

## Data Analysis and Deliverables

Using LaTeX or MS Word, make the following items and give them concise, intelligent captions. Make sure the axes are clearly labeled with units. Plots with multiple data sets on them should have a legend. **Additionally, write several paragraphs describing the plots/tables. Any relevant equations should go in these paragraphs.**

1. Make a table containing the relevant values you measured in Part I: temperatures  $T_{Air}$  and  $T_{max}$ , heater power  $q$ , and the time constant  $\tau$ . Then, use the equations you derived in the pre-lab assignment to determine values  $mc_p$  and  $Ah$ , and include them in the table, as well. Be careful with units!
2. Make two separate plots of the measured temperature and heater power vs. time for the two different set points. Use the 'yyaxis' command in Matlab to plot temperature on the left axis and heater power on the right axis. Be sure to include a legend.
3. Make a table containing the measured periods and duty cycles, as well as the theoretical period and duty cycles for the two data set collected in Part II.
  - a. Use the values of  $T_{Air}$ ,  $\tau$ ,  $mc_p$ , and  $Ah$  from Part I, the set points  $T_{LS}$ ,  $T_{HS}$ , and the heater power  $q$  recorded by LabView from Part II, and the equations you derived in the pre-lab assignment to predict the period of oscillation and duty cycle.
  - b. The table should compare the predicted period and duty cycle to what was observed in Part II.
  - c. Use the high set point values  $T_{HS}$  to distinguish the values from the two different data sets.

**Talking Points** – Discuss these in your paragraphs.

- What are the limitations of the thermostat? How might you overcome these limitations?
- Does the duty cycle increase or decrease with the set-point? Does this make sense?
- Please include the equations you derived in the pre-lab assignment as numbered equations in the technical memo.

## Appendix A

### Equipment

#### Part I

- Breadboard
- NI USB-6341 DAQ
- PC computer with LabView
- LM741 Op-amp
- 2N2222 NPN transistor
- 5k potentiometer

#### Part II

- PC computer with LabView
- Vishay NTCLE100E3103JB0, NTC Thermistor 10k Bead (Digikey part # BC2301-ND)
- 4.7k $\Omega$  resistor