Abstract

The triple Peltier temperature controller is capable of distributing power to between one and three thermoelectric elements in a stacked configuration. The controller attempts to maintain a preset temperature by switching current to the thermoelectric elements in a forward or backward direction when the temperature drifts outside of a preset range. The bi-directionality of the current switching allows control of thermoelectric elements in a heating or cooling capacity. The controller is also capable of switching DC electric heaters (or refrigerators) in a one-sided mode of operation.
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I. Practical Aspects of Thermoelectric Elements

A thermoelectric element is capable of pumping heat in one direction or another depending on the direction of the current applied to the element. Each thermoelectric element is capable of pumping a limited amount of heat: a quantity usually referred to as $Q_{\text{max}}$. Additionally, the maximum amount of heat pumped by a thermoelectric element is a function of the temperature difference between its two large faces, $\Delta T$. The specified $Q_{\text{max}}$ for a given thermoelectric element is usually specified at $\Delta T = 0$. Another specification for a thermoelectric element is the maximum temperature difference between the faces, expressed as $\Delta T_{\text{max}}$. When the temperature difference between the faces is equal to $\Delta T_{\text{max}}$, the heat pumping capability of the device is essentially zero. Furthermore, both $Q_{\text{max}}$ and $\Delta T_{\text{max}}$ are usually specified with either the hot or cold faces held at 25-30°C.

The amount and direction of heat pumped by a thermoelectric element is a function of the magnitude and direction of the current applied to the device. For example, in Figure 1, the direction of heat flow can be reversed when the direction of the current is reversed, and the magnitude of the heat flow in either direction can be controlled by varying the current flowing through the device. The maximum current that can be applied to a thermoelectric element is specified as $I_{\text{max}}$. The effective resistance of a thermoelectric element is a function of the heat flow, $\Delta T$, and the absolute temperature of the device faces, but regardless of this, the maximum voltage that should be applied to the device is specified as $V_{\text{max}}$. Exceeding $I_{\text{max}}$ or $V_{\text{max}}$ of a device can reduce the lifetime of the device. Thermoelectric devices also fail when either face of the device exceeds a maximum temperature specified as $T_{\text{max}}$.

![Figure 1. Illustration of heat pumping capability of a single thermoelectric element. When current is applied to the element in a cooling configuration, heat is taken from the cold side and transferred to the hot side of the element. The amount of heat exiting the hot side is greater than the heat entering the cold side due to electrical losses in the device.](image-url)

Since each thermoelectric device is capable of achieving only a limited $\Delta T$, the devices can be stacked to achieve a larger effective $\Delta T$. Figure 1 illustrates an important aspect of thermoelectric elements that must be considered when doing this. When electrical power is supplied to a thermoelectric device, the amount of heat flowing out of the device is greater than the amount of heat flowing into the device. The amount of heat
flowing out of the device is equal to the amount of heat flowing into the device in addition to some of the electrical power supplied to the device. The effective amount of heat pumped by an individual device is equal to the “heat in” quantity. If identical elements are stacked, only the top or bottom element can be operated at $Q_{\text{max}}$ and successively smaller currents must be applied to each remaining thermoelectric element in order to eliminate the possibility of supplying more heat than the successive elements can handle. This limits the maximum amount of heat that can be pumped through the stack of elements. Thus, when stacking thermoelectric elements, heat pumping capacity is sacrificed for a larger effective $\Delta T$.

When constructing devices from thermoelectric elements, it is necessary to provide a heatsink capable of sinking all of the heat produced by the devices. The heatsink keeps the devices running efficiently and prevents them from overheating. When attaching thermoelectric devices to a heatsink and to one another in stacked configurations, it is necessary to make good thermal contact between the devices and the heatsink. This is accomplished by ensuring all surfaces are smooth, clean, and mated with some type of thermal compound (i.e. silicone grease filled with TiO$_2$, graphite pads, or silver filled adhesive).
II. Controller: Principles of Operation

The triple Peltier temperature controller works in a simple on/off mode of operation. The definition of the set temperatures is shown graphically in Figure 2. The user can set the set temperature, $T_{\text{set}}$, and the temperature window size, $T_{\text{window}}$, via control knobs on the front panel of the instrument. When the actual temperature strays above $T_{\text{set}} + T_{\text{window}}$, the instrument recognizes a “too hot” condition. If the temperature falls below $T_{\text{set}} - T_{\text{window}}$, the instrument recognizes a “too cold” condition. The setpoints are designed with 0.1°C of hysteresis to prevent oscillations in the switching signals caused by slowly varying or noisy temperature signals.

