Controlling Temperature and the Controller Contest

1.0 Expected Learning Outcomes

- Gain experience in using a computer to control external hardware.
- Develop a real-time control system for an experiment.

2.0 Introduction

You will build a computer-based temperature controller that will be used to control the temperature of your cryostat assembly in the range from 50 °C to 100 °C.

Sections 6.7.8 (`Control Systems`) and 8.2 (`The Control of Temperature`) in the text contains information that will be useful in completing this exercise. In fact, you will find this information useful in nearly anything you do that requires controlling hardware. This may include your self-driving car, the neat self-landing drone you purchased, or an advanced automatic lawn sprinkling system that uses temperature, wind, and soil moisture to determine when and for how long to water. Some of this even comes into play in the mental processes you use to negotiate a busy freeway in a car.

3.0 Temperature controller contest

To give you the incentive to develop a quality computer-based temperature controller, we will have a contest between the teams. The required sequence to complete the contest is to

1. Begin at a temperature below 50 °C. The contest time will start when the temperature reaches 50 °C.
2. Raise the temperature to 100 °C.
3. Hold the temperature within ± 0.5 °C for 2.5 *continuous* minutes – if the temperature goes out of range, the timer must be restarted.
4. Cool the temperature to 70 °C.

5. Hold the temperature within ±0.5 °C for 2.5 *continuous* minutes. The contest time will end when this time elapses.

The contest will be to see which team can achieve the shortest time to complete the above sequence. Each member of the team that does this in the shortest time will win a prize. The contestants may use any means at their disposal to make their cryostat heat up or cool down quickly with the following limitations:

1. The contestants may not *manually* disturb the cryostat system (including the coolant) after they start the run. Any action that can be completed entirely under computer control *without any manual intervention* is allowed.
2. The contestants may not change anything on the computer once the run starts.
3. Any modified cryostat heating blocks must retain the original outside and inside diameters and lengths. The cap may not be modified. The internal cavity walls must not be perforated.
4. No power source other than *one* Kepco ATE36-8m supply may be used for the actual heater power.
5. Your LabVIEW program must make all the decisions on whether you are in range of the target value, when you have been in range long enough, and when to switch to a new target value.
6. Your program must maintain a total elapsed time counter showing the total time that has elapsed since the temperature went above 50 °C.

4.0 Equipment

The available equipment for this exercise includes all the equipment necessary for the Thermal Measurements Lab.

5.0 Grading

The grading will be as follows:

- Successfully controlling the temperature of your cryostat assembly over the specified sequence – 40 pts.
- Lab notebook – 40 pts.

You will receive full credit for the controller (for grading purposes) if your computer completes the sequence, regardless of how long it takes to get there (within the bounds of the 170-minute length of a standard class period). The contest is intended to see how creative you can get in making your controller work well.

Your lab notebook entries for the controller and contest will be graded. It is good practice to keep track of

- why you chose the particular method of controlling
- any special information on how you wrote your controller
- any constants needed to make your controller work
- since you will likely be changing these constants in the process of tuning your controller, it is good to keep track of how you have changed them in case you have to revert to a previous set of values.

Valid heating time trials must be made while the instructor or one of the TAs is monitoring your controller.

6.0 Selecting the proper control variable

If possible, your control equation should provide an output controlling value (power supply output) that is linearly related to your controlled value (temperature in this case).

Solving the differential equation derived in section 12.2 in Thermal Measurements Lab: Heating and Cooling of the Cryostat Assembly (Learning Suite, `Content` ⇒ `Thermal Measurements Lab` ⇒ `Thermal Measurements Lab`)

$$T(t) \;=\; T_{\text{eq}} + \frac{P}{\gamma} + A\,\mathrm{e}^{-\gamma\, t/C}$$

where A is a constant determined by the temperature at $t = 0$.

Note that T and P are linearly related in this equation since T_{eq} is a constant, and the exponential term is essentially constant over the control update interval. That means the power would be the logical choice for a controlling variable.

