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Report on Dynamic Temperature control of a Peltier device using bidirectional current source

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A bidirectional current source is needed so as to exploit the Peltier device's heating and cooling phenomenon: one face of the device heats up when current flows in one direction and the same face cools down if the current through it flows in the opposite direction.

The idea is to use transistors as voltage to current amplifiers. The op-amp is used to complement the same purpose: it provides the initial voltage signal at the base of transistor so that the transistor may operate at such aDC-biased base voltage configuration wherecurrent to voltage amplification takes place. Another consideration is the fact that the DAQ (we use DAQ as out input voltage source) only provides a certain amount of output voltage. Keeping this practical constraintin view, the op-amp or any voltage to voltage amplification device becomes a necessary part of the circuit.

Following circuit diagram containsthe current source (the left half of the picture) along with the thermistor (the right half of the picture).

Mainly, following components have been used:

- Dual polarity power supply
- 741 Op-amp
- Resistors of various values as indicated in the diagram above
- BJT BD 243C (NPN transistor)
- BJT BD 244C (PNP transistor)
- Betatherm NTC thermistor 2.2k3A359I
- NI-USB 6001
- Peltier device, labelled as LOAD in the above diagram

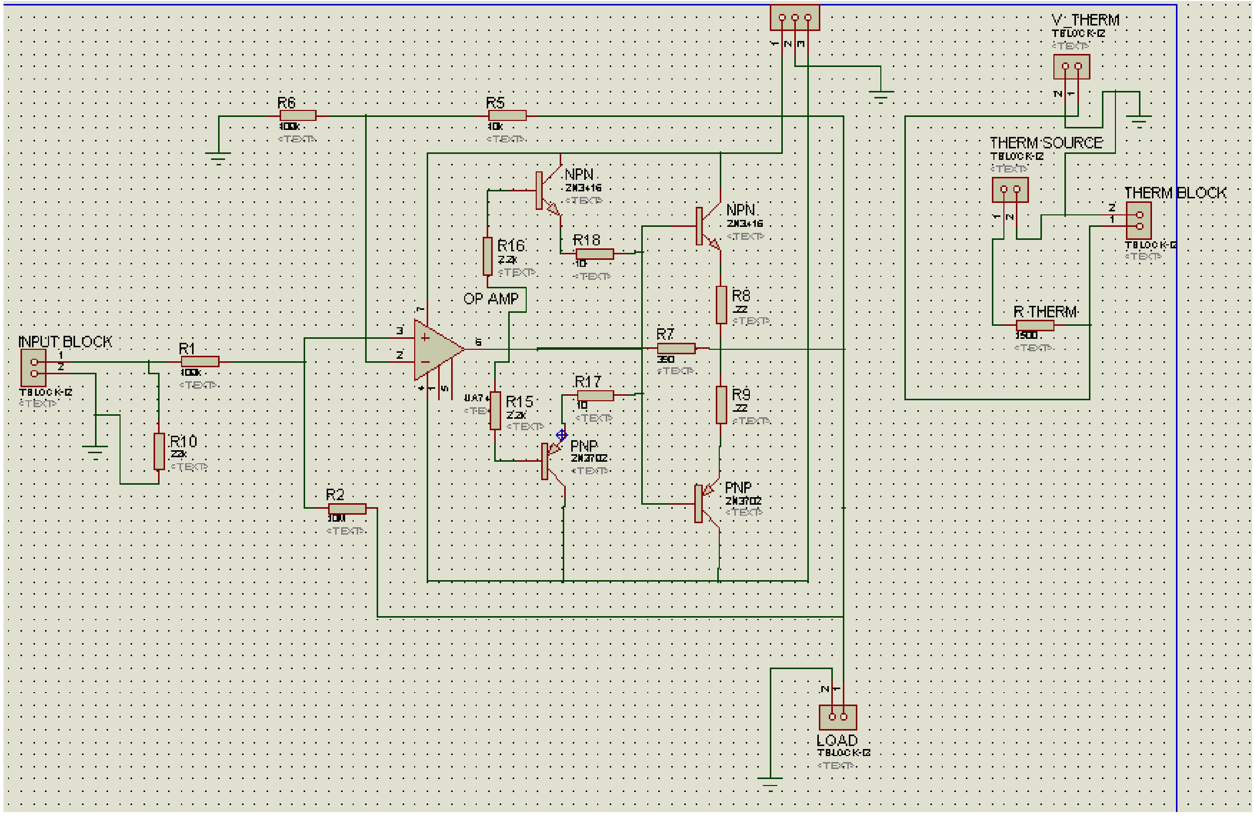


Figure 1: Circuit schematic for temperature control of a Peltier device

As depicted in Figure 1, the input voltage is amplified and hence applied at the base of the transistors. Depending on the polarity of the signal, the relevant transistor starts to operate, the explanation of which lies in the device characteristics. So the two possible current paths are depicted in Figure 2 and Figure 3.