In addition to adjusting the temperature setpoints, the user can also select the instrument’s response to “too hot” and “too cold” conditions with the heating selector switch. Selectable modes of operation include heat only (when too cold), cool only (when too hot), heat and cool, or no response. When the $T_{\text{window}}$ knob is set to zero and the heating selector switch is set to “heat” or “cool”, the instrument behaves like a standard on/off temperature controller with the set temperature defined by $T_{\text{set}}$.

![Figure 2](Image)

**Figure 2.** Three graphs illustrating the actual temperature ($T_{\text{actual}}$), the set temperature ($T_{\text{set}}$), and the temperature window ($T_{\text{window}}$) and the controller response to different temperature conditions over time, $t$. When $T_{\text{actual}}$, as read by a temperature sensor on the sample, falls below $T_{\text{set}} - T_{\text{window}}$, the controller responds by attempting to heat the sample. When $T_{\text{actual}}$ rises above $T_{\text{set}} + T_{\text{window}}$, the controller responds by attempting to cool the sample.

The controller switches currents through the individual Peltier devices using a modified H-bridge configuration as illustrated in Figure 3. In order to cool, the controller closes the blue switches, sending current from right to left in the diagram. When heating, the red switches are closed, causing current to flow in the opposite direction. The controller logic is designed to never allow both the blue and red switches to close at the same time. This condition would lead to a short-circuit of the power supplies.
The H-bridges shown in Figure 3 are designed to prevent overheating in stacked Peltier devices. This is accomplished by using three or fewer independent power sources, externally supplied. The three power sources should be current and voltage limited to protect the thermoelectric elements since the thermoelectric elements’ effective resistances change with temperature. They should be set such that $V_{hi} > V_{mid} > V_{lo}$. The individual voltages are determined by the respective heat pumping capabilities of the individual thermoelectric elements. For example, when cooling, $V_{mid}$ should be low enough to prevent $P_{mid}$ from overpowering $P_{hs}$, which is operating from $V_{hi}$. The temperature controller also supports single and dual stacks of thermoelectric elements. The connections necessary for the various modes of operation are shown in Table 1.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$V_{hi}$</th>
<th>$V_{mid}$</th>
<th>$V_{lo}$</th>
<th>$P_{s}$</th>
<th>$P_{mid}$</th>
<th>$P_{hs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 stacked</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2 stacked</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>1 alone</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Diagram illustrating the electrical connectivity of the three Peltier elements in a triple stack configuration. Each element is incorporated into a modified H-bridge. In order to cool the sample, all blue switches are closed and in order to heat the sample, all red switches are closed. When $V_{hi} > V_{mid} > V_{lo}$, overheating of the stacked Peltier elements is prevented. The controller contains circuitry designed to eliminate the risk of a short-circuit caused by closing the red and blue switches simultaneously.
III. Front Panel Controls, Connectors, and Indicators

Display -- An LCD display that shows the temperature selected by the display selector switch in °C. The display is simply a 0-2V meter that is internally connected to the “T1 out”, “T2 out”, and “T_{set} out” connectors on the front panel.

Display Selector -- The three positions of this switch, “T1”, “T2”, and “T_{set}” select the temperature that is displayed in the display window. *Note -- a design flaw in the instrument can cause harmful voltages to be applied to the display when no temperature sensors are plugged into “T1 in” or “T2 in”. If no temperature sensors are connected to “T1 in” or “T2 in”, leave the switch in the T_{set} position to protect the display circuit.*

Power -- This switch controls the instrument power and also switches the “V_{hi}”, “V_{mid}”, and “V_{lo}” power inputs.

T_{set} -- This knob controls the set temperature of the controller and has a total range of -55°C to 155°C. *Note -- operating the temperature controller at the extremes of this range may damage the temperature sensor or the Peltier elements. Check the specifications of the specific temperature sensor and Peltier elements used.*

T_{window} -- This knob controls the size of the temperature window the controller uses around the temperature determined by “T_{set}” (see Figure 2). The range of settings is from 0 to 2.5°C. To use the controller in a simple one-sided on/off application, set T_{window} to zero and the heating selector to either “cool only” or “heat only”.

