Control Capability of the LDC-3916371 Fine Temperature Resolution Module

TECH NOTE

PURPOSE

This ILX Lightwave Technical Note discusses the theoretical capabilities of the LDC-3916371 Fine Resolution Temperature Control module, and presents empirical results of a capability study.

BACKGROUND

ILX Lightwave thermoelectric cooler controller (TEC) modules control temperature using a thermistor to close the feedback control loop. The module drives an excitation current through the thermistor, typically a 10kΩ (nominal) NTC type, and measures the voltage drop across the thermistor. The temperature control circuit and feedback loop are shown diagrammatically in Figure 1.

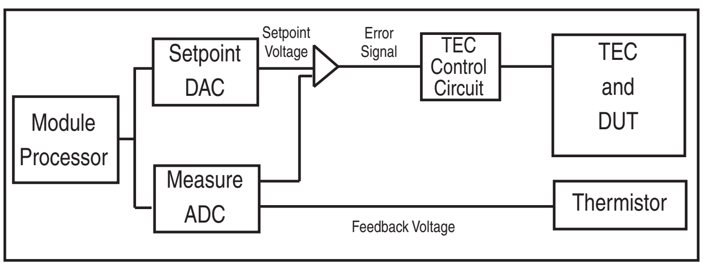

Figure 1 Temperature Control Circuit / Feedback Loop

The diagram shows that the set point digital-analog converter (DAC) converts the [digital] temperature set point value to an analog signal. This signal is input to a comparator, where it is compared to the voltage measured across the thermistor. If there is a difference between the set point voltage and the actual thermistor voltage, the control circuit drives current to the TEC in order to change the temperature measured by the thermistor and, therefore, the voltage across the thermistor. When the error signal is zero the voltage across the thermistor and the set point voltage are the same, and the load is at the set point temperature.

A very important point to note is that the controller uses the analog signal from the feedback thermistor directly; the signal is not converted to a digital value first. The analog feedback circuit results in much greater sensitivity to temperature errors, and operates faster than a control circuit that converts the feedback to a digital value.

Simultaneously, the measurement analog-digital converter (ADC) converts the thermistor voltage to a digital value. This value is converted first to a resistance, and then to a temperature using the Steinhart-Hart equation and three constants entered by the user. The resistance and temperature are displayed on the instrument front panel.

The standard TEC modules for the LDC-3916 mainframe use a 16-bit ADC for temperature measurement, and a 12-bit DAC for the temperature set point circuit. The result is that the module can measure temperature with a much finer resolution than it can set the temperature. This design method is preferred over the alternate, whereby the control resolution is finer than the measurement resolution. The second method results in a greater degree of measurement uncertainty, which means the user will not necessarily know the actual temperature of the load even though the apparent set point resolution is very good.

The LDC-3916371 Fine Resolution Temperature Control module uses a 16-bit DAC for the temperature set point circuit, so it is capable of setting the temperature to a much finer resolution than the standard TEC modules. On the LDC-3916371 module, the theoretical set point resolution matches the measurement resolution; both are 16-bit converters.

PERFORMANCE

Theoretical Performance

The resistance across a thermistors changes non-linearly with temperature changes. The non-linearity is most accurately modeled with the Steinhart-Hart equation which uses three constants to describe the shape of the curve. A typical curve for a 10 kΩ thermistor is shown in Figure 2.

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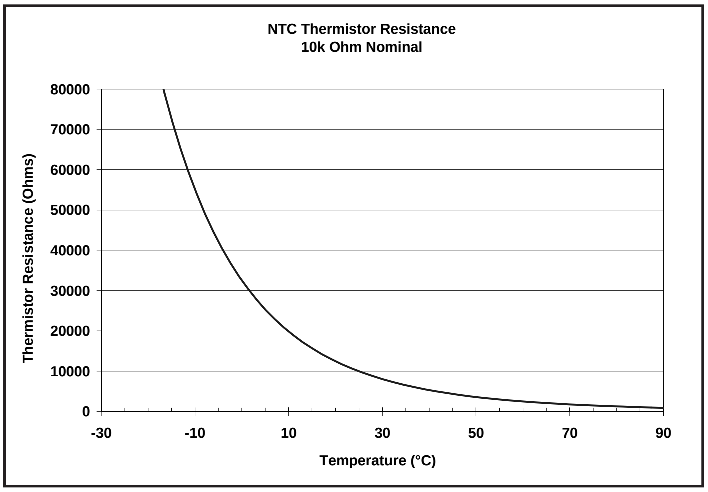

Figure 2 10kW Thermistor Curve

In addition to the higher resolution DAC, the LDC-3916371 module has a restricted set point range compared to the other modules. The restricted range further increases the effective resolution substantially by increasing the number of DAC steps per °C.