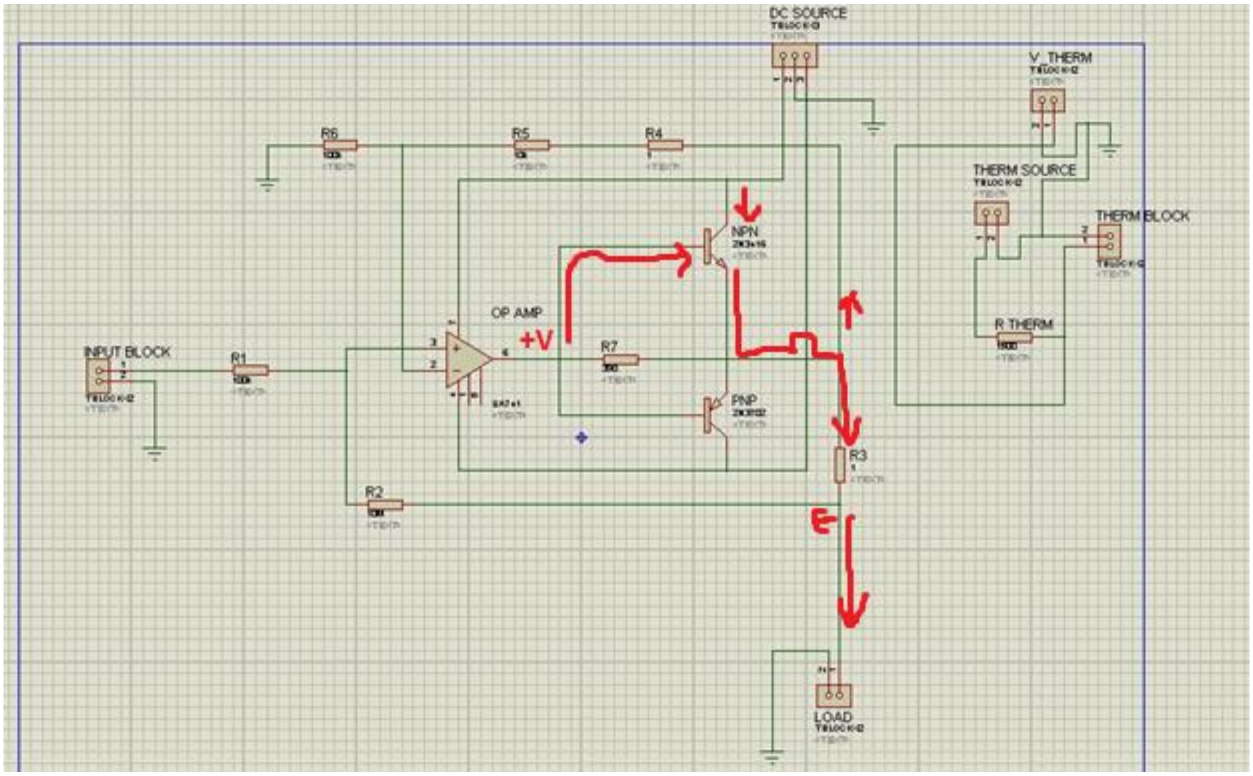


Figure 2: A simplified diagram of NPN transistor when it is operational and PNP is off

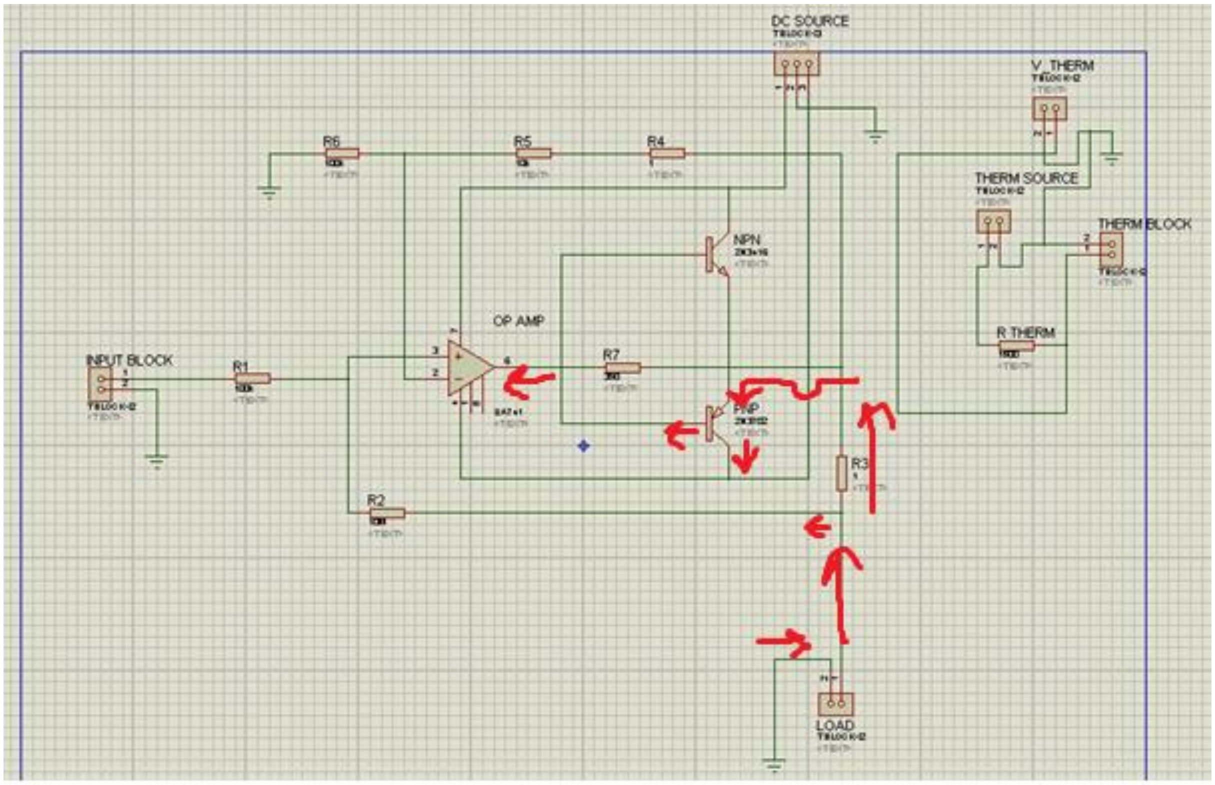
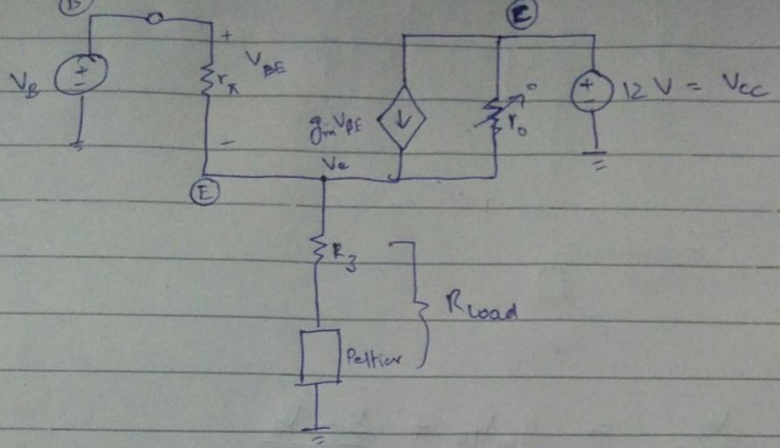