T_{1 in} -- This three pin DIN connector is designed for use with the National Semiconductor LM35 temperature sensor. The pinout of this connector is shown in the following figure. The signal pin is internally connected to the -15V supply as specified in the LM35 datasheet for negative temperature output. The connector barrel shield is internally connected to signal ground. The LM35 sensor should supply a voltage...
corresponding to 10 mV/°C at the signal pin. Any voltage supplied to the signal pin outside the range -0.9 to 1.9 V (-90 - 190°C) will lead to the illumination of the “T1 error” indicator and the controller will not activate the thermoelectric elements. Furthermore, application of a voltage outside the range of -15 V to 15 V (referred to gnd) may permanently damage the instrument.

![Figure 5. T1 in and T2 in connector pinouts.](image)

**T1 error** – This indicator will light if the voltage at the signal pin of the “T1 in” connector is outside of the range -0.9 to 1.9 V. This can occur if no temperature sensor is connected to “T1 in”. When illuminated, the instrument will not switch the thermoelectric elements on.

**T2 in** – This connector is identical to that for T1 and serves as a supply/input for an additional LM35 temperature sensor. The temperature input to T2 plays no role in the function of the temperature controller.  *Note – If no temperature sensor is connected to this input, the display circuit can be damaged if the “display selector” switch is set at the T2 position. This condition can be eliminated by inserting a 300kΩ resistor between the +15V pin and the signal pin.*

**T1 out, T2 out, and Tset out** – These BNC connectors supply voltages proportional to the temperatures T1, T2, and Tset respectively (10 mV/°C). The T1 and T2 outputs are filtered (10 Hz low pass) and buffered (20 mA output max) forms of the original voltages.  *Note - When no temperature sensors are connected to “T1 in” and “T2 in”, voltage on the “T1 out” and “T2 out” connectors can be as low as -15V.*

**Heating Selector** – The heating selector has four positions to determine the mode of operation of the instrument. “Cool only” will switch the Peltier elements on in a cooling mode (see Figure 2) when T1 rises above (Tset + Twindow). “None” will not switch the Peltier elements on under any temperature condition. “Heat only” will switch the Peltier elements on in a heating mode (see Figure 2) when T1 falls below (Tset – Twindow). “Heat and cool” performs the operations of both “heat only” and “cool only” simultaneously.

**V_{hi}, V_{mid}, and V_{lo} inputs** – These red and black banana plugs are where the voltage/current controlled power supplies for each thermoelectric element are connected as per Table 1 and Figure 3. The three black terminals are internally connected to one another and are connected to the controller’s voltage ground. It is important that V_{hi} > V_{mid} > V_{lo} to prevent overheating in a stack of Peltier elements. Each voltage input can sustain 35 V at 10 A maximum. Currents significantly above 10 A will cause the protected MOSFET switches to open until they are recycled by the control logic. When a
voltage greater than ~5 V is successfully connected across each red and black input and the instrument is on, the green indicator light directly beneath the connectors should illuminate. These indicators are powered directly by the external supplies and consume 30-70 mA of current each. Note – The instrument has never been tested with currents greater than 3A. It would be wise to run a thorough test at these current levels before connecting it to anything important. Also, the ground voltage level is at no point connected to earth ground, though the instrument case is.

**P_h, P_mid, and P_s outputs** – These red and black banana plugs are where the heatsink, middle, and sample Peltier elements are connected. Lead determination for Peltier elements can be confusing. If connecting elements for the first time, make sure operation in cooling mode does not lead to heating and vice-versa. If the actual Peltier behavior is the opposite of that desired, simply flip the Peltier elements over or reverse their leads. The red and blue indicators above the Peltier connectors indicate when power is applied to each element in either a cooling or heating mode. These indicators are also powered by the external power supplies and consume 30-70 mA each. The voltages and currents supplied between the red and black Peltier connectors will be slightly smaller than the voltages and currents input at V_h, V_mid, and V_lo due to current consumption by the indicator lights and resistive losses in the MOSFET switches.