Since we can only control the output voltage of the power supply, it will be necessary to convert the power specified by the control equation to the power supply output voltage necessary to deliver that much power to the heating coil. It may be useful to remember that $P = V^2/R$ where R is the resistance of your heating coil and V is the voltage across the coil.

Also, remember that P may be negative (*i.e.* your temperature is too high, and the controller wants to reduce the temperature by removing power). If P is negative, you will end up with the square root of a negative number to arrive at V. If the power is negative, you want to have the supply provide no power.

7.0 Controlling the Kepco power supply

The power for your heating coil will be provided by the large gray Kepco ATE-36-8M power supply (the manual for this supply can be found at `http://www.kepcopower.com/support/ate-operator-half-rack-r1.pdf`.

- This supply is capable of simultaneously supplying 0-36 V and 0-8 A if the load allows that to happen. In other words, once the supply is providing 8 A, any attempt to increase the voltage by adjusting the power supply controls will result in no change. Similarly, once it is providing 36 V any attempt to increase the current will result in no change. You can use the `voltage` and `current` control knobs to change the maximum allowed output voltage or output current respectively. Once the output reaches one of the two maxima, the light above the appropriate knob will be illuminated. For instance, if you have the current knob set to allow a maximum of 6 A, when the supply is providing the specified 6 A the light above the current knob will be illuminated indicating that the output is being controlled by the value set with that knob.
- On the back of the Kepco power supply, there is a black box with a switch and a BNC connector on it. The switch determines whether the output **voltage** is set by the knob on the front panel or by the control voltage applied to the BNC connector. Most of the power supplies are configured so that the switch is *down* for *remote control*.

  Only the *voltage* can be externally controlled. The current is always controlled by either the current knob or the resistance of the load, whichever results in the smaller current.

  Note: You can determine the status of the supply (whether remote or local control) by turning the voltage control knob and seeing if the output voltage changes. Before you try this, turn the current knob clockwise several turns so that the light above the voltage knob is on, indicating that the supply is controlling on voltage and not current.

  It is strongly recommended that you *not* perform this test with the power supply connected to your heater coil.
- As noted above, you can only control the output voltage with the voltage applied to the BNC connector. The current is determined by the load resistance unless your current exceeds either the current set by the current control knob or the maximum limit of the supply (8 A) is reached.

- The control voltage must be in the range of 0–10 V to achieve an output voltage of 0–36 V. Thus, the output voltage is given by $V_{\text{output}} = 3.6 * V_{\text{control}}$.

  Caution: the circuit breaker on the supply will turn off the power supply if you try to output 36 V. It is usually best to limit the control voltage to about 9.8 V or less.

8.0 Controlling the heater with a simple model

It is possible to use the simple analytical model and your knowledge of differential equations to develop a method to control the temperature of the cryostat. This is a powerful method that is used to control a wide variety of systems including robotics.

As noted above, the equation that governs the temperature of the heater block (with a few key assumptions) is

$$T(t) \quad = \quad T_{\text{eq}} + \frac{P(t)}{\gamma} + A\,\mathrm{e}^{-\gamma\,t/C}\,.$$

We have explicitly noted that the power will be a function of time when we are controlling.

You should have already determined T_{eq}, γ, and C by fitting this equation to your heating and cooling curves in the previous exercise. You can control the temperature using the following algorithm:

$$e(t) \quad = \quad T_{\text{target}} - T(t)$$

where T is the current temperature, T_{target} is the desired temperature, and $e(t)$ is the error term giving the difference between the two. For $e(t)$ to approach zero in a fast but smooth way, we require it to decrease exponentially, *i.e.*,

$$e(t) \quad = \quad B\,\mathrm{e}^{-\alpha t}$$

where B is the initial value of $e(t)$. The advantage of this is that it has a very simple derivative

$$\frac{\mathrm{d}e(t)}{\mathrm{d}t} \quad = \quad -\alpha\, e(t)\,.$$

When T_{target} is constant we obtain the following expression linking power P, temperature T, and desired temperature T_{target}

$$\begin{aligned}
\alpha(T_{\text{target}} - T) &= \alpha\, e(t) \\
&= -\frac{\mathrm{d}[T_{\text{target}} - T(t)]}{\mathrm{d}t} \\
&= \frac{\mathrm{d}T(t)}{\mathrm{d}t} \\
&= \frac{1}{\gamma}\frac{\mathrm{d}P(t)}{\mathrm{d}t} - A\frac{\gamma}{C}\mathrm{e}^{-\gamma\, t/C}\,.
\end{aligned}$$