Figure 3: A simplified diagram of when PNP transistor is operational and NPN is off

Following is a basic analysis on a single (NPN) transistor's current path and a justification for the load getting the sum of the currents drawn from base and collector:



Ignoring the Early effect ⇒ $r_o = \infty$

We form two loop equations to check whether $i_e = i_c + i_b$

$$\frac{V_e}{R_{load}} = g_m V_{BE} + \frac{V_{BE}}{r_\pi}$$

$$\frac{V_e}{V_{BE}} = R_{load}\left(\frac{g_m r_\pi + 1}{r_\pi}\right)$$

$$\frac{V_B - V_e}{V_e} = \frac{r_\pi}{R_{load}(g_m r_\pi + 1)}$$

$$\frac{\cancel{B}\, V_B}{V_e} = \frac{r_\pi}{R_{load}(g_m r_\pi + 1)} + 1$$

$$V_e = \frac{V_B}{\dfrac{r_\pi}{R_{load}(g_m r_\pi + 1)} + 1}$$

⇒ $V_B > V_e$ for $V_B > 0$

⇒ Current flows from base and collector to emitter.

Another equation also justifies the current ~~flo~~ path in the following way :-

$$V_{CC} = \left(g_m V_{BE} + \frac{V_{BE}}{r_\pi} \right) R_{Load}$$

$$\frac{V_{CC}}{V_{BE}} = \frac{g_m r_\pi + 1}{r_\pi}$$

$$V_B - V_E = V_{CC} \left(\frac{r_\pi}{g_m r_\pi + 1} \right)$$

$$V_B - V_{CC} \left(\frac{r_\pi}{g_m r_\pi + 1} \right) = V_E$$

$\Rightarrow$ $V_E < V_B$ $\Rightarrow$ same deduction.

At this stage, it is convincing why the op-amp-transistor scheme is plausible for voltage to current amplification.

A DAQ (NI-USB 6001) is used as the control element: referring to Figure 1, 'THERM SOURCE' is connected to a small supply from a DAQ output port. The thermistor is connected in the 'THERM BLOCK'. The thermistor voltage is fed to the DAQ input via 'V_THERM' outlet. This is used by a LabVIEW to generate a control signal at its output i.e. the 'INPUT BLOCK'. The idea is to feed the instantaneous temperature of the device to a PI control algorithm and then the input is fed back to the circuit in accordance with a set point of the temperature.

DAQ

The control signal, called Vin in this report, is connected to the output of the DAQ (in our case it is terminal 0) and the voltage across the thermistor which is essentially the output is connected to the terminal 0 of the DAQ input. A 2V supply is connected to port 1 of the DAQ output for the thermistor. The + sign is the positive terminal and the arrow (**and not the – sign**) is the ground. The terminal description is true for both input and output. Using NI Automation Explorer, the activity of the DAQ can be checked.

VI and Front Panel

So a control algorithm is applied using LabVIEW and an interface is developed to gauge the instantaneous temperature of the device. An NTC thermistor's Steinhart coefficients are calculated using curve fitting technique. These coefficients are named a, b and c in the VI.

The first grey Formula Node is there to convert the commanded set point value of temperature to a set point voltage. Since the Steinhart coefficients are known, Steinhart equation is applied for the said conversion. A note must be made here. Several approaches such as dealing directly with temperature values may work just as well instead of converting temperature readings to voltages, and that several off-the-shelf VI are available for thermistor calibration, but in this VI all calculations are in voltages and the translation of voltage into temperature is done at the moment of exchange between VI and front panel.

The variables 'excitation_v', 'exc_v' and 'V_exc'all refer to the voltage source value and this source would be connected to excite the thermistor in series with a resistor.

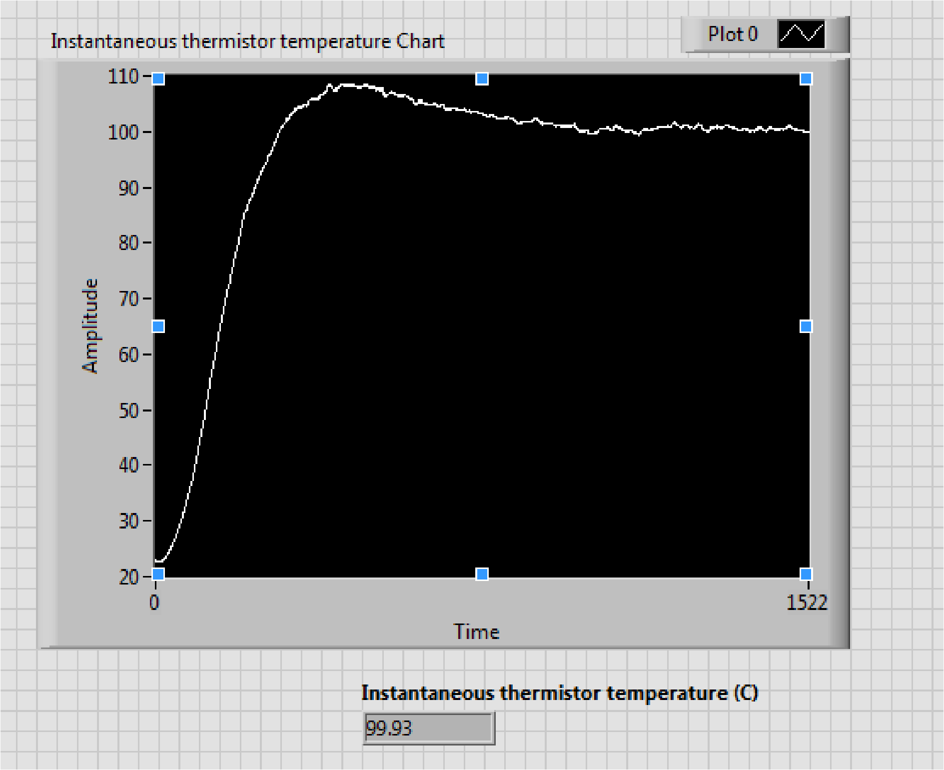
There is a digitizing parameters' control pallet, for adjusting the sampling rate. Now a DAQ Assistant could be used instead of these maroon VIs to configure the input and output terminals, but here this is gives more control over the procedure.