**Rear Panel** – The rear panel contains the line cable input, fuse holder, and two BNC logic-level outputs that indicate when the instrument is cooling or heating the sample.
Appendix A. Electronic Design

A.1 Power Supplies

The +15, +5, and -15V power supplies are of the standard regulated linear type. The supplies can source up to 100 mA of current each. This controller would work fine with only a +5V and a -5V supply with only a few minor changes. This would simplify construction and prevent the display circuit from being overloaded.
A.2 Temperature Input, Set, and Error

In the top circuit, the LM35 temperature sensor connects to the DIN connector and its voltage output is buffered by the first OPA2277 op amp. If ±5 V supplies are used, the 300kΩ tying the LM35 signal to the negative supply should be replaced as per the LM35 datasheet. This is followed by low pass RC filter (~10 Hz) to remove noise. The 100kΩ resistor in this filter may have been replaced with a smaller value prior to construction due to the input bias and offset current of the op amps.

In the bottom circuit, the resistor-potentiometer network connected between a precision 2.5V reference (LT1460-2.5) and its inverse supplies a voltage proportional to the set temperature (10 mV/°C). The 887Ω and 1.80kΩ resistors limit the set temperature to the range -55 to 150°C (-0.55 to 1.5 V). Temperatures at the extremes of this range may cause damage to the LM35 sensor(s) or the Peltier elements. In order to externally control the temperature digitally, a DAC could be inserted into the circuit in place of the potentiometer wiper or after the potentiometer buffer stage with a selector switch.

It should be noted that the output of the op amp buffering the potentiometer wiper is directly connected to the external Tset out connector. The INA131 instrument op amp multiplies the analog temperature difference by a factor of 100, yielding a temperature error output of 1 V/°C.
A.3 Temperature Window Comparator

The temperature window is set by the 10kΩ potentiometer on the left, and the window voltage corresponds to 1 V/°C. The temperature error voltage is filtered before being compared to the window voltage and its inverse by the LM311 comparators. The resistor networks around the comparators are designed with 0.1 V (0.1°C) of positive going hysteresis. This means if the upper window threshold is crossed from above by the temperature error, the threshold will shift upwards by 0.1V (0.1°C). This helps prevent oscillations in the comparator circuits caused by noisy signals.
A.4 Error Indication Circuit

The main purpose of this circuit is to generate a logic level signal if the temperature sensor goes out of range. The dividers hooked up to the +15V and -15V supplies set the threshold voltages for the error at 1.9V and -0.9V respectively. The signal $T_{filt,1}$ can fall outside this range in one of three ways: the temperature sensor is reading $T > 190^\circ C$ or $T < -90^\circ C$ (in which case the sensor should fail), there is no temperature sensor connected, or either the +15V or -15V supply drops significantly in magnitude. As a result, if a redesign were planned using only +5V and -5V supplies, the divider networks would need to be adjusted.
A.5 Heat and Cool Logic

The circuit shown above uses a 2-pole, 4-position rotary switch to select the heating and cooling signals with pole 1 controlling the heating signal and pole 2 controlling the cooling signal. The RC network in conjunction with the Schmitt trigger inverter provides a fully debounced logic signal. The second inverters in the circuit should be omitted in future designs.
The logic circuit shown above first receives signals from the window comparator circuit and determines if the temperature is too hot, too cold, or just right. If the “too hot” and “too cold” ranges overlap, the logic decides it is neither. This decision prevents short-circuits in the H-bridges shown in the next circuit. The logic then makes a decision to heat or cool based upon the “too hot” or “too cold” signals, the selector switch setting, and presence or lack of temperature error.
A.6 Modified H-Bridges

The modified H-bridge circuits shown above control the current to the thermoelectric elements. All switches in the bridge are either the IPS521 high-side protected MOSFET switch or the IRSF3010 MOSFET switch. Both switches have a maximum sustainable voltage of 35 V and are current protected at 10A. Currents over 10 A will cause the switches to open until the logic condition is reset.
A commercial display circuit was used in the construction of the Peltier controller. The rotary switch was connected to the display input to select reading of T1, T2, or the set temperature. Some voltages read by the display (T1 and T2) can be as high as +15V, which can damage the display. Using ±5 V supplies would eliminate this problem.
The circuits shown above cause LED’s to light when a voltage is applied to the red and black connectors. The circuit on the left is connected to the \( V_{hi} \), \( V_{mid} \), and \( V_{lo} \) connectors and supplies power to the green LED when the voltages are connected correctly. The circuit on the right is connected to the Peltier element connectors and supplies power to the red and blue LED’s when the controller is switched on to heat or cool. Both lighting circuits consume between 30 and 70 mA of current, depending on the input voltage.