If we solve the original equation for $A\,\mathrm{e}^{-\gamma\, t/C}$ and substitute that into this equation we get

$$\begin{aligned}
\alpha\, e(t) &= \frac{1}{\gamma}\frac{\mathrm{d}P(t)}{\mathrm{d}t} - \frac{\gamma}{C}\left(T - T_{\text{eq}} - \frac{P(t)}{\gamma}\right) \\
&= \frac{1}{\gamma}\frac{\mathrm{d}P(t)}{\mathrm{d}t} + \frac{P(t)}{C} - \frac{\gamma}{C}(T - T_{\text{eq}})\,.
\end{aligned}$$

We can then solve this equation for $P(t)$

$$P(t) = C\,\alpha\, e(t)) + \gamma(T - T_{\text{eq}}) - \frac{C}{\gamma}\frac{\mathrm{d}P(t)}{\mathrm{d}t}\,.$$

In a real experiment, this controller can be sensitive to changes in the constants (C, γ, and T_{eq}). C and γ are mostly associated with the physical dimensions and materials of your heater block and rod. T_{eq} is a little trickier because it depends on what your ice bath is doing, such as how much ice you have left in the bath at any given time.

9.0 PID controller model

A PID controller is a common control method that works very well with essentially no information on the physics of the process being controlled.

The name, PID controller, is an acronym for the three terms used to determine the control output value.

P=proportional - this term produces a control output that is proportional to the difference between the target value and the current value.

This term gets the controlled value close to the target value as quickly as possible.

I=integral - this term produces a control output that is proportional to the integral over some period of the difference between the target value and the current value.

This term does the last little bit to bring the value to the target value if there is a residual error.

In some cases, the integral term can cause a controller to become unstable and begin to oscillate. If the controller becomes unstable, it may be possible to stabilize the controller by reducing the constant K_I or changing the interval over which the error is being integrated.

D=derivative - this term produces a control output that is proportional to the rate of change of the *difference* between the target value and the current value.

This term helps to suppress overshoot by slowing down the change as you approach the target value and to damp out oscillations.

Sometimes it is necessary to reduce the constant K_D or leave the derivative term out if the controller becomes unstable.

Mathematically, this process looks something like

$$\text{control}(t + \delta t) = K_P\, e(t) + K_I \int_{t_0}^{t} e(\tau)\, \mathrm{d}\tau + K_D\, \frac{\mathrm{d}e(t)}{\mathrm{d}t}$$

where $e(t)$, the error term, is given by

$$e(t) = T_{\text{target}} - T(t)\,.$$

Since we are controlling power (the linear variable) this equation becomes

$$\mathrm{P}(t + \delta t) = K_P\, e(t) + K_I \int_{t_0}^{t} e(\tau)\, \mathrm{d}\tau + K_D\, \frac{\mathrm{d}e(t)}{\mathrm{d}t}\,.$$

A good introduction to a PID controller can be found in the text in Section 8.2.2 (`Temperature Control at Variable Temperatures`) and in the Wikipedia article on this topic.

In the paragraph before equation 8.7 in Section 8.2.2 of the text, there is a reference to "background power." In our case, we know that maintaining a constant temperature requires a background power roughly equal to $P_{\mathrm{B}} = \gamma\,(T - T_{\mathrm{eq}})$ which is approximately the power that is being lost to the ice bath at temperature T. This may be useful in designing your temperature controller.