Before moving to the MathScript, the purpose of the second grey Formula Node is discussed. It is just there to translate instantaneous thermistor voltage to instantaneous device temperature. The former is calculated via a simple circuital loop analysis.

In the MathScript lies the core of the VI-a code for PI algorithm. The first line calculates the error between set point temperature and the instantaneous temperature. The blue 'i' at the bottom left of the while loop is the count for number of iterations. A check is made to see if it's the first iteration so as to erase garbage and reset error memory to zero. If it's not the first iteration, the error adds up. This section serves as the integration of error as followed by the generic feedback equation. For the proportional part, the error is just multiplied by a constant. This generates the control signal Vin. At the end of each iteration, the function of e_previous=mem is performed by the yellow box and the two variables at the top of blue case. This is how the sum of error is kept updated for next iteration. Again, the check for stop button comes into place. The variable ‘stop_command’ acts as the alarm running throughout the VI. The control signal Vin is turned off, and stop command updates the red stop button of the while loop.

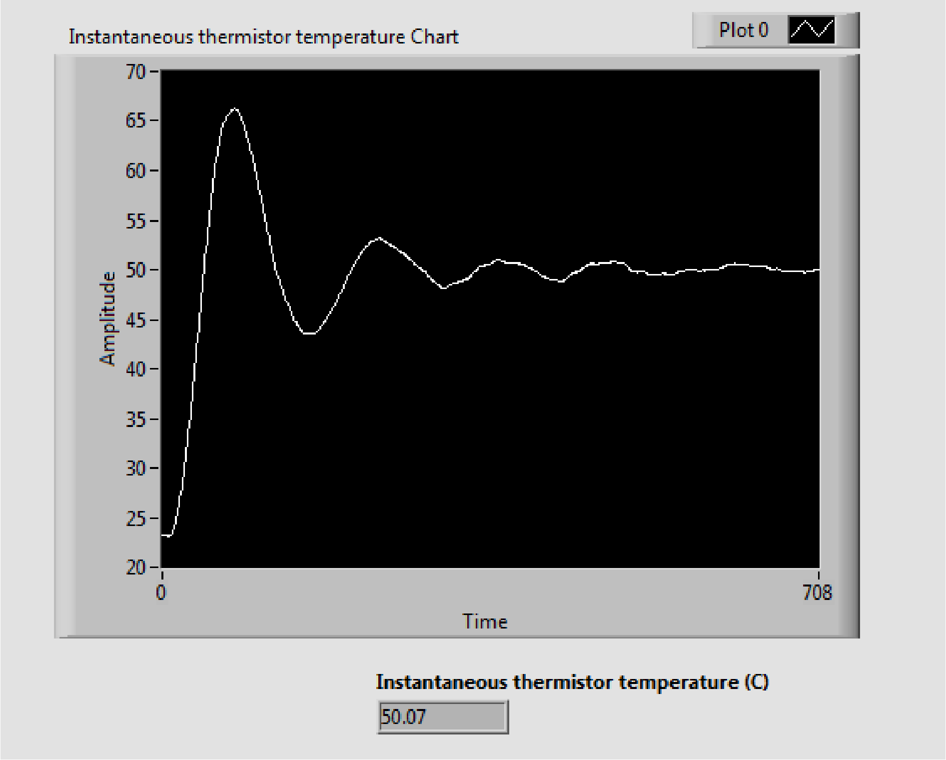
Observations, explanations and frame of conduct

The system is designed for a specific temperature range which is 20 deg C to 100 deg C. This means that parameters such as P, I, and sampling frequency have been tuned with the DAQ output voltage limitations such that if the set point is the extreme of our desired temperature range, the overshoot of the control signal coming through the limited DAQ output stays well within range of the DAQ output voltage. Therefore there is only a certain flexibility that is available in changing these parameters. The VI does not validate this fact when the set parameter values are set. One has to be considerate of choosing the optimal values. Of course, this lack of flexibility makes the process slow but it is safer. To describe this behavior, following two figures are shown. One depicts lesser overshoot and the other depicts more overshoot with lesser time taken.Please note that these two graphs were obtained when real-time-change-of-set-point feature was not installed in the VI which would put more constraints on changing value of the parameters. It is recommended that these parameters may not be changed (in the actual VI) from what values are going to be prescribed in the discussion that follows. A faster VI can be made if the temperature set point control is taken out of the while loop of the VI. With this, real time change of set point feature would be lost.