Table 1 presents calculated numbers for a typical 10kΩ thermistor around 25°C, and demonstrates the real control resolution difference between the 12-bit and 16-bit set point DACs.

Table 1
Calculated Thermistor Numbers

T	R	Vt 100 μA	ΔR/°C	ΔV/°C	°C/Bit (12-bit)	°C/Bit (16-bit)
27.78	8820	0.8820	-361.2	-0.0361	0.0338	0.0021
25.59	9702	0.9702	-402.5	-0.0402	0.0303	0.0019
23.43	10672	1.0672	-448.4	-0.0448	0.0272	0.0017
21.29	11739	1.1739	-499.4	-0.0499	0.0244	0.0015

Starting at the left side of the table and moving to the right: the T column presents a temperature value; R is the corresponding thermistor resistance for that temperature. Vt is the voltage across the thermistor at 100μA drive current. ΔR/°C is the resistance change per °C change; ΔV/°C is the corresponding change in voltage.

The DAC resolution, ΔV/bit, is determined by dividing the output voltage range of the DAC by the number of bits of DAC resolution. The voltage range of the DAC is 5V; divided into 2^{16} steps means that the voltage resolution is 76μV.

Finally, the ΔV/bit value is divided by ΔV/°C to give the °C/bit value. This simple demonstration of capability proves that the theoretical improvement in set point resolution for the 16-bit set point DAC is at least an order of magnitude better than the 12-bit set point DAC.

Another important point to realize is that the set point resolution is better at lower temperatures. This phenomenon is due to the non-linear nature of the thermistor response; the steeper R vs. T curve results in a greater number of DAC counts per degree, and therefore finer control resolution.

Actual Performance

Actual performance of the LDC-3916371 module was investigated using only the module itself to measure thermistor resistance. Keep in mind that all performance figures discussed in this section are for operating temperatures very near to 24°C; other operating temperatures will give different results because of the non-linear thermistor characteristics.

The study was conducted using both front-panel display values and GPIB queries. Table 2 shows the set point and measurement resolutions for different operational aspects of the LDC-3916 with the LDC-3916371 module, operated at approximately 24°C.

Table 2
Set Point and Measurement Resolution

	Front Panel Allowable Digits	Front Panel Actual Resolution	GPIB Allowable Digits	GPIB Actual Resolution	Theoretical System Performance
Temperature Set Point	0.00 °C	0.01 °C	0.0000 °C	**0.0017 °C**	**0.0017 °C**
Resistance Set Point	0 Ω	1 Ω	n/a	**0.8 Ω**	**0.76 Ω**
Temperature Measurement	0.00 °C	0.01 °C	0.0000 °C	**0.0017 °C**	**0.0016 °C**
Resistance Measurement	0 Ω	1 Ω	0.0 Ω	**0.8 Ω**	**0.76 Ω**

* Bold numbers indicate that the actual performance is dependent on the temperature set point. These values are for operation near 24°C.

Minimum Resistance Measurement Resolution
First, an active TEC and thermistor were connected to the module. Then the TEC controller was switched on in Temperature Control mode, and the set point changed so that the temperature ramped to 25°C from the ambient temperature of approximately 23°C. The thermistor resistance, as measured by the module, was recorded via GPIB every 1 second until the module reached the set point temperature. The minimum resistance change registered by the module is 0.8Ω; with a thermistor drive current of 100μA, the minimum voltage measurement resolution is 80μV. Recall that the predicted value, from the theoretical performance evaluation, is 76μV/bit.

DAC Control Mode

A feature of the LDC-3916371 module is the DAC control mode. This mode allows the user to set the actual set point DAC count for the controller to reference, rather than a temperature or resistance that the controller converts to a DAC count.

Operating in DAC mode, it is easy to figure out how many DAC counts are equivalent to a temperature or resistance change. Since the thermistor characteristics are non-linear, it is important to only measure the steps/°C over a small range, perhaps 0.5°C or 5Ω.

Table 3 shows actual performance numbers from DAC mode, including the DAC set point, the controller-calculated equivalent temperature and resistance, and the actual-reported temperature and resistance. The right-most column, °C/Steps, is calculated and exactly matches the predicted performance capability.

Table 3
DAC Mode Performance

DAC Set	T_{eq}	R_{eq}	$T_{display}$	$R_{display}$	°C/Step
12855	25.00°C	10024Ω	25.00°C	10024Ω	
12955	24.82°C	10102Ω	24.82°C	10102Ω	-0.0018
13055	24.64°C	10180Ω	24.64°C	10180Ω	-0.0018
13155	24.47°C	10258Ω	24.47°C	10257Ω	-0.0017

Constant Temperature Control Mode

For this test the controller was set to Constant Temperature control mode. The set point was changed by 0.01°C and the controller allowed to stabilize for a minimum of five minutes before the resistance was recorded from the instrument. Table 4 shows the results of the constant temperature mode study.