9.1 Tuning a PID controller

The most difficult aspect of this controller is determining the values of K_P, K_I, and K_D. There is no obvious physics in the controller. You can get some guidance in picking the constants, especially K_P, by looking at the equation on p. 6. You can also find guidance in determining the constants in the Wikipedia article, but it is necessary to tune the controller constants specifically for your particular system and algorithm.

Opto 22, a company the manufactures PID control modules, has some very good information on PID controllers including an excellent technical note (`http://documents.opto22.com/2171_PID_Loop_Tuning_Technical_Note.pdf`) describing the controllers and some guidelines on tuning them. They also have an online PID loop tuner (`http://www.opto22.com/site/pid.aspx`) that you may find useful.

10.0 Some useful LabVIEW functions

In Range and Coerce is a very useful function. This function will accept a value as well as an allowed range for that value. It will provide an output value that is forced to be within the specified range. If the value is too large, the output will be set to the maximum value of the specified range. If the value is too small, it will be set to the minimum value of the range. If the input value is within the specified range, it will be passed to the output unchanged. The function will also return a boolean value indicating whether the value is within the specified range.

A separate `DAQ Assistant` VI is used to provide an output voltage. This VI is separate from the DAQ Assistant VI you use to acquire the voltage across the diode.

- Set the `Generation Mode` in the configuration screen to `1 Sample (On Demand)`. In this mode, the VI will continue to output the last value set by the VI until a new value is specified.

The `Elapsed Time` VI is a handy timing VI (the "<execution control>" and "<timing>" versions are the same VI). Look carefully at the `Reset`, `Auto Reset`, and `Time Target (s)` inputs as well as the `Time has Elapsed` and `Elapsed Time (s)` outputs. By correctly specifying the values on the inputs and monitoring the correct output(s) you can have this VI perform some of the apparently magical things required for your controller to function properly.

A "shift register" can be an effective way to preserve a value between successive executions of your while loop.

When you are working on tuning the constants for your controller, it is often useful to make any constants front-panel controls. Using controls allows you to make changes to the controller without having to stop it.

11.0 Integrals and derivatives of experimental data

Because real (noisy) data is used in the control process, it is necessary to be very careful when taking derivatives. The derivative of noisy data using adjacent points will result in very large swings in the derivative. It is often possible to use smoothing techniques to reduce that noise and achieve a better value. For example, if we use the most recent j points we will get a derivative that is effectively averaged over $j-1$ time intervals:

$$\frac{\mathrm{d}e(t)}{\mathrm{d}t} = \frac{e(t_i) - e(t_{i-j+1})}{(j-1)\Delta t}$$

where Δt is the time between successive samples in the $e(t)$ array. Note that it is necessary to have some past values to take this derivative.

The integral term also requires some consideration in the PID controller since you will start with the temperature far from the target temperature and it may not be desirable to integrate up a lot of large error that doesn't correlate with the behavior of the system when near the target temperature.

Remember that the integral is just a Riemann sum:

$$\int_{t_0}^{t} e(\tau)\,\mathrm{d}\tau = \sum_{\tau=t_0}^{t} e(\tau)\,\Delta t\,.$$

The integral can either be computed from an array of recent past values or by keeping a running sum of $e(t) * \Delta t$. It may be necessary to limit the number of past values used for the integral. It is usually necessary to reach back at least far enough in time to integrate over several oscillations of the temperature. If the integration interval is too short, this term can act as a positive feedback for any oscillations.

12.0 Making your controller work

Once you have the controller program written, it is necessary to tweak it to work properly. Hopefully, you have taken the advice given earlier and made all the constants governing the operation of your controller into front panel controls. This will allow you to make changes to the controller's operation without having to stop and edit the program. It also means that you will need to keep a record of what you have been using as constants because the computer won't remember them for you.

You should probably read the section on debugging software in The Art of Debugging (`Content ⇒ The Art of Debugging` in Learning Suite).

The use of indicators to watch how the output power is calculated can be very handy in determining whether you choice of constants is correct.

The Wikipedia article on PID controllers referenced earlier in this chapter has some good hints on how to determine the initial constants for a PID controller. The technical note from Opto 22 should also be useful.

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