Instantaneous thermistor temperature (C)
99.93

Figure 4: 100 deg C profile with lesser overshoot



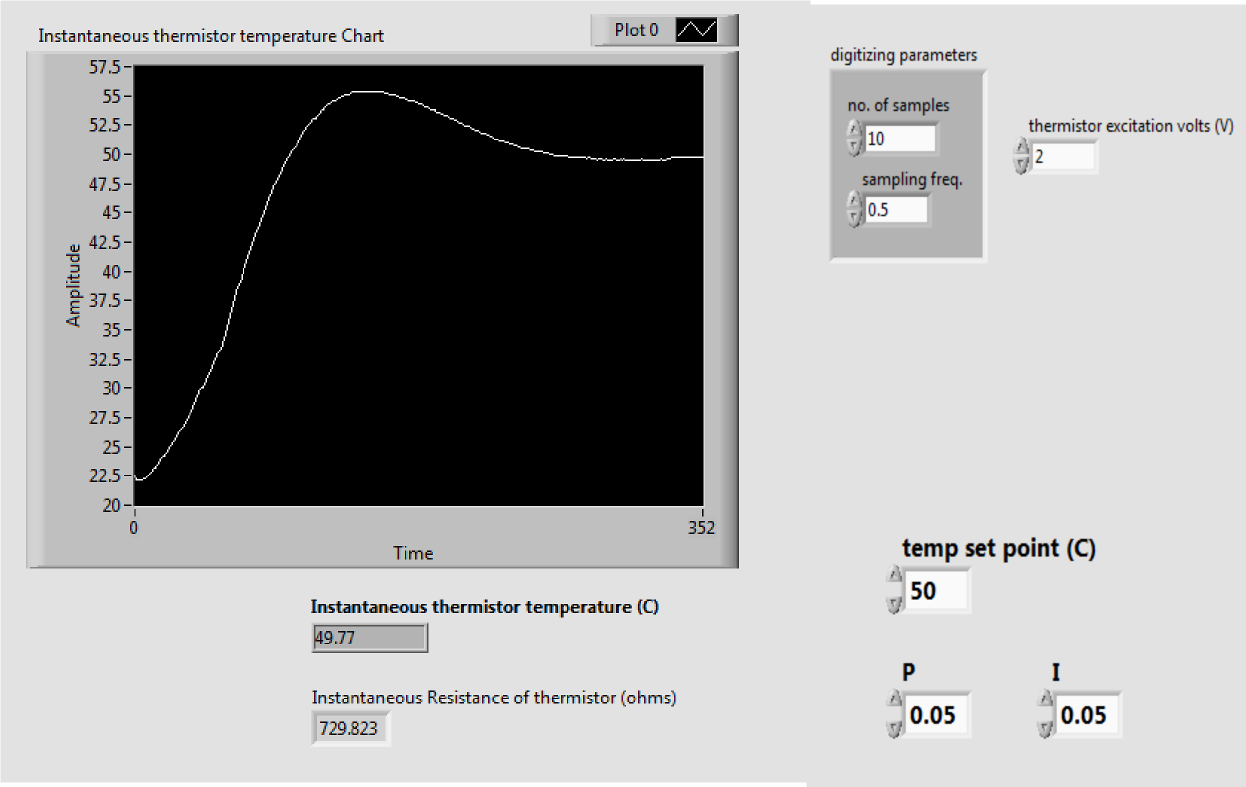
Instantaneous thermistor temperature (C)

50.07

Figure 5: 50 deg profile with higher overshoot

Another feature in the VI which squeezes the flexibility in changing parameters, and hence causes the process to be slower, is that the temperature control is dynamic. Dynamic means that user can change the temperature set-point while the VI is running and approaching a different set point. The fact that this almost fixates the parameter values is first described and then explained below.

Suppose user commands the VI to set the peltier temperature to 70 deg C. The front panel looks like the following figure.



Instantaneous thermistor temperature (C): 49.77

Instantaneous Resistance of thermistor (ohms): 729.823

digitizing parameters

no. of samples: 10

sampling freq.: 0.5

thermistor excitation volts (V): 2

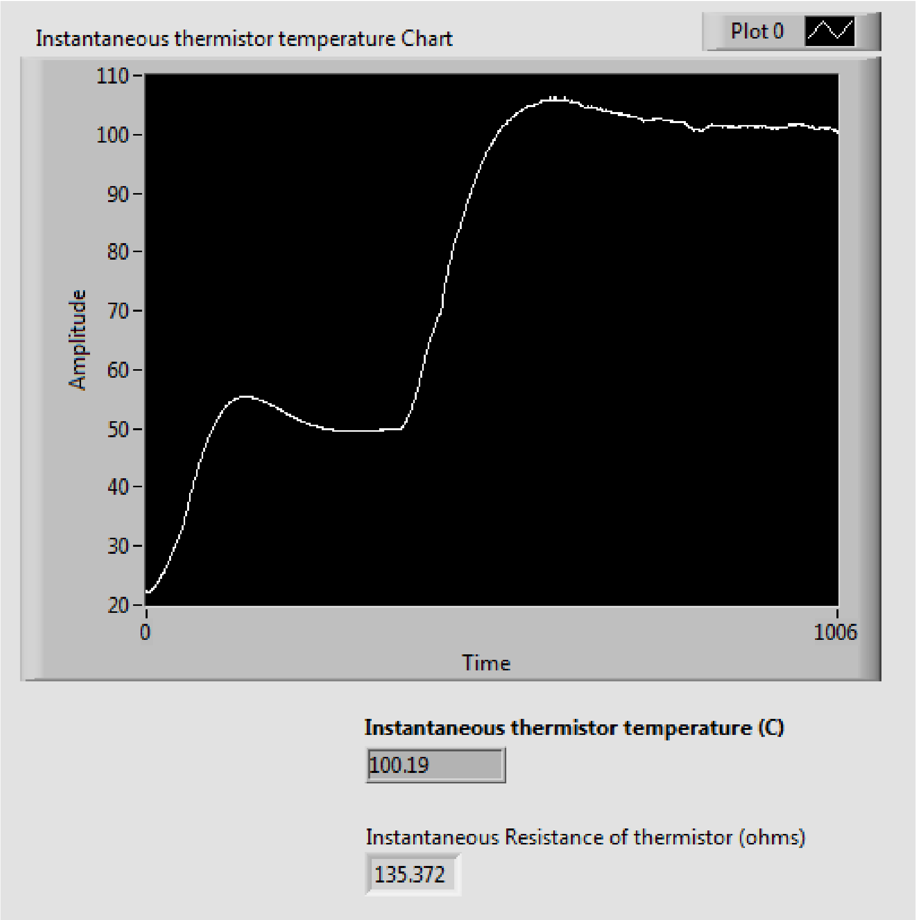
temp set point (C): 50

P: 0.05

I: 0.05

Figure 6: 50 deg C profile

Now suppose the temperature set-point was changed to 100 deg C while the program was running and the temperature was maintained at 50 deg C initially. One does that by simply changing the value under the ‘temp set point (C)’ control on the front panel and then clicking anywhere on the screen. Following behavior is seen. No other parameters were disturbed.