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Table 4
Constant Temperature Mode Data

T_{set}	$T_{display}$	$R_{display}$	R_{GPIB}	$\Delta R_{display}$	ΔR_{GPIB}
24.40	24.40	10289	10288.9		
24.41	24.41	10287	10286.6	-6	-3.8
24.42	24.42	10281	10282.0	-4	-3.9
24.43	24.43	10275	10274.2	-5	-5.8

The results of this study show that the controller is capable of controlling to exactly the temperature set point, with 0.01°C resolution. Notice that the thermistor resistance does not necessarily change the same amount between temperature steps, verified both via GPIB and from the front-panel display. Another point worth noting is that the $R_{display}$ and R_{GPIB} values do not match exactly. The values were not read at the same time, and since the resistance measurement resolution is finer than the temperature display resolution, the controller will actually wander over a few ohms of thermistor resistance while still reading the same temperature.

Although this result may initially be somewhat alarming, it is worth mentioning again that the temperature is calculated from the resistance using the Steinhart-Hart constants, and that a temperature difference of 0.01°C is represented by a range of several ohms. Figure 3 shows the situation more clearly.

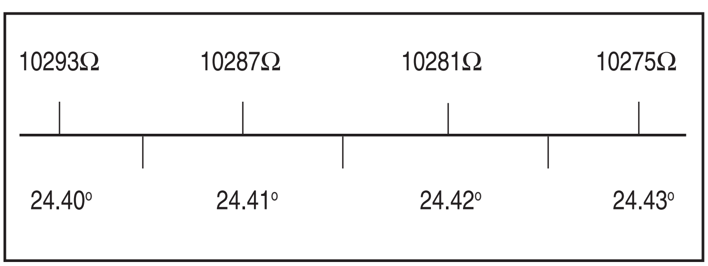

Figure 3 Resistance vs. Temperature Relationship

Constant Resistance Control Mode

The final control mode that is useful for maintaining a constant temperature is constant resistance mode. This mode is essentially the same as constant temperature, except the Steinhart-Hart equation is bypassed and the user enters the actual thermistor control resistance. This mode is more accurate than Constant Temperature control mode, but not as accurate as DAC mode.

The actual thermistor control resolution is 1Ω, which equals approximately 0.0016°C temperature control resolution at 24.4°C. This resolution can also be verified by changing the resistance set point 1Ω at a time: six discrete 1Ω steps are required before the temperature changes by 0.01°C.

Constant Current Control Mode

The 3916 TEC modules also offer another control mode, whereby constant current is driven to the thermoelectric cooler. Although the current set point resolution is very fine, 10mA, this control method is “open loop” with respect to the load temperature, and does not offer any means for controlling the actual temperature of the load.

If the thermal load on the TEC changes at any time, the module does not react to the load change and the temperature will vary from the present value. The only means for controlling the temperature in constant current mode is to use an external software loop to detect temperature changes and adjust the drive current accordingly. Such a control loop would be exceptionally slow to react to thermal load changes because adequate time would have to be allotted for the temperature to stabilize at the new drive current level before another adjustment could be attempted.

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The temperature change effected by a 10mA change in TEC drive current is entirely dependent on the ambient conditions, the thermal load, heat sinking, and the present operating point of the TEC. All of these conditions combine to make the temperature change with respect to drive current change highly unpredictable.

For this report, no effort was made to characterize constant current control mode since it is not a practical method for controlling temperature, especially if precise temperature stability is required.

CONCLUSION

The LDC-3916371 Fine Temperature Control Module offers a marked improvement in temperature control accuracy and set point resolution over the TEC control circuitry in the other LDC-391637X modules. The increase in resolution is due to the higher resolution 16-bit set point DAC, which gives a finer minimum step size, though at a reduced total control range.

Temperature set point and measurement resolution are substantially increased when the instrument is operated via GPIB because there are no front-panel space constraints to limit the number of digits. Even though the GPIB set point resolution for temperature set point is 0.0001°C, the instrument is still, of course, limited ultimately by the DAC and ADC resolution. For operation about 24°C, the ultimate temperature set point and measurement resolution is about 0.0017°C.

The control resolution was measured using only the LDC-3916371 module, so the absolute temperature accuracy was not tested as part of this procedure. Separate tests conducted by ILX during qualification of the design specified the absolute accuracy at 0.2°C, and this specification limit is dominated by the accuracy of the Steinhart-Hart constants entered by the user.

The resistance measurement accuracy of the module is ±5Ω, which translates to approximately 0.017°C at 24°C. Therefore, if the exact temperature-resistance characteristics of the thermistor are known and the module is operated in constant resistance mode, the expected temperature accuracy is ±0.009°C.