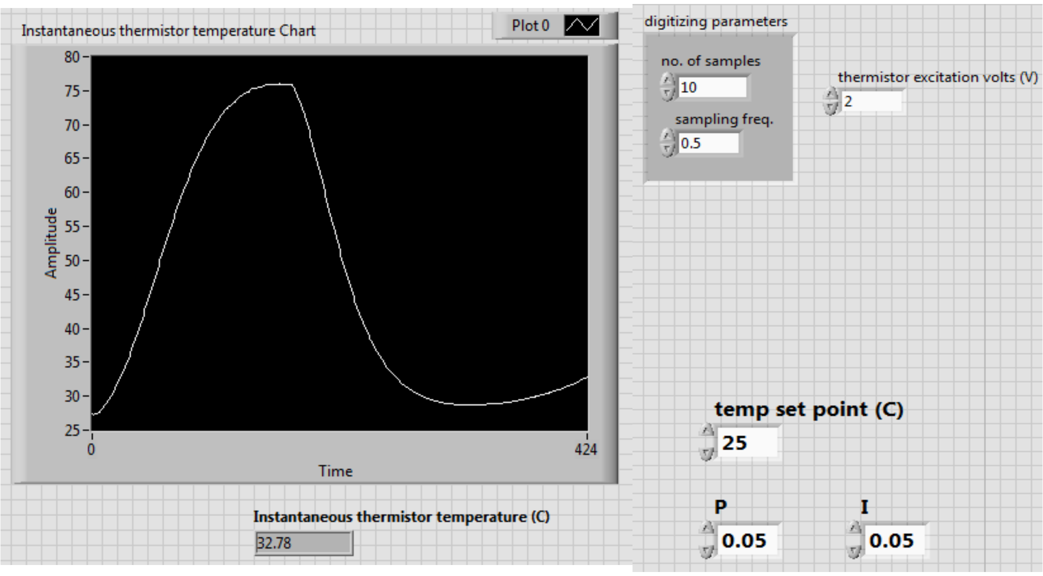


Instantaneous thermistor temperature (C)
100.19

Instantaneous Resistance of thermistor (ohms)
135.372

Figure 7: 50 deg C to 100 deg C profile

Now suppose a different set point for a change. Suppose the temperature set point is 75 deg C in steady state and user changes the temperature setpoint to 25 deg C. Two different things happen if different values of P, I and sampling frequency are used. These two different scenarios are depicted in the following two figures.



no. of samples: 10

sampling freq.: 0.5

thermistor excitation volts (V): 2

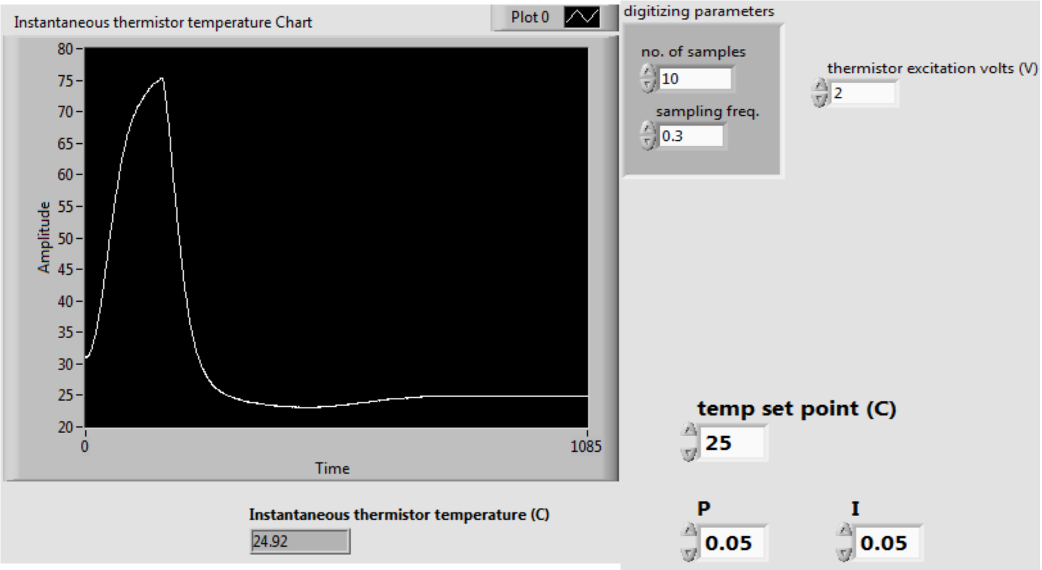
temp set point (C): 25

P: 0.05

I: 0.05

Instantaneous thermistor temperature (C): 32.78

Figure 8: Unexpected scenario for a certain sampling frequency



no. of samples: 10

sampling freq.: 0.3

thermistor excitation volts (V): 2

temp set point (C): 25

P: 0.05

I: 0.05

Instantaneous thermistor temperature (C): 24.92

Figure 9: Correct scenario for a different suitable sampling frequency

This demonstrates the dynamic behavior that is occurring in the system. The focus point is the temperature set point changing from 75 to 25 deg C. Now two independent elements are trying to lower the temperature: the device cooling down itself loosing heat to the surrounding in pursuit of thermal equilibrium and second, the VI changing the control signal.

As shown in the unexpected scenario, with a certain sampling frequency, the temperature does not go to 25 deg C but instead starts increasing at 32 deg C. This error is because of program constraints: if the program is not sampling the values right, the command signal is going to stray away from the target. Here is why. Temperature is partly automatically decreasing without the VI. Initially, the natural temperature downfall is greater than the VI's command signal. This is because VI's parameters are small compared to what we may refer to as nature's parameters. It takes a while for the VI to execute. The instance between the sample taken and the code execution and control signal generation is of utmost importance. Suppose the sample was taken to be 45 deg C, and it took 10 ms for the code to execute and generate an error based on that sample which may not even be the temperature of the device after those 10 ms. This mismatch leads to inaccurate control signal generation. Therefore, the less frequent the sample taken the lesser the VI reacts and lesser the mismatch in that particular time and temperature scale.

Additional support material

Warm up and precautions

Connect the DAQ terminals as shown in the 'DAQ connection' section's figure below. Check DAQ's activity using NI Automation Explorer. Connect the power supplies as labelled. Before turning on any power supply, make sure the current swing is not at the limiting position. Make sure no stripped wires touch each other during the whole process. Make sure the supplies are properly made into +12V and -12V. **Regarding negative banana clips, connect them to the negative sign terminals written on the battery ports and not the ground sign terminals written on the battery port**, since this is a dual supply with one customized common ground (for explanation scroll above).

Open LabVIEW. Set the desired temperature of the device less than or equal to 100 deg C. Keep P=0.05, I=0.05, sampling frequency=1, number of samples=10. **Press 'Run' and not 'Run continuously' option** in the VI and wait for the device to achieve steady state, until stop button needs to be pressed.

Keep an eye on the current being drawn from the battery. After powering up the circuit and before running the VI, the current drawn must not be greater than 0.05 A from any of the two terminals. After running the VI, current is drawn from one of the battery terminals and the other terminal stays at nominal value of around 0.03 A.The terminal from which the current is drawn is seen to increase slowly upto a maximum of 1.3 A if setpoint is 100 deg C and the surrounding temperature from where the peltier took off is 22 deg C. So if too much current is being drawn from the terminals before or during the running VI, press the stop button and turn off the power supply. Look for any short connection while connecting wires and if the problem still persists, check for worn-out soldering of transistors, typically.Also, the VI is designed for a particular face of peltier. If after starting the peltier, the results are opposite, it means the thermistor needs to be placed on the other face.

DAQ connections

The original picture is attached with the main folder for a more readable version.

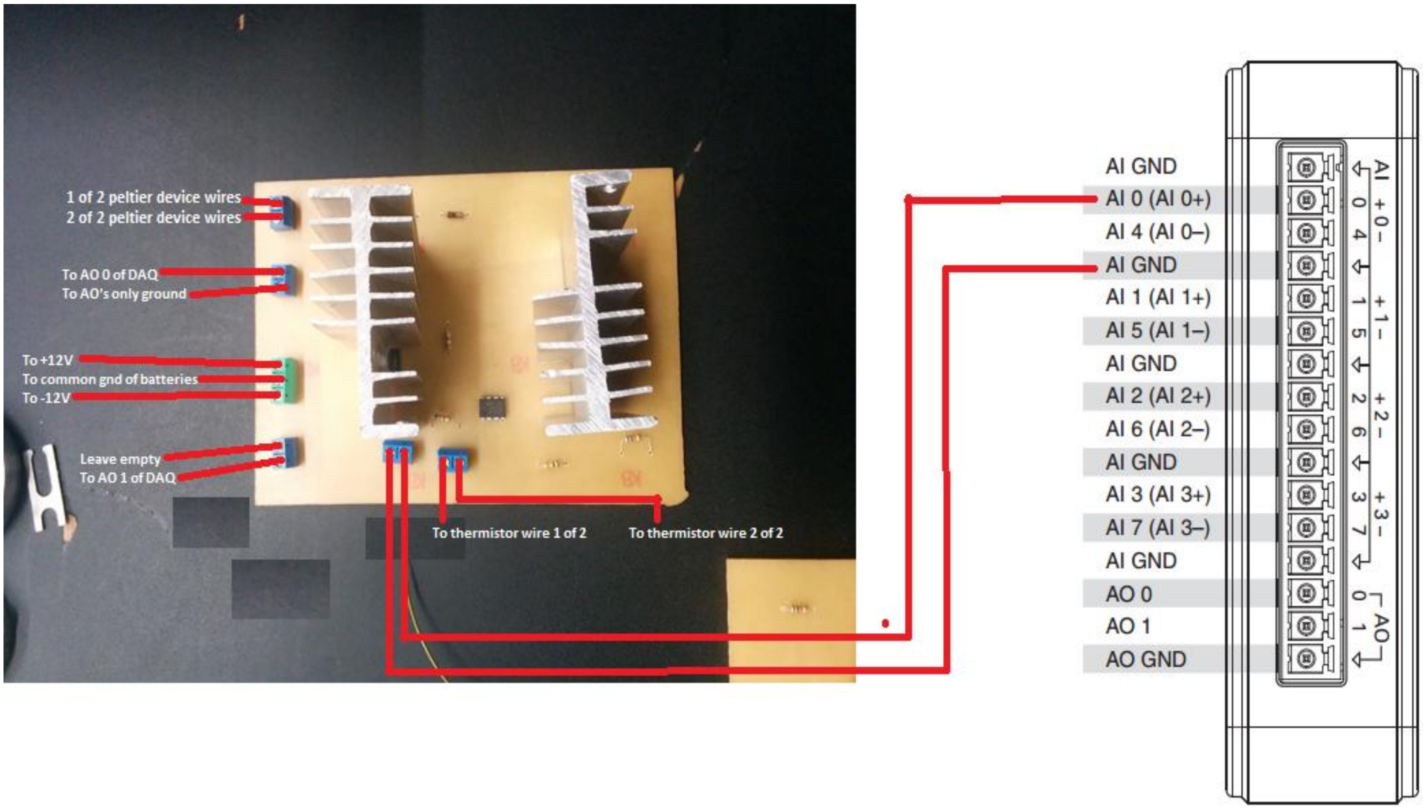


Figure 10: DAQ connections

Making a dual polarity power supply from independent power supplies

To make a dual power supply, consider a toy which needs two cells. We connect the two cells together by joining one positive end with the other's negative end. The other ends of course go to the toy's labelled ends accordingly. The same principal is applied in a power supply. Some power supplies come with 'series' and 'parallel' option but the method prescribed here applies also to those with no such option. Just make sure that while applying this method, the supply is at 'independent' mode, which means the terminals on the supply (if more than one) or two single terminal supplies are not internally connected in any way. Now, connect for example, the right side terminal's negative to the left side terminal's positive. A common ground has been established. Now as one swings both the terminals to let's say 5V, both terminals positives are 5V higher with reference to their originals ground terminals. But since the left terminal's positive was connected to right terminal's negative, the right terminal's positive was bound to be 5V higher and the left terminal's negative was bound to be 5V lower than the new ground. Hence the right terminal's positive is +5V and the left terminal's negative is -5V. One might as well argue that the left terminal's negative is 0V, the ground being at 5V and the right most terminal's positive at +10V, which is absolutely fine. It is the voltage difference that is of the essence.

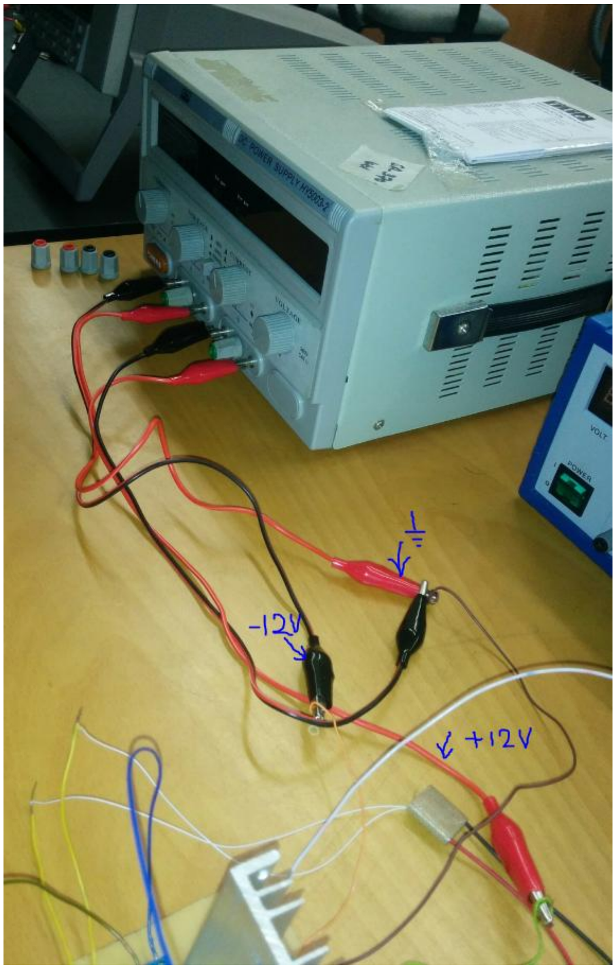


Figure 11: Dual Power Supply connections

Updates in the system

In this phase of the work, we set out to explore the precise reason why the system was not cooling down to low enough temperatures. It turns out that the Peltier device needs proper cooling to behave the way it is meant to. A new fan was installed whose effects on achieving low cooling setpoints were quite evident. Below is an image of the new cooling system.

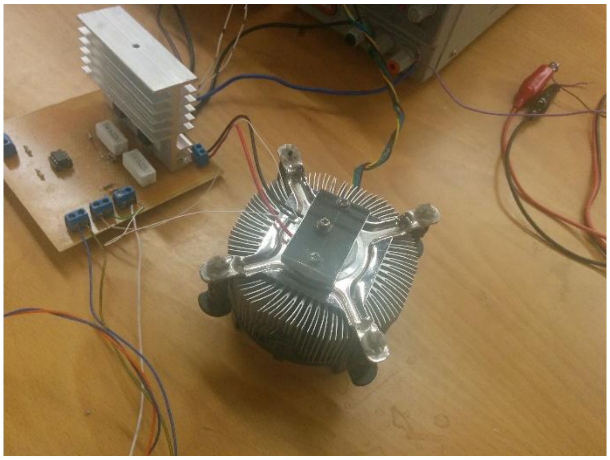


Figure 12: The new cooling system is essential for optimum device behavior

Moreover, we also modified the circuit diagram as shown in Figure 1, in order to increase the gain of the overall sense signal. This would help in sending a larger signal at the base of the transistors, hence drawing more current against same control signal value. This was needed to achieve set-points quickly against the same PI values.

In order to find out the optimum PI values against the range of temperature, manual tuning seemed suggestive. Here is a table that may give an idea of the trend followed by the system against changes in P and I values. The first row is recommended and is set as a reference for the rest of the rows, especially when comparing time taken to reach stability.

Temperature Reference to Set point (C)	P	I	Maximum Overshoot (C)	Time taken to stabilize (s) at 20kHz
20 to 70	2	0.0001	5	Stable with ±0.13 C oscillations, takes time 0.6t
20 to 70	20	0.0001	0	Greater than 2t
20 to 70	2	0.0005	28	t
20 to 70	0.5	1	40	Greater than 2t
20 to 70	1	0.5	20	Greater than 2t
20 to 70	0.1	0.1	20	Greater than 2t

Table: System behavior against changes in P,I values